THE SYNTHESIS AND DESIGN OF VOLTAGE-MODE MULTIFUNCTION FILTERS USING COMMERCIALLY AVIABLE IC: LT1228 AND THEIR APPLICATION TO ACTIVE FILTER DESIGN EDUCATION

MAY PHU PWINT WAI

A THESIS REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY IN ELECTRICAL ENGINEERIN EDUCATION

SCHOOL OF INDUSTRIAL EDUCATION AND TECHNOLOGY

KING MONGKUT’S INSTITUTE OF TECHNOLOGY LADKRABANG

2023

KMITL-2023-ED-D-248-035

Thesis Title	THE SYNTHESIS AND DESIGN OF VOLTAGE-MODE MULTIFUNCTION FILTERS USING COMMERCIALLY AVAILABLE IC: LT1228S AND THEIR APPLICATION TO ACTIVE FILTER DESIGN EDUCATION
Student Name	Ms. May Phu Pwint Wai
Student ID	62603017
Degree	Doctor of Philosophy of Education
Program	Electrical Engineering Education (International Program)
Year	2023
Thesis Advisor	Associate Professor Dr. Winai Jaikla

ABSTRACT

In this research work, there are five proposed filters: four single input multiple output (SIMO) and multiple input single output (MISO) universal filter. The synthesis of the five proposed filters is based on the two loop integrators. The three proposed filters are the electronically controllable voltage-mode (VM) biquad universal filter with one input and three outputs. The fourth proposed filter is the electronically controllable VM biquad universal filter with one input and four outputs. The fifth proposed filter is an electronically controllable VM biquad universal filter with three input and one output. The three proposed filters can simultaneously provide four filtering functions: low-pass filter (LP), high-pass filter (HP), band-pass filter (BP), while the fourth proposed filter can simultaneously provide four filtering functions: LP, HP, BP, band-reject filter (BR) without changing its topology. The fifth proposed filter can simultaneously provide five filtering functions: LP, HP, BP, BR, and all-pass filter (AP) without changing its topology. The parasitic elements of LT1228 are studied and investigated. The performance of five proposed filters is simulated and experimented with LT1228. The results show that they are in good agreement with the expectations such as electronically tuned between the natural frequency (ω_0) and the quality factor (Q). Moreover, some proposed filters can provide the independent tuned of Q without disturbing of ω_0 and some output voltage nodes can provide the low output impedance.

Some proposed LT1228's filters are chosen as the application to provide an instructional package for Active Filter Design. The sample group consisted of 20 second-year students from the Department of Engineering Education, School of Industrial Education and Technology, King Mongkut's Institute of Technology, Ladkrabang (KMITL). According to the research result, it was found that 1) The opinions of five experts about the quality evaluation of the instructional package are divided into 5 sections which are firstly lesson plan based on the MIAP learning model: the overall opinion of the five experts is in good level of suitability (average = 4.47, S.D = 0.57), and secondly laboratory sheets: the overall opinion of the five experts is in very good level of suitability (average = 4.52, S.D = 0.52), and thirdly power points: the overall opinion of the five experts is in good level of suitability (average = 4.20, S.D = 0.68), and fourthly experimental set: the overall opinion of the five experts is in very good level of suitability (average = 4.63, S.D = 0.51), and finally, achievement test and quizzes sheet: the overall opinion of the five experts is in good level of suitability (average = 4.30, S.D = 0.50). According to the data, the efficiency of the analog filter design course E_1/ E_2 was 92.58/90.00, exceeding the 80/80 requirement. In the active filter design course, student satisfaction was likewise determined to be at a satisfactory level (average = 4.47, S.D = 0.66). In conclusion, the instructional package can be utilized to efficiently teach analog filter design while also enhancing the learning experience. Future classrooms may incorporate more sophisticated technologies to improve students' learning outcomes.

Keywords: Active Filter, Voltage-mode Filter, MIAP Learning Model, Instructional Package

ACKNOWLEDGEMENT

I am delighted to use this opportunity as an international student from Myanmar to offer my sincere gratitude to the professors who guided and assisted me throughout my doctoral study.

First, I would like to sincerely thank my advisor, associate professor Dr. Winai Jaikla. I got his many helpful suggestions and materials while performing my research. Now I have a deeper understanding about my thesis and self-improvement due to his patience and guidance.

Second, I would like to thank the members of the thesis examination committee for their insightful comments and recommendations.

Third, I would like to express my gratitude to all my professors, subject matter experts, my juniors Worawut and Wongsakorn and the staffs of the Department of Engineering Education, School of Industrial Education and Technology, King Mongkut's Institute of Technology, Ladkrabang (KMITL) for their kind assistance and generosity throughout my time as a student there.

Finally, I would want to extend a particular thank you to my cherished parents who have always been nice and supportive of me.

MAY PHU PWINT WAI

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

Page

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Cont.)

LIST OF ABBREVIATION

ABB	Active Building Block
SIMO	Single Input Multiple Output
MISO	Multiple Input Single Output
IC	Integrated Circuit
LP	Low-pass
HP	High-pass
BP	Band-pass
BS	Band-stop
AP	All-pass

CHAPTER 1

INTRODUCTION

This chapter describes a brief overview of the research work that presents the statement of the problem, objectives of the study, hypothesis, conceptual framework, limitations of the study, definition of key terms.

1.1 Statement of the Problem

Filters are one of the essential components of signal processing and are widely used in many electronic devices. In terms of elements used in the filter design, filters can be broadly divided into two categories: active filters (using active components such as transistors, Operational Amplifiers (op-amps), and Operational Transconductance Amplifiers (OTAs) in addition to resistors, inductors, and capacitors) and passive filters (using resistors, capacitors, and inductors) (Sedra & Smith 1991). The analog active filters are only focused on being described in this thesis. The synthesis and design of circuits employing an Active Building Block (ABB) to produce new active circuits has gained a lot of attention in analog signal processing systems. The utilization of active building blocks in circuit design results in a structure that is compact and has fewer passive elements. Some active circuits based on the active building block can cascade without the use of extra buffers. Furthermore, the circuit characteristics of the active circuit produced from the electronically controllable ABB can be easily controlled by the microcontroller, which is critical for modern analog signal processing circuits. The feature of electronic control is important in modern analog signal processing circuits. This is because changing the circuit components (resistors, capacitors, and inductors) on the Printed Circuit Board (PCB) that will change the circuit parameters is not easy (Chen & Yang 2017); (Faseehuddin 2021); and (Wang 2019).

Although, the design of circuits to be configured into an integrated circuit has numerous advantages, such as high circuit efficiency, small size, low voltage, and low power, among others. The implementation of an integrated circuit, on the other hand, is pricey. When mass-produced, this approach will be cost-effective. As a result, employing a commercially available ABB in circuit design for specific applications is a more appealing and cost-effective option (Jaikla et al 2020); (Maheshwari and Ansari 2012). Analog circuits made using commercially available ABB for use in specific applications have been published in the open literature on a regular basis (Dogan & Yuce 2020); (Yuce & Minaei 2021); and (Senani et al 2021).

Several decades ago, the transconductance gain g_m of the OTA could be continuously controlled by an external voltage or current which provides an electronic tune to circuit parameters. In the past few years, a lot of commercially available transconductance amplifiers have appeared, such as the CA3080 (Intersil), LM13600 and LM13700 (National Semiconductor), (CA3080: Intersil, 1999; LM13600: National Semiconductor, 1999; LM13700: Texas Instrument, 1999-2015) etc. The LT1228 integrated circuit by Linear Technology is one of the intriguing elements (LT1228: Linear Technology, 2012). It comprises two independent subcircuits: the OTA, whose transconductance g_m can be adjusted by external DC (Direct Current) bias current I_B, and the Current Feedback Amplifier (CFA), which can be used, e.g., as a buffer. This active device, LT1228, has many advantageous features, for example, fast transconductance amplifier, wide tuning range of transconductor, low total harmonic distortion (THD), high input impedance, etc. (Jaikla et al. 2021: 11-17).

In the open literature, many universal biquadratic filters using ABB implemented from the commercially available ICs for examples, four terminal floating nullor (FTFN) (Ranjan et al. 2019), current feedback operational amplifier (CFOA) (Wang et al. 2021: 13330-13343; Wang et al. 2020: 6681; Wang et al. 2019: 2304), second-generation current conveyor (CCII) (Yucel and Yuce 2020: 153138; Horng and Chiu, 2016: 577-582), differential difference current conveyors (DDCC) (Lee, 2017: 71-81; Khateb et al. 2017: 631-637), fully differential current conveyor (FDCCII) (Lee, 2016: 1006-1019), OTA (Wang et al. 2019: 2349; Kumngern et al. 2019: 1950078 and Kumngern et al. 2013: 1118-1133), voltage difference buffered amplifier (VDBA) (Roongmuanpha et al. 2021: 9606), voltage differencing differential inverted buffered amplifier (VD-DIBA) (Jaikla et al. 2021: 153601; Ninsraku et al. 2014: 1239-1246), voltage differencing current conveyor (VDCC) (Roy et al. 2021: 146-160), voltage differencing differential difference amplifier (VDDDA) (Jaikla et al. 2021: 1683; Huaihongthong et al. 2019: 13-23; Sangyaem et al. 2017: 14-25), extra X current controlled conveyor (EX-CCCII) (Agrawal and Maheshwari, 2020: 1127-1151), differential difference current conveyor transconductance amplifier (DDCCTA) (Chen et al. 2016: 1403-1411), LT1228 (Jaikla et al. 2021: 7376; Siripongdee and Jaikla, 2017: 14002; Klungtong et al. 2017: 5240751) etc., were published. Some ABBs (VD-DIBA, VDCC, VDDDA, EX-CCCII, DDCCTA) requiring two or more commercially available ICs have been reported in [14-21]. With no use of grounded capacitors in some ABBs were published in [1,5,13,16,20,22,23]. Some proposed filters require additional buffers to cascade with their output nodes because they do not have low output impedance in [1,5-12,21,23,24]. Both the natural frequency (ω_0) and quality factor (Q) of the proposed filters in [1-9] cannot be offered electronic controllability, while the ω_0 and Q of the proposed filters in [1,12,15,19-23] cannot be offered independent controllability.

Note: Reference of the number system [1] (Ranjan et al. 2019), [2] (Wang et al. 2021: 13330-13343), [3] (Wang et al. 2020: 6681), [4] (Wang et al. 2019: 2304), [5] (Yucel et al. 2020: 153138), [6] (Horng and Chiu, 2016: 577-582), [7] (Lee, 2017: 71-81), [8] (Khateb et al. 2017: 631-637), [9] (Lee, 2016:1006-1019), [10] (Wang et al. 2020: 1493), [11] (Kumngern et al. 2019: 1950078), [12] (Kumngern et al. 2013: 1118-1133), [13] (Roongmuanpha et al. 2021: 9606), [14] (Jaikla et al. 2021: 153601), [15] (Ninsraku et al. 2014: 1239-1246), [16] (Roy et al. 2021: 146-160), [17] (Jaikla et al. 2021: 1683), [18] (Huaihongthong et al. 2019: 13-23), [19] (Sangyaem et al. 2017: 14-25), [20] (Agrawal and Maheshwari, 2020: 1127-1151), [21] (Chen et al. 2016: 1403-1411), [22] (Jaikla et al. 2021:7376), [23] Wang et al. 2019: 2349), [24] (Siripongdee and Jaikla, 2017:14002), [25] (Klungtong et al. 2017:5240751).

From the electronics and electrical engineering education aspects, analog active filter design is an important subject because it is the basis of the operation of most engineering circuits. However, it is a difficult subject to learn for students who do not have the knowledge and skills to understand topics such as mathematical complex equations, circuit principles, and the characteristics of circuit components. First, when the students may be assigned a project, they first analyze a filter circuit in their practical time. Secondly, they calculate the transfer function equation of the filter circuit by using both the circuit principles and mathematical concepts, and finally, they obtain the circuit's component values using the previously calculated transfer function equation. After the students have had to do all these difficult tasks step by step, they can observe in the laboratory the resultant time domain signals (step response or sinewave response) and the frequency response of the filter on the oscilloscope. This can be demotivating. Moreover, such an assignment or project cannot fulfill the objective or practical application of a filter system. Learners also don't study active filters because they don't know how to start or because their teachers don't give them enough teaching materials. They also don't study this subject because it doesn't apply to their daily lives or because they don't know how to put the theoretical ideas into practice. (Oliveira et al. 2010).

This research intends to propose the structures of single-input and multiple-output (SIMO) universal biquad filters and multiple-input and single output (MISO) universal biquad filter using LT1228s. All proposed filter circuits use grounded capacitors. Some input nodes have high impedance, while some output nodes have low impedance. In addition, all proposed filters can provide the features of electronic control between ω_0 and Q. This research also intends to support the electrical and electronic engineering education that systematically applies the engineering knowledge via the new teaching packages in the teaching and learning process of the analog active filter design course using commercially available integrated circuits (IC): LT1228. An instructional package is developed based on the ADDIE model (Branch, 2009: 17-18) to enhance the students' knowledge and skills about active filter design. Furthermore, this teaching system not only helps students understand the theory of fundamental circuit principles, but it also shows them how to apply the theoretical concepts in real-world applications.

1.2 Objectives

(1) To synthesize and design multifunction filters using a commercially available IC, LT1228.
(2) To analyze the performance of the proposed multifunction filters.
(3) To investigate the performance of the proposed multifunction filters through PSpice simulation and experiment.
(4) To develop the instructional package on the active filter design.
(5) To investigate the effectiveness of the instructional package on active filter design.
(6) To evaluate the students' satisfaction with studying the active filter design through the instructional package

1.3 Hypothesis

(1) The quality of the developed instructional package must be at a good level or a very good level.
(2) The ω_0 of the proposed multifunction filter must be electronically controlled.
(3) The efficiency of the developed instructional package must be equal to or exceed the criterion of 80/80 (E_1/E_2).
(4) The students' satisfaction in the learning process by using developed instructional package must be a satisfied level or totally satisfied.

1.4 Conceptual Framework

1.4.1 Engineering aspect

In this section, the conceptual framework for synthesis of SITO universal filters is described in detail.

1.4.1.1 First conceptual framework for synthesis of SIMO filter

The first conceptual framework for synthesis of SIMO universal filter is shown in Figure 1.1 that is modified from (Olmez and Cam, 2009). It consists of four basic blocks: the voltage summing circuit, two lossless integrators, and one voltage amplifier. The input of the voltage summing circuit is V_{in}, while the output voltage node of the summing circuit is V_{HP1}. The output of the first lossless integrator is V_{BP1}, and the output of the second lossless integrator is V_{LP1}. The time constant of the first and the second integrators are defined as *a* and *b*, respectively. It can simultaneously provide three filtering functions: low-pass filter (LP), high-pass filter (HP), band-pass filter (BP) in the same circuit. However, it does not provide orthogonal and independent control of ω_{01} and Q_1.

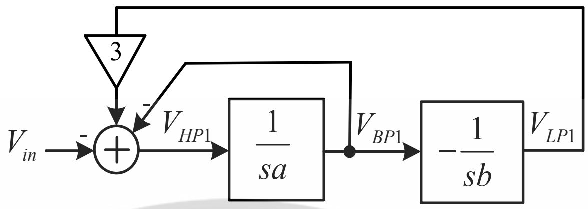


Figure 1.1 First conceptual framework for synthesis of SIMO universal filter

1.4.1.2 Second conceptual framework for synthesis of SIMO filter

To overcome the disadvantages of filter 1, the second configuration is constructed from two lossless integrators, the voltage summing circuit, and two voltage gain amplifiers in Figure.1.2 that is modified from (Olmez and Cam, 2009). The input of the voltage summing circuit is V_{in}, while the output voltage node of the summing circuit is V_{HP2}. The output of the first lossless integrator is V_{BP}, which is multiplied by the voltage gain amplifier, *K*. The output of the second lossless integrator is V_{LP2}. The time constant of the first and the second integrators are defined as *a* and *b*, respectively. It can simultaneously provide three filtering functions: LP, HP, BP in the same circuit. Moreover, it can provide orthogonal and independent control of ω_{02} and Q_2.

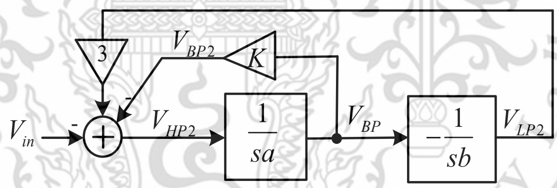


Figure 1.2 Second conceptual framework for synthesis of SIMO universal filter

1.4.1.3 Third conceptual framework for synthesis of SIMO filter

Figure. 1.3 shows the third conceptual framework for synthesis of SIMO universal filter with a single-input four output configuration. This figure is modified from (Olmez and Cam, 2009). Ten basic blocks are used to synthesize the SIMO filter that is double lossless integrators, four voltage gain amplifiers, and four voltage summing circuits. The input of the block diagram is V_{in}, while the output voltage nodes of the block diagram are V_{LP2}, V_{HP2}, V_{BP2} andV_{BR2}. The time constant of the first and the second integrators are defined as *a* and *b*, respectively. It can simultaneously provide four filtering functions: LP, HP, BP, band-reject (BR) in the same circuit. Moreover, it can provide orthogonal control of ω_{04} and Q_4.

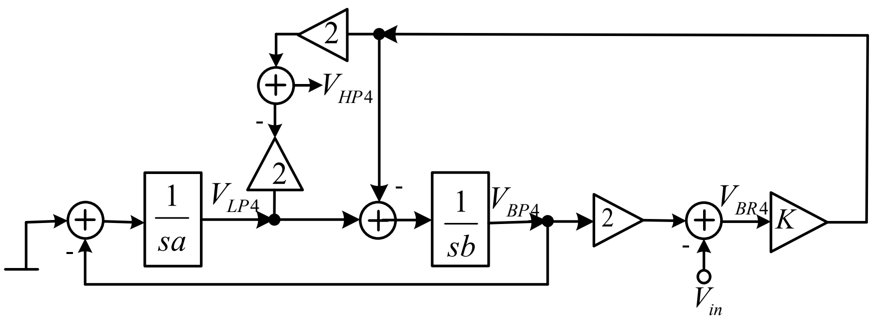


Figure 1.3 Third conceptual framework for synthesis of SIMO universal filter

1.4.1.4 Fourth conceptual framework for synthesis of SIMO filter

Figure.1.4 illustrates the fourth conceptual framework for synthesis of MISO universal filter with the multiple-input and single output configuration. This figure is modified from (Jaikla et. al. 2020). The eight basic blocks are used to synthesize the MISO filter that is double lossless integrators, two voltage gain amplifiers, and four voltage summing circuits. The two LT1228s, two capacitors and four resistors is used to construct the wo lossless integrators, two voltage gain amplifiers, and four voltage summing circuits. It can provide five filtering functions: LP, HP, BP, BR, and all-pass (AP) in the same circuit. Moreover, it can provide independent control of ω_{05} and Q_5.

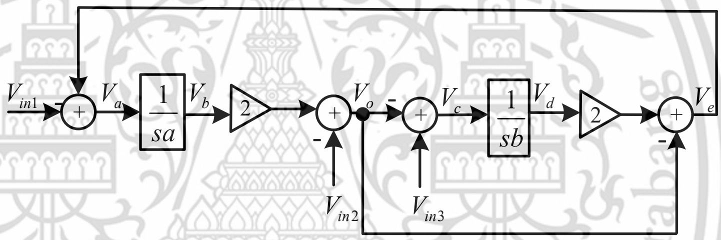


Figure 1.4 Fourth conceptual framework for synthesis of SIMO universal filter

1.4.2 Education aspect

This research aimed to identify the Electrical Engineering Education students preferred the new instructional package in studying the active filter design. The ADDIE model was used to develop the instructional package. The ADDIE model comprises of five phases, specifically: (1) Analyze, (2) Design, (3) Development, (4) Implementation, and (5) Evaluation. The five phases of the turn of events of the strategy above can be illustrated in Figure. 1.5. (Branch, 2009: 17-18).

1.4.2.1 Analyze

In the analyze phase, the potential causes of a performance gap are identified. The primary tasks typically associated with the analyze phase include validating the performance gap, determining instructional objectives, confirming the intended audience, identifying the resources required to complete the entire ADDIE process, determining potential delivery systems (including cost estimates), and composing a project management plan.

1.4.2.2 Design

In the design phase, its goal is to validate the desired performance and appropriate testing methods. The following are the primary tasks typically associated with the design phase: perform a task inventory, compose performance expectations, generate test methods, and calculate return on investment.

1.4.2.3 Development

In the development phase, the learning resources that will be required throughout the lifetime of the instructional modules are generated and validated. The primary procedures typically associated with the analyze phase include generating the content, selecting the supported media that already exist or develop the supported media for the described purpose of this project, develop guidance for the teacher and student, conducting the formative revisions, and conducting a pilot test.

1.4.2.4 Implementation

It is the responsibility of the implementation phase to prepare the learning environment and engage the students. Preparing the teacher and preparing the student are the main procedures typically associated with the implementation phase.

1.4.2.5 Implementation

The evaluation phase's goal is to evaluate the quality of the instructional products and processes both before and after implementation. The Evaluate phase is commonly associated with the following procedures: determining the evaluation criteria for all aspects of the ADDIE process, selecting, or creating all the evaluation tools that will be required to complete the entire ADDIE process, and conducting evaluations.

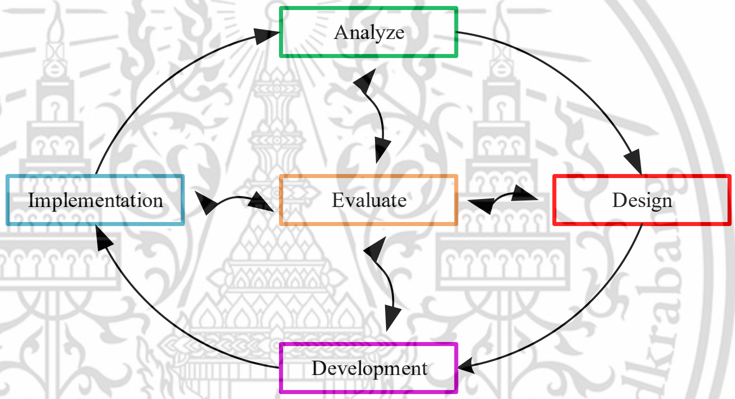


Figure 1.5 The conceptual framework for education aspect of this study.

1.5 limitation of the study

1.5.1 Engineering aspect

The analog active filter design is an important subject because it is the basic concept to design analog processing circuits. If the students do not fully understand the concept of this subjective, they cannot get not only the knowledge of designing the various circuits but also how to apply the characteristics of the circuit components in practice.

1.5.1.1 Population

The population of this research was 75 second year students, department of engineering education, school of industrial education and technology, King Mongkut's Institute of Technology Ladkrabang (KMITL).

1.5.1.2 Sample group

The sample group of this research was 20 second year students, major telecommunication engineering, department of engineering education, school of industrial education and technology, King Mongkut's Institute of Technology Ladkrabang (KMITL).

1.5.1.3 Research instruments

(1) Instructional package

i. Experimental set

ii. Teacher' manual including lesson plan, power point, Lab sheet, and solution.
iii. Quiz at the end of each topic

(2) Achievement test
(3) The instructional package's quality assessment form and the student satisfaction assessment forms.

1.5.1.4 Teaching topics

The new teaching-learning process is based on the ADDIE model that teachers develop the student's learning process. This process is composed of teaching topics are as follows:

(1) Basic concept of LT1228
(2) First order filter using LT1228
(3) Second order filter using LT1228

This package system encourages students to develop their knowledge and skills by themselves with the best of their potential.

1.6 Definition of key terms

Instructional package is a solution for learning needs and problems, it is more convenient to study for all diverse types of learners.

Experimental set refers to a collection of components, equipment, or resources that are specifically designed and organized to support hands-on learning and experimentation within an educational setting.

Teacher manual is a manual that consists of detailed behavioral objectives in teaching content, teaching methods, lesson plans, lab activities and achievement test.

Teaching methods are the principles and methods (such as guidance, direction, and encouragement) used by teachers to enable student learning.

Achievement test refers to the proof of how much the students can successfully learn and the outcome of a students' learning. In this study, students' achievement is representing the analog active filter design score of the case-study and questionnaire that the experts tested them.

Experts refer to those who have taught subjects related to electronics circuit design or subjects with similar content. They have at least a Ph.D. degree, or those with 10 years of teaching and learning experience in electronics circuit design, or subjects of similar content.

Process efficiency (E_1) is a percentage of the average score students obtained during the instruction (quizzes) and **product efficiency (E_2)** is calculated the result (achievement test).

CHAPTER 2

RELATED LITERATURE

2.1 LT1228

The active element used in this design is LT1228, a commercially available IC from Linear Technology Inc. The LT1228 can easily control the gain of signals ranging from DC to very high frequencies. It can perform the function of both transconductance amplifier (voltage to current) and current feedback amplifier. The LT1228 transconductance amplifier provides the gain control feature which is externally controlled by current. The transconductance amplifier has a high impedance differential input (inverting and non-inverting input terminals). The transconductance, g_m, is controlled by the current, I_B. The LT1228 current feedback amplifier is an excellent buffer for the output of the transconductance amplifier because it possesses extremely high input impedance (inverting and non-inverting input terminals). The CFA can keep its wide bandwidth over a wide range of voltage gain as a result it can easily interface the OTA output to another circuitry. The CFA can provide excellent linearity at high frequencies, suitable for driving low impedance loads.

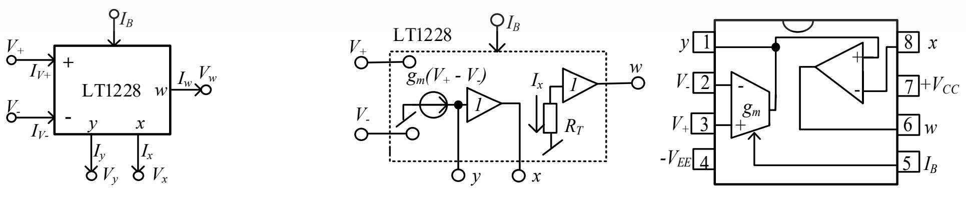
The LT1228 symbolic diagram with eight terminals is illustrated in fig. 2.1(a). The y terminal is output current which has high impedance and the V_+ and V_- terminals are inverting and non-inverting input voltages that also have high impedance. The x and w terminals are low-impedance voltage output terminals. Eq. (2.1) shows the terminal relationships of LT1228 in hybrid matrix form.

$$\begin{pmatrix} I_{V+} \\ I_{V-} \\ I_y \\ V_x \\ V_w \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_T & 0 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_y \\ I_x \\ I_w \end{pmatrix} \tag{2.1}$$

where R_T is the internal transresistance gain and it is infinite in an ideal case. The small signal g_m is obtained by ten times the value of I_B in Eq. (2.2).

$$g_m = 10 I_B \tag{2.2}$$

As defined in Eq. (2.1), the LT1228 characteristics can be represented as equivalent scheme in fig. 2.1(b). The pin connection of LT1228 is illustrated in fig 2.1(c). (LT1228: Linear Technology, 2012).



(a) (b) (c)

Figure 2.1 LT1228 (a) Symbolic diagram (b) Representation (c) Pin connection (LT1228: Linear Technology, 2012).

2.2 Basic theory of filter

There are many types of electronic filters, and they can be classified in many ways. A filter's frequency selectivity is most used to classify the filter type and it is the basic theory to use for synthesis and circuit design. To construct any types of filters, the researcher must consider the important filter specifications such as passband frequency range or operational bandwidth, stop band frequency range, maximum allowable ripple in the pass band, minimum attenuation in the stop band, required phase characteristics, required transient characteristics, input, and output impedances and noise characteristics etc.

2.2.1 Frequency filter circuits

Frequency filter circuits are an extremely important element in electronic circuits. These filters are used in several electronic and telecommunications applications to pass signals in a particular frequency range with little or no reduction in signal level while rejecting or suppressing those in the unwanted frequency range. A frequency filter circuit is a network that processes signals depending on the impedance frequency of the capacitor and inductor. The frequency filter circuit can be divided into two types based on the circuit components and operation. They are:

(1) Active frequency filter - composed of transistors, op-amps, and OTA in addition to resistors and capacitors but inductors are not commonly used due to large circuit size problems (Koseeyaporn, 2008: 161-165).

(2) Passive filter - composed of resistors, capacitors, and inductors.

Thede (2004: 3) said that the following analog frequency filter circuits can be classified by type of equipment used in synthesis and frequency response of the circuit.

2.2.2 Low-pass frequency filter

Figure 2.2 shows the frequency and voltage gain response of the low-pass filter's response. Low-pass filters are very important to eliminate signals in high-frequency bands. It is distinguished into two parts: the passband starts from zero frequency (dc) 0Hz to the -3dB cut-off frequency, f_c; the stopband runs from the f_c to infinity.

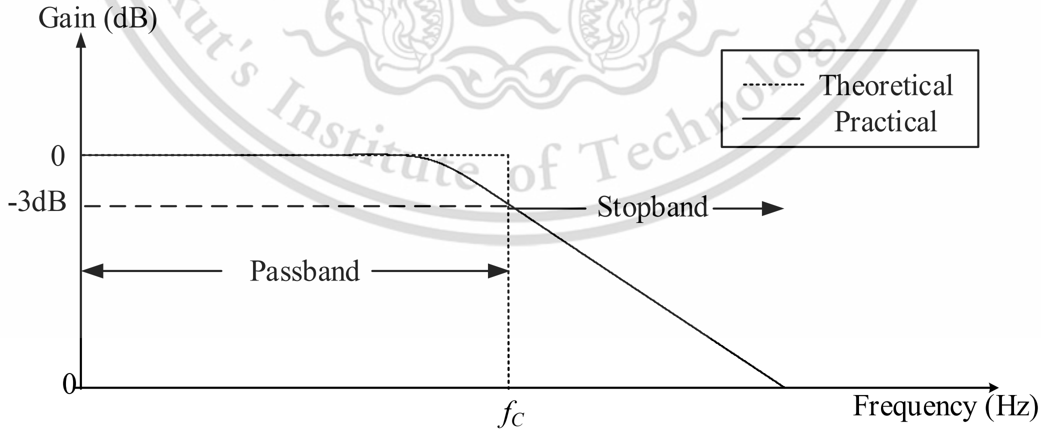


Figure 2.2 Gain response of the low-pass frequency filter

2.2.3 High -pass frequency filter

The frequency and voltage gain response of the high-pass filter's response is as shown in Figure 2.3. High-pass frequency filter circuits are very important to eliminate signals in low frequencies band. It is divided into two parts: stopband starts from zero frequency (dc) 0Hz to the -3 dB cut-off frequency, f_c; the passband runs from the f_c to infinity.

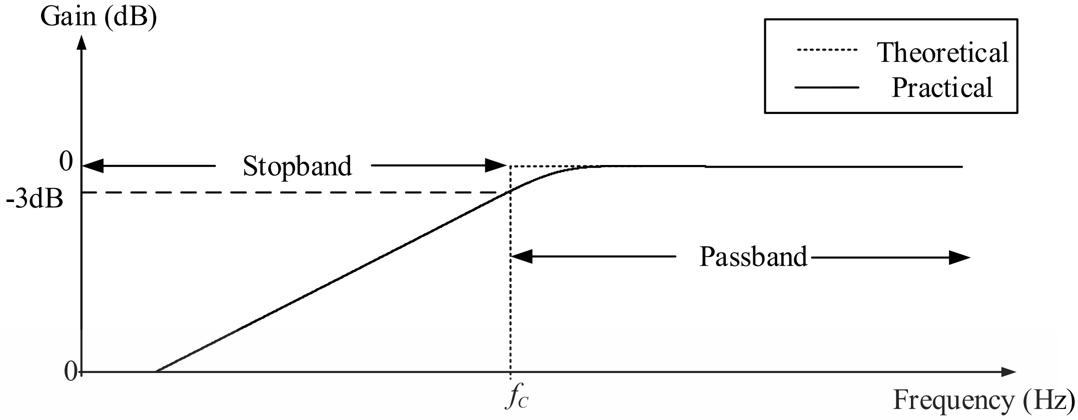


Figure 2.3 Gain (dB) response of the high-pass frequency filter

2.2.4 Band-pass frequency filter

The frequency and voltage gain (dB) response of the band-pass filter's response is shown in Figure 2.4. It will pass a band of frequencies but rejects frequency components above or below that band. In this case the passband exists between the -3dB at low frequencies, f_{CL} and -3dB at high frequencies, f_{CH}. From this fact, the bandwidth is obtained from f_{CH} - f_{CL}.

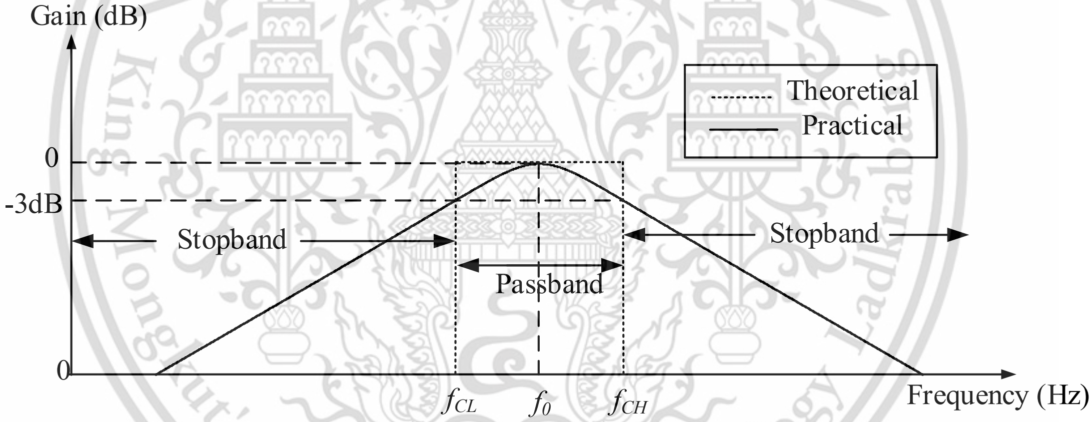


Figure 2.4 Gain response of the band-pass frequency filter

2.2.5 Band-stop frequency filter

The frequency and voltage gain response of the band-stop is shown in Figure 2.5. A band-stop filter has two passbands. The lower passband runs from zero frequency (dc) to -3dB at low frequencies, f_{CL} while the upper passband runs from -3 dB at high frequencies, f_{CH} to infinity. The application of this frequency filter circuit is highly recommended in notch filter that is used in sensitive measurement equipment.

2.2.6 All -pass frequency filter

A filter having a unity or k (k =1, 2, 3, etc.) gain across all frequencies is known as an all-pass filter. This means that no frequency will be amplified or reduced when it passes through the filter. However, it introduces a frequency-dependent delay. There are two types of filters: non-inverting all-pass filter (AP+) and inverting all-pass filter (AP-). The voltage gain response remains constant from 0Hz (dc) to infinity, but the output phase response changes. For the AP+, it possesses the leading phase response for 0Hz (dc) to infinity changed from 0 to -180 degrees. For the AP-, it possesses the lagging phase response for 0Hz (dc) to infinity changed from 180 to 0 degrees. The frequency and voltage gain response of the AP+ and AP- filters are shown in Fig. 2.6 and Fig. 2.7.

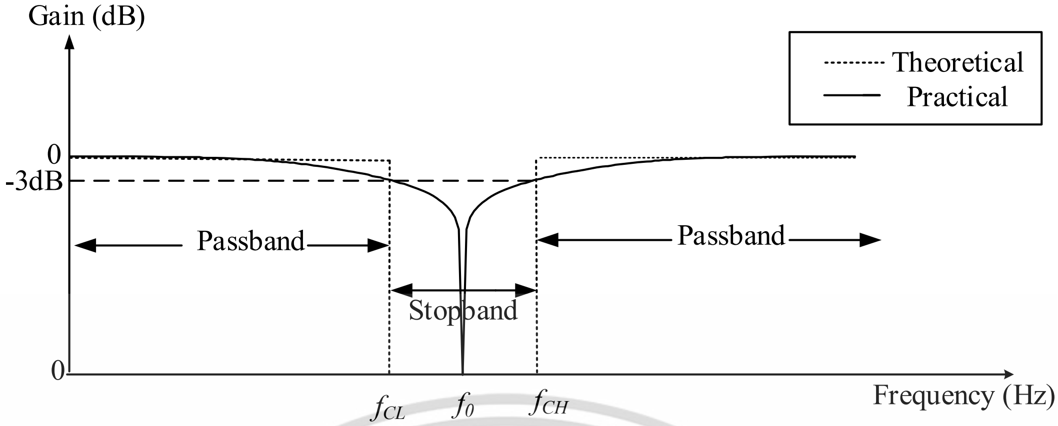


Figure 2.5 Gain response of the band-stop frequency filter

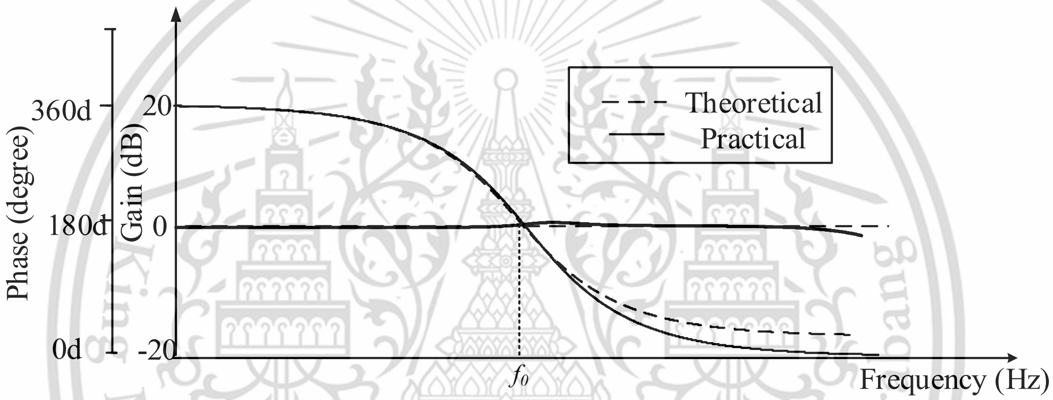


Figure 2.6 Gain response and phase response of the AP+ frequency filter

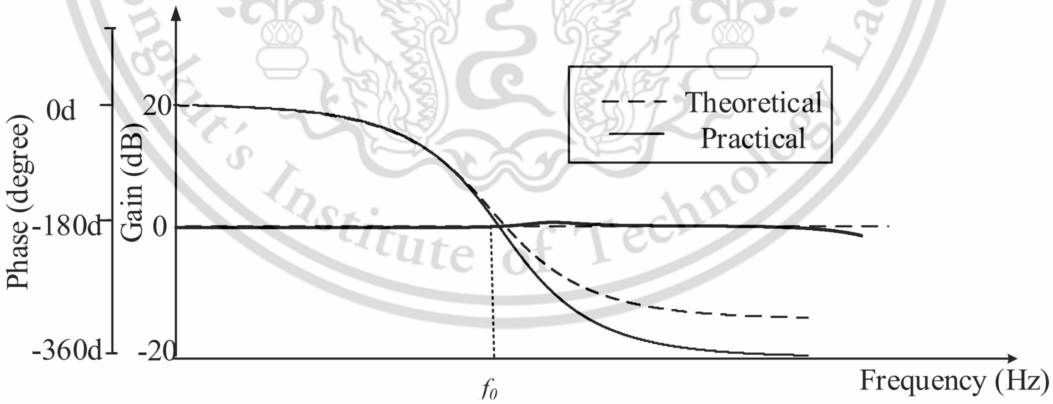


Figure 2.7 Gain response and phase response of the AP+ frequency filter

2.3 Biquad filter

A biquad filter circuit is one of the most useful circuits in an electrical engineering field due to it is a universal filter. It is a linear filter type constructed from a ratio of two quadratic functions that is called a biquadratic or a second order transfer function. It is also known as a Biquad because it is short for biquadratic. Hank (2008) said that analog filter circuit depends on the effect of the frequency response that can change the impedance of capacitors and inductors. The impedance of capacitor and inductor is expressed as follows:

$$Z_L = sL \tag{2.3}$$

$$Z_C = \frac{1}{sC} \tag{2.4}$$

$$s = \sigma + j\omega \tag{2.5}$$

where, $\omega = 2\pi f$

2.3.1 Transfer function characterization

The transfer function $H(s)$ for a filter system can be described by using the circuit analysis. The relationship of complex number impedances to transfer equations is as follows:

$$H(s) = \frac{A(s)}{B(s)} = \frac{k*\left[a_m s^m + a_{m-1}s^{m-1} + \cdots + a_1 s + a_0\right]}{\left[b_n s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0\right]} \tag{2.6}$$

From Eq. (2.6), $H(s)$ is typically represented as the ratio of two polynomials equation in the function of s, where in this case m exponent for the numerator polynomial and the n exponent for denominator polynomial. k assigns an overall gain constant that can take on any value. The $B(s)$ represent the pole values of $H(s)$ and the $A(s)$ represent zero values of $H(s)$. Then pole-zero values can be plotted in a s-plane: the real value (σ) is plotted on the horizontal axis and the complex value (ω) is plotted on the vertical axis. The most used biquad frequency filter circuits are low-pass frequency filter circuits, high-pass frequency filter circuits, band-pass frequency filter circuits, band-stop frequency filter circuits, and all-pass frequency filter circuits. There are important parameters: if Q = 0.707, the natural frequency is equal to $2\pi f_0$ which is the frequency at which the voltage gain is reduced to -3dB; if Q > 0.707, the filter response of the filter circuit will have the voltage gain higher than 0 dB which intervene the natural frequency, if the Q < 0.707, the transition band range is very wide. The general transfer function of biquad filter is as follows:

$$H(s) = \frac{a_0 s^2 + a_1 \frac{\omega_0}{Q} s + a_2 \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \tag{2.7}$$

In Eq. (2.7), where a_0, a_1, and a_2 refers to the overall gain coefficient, which can be both positive, negative.

2.3.2 Low-pass biquad filter

Van Valkenburg (1982) says that the transfer function of the low-pass biquad filter circuit that has two poles, and two infinite zeros are expressed as follows:

$$H(s) = \frac{k\omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \tag{2.8}$$

From Eq. (2.8), it is found that there is no finite zero and the position of the zero and the pole on the s plane is shown in Figure 2.8. The pole values of $H(s)$ can be obtained from the denominator of $H(s)$ in Eq. (2.9).

$$s = -\frac{\omega_0}{2Q} \pm j\omega_0 \sqrt{1 - \left(\frac{1}{4Q^2}\right)} \tag{2.9}$$

2.3.3 High-pass biquad filter

The transfer function of the high-pass biquad filter circuits that has two finite poles, and two finite zeros are described as the following.

$$H(s) = \frac{ks^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2.10}$$

From Eq. (2.10), it is verified that there is the two finite poles and two finite zeros. The position of the zeros and the poles on the *s* plane is shown in Figure 2.9.

2.3.4 Band-pass biquad filter

The transfer function of the band-pass biquad filter circuit that has two finite poles, finite one zero and infinite one zero are as follows:

$$H(s) = \frac{k\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2.11}$$

From Eq. (2.11), zero position and poles on the *s* plane can be illustrated as shown in Figure 2.10.

2.3.5 Band-stop biquad filter

The transfer function of the band-stop biquad filter circuit that has two finite poles, and two finite zeros are as follows:

$$H(s) = \frac{k(s^2 + \omega_0^2)}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2.12}$$

From Eq. (2.12), zero and poles positions on the *s* plane can be displayed as shown in Figure 2.11. From Eq. (2.11) to (2.12), the quality factor (Q) can be obtained in Eq. (2.13).

$$Q = \frac{f_0}{BW} = \frac{\sqrt{f_{CH} * f_{CL}}}{f_{CH} - f_{CL}}; \tag{2.13}$$

where,

BW = Bandwidth
f_0 = natural frequency
f_{CH} = higher cut-off frequency
f_{CL} = lower cut-off frequency

According to Eq. (2.13), the Q is inversely proportional to the bandwidth. If the Q is high, the bandwidth is narrow. Conversely, the bandwidth is wide when the Q is low.

2.3.6 All-pass biquad filter

The transfer function of the all-pass biquad filter circuit has a symmetrical position of two finite poles, and two finite zeros are described as follows:

$$H(s) = \frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2.14}$$

From Eq. (2.14), the zeros and poles position on the plane are illustrated in Figure 2.12. The phase response equation can be written as follows:

$$\theta_{T(s)} = -2\tan^{-1}\frac{\dfrac{\omega}{Q\omega_0}}{\left(1-\left(\dfrac{\omega}{\omega_0}\right)^2\right)} \tag{2.15}$$

Taylor. (2015) states that the phase angle for all-pass filter shifts from 0 degrees at a frequency value of 0Hz to -180 degrees at natural frequency and -360 degrees at higher frequency, in Figure 2.13.

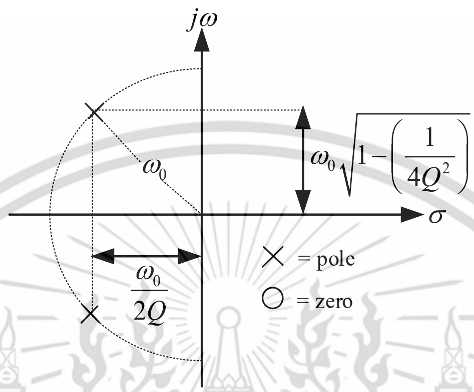


Figure 2.8 Pole and zero configuration for low-pass biquad filter

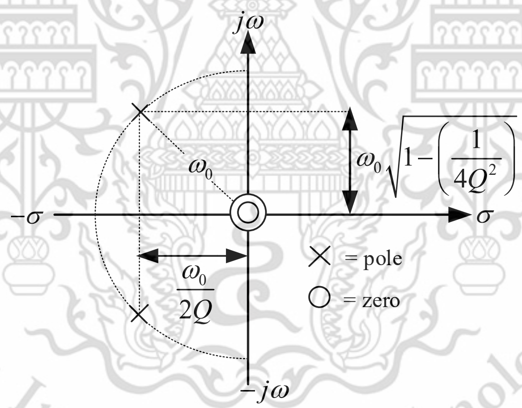


Figure 2.9 Pole and zero configuration for high-pass biquad filter

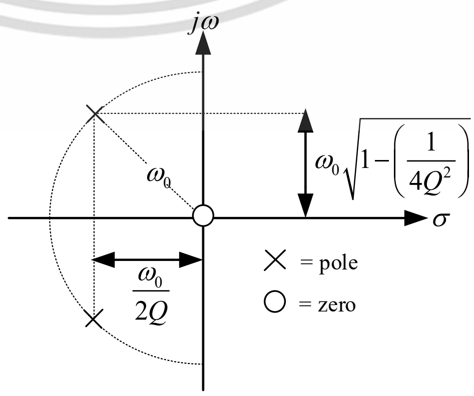


Figure 2.10 Pole and zero configuration for band-pass biquad filter

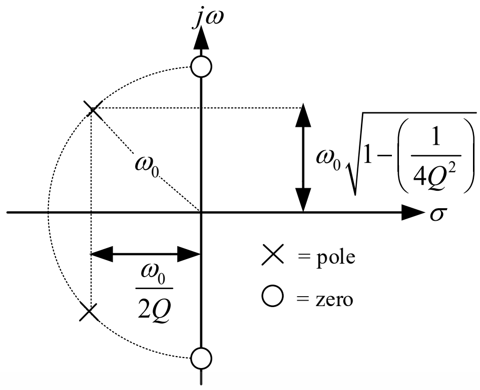


Figure 2.11 Pole and zero configuration for band-stop biquad filter

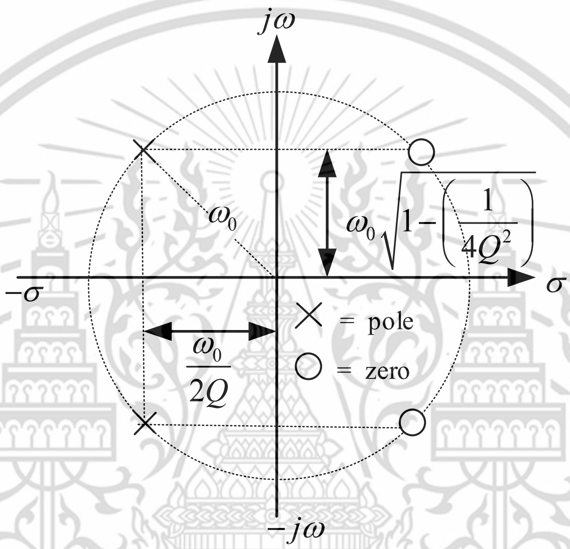


Figure 2.12 Pole and zero configuration for all-pass frequency biquad filter

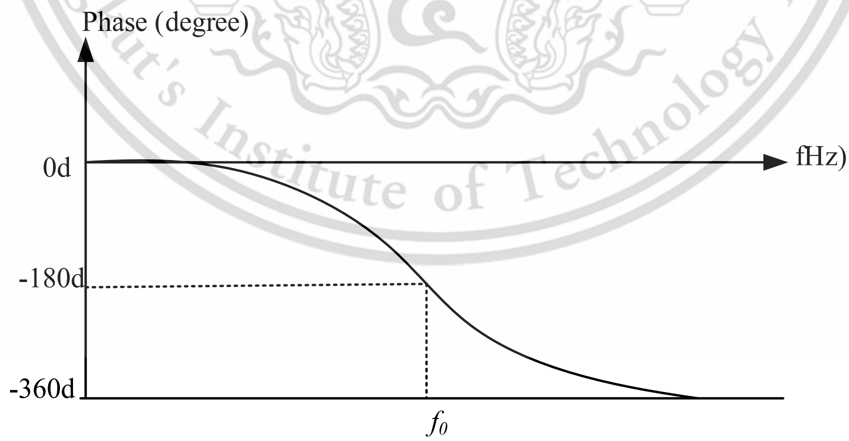


Figure 2.13 Frequency phase response of the all-pass biquad filter

2.3.7 Sensitivity

Promme (2010) state that the filter sensitivity is one of the methods used to determine how much of each component used in the circuit will affect the operation of the circuit. Although the circuit is designed to get high performance, there are usually errors that change according to these conditions such as temperature, humidity, or equipment faults themselves, etc. So, it is necessary to know the changes that will affect the circuit performance. In practice, there is always a change. This is called sensitivity analysis which is used to determine the filter performance. The sensitivity of the circuit is a measure of the circuit efficiency depending on the sensitivity of frequency parameters such as natural frequencies and quality factor. This means the changes in the circuit that affect the natural frequency or quality factors. The sensitivity value does not exceed one refers to the variable will also change by 1% if the circuit considered changes by 1%, examples of how natural frequency sensitivity changes when the circuit performance changes to write equations are as follows:

$$S_R^{\omega} = \lim_{\Delta R \to 0} \frac{\frac{\Delta\omega}{\omega}}{\frac{\Delta R}{R}}; \tag{2.16}$$

Sensitivity determination has the following rules. When p is a constant or not an x function, the sensitivity equation is as follows:

$$S_x^p = 0 \tag{2.17}$$

When $p = cx$ or as a function of x and c as constants, the sensitivity equation is as follows:

$$S_x^p = 1 \tag{2.18}$$

When p refers to the function of x, the sensitivity equation is as follows:

$$S_x^{p_1 p_2} = S_x^{p_1} + S_x^{p_2} \tag{2.19}$$

$$S_x^{p_1/p_2} = S_x^{p_1} - S_x^{p_2} \tag{2.20}$$

$$S_x^{p^n} = nS_x^p \tag{2.21}$$

$$S_x^{p_1+p_2} = \frac{p_1 S_x^{p_1} + p_2 S_x^{p_2}}{p_1 + p_2} \tag{2.22}$$

2.4 Instructional package

The instructional package is an effective instructional plan that must include students' general education skills development, connection between the course activities or material and the industrial work, creativity of interactive learning process. Instructional design is intended to be an iterative process for obtaining the desired outcomes, choosing effective strategies for teaching-learning process, selecting appropriate modern teaching-aid tools, identifying teaching media, and measuring students' performance such as knowledge and skills. This package is a well-organized program to help the students to develop their knowledge and skills, to overcome the difficulties encountered during the lessons, to understand more the lessons and practical works, to assist in the transition from observation to creation the new product etc., (Rattanaphinyowanich. 2021).

The instructional package includes two sections: the teacher's manual and the experimental set. The first is the teacher's manual that must be consistent with the teaching style, for example science, technology, engineering, art, and mathematics (STEAM), and MIAP model. This teacher's manual consists of lesson plan, power point, solution, lab sheets, quiz after each topic and achievement test. All of them are essential knowledge about analog filter design. The second is the experimental set which is to develop the students' learning skills in filter design.

2.4.1 MIAP learning model

The practical industrial practice of MIAP teaching model can be divided into 4 important processes: 1) M=Motivation, 2) I=information, 3) A=application and 4) P=progress (Sirisukpaiboon (2011), and Promchan, (2014)). Kaewsai et al. (2013) recommended an advantage of using MIAP teaching model for specific purposes that it can be the conceptual pattern for creating specific teaching model. It is helpful for the deaf to effectively learn and be able to work on industrial work, it also should be the solution to the shortage of industrial technical workers as well.

MIAP based Integrated Learning Activities for Electrical Engineering Education was presented by Chumchuen et al., (2020) to encourage the students get self-study and lifelong learning skills that are needed for social changes in the 21st century educational management system. MIAP learning model consists of four learning processes that developed according to the constructionism theory focuses on the students-centered approach. This model can be applied in teaching and learning to produce professional teachers with knowledge, skills, and a good attitude. In this paper, the constructed new instruction package includes teacher' manual, learning activity plan, test, and diverse teaching aids such as laboratory set, fundamental electrical circuit measuring set, circuit simulation program etc. It was quasi-experimental research using a sample group of 12 Science students in the Bachelor of Science in technical education at King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand. The practical teaching process of this paper consists of introduction to integrated learning method, using MIAP learning integrating to developed experimental package, teacher- students discussion and suggestion based on feedback information, test and adjustment methods for students' knowledge and skills, and conclusion. The result of evaluation for the information sheet and the experimental media package were at the highest appropriate level so the developed instructional package can be used for professional teaching practice through management of MIAP based integrated learning model emphasizing the enhancement of teaching practice using diverse teaching activities. From the result of the learning achievement of the sample group, it can be found that the score of teaching practice skills was higher than the specified benchmark at 75%. Promoting for students to achieve higher learning achievement and professional teaching competencies as an expected learning outcome of the curriculum, the using of the developed MIAP based integrated learning activities in electrical engineering education is highly recommended according to the results.

Benjamaha et al., (2021) stated that proactive learning management is based on the MIAP learning model to encourage learners to change their behavior according to the nature of learning. This research aims to enhance the competency of electronic technicians in the field of IC circuit and application through active learning management based on the MIAP learning model. The research's results were found that 1) the results of the quality assessment of developed research instruments were high quality (mean=4.47 and S.D.= 0.25) because of learning activities and processes that motivate students to become competent electronic technicians, 2) the learners' pre-learning achievement was much higher after study at the.05 level because teaching and learning management employs a high-quality learning model with features such practice doing one's own work, independent learning exchange, presentation skills, etc., 3) The learners' satisfaction with the created learning process was high quality (mean=4.22 and S.D.= 0.23) due to the learners' freedom to carry out independent tasks and take part in activities.

To promote the students' digital intelligence, Sathiya et al. (2021) investigates the appropriateness of leaning management adopting an AL MIAP leaning model. The

MIAP teaching method included the following four steps: Step 1: Motivation. This involves motivating the learners' interest through a clear introduction to the title and objectives as well as instructional materials, a concisely use of class time, encouragement of group work, and a conclusion that suitably and relevantly learners to the next step. Step 2: Information, in which students acquired knowledge through textbooks, self-learning, meta-skills learning from a variety of sources, teaching aids, and the preparation of a step-by-step progression from teaching less and easier knowledge to more and tougher ones. Step 3: application, which involves using the knowledge that has been learned, allowing an experiment or simulation to be conducted after learning the material to gauge how well learners retain it (learning less or more), reviewing memories to prevent data loss, encouraging the use of critical thinking and problem-solving skills while learning, and encouraging the transfer of knowledge. Step 4: Progress: Measuring and assessing outcomes, such as abilities, behaviors, knowledge, and attitude, to evaluate learning outcomes or progress. The research's findings revealed that 1) an AL MIAP learning model can promote a better score (digital intelligence) because post-learning achievement was higher than the pre-learning period, with statistical significance at 0.01 (total score: 17.06), which was 7.16 points higher than the pre-learning scores, and 2) the appropriateness of learning management with an AL MIAP model to promote digital intelligence of Suan Sunandha Rajabhat University's (SSRU's) undergraduate students because their scores were the highest level ($\bar{x}$ = 4.63, S.D. = 0.39).

2.4.2 ADDIE model

Based on Gagne's theory of instruction, instructional theorists began to experiment with diverse ways to present instructional materials in the 1970s (Solis. 2007). During this time, Florida State University collaborated with the Department of Defense to develop the ADDIE model for military instructional design (Watson, 1981). Gagne's nine steps of instruction were organized into five high-level phases by the ADDIE model to guide instructional designers as they approached the practice of instructional design (Bichelmeyer, 2005). The ADDIE model has five phases: analysis, design, development, implementation, and evaluation. The model's first four phases are sequential in nature, but the evaluation phase is a continuous and iterative process that should be carried out in tandem with the other phases (Watson, 1981). Early on, ADDIE aspired to be an engineering model, with the premise that if followed precisely, it would produce repeatable results (Merrill, Drake, Lacy, & Pratt. 1966). The models assumed "one best way," and this way of thinking appealed to the bureaucratic thinking prevalent at the time.

According to Molenda (2003), a recent trend in literature is to accept ADDIE as an umbrella term before moving on to more elaborate models and narrative descriptions. Most current instructional design models, according to one widely held belief, are spin-offs or variations of the ADDIE instructional design model. Many people have criticized the ADDIE model over the years. Michael Allen has recently called for its rejection (Sites 2012). He has described ADDIE as being out of date with current needs and has urged instructional designers to use the Rapid Development Approach. His model, known as the Successive Approximation Model, emphasizes that the instructional design should be iterative, collaborative, efficient, effective, and manageable (Allen. 2012). At the same time, the ADDIE models have many supporters who believe that the criticism of the models stems primarily from an arrow view of the model as rigid and linear (Peterson 2003). To give the critics their due, it is undeniably true that training departments frequently attempt to explain designs with storyboards and content outlines, and once these are approved, redesigning them to meet learners' evolving need for performance focused learning experiences becomes costly in terms of money and time. This adds rigidity to the process and may result in low-quality instructional and training modules. However, the ADDIE set of criteria has inherent flexibility that can be used to create a successful, efficient, and manageable process when used creatively (Riecker 2012).

While the more accurate description of the ADDIE model is as a generic process that is traditionally used as a starting point by instructional designers and training developers, ADDIE is also frequently used as an instruction design (ID) model in and of itself. Prior to creating a lesson, one of its five components is analysis, which consists of analyzing the problem or goal(s), what the learners know and need to know, and various other aspects. Design is the creation of a pre-lesson: determining how the lesson or objective will be taught. The creation of content and any materials that the learners will use during the lesson is referred to as development. This includes determining whether the lesson meets the learning objectives, ensuring that the content is complete and accurate, and developing prototypes. The lesson and objectives are then presented to the learners during the implementation stage. The last step is to use formative and summative assessments to determine whether the objectives have been met. Any necessary revisions are also completed currently (Williams 2014).

Nichols Hess and Greer (2016) stated that the ADDIE model can be used to achieve a variety of goals in information literacy instruction. Firstly, it can serve as a framework for librarians to create a range of instructional interactions. Secondly, it can assist librarians in more intentionally considering learner engagement, learning, and assessment. Thirdly, it can aid in the integration of information literacy standards and other learning guidelines, such as high-impact practices and e-learning best practices. Other academic librarians, based on the authors' experience, may find its application for effective instructional frameworks in their own teaching practices, both online and in face-to-face learning environments.

These processes represent a dynamic, adaptable framework for developing effective training tools that ensure alignment between goals, strategies, and evaluation, resulting in effective instruction. ADDIE activities are rarely completed in a linear, step-by-step fashion, although they are sometimes presented in that format for convenience. The current generation of instructional designers, on the other hand, dislikes the prescriptive approach of formal ISD in general and ADDIE (Vejvodova, 2009). Technology has also provided designers and learners with tools that have profoundly changed the process of instructional design and the need for a process like ADDIE. While rejection of ADDIE is the current political correctness, many practicing instructional designers believe that in organizations that require formal learning, an authentic learning design and a systematic ID model like ADDIE are essential.

2.5 Review of biquad filters using ABBs

The realization of the biquad filters is constructed from ABBs (such as VDDDA, VD-DIBA, CCII, CFOAs, DDCC, CDBAs, VDTA, LT1228, etc.) are still interesting research topics in the field of analog processing circuits. Biquad filter circuits can provide three filtering functions namely, low-pass (LP), band-pass (BP), high-pass (HP) or even two functions only. These filters are used in many communication applications which are touch-tone telephone tone decoders, phase locked loops, FM stereo demodulators, and crossover networks used in a three-wave high-fidelity loudspeaker; control application such as sound systems and loudspeakers.

In earlier traditional filters comprise passive elements which occupies large space area and consumes more power. Moreover, some active filters use BJT or CMOS transistors which can only test simulation computer programs due to the chip fabrication cost. Those passive elements are replaced by commercially available IC: LT1228 which has low THD, high impedance differential input, fast transconductance amplifier, a wide bandwidth over a wide range of voltage gain, etc.

2.5.1 SITO current-mode (CM) multifunction biquad filter

Roongmuanpha & Tangsrirat (2020) presented a single input three outputs (SITO) current-mode (CM) multifunction biquad filter using two LT1228s with three grounded passive elements (i.e., two capacitors and one resistor) in Figure. 2.14. It can simultaneously generate LP, HP, BP responses. Using circuit analysis with $R_1 = 1/g_{m2}$, the following three current transfer functions are expressed.

$$\frac{I_{HP}}{I_{in}} = \frac{s^2}{D(s)} \; ; \; \frac{I_{LP}}{I_{in}} = \frac{-\dfrac{g_{m1}g_{m2}}{C_1C_2}}{D(s)} \; ; \; \frac{I_{BP}}{V_{in}} = \frac{\left(-\dfrac{g_{m1}}{g_{m2}}\right)\left(\dfrac{sg_{m2}}{C_1}\right)}{D(s)} \quad (2.23)$$

$$D(s) = s^2 + s\frac{g_{m2}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2} \quad (2.24)$$

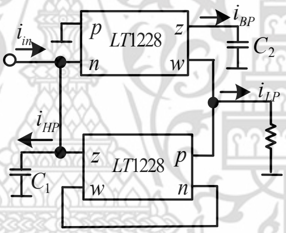


Figure 2.14 SITO biquad filter using two LT1228s

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q = \sqrt{\frac{g_{m1}C_1}{g_{m2}C_2}} \quad (2.25)$$

By simultaneously adjusting for three different bias currents (I_{B1} and I_{B2}) and resistor values, the ω_0 value can be controlled without affecting the Q value. Moreover, the electronic control of Q with constant the ω_0 value can be done by varying I_{B1} and capacitor values. High current input impedance and low current output impedance are disadvantages of this proposed SITO CM multifunction biquad filter.

2.5.2 The versatile (VM) biquad filter

The versatile VM biquad filter employing four OTAs and two grounded capacitors was published by Wang et al (2020) that can be used as a multifunction filter with a single input and three outputs, as well as a universal filter with four inputs and a single output. Now filter that generates LP, BP, BR responses only described. Fig 2.15 shows this biquad filter that use commercially available IC: LT1228 and discrete components can be used to implement the proposed OTA-based circuits. All input terminals of this filter have high input impedance so it can directly connect to other VM circuits.

If the input voltage signal is applied at the V_{in3} node and the other V_{in1}, V_{in2}, V_{in4} nodes are grounded, the three biquadratic filtering functions can be obtained as shown in Eq. (2.26) through (2.28).

$$\frac{V_{o1}}{V_{in}} = \frac{g_{m1}g_{m3}g_{m4}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m13}g_{m2}g_{m3}} \tag{2.26}$$

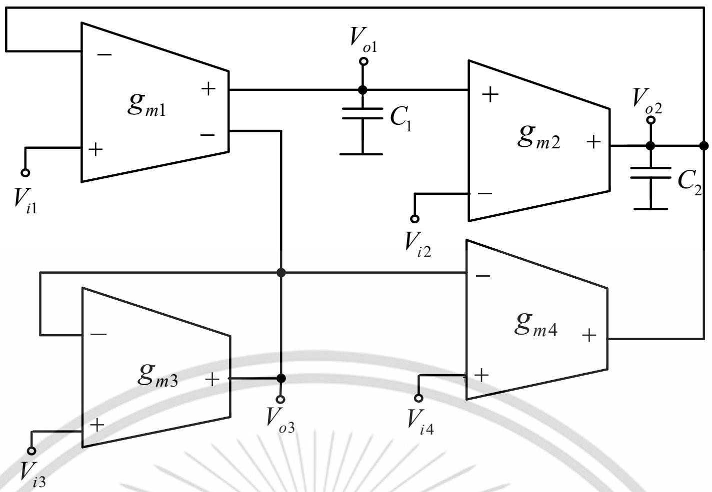


Figure 2.15 Versatile VM biquad filter using four OTAs

$$\frac{V_{o2}}{V_{in}} = \frac{-sC_1g_{m3}g_{m4}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \tag{2.27}$$

$$\frac{V_{o3}}{V_{in}} = \frac{s^2C_1C_2g_{m3} + g_{m1}g_{m2}g_{m3}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \tag{2.28}$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q = \frac{g_{m3}}{g_{m4}}\sqrt{\frac{C_2g_{m2}}{C_1g_{m1}}} \tag{2.29}$$

Substituting $g_{m1} = g_{m2} = g_m$ and $C_1 = C_2 = C$ into Eq. (2.29), the ω_0 and Q are as follows:

$$\omega_0 = \frac{g_m}{C} \text{ and } Q = \frac{g_{m3}}{g_{m4}} \tag{2.30}$$

This biquad filter can provide non-interactive electronic control of the filtering parameters: ω_0 and Q by varying g_m, g_{m3} and/or g_{m4}. The disadvantage of this filter is that it cannot provide the low output impedance.

2.5.3 Independently tunable voltage-mode (VM) universal filter

Wang et al (2019) presents the independently tunable voltage-mode biquadratic filter using five single-ended OTAs with two grounded capacitors in Fig. 2.16. By choosing the different input signals, the proposed circuit with SITO type and five-input single-output type can be obtained. However, this paper can only describe SITO type that can simultaneously realize an inverting band-pass (IBP), a BP, a LP, an inverting low-pass (ILP), a BR and an inverting band-reject (IBR) filtering functions according to the different input and output conditions. The commercially available OTAs, LT1228, are used for the PSpice computer simulation and experimental results to match with the characteristics of the proposed voltage-mode universal filter.

$$V_{o1} = \frac{-s\dfrac{g_{m4}}{C_1}V_{in1} - s\dfrac{g_{m1}}{C_1}V_{in2} + s\dfrac{g_{m4}}{C_1}V_{in3} + \dfrac{g_{m1}g_{m2}}{C_1C_2}V_{in4} + s\dfrac{g_{m4}g_{m5}}{C_1g_{m3}}V_{in5}}{D(s)} \tag{2.31}$$

$$V_{o2} = \frac{\frac{g_{m2}g_{m4}}{C_1C_2}V_{in1} + \frac{g_{m1}g_{m2}}{C_1C_2}V_{in2} - \frac{g_{m2}g_{m4}}{C_1C_2}V_{in3} + \left(s\frac{g_{m2}}{C_2} + \frac{g_{m2}g_{m4}g_{m5}}{C_1C_2g_{m3}}\right)V_{in4} - \frac{g_{m2}g_{m4}g_{m5}}{C_1C_2g_{m3}}V_{in5}}{D(s)} \tag{2.32}$$

$$V_{o3} = \frac{\left\{\begin{array}{l}\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)V_{in1} - s\frac{g_{m1}g_{m5}}{C_1g_{m3}}V_{in2} + s\frac{g_{m4}g_{m5}}{C_1g_{m3}}V_{in3} + \\ \frac{g_{m5}}{g_{m3}}\left[\frac{g_{m1}g_{m2}}{C_1C_2}V_{in4} - \left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)V_{in5}\right]\end{array}\right\}}{D(s)} \tag{2.33}$$

$$D(s) = s^2 + s\frac{g_{m4}g_{m5}}{C_1g_{m3}} + \frac{g_{m1}g_{m2}}{C_1C_2} \tag{2.34}$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q = \frac{g_{m3}}{g_{m4}g_{m5}}\sqrt{\frac{C_1g_{m1}g_{m2}}{C_2}} \tag{2.35}$$

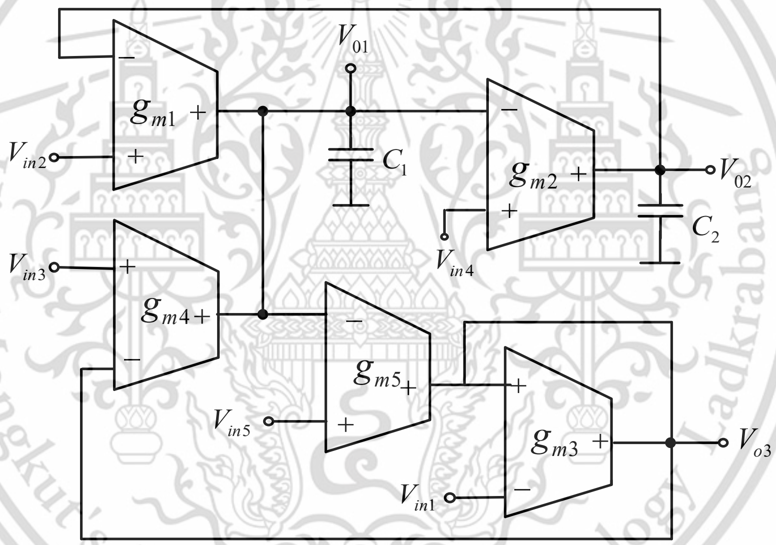


Figure 2.16 Independently tunable voltage-mode universal filter

From Eq. (2.35), the ω_0 and Q can be done orthogonally by tuning the g_{m1} and g_{m2} for ω_0 first, and then g_{m3} and/or g_{m4}, g_{m5} without affecting ω_0. From Eq. (2.31) through (2.33), the proposed voltage-mode universal filter can provide the following SITO type by applying the input voltage signal at V_{in1} node and the others, V_{in2}, V_{in3}, V_{in4}, and V_{in5} must be grounded.

$$\frac{V_{o1}}{V_{in}} = \frac{-s\frac{g_{m4}}{C_1}}{D(s)} \tag{2.36}$$

$$\frac{V_{o2}}{V_{in}} = \frac{\frac{g_{m2}g_{m4}}{C_1C_2}}{D(s)} \tag{2.37}$$

$$\frac{V_{o3}}{V_{in}} = \frac{s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}}{D(s)} \tag{2.38}$$

Eq. (2.36) through (2.38) verify that the proposed voltage-mode universal filter can provide the IBP, LP, BR responses from their different outputs. Similarly, the following three voltage transfer functions are obtained by applying the input voltage signal at V_{in5} node and the others, V_{in1}, V_{in2}, V_{in3}, and V_{in4}, must be grounded.

$$\frac{V_{o1}}{V_{in}} = \frac{s\frac{g_{m4}g_{m5}}{C_1g_{m3}}}{D(s)} \tag{2.39}$$

$$\frac{V_{o2}}{V_{in}} = \frac{-\frac{g_{m2}g_{m4}g_{m5}}{C_1C_2g_{m3}}}{D(s)} \tag{2. 40}$$

$$\frac{V_{o3}}{V_{in}} = \frac{-\frac{g_{m5}}{g_{m3}}\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{D(s)} \tag{2.41}$$

Eq. (2.39) to (2.41) verify that the proposed filter can provide the ILP, BP and IBR filtering function from their different outputs. The disadvantage of this biquadratic filter is that it cannot provide low output impedance.

2.5.4 Voltage-mode universal filter

Voltage-mode universal filter using five single-ended OTAs with two grounded capacitors in Fig. 2.17 was presented by Wang, et al (2019). It possesses high-input impedance voltage terminals, and it generates five filtering responses (LP, HP, BP, BR, AP) without requiring any extra inverting or non-inverting amplifiers for special input signals. The commercially available OTAs, LT1228, are used for the PSpice computer simulation and experimental results to match with the characteristics of the proposed voltage-mode universal filter.

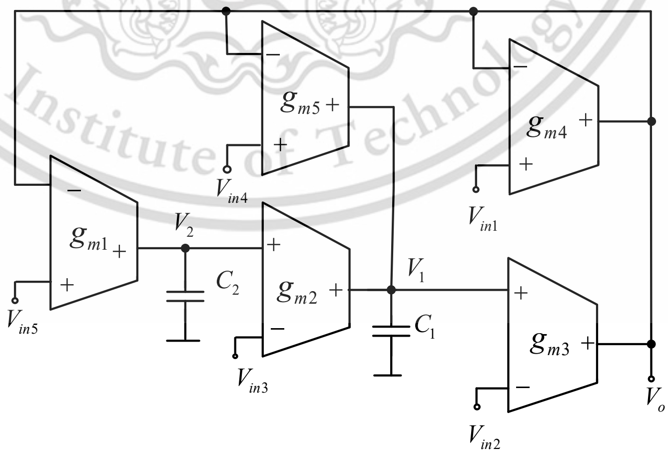


Figure 2.17 Voltage-mode universal filter using five single-ended OTAs

From Eq. (2.43), the Q can be done arbitrarily without affecting ω_0 by tuning the g_{m5}, but not vice versa. In other words, the parameters ω_0 and Q can be orthogonally controlled. If $k_1 g_{m1} = g_{m2} = g_{m5}$ and $k_2 = \frac{g_{m3}}{g_{m4}}$ (Where k_1 and k_2 are two scaling factors), the output voltage in Eq. (2.44) can be described as

$$V_o = \frac{s^2 V_{in1} - s^2 \frac{g_{m3}}{g_{m4}} V_{in2} - s\frac{g_{m2}g_{m3}}{C_1 g_{m4}} V_{in3} + s\frac{g_{m3}g_{m5}}{C_1 g_{m4}} V_{in4} + \frac{g_{m1}g_{m2}g_{m3}}{C_1 C_2 g_{m4}} V_{in5}}{s^2 + s\frac{g_{m3}g_{m5}}{C_1 g_{m4}} + \frac{g_{m1}g_{m2}g_{m3}}{C_1 C_2 g_{m4}}} \quad (2.42)$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}g_{m3}}{C_1 C_2 g_{m4}}} \text{ and } Q = \frac{1}{g_{m5}}\sqrt{\frac{C_1 g_{m1} g_{m2} g_{m4}}{C_2 g_{m3}}} \quad (2.43)$$

$$V_o = \frac{s^2 V_{in1} - k_2 s^2 V_{in2} - s\frac{k_1 k_2}{\tau_1}(V_{in3} - V_{in4}) + \frac{k_2}{\tau_1 \tau_2} V_{in5}}{s^2 + s\frac{k_1 k_2}{\tau_1} + \frac{k_2}{\tau_1 \tau_2}} \quad (2.44)$$

(1) To get the LP function at the output node V_o, the input voltage signal must be applied at the V_{in5} node and the others V_{in1}, V_{in2}, V_{in3}, and V_{in4} must be grounded.
(2) To get the inverting HP function at the output node V_o, the input voltage signal must be applied at the V_{in2} node, and the others V_{in1}, V_{in3}, V_{in4} and V_{in5} must be grounded.
(3) To get the non-inverting HP function at the output node V_o, the input voltage signal must be applied at the V_{in1} node, and the others V_{in2}, V_{in3}, V_{in4} and V_{in5} must be grounded.
(4) To get the inverting BP function at the output node V_o, the input voltage signal must be applied at the V_{in4} node and the others V_{in1}, V_{in2}, V_{in3} and V_{in5} must be grounded.
(5) To get the non-inverting BP function at the output node V_o, the input voltage signal must be applied at the V_{in3} node and the others V_{in1}, V_{in2}, V_{in4} and V_{in5} must be grounded.
(6) To get the BR function at the output node V_o, the input voltage signal must be applied at the V_{in1} and V_{in5} node, respectively and the other V_{in2}, V_{in3}, and V_{in4} must be grounded.
(7) To get the AP function at the output node Vo, the input voltage signal must be applied at both V_{in1}, V_{in3}, and V_{in5} and the other V_{in2}, and V_{in4} must be grounded.

As can be seen from Eq. (2.44), the LP, HP, BP, IBP, BR, and AP filtering functions have unity gain, and an IHP (Inverting High Pass) filtering functions have gain k_2. In this design, the filter circuit does not require the passive component-matching conditions and the inverting voltage input signals to obtain the above filtering functions. The disadvantage of this VM universal filter is that it cannot provide low output impedance.

2.5.5 Three inputs and single output (TISO) voltage-mode biquad filter

Three inputs and single-output (TISO) voltage-mode biquad filter using single LT1228 was presented by Klungtong et al (2017) that uses one resistor, and two capacitors. This TISO biquad filter can provide the five responses: LP, HP, BP, BR, AP functions without requirement matching condition (i.e., active, and passive component values are not same). This filter is shown in Fig. 2.18, and it requires the inverting unity gain amplifier circuit for all pass functions.

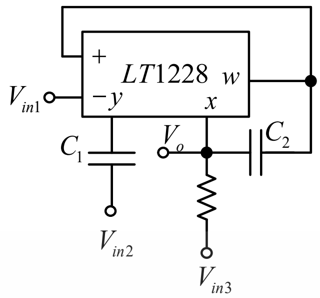


Figure 2.18 Three inputs and single-output (TISO) voltage-mode biquad filter

$$V_o = \frac{s^2 V_{in2} + s(g_m/C_1)V_{in1} + (g_m/C_1C_2R)V_{in3}}{s^2 + s(g_m/C_1) + (g_m/C_1C_2R)} \tag{2.45}$$

$$\omega_0 = \sqrt{\frac{g_m}{C_1C_2R}} \text{ and } Q = \sqrt{\frac{C_1}{C_2 g_m R}} \tag{2.46}$$

(1) To get the LP function at the output node V_o, the input voltage signal must be applied at the V_{in3} node and the others V_{in1} and V_{in2} must be grounded.
(2) To get the HP function at the output node V_o, the input voltage signal must be applied at the V_{in2} node, and the others V_{in1} and V_{in3} must be grounded.
(3) To get the BP function at the output node V_o, the input voltage signal must be applied at the V_{in1} node and the others V_{in2} and V_{in3} must be grounded.
(4) To get the BR function at the output node V_o, the input voltage signal must be applied at the V_{in2} and V_{in3} node, respectively and the other V_{in1} must be grounded.
(5) To get the AP function at the output node V_o with gain one, the inverting input voltage signal must be applied at the V_{in1}, and the non-inverting input voltage signal must be applied at both V_{in2} and V_{in3}.

According to Eq. (2.45), this biquad filter can provide electronic control of the filtering parameters: ω_0 and Q by varying g_m. The disadvantage of this biquad filter is that it cannot provide high input impedance, low output impedance, orthogonal control, and independent control. Moreover, it does not use grounded capacitors.

2.5.6 Universal VM biquad filter

Siripongdee & Jaikla (2017) introduced that universal filter using single LT1228 using single resistor and two capacitors in Fig. 2.19. The proposed filters can simultaneously provide the five filtering responses: LP, HP, BP, BR, AP without requiring additional circuits such as the inverting voltage gain or double gain amplifier. The five voltage transfer function equations are described as the following.

$$V_o = \frac{s^2 V_{in2} + s\frac{V_{in3}}{C_2R} + \frac{g_m V_{in1}}{C_1C_2R}}{s^2 + \frac{s}{C_2R} + \frac{g_m}{C_1C_2R}} \tag{2.47}$$

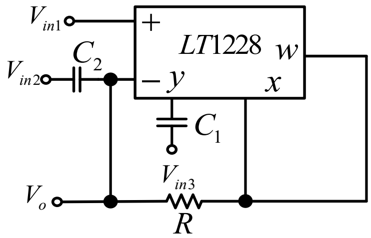


Figure 2.19 Universal filter using single LT1228

(1) To get the LP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in1} node and the others V_{in2} and V_{in3} must be grounded.
(2) To get the HP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in2} node, and the others V_{in1} and V_{in3} must be grounded.
(3) To get the BP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in3} node and the others V_{in1} and V_{in2} must be grounded.
(4) To get the BR function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in1} and V_{in2} node, respectively and the other V_{in3} must be grounded.
(5) To get the AP function at the output node V_o with gain one, the inverting input voltage signal must be applied at the $V_{in3,}$ and the non-inverting input voltage signal must be applied at both V_{in1} and V_{in2}.

According to Eq. (2.47), the natural frequency and the quality factor are expressed as the following.

$$\omega_0 = \sqrt{\frac{g_m}{C_1 C_2 R}} \text{ and } Q = \sqrt{\frac{g_m C_2 R}{C_1}} \tag{2.48}$$

From Eq. (2.48), the electronic control of f_0 and Q can be done via bias current which is attractive for controlling by microcontroller or micro-computer. In case $C_1 = C_2$, it is verified that the f_0 and Q can be independently controlled.

$$\omega_0 = \frac{1}{C}\sqrt{\frac{10 I_B}{R}} \text{ and } Q = \sqrt{10 I_B R} \tag{2.49}$$

The disadvantage of this biquad filter is that it cannot provide high input impedance, low output impedance, orthogonal control, and independent control. Moreover, it does not use grounded capacitors.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Synthesis of filter 1

3.1.1 Synthesis procedure of filter 1

The first proposed filter is synthesized from the block diagram in Figure. 3.1 that is modified from (Olmez and Cam 2009). It consists of four basic blocks: the voltage summing circuit, two lossless integrators, and one voltage amplifiers. The inputs of the voltage summing circuit are the $3V_{LP1}$, V_{BP1} and V_{in} while the output voltage node of the summing circuit is the V_{HP1}. The voltage node, V_{BP1} is the output of the first lossless integrator. The V_{LP1} is the output of the second lossless integrator. The time constants of the first and second integrators are defined as *a* and *b*, respectively.

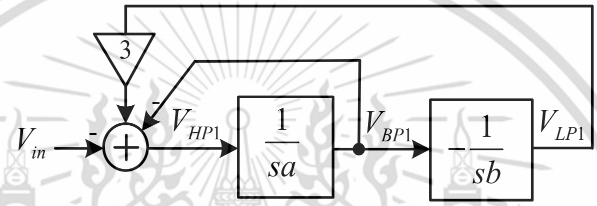


Figure 3.1 Synthesis block diagram of the first proposed filter.

From Fig 3.1, the transfer function for the first lossless integrator at V_{BP1} node is

$$\frac{V_{BP1}}{V_{HP1}}=\frac{1}{sa} \tag{3.1}$$

The transfer function for the second lossless integrator at V_{LP1} node is

$$\frac{V_{LP1}}{V_{BP1}}=-\frac{1}{sb} \tag{3.2}$$

Substituting V_{BP1} from Eq. (3.1) into Eq. (3.2), the transfer function at V_{LP1} node becomes

$$\frac{V_{LP1}}{V_{HP1}}=-\frac{1}{s^2ab} \tag{3.3}$$

The output voltage equation for the first summing block is

$$V_{HP1}=3V_{LP1}-V_{BP1}-V_{in} \tag{3.4}$$

Substituting V_{LP1} and V_{BP1} from Eq. (3.2) and (3.3) into Eq. (3.4), the output voltage at V_{HP1} node becomes

$$V_{HP1}=-3\frac{1}{s^2ab}V_{HP1}-\frac{1}{sa}V_{HP1}-V_{in} \tag{3.5}$$

Eq. (3.5) is multiplied by s^2, the V_{HP1} is obtained as follows:

$$s^2V_{HP1}=-3\frac{1}{ab}V_{HP1}-\frac{s}{a}V_{HP1}-s^2V_{in} \tag{3.6}$$

Moving V_{HP1} to the left side of Eq. (3.6), the V_{HP1} is

$$\left(s^2+\frac{s}{a}+\frac{3}{ab}\right)V_{HP1}=-s^2V_{in} \tag{3.7}$$

From Eq. (3.7), the transfer function for V_{HP1} of the block diagram shown in Fig. 3.1 is described as

$$\frac{V_{HP1}}{V_{in}} = \frac{-s^2}{s^2 + \dfrac{s}{a} + \dfrac{3}{ab}} \tag{3.8}$$

Substituting V_{HP1} from Eq. (3.8) into Eq. (3.3), transfer function of V_{LP1} becomes

$$\frac{V_{LP1}}{V_{in}} = \left(-\frac{1}{s^2 ab}\right) \times \frac{\left(-s^2\right)}{s^2 + \dfrac{s}{a} + \dfrac{3}{ab}} \tag{3.9}$$

According to Eq. (3.9), the voltage transfer functions for V_{LP1} are obtained as follows:

$$\frac{V_{LP1}}{V_{in}} = \frac{\dfrac{1}{ab}}{s^2 + \dfrac{s}{a} + \dfrac{3}{ab}} \tag{3.10}$$

Substituting like this, the voltage transfer function for V_{BP1} is

$$\frac{V_{BP1}}{V_{in}} = \frac{-\dfrac{s}{a}}{s^2 + \dfrac{s}{a} + \dfrac{3}{ab}} \tag{3.11}$$

Eq. (3.8), (3.10), and (3.11) indicate that the inverting passband voltage gain with one is obtained for BP and HP functions and non-inverting passband voltage-gain with one-third is obtained for LP function. The centre frequency (ω_{01}) and the quality factor (Q_1) are respectively obtained as

$$\omega_{01} = \sqrt{\frac{3}{ab}} \text{ and } Q_1 = \sqrt{\frac{3a}{b}} \tag{3.12}$$

From the synthesis block diagram in Figure. 3.1, it is divided into two parts and synthesized the circuit by LT1228. The first part of the synthesis block diagram is the first lossless integrator and the voltage summing circuit. The capacitor C_1 and first LT1228 are built as a first lossless integrator. The voltage summing circuit is constructed from the resistors R_1, R_2, R_3 (they are same resistance value) and first LT1228. This first part is successfully synthesized from the first LT1228 with one grounded capacitor and the three resistors in Figure. 3.2.

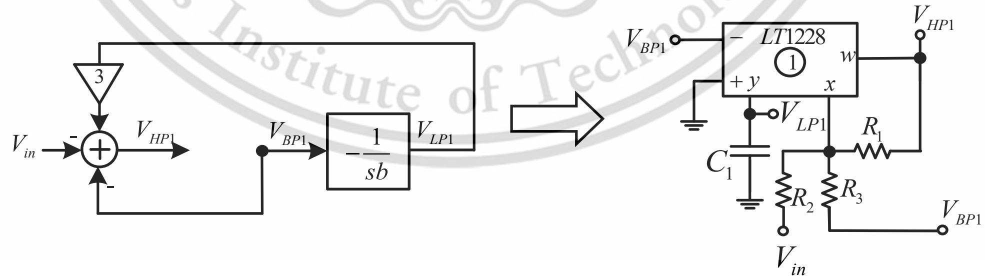


Figure 3.2 Inverting lossless integrator with voltage summing circuit synthesized from LT1228

The second part of the synthesis block diagram is the second lossless integrator circuit that is successfully synthesized from the the capacitor C_2 and second LT1228 in Fig. 3.3. The complete schematic of the first presented universal second order filter utilized LT1228 is shown in Fig. 3.4. It comprises two lossless integrators and one voltage summing circuit. It is constructed from two LT1228s with a single input voltage signal V_{in}, three resistors, and two grounded capacitors. The three output voltages are

V_{HP1}, V_{LP1} and V_{BP1}. The filter shows low output impedance at V_{HP1} and V_{BP1} node that can cascade to other circuits while no exploitation of the buffer.

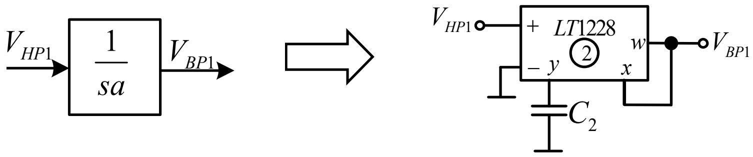


Figure 3.3 Non- inverting lossless integrator synthesized from LT1228

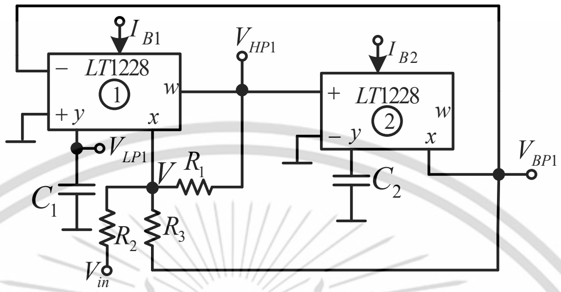


Figure 3.4 First proposed SIMO universal filter

3.1.2 Ideal analysis

Analyzing the circuit performance in Figure. 3.4, the first proposed filter circuit using two LT1228s that has the following current and voltage terminal relationships is expressed.

$$\begin{pmatrix} I_{V+} \\ I_{V-} \\ I_y \\ V_x \\ V_w \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_T & 0 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_y \\ I_x \\ I_w \end{pmatrix} \tag{3.13}$$

where R_T is the internal transresistance gain and it is infinite in an ideal case. The LT1228's g_m is controlled electronically via external DC bias current (I_B) as follows:

$$g_m = 10 I_B \tag{3.14}$$

From Fig. 3.4 and Eq. (3.13) through (3.14), the following transfer function equation can be described in detail. The lossless integrator outputs: V_{LP1} and V_{BP1} are obtained as follows:

$$V_{LP1} = \frac{-g_{m1}}{sC_1} V_{BP1} \tag{3.15}$$

$$V_{BP1} = \frac{g_{m2}}{sC_2} V_{HP1} \tag{3.16}$$

Substituting V_{BP1} from Eq. (3.16) into Eq. (3.15),

$$V_{LP1} = \frac{-g_{m1} g_{m2}}{s^2 C_1 C_2} V_{HP1} \tag{3.17}$$

According to ideal characteristic of CFA, $V = V_{LP1}$. Using Kirchhoff's current law (KCL) at V node, the current equation becomes

$$\frac{V_{LP1} - V_{HP1}}{R_1} + \frac{V_{LP1} - V_{in}}{R_2} + \frac{V_{LP1} - V_{BP1}}{R_3} = 0 \tag{3.18}$$

Moving V_{LP1} to the left and others (V_{HP1}, V_{BP1} and V_{in}) to the right side, the Eq. (3.18) becomes

$$V_{LP1}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right)=\frac{V_{HP1}}{R_1}+\frac{V_{in}}{R_2}+\frac{V_{BP1}}{R_3} \quad (3.19)$$

If $R_1=R_2=R_3=R$, the voltage equation becomes

$$V_{HP1}=3V_{LP1}-V_{BP1}-V_{in} \quad (3.20)$$

Substituting $V_{BP1}$and V_{LP1} from Eq. (3.16) and (3.17) into Eq. (3.20), the output voltage at V_{HP1} node becomes

$$V_{HP1}=\frac{-3g_{m1}g_{m2}}{s^2C_1C_2}V_{HP1}-\frac{g_{m2}}{sC_2}V_{HP1}-V_{in} \quad (3.21)$$

Eq. (3.21) is multiplied by $s^2C_1C_2$, the V_{HP1} is obtained as follows:

$$s^2C_1C_2V_{HP1}=-3g_{m1}g_{m2}V_{HP1}-g_{m2}sC_1V_{HP1}-s^2C_1C_2V_{in} \quad (3.22)$$

Moving all V_{HP1} to the left, Eq. (3.22) becomes

$$\left(s^2C_1C_2+sg_{m2}C_1+3g_{m1}g_{m2}\right)V_{HP1}=-s^2C_1C_2V_{in} \quad (3.23)$$

Reordering and dividing C_1C_2 to both sides of Eq. (3.23), the voltage equation becomes

$$\left(s^2+s\frac{g_{m2}}{C_2}+\frac{3g_{m1}g_{m2}}{C_1C_2}\right)V_{HP1}=-s^2V_{in} \quad (3.24)$$

Interchanging to both sides of Eq. (3.24), the transfer function for HP1 response becomes

$$\frac{V_{HP1}}{V_{in}}=\frac{-s^2}{\left(s^2+s\frac{g_{m2}}{C_2}+\frac{3g_{m1}g_{m2}}{C_1C_2}\right)} \quad (3.25)$$

where

$$D_1(s)=s^2+\frac{sg_{m2}}{C_2}+\frac{3g_{m1}g_{m2}}{C_1C_2} \quad (3.26)$$

$$\frac{V_{HP1}}{V_{in}}=\frac{-s^2}{D_1(s)} \quad (3.27)$$

By calculating like this HP1 response, the other transfer function for LP1 and BP1 responses are respectively obtained as follows:

$$\frac{V_{LP1}}{V_{in}}=\frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{D_1(s)} \text{ and } \frac{V_{BP1}}{V_{in}}=\frac{-\frac{sg_{m2}}{C_2}}{D_1(s)} \quad (3.28)$$

From Eq. (3.27) and (3.28), the passband voltage gains for HP1 and BP1 filtering function are unity and LP1 filtering function is one-third. Also from them, ω_{01} and Q_1 are obtained as the following:

$$\omega_{01}=\sqrt{\frac{3g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q_1=\sqrt{\frac{3g_{m1}C_2}{g_{m2}C_1}} \quad (3.29)$$

Substituting the transconductances g_{m1} and g_{m2} in function of the bias currents, I_{B1} and I_{B2} as appeared in Eq. (3.14) into Eq. (3.29), the ω_{01} and Q_1 of the proposed circuit are

$$\omega_{01}=10\sqrt{\frac{3I_{B1}I_{B2}}{C_1C_2}} \text{ and } Q_1=\sqrt{\frac{3I_{B1}C_2}{I_{B2}C_1}} \quad (3.30)$$

It is found from (3.30) that the ω_{01} and Q_1 are electronically adjusted. However, the first presented filter cannot provide the independent control of ω_{01} and Q_1. In case I_{B1}=I_{B2} (this feature is easily implemented by using microcontroller or microcomputer) is changing at the same time, it is found that the ω_{01} can be adjusted linearly without affecting the Q_1.

3.1.3 Parasitic effects analysis

In a genuine application, the impacts of parasitic components in LT1228 are not ignorable because it might influence the performance of the first proposed filter. So, the parasitic elements that appeared at all terminals of LT1228 will be considered. These parasitic elements are as follows: R_- and C_- appear in parallel at V_- terminal to ground; R_+ and C_+ appear in parallel at V_+ terminal to ground; R_y and C_y appear in parallel at y terminal to ground; R_x appears in series at x terminal; R_w appears in series at w terminal and the internal transresistance gain is considered as R_T // C_T. Figure. 3.5 shows the parasitic elements appeared at all terminals of LT1228.

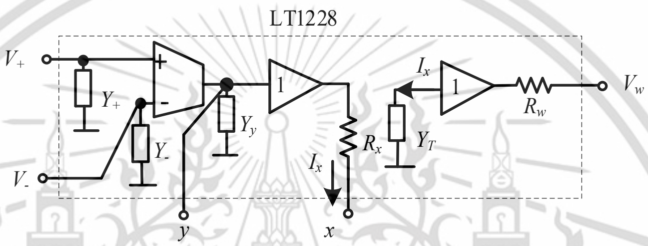


Figure 3.5 LT1228 with parasitic elements

When the parallel of passive devices replace to admittance, each terminal of LT1228 with parasitic elements is shown in Figure. 3.5.

$$Y_+ = sC_+ + G_+ \tag{3.31}$$

$$Y_- = sC_- + G_- \tag{3.32}$$

$$Y_y = sC_y + G_y \tag{3.33}$$

and

$$Y_t = sC_t + G_t \tag{3.34}$$

Now, the effect of Y_T in the summing circuit of the proposed filter in Fig. 3.6 will be studied first.

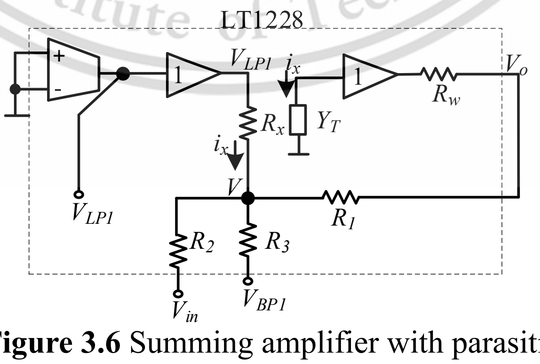


Figure 3.6 Summing amplifier with parasitic elements

Using Kirchhoff's current law (KCL) at Node V ,

$$\frac{V - V_{LP1}}{R_x} + \frac{V - V_{BP1}}{R_3} + \frac{V - V_{in}}{R_2} + \frac{V - V_{HP1}}{R_1} = 0 \tag{3.35}$$

Moving all V variables to the left, the Eq. (3.35) becomes

$$V\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_x}\right)=\frac{V_{LP1}}{R_x}+\frac{V_{in}}{R_2}+\frac{V_{BP1}}{R_3}+\frac{V_{HP1}}{R_1} \tag{3.36}$$

Multiplying R_x to both sides of the equation, the V is obtained as follows:

$$V\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)=V_{LP1}+\frac{V_{in}R_x}{R_2}+\frac{V_{BP1}R_x}{R_3}+\frac{V_{HP1}R_x}{R_1} \tag{3.37}$$

Dividing $\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)$ to both sides of the equation, the V is obtained as follows:

$$V=\left\{\begin{array}{l}\dfrac{V_{LP1}}{\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)}+\dfrac{V_{in}R_x}{R_2\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)}+\\ \dfrac{V_{BP1}R_x}{R_3\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)}+\dfrac{V_{HP1}R_x}{R_1\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)}\end{array}\right\} \tag{3.38}$$

where A is defined as $\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)$, the final V is obtained as follows:

$$V=\frac{V_{LP1}}{A}+\frac{V_{in}R_x}{R_2A}+\frac{V_{BP1}R_x}{R_3A}+\frac{V_{HP1}R_x}{R_1A} \tag{3.39}$$

Use Kirchhoff's current law (KCL) at Node V_{HP1}, the current equation is obtained as follows:

$$\frac{V_{HP1}-V_w}{R_w}+\frac{V_{HP1}-V}{R_1}=0 \tag{3.40}$$

Substituting $V_w=\frac{V_{LP1}-V}{R_xY_T}$ into Eq. (3.40), the current equation becomes

$$\frac{V_{HP1}}{R_w}-\frac{V_{LP1}-V}{R_xY_TR_w}+\frac{V_{HP1}-V}{R_1}=0 \tag{3.41}$$

Moving all V_{HP1} variables to the left and other variables (V_{LP1}, and V) to the right, the Eq. (3.41) becomes

$$V_{HP1}\left(\frac{1}{R_w}+\frac{1}{R_1}\right)=V\left(\frac{1}{R_1}-\frac{1}{R_xY_TR_w}\right)+V_{LP1}\frac{1}{R_xY_TR_w} \tag{3.42}$$

Multiplying $R_xY_TR_w$ to both sides of the equation, the Eq. (3.42) becomes

$$V_{HP1}R_xY_TR_w\left(\frac{1}{R_w}+\frac{1}{R_1}\right)=V\left(\frac{R_xY_TR_w}{R_1}-1\right)+V_{LP1} \tag{3.43}$$

Substituting Eq. (3.39) into Eq. (3.43), the Eq. (3.43) becomes

$$V_{HP1}R_xY_T\left(\frac{R_w}{R_1}+1\right)=\begin{pmatrix}\dfrac{V_{LP1}}{A}+\dfrac{V_{in}R_x}{R_2A}+\\ \dfrac{V_{BP1}R_x}{R_3A}+\dfrac{V_{HP1}R_x}{R_1A}\end{pmatrix}\left(\frac{R_xY_TR_w}{R_1}-1\right)+V_{LP1} \tag{3.44}$$

Putting all same terms together one group, the Eq. (3.44) becomes

$$V_{HP1}\left\{\begin{bmatrix} R_xY_T\left(\dfrac{R_w}{R_1}+1\right)- \\ \dfrac{R_x}{AR_1}\left(\dfrac{R_xY_TR_w}{R_1}-1\right)\end{bmatrix}\right\}=\left\{\begin{matrix} V_{LP1}\left[1+\dfrac{1}{A}\left(\dfrac{R_xY_TR_w}{R_1}-1\right)\right]+\dfrac{V_{in}R_x}{R_2A} \\ \left(\dfrac{R_xY_TR_w}{R_1}-1\right)+\dfrac{V_{BP1}R_x}{R_3A}\left(\dfrac{R_xY_TR_w}{R_1}-1\right)\end{matrix}\right\} \tag{3.45}$$

Simplifying to both sides of the equation, the Eq. (3.45) becomes

$$V_{HP1}\left\{\frac{R_xY_TR_w}{R_1}+R_xY_T-\frac{R_x^2Y_TR_w}{AR_1^2}+\frac{R_x}{AR_1}\right\}=\left\{\begin{matrix} V_{LP1}\left[1+\dfrac{R_xY_TR_w}{AR_1}-\dfrac{1}{A}\right]+ \\ V_{in}\left[\dfrac{R_x^2Y_TR_w}{AR_1R_2}-\dfrac{R_x}{R_2A}\right]+ \\ V_{BP1}\left[\dfrac{R_x^2Y_TR_w}{AR_1R_3}-\dfrac{R_x}{R_3A}\right]\end{matrix}\right\} \tag{3.46}$$

Multiplying AR_1^2 to both sides of the equation, the Eq. (3.46) becomes

$$V_{HP1}\left\{\begin{matrix} Y_TAR_xR_wR_1R_2R_3+ \\ Y_TAR_xR_1^2R_2R_3 \\ -R_x^2Y_TR_wR_2R_3+ \\ R_xR_1R_2R_3\end{matrix}\right\}=\left\{\begin{matrix} V_{LP1}\begin{bmatrix} AR_1^2R_2R_3+Y_TR_xR_wR_1R_2R_3 \\ -R_1^2R_2R_3\end{bmatrix} \\ +V_{in}\left[Y_TR_x^2R_wR_1R_3-R_xR_1^2R_3\right] \\ +V_{BP1}\left[Y_TR_x^2R_wR_1R_2-R_xR_1^2R_2\right]\end{matrix}\right\} \tag{3.47}$$

Reordering and regrouping all equal terms, the Eq. (3.47) becomes

$$V_{HP1}\left\{\begin{matrix} Y_TR_xR_2R_3\begin{bmatrix} AR_1(R_w+R_1) \\ -R_xR_w\end{bmatrix} \\ +R_xR_1R_2R_3\end{matrix}\right\}=\left\{\begin{matrix} V_{LP1}\begin{bmatrix} R_1^2R_2R_3(A-1) \\ +Y_TR_xR_wR_1R_2R_3\end{bmatrix} \\ +V_{in}\begin{bmatrix} Y_TR_x^2R_wR_1R_3- \\ R_xR_1^2R_3\end{bmatrix}+ \\ V_{BP1}\begin{bmatrix} Y_TR_x^2R_wR_1R_2- \\ R_xR_1^2R_2\end{bmatrix}\end{matrix}\right\} \tag{3.48}$$

Substituting the original form of $A=\left(\dfrac{R_x}{R_1}+\dfrac{R_x}{R_2}+\dfrac{R_x}{R_3}+1\right)$ into both sides of the equation, the transfer functions is obtained as follows:

$$V_{HP1}\left\{\begin{matrix} Y_TR_xR_2R_3 \\ \begin{bmatrix}\left(\dfrac{R_x}{R_1}+\dfrac{R_x}{R_2}+\dfrac{R_x}{R_3}+1\right) \\ R_1(R_w+R_1)-R_xR_w\end{bmatrix}+ \\ R_xR_1R_2R_3\end{matrix}\right\}=\left\{\begin{matrix} V_{LP1}\begin{bmatrix} R_1^2R_2R_3\left(\dfrac{R_x}{R_1}+\dfrac{R_x}{R_2}+\dfrac{R_x}{R_3}\right) \\ +Y_TR_xR_wR_1R_2R_3\end{bmatrix} \\ +V_{in}\left[Y_TR_x^2R_wR_1R_3-R_xR_1^2R_3\right]+ \\ V_{BP1}\left[Y_TR_x^2R_wR_1R_2-R_xR_1^2R_2\right]\end{matrix}\right\} \tag{3.49}$$

Simplifying to both sides of the equation, the Eq. (3.49) becomes

$$V_{HP1}R_xR_1R_2R_3\left\{1+Y_T\left[\left(\frac{R_x}{R_1}+\frac{R_x}{R_2}+\frac{R_x}{R_3}+1\right)(R_w+R_1)-\frac{R_xR_w}{R_1}\right]\right\}=\left\{\begin{matrix}V_{LP1}R_xR_1R_2R_3\left[\left(1+\frac{R_1}{R_2}+\frac{R_1}{R_3}\right)+Y_TR_w\right]+\\ V_{in}R_xR_1R_3\left[Y_TR_xR_w-R_1\right]+\\ V_{BP1}R_xR_1R_2\left[Y_TR_xR_w-R_1\right]\end{matrix}\right\} \quad (3.50)$$

Making the factored form of $R_xR_1R_2R_3$ to both sides of the equation, the Eq. (3.50) becomes

$$V_{HP1}R_xR_1R_2R_3\left\{1+Y_T\left[\frac{R_wR_x}{R_2}+\frac{R_wR_x}{R_3}+\frac{R_1R_x}{R_2}+\frac{R_1R_x}{R_3}+R_x+R_w+R_1\right]\right\}=R_xR_1R_2R_3\left\{\begin{matrix}V_{LP1}\left[\left(1+\frac{R_1}{R_2}+\frac{R_1}{R_3}\right)+Y_TR_w\right]\\ +V_{in}\left[Y_T\frac{R_xR_w}{R_2}-\frac{R_1}{R_2}\right]\\ +V_{BP1}\left[Y_T\frac{R_xR_w}{R_3}-\frac{R_1}{R_3}\right]\end{matrix}\right\} \quad (3.51)$$

R_x and R_w << R_1, R_2 and R_3

$$V_{HP1}\left(1+Y_TR_1\right)=V_{LP1}\left[\left(1+\frac{R_1}{R_2}+\frac{R_1}{R_3}\right)+Y_TR_w\right]-\frac{R_1}{R_2}V_{in}-\frac{R_1}{R_3}V_{BP1} \quad (3.52)$$

From Eq. (3.52), both sides have the parasitic elements Y_T (G_T + sC_T) that affect the pass-band gain in real application. The parasitic resistances R_T affects the pass-band gain at low frequency while the parasitic capacitance C_T affects the pass-band gain at high frequency. The pole that limits the operational frequency (at high frequency) or bandwidth of the proposed circuit is approximately 26MHz that can be obtained from substituting the R_T and C_T values ($R_T \approx 197.093k\Omega$ and $C_T \approx 6.215pF$) in the first term of the left side of Eq. (3.52). However, the expected operational frequency of the proposed filter circuit is lower than 10MHz i.e., $f_{op} \ll \frac{1}{2\pi(R_1 \parallel R_T)C_T}$, the effect of R_T and C_T are ignored. If R_T >> R_1, the operational frequency of the proposed filter is determined by

$$f_{op} \ll \frac{1}{2\pi R_1 C_T} \tag{3.53}$$

At high frequency, the operational frequency is still higher than the expected frequency. So, the effect of C_T is ignored in Eq. (3.53). According to the data sheet of LT1228 (LT1228: Linear Technology, 2012), to reduce the effect of R_T and C_T and to get higher operating frequency, the feedback resistor (R_1 in this filter 1) connecting from *w* to *x* terminal in the summing circuit should be low. In consideration of these parasitic elements, the output voltage of the summing circuit realized in Fig. 3 is obtained as

$$V_{HP1} = V_{LP1}\left(1 + \frac{R_1}{R_2} + \frac{R_1}{R_3}\right) - \frac{R_1}{R_2}V_{in} - \frac{R_1}{R_3}V_{BP1} \tag{3.54}$$

If $R_1=R_2=R_3=R$, the output voltage equation becomes

$$V_{HP1} = 3V_{LP1} - V_{in} - V_{BP1} \tag{3.55}$$

Next, these mentioned parasitic elements are considered and the voltage transfer functions of the proposed filter in Fig 3.7 are expressed in detail as follows:

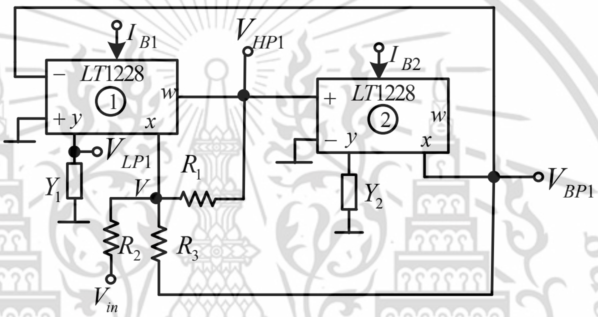


Figure 3.7 First proposed SIMO filter with parasitic elements

$$Y_1 = G_{y1} + s(C_1 + C_{y1}) \tag{3.56}$$

and

$$Y_2 = G_{y2} + s(C_2 + C_{y2}) \tag{3.57}$$

The lossless integrator outputs: V_{LP1} and V_{BP1} are obtained as follows:

$$V_{LP1} = -\frac{g_{m1}}{Y_1}V_{BP1} \tag{3.58}$$

$$V_{BP1} = \frac{g_{m2}}{Y_2}V_{HP1} \tag{3.59}$$

Substituting V_{BP1} from Eq. (3.59) into (3.58),

$$V_{LP1} = -\frac{g_{m1}g_{m2}}{Y_1Y_2}V_{HP1} \tag{3.60}$$

According to ideal characteristic of CFA, $V = V_{LP1}$. Using Kirchhoff's current law (KCL) at V node, the current equation becomes

$$\frac{V_{LP1} - V_{HP1}}{R_1} + \frac{V_{LP1} - V_{in}}{R_2} + \frac{V_{LP1} - V_{BP1}}{R_3} = 0 \tag{3.61}$$

Moving V_{LP1} to the left and others (V_{HP1}, V_{BP1} and V_{in}) to the right side, the Eq. (3.61) becomes

$$V_{LP1}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = \frac{V_{HP1}}{R_1} + \frac{V_{in}}{R_2} + \frac{V_{BP1}}{R_3} \tag{3.62}$$

If $R_1=R_2=R_3=R$, the voltage equation becomes

$$V_{HP1} = 3V_{LP1} - V_{BP1} - V_{in} \tag{3.63}$$

Substituting V_{LP1} and V_{BP1} from Eq. (3.59) and (3.60) into Eq. (3.63), the output voltage at V_{HP1} node becomes

$$V_{HP1} = \frac{-3g_{m1}g_{m2}}{Y_1Y_2}V_{HP1} - \frac{g_{m2}}{Y_2}V_{HP1} - V_{in} \tag{3.64}$$

Eq. (3.64) is multiplied by Y_1 Y_2, the V_{HP1} is obtained as follows:

$$Y_1Y_2V_{HP1} = -3g_{m1}g_{m2}V_{HP1} - g_{m2}Y_1V_{HP1} - Y_1Y_2V_{in} \tag{3.65}$$

Moving all V_{HP1} to the left, Eq. (3.65) becomes

$$\left(3g_{m1}g_{m2} + g_{m2}Y_1 + Y_1Y_2\right)V_{HP1} = -Y_1Y_2V_{in} \tag{3.66}$$

Substituting Eq. (3.56) and (3.57) into Eq. (3.66), the V_{HP1} is described as follow:

$$\left\{\begin{matrix} 3g_{m1}g_{m2} + g_{m2}\left[G_{y1} + s(C_1 + C_{y1})\right] + \\ \left[G_{y1} + s(C_1 + C_{y1})\right] \\ \left[G_{y2} + s(C_2 + C_{y2})\right] \end{matrix}\right\}V_{HP1} = -\left\{\begin{matrix} \left[G_{y1} + s(C_1 + C_{y1})\right] \\ \left[G_{y2} + s(C_2 + C_{y2})\right] \end{matrix}\right\}V_{in} \tag{3.67}$$

Assigning $C_1^* = C_1 + C_{y1}$; $C_2^* = C_2 + C_{y2}$ into Eq. (3.67), the voltage equation is obtained as follows:

$$\begin{bmatrix} 3g_{m1}g_{m2} + g_{m2}\left(G_{y1} + sC_1^*\right) + \\ \left(G_{y1} + sC_1^*\right)\left(G_{y2} + sC_2^*\right) \end{bmatrix}V_{HP1} = -\left[\left(G_{y1} + sC_1^*\right)\left(G_{y2} + sC_2^*\right)\right]V_{in} \tag{3.68}$$

Simplifying Eq. (3.68), the voltage equation becomes

$$\begin{pmatrix} 3g_{m1}g_{m2} + g_{m2}G_{y1} + sg_{m2}C_1^* \\ +G_{y1}G_{y2} + sG_{y2}C_1^* + \\ sG_{y1}C_2^* + s^2C_1^*C_2^* \end{pmatrix}V_{HP1} = -\begin{pmatrix} G_{y1}G_{y2} + sG_{y2}C_1^* + \\ sG_{y1}C_2^* + s^2C_1^*C_2^* \end{pmatrix}V_{in} \tag{3.69}$$

Reordering and dividing $C_1^*C_2^*$ to both sides of Eq. (3.69), the voltage equation becomes

$$\begin{pmatrix} s^2 + \dfrac{G_{y1}C_2^* + G_{y2}C_1^* + g_{m2}C_1^*}{C_1^*C_2^*}s \\ + \dfrac{G_{y1}G_{y2} + 3g_{m1}g_{m2} + g_{m2}G_{y1}}{C_1^*C_2^*} \end{pmatrix}V_{HP1} = -\begin{pmatrix} s^2 + \dfrac{G_{y1}C_2^* + G_{y2}C_1^*}{C_1^*C_2^*}s \\ + \dfrac{G_{y1}G_{y2}}{C_1^*C_2^*} \end{pmatrix}V_{in} \tag{3.70}$$

Interchanging to both sides of Eq. (3.70), the transfer function for HP1 response becomes

$$\frac{V_{HP1}}{V_{in}} = \frac{-\left(s^2 + \dfrac{G_{y1}C_2^* + G_{y2}C_1^*}{C_1^*C_2^*}s + \dfrac{G_{y1}G_{y2}}{C_1^*C_2^*}\right)}{s^2 + \left(\dfrac{G_{y1}C_2^* + G_{y2}C_1^* + g_{m2}C_1^*}{C_1^*C_2^*}\right)s + \dfrac{G_{y1}G_{y2} + 3g_{m1}g_{m2} + g_{m2}G_{y1}}{C_1^*C_2^*}} \tag{3.71}$$

From Eq. (3.71), the nominator term $\dfrac{G_{y1}G_{y2}}{C_1^*C_2^*}$ slightly deviates the high-pass response at low frequency. In ideal HP1 response, the passband gain of HP1 response gradually increases below the natural frequency but in real the passband gain of HP1 response is constant below the natural frequency. The passband voltage gain for HP1 is unity. By calculating like this HP1 response, the other transfer function for LP1 response is obtained as follows:

$$\frac{V_{LP1}}{V_{in}}=\frac{\dfrac{g_{m1}g_{m2}}{C_1^*C_2^*}}{s^2+\left(\dfrac{G_{y1}C_2^*+G_{y2}C_1^*+g_{m2}C_1^*}{C_1^*C_2^*}\right)s+\dfrac{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}{C_1^*C_2^*}} \tag{3.72}$$

In Eq. (3.72), the passband voltage gain for LP1 is $\dfrac{g_{m1}g_{m2}}{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}$. The BP1 response is as follows:

$$\frac{V_{BP1}}{V_{in}}=\frac{-\dfrac{g_{m2}G_{y1}}{C_1^*C_2^*}-\dfrac{g_{m2}}{C_2^*}s}{s^2+\left(\dfrac{G_{y1}C_2^*+G_{y2}C_1^*+g_{m2}C_1^*}{C_1^*C_2^*}\right)s+\dfrac{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}{C_1^*C_2^*}} \tag{3.73}$$

From Eq. (3.73), the nominator term $\dfrac{g_{m2}G_{y1}}{C_1^*C_2^*}$ slightly deviates the band-pass response at low frequency. In ideal BP1 response, the passband gain of BP1 response gradually increases below the natural frequency but in real the passband gain of BP1 response is constantly below the natural frequency. The passband voltage gain for BP1 is $\dfrac{g_{m2}C_1^*}{G_{y1}C_2^*+G_{y2}C_1^*+g_{m2}C_1^*}$, where $G_{y1}=\dfrac{1}{R_{y1}}$; $G_{y2}=\dfrac{1}{R_{y2}}$.

$$D_1(s)=s^2+\left(\frac{G_{y1}C_2^*+G_{y2}C_1^*+g_{m2}C_1^*}{C_1^*C_2^*}\right)s+\frac{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}{C_1^*C_2^*} \tag{3.74}$$

$$\frac{V_{HP1}}{V_{in}}=\frac{-s^2-\left(\dfrac{G_{y1}C_2^*+G_{y2}C_1^*}{C_1^*C_2^*}\right)s-\dfrac{G_{y1}G_{y2}}{C_1^*C_2^*}}{D_1(s)} \tag{3.75}$$

$$\frac{V_{LP1}}{V_{in}}=\frac{\dfrac{g_{m1}g_{m2}}{C_1^*C_2^*}}{D_1(s)} \tag{3.76}$$

$$\frac{V_{BP1}}{V_{in}}=\frac{-\dfrac{g_{m2}G_{y1}}{C_1^*C_2^*}-\dfrac{g_{m2}}{C_2^*}s}{D_1(s)} \tag{3.77}$$

From Eq. (3.74), the non-ideal natural freqeuncy and quality factor of the first proposed filter become

$$\omega_{01}^*=\sqrt{\frac{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}{C_1^*C_2^*}} \tag{3.78}$$

$$Q_1^*=\frac{\sqrt{C_1^*C_2^*\left(G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}\right)}}{G_{y1}C_2^*+G_{y2}C_1^*+g_{m2}C_1^*} \tag{3.79}$$

It is seen from Eq. (3.78) to Eq. (3.79) that the parasitic elements in LT1228 affect the filtering performances which are the operational frequency, passband voltage gain, natural frequency, and quality factor.

3.2 Synthesis of filter 2

3.2.1 Synthesis procedure of filter 2

The second proposed filter is synthesized from the block diagram in Fig 3.8 that is modified from (Olmez and Cam, 2009). It consists of five basic blocks: the voltage summing circuit, two lossless integrators, and two voltage amplifiers. The inputs of the voltage summing circuit are the $3V_{LP2}$, V_{BP2} and V_{in} while the output voltage node of the summing circuit is the V_{HP2}. The voltage node, V_{BP2} is the output of the first lossless integrator multiplied by the voltage gain amplifier, K. The V_{LP2} is the output of the second lossless integrator. The time constants of the first and second integrators are defined as a and b, respectively.

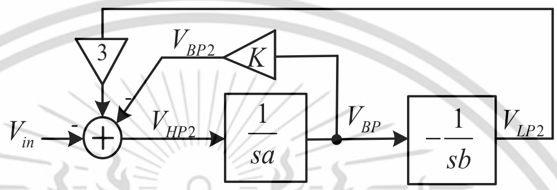


Figure 3.8 Synthesis block diagram of the second proposed filter.

From Fig 3.8, the transfer function for the first lossless integrator at V_{BP} node is

$$\frac{V_{BP}}{V_{HP2}} = \frac{1}{sa} \tag{3.80}$$

The transfer function for the second lossless integrator at V_{LP2} node is

$$\frac{V_{LP2}}{V_{HP2}} = -\frac{1}{s^2 ab} \tag{3.81}$$

Substituting V_{BP} from Eq. (3.79) into (3.80), the transfer function at V_{LP2} node becomes

$$\frac{V_{LP2}}{V_{HP2}} = -\frac{1}{s^2 ab} \tag{3.82}$$

The output voltage equation for the first summing block is

$$V_{HP2} = 3V_{LP2} - V_{BP2} - V_{in} \tag{3.83}$$

where $V_{BP2} = KV_{BP}$ and substituting V_{LP2} and V_{BP} from Eq. (3.80) and (3.82) into (3.83), the output voltage at V_{HP2} node becomes

$$V_{HP2} = -3\frac{1}{s^2 ab}V_{HP2} - \frac{K}{sa}V_{HP2} - V_{in} \tag{3.84}$$

Eq. (3.84) is multiplied by s^2, the V_{HP2} is obtained as follows:

$$s^2 V_{HP2} = -3\frac{1}{ab}V_{HP2} - s\frac{K}{a}V_{HP2} - s^2 V_{in} \tag{3.85}$$

Moving V_{HP2} to the left side of Eq. (3.85), the V_{HP2} is

$$\left(s^2 + s\frac{K}{a} + \frac{3}{ab}\right)V_{HP2} = -s^2 V_{in} \tag{3.86}$$

From Eq. (3.86), the transfer function for V_{HP2} of the block diagram shown in Fig. 3.8 is described as

$$\frac{V_{HP2}}{V_{in}} = \frac{-s^2}{s^2 + s\frac{K}{a} + \frac{3}{ab}} \tag{3.87}$$

Substituting V_{HP2} from Eq. (3.87) into (3.81), transfer function of V_{LP2} becomes

$$\frac{V_{LP2}}{V_{in}} = \left(-\frac{1}{s^2 ab}\right) \times \frac{\left(-s^2\right)}{s^2 + s\frac{K}{a} + \frac{3}{ab}} \tag{3.88}$$

According to Eq. (3.88), the voltage transfer functions for V_{LP2} is obtained as follows:

$$\frac{V_{LP2}}{V_{in}} = \frac{\frac{1}{ab}}{s^2 + s\frac{K}{a} + \frac{3}{ab}} \tag{3.89}$$

Substituting like this V_{LP2}, the voltage transfer functions for V_{BP2} is

$$\frac{V_{BP2}}{V_{in}} = \frac{-s\frac{K}{a}}{s^2 + s\frac{K}{a} + \frac{3}{ab}} \tag{3.90}$$

Eq. (3.87), (3.89), and (3.90) indicate that the inverting passband voltage gain with one is obtained for BP and HP functions and non-inverting passband voltage-gain with one-third is obtained for LP function. The (ω_{02}) and (Q_2) are respectively obtained as

$$\omega_{02} = \sqrt{\frac{3}{ab}} \text{ and } Q_2 = \frac{1}{K}\sqrt{\frac{3a}{b}} \tag{3.91}$$

Eq. (3.91) shows that the Q_2 can be adjusted without disturbing the ω_{02} by varying the voltage gain, K. Simultaneously adjusting the time constant a and b of the integrator circuits can control the ω_{02} without affecting the Q_2. Then ω_{02} and Q_2 are independently controlled where the Q_2 can be adjusted by the voltage gain, K and the ω_{02} can be linearly adjusted by time constants of both integrators. From the synthesis block diagram in Fig 3.8, it is divided into two parts and synthesized the circuit by LT1228. The first part of the synthesis block diagram is the first lossless integrator and the voltage summing circuit. The capacitor C_1 and first LT1228 are built as a first lossless integrator. The voltage summing circuit is constructed from the resistors R_1, R_2, R_3 (they are same resistance value) and first LT1228. The first part is successfully synthesized from the first LT1228 with one grounded capacitor and the three resistors in Fig 3.9.

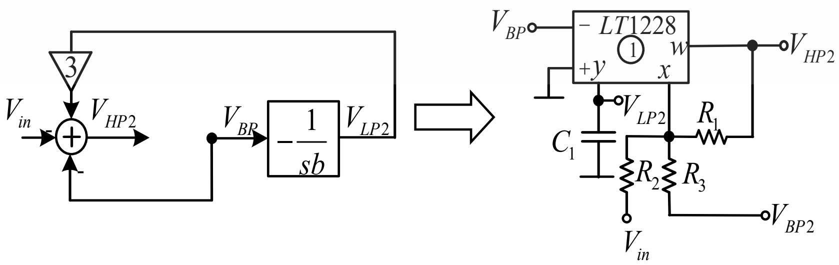


Figure 3.9 Inverting lossless integrator with voltage summing circuit synthesized from LT1228

The second part of the synthesis block diagram is the second lossless integrator and the voltage summing circuit. The capacitor C_2 and second LT1228 are built as a second lossless integrator. The voltage gain amplifier circuit (*K*) is constructed from the resistors (R_4 and R_5) and second LT1228. The second part is successfully synthesized from the second LT1228 with one grounded capacitor and the two resistors in Fig 3.10.

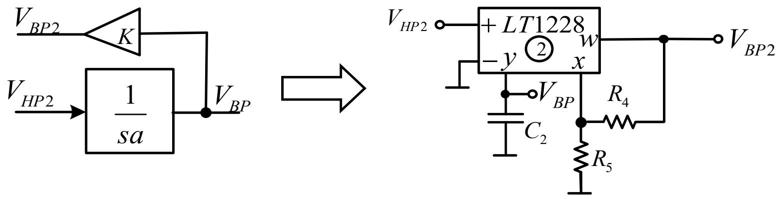


Figure 3.10 Non-inverting lossless integrator with voltage summing circuit synthesized from LT1228

The complete schematic of the second presented universal second order filter utilized LT1228 is shown in Fig. 3.11. It comprises two lossless integrators, one voltage gain amplifier, and one voltage summing circuit. It is constructed from two LT1228s with a single input voltage signal V_{in}, five resistors, and two grounded capacitors. The three output voltages are V_{HP2}, V_{LP2} and V_{BP2}. The filter shows low output impedance at V_{HP2} and V_{BP2} nodes that can cascade to other circuits while no exploitation of the buffer.

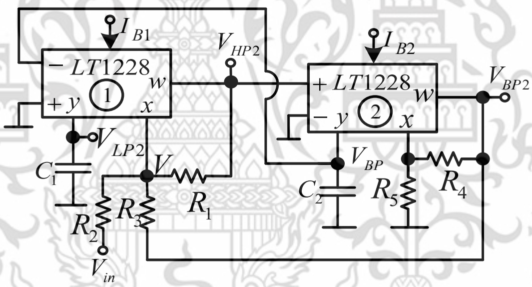


Figure 3.11 Second proposed SIMO universal filter.

3.2.2 Ideal analysis

From Fig 3.11 and Eq. (3.13) through (3.14), the following transfer function equation can be described in detail. The lossless integrator outputs: V_{LP2} and V_{BP} are obtained as follows:

$$V_{LP2} = -\frac{g_{m1}}{sC_1} V_{BP} \tag{3.92}$$

$$V_{BP} = \frac{g_{m2}}{sC_2} V_{HP2} \tag{3.93}$$

Substituting V_{BP} from Eq. (3.93) into (3.92),

$$V_{LP2} = -\frac{g_{m1} g_{m2}}{s^2 C_1 C_2} V_{HP2} \tag{3.94}$$

According to ideal characteristic of CFA, $V = V_{LP2}$.Using Kirchhoff's current law (KCL) at *V* node, the current equation becomes

$$\frac{V_{LP2} - V_{HP2}}{R_1} + \frac{V_{LP2} - V_{in}}{R_2} + \frac{V_{LP2} - KV_{BP}}{R_3} = 0 \tag{3.95}$$

Moving V_{LP2} to the left and others (V_{HP2}, V_{BP2} and V_{in}) to the right side, the Eq. (3.95) becomes

$$V_{LP2}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right)=\frac{V_{HP2}}{R_1}+\frac{V_{in}}{R_2}+\frac{KV_{BP}}{R_3} \tag{3.96}$$

If $R_1=R_2=R_3=R$, the voltage equation becomes

$$V_{HP2}=3V_{LP2}-KV_{BP}-V_{in} \tag{3.97}$$

Substituting V_{BP} and V_{LP2} from Eq. (3.93) and (3.94) into (3.97), the output voltage at V_{HP2} node becomes

$$V_{HP2}=\frac{-3g_{m1}g_{m2}}{s^2C_1C_2}V_{HP2}-\frac{Kg_{m2}}{sC_2}V_{HP2}-V_{in} \tag{3.98}$$

Eq. (3.98) is multiplied by $\hat{s}$, the V_{HP2} is obtained as follows:

$$s^2V_{HP2}=\frac{-3g_{m1}g_{m2}}{C_1C_2}V_{HP2}-\frac{Kg_{m2}}{C_2}sV_{HP2}-s^2V_{in} \tag{3.99}$$

Moving all V_{HP2} to the left, Eq. (3.97) becomes

$$\left(s^2+\frac{Kg_{m2}}{C_2}s+\frac{3g_{m1}g_{m2}}{C_1C_2}\right)V_{HP2}=-s^2V_{in} \tag{3.100}$$

Interchanging to both sides of Eq. (3.100), the transfer function for HP2 response becomes

$$\frac{V_{HP2}}{V_{in}}=\frac{-s^2}{s^2+\frac{Kg_{m2}}{C_2}s+\frac{3g_{m1}g_{m2}}{C_1C_2}} \tag{3.101}$$

where,

$$D_2(s)=s^2+\frac{Kg_{m2}}{C_2}s+\frac{3g_{m1}g_{m2}}{C_1C_2} \tag{3.102}$$

$$\frac{V_{HP2}}{V_{in}}=\frac{-s^2}{D_2(s)} \tag{3.103}$$

By calculating like this HP2 response, the other transfer function for LP2 and BP2 responses are respectively obtained as follows:

$$\frac{V_{LP2}}{V_{in}}=\frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{D_2(s)}\ \text{and}\ \frac{V_{BP2}}{V_{in}}=\frac{-\frac{Kg_{m2}}{C_2}s}{D_2(s)} \tag{3.104}$$

where $K=1+\frac{R_4}{R_5}$. From Eq. (3.103) and (3.104), the voltage gains of HP2 and BP2 filtering function are unity and LP2 filtering function is one-third. Also from them, ω_{02} and Q_2 are obtained as the following:

$$\omega_{02}=\sqrt{\frac{3g_{m1}g_{m2}}{C_1C_2}}\ \text{and}\ Q_2=\frac{1}{K}\sqrt{\frac{3g_{m1}C_2}{g_{m2}C_1}} \tag{3.105}$$

Substituting the transconductances g_{m1} and g_{m2} in function of the bias currents, I_{B1} and I_{B2} as appeared in Eq. (3.14) into Eq. (3.105), the ω_{02} and Q_2 of the proposed circuit are

$$\omega_{02}=10\sqrt{\frac{3I_{B1}I_{B2}}{C_1C_2}}\ \text{and}\ Q_2=\frac{R_5}{R_4+R_5}\sqrt{\frac{3I_{B1}C_2}{I_{B2}C_1}} \tag{3.106}$$

It is found from (3.106) that the ω_{02} can be electronically tuned by I_{B1} and I_{B2}. Moreover, the Q_2 can be altered without affecting ω_{02} by changing the value of R_5 (as stated in data sheet of LT1228 (LT1228: Linear Technology, 2012), R_4 should not be adjusted to keep the constant bandwidth.). Other advantages for tuning filter parameter can be achieved by simultaneously adjusting $I_{B1} = I_{B2} = I_B$ (this feature is easily implemented by using a microcontroller or microcomputer) are simultaneously adjusted and choosing $C_1 = C_2 = C$, the filtering parameters in Eq. (3.106) becomes

$$\omega_{02} = \frac{10 I_B}{C}\sqrt{3} \text{ and } Q_2 = \frac{R_5}{R_4 + R_5}\sqrt{3} \tag{3.107}$$

It can be remarked from Eq. (3.107) that ω_{02} and Q_2 are independently, electronically controlled. Moreover, the ω_{02} can be linearly and electronically adjusted. Also, the control of ω_{02} and Q_2 does not affect the passband voltage gain for all filtering responses.

3.2.3 Parasitic effect analysis

The parasitic effects of LT1228 are described in detail in section 3.13. Similarly, the effect of Y_T in the summing circuit of the second proposed filter in Fig 3.11 is the same above-mentioned calculation in section 3.1.3. The effect of Y_T in the voltage gain amplifier circuit of the second proposed filter is the same calculation but V_{BP1} is grounded and R_2 is infinity in Eq. (3.52). So, the output voltage equation becomes

$$\frac{V_{HP1}}{V_{LP1}} = \left(1 + \frac{R_4}{R_5}\right) \tag{3.108}$$

If $R_4 = R_5 = R$, the final output voltage equation becomes

$$\frac{V_{HP1}}{V_{LP1}} = 2 \tag{3.109}$$

From above calculation, the V_{BP2} and V_{BP} of the second proposed filter is as same V_{HP1} and V_{LP1} of the first proposed filter. The voltage gain amplifier circuit of the second proposed filter is considered as 2. In summary, the R_T and C_T effects in the summing circuit of the first LT1228 are ignored, the R_T and C_T effects in the voltage gain amplifier of the second LT1228 are ignored. According to the data sheet of LT1228 (LT1228: Linear Technology, 2012), to reduce the effect of C_T and R_T and to get higher operating frequency, the feedback resistor (R_1, in this filter) connecting from w to x terminal in summing circuit should be low. Also, if the bandwidth of the presented filter is expected to be lower than 10MHz, the most effect stems from R_-, C_-, R_+, C_+, R_y and C_y (the effect of R_x, R_w, R_T and C_T are ignored). Next, these mentioned parasitic elements are considered and the voltage transfer functions of the second proposed filter in Fig. 3.12 are expressed in detail as follows:

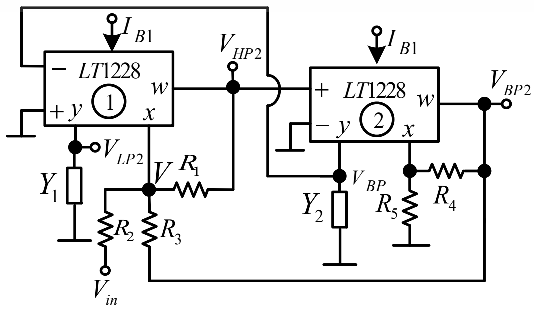


Figure 3.12 Second proposed SIMO filter with parasitic elements

$$Y_1 = G_{y1} + s(C_1 + C_{y1}) \tag{3.110}$$

and

$$Y_2 = G_{y2} + G_{-1} + s(C_2 + C_{y2} + C_{-1}) \tag{3.111}$$

The lossless integrator outputs: V_{LP2} and V_{BP} are obtained as follows:

$$V_{LP2} = \frac{-g_{m1}}{Y_1} V_{BP2} \tag{3.112}$$

$$V_{BP2} = \frac{g_{m2}}{Y_2} V_{HP2} \tag{3.113}$$

Substituting V_{BP} from Eq. (3.113) into (3.112),

$$V_{LP2} = \frac{-g_{m1} g_{m2}}{Y_1 Y_2} V_{HP2} \tag{3.114}$$

According to ideal characteristic of CFA, $V = V_{LP2}$.Using Kirchhoff's current law (KCL) at V node, the current equation becomes

$$\frac{V_{LP2} - V_{HP2}}{R_1} + \frac{V_{LP2} - V_{in}}{R_2} + \frac{V_{LP2} - V_{BP2}}{R_3} = 0 \tag{3.115}$$

Moving V_{LP2} to the left and others (V_{HP2}, V_{BP2} and V_{in}) to the right side, the Eq. (3.115) becomes

$$V_{LP2}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = \frac{V_{HP2}}{R_1} + \frac{V_{in}}{R_2} + \frac{V_{BP2}}{R_3} \tag{3.116}$$

If $R_1 = R_2 = R_3 = R$, the voltage equation becomes

$$V_{HP2} = 3V_{LP2} - KV_{BP2} - V_{in} \tag{3.117}$$

Substituting V_{LP2} and V_{BP2} from Eq. (3.110) and (3.111) into Eq. (3.117), the output voltage at V_{HP2} node becomes

$$V_{HP2} = -\frac{3g_{m1} g_{m2}}{Y_1 Y_2} V_{HP2} - \frac{K g_{m2}}{Y_2} V_{HP2} - V_{in} \tag{3.118}$$

Eq. (3.118) is multiplied by Y_1 Y_2, the V_{HP2} is obtained as follows:

$$Y_1 Y_2 V_{HP2} = -3g_{m1} g_{m2} V_{HP2} - K g_{m2} Y_1 V_{HP2} - Y_1 Y_2 V_{in} \tag{3.119}$$

Moving all V_{HP2} to the left, Eq. (3.119) becomes

$$\left(3g_{m1} g_{m2} + K g_{m2} Y_1 + Y_1 Y_2\right) V_{HP2} = -Y_1 Y_2 V_{in} \tag{3.120}$$

Substituting Eq. (3.110) and (3.111) into Eq. (3.120), the V_{HP2} is described as follow:

$$\left\{\begin{matrix} 3g_{m1} g_{m2} + K g_{m2}\left[G_{y1} + s(C_1 + C_{y1})\right] + \\ \left[G_{y1} + s(C_1 + C_{y1})\right] \\ \begin{bmatrix} G_{y2} + G_{-1} + \\ s(C_2 + C_{y2} + C_{-1}) \end{bmatrix} \end{matrix}\right\} V_{HP2} = -\left\{\begin{matrix} \left[G_{y1} + s(C_1 + C_{y1})\right] \\ \begin{bmatrix} G_{y2} + G_{-1} + \\ s(C_2 + C_{y2} + C_{-1}) \end{bmatrix} \end{matrix}\right\} V_{in} \tag{3.121}$$

Assigning $G_2^* = G_{y2} + G_{-1}$; $C_1^* = C_1 + C_{y1}$; $C_2^* = C_2 + C_{y2} + C_{-1}$ into Eq. (3.121), the voltage equation is obtained as follows:

$$\left\{\begin{matrix} 3g_{m1} g_{m2} + K g_{m2}\left[G_{y1} + sC_1^*\right] + \\ \left[G_{y1} + sC_1^*\right]\left[G_2^* + sC_2^*\right] \end{matrix}\right\} V_{HP2} = -\left\{\begin{matrix} \left[G_{y1} + sC_1^*\right] \\ \left[G_2^* + sC_2^*\right] \end{matrix}\right\} V_{in} \tag{3.122}$$

Simplifying Eq. (3.122), the voltage equation becomes

$$\left\{\begin{matrix}3g_{m1}g_{m2}+Kg_{m2}G_{y1}+Kg_{m2}C_1^*s+G_{y1}G_2^* \\ +sG_2^*C_1^*+sG_{y1}C_2^*+s^2C_1^*C_2^*\end{matrix}\right\}V_{HP2}=-\left\{\begin{matrix}G_{y1}G_2^*+sG_2^*C_1^*+ \\ sG_{y1}C_2^*+s^2C_1^*C_2^*\end{matrix}\right\}V_{in} \quad (3.123)$$

Reordering and dividing $C_1^*C_2^*$ to both sides of Eq. (3.123), the voltage equation becomes

$$\left\{\begin{matrix}s^2+\dfrac{G_{y1}C_2^*+G_2^*C_1^*+Kg_{m2}C_1^*}{C_1^*C_2^*}s \\ +\dfrac{G_{y1}G_2^*+3g_{m1}g_{m2}+Kg_{m2}G_{y1}}{C_1^*C_2^*}\end{matrix}\right\}V_{HP2}=-\left\{\begin{matrix}s^2+\dfrac{G_{y1}C_2^*+G_2^*C_1^*}{C_1^*C_2^*}s \\ +\dfrac{G_{y1}G_2^*}{C_1^*C_2^*}\end{matrix}\right\}V_{in} \quad (3.124)$$

Interchanging to both sides of Eq. (3.124), the transfer function for HP2 response becomes

$$\frac{V_{HP2}}{V_{in}}=\frac{-s^2-\dfrac{G_{y1}C_2^*+G_2^*C_1^*}{C_1^*C_2^*}s-\dfrac{G_{y1}G_2^*}{C_1^*C_2^*}}{\left[\begin{matrix}s^2+\left(\dfrac{G_{y1}C_2^*+G_2^*C_1^*+Kg_{m2}C_1^*}{C_1^*C_2^*}\right)s+ \\ \dfrac{G_{y1}G_2^*+3g_{m1}g_{m2}+Kg_{m2}G_{y1}}{C_1^*C_2^*}\end{matrix}\right]} \quad (3.125)$$

From (Eq. 3.125), the nominator term $\dfrac{G_{y1}G_2}{C_1^*C_2^*}$ slightly deviates the high-pass response at low frequency. In ideal HP2 response, the passband gain of HP2 response gradually increases below the natural frequency but in real the passband gain of HP2 response is constant below the natural frequency. The passband voltage gain for HP2 is unity. By calculating like this HP2 response, the other transfer function for LP2 response is obtained as follows:

$$\frac{V_{LP2}}{V_{in}}=\frac{\dfrac{g_{m1}g_{m2}}{C_1^*C_2^*}}{\left[\begin{matrix}s^2+\left(\dfrac{G_{y1}C_2^*+G_2^*C_1^*+Kg_{m2}C_1^*}{C_1^*C_2^*}\right)s+ \\ \dfrac{G_{y1}G_2^*+3g_{m1}g_{m2}+Kg_{m2}G_{y1}}{C_1^*C_2^*}\end{matrix}\right]} \quad (3.126)$$

The passband voltage gain for LP2 is $\dfrac{g_{m1}g_{m2}}{G_{y1}G_2^*+3g_{m1}g_{m2}+Kg_{m2}G_{y1}}$. The other transfer function for BP2 response is obtained as follows:

$$\frac{V_{BP2}}{V_{in}} = \frac{-\frac{Kg_{m2}G_{y1}}{C_1^*C_2^*} - \frac{Kg_{m2}}{C_2^*}s}{\left[s^2 + \left(\frac{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*}{C_1^*C_2^*} \right)s + \frac{G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}}{C_1^*C_2^*} \right]} \quad (3.127)$$

From Eq. (3.127), the nominator term $\frac{Kg_{m2}G_{y1}}{C_1^*C_2^*}$ slightly deviates the band-pass response at low frequency. In ideal BP2 response, the passband gain of BP2 response gradually increases below the natural frequency but in real the passband gain of BP2 response is constant below the natural frequency. The passband voltage gain for BP2 is $\frac{Kg_{m2}C_1^*}{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*}$, where, $K = 1 + \frac{R_4}{R_5}$; $G_{y1} = \frac{1}{R_{y1}}$; $G_2^* = \frac{1}{R_{y2}} + \frac{1}{R_{-1}}$.

$$D_2(s) = \left[s^2 + \left(\frac{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*}{C_1^*C_2^*} \right)s + \frac{G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}}{C_1^*C_2^*} \right] \quad (3.128)$$

$$\frac{V_{HP2}}{V_{in}} = \frac{-s^2 - \frac{G_{y1}C_2^* + G_2^*C_1^*}{C_1^*C_2^*}s - \frac{G_{y1}G_2^*}{C_1^*C_2^*}}{D_2(s)} \quad (3.129)$$

$$\frac{V_{LP2}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1^*C_2^*}}{D_2(s)} \quad (3.130)$$

$$\frac{V_{BP2}}{V_{in}} = \frac{-\frac{Kg_{m2}G_{y1}}{C_1^*C_2^*} - \frac{Kg_{m2}}{C_2^*}s}{D_2(s)} \quad (3.131)$$

From Eq. (3.128), the non-ideal natural freqeuncy and quality factor of the first proposed filter becomes

$$\omega_{02}^* = \sqrt{\frac{G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}}{C_1^*C_2^*}} \quad (3.132)$$

$$Q_2^* = \frac{\sqrt{C_1^*C_2^*\left(G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}\right)}}{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*} \quad (3.133)$$

It is seen from Eq. (3.132) to Eq. (3.133) that the parasitic elements in LT1228 affect the filtering performances which are the operational frequency, passband voltage gain, natural frequency, and quality factor.

3.3 Synthesis of filter 3

3.3.1 Synthesis procedure of filter 3

The third proposed filter is synthesized from the block diagram in Fig 3.8. It consists of five basic blocks: the voltage summing circuit, two lossless integrators, and two voltage gain amplifiers. From the synthesis block diagram in Fig 3.8, it is divided into three parts and synthesized the circuit by LT1228. The first part of the synthesis block diagram for filter 3 is the same as Fig. 3.9.

The second part of the synthesis block diagram for filter 3 is the different part from filter 2 is that the capacitor C_2 and second LT1228 are built as a second lossless integrator. The second part is successfully synthesized from the second LT1228 with one grounded capacitor in Fig. 3.13.

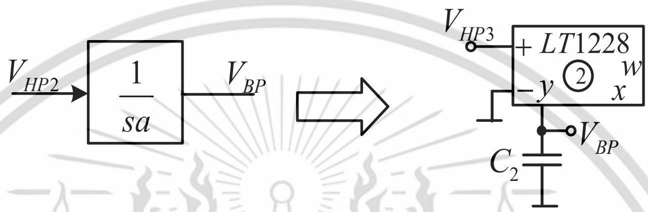


Figure 3.13 Non-inverting lossless integrator synthesized from LT1228

The third part of the synthesis block diagram for filter 3 is the different part from filter 2 is that the voltage gain amplifier. The amplifier consisting of resistor R_4 and third LT1228 in Fig. 3.14.

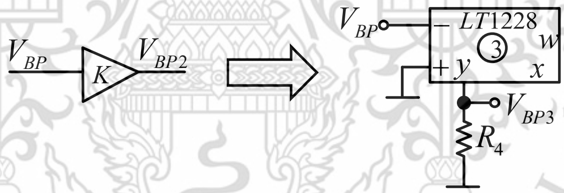


Figure 3.14 Inverting voltage gain amplifier synthesized from LT1228

The complete schematic of the third presented universal second order filter utilized LT1228 is shown in Fig. 3.16. It comprises two lossless integrators, two voltage gain amplifiers, and one voltage summing circuit. It is constructed from three LT1228s with a single input voltage signal V_{in}, four resistors, and two grounded capacitors. The three output voltages are V_{HP3}, V_{LP3} and V_{BP3}. The filter shows low output impedance at V_{HP3} node that can be cascaded to other circuits while no exploitation of the buffer.

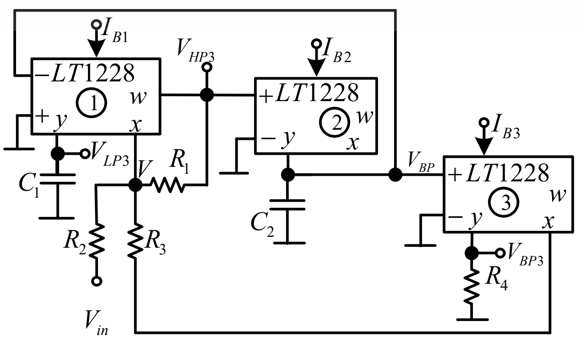


Figure 3.15 Third proposed SIMO universal filter.

3.3.2 Ideal analysis

From Fig 3.15 and Eq. (3.13) through (3.14), the following transfer function equation can be described in detail. The lossless integrator outputs: V_{LP3} and V_{BP} are obtained as follows:

$$V_{LP3} = \frac{-g_{m1}}{sC_1} V_{BP} \tag{3.134}$$

$$V_{BP} = \frac{g_{m2}}{sC_2} V_{HP3} \tag{3.135}$$

Substituting V_{BP} from Eq. (3.135) into (3.134),

$$V_{LP3} = -\frac{g_{m1}g_{m2}}{s^2C_1C_2} V_{HP3} \tag{3.136}$$

According to ideal characteristic of CFA, $V = V_{LP3}$ .Using Kirchhoff's current law (KCL) *at V* node, the current equation becomes

$$\frac{V_{LP3} - V_{HP3}}{R_1} + \frac{V_{LP3} - V_{in}}{R_2} + \frac{V_{LP3} - KV_{BP}}{R_3} = 0 \tag{3.137}$$

Moving V_{LP3} to the left and others (V_{HP3}, V_{BP3} and V_{in}) to the right side, the Eq. (3.137) becomes

$$V_{LP3}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = \frac{V_{HP3}}{R_1} + \frac{V_{in}}{R_2} + \frac{KV_{BP}}{R_3} \tag{3.138}$$

If R_1=R_2=R_3=R, the voltage equation becomes

$$V_{HP3} = 3V_{LP3} - KV_{BP} - V_{in} \tag{3.139}$$

Substituting V_{BP} and V_{LP3} from Eq. (3.136) and (3.135) into (3.139), the output voltage at V_{HP3} node becomes

$$V_{HP3} = -\frac{3g_{m1}g_{m2}}{s^2C_1C_2} V_{HP3} - \frac{Kg_{m2}}{sC_2} V_{HP3} - V_{in} \tag{3.140}$$

Multiplying by s^2 and assigning $K = g_{m3}R_4$ into Eq. (3.140), the V_{HP3} is obtained as follows:

$$s^2V_{HP3} = \frac{-3g_{m1}g_{m2}}{C_1C_2} V_{HP3} - \frac{g_{m2}g_{m3}R_4}{C_2} sV_{HP3} - s^2V_{in} \tag{3.141}$$

Moving all V_{HP3} to the left, Eq. (3.141) becomes

$$\left(s^2 + \frac{g_{m2}g_{m3}R_4}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2}\right)V_{HP3} = -s^2V_{in} \tag{3.142}$$

Interchanging to both sides of Eq. (3.142), the transfer function for HP3 response becomes

$$\frac{V_{HP3}}{V_{in}} = \frac{-s^2}{s^2 + \frac{g_{m2}g_{m3}R_4}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2}} \tag{3.143}$$

$$\text{where, } D_3(s) = s^2 + \frac{g_{m2}g_{m3}R_4}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2} \tag{3.144}$$

$$\frac{V_{HP3}}{V_{in}} = \frac{-s^2}{D_3(s)} \tag{3.145}$$

By calculating like this HP3 response, the other transfer function for LP3 and BP3 responses are respectively obtained as follows:

$$\frac{V_{LP3}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{D_3(s)} \tag{3.146}$$

$$\frac{V_{BP3}}{V_{in}} = \frac{-\frac{g_{m2}g_{m3}R_4}{C_2}s}{D_3(s)} \tag{3.147}$$

From Eq. (3.145) through (3.147), the voltage gains of HP3 and BP3 filtering function are unity and LP3 filtering function is one-third. Also from them, ω_{03} and Q_3 are obtained as the following:

$$\omega_{03} = \sqrt{\frac{3g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q_3 = \frac{1}{g_{m3}R_4}\sqrt{\frac{3g_{m1}C_2}{g_{m2}C_1}} \tag{3.148}$$

Substituting the transconductances g_{m1} and g_{m2} in function of the bias currents, I_{B1}, I_{B2} and I_{B3} as appeared in Eq. (3.14) into Eq. (3.148), the ω_{03} and Q_3 of the proposed circuit are

$$\omega_{03} = 10\sqrt{\frac{3I_{B1}I_{B2}}{C_1C_2}} \text{ and } Q_3 = \frac{1}{I_{B3}R_4}\sqrt{\frac{3I_{B1}C_2}{I_{B2}C_1}} \tag{3.149}$$

It is found from Eq. (3.149) that the ω_{03} can be electronically tuned by I_{B1} and I_{B2}. Moreover, the Q_3 can be altered without disturbing ω_{03} by changing the value of I_{B3}. If the bias currents $I_{B1} = I_{B2} = I_B$ (this property is easily implemented by using a microcontroller or microcomputer) are simultaneously adjusted and choosing $C_1 = C_2 = C$, the filtering parameters in Eq. (3.149) becomes

$$\omega_{03} = \frac{10I_B}{C}\sqrt{3} \text{ and } Q_3 = \frac{\sqrt{3}}{I_{B3}R_4} \tag{3.150}$$

It can be remarked from Eq. (3.150) that ω_{03} and Q_3 are independently, electronically controlled. Moreover, the ω_{03} and Q_3 can be linearly and electronically adjusted.

3.3.3 Parasitic effect analysis

In real response, the parasitic effects of LT1228 are described in detail in section 3.1.3. Similarly, the effect of Y_T in the summing circuit of the first LT1228 for the third proposed filter in Fig is the same above-mentioned calculation in section 3.1.3. Now, the voltage gain amplifier circuit of third LT1228 for the third proposed filter in Fig. 3.16 will be studied.

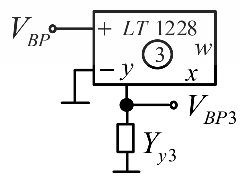


Figure 3.16 Summing amplifier with parasitic elements

The resistor, R_4 is paralleled the parasitic element Y_y and it is assigned as follows.

$$Y_{y3} = G_4 + G_{y3} + sC_{y3} \tag{3.151}$$

The voltage transfer function for non-inverting OTA is obtained as follows:

$$\frac{V_{BP3}}{V_{BP}} = \frac{g_{m3}}{Y_{y3}} \tag{3.152}$$

Substituting Eq. (3.151) into Eq. (3.152), the voltage transfer function becomes

$$\frac{V_{BP3}}{V_{BP}} = \frac{g_{m3}}{G_4 + G_{y3} + sC_{y3}} \tag{3.153}$$

Assigning $G_{y3}^* = \left(\frac{1}{R_{y3}} + \frac{1}{R_4}\right)$ into Eq. (3.153), the transfer function becomes

$$\frac{V_{BP3}}{V_{BP}} = \frac{g_{m3}}{G_{y3}^* + sC_{y3}} \tag{3.154}$$

From Eq. (3.154), the denominator has the parasitic elements (G_{y3}^* and C_{y3}) that affects the pass-band gain in real application. The parasitic resistance G_{y3}^* affects the pass-band gain at low frequency and the parasitic capacitance C_{y3}^* affects the pass-band gain at high frequency. The pole that limits the operational frequency (at high frequency) or bandwidth of the proposed circuit is approximately 29MHz that can be obtained from substituting the G_{y3} and C_{y3} values ($G_{y3} = 1.1M\Omega$ and $C_{y3} = 6pF$) in denominator of the Eq. (3.154). If $R_{y3} >> R_4$, the operational frequency of the proposed filter is determined by

$$f_{op} \ll \frac{1}{2\pi R_4 C_{y3}} \tag{3.155}$$

The operational frequency of the proposed filter circuit is lower than 10MHz i.e., $f_{op} \ll \frac{1}{2\pi(R_4 // R_{y3})C_{y3}}$, the effect of C_{y3}^* is ignored). The transfer function is obtained as follows:

$$\frac{V_{BP3}}{V_{BP}} = g_{m3} R_4 \tag{3.156}$$

Considering the above parasitic elements, the voltage transfer functions of the third presented filter circuit are realized in Fig 3.17 are expressed in detail as follows:

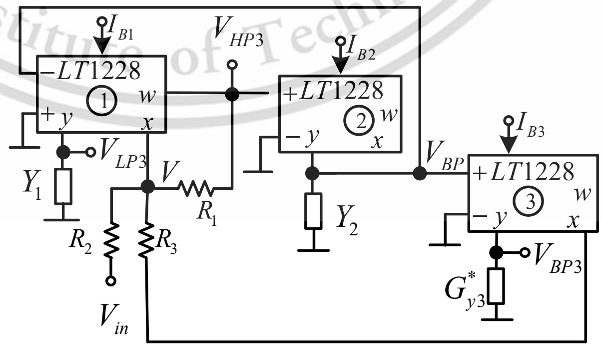


Figure 3.17 Third proposed SIMO filter with parasitic elements

$$Y_1 = G_{y1} + s(C_1 + C_{y1}) \tag{3.157}$$

$$Y_2 = G_{y2} + G_{-1} + G_{+3} + s(C_2 + C_{y2} + C_{-1} + C_{+3}) \tag{3.158}$$

and

$$G_{y3}^{*} = \left(\frac{1}{R_{y3}} + \frac{1}{R_4} \right) \quad (3.159)$$

The lossless integrator outputs: V_{LP3} and V_{BP3} are obtained as follows:

$$V_{LP3} = -\frac{g_{m1}}{Y_1} V_{BP} \quad (3.160)$$

$$V_{BP} = \frac{g_{m2}}{Y_2} V_{HP3} \quad (3.161)$$

Substituting V_{BP} from Eq. (3.161) into (3.160),

$$V_{LP3} = -\frac{g_{m1} g_{m2}}{Y_1 Y_2} V_{HP3} \quad (3.162)$$

According to ideal characteristic of CFA, $V = V_{LP3}$ .Using Kirchhoff's current law (KCL) at V node, the current equation becomes

$$\frac{V_{LP3} - V_{HP3}}{R_1} + \frac{V_{LP3} - V_{in}}{R_2} + \frac{V_{LP3} - V_{BP3}}{R_3} = 0 \quad (3.163)$$

Moving V_{LP3} to the left and others (V_{HP3}, V_{BP3} and V_{in}) to the right side, the Eq. (3.163) becomes

$$V_{LP3} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) = \frac{V_{HP3}}{R_1} + \frac{V_{in}}{R_2} + \frac{V_{BP3}}{R_3} \quad (3.164)$$

If $R_1 = R_2 = R_3 = R$, the voltage equation becomes

$$V_{HP3} = 3V_{LP3} - K^{*} V_{BP} - V_{in} \quad (3.165)$$

Substituting V_{LP3} and V_{BP} from Eq. (3.161) and (3.162) into (3.165), the output voltage at V_{HP3} node becomes

$$V_{HP3} = -\frac{3 g_{m1} g_{m2}}{Y_1 Y_2} V_{HP3} - \frac{K^{*} g_{m2}}{Y_2} V_{HP3} - V_{in} \quad (3.166)$$

Eq. (3.166) is multiplied by Y_1 Y_2, the V_{HP3} is obtained as follows:

$$Y_1 Y_2 V_{HP3} = -3 g_{m1} g_{m2} V_{HP3} - K^{*} g_{m2} Y_1 V_{HP3} - Y_1 Y_2 V_{in} \quad (3.167)$$

Moving all V_{HP3} to the left, Eq. (3.167) becomes

$$\left(3 g_{m1} g_{m2} + K^{*} g_{m2} Y_1 + Y_1 Y_2 \right) V_{HP3} = -Y_1 Y_2 V_{in} \quad (3.168)$$

Substituting Eq. (3.157) and (3.158) into Eq. (3.168), the V_{HP3} is described as follow:

$$\left\{ \begin{array}{l} 3 g_{m1} g_{m2} + \\ K^{*} g_{m2} \left[G_{y1} + s(C_1 + C_{y1}) \right] + \\ \left[G_{y1} + s(C_1 + C_{y1}) \right] \\ \left[\begin{array}{l} G_{y2} + G_{-1} + G_{+3} + \\ s(C_2 + C_{y2} + C_{-1} + C_{+3}) \end{array} \right] \end{array} \right\} V_{HP3} = -\left\{ \begin{array}{l} \left[G_{y1} + s(C_1 + C_{y1}) \right] \\ \left[\begin{array}{l} G_{y2} + G_{-1} + G_{+3} + \\ s(C_2 + C_{y2} + C_{-1} + C_{+3}) \end{array} \right] \end{array} \right\} V_{in} \quad (3.169)$$

Assigning $G_{y2}^{*} = \frac{1}{R_{y2}} + \frac{1}{R_{+3}} + \frac{1}{R_{-1}}$; $C_1^{*} = C_1 + C_{y1}$; $C_2^{*} = C_2 + C_{y2} + C_{-1} + C_{+3}$ into Eq. (3.169), the voltage equation is obtained as follows:

$$\left\{ \begin{array}{l} 3 g_{m1} g_{m2} + K^{*} g_{m2} \left[G_{y1} + sC_1^{*} \right] + \\ \left[G_{y1} + sC_1^{*} \right] \left[G_{y2}^{*} + sC_2^{*} \right] \end{array} \right\} V_{HP3} = -\left\{ \begin{array}{l} \left[G_{y1} + sC_1^{*} \right] \\ \left[G_{y2}^{*} + sC_2^{*} \right] \end{array} \right\} V_{in} \quad (3.170)$$

Simplifying Eq. (3.170), the voltage equation becomes

$$\left\{\begin{matrix} 3g_{m1}g_{m2}+K^{*}g_{m2}G_{y1}+K^{*}g_{m2}C_{1}^{*}s+ \\ G_{y1}G_{y2}^{*}+sG_{y2}^{*}C_{1}^{*}+sG_{y1}C_{2}^{*}+s^{2}C_{1}^{*}C_{2}^{*} \end{matrix}\right\}V_{HP3}=-\left\{\begin{matrix} G_{y1}G_{y2}^{*}+sG_{y2}^{*}C_{1}^{*}+ \\ sG_{y1}C_{2}^{*}+s^{2}C_{1}^{*}C_{2}^{*} \end{matrix}\right\}V_{in} \quad (3.171)$$

Reordering and dividing $C_1^*C_2^*$ to both sides of Eq. (3.171), the voltage equation becomes

$$\left\{\begin{matrix} s^{2}+\dfrac{G_{y1}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s \\ +\dfrac{G_{y1}G_{y2}^{*}+3g_{m1}g_{m2}+K^{*}g_{m2}G_{y1}}{C_{1}^{*}C_{2}^{*}} \end{matrix}\right\}V_{HP3}=-\left\{\begin{matrix} s^{2}+\dfrac{G_{y1}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s \\ +\dfrac{G_{y1}G_{y2}^{*}}{C_{1}^{*}C_{2}^{*}} \end{matrix}\right\}V_{in} \quad (3.172)$$

Interchanging to both sides of Eq. (3.172), the transfer function for HP3 response becomes

$$\frac{V_{HP3}}{V_{in}}=-\frac{\left[s^{2}+\left(\dfrac{G_{y1}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}\right)s+\dfrac{G_{y1}G_{y2}^{*}}{C_{1}^{*}C_{2}^{*}}\right]}{\left[\begin{matrix} s^{2}+\left(\dfrac{G_{y1}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}\right)s+ \\ \dfrac{G_{y1}G_{y2}^{*}+3g_{m1}g_{m2}+K^{*}g_{m2}G_{y1}}{C_{1}^{*}C_{2}^{*}} \end{matrix}\right]} \quad (3.173)$$

From Eq. (3.173) the nominator term $\dfrac{G_{y1}G_{y2}^{*}}{C_{1}^{*}C_{2}^{*}}$ slightly deviates the high-pass response at low frequency. In ideal HP3 response, the passband gain of HP3 response gradually increases below the natural frequency but in real the passband gain of HP3 response is constant below the natural frequency. The passband voltage gain for HP3 is unity. By calculating like this HP3 response, the other transfer function LP3 is obtained as follows:

$$\frac{V_{LP3}}{V_{in}}=\frac{\dfrac{g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}}{\left[\begin{matrix} s^{2}+\left(\dfrac{G_{y1}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}\right)s+ \\ \dfrac{G_{y1}G_{y2}^{*}+3g_{m1}g_{m2}+K^{*}g_{m2}G_{y1}}{C_{1}^{*}C_{2}^{*}} \end{matrix}\right]} \quad (3.174)$$

The passband voltage gain for LP3 is $\dfrac{g_{m1}g_{m2}}{G_{y1}G_{y2}+3g_{m1}g_{m2}+g_{m2}G_{y1}}$. The other transfer function BP3 is obtained as follows:

$$\frac{V_{BP3}}{V_{in}} = -\frac{\left(\frac{g_{m2}g_{m3}R_4G_{y1}}{C_1^*C_2^*} + \frac{g_{m2}g_{m3}R_4}{C_2^*}s\right)}{\left[s^2 + \left(\frac{G_{y1}C_2^* + G_{y2}^*C_1^* + K^*g_{m2}C_1^*}{C_1^*C_2^*}\right)s + \frac{G_{y1}G_{y2}^* + 3g_{m1}g_{m2} + K^*g_{m2}G_{y1}}{C_1^*C_2^*}\right]} \tag{3.175}$$

From Eq. (3.175), the nominator term $\frac{g_{m2}g_{m3}R_4}{C_2^*}$ slightly deviates the band-pass response at low frequency. In ideal BP3 response, the passband gain of BP3 response gradually increases below the natural frequency but in real the passband gain of BP3 response is constant below the natural frequency. The passband voltage gain for BP3 is $\frac{g_{m2}g_{m3}R_4C_1^*}{G_{y1}C_2^* + G_{y2}^*C_1^* + g_{m2}g_{m3}R_4C_1^*}$, where $K^* = \frac{g_{m3}}{G_{y3}^*}$; $G_{y1} = \frac{1}{R_{y1}}$ and $G_{y3}^* = \frac{1}{R_{y3}} + \frac{1}{R_4}$.

$$D_3(s) = \left[s^2 + \left(\frac{G_{y1}C_2^* + G_{y2}^*C_1^* + K^*g_{m2}C_1^*}{C_1^*C_2^*}\right)s + \frac{G_{y1}G_{y2}^* + 3g_{m1}g_{m2} + K^*g_{m2}G_{y1}}{C_1^*C_2^*}\right] \tag{3.176}$$

$$\frac{V_{HP3}}{V_{in}} = \frac{-s^2 - \left(\frac{G_{y1}C_2^* + G_{y2}^*C_1^*}{C_1^*C_2^*}\right)s - \frac{G_{y1}G_{y2}^*}{C_1^*C_2^*}}{D_3(s)} \tag{3.177}$$

$$\frac{V_{LP3}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1^*C_2^*}}{D_3(s)} \tag{3.178}$$

$$\frac{V_{BP3}}{V_{in}} = \frac{-\frac{g_{m2}g_{m3}R_4G_{y1}}{C_1^*C_2^*} - \frac{g_{m2}g_{m3}R_4}{C_2^*}s}{D_3(s)} \tag{3.179}$$

From Eq. (3.176), the non-ideal natural freqeuncy and quality factor of the third proposed filter become

$$\omega_{03}^* = \sqrt{\frac{G_{y1}G_{y2}^* + K^*g_{m2}G_{y1} + 3g_{m1}g_{m2}}{C_1^*C_2^*}} \tag{3.180}$$

$$Q_3^* = \frac{1}{\frac{G_{y1}}{C_1^*} + \frac{G_{y2}^*}{C_2^*} + \frac{K^*g_{m2}}{C_2^*}}\sqrt{\frac{G_{y1}G_{y2}^* + K^*g_{m2}G_{y1} + 3g_{m1}g_{m2}}{C_1^*C_2^*}} \tag{3.181}$$

It is seen from Eq. (3.180) to (3.181) that the parasitic elements in LT1228 affects the filtering performances which are the operational frequency, passband voltage gain, natural frequency, and quality factor.

3.4 Synthesis of filter 4

3.4.1 Synthesis procedure of filter 4

Fig. 3.18 shows the fundamental block diagram for acquiring the proposed filter utilizing the ten basic blocks. It is modified from (Olmez and Cam, 2009). It consists of the double lossless integrators that have the two variables a and b represent time constants of both integrators, four voltage summing circuits, and four voltage gain amplifier that has one variable *K* denote its voltage gain. The V_{in} is one input voltage node of the function block diagram and V_{BP}, V_{BR}, V_{LP}, and V_{HP} are its output voltage nodes.

The output voltage equation for the summing block is

$$V_{BR4} = 2V_{BP4} - V_{in} \tag{3.182}$$

From Fig. 3.18, the output voltage of the lossless integrator at V_{BP4} node is

$$V_{BP4} = \frac{1}{sb}(V_{LP4} - KV_{BR4}) \tag{3.183}$$

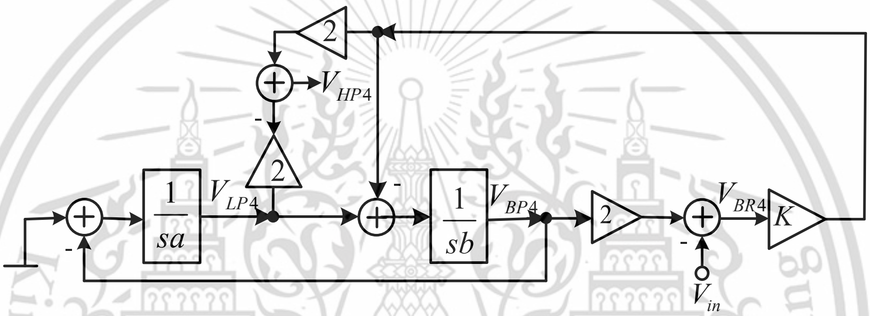


Figure 3.18 Synthesis block diagram of the fourth proposed filter.

Substituting V_{BR4} from Eq. (3.182) into (3.183), the V_{BP4} becomes

$$V_{BP4} = \frac{1}{sb}\left[V_{LP4} - K\left(2V_{BP4} - V_{in}\right)\right] \tag{3.184}$$

Multiplying sb to both sides of the Eq. (3.184), the V_{BP4} is obtained as follows:

$$sbV_{BP4} = V_{LP4} - 2KV_{BP4} + KV_{in} \tag{3.185}$$

Simplifying to both sides of the Eq. (3.185), the transfer function becomes

$$V_{BP4} = \frac{1}{sb+2K}\left(V_{LP4} + KV_{in}\right) \tag{3.186}$$

The output voltage for the lossless integrator at V_{LP4} node is

$$V_{LP4} = -\frac{1}{sa}V_{BP4} \tag{3.187}$$

Substituting V_{BP4} from Eq. (3.186) into (3.187), the transfer function at V_{LP4} node becomes

$$V_{LP4} = -\frac{1}{sa}\left[\frac{1}{sb+2K}\left(V_{LP4} + KV_{in}\right)\right] \tag{3.188}$$

Multiplying $s^2ab + s2aK$ to both sides of the equation, the V_{LP4} is obtained as follows:

$$\left(s^2ab + s2aK\right)V_{LP4} = -V_{LP4} - KV_{in} \tag{3.189}$$

Dividing ab to both sides of the equation, the V_{LP4} is obtained as follows:

$$\left(s^2 + s\frac{2K}{b}\right)V_{LP4} = -\frac{1}{ab}V_{LP4} - \frac{K}{ab}V_{in} \tag{3.190}$$

Moving and interchanging V_{LP4} to the left side of Eq. (3.190), the transfer function for LP4 response is

$$\frac{V_{LP4}}{V_{in}} = \frac{-\frac{K}{ab}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{3.191}$$

Substituting Eq. (3.191) into (3.186), the V_{BP4} is obtained as follows:

$$V_{BP4} = \frac{1}{sb+2K}\left(\frac{-\frac{K}{ab}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}}V_{in} + KV_{in}\right) \tag{3.192}$$

Simplifying to both sides of the equation, the V_{BP4} becomes

$$V_{BP4} = \frac{1}{sb+2K}\left(\frac{s\frac{K}{b}(sb+2K)}{s^2 + s\frac{2K}{b} + \frac{1}{ab}}V_{in}\right) \tag{3.193}$$

Interchanging the Eq. (3.193), the transfer function for BP4 response is

$$\frac{V_{BP4}}{V_{in}} = \frac{s\frac{K}{b}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{3.194}$$

The output voltage equation for the first summing block is

$$V_{HP4} = 2KV_{BR4} - V_{LP4} \tag{3.195}$$

Substituting V_{BR4} from Eq. (3.182) into (3.195), the output voltage at V_{HP4} node becomes

$$V_{HP4} = 2K(2V_{BP4} - V_{in}) - V_{LP4} \tag{3.196}$$

Substituting V_{LP4} from Eq. (3.187) into (3.196), the V_{HP4} is obtained as follows:

$$V_{HP4} = \left(4K + \frac{1}{sa}\right)V_{BP4} - 2KV_{in} \tag{3.197}$$

Substituting V_{BP4} from Eq. (3.194) into (3.197), the V_{HP4} is

$$V_{HP4} = \left(\frac{4aKs+1}{sa}\right)\frac{s\frac{K}{b}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}}V_{in} - 2KV_{in} \tag{3.198}$$

Simplifying and interchanging the Eq. (3.198), the transfer function for HP4 response is

$$\frac{V_{HP4}}{V_{in}} = \frac{-2Ks^2}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{3.199}$$

Substituting V_{BP4} from Eq. (3.194) into (3.182), the transfer function of V_{BR4} becomes

$$V_{BR4} = 2\frac{s\frac{K}{b}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}}V_{in} - V_{in} \tag{3.200}$$

Simplifying and interchanging the Eq. (3.200), the transfer function for BR4 response is

$$\frac{V_{BR4}}{V_{in}} = \frac{-s^2 - \frac{1}{ab}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{3.201}$$

The K gain for inverting lowpass (ILP) and $2K$ gain for inverting lowpass (IHP) functions can be confirmed in Eq. (3.191) and (3.199). The voltage gains for non-inverting bandpass (NBP) is half and the voltage gain for inverting band-reject (IBR) functions are one in Eq. (3.194) and (3.201). The ω_{04} and Q_4 are respectively obtained as

$$\omega_{04} = \sqrt{\frac{1}{ab}} \text{ and } Q_4 = \frac{1}{2K}\sqrt{\frac{b}{a}} \tag{3.202}$$

To control the Q_4 without disturbing the ω_{04}, it can be obtained by changing the voltage gain value of amplifier K in Eq. (3.202). By simultaneously adjusting the time constants a and b of the lossless integrator circuits, the ω_{04} can be tuned with no disturbance of the Q_4. Then the independent controlling of the ω_{04} and Q_4 can be done where the ω_{04} can be linearly adjusted by the two variables (a and b) and the Q_4 can be controlled by the voltage gain. Despite K changing the bandwidth of ILP and IHP filtering functions, K can control the Q_4. From the synthesis block diagram in Fig 3.18, it is divided into three parts and synthesized the circuit by LT1228. The first part of the synthesis block diagram is the OTA-C inverting lossless integrator and the voltage gain amplifier circuit. The capacitor C_1 and first LT1228 are built as an OTA-C inverting lossless integrator. The voltage gain amplifier circuit is constructed from the resistors R_1 and R_2 (they are same resistance value) and first LT1228. The first part is successfully synthesized from the first LT1228 with one grounded capacitor and the two resistors in Fig 3.19.

Figure 3.19 Inverting lossless integrator with voltage gain amplifier circuit synthesized from LT1228

The second part of the synthesis block diagram is the OTA-C voltage differencing lossless integrator and the voltage gain amplifier. The capacitor C_2 and second LT1228 are built as an OTA-C voltage differencing lossless integrator. The voltage gain amplifier circuit is constructed from the resistors R_3 and R_4 (they are same resistance value) and second LT1228. The second part is successfully synthesized from the second LT1228 with one grounded capacitor and two resistors in Fig 3.20.

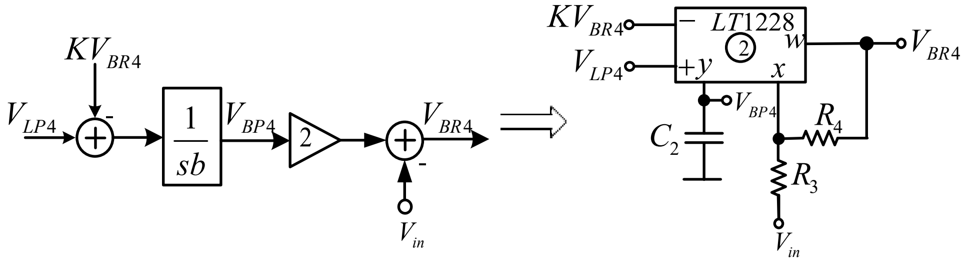


Figure 3.20 Voltage differencing lossless integrator and voltage summing circuit synthesized from LT1228

The third part of the synthesis block diagram is the non-inverting OTA and voltage gain amplifier. The non-inverting amplifier is constructed from grounded resistor R_5 with third LT1228 while the voltage gain amplifier is built from the feedback resistor R_6 through R_7. The third part is successfully synthesized from the third LT1228 with three resistors in Fig 3.21. The complete schematic of the presented biquad filter utilized LT1228s as the active function block is shown in Fig 3.22. It comprises two lossless integrators, two voltage gain amplifiers, and two voltage summing circuits. It is constructed from three LT1228s with a single input voltage signal V_{in}, seven resistors, and two grounded capacitors. The four output voltages are V_{HP4}, V_{LP4}, V_{BP4} and V_{BR4}. The filter shows low output impedance at V_{HP4} and V_{BR4} node that can cascade to other circuits while no exploitation of the buffer.

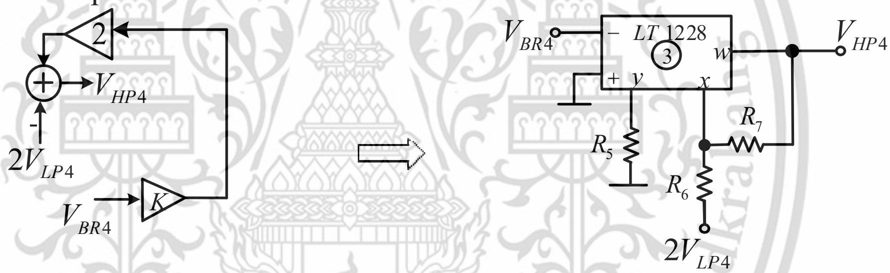


Figure 3.21 Voltage differencing lossless integrator and voltage summing circuit synthesized from LT1228

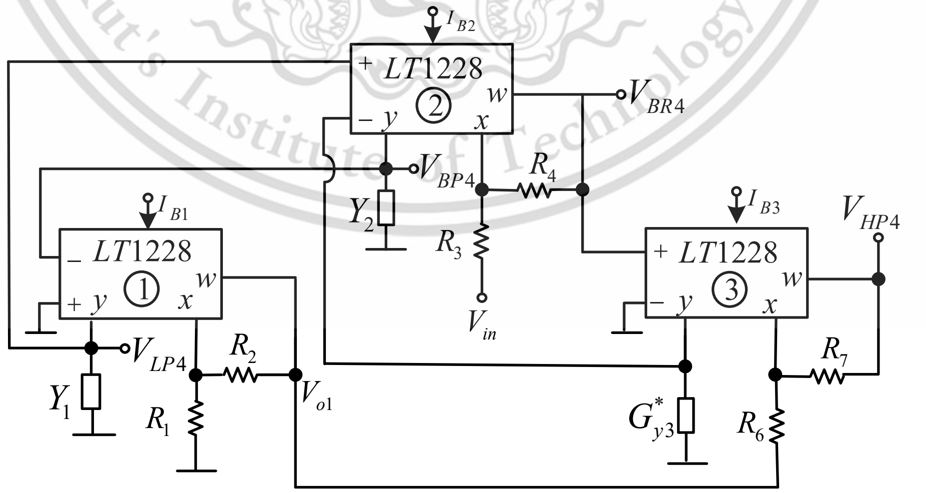


Figure 3.22 Fourth proposed SIMO universal filter.

3.4.2 Ideal analysis

From Fig. 3.22 and Eq. (3.13) through (3.14), the following transfer function equation can be described in detail. The OTA-C inverting lossless integrator output, V_{LP4} is obtained as follows:

$$V_{LP4} = -\frac{g_{m1}}{sC_1} V_{BP4} \tag{3.203}$$

The OTA-C voltage differencing lossless integrator output, V_{BP4} is obtained as follows:

$$V_{BP4} = \frac{g_{m2}}{sC_2}\left(V_{LP4} - KV_{BR4}\right) \tag{3.204}$$

The summing circuit output for second LT1228 is

$$V_{BR4} = 2V_{BP4} - V_{in} \tag{3.205}$$

Substituting V_{BR4} from Eq. (3.205) into (3.204), the voltage equation becomes

$$V_{BP4} = \frac{g_{m2}}{sC_2}\left[V_{LP4} - K\left(2V_{BP4} - V_{in}\right)\right] \tag{3.206}$$

Multiplying sC_2 into both sides of the equation, the voltage equation becomes

$$sC_2 V_{BP4} = g_{m2}\left[V_{LP4} - K\left(2V_{BP4} - V_{in}\right)\right] \tag{3.207}$$

Simplifying and reordering to both sides of the equation, the voltage equation becomes

$$V_{BP4} = \frac{g_{m2}}{sC_2 + 2Kg_{m2}}\left(V_{LP4} + KV_{in}\right) \tag{3.208}$$

Substituting V_{BP4} from Eq. (3.208) into (3.203), the voltage equation becomes

$$V_{LP4} = -\frac{g_{m1}g_{m2}}{sC_1\left(sC_2 + 2Kg_{m2}\right)}\left(V_{LP4} + KV_{in}\right) \tag{3.209}$$

Simplifying and reordering to both sides of the equation, the voltage equation becomes

$$V_{LP4} = \frac{-g_{m1}g_{m2}}{s^2C_1C_2 + 2Kg_{m2}sC_1}\left(V_{LP4} + KV_{in}\right) \tag{3.210}$$

Multiplying $s^2C_1C_2 + 2Kg_{m2}sC_1$ into both sides of the equation, the voltage equation becomes

$$\left(s^2C_1C_2 + 2Kg_{m2}sC_1\right)V_{LP4} = -g_{m1}g_{m2}\left(V_{LP4} + KV_{in}\right) \tag{3.211}$$

Dividing C_1C_2 into both sides of the equation, the voltage equation becomes

$$\left(s^2 + \frac{2Kg_{m2}}{C_2}s\right)V_{LP4} = \frac{-g_{m1}g_{m2}}{C_1C_2}\left(V_{LP4} + KV_{in}\right) \tag{3.212}$$

Interchanging and reordering to both sides of the equation, the transfer function for LP4 response is

$$\frac{V_{LP4}}{V_{in}} = \frac{\frac{-Kg_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{3.213}$$

Substituting V_{LP4} from Eq. (3.213) into (3.208), the voltage equation becomes

$$V_{BP4} = \frac{g_{m2}}{sC_2 + 2K}\left(\frac{\frac{-Kg_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}V_{in} + KV_{in}\right) \tag{3.214}$$

Interchanging and reordering to both sides of the equation, the transfer function for BP4 response is

$$\frac{V_{BP4}}{V_{in}} = \frac{\frac{Kg_{m2}}{C_2}s}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{3.215}$$

Substituting V_{BP4} from Eq. (3.215) into (3.205), the voltage equation becomes

$$\frac{V_{BR4}}{V_{in}} = \frac{-s^2 - \frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{3.216}$$

If $R_1=R_2=R$, the output voltage of w terminal V_{o1} is obtained as follows:

$$V_{o1} = 2V_{LP4} \tag{3.217}$$

The summing circuit output for third LT1228 is

$$V_{HP4} = 2KV_{BR4} - 2V_{LP4} \tag{3.218}$$

Substituting V_{BR4} from Eq. (3.217) into (3.218), the voltage equation becomes

$$V_{HP4} = 2K\frac{-s^2 - \frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}V_{in} - 2\frac{\frac{-Kg_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}V_{in} \tag{3.219}$$

Interchanging and reordering to both sides of the equation, the transfer function for HP4 response is

$$\frac{V_{HP4}}{V_{in}} = \frac{-2Ks^2}{s^2 + \frac{2Kg_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{3.220}$$

where $K = g_{m3}R_5$. Eq. (3.213) and (3.220) show that K is the voltage gain for ILP and $2K$ is the voltage gain for IHP functions. Eq. (3.215) and (3.217) confirm that the voltage gains for NBP and IBR functions are half and one, respectively. The relationship between the ω_{04} and Q_4 can be expressed as

$$\omega_{04} = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q_4 = \frac{1}{2g_{m3}R_5}\sqrt{\frac{C_2g_{m1}}{C_1g_{m2}}} \tag{3.221}$$

Substituting the transconductances g_{m1} and g_{m2} in function of the bias currents, I_{B1}, I_{B2} and I_{B3} as appeared in Eq. (3.14) into (3.221), the ω_{04} and Q_4 of the proposed circuit are

$$\omega_{04} = 10\sqrt{\frac{I_{B1}I_{B2}}{C_1C_2}} \text{ and } Q_4 = \frac{1}{20I_{B3}R_5}\sqrt{\frac{I_{B1}C_2}{I_{B2}C_1}} \tag{3.222}$$

By simultaneously adjusting the value of bias currents (I_{B1} and I_{B2}), the ω_{04} can be tuned with no disturbance of the Q_4 in Eq. (3.222). Moreover, the Q_4 also can be controlled without disturbing the ω_{04} by varying the value of bias current of the third LT1228, I_{B3}. Then the independent controlling of the ω_{04} and Q_4 can be done where the ω_{04} can be linearly and electronically adjusted. Yet it could be a good design for tuning the Q_4, the K will change the bandwidth of ILP and IHP filtering functions. Also, the drawback of the presented filter is that it can only provide four filtering responses except for the AP response.

3.4.3 Parasitic effect analysis

Similarly, the effect of Y_T in the voltage amplifier circuit in Fig 3.22 is the same above-mentioned calculation in section 3.2.3. In consideration of these parasitic elements, the output voltage of the summing circuit realized in Fig 3.23 are obtained as

$$V_{BR4}=\left(1+\frac{R_4}{R_3}\right)V_{BP4}-\frac{R_4}{R_3}V_{in} \tag{3.223}$$

If $R_4=R_3=R$, the output voltage equation becomes

$$V_{BR4}=2V_{BP4}-V_{in} \tag{3.224}$$

Similarly, the R_T and C_T effects in the voltage gain amplifier of the third LT1228 for this filter are ignored as like above calculation. The effect of C_{y3}^* (i.e., $C_{y3}^*=s\left(C_{y3}+C_{-2}\right)$) for third LT1228 is also ignored like section 3.3.3. In summary, the R_T and C_T effects in the summing circuit of the first LT1228 are ignored, the R_T and C_T effects in the voltage gain amplifier of the second and third LT1228 are ignored and the C_{y3}^* effect for the third LT1228 is also ignored. According to the data sheet of LT1228 (LT1228: Linear Technology, 2012), to reduce the effect of C_T and R_T and to get higher operating frequency, the feedback resistor (R_1, in this filter) connecting from w to x terminal in summing circuit should be low. Also, if the bandwidth of the presented filter is expected to be lower than 10MHz, the most effect stems from R_-, C_-, R_+, C_+, R_y and C_y (the effect of R_x, R_w, R_T and C_T are ignored). Considering these parasitic elements, the voltage transfer functions of the other presented filter circuit realized in Fig. 3.23 are expressed in detail as follows:

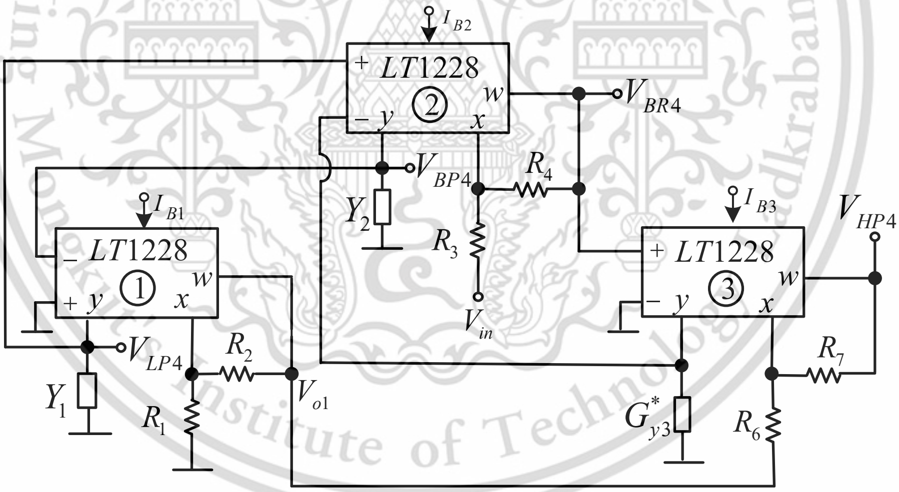


Figure 3.23 Fourth proposed SIMO universal filter with parasitic elements

$$Y_1=G_{y1}+G_{+2}+s(C_1+C_{y1}+C_{+2}) \tag{3.225}$$

$$Y_2=G_{y2}+G_{-1}+s(C_2+C_{y2}+C_{-1}) \tag{3.226}$$

and

$$G_{y3}^*=\frac{1}{R_{y2}}+\frac{1}{R_{-2}}+\frac{1}{R_5} \tag{3.227}$$

The lossless integrator outputs: V_{LP4} and V_{BP4} are obtained as follows:

$$V_{LP4}=-\frac{g_{m1}}{Y_1}V_{BP4} \tag{3.228}$$

$$V_{BP4} = \frac{g_{m2}}{Y_2}\left(V_{LP4} - K^* V_{BR4}\right) \tag{3.229}$$

The output voltage of the summing circuit for the second LT1228, V_{BR4} is obtained as follows:

$$V_{BR4} = 2V_{BP4} - V_{in} \tag{3.230}$$

Substituting V_{BR4} from Eq. (3.229) into (3.230), the V_{BP4} becomes

$$V_{BP4} = \frac{g_{m2}}{Y_2}\left[V_{LP4} - K^*\left(2V_{BP4} - V_{in}\right)\right] \tag{3.231}$$

Multiplying Y_2 to the left and simplifying to the right side of the equation, the Eq. (3.231) becomes

$$Y_2 V_{BP4} = g_{m2}\left(V_{LP4} - 2K^* V_{BP4} + KV_{in}\right) \tag{3.232}$$

Reordering to the equation, the Eq. (3.232) becomes

$$\left(Y_2 + 2K^* g_{m2}\right)V_{BP4} = g_{m2}\left(V_{LP4} + KV_{in}\right) \tag{3.233}$$

Dividing $\left(Y_2 + 2K^* g_{m2}\right)$ to the equation, the Eq. (3.233) becomes

$$V_{BP4} = \frac{g_{m2}}{\left(Y_2 + 2K^* g_{m2}\right)}\left(V_{LP4} + K^* V_{in}\right) \tag{3.234}$$

Substituting V_{BP4} from Eq. (3.234) into (3.228), the V_{LP4} becomes

$$V_{LP4} = \frac{-g_{m1}g_{m2}}{Y_1\left(Y_2 + 2K^* g_{m2}\right)}\left(V_{LP4} + K^* V_{in}\right) \tag{3.235}$$

Multiplying $Y_1\left(Y_2 + 2K^* g_{m2}\right)$ to the left side of the equation, the Eq. (3.235) becomes

$$\left(g_{m1}g_{m2} + 2K^* g_{m2}Y_1 + Y_1Y_2\right)V_{LP4} = -K^* g_{m1}g_{m2}V_{in} \tag{3.236}$$

Interchanging both sides of Eq. (3.236), the transfer function for LP4 response becomes

$$\frac{V_{LP4}}{V_{in}} = \frac{-K^* g_{m1}g_{m2}}{g_{m1}g_{m2} + 2K^* g_{m2}Y_1 + Y_1Y_2} \tag{3.237}$$

Substituting Eq. (3.225) and (3.226) into Eq. (3.237), the LP4 response becomes

$$\frac{V_{LP4}}{V_{in}} = \frac{-K^* g_{m1}g_{m2}}{\left[\begin{array}{c} g_{m1}g_{m2} + 2K^* g_{m2}\begin{pmatrix} G_{y1} + G_{+2} + \\ s(C_1 + C_{y1} + C_{+2}) \end{pmatrix} + \\ \begin{pmatrix} G_{y1} + G_{+2} + \\ s(C_1 + C_{y1} + C_{+2}) \end{pmatrix}\begin{pmatrix} G_{y2} + G_{-1} + \\ s(C_2 + C_{y2} + C_{-1}) \end{pmatrix} \end{array}\right]} \tag{3.238}$$

Assigning $G_{y1}^* = \frac{1}{R_{y1}} + \frac{1}{R_{+2}}$; $G_{y2}^* = \frac{1}{R_{y2}} + \frac{1}{R_{-1}}$; $C_1^* = C_1 + C_{y1} + C_{+2}$; $C_2^* = C_2 + C_{y2} + C_{-1}$ into Eq. (3.238), the LP4 response becomes

$$\frac{V_{LP4}}{V_{in}} = \frac{-K^* g_{m1}g_{m2}}{\left[g_{m1}g_{m2} + 2K^* g_{m2}\left(G_{y1}^* + sC_1^*\right) + \left(G_{y1}^* + sC_1^*\right)\left(G_{y2}^* + sC_2^*\right)\right]} \tag{3.239}$$

Reordering to the equation, the LP response becomes

$$\frac{V_{LP4}}{V_{in}}=\frac{-K^{*}g_{m1}g_{m2}}{\begin{pmatrix}s^{2}C_{1}^{*}C_{2}^{*}+sG_{y2}^{*}C_{1}^{*}+sG_{y1}^{*}C_{2}^{*}+2K^{*}g_{m2}sC_{1}^{*}+G_{y1}^{*}G_{y2}^{*}+\\2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}\end{pmatrix}}\tag{3.240}$$

Dividing $C_1^*C_2^*$ to both sides of Eq. (3.240), the transfer function for LP4 response becomes

$$\frac{V_{LP4}}{V_{in}}=\frac{\dfrac{-K^{*}g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}}{\begin{pmatrix}s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\\\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\end{pmatrix}}\tag{3.241}$$

Substituting V_{LP4} Eq. (3.241) into Eq. (3.234), the voltage equation becomes

$$V_{BP4}=\frac{g_{m2}}{\left(Y_{2}+2K^{*}g_{m2}\right)}\left(\frac{-K^{*}g_{m1}g_{m2}}{g_{m1}g_{m2}+2K^{*}g_{m2}Y_{1}+Y_{1}Y_{2}}V_{in}+K^{*}V_{in}\right)\tag{3.242}$$

Simplifying the Eq. (3.242), the V_{BP4} becomes

$$V_{BP4}=\frac{g_{m2}Y_{1}K^{*}}{g_{m1}g_{m2}+2K^{*}g_{m2}Y_{1}+Y_{1}Y_{2}}V_{in}\tag{3.243}$$

Substituting Y_1 and Y_2 into Eq. (3.243), the transfer function for BP4 response becomes

$$\frac{V_{BP4}}{V_{in}}=\frac{g_{m2}\left(G_{y1}^{*}+sC_{1}^{*}\right)K^{*}}{\left[g_{m1}g_{m2}+2K^{*}g_{m2}\left(G_{y1}^{*}+sC_{1}^{*}\right)+\left(G_{y1}^{*}+sC_{1}^{*}\right)\left(G_{y2}^{*}+sC_{2}^{*}\right)\right]}\tag{3.244}$$

Reordering and simplifying to the equation, the BP response becomes

$$\frac{V_{BP4}}{V_{in}}=\frac{K^{*}g_{m2}\left(G_{y1}^{*}+sC_{1}^{*}\right)}{\begin{pmatrix}s^{2}C_{1}^{*}C_{2}^{*}+sG_{y2}^{*}C_{1}^{*}+sG_{y1}^{*}C_{2}^{*}+2K^{*}g_{m2}sC_{1}^{*}+G_{y1}^{*}G_{y2}^{*}+\\2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}\end{pmatrix}}\tag{3.245}$$

Dividing $C_1^*C_2^*$ to both sides of Eq. (3.245), the transfer function for LP4 response becomes

$$\frac{V_{BP4}}{V_{in}}=\frac{\dfrac{K^{*}g_{m2}(G_{y1}^{*}+sC_{1}^{*})}{C_{1}^{*}C_{2}^{*}}}{\begin{pmatrix}s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\\\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\end{pmatrix}}\tag{3.246}$$

Substituting V_{BP4} from Eq. (3.246) into (3.230), the V_{BR4} becomes

$$V_{BR4}=2\frac{\dfrac{K^{*}g_{m2}(G_{y1}^{*}+sC_{1}^{*})}{C_{1}^{*}C_{2}^{*}}}{\left(s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right)}V_{in}-V_{in} \tag{3.247}$$

Simplifying the Eq. (3.247), the V_{BP4} becomes

$$\frac{V_{BR4}}{V_{in}}=\frac{-\left[s^{2}+\left(\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}\right)s+\dfrac{G_{y1}^{*}G_{y2}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right]}{\left(s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right)} \tag{3.248}$$

If $R_1=R_2=R$, the output voltage of w terminal V_{o1} is obtained as follows:

$$V_{o1}=2V_{LP4} \tag{3.249}$$

If $R_6=R_7=R$, the output voltage V_{HP4} is obtained as follows:

$$V_{HP4}=2K^{*}V_{BR4}-V_{o1} \tag{3.250}$$

Substituting V_{o1} into Eq. (3.250), the output voltage V_{HP4} becomes

$$V_{HP4}=2K^{*}V_{BR4}-2V_{LP4} \tag{3.251}$$

Substituting V_{LP4} and V_{BR4} into Eq. (3.251), the output voltage V_{HP4} becomes

$$V_{HP4}=\left\{\begin{array}{l}\dfrac{-2K^{*}\left[s^{2}+\left(\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}\right)s+\dfrac{G_{y1}^{*}G_{y2}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right]}{\left(s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right)}V_{in}+\\[2ex]\dfrac{\dfrac{2K^{*}g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}}{\left(s^{2}+\dfrac{G_{y1}^{*}C_{2}^{*}+G_{y2}^{*}C_{1}^{*}+2K^{*}g_{m2}C_{1}^{*}}{C_{1}^{*}C_{2}^{*}}s+\dfrac{G_{y1}^{*}G_{y2}^{*}+2K^{*}g_{m2}G_{y1}^{*}+g_{m1}g_{m2}}{C_{1}^{*}C_{2}^{*}}\right)}V_{in}\end{array}\right\} \tag{3.252}$$

Simplifying the equation, the transfer function for HP4 response becomes

$$\frac{V_{HP4}}{V_{in}}=\frac{-2K^*\left[s^2+\left(\frac{G_{y1}^*C_2^*+G_{y2}^*C_1^*}{C_1^*C_2^*}\right)s+\frac{G_{y1}^*G_{y2}^*}{C_1^*C_2^*}\right]}{\left(\begin{array}{l}s^2+\frac{G_{y1}^*C_2^*+G_{y2}^*C_1^*+2K^*g_{m2}C_1^*}{C_1^*C_2^*}s+\\ \frac{G_{y1}^*G_{y2}^*+2K^*g_{m2}G_{y1}^*+g_{m1}g_{m2}}{C_1^*C_2^*}\end{array}\right)} \tag{3.253}$$

From Eq. (3.253), the nominator term $\frac{2K^*G_{y1}^*G_{y2}^*}{C_1^*C_2^*}$ slightly deviates the high-pass response at low frequency. In ideal HP4 response, the passband gain of HP4 response gradually increases below the natural frequency but in real the passband gain of HP4 response is constantly below the natural frequency. The passband voltage gain for HP4 is $2K^*$. By calculating like this HP4 response, the other transfer function for LP4 response is obtained as follows:

$$\frac{V_{LP4}}{V_{in}}=\frac{-\frac{Kg_{m1}g_{m1}}{C_1^*C_2^*}}{\left[\begin{array}{l}s^2+\left(\frac{G_{y1}^*C_2^*+G_{y2}^*C_1^*+2K^*g_{m1}C_1^*}{C_1^*C_2^*}\right)s+\\ \frac{G_{y1}^*G_{y2}^*+2K^*g_{m1}G_{y1}^*+g_{m1}g_{m2}}{C_1^*C_2^*}\end{array}\right]} \tag{3.254}$$

The passband voltage gain for LP4 is $\frac{Kg_{m1}g_{m2}}{G_{y1}^*G_{y2}^*+2K^*g_{m1}G_{y1}^*+g_{m1}g_{m2}}$. The BP4 response is obtained as follows:

$$\frac{V_{BP4}}{V_{in}}=\frac{\frac{Kg_{m2}(G_{y1}^*+sC_1^*)}{C_1^*C_2^*}}{\left[\begin{array}{l}s^2+\left(\frac{G_{y1}^*C_2^*+G_{y2}^*C_1^*+2K^*g_{m1}C_1^*}{C_1^*C_2^*}\right)s+\\ \frac{G_{y1}^*G_{y2}^*+2K^*g_{m1}G_{y1}^*+g_{m1}g_{m2}}{C_1^*C_2^*}\end{array}\right]} \tag{3.255}$$

From Eq. (3.255), the nominator term $\frac{Kg_{m2}G_{y1}^*}{C_1^*C_2^*}$ slightly deviates the band-pass response at low frequency. In ideal BP4 response, the passband gain of BP4 response gradually increases below the natural frequency but in real the passband gain of BP4 response is constant below the natural frequency. The passband voltage gain for BP4 is $\frac{Kg_{m2}G_{y1}^*}{\left(G_{y1}^*C_2^*+G_{y2}^*C_1^*\right)+2K^*g_{m1}C_1^*}$. The BR4 response is obtained as follows:

$$\frac{V_{BR4}}{V_{in}} = \frac{-\left[s^2 + \left[\frac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right)}{C_1^* C_2^*}\right] s + \frac{G_{y1}^* G_{y2}^* + g_{m1} g_{m2}}{C_1^* C_2^*}\right]}{\left[\begin{array}{l} s^2 + \left(\frac{G_{y1}^* C_2^* + G_{y2}^* C_1^* + 2K^* g_{m1} C_1^*}{C_1^* C_2^*}\right) s + \\ \frac{G_{y1}^* G_{y2}^* + 2K^* g_{m1} G_{y1}^* + g_{m1} g_{m2}}{C_1^* C_2^*} \end{array}\right]} \tag{3.256}$$

From Eq. (3.256), the nominator term $\frac{K g_{m2} G_{y1}^*}{C_1^* C_2^*}$ slightly deviates the band-pass response at low frequency. In ideal BP4 response, the passband gain of BP4 response gradually increases below the natural frequency but in real the passband gain of BP4 response is constant below the natural frequency. The passband voltage gain for BP4 is $\frac{K g_{m2} G_{y1}^*}{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right) + 2K^* g_{m1} C_1^*}$, where $K^* = \frac{g_{m3}}{G_{y3}^*}$

$$D^*(s) = \left\{\begin{array}{l} s^2 + \left[\frac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right) + 2K^* g_{m1} C_1^*}{C_1^* C_2^*}\right] s + \\ \frac{G_{y1}^* G_{y2}^* + 2K^* g_{m1} G_{y1}^* + g_{m1} g_{m2}}{C_1^* C_2^*} \end{array}\right\} \tag{3.257}$$

$$\frac{V_{HP4}}{V_{in}} = \frac{-2K^* \left\{s^2 + \left[\frac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right)}{C_1^* C_2^*}\right] s + \frac{G_{y1}^* G_{y2}^*}{C_1^* C_2^*}\right\}}{D^*(s)} \tag{3.258}$$

$$\frac{V_{LP4}}{V_{in}} = \frac{-\frac{K g_{m1} g_{m1}}{C_1^* C_2^*}}{D^*(s)} \tag{3.259}$$

$$\frac{V_{BP4}}{V_{in}} = \frac{\frac{K g_{m2} (G_{y1}^* + s C_1^*)}{C_1^* C_2^*}}{D^*(s)} \tag{3.260}$$

$$\frac{V_{BR4}}{V_{in}} = \frac{-\left\{s^2 + \left[\frac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right)}{C_1^* C_2^*}\right] s + \frac{G_{y1}^* G_{y2}^* + g_{m1} g_{m2}}{C_1^* C_2^*}\right\}}{D^*(s)} \tag{3.261}$$

From Eq. (3.258) through (3.261), the non-ideal natural freqeuncy and quality factor of the first proposed filter becomes

$$\omega_{04}^* = \sqrt{\frac{G_{y1}^* G_{y2}^* + 2K^* g_{m1} G_{y1}^* + g_{m1} g_{m2}}{C_1^* C_2^*}} \tag{3.262}$$

$$Q_{04}^* = \frac{\sqrt{\left[G_{y1}^* G_{y2}^* + 2K^* g_{m1} G_{y1}^* + g_{m1} g_{m2}\right] C_1^* C_2^*}}{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right) + 2K^* g_{m1} C_1^*} \tag{3.263}$$

It is seen from Eq. (3.262) to (3.263) that the parasitic elements in LT1228 affect the filtering performances which are the operational frequency, passband voltage gain, natural frequency, and quality factor.

3.5 Synthesis of filter 5

3.5.1 Synthesis procedure of filter 5

The procedure for the block diagram of the VM filter with MISO configuration is illustrated in Fig 3.24 that is modified from (Jaikla et. al. 2020). Using eight basic blocks to synthesize the MISO filter that is two lossless integrators, two voltage gain amplifiers, and four voltage summing circuits. The input voltages of the first summing block are V_{in1} and V_e and the output voltage node is V_a. The input voltage of the first lossless integrator is V_a and its output voltage node V_b is multiplied by the double voltage gain amplifier. The second summing block comprises double input voltage nodes: V_{in2}, and V_b multiplied by gain two, and an output voltage node: V_o. The input voltages of the third summing block are *Vin3,* and V_o and its output voltage node is V_c. The input voltage of the second lossless integrator is V_c and its output voltage node, V_d is multiplied by the double voltage gain amplifier. The fourth summing block has dual input voltage nodes: V_d multiplied by gain two, and V_o and the output voltage node: V_e. The *a* and *b* assign the time constants of the two lossless integrators stage. The block diagram has three input voltage nodes V_{in1}, $V_{in2,}$ and V_{in3} while the one voltage output node V_o.

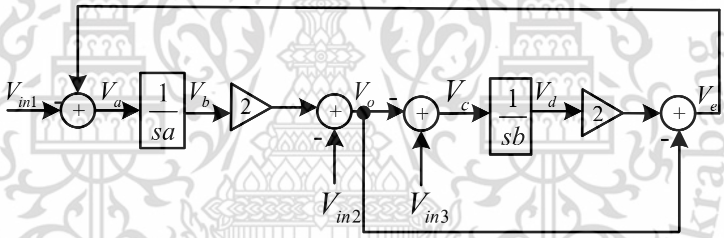


Figure 3.24 Synthesis block diagram of the fifth proposed filter.

The output voltage equation for the first summing block is

$$V_a = V_e - V_{in1} \tag{3.264}$$

From Fig. 3.24, the output voltage of the first lossless integrator is

$$V_b = \frac{1}{sa} V_a \tag{3.265}$$

Substituting V_a from Eq. (3.264) into (3.265), the V_b becomes

$$V_b = \frac{1}{sa}\left(V_e - V_{in1}\right) \tag{3.266}$$

The output voltage equation for the second summing block is

$$V_o = 2V_b - V_{in2} \tag{3.267}$$

Substituting V_b from Eq. (3.266) into (3.267), the V_o becomes

$$V_o = 2\left[\frac{1}{sa}\left(V_e - V_{in1}\right)\right] - V_{in2} \tag{3.268}$$

The output voltage equation for the third summing block is

$$V_c = V_{in3} - V_o \tag{3.269}$$

The output voltage of the first lossless integrator is

$$V_d = \frac{1}{sb} V_c \tag{3.270}$$

Substituting V_c from Eq. (3.269) into (3.270), the V_d becomes

$$V_d = \frac{1}{sb}\left(V_{in3} - V_o\right) \tag{3.271}$$

The output voltage equation for the fourth summing block is

$$V_e = 2V_d - V_o \tag{3.272}$$

Substituting V_d from Eq. (3.271) into (3.272), the V_e becomes

$$V_e = \frac{2}{sb}\left(V_{in3} - V_o\right) - V_o \tag{3.273}$$

Substituting V_e from Eq. (3.273) into (3.268), the V_o becomes

$$V_o = \frac{2}{sa}\left\{\left[\frac{2}{sb}\left(V_{in3} - V_o\right) - V_o\right] - V_{in1}\right\} - V_{in2} \tag{3.274}$$

Simplifying to both sides of the equation, the V_o becomes

$$V_o = \frac{4}{s^2ab} V_{in3} - \frac{4}{s^2ab} V_o - \frac{2}{sa} V_o - \frac{2}{sa} V_{in1} - V_{in2} \tag{3.275}$$

Multiplying s^2ab to both sides of the equation, the V_o is obtained as follows:

$$\left(s^2ab + 2sb + 4\right)V_o = -2sbV_{in1} - s^2abV_{in2} + 4V_{in3} \tag{3.276}$$

Dividing ab and interchanging to both sides of the equation, the transfer function becomes

$$V_o = \frac{-\frac{2}{a}sV_{in1} - s^2V_{in2} + \frac{4}{ab}V_{in3}}{s^2 + \frac{2}{a}s + \frac{4}{ab}} \tag{3.277}$$

Eq. (3.277) show that the passband voltage gains with one can be obtained for five filtering functions and the ω_0 and Q are respectively obtained as

$$\omega_{05} = \frac{2}{\sqrt{ab}} \text{ and } Q_5 = \sqrt{\frac{a}{b}} \tag{3.278}$$

Eq. (3.278) indicates that the ω_{05} can be done linearly and independently tuned by simultaneously varying the time constants (a and b) of the two integrator circuits with no effect of the Q_5. From the synthesis block diagram in Fig. 3.24, it is divided into two parts and synthesized the circuit by LT1228. The first part of the synthesis block diagram is the OTA-C voltage differencing lossless integrator and the voltage summing circuit. The capacitor C_1 and first LT1228 are built as an OTA-C voltage differencing lossless integrator. The voltage summing circuit is constructed from the resistors R_1 and R_2 (they are same resistance value) and first LT1228. The first part is successfully synthesized from the first LT1228 with one grounded capacitor and the two resistors in Fig. 3.25. The second part of the synthesis block diagram is the OTA-C voltage differencing lossless integrator and the voltage summing circuit. The capacitor C_2 and second LT1228 are built as an OTA-C voltage differencing lossless integrator. The voltage summing circuit is constructed from the resistors R_3 and R_4 (they are same resistance value) and second LT1228. The second part is successfully synthesized from the second LT1228 with one grounded capacitor and two resistors in Fig 3.26.

Fig. 3.27 illustrates the synthesis of the complete block diagram of the MISO VM universal biquad filter using LT1228 as ABB. It is composed of double voltage summing circuits and two lossless integrators. The synthesis configuration of the first lossless integrator is obtained by using the grounded capacitor C_1 and the first LT1228. Using the grounded capacitor C_2 and the second LT1228, the second lossless integrator can be obtained. To get the first voltage summing circuit, the first LT1228 and the resistors R_1, R_2 are used. The second voltage summing circuit is also built utilizing the second LT1228 and the resistors R_3, R_4. However, V_{in2} is applied to series resistance R_2, the input voltage nodes, V_{in1} and V_{in3} have high impedance. The output voltage node (V_o) also provides a low impedance.

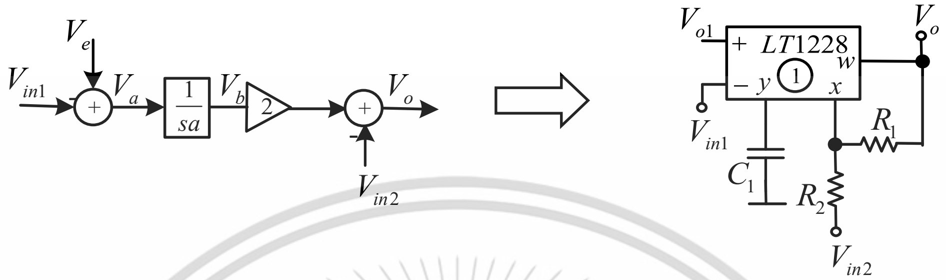


Figure 3.25 Voltage differencing lossless integrator and voltage summing circuit synthesized from LT1228

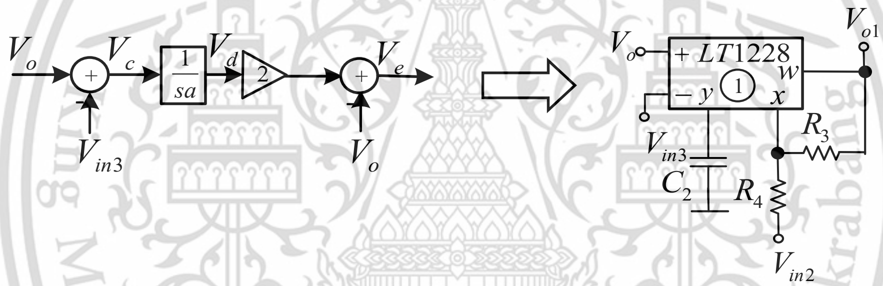


Figure 3.26 Voltage differencing lossless integrator and voltage summing circuit synthesized from LT1228

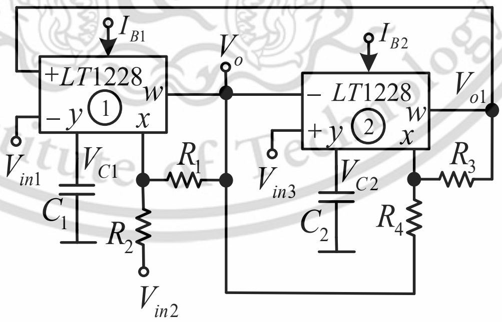


Figure 3.27 Fifth proposed MISO VM biquad universal filter.

3.5.2 Ideal Analysis

From Fig 3.27 and Eq. (3.13) through (3.14), the following transfer function equation can be described in detail. The output of the first OTA-C voltage differencing lossless integrator, V_{C1} is obtained as follows:

$$V_{C1} = \frac{g_{m1}}{sC_1}\left(V_{o1} - V_{in1}\right) \tag{3.279}$$

The summing circuit output for first LT1228 is

$$V_o = 2V_{C1} - V_{in2} \tag{3.280}$$

The output of the second OTA-C voltage differencing lossless integrator, V_{C2} is obtained as follows:

$$V_{C2} = \frac{g_{m2}}{sC_2}\left(V_{in3} - V_o\right) \tag{3.281}$$

The summing circuit output for second LT1228 is

$$V_{o1} = 2V_{C2} - V_o \tag{3.282}$$

Substituting V_{C2} from Eq. (3.281) into (3.282), the voltage equation becomes

$$V_{o1} = 2\left[\frac{g_{m2}}{sC_2}\left(V_{in3} - V_o\right)\right] - V_o \tag{3.283}$$

Substituting V_{o1} from Eq. (3.283) into (3.279), the voltage equation becomes

$$V_{C1} = \frac{g_{m1}}{sC_1}\left\{2\left[\frac{g_{m2}}{sC_2}\left(V_{in3} - V_o\right)\right] - V_o - V_{in1}\right\} \tag{3.284}$$

Simplifying and reordering to both sides of the equation, the voltage equation becomes

$$V_{C1} = -\frac{2g_{m1}g_{m2}}{s^2C_1C_2}V_o + \frac{2g_{m1}g_{m2}}{s^2C_1C_2}V_{in3} - \frac{g_{m1}}{sC_1}V_o - \frac{g_{m1}}{sC_1}V_{in1} \tag{3.285}$$

Substituting V_{C1} from Eq. (3.285) into (3.280), the voltage equation becomes

$$V_o = 2\left(-\frac{2g_{m1}g_{m2}}{s^2C_1C_2}V_o + \frac{2g_{m1}g_{m2}}{s^2C_1C_2}V_{in3} - \frac{g_{m1}}{sC_1}V_o - \frac{g_{m1}}{sC_1}V_{in1}\right) - V_{in2} \tag{3.286}$$

Multiplying s^2 and reordering into both sides of the equation, the voltage equation becomes

$$\left(s^2 + \frac{2g_{m1}}{C_1}s + \frac{4g_{m1}g_{m2}}{C_1C_2}\right)V_o = -s^2V_{in2} - \frac{2g_{m1}}{C_1}sV_{in1} + \frac{4g_{m1}g_{m2}}{C_1C_2}V_{in3} \tag{3.287}$$

Simplifying to both sides of the equation, the voltage transfer function becomes

$$V_o = \frac{-s^2V_{in2} - \frac{2g_{m1}}{C_1}sV_{in1} + \frac{4g_{m1}g_{m2}}{C_1C_2}V_{in3}}{s^2 + \frac{2g_{m1}}{C_1}s + \frac{4g_{m1}g_{m2}}{C_1C_2}} \tag{3.288}$$

According to Eq. (3.288), a single output voltage node that has low impedance provides the following five filtering output responses.

(1) To get the NLP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in3} node and the others V_{in1} and V_{in2} must be grounded.

(2) To get the IHP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in2} node, and the others V_{in1} and V_{in3} must be grounded.

(3) To get the IBP function at the output node V_o with gain one, the input voltage signal must be applied at the V_{in1} node and the others V_{in2} and V_{in3} must be grounded.

(4) To get the NBR function at the output node V_o with gain one, the inverting input and non-inverting voltage signal must be applied at the V_{in2} and V_{in3} node, respectively and the other V_{in1} must be grounded.

(5) To get the NAP function at the output node V_o with gain one, the inverting input voltage signal must be applied at the V_{in2}, and the non-

inverting input voltage signal must be applied at both V_{in1} and V_{in3}.

From (3.288), the five filtering output responses with unity passband voltage gain are provided. The filtering parameters, the ω_0 and Q of this MISO biquad filter are described as follows:

$$\omega_{05} = \sqrt{\frac{4g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q_5 = \sqrt{\frac{g_{m2}C_1}{g_{m1}C_2}} \tag{3.289}$$

By replacing the I_{B1} and I_{B2} from Eq (3.14) to transconductances g_{m1} and g_{m2} in Eq. (3.289), the ω_{05} and Q_5 of the presented MISO filtering circuit are described as follows:

$$\omega_{05} = 20\sqrt{\frac{I_{B1}I_{B2}}{C_1C_2}} \text{ and } Q_5 = \sqrt{\frac{I_{B2}C_1}{I_{B1}C_2}} \tag{3.290}$$

According to Eq. (3.290), the electronic tuning of the presented circuit for ω_{05} and Q_5 is provided by varying the external DC bias currents value. By simultaneously changing the bias currents $I_{B1}=I_{B2}=I_B$ (this attribute can be easily done by utilizing a microcomputer or microcontroller) and assigning equal values of the grounded capacitors $C_1=C_2=C$. The following Eq (3.290) can be verified that independent controlling of the presented MISO filter circuit for the ω_{05} and Q_5 can be achieved. Moreover, the ω_{05} of this filter can be linearly and electronically controlled. The following parameter ω_{05} and Q_5 of this filtering circuit can be expressed as

$$\omega_0 = \frac{20I_B}{C} \text{ and } Q_5 = 1 \tag{3.291}$$

3.5.3 Parasitic effects analysis

The parasitic effects of LT1228 are described in detail in section 3.1.3. Similarly, the effect of Y_T in the voltage summing circuit of the first and second LT1228 for the filter 5 in Fig. 3.27 is the same above-mentioned calculation in section 3.4.3. In consideration of these parasitic elements, the voltage transfer functions of the other presented filter circuit realized in Fig. 3.28 are expressed in detail as follows:

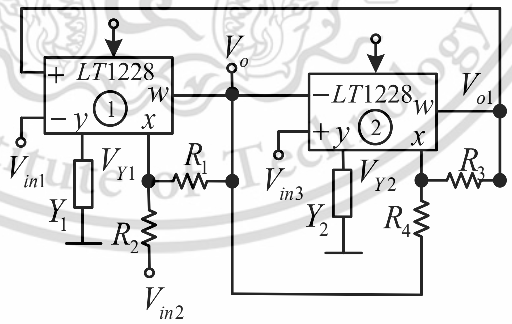


Figure 3.28 Fifth proposed MISO universal filter with parasitic elements

$$Y_1 = G_{y1} + s(C_1 + C_{y1}) \tag{3.292}$$

and

$$Y_2 = G_{y2} + s(C_2 + C_{y2}) \tag{3.293}$$

The voltage differencing lossless integrator output for first LT1228, V_{Y1} is obtained as follows:

$$V_{Y1} = \frac{g_{m1}}{Y_1}\left(V_{o1} - V_{in1}\right) \tag{3.294}$$

The output voltage of the summing circuit for the first LT1228, V_o is obtained as follows:

$$V_o = 2V_{LP} - V_{in2} \tag{3.295}$$

The voltage differencing lossless integrator output for second LT1228 V_{Y2} is obtained as follows:

$$V_{Y2} = \frac{g_{m2}}{Y_2}\left(V_{in3} - V_o\right) \tag{3.296}$$

The output voltage of the summing circuit for the second LT1228, V_{o1} is obtained as follows:

$$V_{o1} = 2V_{BP} - V_o \tag{3.297}$$

Substituting V_{Y2} from Eq. (3.296) into (3.297), the V_{o1} becomes

$$V_{o1} = 2\left[\frac{g_{m2}}{Y_2}\left(V_{in3} - V_o\right)\right] - V_o \tag{3.298}$$

Substituting V_{o1} from Eq. (3.298) into (3.295), the V_{Y1} becomes

$$V_{Y1} = \frac{g_{m1}}{Y_1}\left\{2\left[\frac{g_{m2}}{Y_2}\left(V_{in3} - V_o\right)\right] - V_o - V_{in1}\right\} \tag{3.299}$$

Simplifying the Eq. (3.299), the V_{Y2} becomes

$$V_{Y1} = \frac{2g_{m1}g_{m2}}{Y_1Y_2}V_{in3} - \frac{2g_{m1}g_{m2}}{Y_1Y_2}V_o - \frac{g_{m1}}{Y_1}V_o - \frac{g_{m1}}{Y_1}V_{in1} \tag{3.300}$$

Substituting V_{Y1} from Eq. (3.300) into (3.295), the V_o becomes

$$V_o = 2\left(\frac{2g_{m1}g_{m2}}{Y_1Y_2}V_{in3} - \frac{2g_{m1}g_{m2}}{Y_1Y_2}V_o - \frac{g_{m1}}{Y_1}V_o - \frac{g_{m1}}{Y_1}V_{in1}\right) - V_{in2} \tag{3.301}$$

Multiplying Y_1Y_2 to the left and simplifying to the right side of the equation, the Eq. (3.301) becomes

$$\left(Y_1Y_2 + 4g_{m1}g_{m2} + 2g_{m1}Y_2\right)V_o = -Y_1Y_2V_{in2} - 2g_{m1}Y_2V_{in1} + 4g_{m1}g_{m2}V_{in3} \tag{3.302}$$

Substituting Y_1 Y_2 from Eq. (3.292) and (3.293) into (3.302), the V_o becomes

$$\left\{\begin{matrix} \left[G_{y1} + s(C_1 + C_{y1})\right] \\ \left[G_{y2} + s(C_2 + C_{y2})\right] \\ +2g_{m1}\left[G_{y2} + s(C_2 + C_{y2})\right] \\ +4g_{m1}g_{m2} \end{matrix}\right\} V_o = \left\{\begin{matrix} -\left[G_{y1} + s(C_1 + C_{y1})\right] \\ \left[G_{y2} + s(C_2 + C_{y2})\right]V_{in2} - \\ 2g_{m1}\left[G_{y2} + s(C_2 + C_{y2})\right]V_{in1} \\ +4g_{m1}g_{m2}V_{in3} \end{matrix}\right\} \tag{3.303}$$

Assigning $G_{y1} = \frac{1}{R_{y1}}$, $G_{y2} = \frac{1}{R_{y2}}$; $C_1^* = C_1 + C_{y1}$, $C_2^* = C_2 + C_{y2}$, into Eq. (3.303), the V_o becomes

$$\left[\begin{matrix} \left(G_{y1} + sC_1^*\right)\left(G_{y2} + sC_2^*\right) \\ +4g_{m1}g_{m2} + 2g_{m1}\left(G_{y2} + sC_2^*\right) \end{matrix}\right] V_o = \left[\begin{matrix} -\left(G_{y1} + sC_1^*\right)\left(G_{y2} + sC_2^*\right)V_{in2} - \\ 2g_{m1}\left(G_{y2} + sC_2^*\right)V_{in1} + 4g_{m1}g_{m2}V_{in3} \end{matrix}\right] \tag{3.304}$$

Simplifying and interchanging to the equation, the Eq. (3.304) becomes

$$V_o = \frac{\begin{bmatrix} \left(s^2C_1^*C_2^* + sG_{y2}C_1^* + sG_{y1}C_2^* + G_{y1}G_{y2}\right)V_{in2} + \\ 2g_{m1}\left(G_{y2} + sC_2^*\right)V_{in1} + 4g_{m1}g_{m2}V_{in3} \end{bmatrix}}{\begin{pmatrix} s^2C_1^*C_2^* + sG_{y2}C_1^* + sG_{y1}C_2^* + 2g_{m1}sC_2^* + \\ G_{y1}G_{y2} + 2g_{m1}G_{y2} + 4g_{m1}g_{m2} \end{pmatrix}} \quad (3.305)$$

Dividing $C_1^*C_2^*$ to both denominator and nominator of Eq. (3.305), the Eq. (3.305) becomes

$$V_o = \frac{\begin{Bmatrix} \left(s^2C_1^*C_2^* + sG_{y2}C_1^* + sG_{y1}C_2^* + G_{y1}G_{y2}\right)V_{in2} + \\ 2g_{m1}\left(G_{y2} + sC_2^*\right)V_{in1} + 4g_{m1}g_{m2}V_{in3} \end{Bmatrix}}{\begin{pmatrix} s^2C_1^*C_2^* + sG_{y2}C_1^* + sG_{y1}C_2^* + 2g_{m1}sC_2^* + \\ G_{y1}G_{y2} + 2g_{m1}G_{y2} + 4g_{m1}g_{m2} \end{pmatrix}} \quad (3.306)$$

$$V_o^* = \frac{\begin{Bmatrix} \left[s^2 + \left(\frac{G_{y1}C_2^* + G_{y2}C_1^*}{C_1^*C_2^*}\right)s + \frac{G_{y1}G_{y2}}{C_1^*C_2^*}\right]V_{in2} + \\ \left[\frac{2g_{m1}(G_{y2} + sC_2^*)}{C_1^*C_2^*}\right]V_{in1} + \frac{4g_{m1}g_{m2}}{C_1^*C_2^*}V_{in3} \end{Bmatrix}}{D^*(s)} \quad (3.307)$$

$$D^*(s) = s^2 + \left(\frac{G_{y1}C_2^* + G_{y2}C_1^* + 2g_{m1}C_2^*}{C_1^*C_2^*}\right)s + \frac{G_{y1}G_{y2} + 2g_{m1}G_{y2} + 4g_{m1}g_{m2}}{C_1^*C_2^*} \quad (3.308)$$

where,

$G_{y1} = \frac{1}{R_{y1}}$; $G_{y2} = \frac{1}{R_{y2}}$; $C_1^* = C_1 + C_{y1}$; $C_2^* = C_2 + C_{y2}$. According to Eq. (3.308), the natural angular frequency and the quality factor with parasitic elements are as follows:

$$\omega_{05}^* = \sqrt{\frac{G_{y1}G_{y2} + 4g_{m1}g_{m2} + 2g_{m2}G_{y1}}{C_1^*C_2^*}} \quad (3.309)$$

$$Q_5^* = \frac{C_1^*C_2^*\sqrt{G_{y1}G_{y2} + 2g_{m1}G_{y2} + 4g_{m1}g_{m2}}}{G_{y1}C_2^* + G_{y2}C_1^* + 2g_{m1}C_2^*} \quad (3.310)$$

According to Eq. (3.309) to (3.310), the non-ideal of LT1228 affects the performances of the MISO filter response such as the operational frequency, passband voltage gain, natural angular frequency, and quality factor.

3.6 Instructional package on active filter design

Research tools are made up of instructional packages: teacher's manual, an activity plan based on the ADDIE model, a specialized experimental set (such as Lab manuals, trainer kits), a quiz sheet and an evaluation sheet. The development of a teaching model for instructional package based on the ADDIE model learning process that the problem-solving and co-operative objectives must be considered and consistent with the content of the analog active filter design course in order to motivate learners to learn, to achieve practical thinking skills and practical skills, to solve problem, to work as a team by using problem-based or real-world situations, and to obtain maximum efficiency for 21st century learning skills. The quality of the developed instructional package based on the ADDIE model was evaluated by experts, and a questionnaire about the study was completed by students. Research tools focused on student learning outcomes, assessed students' process, and output efficiency.

3.6.1 Population

The population of this research was 75 second year students, department of engineering education, school of industrial education and technology, King Mongkut's Institute of Technology Ladkrabang (KMITL).

3.6.2 Sample group

The sample group of this research was 20 second year students, major telecommunication engineering, department of engineering education, school of industrial education and technology, King Mongkut's Institute of Technology Ladkrabang (KMITL).

3.6.1 Research instruments

Research instruments in this research are as follows:

(1) Instructional package
   i. Experimental set
   ii. Teacher' manual including lesson plan, power point, lab sheet and solution,)
   iii. Quiz at the end of the topics
(2) Achievement test
(3) The instructional package's quality assessment form and the student satisfaction assessment forms.

3.6.4 Development of the instructional package using ADDIE model

The development of the instructional package on active filter design is based on ADDIE model. This design model was created for undergraduate students to focus on the fundamental filter concepts and an analog circuit analysis. The development of the instructional package on active filter design using the ADDIE model is comprised of five steps as shown in Fig. 3.29.

(1) Analyze

In the "Analyze" step, the following procedures are carried out: Analyze course descriptions related to active filter design such as Telecommunication Laboratory 2.

i. Analysis the basic data and knowledge of student for implementing learning in the analog active filter design topic, looking for inconsistencies between behavioral objectives and the reality of the classroom activities that have been implemented.
ii. Analyzing the necessity of developing teaching medias and adapting to various aspects of supporting the teaching media for the active filter design topic.

(2) Design

i. Set the units for teaching including (1) basic concept of LT1228, (2) first-order filter using LT1228 and (3) second order filter using LT1228.
ii. Set the behavioral objectives for each topic.
iii. Design the lesson plans
iv. Set the teaching methods, learning activity, teaching medias and assessment of learning.
v. Design the instructional package including the experimental set, teacher's manual (including lesson plan, lab sheet and solution, power

point), and quiz at the end of the topic.

vi. Bring the designed instructional package to the thesis advisor for verification of its appropriateness and accuracy.

vii. Improve the instructional package according to the recommendation of the thesis advisor.

(3) Develop

i. Create the instructional package including the experimental set, teacher's manual (including lesson plan, lab sheet and solution, power point), and quiz at the end of the topic.

ii. Create the achievement test.

iii. Create the instructional package's quality assessment form and the student satisfaction assessment forms.

iv. Bring the instructional package, the achievement test, the instructional package's quality assessment form and the student satisfaction assessment forms to the thesis advisor for verification of its appropriateness and accuracy.

v. Improve the instructional package, the achievement test, the instructional package's quality assessment form and the student satisfaction assessment forms according to the recommendation of the thesis advisor.

vi. Bring the instructional package, the achievement test, the instructional package's quality assessment form and the student satisfaction assessment forms to five experts to evaluate index of item objective congruence (IOC) and the quality of the instructional package.

vii. Improve the instructional package, the achievement test, the instructional package's quality assessment form and the student satisfaction assessment forms according to the recommendation of the experts.

viii. Try out the experimental set with 3 students (not sample group) that have similar characteristics to the sample group of this research.

ix. Improve the experimental set after trying it out.

(4) Implementation

i. Bring the instructional package to use with samples which are 20 undergraduate students in the department of engineering education, school of industrial education, King Mongkut Institute of Technology Ladkrabang that registered on the Telecommunication engineering. Fig. 3.30 and 3.31 show the 20 students group studying the Analog filter design course at KMITL's Telecommunication Laboratory 2.

ii. After finishing each topic, students must do an experiment in Fig. 3.32 and complete a quiz at the end of each topic in Fig 3.33.

iii. When students complete learning for all three topics, they are required to take the achievement test in Fig 3.34 and evaluate the student satisfaction assessment forms.

(5) Evaluation

i. Find the quality of the instructional package

ii. Find the effectiveness of the instructional package

iii. Find the students' satisfaction in the learning process by using the developed instructional package.

iv. package.

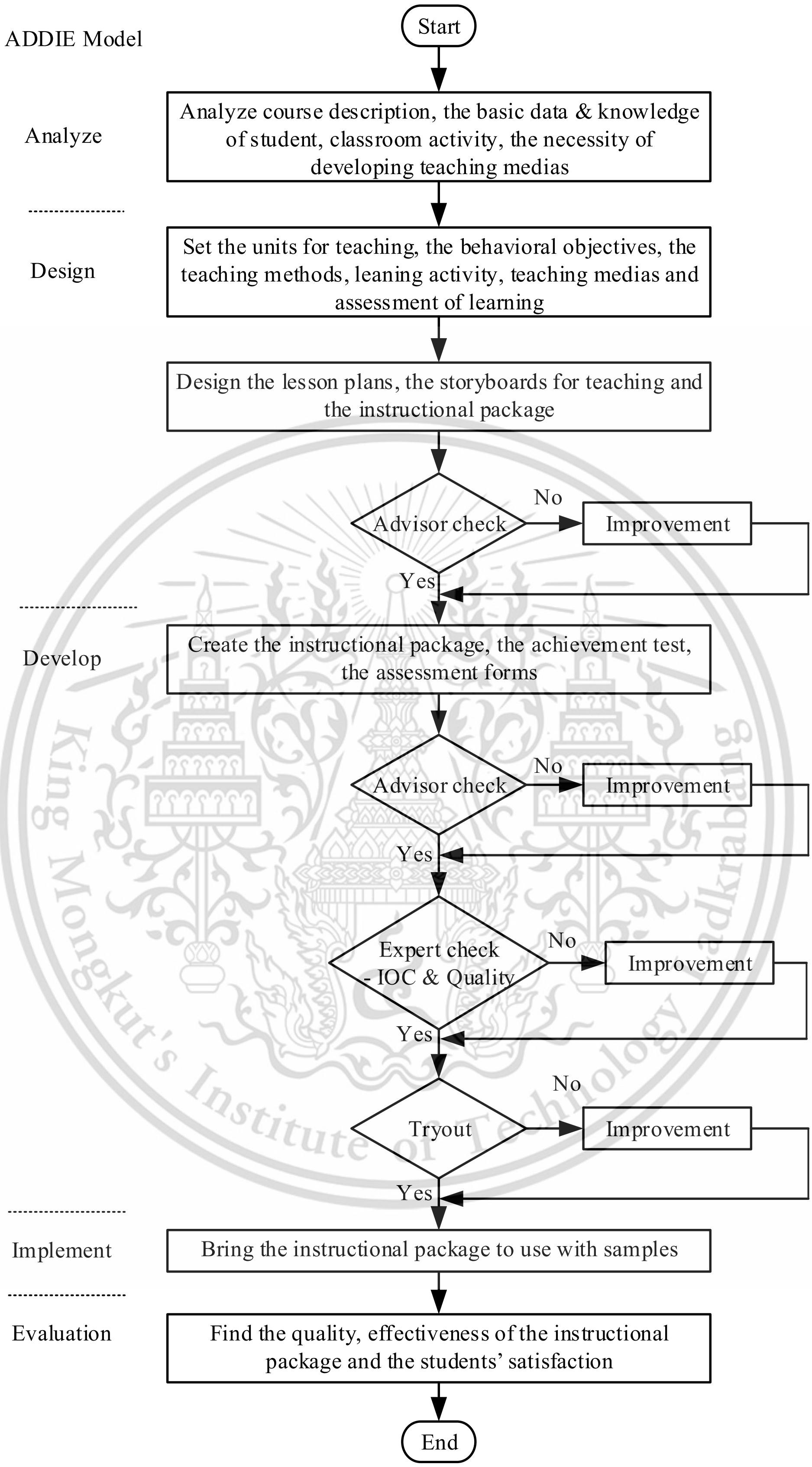


Figure 3.29 Flow chart development of the instructional package using ADDIE model developed instructional package.

Figure 3.30 First ten students group studying the Analog filter design course at KMITL's Telecommunication Laboratory 2

Figure 3.31 Second ten students group studying the Analog filter design course at KMITL's Telecommunication Laboratory 2

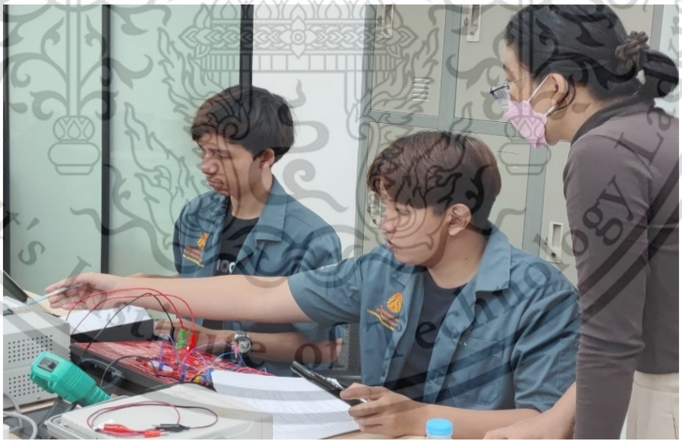


Figure 3.32 Students do the experiments after studying each topic.

Figure 3.33 Students take the quizzes after studying each topic.

Figure 3.34 Students take the achievement tests after studying all three topics.

3.6.5 Statistical and Data Analysis

3.6.5.1 The Index of Item Objective Congruence (IOC)

To check the validity of contents and objectives, the Index of Item Objective Congruence (IOC) is evaluated by the experts. The accepted value had to be more than 0.5, and there were three levels of scoring criteria. According to Equation (3.313) (Chai & Cheevapruk, 2014), a score of +1 indicates that the test content is positively congruent with the objective, a score of 0 indicates that it was unclear whether the test content is congruent with the objective or determined content, and a score of -1 indicates that the test content is positively certain that it is not congruent with the objective or strong-minded content. The data from the experts was applied with the following formula:

$$IOC = \frac{\sum R}{N} \quad (3.311)$$

where, IOC = Index of item-Objective Congruence between tests and objectives

R = score summary experts

N = Number of experts

Questions rated less than 0.5 by the experts were considered and improved.

3.6.5.2 Process Efficiency (E_1) and Output Efficiency (E_2) Assessments

To determine the proposed lesson plan's efficiency, the process efficiency (E_1) and output efficiency (E_2) assessments were used. From the E_1/E_2 criteria (Anirut Poomorn, 2015) where E_1 is a percentage of the average score students received throughout the instruction (exercises), and E_2 is determined as the outcome (achievement test), were used. Equations (3.314) and (3.315) explain how to calculate the E_1/E_2 efficiency as follows:

$$E_1 = \frac{\bar{x}_1}{N_1} \times 100 \quad (3.312)$$

Where, E_1 = the efficiency of the learning process

$\bar{x}_1$ = the average score of all the students obtained from the quizzes

N_1 = the total score of the quizzes in the lesson

$$E_2 = \frac{\bar{x}_2}{N_2} \times 100 \quad (3.313)$$

where, E_2 = the efficiency of the products
$\bar{x_2}$ = the average score of all the students obtained from the achievement test
N_2 = the total score of the achievement test in the lesson

3.6.5.3 Quality Assessment of Instructional Package

The five-level rating scale is used to score the quality of the instructional package. The score level can be translated by the interval of average scores, which are

4.51-5.00 means that the quality of the instructional package is very good level.

3.51-4.50 means that the quality of the instructional package is good level.

2.51-3.50 means that the quality of the instructional package is of a moderate level.

1.51-2.50 means that the quality of the instructional package is fair level.

1.00-1.50 means that the quality of the instructional package is improved level.

3.6.5.4 Students' satisfactions of teaching instructional package

The 5-level rating scale is also used to score the students' satisfactions of teaching instructional package. The score level can be translated by the interval of average scores, which are

4.51-5.00 means that students are totally satisfied with the instructional package.

3.51-4.50 means that the students are satisfied with the instructional package.

2.51-3.50 means that students are unsure of the instructional package.

1.51-2.50 means students are unsatisfied with the instructional package.

1.00-1.50 means that students are totally unsatisfied to the instructional package.

CHAPTER 4

RESULTS

4.1 Engineering aspect

In this chapter, the test results for performance of the voltage mode frequency filter circuit, the quality evaluation and the student satisfaction of an instructional package will be presented. To confirm the circuit performance of the proposed filters, it can be described by using PSpice program simulation and actual circuit test results from the circuit board. And it also shows the experimental set on electronically controllable analog filter using LT1228. The results of the test are compared with the results obtained from the theoretical analysis, which are detailed as the following.

4.1.1 Simulation and experimental results of the proposed filter 1

The performance of proposed filter 1 in Fig. 3.4 was simulated by using the LT1228 PSPICE macro model and experiments were carried out by using the commercially available LT1228 IC. Supply voltages of ±5 V were applied in both simulations and experiments in Fig. 4.1. A Keysight DSOX-1102G oscilloscope with a function generator was used for the experiments. The LT1228's parasitic components are taken from the datasheet with I_B=100µA, R_+=R_-=200kΩ, C_+ = C_- =3pF, R_y =8MΩ, C_y=6pF and taken from simulation is R_T =197.66kΩ, C_T =5.95pF, R_x=46.92Ω, R_w=19.80Ω. The following circuit components values are selected C_1=C_2=1nF, R_1=R_2=R_3=1kΩ, and I_{B1}=I_{B2}=123.5µA. The proposed filter was designed to have f_{01}=340.44kHz and Q_1 (theoretical) = 1.73, with a passband gain of 1 (0dB) for HP and BP, and a passband gain of 1/3 (-9.55dB) for LP. Figure. 4.2 depicts the LP, HP, BP simulated, theoretical, and experimental gain responses of the proposed filter 1. The simulation and experimental natural frequencies are 327.34kHz and 337kHz. The percentage errors in the simulated and experimental natural frequencies were 3.8% and 1.01%, respectively. Figs. 4.1 to 4.2 show that the simulated and experimental results of the proposed filter 1 operate under the theoretical facts. It is obvious that theLT1228 parasitic elements (especially RT) as analyzed in section 3.1.3 noticeably affect the performance of the proposed filter at high frequency. According to the experiment, this effect also appears from the wiring and breadboard. The simulated output impedance is around 22 Ω. The simulated, theoretical, and experimental frequency band of this filter is about 10MHz. Also, the control of $f_{01}$and Q_1 doesn't affect the passband voltage gain for all filtering responses.

Figure. 4.3 show the simulated BP gain response with different I_B values (I_{B1} = I_{B2} = 100µA, 200µA and 300µA). The simulation result of the natural frequencies was situated at 271.01kHz, 543.25kHz and 818.46kHz. It is observed that the f_{01} is electronically controlled without disturbing the Q_1 as analyzed in Eq. (3.30). The linearity of the proposed filter was evaluated in the case of BP response by applying different sinusoidal input voltages of 133.05kHz. Figure 4.4 shows the plot of percent of THD against magnitudes of input voltage. The proposed filter 1 was designed at natural frequency of 133.05 kHz.

The simulated, theoretical, and experimental results show that the first proposed filter is more beneficial than other proposed filters from literature review. First, it can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Second, its output nodes at V_{HP1} and V_{BP1} can cascade with other voltage-mode circuits without the need for additional buffers.

Finally, it only requires two commercially accessible integrated circuits, it is simpler structure than other filters requiring multiple ICs.

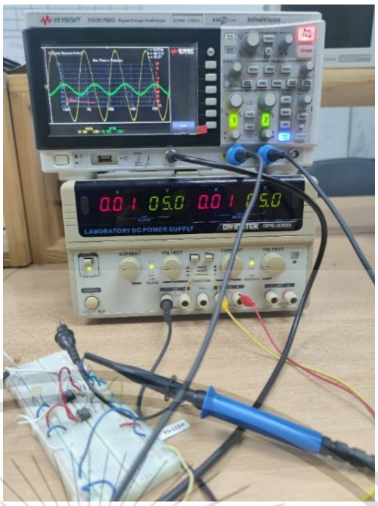


Figure 4.1 Experimental set up

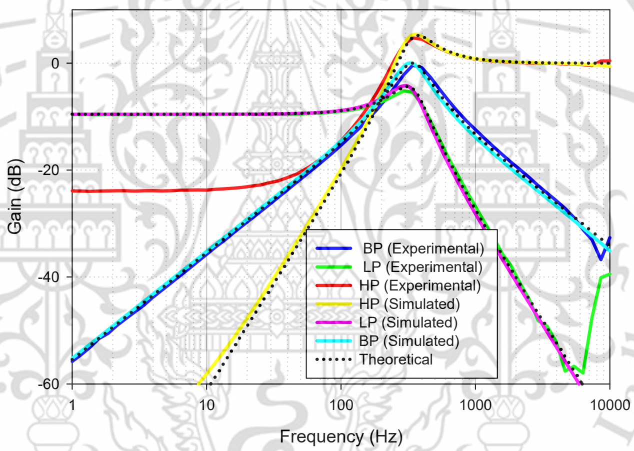


Figure 4.2 LP, HP, BP of the simulated, theoretical, and experimental gain response

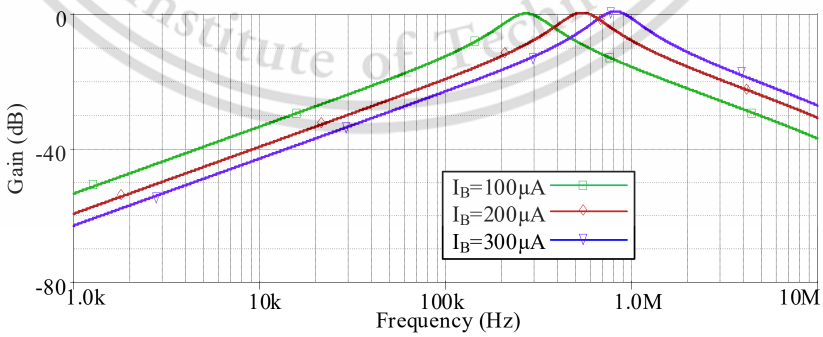


Figure 4.3 The gain responses of V_{BP1} where I_B was varied

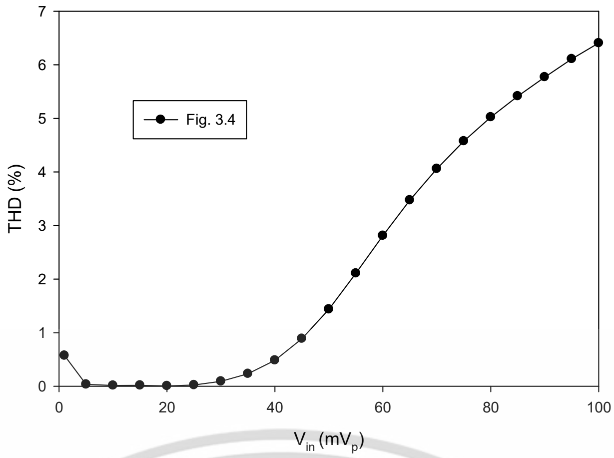


Figure 4.4 THD test of the simulated BP1 versus input voltage amplitude

4.1.2 Simulation and experimental results of the proposed filter 2

The LT1228's parasitic components and the experimental procedures are as given in section 4.1. The following circuit components values are selected C_1 =1nF, C_2 =10nF, R_1=R_2=R_3= R_4=R_5=R=1kΩ, and I_{B1}=I_{B2}=123.5μA. The second proposed filter in Fig. 3.11 was designed to have f_{02} = 107.66kHz, with a passband gain of 1 (0dB) for HP and BP, and a passband gain of 1/3 (-9.55dB) for LP. Figure. 4.5 depicts the LP, HP, BP simulated, theoretical, and experimental gain responses of the proposed filter 2. The simulation and experimental natural frequencies are 105.68kHz and 114kHz. The percentage errors in the simulated and experimental natural frequencies were 1.83% and 5.6%, respectively. Due to parasitic elements of LT1228 slightly deviating the experimental results from ideal results at low-frequency and tolerances of the parasitic capacitance effects at high frequency (higher 10MHz).

Figure. 4.6 shows that Q_2 can be controlled by changing the value of resistance R_5 without disturbing f_{02} as expected in Eq. (3.107), where R_5 is denoted to 0.47kΩ, 1kΩ, 3kΩ. The electronic tuning of the natural frequency, f_{02} by simultaneously altering I_{B1} and I_{B2} (I_{B1} = I_{B2} = I_B) for the proposed filter 2 is described in Fig. 3.11 where value of I_B was assigned to 67μA, 123.5μA and 245μA. The experimental natural frequency tuned from these bias currents are situated at 60kHz, 114kHz, and 230kHz. The result in Figure. 4.7 indicates that the natural frequency of the second proposed filter can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in Eq. (3.107). However, it cannot be electronically controlled both f_{02} and Q_2.

The simulated high-pass filtering response with different values of resistor R (R_1 = R_2 = R_3 = R) in summing circuit of the filter 2 is illustrated in Figure 4.8. In this simulation, the values of R were set to 0.2kΩ, 0.6kΩ and 5kΩ. It is found that with low value of the feedback resistor (R), the bandwidth of the proposed filter is higher than the bandwidth at high value of R as expected in section 3.1.3. Thus, these resistors are chosen as 1kΩ to achieve higher operational frequency. The linearity of the proposed filter 2 was evaluated in the case of BP response by applying different sinusoidal input voltages of 100kHz. Figure 4.9 shows the plot of percent of THD against magnitudes of input voltage. The second proposed filter was designed at a natural frequency of 100kHz.

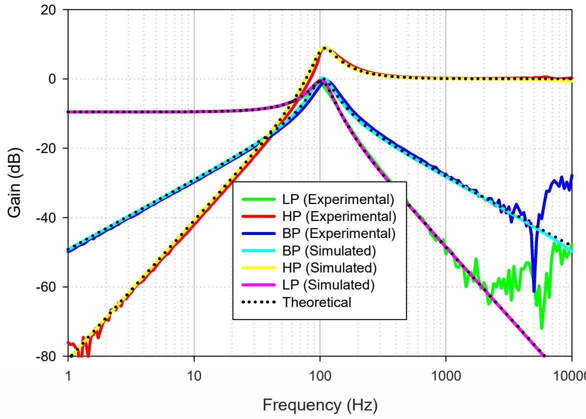


Figure 4.5 LP, HP, BP of the simulated, theoretical, and experimental gain responses

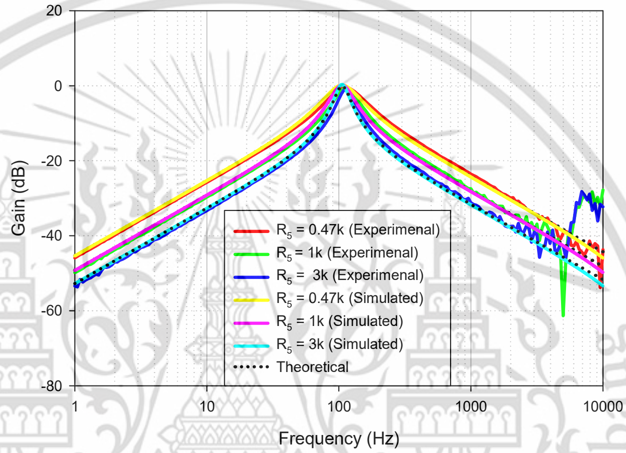


Figure 4.6 BP of the simulated, theoretical, and experimental gain responses with different values of R_5

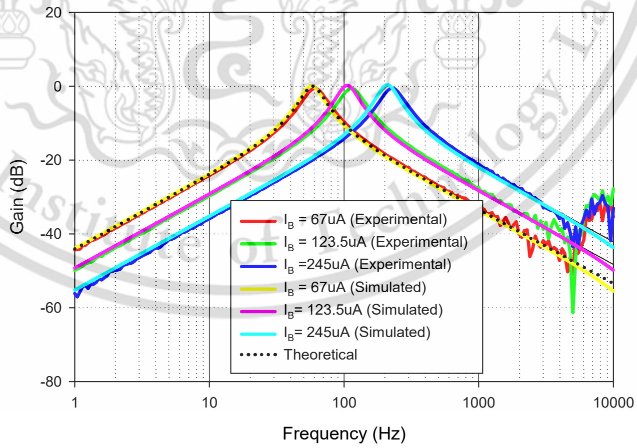


Figure 4.7 BP of the simulated, theoretical, and experimental gain responses with different values of I_B ($I_{B1} = I_{B2} = I_B$)

The simulated, theoretical, and experimental results show that the proposed filter 2 is more beneficial than other proposed filters from literature review. First, it can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Second, it can provide orthogonally and independently controlled that it can be achieved the desired center frequency f_{02} and quality factor Q_2 value. Third, its output nodes at V_{HP2} and V_{BP2} can cascade with other voltage-mode circuits without the need for additional buffers. Finally, it only requires two commercially accessible integrated circuits, it is simpler structure than other filters requiring multiple ICs.

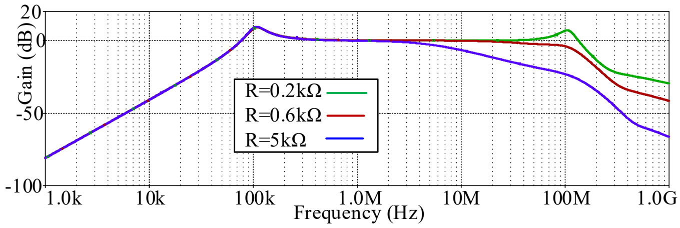


Figure 4.8 High-pass response of the filter in Fig. 3.11 with different values of R ($R_1 = R_2 = R_3 = R$)

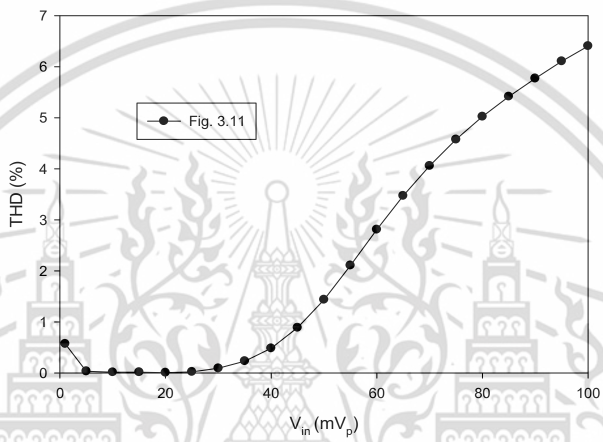


Figure 4.9 THD test of the simulated BP2 versus input voltage amplitude

4.1.3 Simulation and experimental results of the proposed filter 3

The LT1228's parasitic components and the experimental procedures are as given in section 4.1. The following circuit components values are selected C_1=C_2=2.7nF, R_1=R_2=R_3=R_4=1kΩ, and I_{B1}=I_{B2}= I_{B3}=100µA. The proposed filter 3 in Fig. 3.15 was designed to have f_{03} = 102.09kHz, with a passband gain of 1 (0dB) for HP and BP, and a passband gain of 1/3 (-9.55dB) for LP. Figure. 4.10 depicts the LP, HP, BP simulated, theoretical, and experimental gain responses of the proposed filter 3. The simulation and experimental center frequencies are 100.46kHz and 100kHz. The percentage errors in the simulated and experimental pole frequencies were 2.05% and 1.59%, respectively. Due to parasitic elements of LT1228 slightly deviating the experimental results from ideal results at low-frequency and tolerances of the parasitic capacitance effects at high frequency (higher 10MHz).

Figure. 4.11 shows that Q_3 can be controlled by altering I_{B3} for the proposed filter 3 is described in Fig. 3.15 where value of I_{B3} was assigned to 123.5µA, 185.5µA and 371µA. The result in Figure. 4.11 indicates that the natural frequency of the proposed filter 3 can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in Eq. (3.150). Fig. 4.12 shows that Q_3 can be controlled by changing the value of resistance R_4 without disturbing f_{03} as expected in Eq. (3.150), where R_4 is as denoted to 1kΩ, 2kΩ, and 3kΩ. The electronic tuning of the center frequency, f_{03} by simultaneously altering I_B ($I_{B1} = I_{B2} = I_B$) for the proposed filter 3 is described in Fig. 3.15 where value of I_B was assigned to 123.5µA, 185.5µA and 371µA. The experimental center frequency tuned from these bias currents are situated at 123kHz, 185kHz, and 373kHz at the same value of Q_3=1.6. The result in Fig. 4.13 indicates that the center frequency of the proposed filter 3 can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in Eq. (3.150).

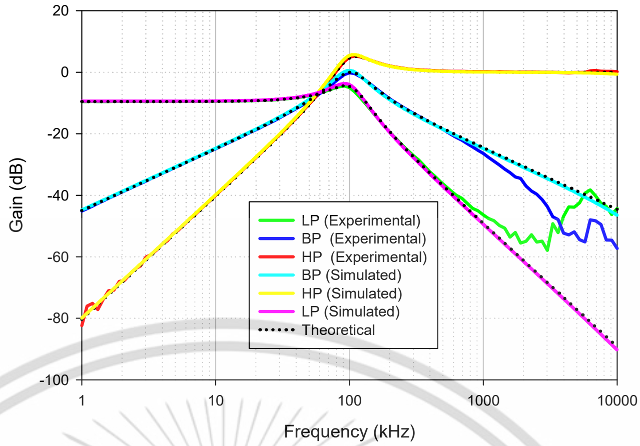


Figure 4.10 LP, HP, BP of the simulated, theoretical, and experimental gain response

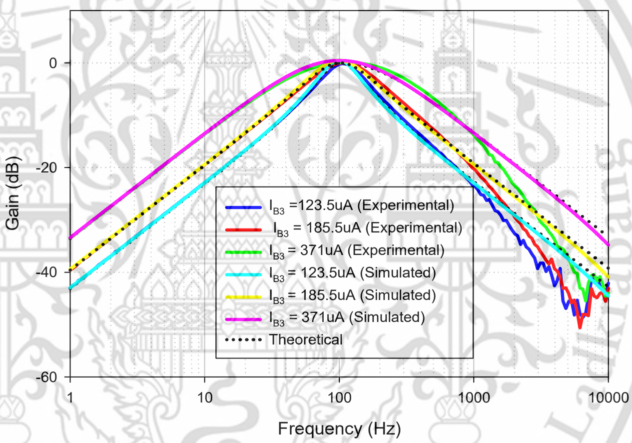


Figure 4.11 BP of the simulated, theoretical, and experimental gain responses with different values of I_{B3}

The simulated high-pass filtering response with different values of resistor R ($R_1 = R_2 = R_3 = R$) in summing circuit of the filter 3 is illustrated in Fig. 4.14. In this simulation, the values of R were set to 0.2kΩ, 0.6kΩ and 5kΩ. It is found that with low value of the feedback resistor (R), the bandwidth of the proposed filter is higher than the bandwidth at high value of R as expected in section 3.1.3. Thus, these resistors are chosen as 1kΩ to achieve higher operational frequency. Fig. 4.15 indicates the test of the transient response of the presented voltage-mode band-pass filter where the sinusoidal input voltage is applied to 50mV$_p$ and f_{03} =100kHz. The linearity of the proposed filter 3 was evaluated in the case of BP response by applying different sinusoidal input voltages of 100kHz. Figure 4.16 shows the plot of percent of THD against magnitudes of input voltage.

The proposed filter 3 was designed at a natural frequency of 100kHz. The 10mV$_p$ of the sinusoidal input voltage signal is applied with three frequencies such as 10kHz, 100kHz, and 1MHz. The input and output voltage signal for the BP frequency spectrum result is demonstrated in Fig. 4.17. It was found that the attenuation between the pole frequency (100kHz) and f = 10kHz is -19dB, while the attenuation between the pole frequency (100kHz) and f = 1MHz is -19dB. The simulation results in Figs. 4.14 to 4.17 indicate that the proposed filter operates well as expected. The operational frequency is around 10MHz. The total harmonic distortion is lower 1% when the applied amplitude of input signal is lower than $50mV_p$. The simulated, theoretical, and experimental results in Fig 4.10 through 4.17 indicate that the proposed filter 3 operates well as expected. However, at high frequency the parasitic capacitances in LT1228 will affect the performance of the proposed filter as results in Figs. 4.10 through 17. Moreover, the proposed filter 3 can provide electronic tunes for both f_{03} and Q_3.

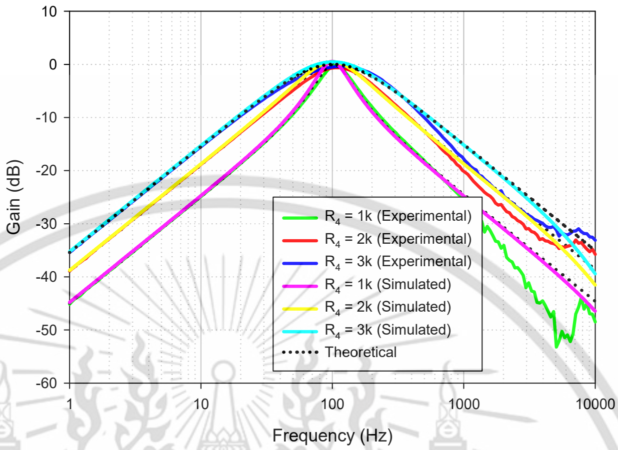


Figure 4.12 BP of the simulated, theoretical, and experimental gain responses with different values of R_4

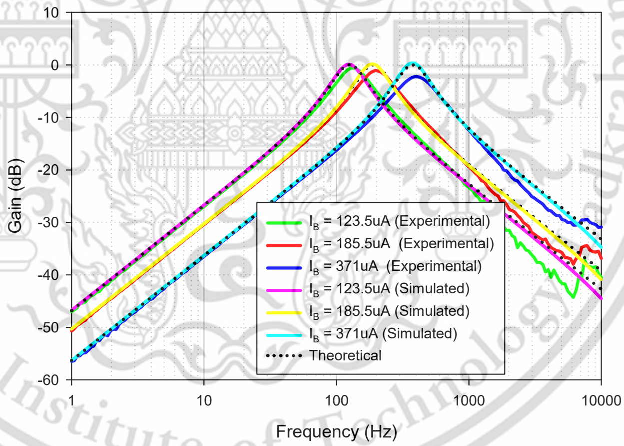


Figure 4.13 BP of the simulated, theoretical, and experimental gain responses with different values of I_B ($I_{B1} = I_{B2} = I_B$)

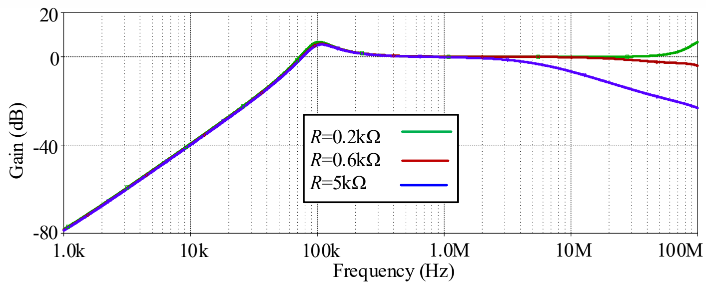


Figure 4.14 Simulated HP frequency responses of the biquadratic filter with different values of R ($R_1 = R_2 = R_3 = R$)

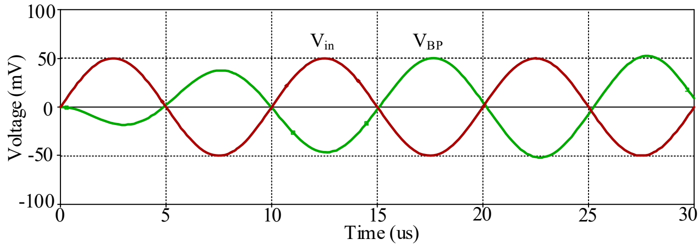


Figure 4.15 Time-domain response of the presented BP function.

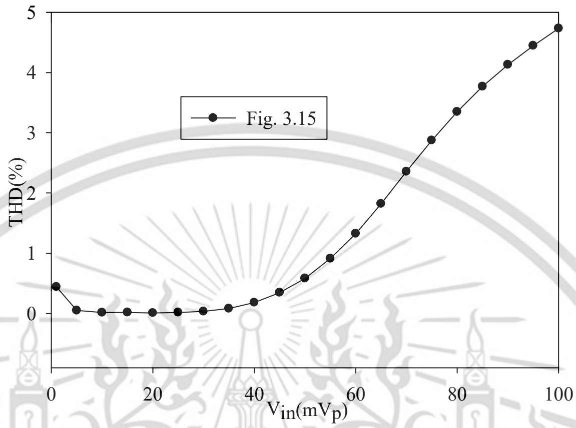


Figure 4.16 THD test of the simulated BP3 versus input voltage amplitude.

The simulated, theoretical, and experimental results show that the proposed filter 3 is more beneficial than other proposed filters from literature review. First, it can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Second, it can provide orthogonally and independently controlled that it can be achieved the desired center frequency f_{03} and quality factor Q_3 value. Finally, its output nodes at V_{HP3} and V_{BP3} can cascade with other voltage-mode circuits without the need for additional buffers.

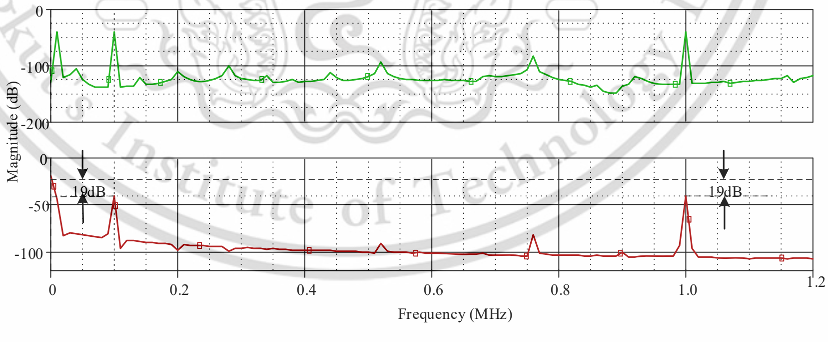


Figure 4.17 The desirable test signal of the BP.

4.1.4 Simulation and experimental results of the proposed filter 4

The LT1228's parasitic components and the experimental procedures are as given in section 4.1. The following circuit components values are selected C_1 = 1nF, C_2 = 10nF, $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = R_7$ =1kΩ, and $I_{B1} = I_{B2}$ = 204.4μA I_{B3} = 100.4μA. The proposed filter 4 in Fig. 3.22 was designed to have f_{04} = 102.87kHz, with a passband gain of 1 (0dB) for LP and BR, and a passband gain of 1/2 (-6.02dB) for BP and a passband gain of 2 (6.02dB) for HP. Fig. 4.18 depicts the LP, HP, BP, BR simulated, theoretical, and experimental gain responses of the proposed filter 4. The simulation and experimental center frequencies are 100.92kHz and 103.75kHz kHz. The percentage errors in the simulated and experimental pole frequencies were 0.9% and 3.6%, respectively.

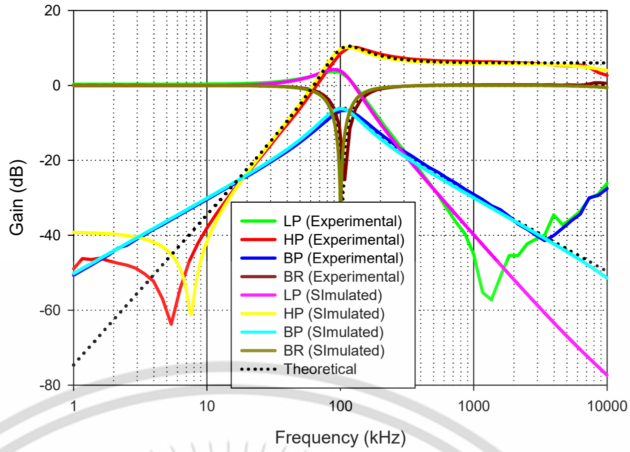


Figure 4.18 LP, HP, BP, BR of the simulated, theoretical, and experimental gain response

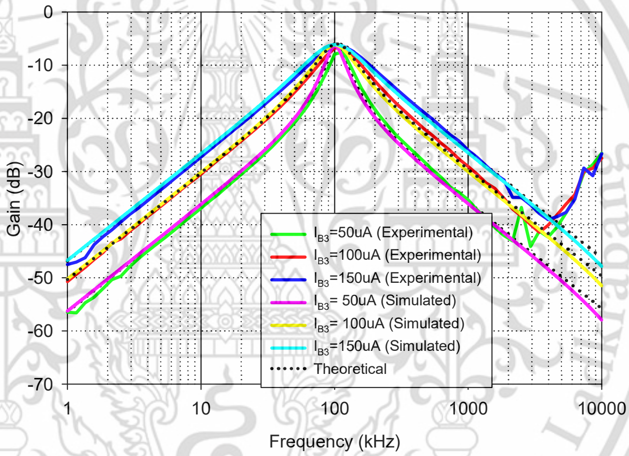


Figure 4.19 BP of the simulated, theoretical, and experimental gain responses with different values of I_{B3}

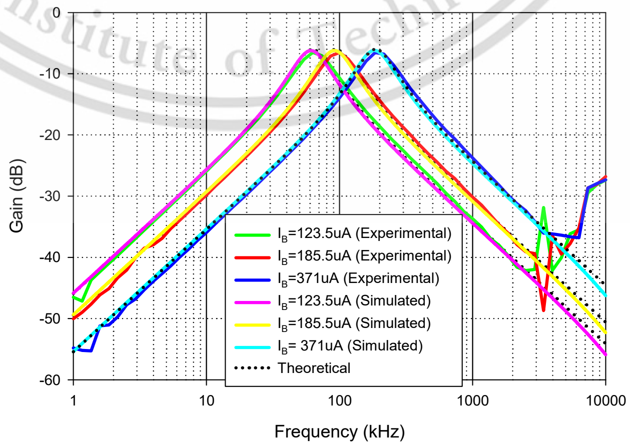


Figure 4.20 BP of the simulated, theoretical, and experimental gain responses with different values of I_B ($I_{B1} = I_{B2} = I_B$)

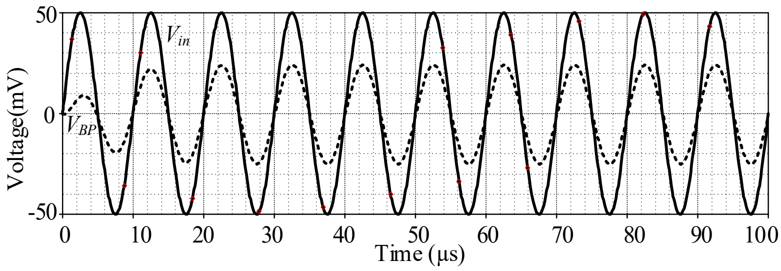


Figure 4.21 BP filtering time-domain response

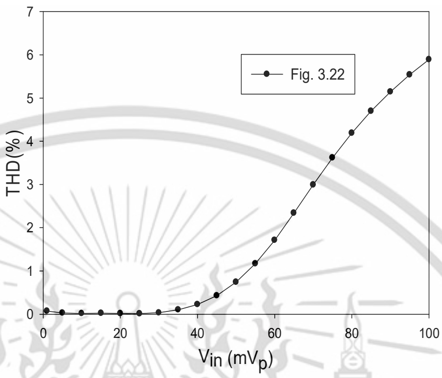


Figure 4.22 THD test of the simulated BP4 versus input voltage amplitude

Figure. 4.19 shows that Q_4 can be controlled by altering I_{B3} for the proposed filter 3 is described in Figure. 3.22 where value of I_{B3} was assigned to 50µA, 100µA and 150µA. The result in Figure. 4.19 indicates that the center frequency of the proposed filter 4 can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in Eq. (3.222). The electronic tuning of the center frequency, f_{04} by simultaneously altering I_{B1} and I_{B2} (I_{B1} = I_{B2} = I_B) for the proposed filter 4 is described in Fig. 3.22 where value of I_B was assigned to 123.5µA, 185.5µA and 371µA. The experimental center frequency tuned from these bias currents are situated at 63.4kHz, 95.6kHz, and 185.8kHz at the same value of Q_4 =1.58. The result in Fig. 4.20 indicates that the center frequency of the proposed filter 4 can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in Eq. (3.222). The test of the natural response for the simulated BP filter function is illustrated in Fig. 4.21 where the sine wave input voltage signal was applied to 50m$V_{p\text{-}p}$ and f_0 =100kHz. The THD value of the BP function is steady straight up at 3% below 30m$V_{p\text{-}p}$ and then it gradually increases to 5.89%, as described in Figure. 4.22. From Figures. 4.18 to 4.22, it is verified that the simulated and experimental results of the proposed filter 4 operate under the theoretical facts. It is obvious that the LT1228 parasitic elements (especially R_T) as analyzed in section 3.1.3 noticeably affect the performance of the proposed filter at high frequency. According to the experiment, this effect also appears from the wiring and breadboard. The simulated, theoretical, and experimental frequency band of this filter is about 10MHz.

The simulated, theoretical, and experimental results show that the proposed filter 4 is more beneficial than other proposed filters from literature review. Firstly, it can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Second, it can provide orthogonally and independently controlled that it can be achieved the desired center frequency f_{04} and quality factor Q_4 value. Third, its output nodes at V_{HP4} and V_{BP4} can cascade with other voltage-mode circuits without the need for additional buffers. Finally, it only requires two commercially accessible integrated circuits, it is simpler structure than other filters requiring multiple ICs.

4.1.5 Simulation and experimental results of the proposed filter 5

The LT1228's parasitic components and the experimental procedures are as given in section 4.1. The following circuit components values are selected $C_1=C_2=2.7\text{nF}$, $R_1=R_2=R_3=R_4=1\text{k}\Omega$, and $I_{B1}=I_{B2}=123.5\mu\text{A}$. The proposed filter 5 in Fig. 3.27 was designed to have f_0 = 145.72kHz, with a passband gain of 1 (0dB) for all responses. Fig. 4.23 depicts the LP, HP, BP, BR, AP simulated, theoretical, and experimental gain responses of the proposed filter 5. The simulation and experimental center frequencies are 143.55kHz and 144kHz. The percentage errors in the simulated and experimental pole frequencies were 1.49% and 1.18%, respectively. The experimental phase response of AP is demonstrated in Fig. 4.24. This illustration demonstrates how the TISO filter's phase angle is adjusted between 0 and 360 degrees.

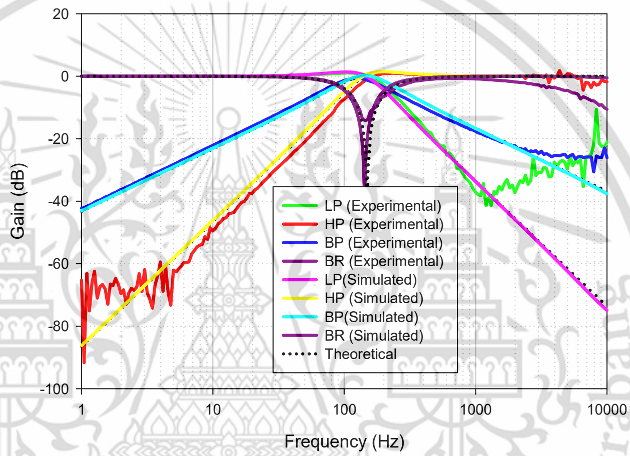


Figure 4.23 LP, HP, BP, BR of the simulated, theoretical, and experimental gain response

Three different bias currents, $I_{B1} = I_{B2} = I_B$, are assigned to 70μA, 140μA, and 210μA in this experiment. Figure. 4.25 shows the result of the experimental center frequency with these bias currents. The tested center frequencies are at respective frequencies of 82.6kHz, 163.5kHz, and 246.8kHz with keeping constant at Q = 0.98 as analyzed in Eq. (3.288). It is simple to change the values of I_{B1} and I_{B2} in actual work by utilizing a microcontroller.

Figure. 4.26 presents the simulated BP functions of THD values versus the amplitude of the input voltage, where the sinusoidal input voltage ranges from 1mV$_P$ to 100mV$_P$. The proposed filter 5 is designed to have f_{05} = 143.55kHz. It can be verified that the range of THD values is adjusted from 0.018% to 9.5236%, and that the value of BP function is not above 1% below 40mV$_P$ of the sinusoidal input voltage signal. The range of THD value is lower than 1% when the applied amplitude of the sine wave input signal is lower than 40mV$_P$.

Figs. 4.23 to 4.26 show that the simulated and experimental results of the proposed filter 5 operate under the theoretical facts. It is obvious that the LT1228 parasitic elements (especially R_T) as analyzed in section 3.1.3 noticeably affect the performance of the proposed filter at high frequency. According to the experiment, this effect also appears from the wiring and breadboard. The simulated output impedance is around 60.12Ω. The simulated, theoretical, and experimental frequency band of this filter is about 10MHz.

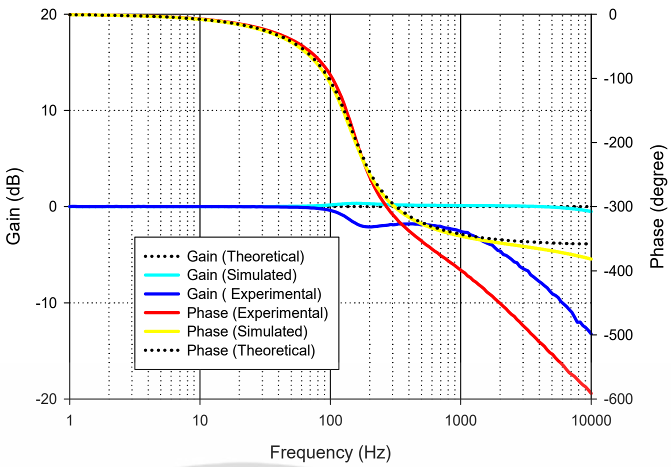


Figure 4.24 The experimental phase response of AP

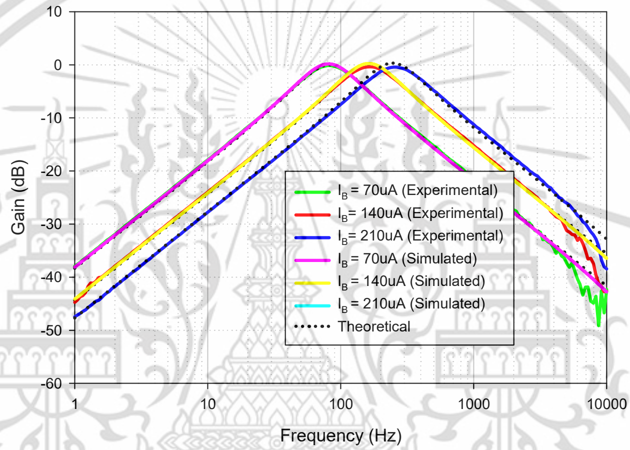


Figure 4.25 BP of the simulated, theoretical, and experimental gain responses with different values of I_B ($I_{B1} = I_{B2} = I_B$)

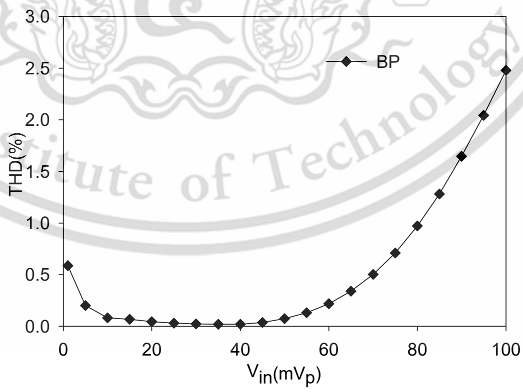


Figure 4.26 THD test of the simulated BP5 versus input voltage amplitude

The simulated, theoretical, and experimental results show that the proposed filter 5 is more beneficial than other proposed filters from literature review. First, it can provide five filtering output responses with unity passband gain. Second, it can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Third, it can provide independently controlled that it can be achieved the desired center frequency f_{05} and quality factor Q_5 value. Fourth, its output nodes at

V_{HP5} and V_{BP5} can cascade with other voltage-mode circuits without the need for additional buffers. Fifth, its input nodes possess high input impedance. Finally, it only requires two commercially accessible integrated circuits, it is simpler structure than other filters requiring multiple ICs.

4.2 Educational aspect

The purpose of this study is to develop the instructional package on the active filter design and investigate the effectiveness of the instructional package. This chapter mostly discusses the results of the investigation. The outcomes of this study included IOC values, the quality evaluation from experts, quizzes administered following the teaching of each topic, the efficiency (E_1/E_2) results, and student satisfaction on this study. The study results are presented in the tables and discussions that follow when utilizing the instructional package to create an active filter design and test it with an experimental set.

4.2.1 Results of IOC values

In this section, the researcher created an index of item-objective congruences for quiz and achievement test. Evaluation forms for IOC values between behavioral objectives and quizzes as well as between behavioral objectives and achievement tests were sent to five experts in Electronics Engineering Fields (Appendix A). The results of the analysis are displayed in Tables 4-1 and Table 4-2. In this course, there were three study topics to cover. The first study topic, learning the basic concepts of LT1228, has four behavioral objectives. After experts evaluated the IOC values, all four behavioral objectives are consistent with the course content. The behavioral objectives for the remaining two study topics: first order multifunction filter using a single LT1228 and second order universal filter using three LT1228s that agree with the design content.

Table 4.1 The IOC results between number of quizzes and behavioral objectives by experts

Study topic	Number of questions	Number of behavioral objectives which had IOC value higher than 0.5	Number of behavioral objectives which had IOC value lower than 0.5
Basic concepts of LT1228	15	15	None
First order multi-function filter using single LT1228	22	21	1
Second order multifunction filter using three LT1228s	22	21	1
Total	59	57	2

After calculating IOC results to assess the validity of the design content and behavioral objectives for all three study themes, it was determined that all 12 behavioral objectives had been satisfied by the design content and did not need to be improved. As can be seen in Table 4-1 (the detail of IOC analysis in Appendix D), the outcome showed the IOC results between behavioral objectives and quizzes. There were 59 questions with IOC value greater than 0.5 which were adequate and consistent with the behavioral objectives of the lesson after calculating the IOC results between behavioral objectives and questions, and eight questions that had an IOC value lower than 0.5 needed to be eliminated.

Table 4.2 The IOC results between number of achievement test and behavioral objectives by experts

Study topic	Number of questions	Number of behavioral objectives which had IOC value higher than 0.5	Number of behavioral objectives which had IOC value lower than 0.5
Basic concepts of LT1228	15	11	4
First order multi-function filter using single LT1228	22	20	2
Second order multifunction filter using three LT1228s	23	21	2
Total	60	52	8

The results of the achievement test showed the IOC results between behavioral objectives and questions in Table 4-2 (the detail of IOC analysis in Appendix D). There were 60 questions with IOC value greater than 0.5 which were adequate and consistent with the behavioral objectives of the lesson after calculating the IOC results between behavioral objectives and questions, and only two questions that had an IOC value lower than 0.5 needed to be eliminated.

4.1.2 Results of the quality evaluation of an instructional package by experts

The result of the quality of an instructional package (lesson plan based on the MIAP learning model, laboratory sheet, power point, experimental set, achievement test and quizzes sheet) is shown in Table 4-3 (the detail of quality analysis in Appendix D). The average values and standard deviation data were integrated into their respective topics after gathering the evaluation results. The quality of instructional package was done by five experts. The results of the evaluated topics are calculated and interpreted. The following are the interpreted criteria:

4.51 – 5.00 means “Very Good”
3.51 – 4.5 means “Good”
2.51 – 3.5 means “Moderate”
1.51 – 2.5 means “Fair”
1.00 – 1.5 means “Improve”

The result of evaluated topic for 1) lesson plan based on the MIAP learning model has an average value of 4.47 and S.D value of 0.57, it means a good level. For the result of 2) laboratory sheets (Average =4.52, S.D.= 0.52), it means a very good level. 3) power points (average value of 4.20 and S.D. value of 0.68), it means a good level. For the result of 4) experimental set (average = 4.63, S.D.= 0.51), it means a very good level and 5) achievement test and quizzes sheet (average = 4.30, S.D.= 0.50), it means a good level. The result of calculating the total value of average and S.D. showed that the generated the quality of instruction package was at a good level (total average = 4.42, S.D. = 0.56) as determined by the five experts represented in Table 4-3. Table 4-4 displays detailed results of the quality evaluation of an analog active filter design course for each question from the 29 evaluated topics for the five main topics.

Table 4.3 Quality evaluation result from experts

Assessment Items	Average	S.D.	Interpret
1. Lesson plan based on the MIAP learning model	4.47	0.57	Good
2.Laboratory Sheet	4.52	0.52	Very Good
3. PowerPoints	4.20	0.60	Good
4.Experimental set	4.63	0.51	Very Good
5. Achievement test and quizzes sheet	4.30	0.50	Good
Total average	**4.42**	**0.56**	**Good**

Table 4.4 Quality evaluation of an instructional package (Detail) (Number of experts, N= 5)

Assessment Items	Average	S.D.	Interpret
2. Lesson plan based on MIAP learning model			
1.1. Behavioral objectives are clear.	4.80	0.45	Very Good
1.2. The time spent on each activity is appropriate to the level of the student.	4.20	0.45	Good
1.3. The sorting of activities is appropriate.	4.40	0.55	Good
1.4. Teaching activities are consistent with the behavioral objectives.	4.40	0.55	Good
1.5. Teaching media are consistent with behavioral objectives.	4.40	0.89	Good
1.6. Learning activities develop the students' self-learning and problem-solving skills.	4.60	0.55	Very Good
Average	**4.47**	**0.57**	**Good**
2. Laboratory sheets			
2.1. The content of the laboratory sheets is correct	4.60	0.55	Very Good
2.2. The content of the laboratory sheets is consistent with the teaching objectives.	4.80	0.45	Very Good
2.3. The content of the laboratory sheets is difficult and easy, suitable for the student's level.	4.40	0.55	Good
2.4. The language used in the laboratory sheets is appropriate.	4.40	0.55	Good

Table 4.4 (Cont.) Quality evaluation of an instructional package (Detail) (Number of experts, N= 5)

Assessment Items	Average	S.D.	Interpret
2.7. The experimental procedures in the laboratory sheets are described in detail and clearly.	4.80	0.45	Very Good
Average	**4.52**	**0.52**	**Very Good**
3. Power points			
3.1. The content of the power points is correct, interesting, and appropriate.	4.00	1.00	Good
3.2. The content of the PowerPoints is consistent with the teaching objectives.	4.40	0.55	Good
3.3. The content of the PowerPoints is difficult and easy, suitable for the student's level.	4.20	0.45	Good
3.4. The font colors and font sizes on the PowerPoints are appropriate.	4.00	0.71	Good
3.5. The clarity of the figures, tables, or graphs on the PowerPoints is appropriate.	4.20	0.84	Good
3.6. The content of the PowerPoints encourages learning.	4.40	0.55	Good
Average	**4.20**	**0.68**	**Good**
4. Experimental set			
4.1. The color and size of the experimental set are appropriate.	4.80	0.45	Very Good
4.2. The font colors and font sizes on the experimental set are appropriate.	4.60	0.55	Very Good
4.3. The placement of the devices on the experimental set is appropriate.	4.80	0.45	Very Good
4.4. The position of the devices on the experimental set makes it convenient to conduct experiments.	4.60	0.55	Very Good
4.5. The use of the experimental set is easy and safe.	4.40	0.55	Good
4.6. The ease of transport and storage of the experimental set is appropriate.	4.60	0.55	Very Good
Average	**4.63**	**0.51**	**Very Good**
5. Achievement test and quizzes			
5.1. The questions in the achievement test and quizzes are consistent with the teaching objectives.	4.40	0.55	Good
5.2. The questions in the achievement test and quizzes are difficult and easy, suitable for the student's level.	4.20	0.45	Good

Table 4.4 (Cont.) Quality evaluation of an instructional package (Detail) (Number of experts, N= 5)

Assessment Items	Average	S.D.	Interpret
5.3. The number of questions in the achievement test and quizzes is appropriate.	4.20	0.45	Good
5.4. The nature of the question format is clear and simple to comprehend.	4.40	0.55	Good
Average	**4.30**	**0.50**	**Good**
Total average	**4.42**	**0.56**	**Good**

4.1.2 Results of E_1/E_2 for instructional package

The E_1/E_2 result for instructional package from 20 second year students majoring in Engineering Education was shown in Table 4-6 and Table 4-7 (the detail of E_1/E_2 analysis in Appendix D). The outcomes of the 20 students' quiz results, which were used to calculate the learning process efficiency, are shown in Table 4-6. The second-year students completed the experiments, three learning units of study, and quiz questions on the quiz sheets. There were 30 different quiz questions for the three learning units, and the efficiency of the learning process E_1 result for those units was 92.50%. There are also 30 different achievement test questions in total for the three learning units, and the E_2 score is 90.00%. This result shows that the E_1 is higher than E_2 because the students remember the lessons after studying them. E_1 is obtained from the quiz scores after each topic.

Table 4.5 Result of the efficiency of the quizzes and achievement test

Items	Number of Students	Number of Questions	Total score of questions	Total correct answers	E_1(%)	E_2(%)
Quizzes	20	30	600	555	92.5	
Achievement test	20	30	600	540		90

4.1.2 Results of the student's satisfaction form on instructional package

The student's satisfaction form on the instructional package consisted of evaluated topics with 15-point scale. According to the students' satisfaction, the average values and standard deviation results are displayed in Table 4-6 (the detail of satisfaction analysis in Appendix D). The results of the evaluated topics are calculated and interpreted. The following are the interpreted criteria:

4.51 – 5.00 means "Totally Satisfied"
3.51 – 4.5 means "Satisfied"
2.51 – 3.5 means "Unsure"
1.51 – 2.5 means "Unsatisfied"
1.00 – 1.5 means "Totally Unsatisfied"

Overall, the students satisfaction on the developed instructional package had an average value of 4.47 and a standard deviation of 0.66, indicating a satisfied level. As a result, it was discovered that using the developed instructional package to teach an active filter design course was beneficial. There are evaluated topics with 1,2,9,10-point scale receives the highest satisfaction because the students agree the instructional package is suitable for teaching and learning an active filter design. On other points (3, 4…8), such learning activities, time management, questions, etc., they receive less satisfaction. They receive less satisfaction because of the limited time and some difficult questions.

Table 4.6 Result of the student's satisfaction on instructional package (N=20)

No	Evaluated topics	Average	S.D.	Interpret
1	The content of the instructional package is correct.	4.70	0.47	Totally satisfied
2	The content of the instructional package is consistent with the teaching objectives.	4.80	0.41	Totally satisfied
3	The content is difficult and easy, suitable for the student's level.	4.20	0.83	Satisfied
4	The language used in the instructional package is appropriate.	4.20	0.89	Satisfied
5	The clarity of the figures, tables, or graphs on the instructional package is appropriate.	4.45	0.60	Satisfied
6	The order of the experimental steps in the laboratory sheets is appropriate.	4.55	0.69	Totally Satisfied
7	Learning activities make it easier for students to comprehend the subject matter.	4.55	0.60	Totally Satisfied
8	Learning activities are fun and promote learning analog filter design.	4.50	0.61	Satisfied
9	The use of the experimental set is easy and safe.	4.80	0.41	Totally satisfied
10	The experimental procedures are described in detail and clearly.	4.65	0.59	Totally satisfied
11	The experimental set helps students improve their understanding of analog filter design.	4.60	0.60	Satisfied
12	The time spent on learning activities is appropriate.	3.85	1.18	Satisfied
13	Learning with an instructional package makes students like to learn analog filter.	4.40	0.68	Satisfied
14	Students have better analog filter design skills.	4.40	0.68	Satisfied
15	The questions in the achievement test and quizzes are difficult and easy, suitable for the student's level	4.45	0.69	Satisfied
Total average		**4.47**	**0.66**	**Satisfied**

CHAPTER 5

CONCLUSION

The objectives of the research for engineering aspect are 1) to synthesize and design multifunction filters using a commercially available IC, LT1228, 2) to analyze the performance of the proposed multifunction filters, 3) to investigate the performance of the proposed multifunction filters through PSpice simulation and experiment. In this research, the researcher constructed the electronically controllable five proposed filters. The simulated, theoretical, and experimental results for five proposed filters were described.

The objectives of the research for education aspect are 4) to develop the instructional package on the active filter design, 5) to investigate the effectiveness of the instructional package on active filter design, 6) to evaluate the students' satisfaction with studying the active filter design through the instructional package. In this research, the researcher constructed the development of instructional package on an analog active filter design course for Engineering Education students. The population was 20 second year students at King Mongkut's Institute of Technology Ladkrabang (KMITL). The data were collected, compared, and analyzed by using real student groups. The following section provides details on the conclusion of this research, discussion, and future work:

5.1 Conclusion

From the engineering aspect, it can be clearly seen that the five proposed filters operate under the theoretical facts according to their simulated and experimental results. The five proposed filters are more beneficial than other proposed filters from literature review. Firstly, they can provide electronically controlled which is easily controlled by microcontroller or microcomputer. Second, the constant passband gains during tuning the natural frequency and the quality factor for all responses of the five proposed filters (except filter 4) is achieved. Third, filter 3 and filter 4 can provide linearly and electronically controlled. Fourth, some of their output nodes can cascade with other voltage-mode circuits without the need for additional buffers. Finally, some proposed filters only require two or more commercially accessible integrated circuits, it is simple structure than the filters requiring multiple ICs.

In this study, basic concept of LT1228, first-order multifunction filter using a single LT1228 and second-order multifunction filter utilizing three LT1228s were selected as the topics for developing an active filter design course using the MIAP learning model. An active filter design course quality was determined to be at a very good level (average 4.42 and S. D. 0.56), according to the results of a five experts' evaluation. The efficiency of the E_1/E_2 course in analog filter design is 92.50/90.00, exceeding the required level for E_1/E_2 (80/80). This indicates that the designed analog filter design course effectively enhanced the student's learning outcomes.

The average student satisfaction score was 4.47, with a standard deviation of 0.66. Thus, it can be said that the instruction package created has good quality to use in the teaching of an active filter design course. Additionally, this study could tackle the research hypothesis. In conclusion, the created instruction package can be effectively used in the teaching of an active filter design course, and it helps in increasing the students' enjoyment of learning.

5.2 Discussion

The experimental results showed that the proposed circuits match the theoretical and simulation results. Moreover, they have advantages over other circuits. The five proposed filters are compared with other filters using different ABBs in Table 5.1. The literature review revealed that the research's findings are as follows:

Some ABBs (VD-DIBA, VDCC, VDDDA, EX-CCCII, DDCCTA) requiring two or more commercially available ICs have been reported in [14-21]. With no use of grounded capacitors in some ABBs were published in [1,5,13,16,20,22,23]. Some proposed filters require additional buffers to cascade with their output nodes because they do not have low output impedance in [1,5-12,21,23,24]. Both the natural frequency (ω_0) and quality factor (Q) of the proposed filters in [1-9] cannot be offered electronic controllability, while the ω_0 and Q of the proposed filters in [1,12,15,19-23] cannot be offered independent controllability.

The study's findings showed that the instructional package's mix of theoretical and practical knowledge, as well as the use of the MIAP learning model, increased the learning process and student accomplishment. The review and data analysis revealed that the research's findings can be divided into the following sections:

(1) The instructional package's quality was cross-checked with IOC results between behavioral objectives and quizzes by 5 experts. The findings revealed that the IOC results of three study themes required the elimination of two items with IOC values less than 0.5. Only one eliminated question is utilized in the quizzes, although these questions are adjusted based on expert evaluation to be consistent with the behavioral objectives. The remaining questions with IOC values greater than 0.5 are acceptable and correspond to behavioral objectives.

(2) Five experts used the IOC values between behavioral objectives and achievement test to evaluate the instructional package's excellence. According to the findings, eight questions with IOC values less than 0.5 from three study topics need to be eliminated. Four eliminated questions remain on the quizzes sheet, but it modified the expert's evaluation and behavioral objectives. The remaining questions with an IOC value higher than 0.5 are good to use and match behavioral objectives.

(3) The quality of the instructional package was evaluated by five experts. The result of evaluated topic for 1) lesson plan based on the MIAP learning model has an average value of 4.47 and S.D value of 0.57, it means a good level. For the result of 2) laboratory sheets (Average =4.52, S.D.= 0.52), it means a very good level. 3) power points (average value of 4.20 and S.D. value of 0.68), it means a good level. For the result of 4) experimental set (average = 4.63, S.D.= 0.51), it means a very good level and 5) achievement test and quizzes sheet (average = 4.30, S.D.= 0.50), it means a good level. The result showed that the quality of the teaching package was of a good level (total average = 4.42, S.D. = 0.56).

(4) The efficiency of an analog filter design course E_1/E_2 is 92.50/90.00, which is higher than the standard criteria of E_1/E_2 80/80. It is obvious that E_1 is higher than E_2 because the students remember the lessons after studying it. E_1 is obtained from the quiz scores after each topic. This result suggests that the designed analog filter design course was

able to improve the students' learning outcomes.

(5) The creation of an instructional package based on the MIAP learning model to enhance students' learning outcomes in an active filter design. The satisfactions of the students were focused on learning activities, instructional packaging, teaching, and learning management in a laboratory. The students' satisfaction was 4.47 on average, with a standard deviation of 0.66, and this active filter design with the MAIP learning model has a satisfied level and may be utilized effectively in teaching engineering subjects, making studying more interesting for the students. According to the student satisfaction form, many students report that it is more convenient to complete the experimental work when more time is spent on learning activities.

TABLE 5.1 Comparison of the five proposed filters and other filters using different ABBs.

a	b	c	d	e	f	g	h	i	j	k
[1]	FTFN	1	2	MISO	X	LP, BP, HP, BR, AP	0	X	X	√
[2]	CFOA	3	3	MIMO	√	LP, HP, BP	3	X	√	√
[3]	CFOA	3	3	SIMO	√	LP, BP, BR	3	X	√	√
[4]	CFOA	3	3	MIMO	√	LP, BP, HP, BR	3	X	√	√
[5]	CCII	2	3	MISO	X	LP, BP, HP, BR, AP	0	X	√	√
[6]	CCII	4	4	SIMO	√	LP, BP, HP, BR, AP	0	X	√	√
[7]	DDCC	3	3	MISO	√	LP, BP, HP, BR, AP	0	X	√	√
	DDCC	3	3	SIMO	√	LP, BP, HP, BR, AP	0	X	√	√
[8]	DDCC (Fig 4(b))	4	NA	SIMO	√	LP, BP, HP	0	X	√	√
[9]	FDCCII DDCC	1 1	1 1	SIMO	√	LP, BP, HP, BR, AP	0	X	√	√
	FDCCII DDCC	1 1	1 1	MISO	√	LP, BP, HP, BR, AP	0	X	√	√
[10]	OTA	5	5	MIMO	√	LP, BP, HP, BR, AP	0	√	√	√
[11]	OTA	6	6	MISO	√	LP, BP, HP, BR, AP	0	√	√	√
[12]	OTA	8	8	SIMO	√	LP, BP, HP, BR, AP	0	√	X	√

Table 5.1 (Cont.) Comparison of the five proposed filters and other filters using different ABBs

a	b	c	d	e	f	g	h	i	j	k
[13]	VDBA	2	2	MISO	X	LP, BP, HP, BR, AP	1	√	√	√
[14]	VD-DIBA	2	4	MIMO	√	LP, BP, HP, BR, AP	2	√	√	√
	VD-DIBA	2	4	SIMO	√	LP, BP, HP, BR	2	√	√	√
[15]	VD-DIBA	2	4	MISO	√	LP, BP, HP, BR, AP	1	√	X	√
[16]	VDCC	1	4	MISO	X	LP, BP, HP, BR, AP	1	√	√	√
[17]	VDDDA	2	4	MISO	√	LP, BP, HP, BR, AP	1	√	√	√
[18]	VDDDA	2	4	SIMO	√	LP, BP, HP, BR, AP	2	√	√	√
[19]	VDDDA	2	4	MISO	√	LP, BP, HP, BR, AP	1	√	X	√
[20]	EX-CCCII	1	5	MISO	X	LP, BP, HP, BR, AP	1	√	X	√
[21]	DDCCTA	1	3	MIMO	√	LP, BP, HP	0	√	X	√
	DDCCTA	1	3	MIMO	√	LP, BP, HP, BR, AP	0	√	X	√
	DDCCTA	1	3	SIMO	√	LP, BP, HP, BR, AP	0	√	X	√
[22]	LT1228	1	1	MISO	X	LP, BP, AP	1	√	X	√
[23]	LT1228	1	1	MISO	X	LP, BP, HP, BR, AP	0	√	X	√
[24]	LT1228	1	1	MISO	√	LP, BP, HP, BR, AP	0	√	√	√
Filter 1	LT1228	2	2	SIMO	√	LP, BP, HP	2	√	X	√
Filter 2	LT1228	2	2	SIMO	√	LP, BP, HP	2	√	√	√
Filter 3	LT1228	3	3	SIMO	√	LP, BP, HP	2	√	√	√
Filter 4	LT1228	3	3	SIMO	√	LP, BP, HP, BR	2	√	√	√
Filter 5	LT1228	2	2	MISO	√	LP, HP, BP, BR, AP	5	√	√	√

a = Ref; b = ABB; c = No. of ABBs; d = No. of Commercial ICs; e = Filtering category;

f = use of grounded capacitors; g = filtering function; h = No. of low output impedance; i = Electronic tune both f_0 and Q; j = Independent tune of Q without disturbing of f_0; k = Independent tune of Q without disturbing of f_0; l = Experimental results

Note: Reference of the number system [1] (Ranjan et al. 2019), [2] (Wang et al. 2021: 13330-13343), [3] (Wang et al. 2020: 6681), [4] (Wang et al. 2019: 2304), [5] (Yucel et al. 2020: 153138), [6] (Horng and Chiu, 2016: 577-582), [7] (Lee, 2017: 71-81), [8] (Khateb et al. 2017: 631-637), [9] (Lee, 2016:1006-1019), [10] (Wang et al. 2020: 1493), [11] (Kumngern et al. 2019: 1950078), [12] (Kumngern et al. 2013: 1118-1133), [13] (Roongmuanpha et al. 2021: 9606), [14] (Jaikla et al. 2021: 153601), [15] (Ninsraku et al. 2014: 1239-1246), [16] (Roy et al. 2021: 146-160), [17] (Jaikla et al. 2021: 1683), [18] (Huaihongthong et al. 2019: 13-23), [19] (Sangyaem et al. 2017: 14-25), [20] (Agrawal and Maheshwari, 2020: 1127-1151), [21] (Chen et al. 2016: 1403-1411), [22] (Jaikla et al. 2021:7376), [23] Wang et al. 2019: 2349), [24] (Siripongdee and Jaikla, 2017:14002), [25] (Klungtong et al. 2017:5240751).

5.3 Future work

In the future, the next step we will construct the SIMO universal filters that can provide five filtering responses, orthogonally and require fewer ICs with passive components. From education aspect, we will take to construct time management, quizzes and achievement test might be modified. Additionally, some more sophisticated, and affective technologies for example AI or IOT technologies might be integrated into the classroom and laboratory at King Mongkut's Institute of Technology Ladkrabang (KMITL) to enhance the learning outcomes of the students.

REFERENCES

Agrawal, D., and Maheshwari, S. (2020) High-Performance Electronically Tunable Analog Filter Using a Single EX-CCCII. **Circuits, Systems, and Signal Processing**, 40(3), 1127-1151.

Allen, M. (2012 September 26). Re: Leaving ADDIE for SAM: A Conversation with Authors. [SlideShare]. Retrieved from: http://www.slideshare.net/alleninteractions/leaving-addie-for-sam

Benjamaha J., and Uantrai, P. (2021). Active Learning Management based on MIAP Learning Model to Enhance Electronic Technician Competence.2021 6th International STEM Education Conference (iSTEM-Ed). 1-4.

Branch, Robert. (2009). Instructional design: The ADDIE approach. Springer New York Dordrecht Heidelberg London

Bichelmeyer, B. A. (2005). The ADDIE model — A metaphor for the lack of clarity in the field of IDT. IDT Record. Retrieved March 25, 2012, from www.unco.edu/cetl/sir/clt/documents/IDTf_Bic.pdf

CA3080, 2MHz, Operational Transconductance Amplifier (OTA). Intersil, [Online], available:https://pdf1.alldatasheet.com/datasheetpdf/view/66315/INTERSIL/CA3080.html

Chai T. C. & Cheevapruk. S. (November 2014). A Development of Electronic Media for 336269 Logistics I. **In Proceedings of 2nd International Conference on Technical Education**, 19-23.

Chen, H.P.; Yang, W.S. (2017) Electronically Tunable Current Controlled Current Conveyor Transconductance Amplifier-Based Mixed-Mode Biquadratic Filter with Resistorless and Grounded Capacitors. **Applied Sciences**, 7, 244.

REFERENCES (CONT.)

Chutchavong, Vanvisa & Muantoei, Tapakorn & Janchitrapongvej, Kanok. (2014). A new method for design of the three-way crossover networks. 1-5.

Chen, H.-P., Hwang, Y.-S., Ku, Y.-T. and Lin, T.-J. (2016) Voltage-Mode Biquadratic Filters Using Single DDCCTA. **AEÜ—International Journal of Electronics and Communications**, 70(10), 1403-1411.

Chumchuen, N., Klinbumrung, K., and Meesomklin, S. (2020). Professional Teaching Practice Through MIAP based Integrated Learning Activities for Electrical Engineering Education. **2020 5th International STEM Education Conference (iSTEM-Ed)**, 95-98.

Dogan, M.; & Yuce, E. A new CFOA based grounded capacitance multiplier. **AEU International Journal of Electronics and Communications. 2020**, 115, 153034.

Hank, Z. (2008) Linear Circuit Design Handbook. **Elsevier**

Hess, A.K.N. & Greer, Katie. (2016). Designing for Engagement: Using the ADDIE Model to Integrate High-Impact Practices into an Online Information Literacy Course. **Communications in Information Literacy**, 264-282.

Horng, J. W., Chiu, and W.Y. (2016) High input impedance voltage-mode biquad with one input and five outputs employing four CCII ICs. **Indian Journal of Pure & Applied Physics**, 54, 577-582.

Huaihongthong, P. Chaichana, A. Suwanjan, P. Siripongdee, S. Sunthonkanokpong, W. Supavarasuwat, P., et al. (2019) Single-Input Multiple-Output Voltage-Mode Shadow Filter Based on VDDDAs. **AEÜ—International Journal of Electronics and Communications,** 103, 13-23.

REFERENCES (CONT.)

Huang, S. T., Cho Y. P., and Lin, Y. J. (2005). ADDIE Instruction Design and Cognitive Apprenticeship for Project-based Software Engineering Education in MIS. **In Proceedings of 12th Asia-Pacific Software Engineering Conference (APSEC'05)**, 95-102.

Hoi, Tran & Long, Hoang & Duong, Bach. (2013). Low noise block downconverter design for satellite receiver system Vinasat 1 operating at C-band. **Proceedings of the 2013 IEICE International Conference on Intergrated Circuits, Design, and Verification**. 110-115.

Jaikla, W., Buakhong, U., Siripongdee, S., Khateb, F., Sotner, R., Silapan, P., and Chaichana, A. (2021). Single Commercially Available IC-Based Electronically Controllable Voltage-Mode First-Order Multifunction Filter with Complete Standard Functions and Low Output Impedance. **Sensors**, 21(21), 7376.

Jaikla, W., Khateb, F., Kulej, T., and Pitaksuttayaprot, K. (2021) Universal filter based on compact CMOS structure of VDDDA. **Sensors,** 21(5), 1683.

Jaikla, W., Siripongdee, S., Khateb, F., Sotner, R., Silapan, P., Suwanjan, P., and Chaichana, A. (2020) Synthesis of biquad filters using two VD-DIBAs with independent control of quality factor and natural frequency. **AEU - International Journal of Electronics and Communications,**

Jaikla, W., Adhan, S.; Suwanjan, P.; Kumngern, M. (2020) Current/voltage controlled quadrature sinusoidal oscillators for phase sensitive detection using commercially available IC. **Sensors 2020**, 20, 1319.

Jaikla, W. et al. (2021). Single Commercially Available IC-Based Electronically Controllable Voltage-Mode First-Order Multifunction Filter with Complete Standard Functions and Low Output Impedance. Sensors. 21. 7376.

REFERENCES (CONT.)

Koseeyaporn J. (2008), Engineering Electronics, Bangkok, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang.

Kumngern, M., Suksaibul, P., and F. Khateb, F. (2019) Four-Input One-Output Voltage-Mode Universal Filter Using Simple OTAs. **Journal of Circuits, Systems, and Computers**, 28(5), 1950078.

Khateb, F., Jaikla, W., Kulej, Kumngern, M., and Kubánek, D. (2017) Shadow Filters Based on DDCC. **IET Circuits, Devices, and System,** 11(6), 631-637.

Klungtong, S., Thanapatay, D., and Jaikla, W. (2017) Three-Input Single-Output Voltage-Mode Multifunction Filter with Electronic Controllability Based on Single Commercially Available IC. **Active and Passive Electronic Components,** 2017, 5240751.

Kumngern, M., Suwanjan, P., and Dejhan, K. (2013) Electronically Tunable Voltage-Mode Universal Filter with Single-InputFive-Output Using Simple OTAs. **International Journal of Electronics,** 100(8), 1118-1133.

Kaewsai et al. (2013) Teaching Model for Competency Improvement of Deaf People on the Industrial Job. The Asian Conference on Education 2013. The International Academic Forum (iafor). Osaka, Japan, 1-11.

Lee, C.N. (2017) Independently tunable plus-type DDCC-based voltage-mode universal biquad filter with MISO and SIMO types. **Microelectronics Journal,** 67, 71-81.

Lee, C. N. (2016) Independently Tunable Mixed-Mode Universal Biquad Filter with Versatile Input/Output Functions. **AEU—International Journal of Electronics and Communications,** 70(8), 1006-1019.

REFERENCES (CONT.)

LT1228 "100MHz Current Feedback Amplifier with DC Gain Control" Linear Technology Corporation, [Online]. Available: http://cds.linear.com/docs/en/datasheet/1228fd.pdf

LM13600 Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers National Semiconductor, [Online], available: https://www.ti.com/lit/ds/symlink/lm13700.pdf

LM13700 Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers National Semiconductor, [Online], available: https://vakits.com/sites/default/files/LM13600.pdf

Latour, A.D, Cibiel, G, Dantepal, J, Dutrey, Jean-François, Brunet, M, Ries, Lionel & Issler, Jean-Luc. (2005). Dual frequency absolute calibration of GPS receiver for time transfer.

Maheshwari, S., & Ansari, M.S. (2012) Catalog of Realizations for DXCCII using Commercially Available ICs and Applications. **Radioengineering** 21, 281–289.

Molenda, M. (2003). In search of the elusive ADDIE model. **Performance Improvement**, 44(3), 55–63.

Merrill, M.D., Drake, L., Lacy, M.J., & Pratt, J., & ID2_Research_Group. (1966) Reclaiming Instructional Design. **Educational Technology**, 36, 5-7.

Ninsraku, W. Biolek, D. Jaikla, W. Siripongdee, S., and P. Suwanjan, P. (2014) Electronically Controlled High Input and Low Output Impedance Voltage Mode Multifunction Filter with Grounded Capacitors. **AEÜ—International Journal of Electronics and Communications,** 68(12), 1239-1246.

REFERENCES (CONT.)

Olmez, S. & Çam, Uğur. (2009). A novel square root domain lossless integrator and its application to KHN biquad filter design. **ELECO 2009 - 6th International Conference on Electrical and Electronics Engineering**, 1-5.

Oliveira, L. B., Paulino N., & Pereira, N. (2014). The design of a light barrier system as an undergraduate laboratory project, **2014 IEEE International Symposium on Circuits and Systems (ISCAS)**, 2014, 2425-2428.

Peterson, C. (2003). Bringing ADDIE to Life: Instructional Design at Its Best. **Journal of Educational Multimedia and Hypermedia**, 12(3), 227-241.

Promchan. S. (2011). Didactic for Technical Education. Bangkok: KMUTNB TextbookPublishing Center.

Promme, P. (2010), Principle of Analog Filter, Bangkok, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang.

Promchan. S. (2011). Didactic for Technical Education. Bangkok: KMUTNB Textbook Publishing Center.

Roy, S., Paul, T. K., Maiti, S., and Pal, R. R. (2021) Voltage Differencing Current Conveyor Based Voltage-Mode and Current-Mode Universal Biquad Filters with Electronic Tuning Facility. **International Journal of Engineering and Technology Innovation**.11(2), 146-160.

Rattanaphinyowanich T. (2021) The development of an instructional package the life skills of higher education students.

Ranjan, A., Perumalla, S., Kumar, R., John, V., and Yumnam, S. (2019) Second Order Universal Filter Using Four Terminal Floating Nullor (FTFN). **Journal of Circuits, Systems and Computers**, 28, 1-15.

REFERENCES (CONT.)

Roongmuanpha, N. Pukkalanun, T., and Tangsrirat, W. (2021) Practical realization of electronically adjustable universal filter using commercially available IC-based VDBA. **Engineering Review**, 41, 76-85.

Riecker, T. (2012 November 23). Re: The Death of ADDIE? Retrieved from: https://timothyriecker.com/2012/11/23/the-death-of-addie/ comment-page-1/

Safari, L., Yuce, E., Minaei, S. (2017) A new ICCII based resistor-less current-mode first-order universal filter with electronic tuning capability. **Microelectronic Journal**, 67, 101–10.

Sangyaem, S. Siripongdee, S., Jaikla, W., and Khateb, F. (2017) Five-Input Single-Output Voltage Mode Universal Filter with High Input and Low Output Impedance Using VDDDAs. **Optik,** 128, 14-25.

Sedra, A.S., and Smith, K.C. Microelectronic Circuits. 3rd ed. Floida: Holt, Rinehart, and Winston, 1991.

Senani, R.; Bhaskar, D.R.; Kumar, P. (2021) Two-CFOA-Grounded-Capacitor First-order All-pass Filter Configurations with Ideally Infinite Input Impedance. **AEU - International Journal of Electronics and Communications**, 137, 153742.

Sathiya. P., Prachyanun. N., and Jarumon. J. (2021). Effects of AL-MIAP-based Learning Management to Promote Digital Intelligence for Undergraduate. **Multidisciplinary Journal for Education Social and Technological Sciences.** 8, 13-29.

Siripongdee, S., & Jaikla, W. (2017). Universal Filter Using Single Commercially Available IC: LT1228.

REFERENCES (CONT.)

Sites, R. (2012). Re: Its an ICE Time to Leave ADDIE Behind [Web log comment]. Retrieved from http://info.alleninteractions.com/bid/86482/It-s-an-ICE-Time-to-Leave-ADDIE-Behind.

Sirisukpaiboon. S. (2011). Techniques and methods of vocational teaching. Bangkok: KMUTNB Textbook Publishing Center.

Solis John D. (2007). Robert A. Reiser, and John V. Dempsey, Trends and Issues in Instructional Design and Technology (2nd Edition).

Thede, L.D. (2004). Practical Analog and Digital Filter Design.

Taylor, R. (2015). Second-Order Allpass Filters for Phase Alignment, [Online]. https://faculty.tru.ca/rtaylor/publications/allpass2_align.pdf

Van Valkenburg, M. E. (1982). Analog Filter Design: Oxford University Press.

Vejvodová, J. (2009). The ADDIE Model: Dead or Alive. In 10th International Conference Virtual University Retrieved from http://virtuni.eas.sk/rocnik/2009/pdf/paper_127.pdf

Wang, S.-F., Chen, H.-P., Ku, Y., & Zhong, M. X. (2021) Analytical Synthesis of High-Pass, Band-Pass and Low-Pass Biquadratic Filters and its Quadrature Oscillator Application Using Current-Feedback Operational Amplifiers. **IEEE Access**, 9, 13330-13343.

Wang, S.-F., Chen, H.-P., Ku, Y., & Zhong, M. X. (2020) Voltage-mode multifunction biquad filter and its application as fully-uncoupled quadrature oscillator based on current-feedback operational amplifiers. **Sensors**, 20(22), 6681.

REFERENCES (CONT.)

Wang, S.-F., Chen, H.-P., Ku, Y., & P.-Y. Chen, (2019) A CFOA-based voltage-mode multifunction biquadratic filter and a quadrature oscillator using the CFOA-based biquadratic filter", **Applied Sciences**, 9(11), 2304.

Wang, S.-F., Chen, H.-P., Ku, Y., & Lin, Y.-C. (2019) Versatile tunable voltage-mode biquadratic filter and its application in quadrature oscillator. **Sensors,** vol. 19(10), 2349.

Wang, S.-F.; Chen, H.-P.; Ku, Y.; Yang, C.-M. (2019) Independently tunable voltage-mode OTA-C biquadratic filter with five inputs and three outputs and its fully-uncoupled quadrature sinusoidal oscillator application. **AEU - International Journal of Electronics and Communications**, 110, 152822.

Watson, Russell (October 1981). Instructional System Development. International Congress for Individualized Instruction. **EDRS publication ED**, 209-239.

Williams, A. (2014 October 30) RE: Comparison of ADDIE. [Web log comment]. Retrieved from: http://amwilliams.wikispaces.com/

Yucel, F., & Yuce, E. (2020) Supplementary CCII based second-order universal filter and quadrature oscillators. **AEU - International Journal of Electronics and Communications**, 118, 153138.

Yuce, E.; & Minaei, S. (2017) Commercially Available Active Device Based Grounded Inductor Simulator and Universal Filter with Improved Low Frequency Performances. **Journal of Circuits Systems and Computers**, 26, 1750052.

APPENDIX

Appendix A: List of Experts

Appendix B: Assessment form

Appendix C: Lesson plan

Appendix D: Data Analysis

APPENDIX A

There were five experts for evaluating the quality of the analog active filter design course. They are:

Expert (1)

Name	- Dr. Danupat Duangmalai
Academic Position	- Assistant Professor
Department	- Department of Electronics, Faculty of Industrial Technology
University	- Nakhon Phanom University

Expert (2)

Name	- Dr. Amornchai Chaichana
Academic Position	- Associate Professor
Department	- Department of Engineering Education, School of Industrial Education and Technology
University	- King Mongkut's Institute of Technology Ladkrabang, (KMITL)

Expert (3)

Name	– Dr Adirek Jantakun
Academic Position	- Assistant Professor
Department	- Department of Electrical and Computer Engineering, Faculty of Engineering
University	- Rajamangala University of Technology Isan, Khon Kaen Campus

Expert (4)

Name	- Dr. Montree Kumngern
Academic Position	- Associate Professor
Department	- Department of Telecommunications Engineering, School of Engineering
University	- King Mongkut's Institute of Technology Ladkrabang, (KMITL)

Expert (5)

Name	- Dr. Chaiyan Chanapromma
Academic Position	- Assistant Professor
Department	- Department of Electrical Engineering, Faculty of Industrial Technology
University	- Uttaradit Rajabhat University, Muang Uttaradit, Thailand

Appendix B

B-1 Quality Evaluation Form on Analog filter design Course by experts

Assessment Items	5	4	3	2	1
1.Lesson plan based on the MIAP learning model					
1.1. Behavioral objectives are clear.					
1.2. The time spent on each activity is appropriate to the level of the student.					
1.3. The sorting of activities is appropriate.					
1.4. Teaching activities are consistent with the behavioral objectives.					
1.5. Teaching media are consistent with behavioral objectives.					
1.6. Learning activities develop the students' self-. learning and problem-solving skills.					
2. Laboratory sheets					
2.1. The content of the laboratory sheets is correct					
2.2. The content of the laboratory sheets is consistent with the teaching 5objectives.					
2.3. The content of the laboratory sheets is difficult and easy, suitable for the student's level.					
2.4. The language used in the laboratory sheets is appropriate.					
2.5. The clarity of the figures, tables, or graphs on the laboratory sheets is appropriate.					
2.6. The order of the experimental steps in the laboratory sheets is appropriate.					
2.7. The experimental procedures in the laboratory sheets are described in detail and clearly.					
3. PowerPoints					
3.1. The content of the PowerPoints is correct, interesting, and appropriate.					
3.2. The content of the PowerPoints is consistent with the teaching objectives.					
3.3. The content of the PowerPoints is difficult and easy, suitable for the student's level.					
3.4. The font colors and font sizes on the PowerPoints are appropriate.					

3.5. The clarity of the figures, tables, or graphs on the PowerPoints is appropriate.					
3.6. The content of the PowerPoints encourages learning.					
4. Experimental set					
4.1. The color and size of the experimental set are appropriate.					
4.2. The font colors and font sizes on the experimental set are appropriate.					
4.3. The placement of the devices on the experimental set is appropriate.					
4.4. The position of the devices on the experimental set makes it convenient to conduct experiments.					
4.5. The use of the experimental set is easy and safe.					
4.6. The ease of transport and storage of the experimental set is appropriate.					
5. Achievement Test and quizzes					
5.1. The questions in the achievement test and quizzes are consistent with the teaching objectives.					
5.2. The questions in the achievement test and quizzes are difficult and easy, suitable for the student's level.					
5.3. The number of questions in the achievement test and quizzes is appropriate.					
5.4. The nature of the question format is clear and simple to comprehend.					

B-2 Students Satisfaction Form on Analog filter design Course

No	Evaluated topics	5	4	3	2	1
1	The content of the instructional package is correct.					
2	The content of the instructional package is consistent with the teaching objectives.					
3	The content is difficult and easy, suitable for the student's level.					
4	The language used in the instructional package is appropriate.					
5	The clarity of the figures, tables, or graphs on the instructional package is appropriate.					
6	The order of the experimental steps in the laboratory sheets is appropriate.					
7	Learning activities make it easier for students to comprehend the subject matter.					
8	Learning activities are fun and promote learning analog filter design.					
9	The use of the experimental set is easy and safe.					
10	The experimental procedures are described in detail and clearly.					
11	The experimental set helps students improve their understanding of analog filter design.					
12	The time spent on learning activities is appropriate.					
13	Learning with an instructional package makes students like to learn analog filter.					
14	Students have better analog filter design skills.					
15	The questions in the achievement test and quizzes are difficult and easy, suitable for the student's level					

Appendix C

Basic concepts of LT1228

1. Evaluation form of Behavioral Objectives and Quizzes
2. Evaluation form of Behavioral Objectives and Achievement test
3. Experimental Set
4. Teacher manual
   - 4.1 Lesson Plan
   - 4.2 Power point
   - 4.3 Lab sheet
   - 4.4 Quizzes sheet (solution)
   - 4.5 Achievement test (solution)
5. Coding

C-1 Evaluation form of Behavioral Objectives and Quizzes

	Field of Study: Engineering Education **Title: Basic concept of LT1228** **Class: Second Year**	**IOC value**

Behavioral Objectives	**Quizzes**	**Consideration score**		
		+1	**0**	**-1**
	Questions 1 to 15 Choose the correct letter, a, b, c, or d. Circle the correct answer.			
	1. Which of the following functions can perform LT1228? **a)** Operational amplifier (Op-amp) and current feedback amplifier (CFA) **b)** Operational transconductance amplifier (OTA) and current follower **c)** Operational transconductance amplifier (OTA) and current feedback amplifier (CFA) **d)** Operational amplifier (Op-amp) and current follower			
1. Describes the basic features of LT1228.	2. Which terminals of OTA have high impedances, so the currents flow into these two terminals are zero? **a)** Non-inverting and inverting terminals **b)** *x* and *y* terminals **c)** Non-inverting and *y* terminals **d)** *x* and *w* terminals			
	3. In ideal OTA part of LT1228, the current at *y* terminal is as follows: **a)** $I_y = g_m(V_- - V_+)$ **b)** $I_y = g_m(V_+ - V_-)$ **c)** $I_y = g_m V_-$ **d)** $I_y = g_m V_+$			
	4. In ideal current feedback amplifier (CFA) part of LT1228, which terminals possess the same amount of voltage? **a)** *x* and *w* terminals **b)** *x* and *y* terminals **c)** *w* and *y* terminals			

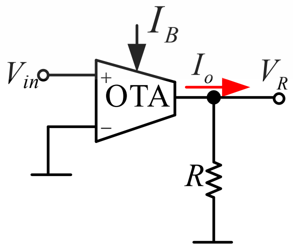
	d) *x* and *z* terminals			
	5. In ideal CFA part of LT1228, its output voltage can be seen as **a)** $V_w = I_x R_T$ **b)** $V_w = I_x R_w$ **c)** $V_w = I_y R_T$ **d)** $V_w = I_y R_w$			
	6. Which terminals of LT1228 possess high impedance output current and high impedance input voltages? **a)** x, V_+ and V_- terminals **b)** w, V_+ and y terminals **c)** x, V_+ and y terminals **d)** y, V_+ and V_- terminals			
	7. The *x* and *w* terminals possess **a)** low-impedance voltage output terminals **b)** low-impedance current output terminals **c)** low-impedance voltage input terminals **d)** high-impedance voltage output terminals			
	8. The transconductance, g_m is obtained by **a)** $g_m = \frac{I_B}{2V_T}$ **b)** $g_m = 10I_B$ **c)** $g_m = \frac{I_B}{10}$ **d)** $g_m = \frac{2I_B}{V_T}$			
1. Calculate the parameters of LT1228.	9. Determine the OTA voltage gain when R = 1kΩ and I_B = 50uA?  			

Fig. 1

a) 0.5
b) 1.5
c) 2.5
d) 3.5

10. Determine the CFA voltage gain for when R_f = 1kΩ and R_1 =5kΩ.

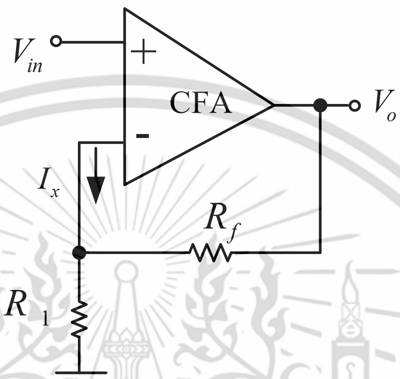


Fig. 2

a) 4.2
b) 3.2
c) 1.2
d) 0.2

11. The input voltage is 50mV$_{p\text{-}p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 300uA in Fig. 3?

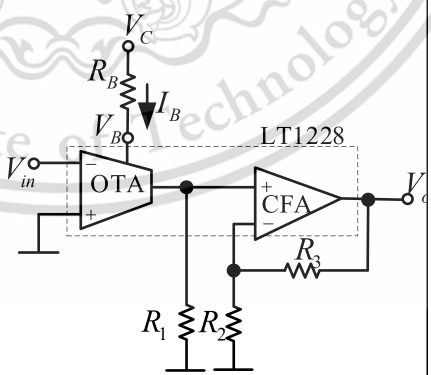
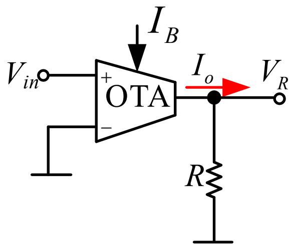
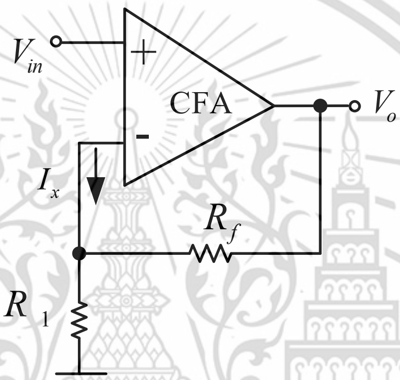
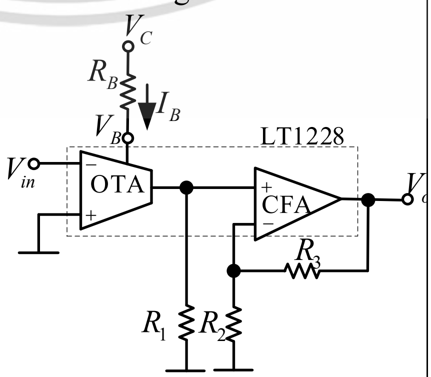


Fig. 3

a) -5
b) -6
c) -7
d) -8

12. Design the OTA voltage gain of 9 when I_B = 123.5μA in Fig. 1.

2. Design the parameters of the voltage amplifier using LT1228.	 Fig. 1 **a)** $R = 7.3\text{k}\Omega$ **b)** $R = 6.8\text{k}\Omega$ **c)** $R = 5.6\text{k}\Omega$ **d)** $R = 4.7\text{k}\Omega$			
	13. Design the CFA voltage gain of 5 when R_f =1kΩ in Fig. 2.  Fig. 2 **a)** R_1 =2kΩ **b)** R_1 =3.5kΩ **c)** R_1 =0.25kΩ **d)** R_1 =5.2kΩ			
	14. Design the voltage gain amplifier using LT1228 to provide gain of -5 with external DC bias current is 100uA**.** The input voltage is 50mV$_{p\text{-}p}$, and R_3 = 1kΩ and R_2 =1kΩ. Determine R_1 in Fig. 3**.**  Fig. 3			

	a) R_1 =2.5kΩ **b)** R_1 =3.5kΩ **c)** R_1 =4.5kΩ **d)** R_1 =5.5kΩ			
	15. Design the voltage gain amplifier using LT1228 to provide gain of -5. The input voltage is 50mV_{p-p}, and R_1 = 1kΩ and R_2 =1kΩ and R_3 = 1kΩ. Determine the external DC bias current in Fig. 3. **a)** I_B =300μA **b)** I_B =567μA **c)** I_B =166.67μA **d)** I_B =250μA			

C-2 Evaluation form of Behavioral Objectives and Achievement test

	Field of Study: Engineering Education **Title: Basic concept of LT1228** **Class: Second Year**	**IOC value**

Behavioral Objectives	**Achievement Test**	**Consideration score**		
		+1	**0**	**-1**
	Questions 1 to 15 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.			
1. Describes the basic features of LT1228.	**1.** What is the transconductance equation for LT1228? a) $g_m = \frac{I_B}{2V_T}$ b) $g_m = \frac{2I_B}{V_T}$ c) $g_m = \frac{I_B}{10}$ d) $g_m = 10I_B$			
	2. Which terminals of OTA have high impedances, so the currents flow into these two terminals are zero? **a)** x and y terminals **b)** Non-inverting and y terminals **c)** Non-inverting and inverting terminals **d)** x and w terminals			
	3. In ideal OTA part of LT1228, the current at y terminal is as follows: **a)** $I_y = g_m V_+$ **b)** $I_y = g_m V_-$ **c)** $I_y = g_m (V_+ - V_-)$ **d)** $I_y = g_m (V_- - V_+)$			
	4. In ideal current feedback amplifier (CFA) part of LT1228, which terminals possess the same voltage value? a) x and y terminals b) x and z terminals c) x and w terminals d) w and y terminals			

	5. What is the input voltage signal of LT1228 to provide linear output voltage? **a)** below 50mV **b)** above 50mV **c)** less than or equal to 50mV **d)** approximately about 50mV			
	6. All the following statements show in which LT1228 can perform both functions. **a)** operational transconductance amplifier (OTA) and current feedback amplifier (CFA) **b)** operational amplifier (Op-amp) and current follower (CFA) **c)** operational transconductance amplifier (OTA) and voltage feedback amplifier (VFA) **d)** operational amplifier (Op-amp) and current feedback amplifier (CFA)			
	7. In ideal CFA part of LT1228, its output voltage can be seen as **a)** $V_w = I_y R_w$ **b)** $V_w = I_x R_w$ **c)** $V_w = I_x R_T$ **d)** $V_w = I_y R_T$			
	8. The *x* and *w* terminals possess **a)** low-impedance current output terminals **b)** low-impedance voltage input terminals **c)** high-impedance voltage output terminals **d)** low-impedance voltage output terminals			
	9. Determine the OTA voltage gain when R = 1kΩ and I_B = 185µA?			

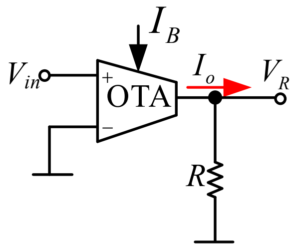
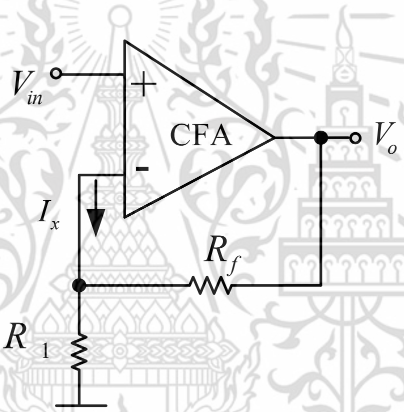
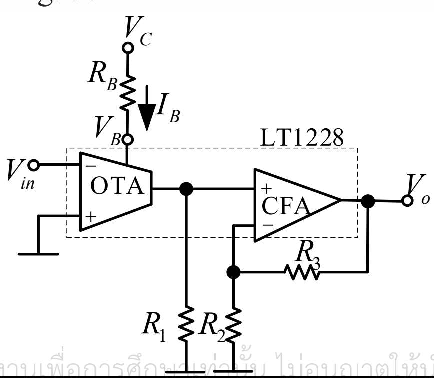
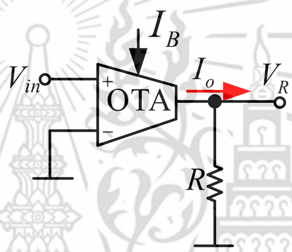
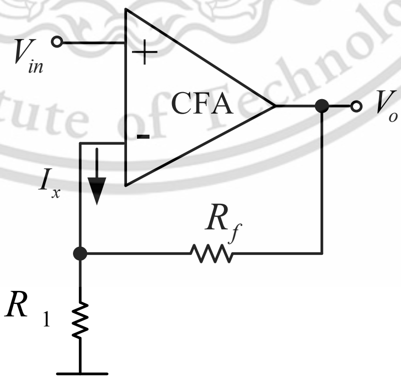
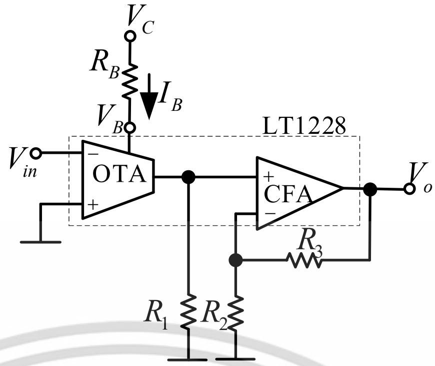
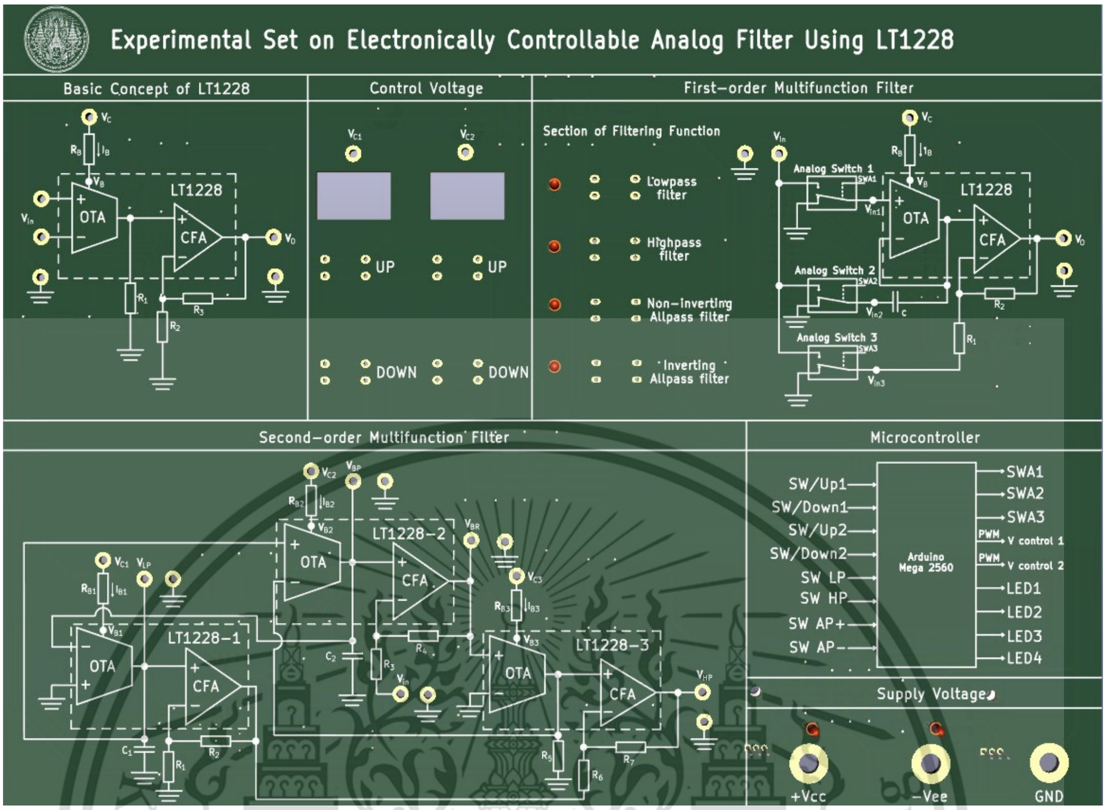
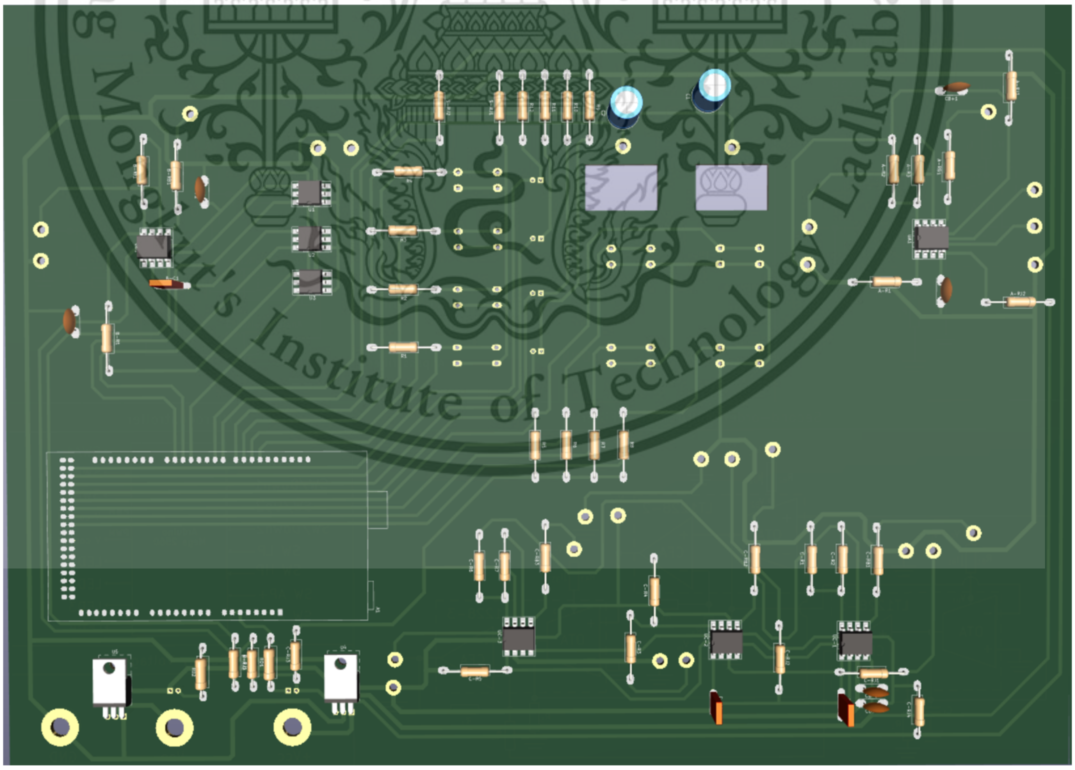
	 Fig. 1 **a)** 6.85 **b)** 7.85 **c)** 6.85 **d)** 1.85			
2. Calculate the parameters of LT1228.	10. Determine the CFA voltage gain for when R_f = 1kΩ and R_1 =2kΩ.  Fig. 2 **a)** 1.5 **b)** 2.5 **c)** 3.5 **d)** 4.5			
	11. The input voltage is $50mV_{p-p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 150µA in Fig. 3? 			

	Fig. 3 **a) -4** **b) -3** **c) -2** **d) -1**			
	12. The input voltage is $50mV_{p\text{-}p}$, the external DC bias current is 75μA and all resistors are 1kΩ. How much is its voltage gain in Fig. 3? **a)** -0.15 **b)** -0.3 **c)** -0.5 **d)** -1.5			
3. Design the parameters of voltage gain amplifier using LT1228.	13. Design the OTA voltage gain of 5 when I_B= 100μA in Fig. 1. Determine R in Fig. 1.  Fig. 1 **a)** R = 2kΩ **b)** R = 3kΩ **c)** R = 4kΩ **d)** R = 5kΩ			
	14. Design the CFA voltage gain of 4 when R_f=1.2kΩ in Fig. 2.  Fig. 2 **a)** R_1 = 0.2kΩ **b)** R_1 = 0.3kΩ **c)** R_1 = 0.4kΩ **d)** R_1 = 0.5kΩ			
	15. Design the voltage gain amplifier using LT1228 to provide gain of -2			

	with external DC bias current is 100uA. The input voltage is $50mV_{p\text{-}p}$, and R_3 = 1kΩ and R_2 =1kΩ. Determine R_1 in Fig. 3.  Fig. 3 **a)** R_1 = 1kΩ **b)** R_1 = 3.5kΩ **c)** R_1 = 4kΩ **d)** R_1 = 6.5kΩ				

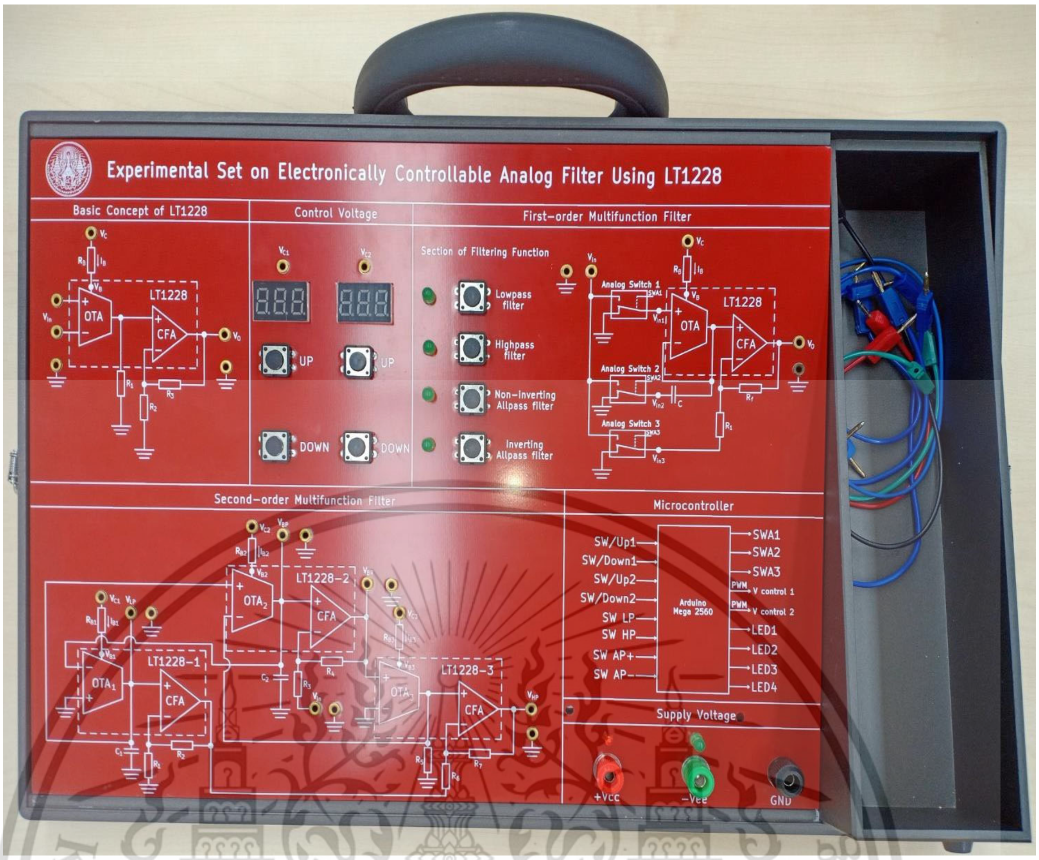
C-3 Experimental Set





PCB

Cover box



Picture of experimental set

C-4 Teacher manual

Teacher Manual

By

MS. May Phu Pwint Wai

Department of Engineering Education

Faculty of Industrial Education and Technology

King Mongkut's Institute of Technology Ladkrabang (KMITL)

62603017@kmitl.ac.th

C-4.1 Lesson Plan

Lesson Plan **Department of Engineering Education**

Title: (1) Basic Concept of LT1228

Class:

Date: ____________ **Time:** 120 min **Instructor:** ______________

I. Objectives

(a) Abilities: (new knowledge and skills)

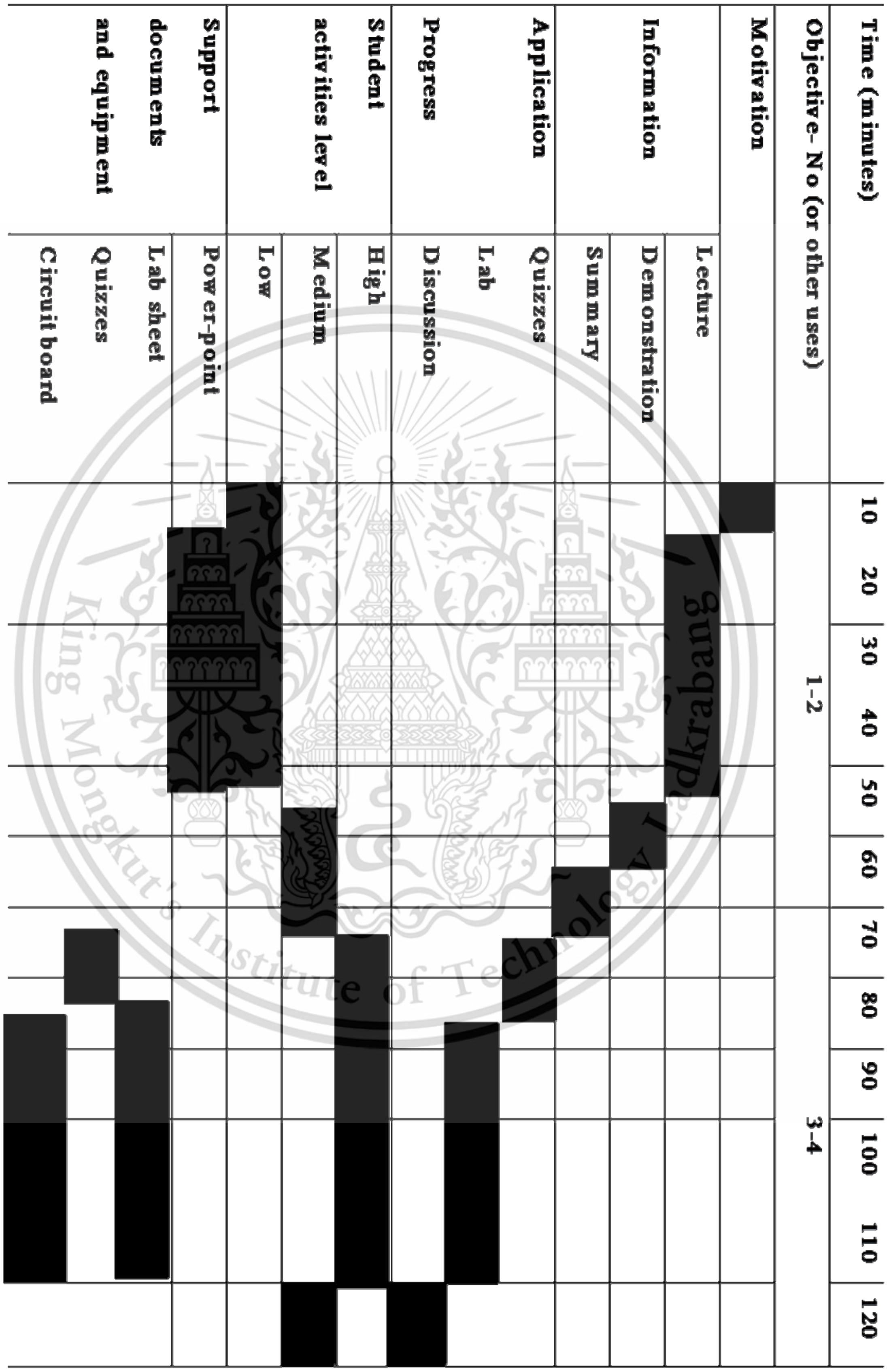
1. Describe the basic features of LT1228.
2. Calculate the parameters of the LT1228.
3. Design the voltage gain amplifier using LT1228.
4. Measure and test the voltage gain amplifier using LT1228.

II. Previous Knowledge and Skills: (students will apply future)

____

____

III. Performance



C-4.3 Lab sheet

	Field of Study: Engineering Education **Title**: **Basic concept of LT1228** **Class: Second year**	**Lab Sheet**

Objectives

1. Describe the basic features of LT1228.
2. Calculate the parameters of voltage amplifier using LT1228.
3. Design the parameters of voltage amplifier using LT1228.
4. Measure and test the parameters of voltage amplifier using LT1228.

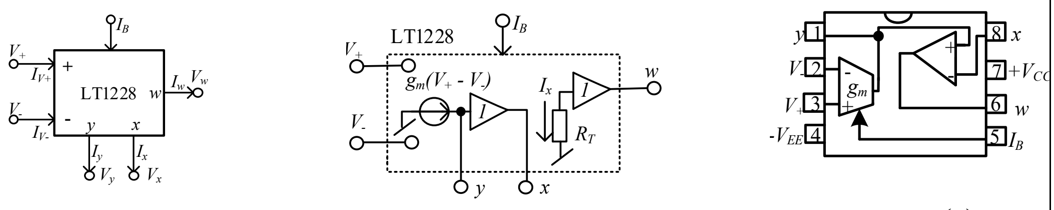
Tools & Equipment

1. Experimental Set on Electronically Controllable Analog Filter Using LT1228
2. Oscilloscope 1 piece
3. Voltage Supply 1 piece
4. Signal Generator 1 piece
5. Digital Multimeter 1 piece
6. Electrical wiring 1 piece

1. Preliminary theory

The LT1228 integrated circuit by Linear Technology (LT1228: Linear Technology, 2012) is one of the intriguing elements. It comprises two independent sub-elements: the operational transconductance amplifier (OTA), whose transconductance (g_m) can be electronically controlled by bias current and the CFA which can be used as voltage buffer or amplifier. The LT1228's OTA has a current source with high output impedance (Pin 1) and a differential voltage with high input impedance (Pin 2 and 3). Pins 4 and 7 are positive and negative supply voltages. The transconductance, g_m, is controlled by the current that flows into Pin 5, I_B. The CFA's non-inverting input is designed to drive the voltage terminals with low output impedance (Pin 6) to give excellent linearity at high frequencies. While the pin 8 is low inverting input voltage of CFA, the pin 1 is high input voltage of

CFA. The schematic symbol, equivalent circuit, and pin diagram of LT1228 are illustrated in Figures 1 (a), (b) and (c).



(a) (b) (c)

Figure 1 (a) schematic symbol (b) equivalent circuit (c) pin diagram of LT1228

$$
\begin{aligned}
&I_{v+} = I_{v-} = 0; \\
&I_y = g_m\left(V_+ - V_-\right); \\
&V_x = V_y; \\
&g_m = 10 I_B;
\end{aligned}
\qquad (1)
$$

2. Inverting voltage gain amplifier using LT1228

The voltage transfer function (TF) of the voltage gain amplifier using LT1228 in Fig. 2 is expressed as follows:

$$A_v = \frac{V_o}{V_{in}} = -g_m R_1\left(1 + \frac{R_3}{R_2}\right) \qquad (2)$$

Substitute $g_m = 10 I_B$ in Eq (4)

$$A_v = \frac{V_o}{V_{in}} = -10 I_B R_1\left(1 + \frac{R_3}{R_2}\right) \qquad (3)$$

From Eq (3), it is found that the gain can be electronically adjusted by the external Dc bias current. In practical, the control voltage V_C can be applied to adjust the current. The control voltage V_C is controlled by microcontroller or microcomputer. If the resistor R_B is connected to the bias voltage at the pin 5 of LT1228, V_B as shown in Fig. 2. The current equation can be written as the follows:

$$I_B = \frac{V_C - V_B}{R_B} \qquad (4)$$

where V_C = control voltage from microcontroller and $V_B \cong 4V$ when V_{EE} = -7V.

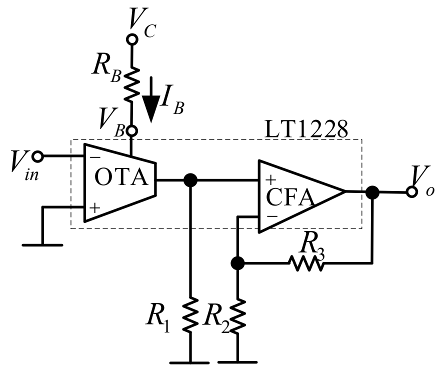


Figure 2 Inverting voltage gain amplifier using LT1228.

3. Non-Inverting voltage gain amplifier using LT1228

The voltage transfer function (TF) of the voltage gain amplifier using LT1228 in Fig. 3 is expressed as follows:

$$A_v = \frac{V_o}{V_{in}} = 10 I_B R_1 \left(1 + \frac{R_3}{R_2}\right) \tag{5}$$

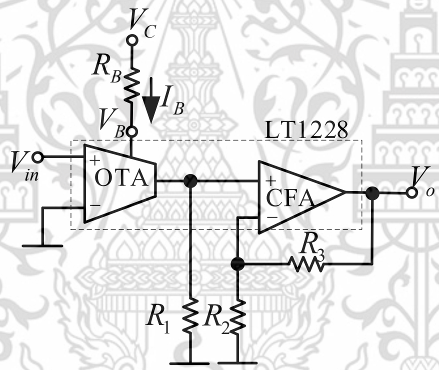


Figure 3 Non-inverting voltage gain amplifier using LT1228.

Experiment 1 Inverting voltage gain amplifier using LT1228

Experimental procedures

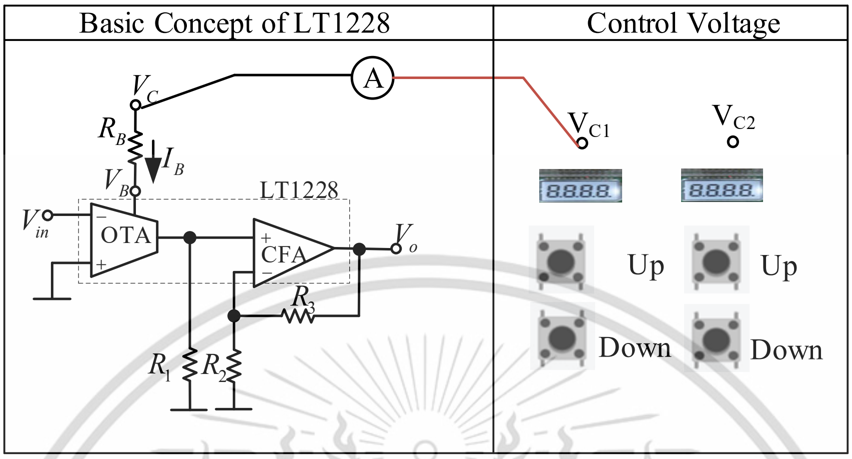
1.1.The power supply +7V, -7V, and ground is applied to the $+V_{CC}$, $-V_{EE}$ and GND on the circuit board.

1.2.An electrical wire is used to connect V_C from pin 5 of basic concept of LT1228 and V_{C1} from microcontroller. The experimental setup is made by applying the sinewave signal of

100mV$_{p\text{-}p}$ at the non-inverting input voltage (V_{in}) and the inverting input is connected to the ground. The probe line at the oscilloscope CH1 is measured to V_{in}, the probe line at the oscilloscope CH2 is measured to V_o.

1.3.Use an ammeter to measure the current at pin 5 and no press the UP or DOWN button (V_C = 0V) which flows the current I_B = _____ μA.

1.4.Use $R_1 = R_2 = R_3$ = 1kΩ and calculate the voltage gain from Eq (3). It will get A_v= ____.

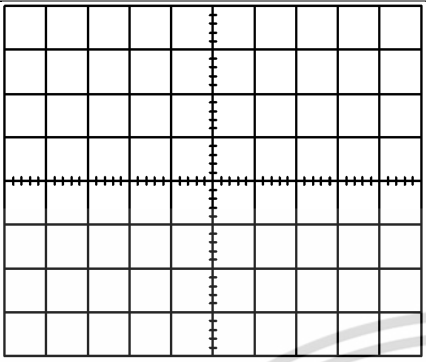


1.5.If the increased voltage gain is desired, it can be obtained by controlling the bias current I_B. According to Eq. (2), the I_B can be controlled via voltage (V_C) from the microcontroller. To get V_C = 0.5V, an up pushbutton is pressed one time. The multimeter is set to measure DC current in the appropriate range. Connect the red (positive) lead of the multimeter to the V_C from the microcontroller and the black (negative) lead of the multimeter to the resistor in pin 5 and then a multimeter is used to measure the current I_B = _____ μA.

1.6.Record the output voltage results of the experiment in the table that changes with the bias current I_B and record also the calculated the gain from Eq. (3).

V_C	I_B (μA)	V_o (measured)	V_o (calculated)	Gain (measured)	Gain (calculated)
0.5V					
1.5V					
3V					
4.5V					
5V					

1.7.The sinewave signal of 100mV$_{p-p}$ at the input voltage (V_{in}) and f_0 = 10kHz is applied to the input of the filter circuit. Then the measured input voltage V_{in} and the output voltage V_o node from the oscilloscope into Fig. 4.

	CH1 VOLTS/DIV = ____ TIME/DIV= _______ $V_{P\text{-}P}$ = _______ f = _______ CH2 VOLTS/DIV = _____TIME/DIV = _______ $V_{P\text{-}P}$ = _______ f = _______ Gain (measured) = _______

Experiment 2 Non-inverting voltage gain amplifier using LT1228

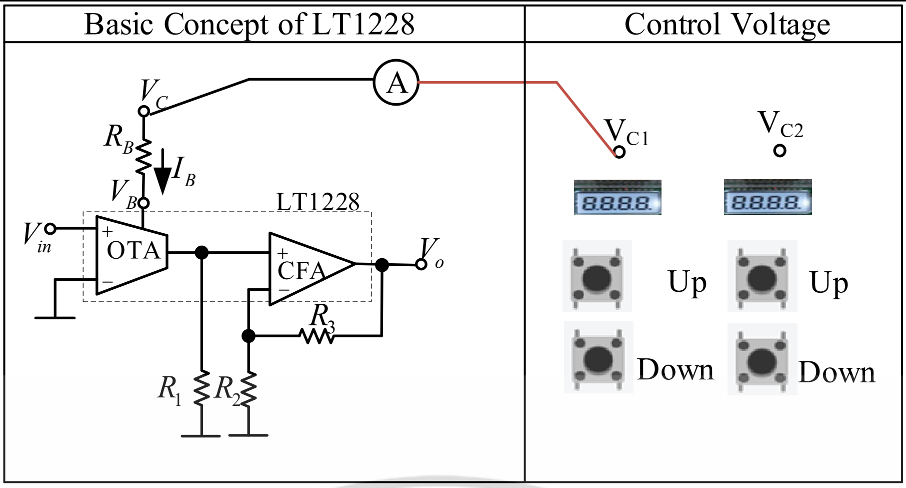
Experimental procedures

2.1.The power supply +7V, -7V, and ground is applied to the $+V_{CC}$, $-V_{EE}$ and GND on the circuit board.

2.2.An electrical wire is used to connect V_C from pin 5 of basic concept of LT1228 and V_{C1} from microcontroller. The experimental setup is made by applying the sinewave signal of 100m$V_{p\text{-}p}$ at the non-inverting input voltage (V_{in}) and the inverting input is connected to the ground. The probe line at the oscilloscope CH1 is measured to V_{in}, the probe line at the oscilloscope CH2 is measured to V_o.

2.3.Use an ammeter to measure the current at pin 5 and no press the UP or DOWN button (V_C = 0V) which flows the current I_B = _____ µA.

2.4.Use $R_1 = R_2 = R_3$ = 1kΩ and calculate the voltage gain from Eq (3). It will get A_v= ____.

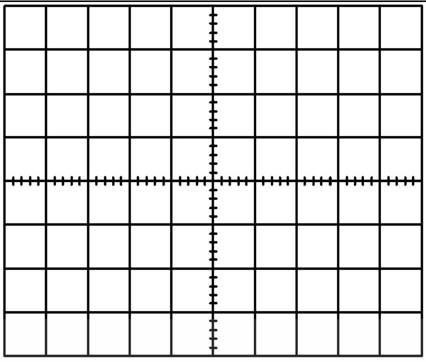


2.5. If the increased voltage gain is desired, it can be obtained by controlling the bias current I_B. According to Eq. (2), the I_B can be controlled via voltage (V_C) from the microcontroller. To get V_C = 0.5V, an up pushbutton is pressed one time. The multimeter is set to measure DC current in the appropriate range. Connect the red (positive) lead of the multimeter to the V_C from the microcontroller and the black (negative) lead of the multimeter to the resistor in pin 5 and then a multimeter is used to measure the current I_B = ______ μA.

2.6. Record the output voltage results of the experiment in the table that changes with the bias current I_B and record also the calculated the gain from Eq. (5).

V_C	I_B (μA)	V_o (measured)	V_o (calculated)	Gain (measured)	Gain (calculated)
0.5V					
1.5V					
3V					
4.5V					
5V					

2.7. The sinewave signal of $100mV_{p\text{-}p}$ at the input voltage (V_{in}) and f_0 = 10kHz is applied to the input of the filter circuit. Then the measured input voltage V_{in} and the output voltage V_o node from the oscilloscope into Fig. 4.

	CH1 VOLTS/DIV = ___ TIME/DIV= _______ V_{P-P} = _______ f = _______ CH2 VOLTS/DIV = _____TIME/DIV = _______ V_{P-P} = _______ f = _______ Gain (measured) = _______

C-4.4 Lab sheet (Solution)

	Field of Study: Engineering Education **Title: Basic concept of LT1228** **Class: Second year**	**Lab Sheet**

Objectives

5. Describe the basic features of LT1228.
6. Calculate the parameters of voltage amplifier using LT1228.
7. Design the parameters of voltage amplifier using LT1228.
8. Measure and test the parameters of voltage amplifier using LT1228.

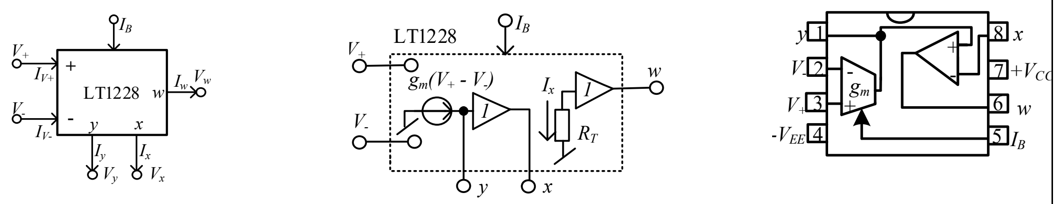
Tools & Equipment

7. Experimental Set on Electronically Controllable Analog Filter Using LT1228
8. Oscilloscope 1 piece
9. Voltage Supply 1 piece
10. Signal Generator 1 piece
11. Digital Multimeter 1 piece
12. Electrical wiring 1 piece

4. Preliminary theory

The LT1228 integrated circuit by Linear Technology (LT1228: Linear Technology, 2012) is one of the intriguing elements. It comprises two independent sub-elements: the operational transconductance amplifier (OTA), whose transconductance (g_m) can be electronically controlled by bias current and the CFA which can be used as voltage buffer or amplifier. The LT1228's OTA has a current source with high output impedance (Pin 1) and a differential voltage with high input impedance (Pin 2 and 3). Pins 4 and 7 are positive and negative supply voltages. The transconductance, g_m, is controlled by the current that flows into Pin 5, I_B. The CFA's non-inverting input is designed to drive the voltage terminals with low output impedance (Pin 6) to give excellent linearity at high frequencies. While the pin 8 is low inverting input voltage of CFA, the pin 1 is high input voltage of

CFA. The schematic symbol, equivalent circuit, and pin diagram of LT1228 are illustrated in Figures 1 (a), (b) and (c).



(a) (b) (c)

Figure 1 (a) schematic symbol (b) equivalent circuit (c) pin diagram of LT1228

$$\begin{aligned} I_{v+} &= I_{v-} = 0; \\ I_y &= g_m\left(V_+ - V_-\right); \\ V_x &= V_y; \\ g_m &= 10I_B; \end{aligned} \qquad (1)$$

5. Inverting voltage gain amplifier using LT1228

The voltage transfer function (TF) of the voltage gain amplifier using LT1228 in Fig. 2 is expressed as follows:

$$A_v = \frac{V_o}{V_{in}} = -g_m R_1\left(1 + \frac{R_3}{R_2}\right) \qquad (2)$$

Substitute $g_m = 10I_B$ in Eq (4)

$$A_v = \frac{V_o}{V_{in}} = -10 I_B R_1\left(1 + \frac{R_3}{R_2}\right) \qquad (3)$$

From Eq (3), it is found that the gain can be electronically adjusted by the external Dc bias current. In practical, the control voltage V_C can be applied to adjust the current. The control voltage V_C is controlled by microcontroller or microcomputer. If the resistor R_B is connected to the bias voltage at the pin 5 of LT1228, V_B as shown in Fig. 2. The current equation can be written as the follows:

$$I_B = \frac{V_C - V_B}{R_B} \qquad (4)$$

where V_C = control voltage from microcontroller and $V_B \cong 4V$ when V_{EE} = -7V.

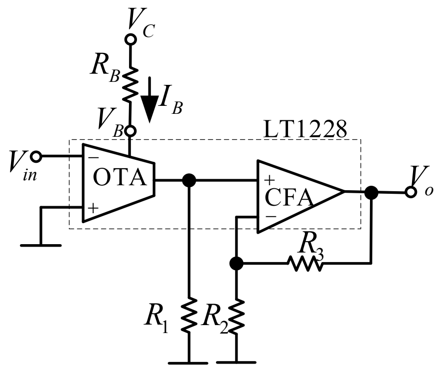


Figure 2 Inverting voltage gain amplifier using LT1228.

6. Non-Inverting voltage gain amplifier using LT1228

The voltage transfer function (TF) of the voltage gain amplifier using LT1228 in Fig. 3 is expressed as follows:

$$A_v = \frac{V_o}{V_{in}} = 10 I_B R_1 \left(1 + \frac{R_3}{R_2}\right) \quad (5)$$

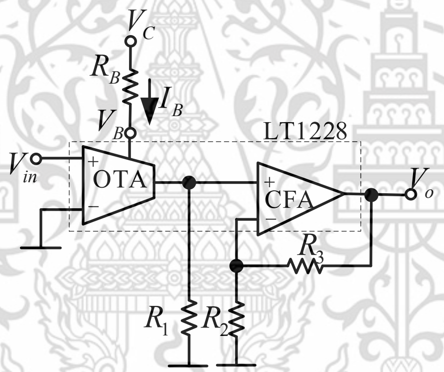


Figure 3 Non-inverting voltage gain amplifier using LT1228.

Experiment 1 Inverting voltage gain amplifier using LT1228

Experimental procedures

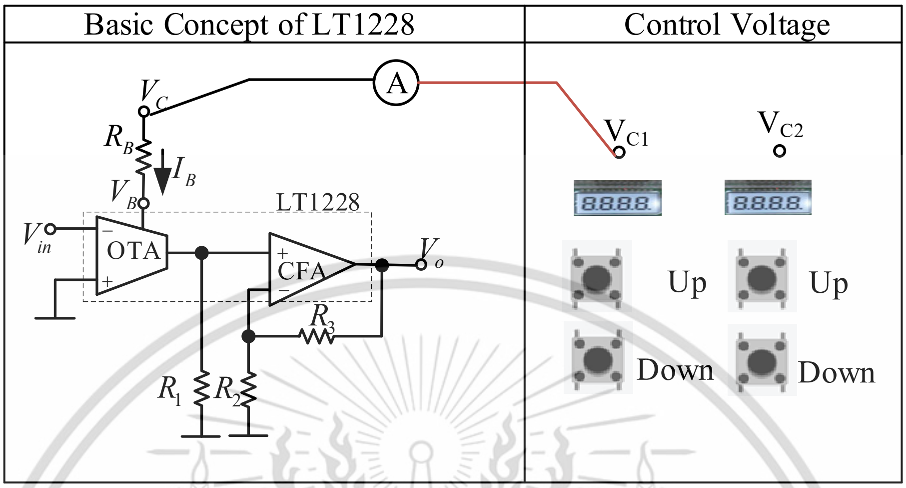
1.1. The power supply +7V, -7V, and ground is applied to the $+V_{CC}$, $-V_{EE}$ and GND on the circuit board.

1.2. An electrical wire is used to connect V_C from pin 5 of basic concept of LT1228 and V_{C1} from microcontroller. The experimental setup is made by applying the sinewave signal of

100mV$_{p\text{-}p}$ at the non-inverting input voltage (V_{in}) and the inverting input is connected to the ground. The probe line at the oscilloscope CH1 is measured to V_{in}, the probe line at the oscilloscope CH2 is measured to V_o.

1.3. Use an ammeter to measure the current at pin 5 and no press the UP or DOWN button (V_C = 0V) which flows the current I_B = 123μA.

1.4.Use $R_1 = R_2 = R_3$ = 1kΩ and calculate the voltage gain from Eq (3). It will get A_v= -2.5.

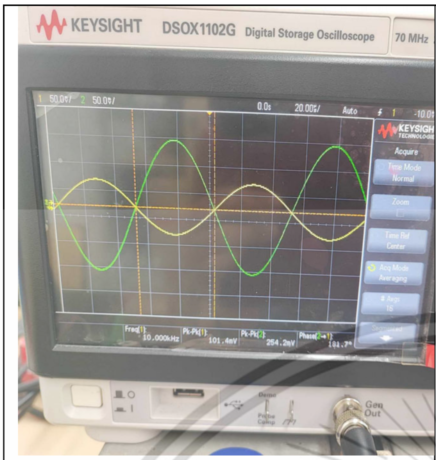


1.5.If the increased voltage gain is desired, it can be obtained by controlling the bias current I_B. According to Eq. (2), the I_B can be controlled via voltage (V_C) from the microcontroller. To get V_C = 0.5V, an up pushbutton is pressed one time. The multimeter is set to measure DC current in the appropriate range. Connect the red (positive) lead of the multimeter to the V_C from the microcontroller and the black (negative) lead of the multimeter to the resistor in pin 5 and then a multimeter is used to measure the current I_B = 130 μA.

1.6.Record the output voltage results of the experiment in the table that changes with the bias current I_B and record also the calculated the gain from Eq. (3).

V_C	I_B (μA)	V_o (measured)	V_o (calculated)	Gain (measured)	Gain (calculated)
0.5V	130	-290mV	-260mV	-2.90	-2.60
1.5V	170	-350 mV	-340mV	-3.50	-3.40
3V	210	-443mV	-420mV	-4.43	-4.20
4.5V	260	-504mV	-520mV	-5.04	-5.20
5V	280	-510mV	-560mV	-5.10	-5.60

1.7.The sinewave signal of 100m$V_{p\text{-}p}$ at the input voltage (V_{in}) and f_0 = 10kHz is applied to the input of the filter circuit. Then the measured input voltage V_{in} and the output voltage V_o node from the oscilloscope into Fig. 4.

	CH1 VOLTS/DIV = 50mV TIME/DIV = 20µs V_{P-P} = 101.4mV f = 10kHz CH2 VOLTS/DIV = 50mV TIME/DIV = 20µs V_{P-P} = -254.2mV f = 10kHz Gain (measured) = -2.5

Experiment 2 Non-inverting voltage gain amplifier using LT1228

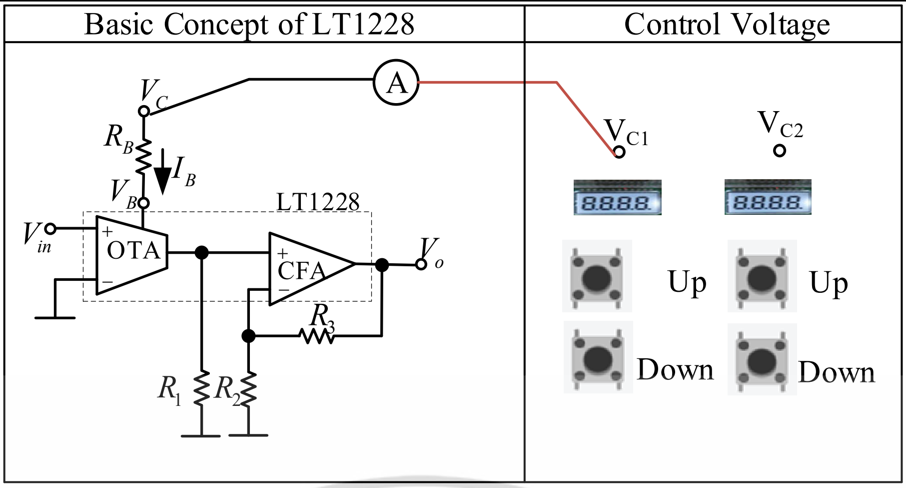
Experimental procedures

2.1. The power supply +7V, -7V, and ground is applied to the $+V_{CC}$, $-V_{EE}$ and GND on the circuit board.

2.2. An electrical wire is used to connect V_C from pin 5 of basic concept of LT1228 and V_{C1} from microcontroller. The experimental setup is made by applying the sinewave signal of 100mV_{p-p} at the non-inverting input voltage (V_{in}) and the inverting input is connected to the ground. The probe line at the oscilloscope CH1 is measured to V_{in}, the probe line at the oscilloscope CH2 is measured to V_o.

2.3. Use an ammeter to measure the current at pin 5 and no press the UP or DOWN button (V_C = 0V) which flows the current I_B = 123µA.

2.4. Use $R_1 = R_2 = R_3$ = 1kΩ and calculate the voltage gain from Eq (3). It will get A_v= 2.5.

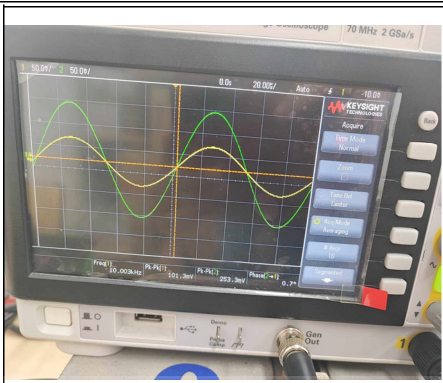


2.5.If the increased voltage gain is desired, it can be obtained by controlling the bias current I_B. According to Eq. (2), the I_B can be controlled via voltage (V_C) from the microcontroller. To get V_C = 0.5V, an up pushbutton is pressed one time. The multimeter is set to measure DC current in the appropriate range. Connect the red (positive) lead of the multimeter to the V_C from the microcontroller and the black (negative) lead of the multimeter to the resistor in pin 5 and then a multimeter is used to measure the current I_B = 130μA .

2.6.Record the output voltage results of the experiment in the table that changes with the bias current I_B and record also the calculated the gain from Eq. (5).

V_C	I_B (μA)	V_o (measured)	V_o (calculated)	Gain (measured)	Gain (calculated)
0.5V	130	290mV	260mV	2.90	2.60
1.5V	170	350 mV	340mV	3.50	3.40
3V	210	443mV	420mV	4.43	4.20
4.5V	260	504mV	520mV	5.04	5.20
5V	280	510mV	560mV	5.10	5.60

2.7.The sinewave signal of $100mV_{p\text{-}p}$ at the input voltage (V_{in}) and f_0 = 10kHz is applied to the input of the filter circuit. Then the measured input voltage V_{in} and the output voltage V_o node from the oscilloscope into Fig. 4.

	CH1 VOLTS/DIV = 50mV TIME/DIV = 20μs V_{P-P} = 101.4mV f = 10kHz CH2 VOLTS/DIV = 50mV TIME/DIV = 20μs V_{P-P} = 254.2mV f = 10kHz Gain (measured) = 2.5

C-4.5 Quizzes sheet (Solution)

	Field of Study: Engineering Education **Title: Basic concept of LT1228** **Class: Second Year**	**Quizzes sheet**

Questions 1 to 10

Choose the correct letter, a, b, c, or d. Circle the correct answer.

1. Which of the following functions can perform LT1228?
   - **a)** Operational amplifier (Op-amp) and current feedback amplifier (CFA)
   - **b)** Operational transconductance amplifier (OTA) and current follower
   - **c)** Operational transconductance amplifier (OTA) and current feedback amplifier (CFA)
   - **d)** Operational amplifier (Op-amp) and current follower

2. In ideal OTA part of LT1228, the current at *y* terminal is as follows:
   - **a)** $I_y = g_m(V_- - V_+)$
   - **b)** $I_y = g_m(V_+ - V_-)$
   - **c)** $I_y = g_m V_-$
   - **d)** $I_y = g_m V_+$

3. In ideal CFA part of LT1228, its output voltage can be seen as
   - **a)** $V_w = I_x R_T$
   - **b)** $V_w = I_x R_w$
   - **c)** $V_w = I_y R_T$
   - **d)** $V_w = I_y R_w$

4. The transconductance, g_m is obtained by
   - **a)** $g_m = \frac{I_B}{2V_T}$
   - **b)** $g_m = 10I_B$

c) $g_m = \frac{I_B}{10}$

d) $g_m = \frac{2I_B}{V_T}$

5. Determine the OTA voltage gain when R = 1kΩ and I_B = 50uA?

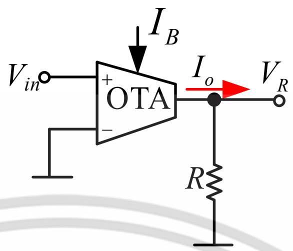


Fig. 1

a) 0.5

b) 1.5

c) 2.5

d) 3.5

6. Determine the CFA voltage gain for when R_f = 1kΩ and R_1 =5kΩ.

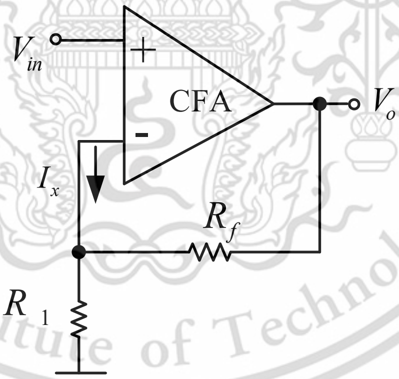


Fig. 2

a) 4.2

b) 3.2

c) 1.2

d) 0.2

7.The input voltage is $50mV_{p-p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 300uA in Fig. 3?

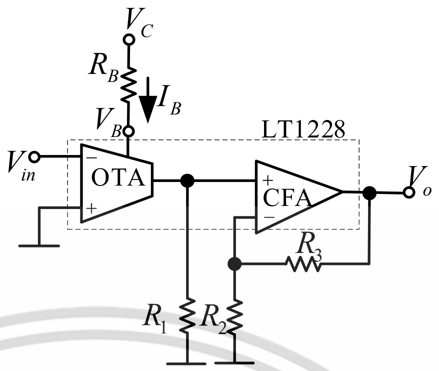


Fig. 3

a) -5

b) -6

c) -7

d) -8

8. Design the OTA voltage gain of 9 when I_B = 123.5μA in Fig. 1.

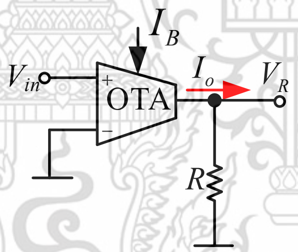


Fig. 1

a) R = 7.3kΩ

b) R = 6.8kΩ

c) R = 5.6kΩ

d) R = 4.7kΩ

9. Design the CFA voltage gain of 5 when R_f =1kΩ in Fig. 2.

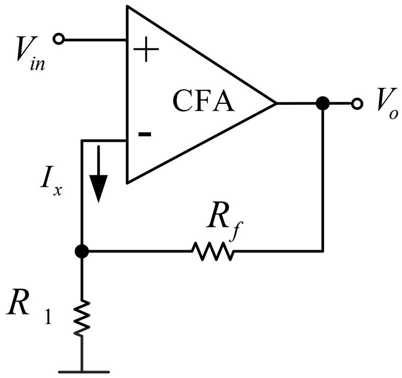


Fig. 2

a) R_1 =5.2kΩ

b) R_1 =3.5kΩ

c) R_1 =2.2kΩ

d) R_1 =0.25kΩ

10. Design the voltage gain amplifier using LT1228 to provide gain of -5 with external DC bias current is 100uA. The input voltage is 50mV_{p-p}, and R_3 = 1kΩ and R_2 =1kΩ. Determine R_1 in Fig. 3.

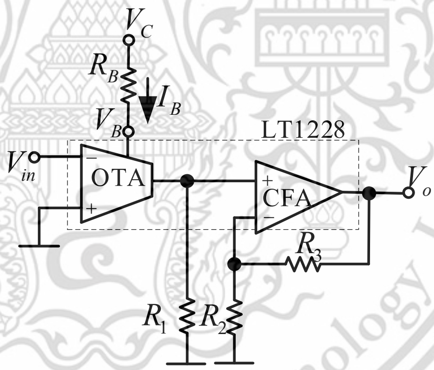


Fig. 3

a) R_1 =2.5kΩ

b) R_1 =3.5kΩ

c) R_1 =4.5kΩ

d) R_1 =5.5kΩ

	Field of Study: Engineering Education **Title**: **First order multifunction filter using single LT1228** **Class: Second Year**	**Quizzes sheet**

Questions 1 to 10 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.
1. The point at which the response drops –3 dB from the passband is called **a)** Cutoff frequency **b)** Natural frequency **c)** Center frequency **d)** All the above
2. Which filter rejects the low frequency and passes the high frequency. **a)** Low-pass filter **b)** High pass filter **c)** All-pass filter **d)** Band-stop filter
3. Which statements agree with the output and input voltages are equal in amplitude for all frequencies? **a)** High pass filter **b)** Band-pass filter **c)** All-pass filter **d)** Band-stop filter
4. The input voltage is $50\text{mV}_{p\text{-}p}$, all resistors are 1kΩ and the external DC bias current is 60µA and capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 4 is as follows: $$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$ Determine i. the natural frequency, f_0

ii. the passband gain

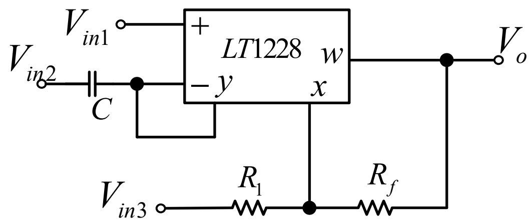


Fig. 4

a) f_0 = 20kHz, passband gain = 1

b) f_0 = 30kHz, passband gain = 1.5

c) f_0 = 47.7kHz, passband gain = 2

d) f_0 = 50kHz, passband gain = 2.5

5. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right)(\because V_{in2}=V_{in})$$

Determine the high pass phase response at f = 50kHz.

a) 33°

b) 63°

c) 93°

d) 103°

6. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order non-inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}}(\because V_{in2}=V_{in3}=V_{in})$$

Determine the non-inverting AP phase response at f = 500kHz.

a) 42°

b) 52°

c) 62°

d) 22º

7. Design the first order multifunction filter using single LT1228 to provide passband gain 1.5, the natural frequency, f_0 = 40kHz, the input voltage is 50m$V_{p\text{-}p}$, R_f =1kΩ, and capacitor C = 2nF in Fig. 1. The first order low pass voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$

Determine

i. the external DC bias currents

ii. the value of R_1

a) I_B =162µA, and R_1 =3kΩ

b) I_B =50µA, and R_1 =2kΩ

c) I_B =123µA and R_1 =1kΩ

d) I_B =62µA and R_1 =1kΩ

8. Design the first order multifunction filter using single LT1228 when the input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF in Fig. 4. The first order high pass voltage gain equation in Fig. 1 is as follows:

$$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right) (\because V_{in2} = V_{in})$$

Determine the external DC bias current at f_0 = 80 kHz.

a) 25uA

b) 70uA

c) 125uA

d) 100uA

9. Design the first order multifunction filter using single LT1228 when the input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order non-inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{s - \frac{g_m}{C}}{s + \frac{g_m}{C}} (\because V_{in2} = V_{in3} = V_{in})$$

Determine the frequency to provide its non-inverting AP phase response is 135º.

a) 40kHz

b) 90kHz

c) 100kHz

d) 110kHz

10. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{-\left(s - \frac{g_m}{C}\right)}{s + \frac{g_m}{C}} (\because V_{in1} = V_{in3} = V_{in})$$

Determine the frequency to provide its inverting AP phase response is -90º.

a) 118kHz

b) 98 kHz

c) 108kHz

d) 88kHz

	Field of Study: Engineering Education **Title: Second order multifunction filter using three LT1228s** **Class: Second Year**	**Quizzes sheet**

Questions 1 to 10 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.

1. The transfer function of second order low pass function is

$$\frac{V_{LP}}{V_{in}} = \frac{\dfrac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \dfrac{2g_{m2}g_{m3}R_5}{C_2}s + \dfrac{g_{m1}g_{m2}}{C_1C_2}}$$

. What is the natural frequency for second order low pass function?

a) $\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$

b) $\omega_0 = \frac{g_{m1}g_{m2}}{C_1C_2}$

c) $\omega_0 = \frac{g_{m1}}{C_2}$

d) $\omega_0 = \frac{g_{m2}}{C_1}$

2. In band pass filter, the BW and Q relationship is

a) $BW = \frac{f_0}{Q}$

b) $f_0 = \frac{BW}{Q}$

c) $BW = \frac{Q}{f_0}$

d) $BW = f_0 \times Q$

3. Which statements describe the formula for the center frequency of band pass filter?

a) $f_0 = \frac{f_H + f_L}{2}$

b) $f_0 = \sqrt{f_H * f_L}$

c) $f_0 = \sqrt{f_H^2 + f_L^2}$

d) $f_0 = \sqrt{f_H - f_L}$

4. The input voltage is $50\text{mV}_{p\text{-}p}$, all resistors are 1kΩ, $I_{B1} = I_{B2} = I_{B3} = 125.66\mu\text{A}$ and capacitor $C_1 = C_2 = 10\text{nF}$. The voltage gain for the second order low pass response is as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{\dfrac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \dfrac{2g_{m2}g_{m3}R_5}{C_2}s + \dfrac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

(i) the natural frequency, f_0 and

(ii) the quality factor, Q

(iii) the passband gain

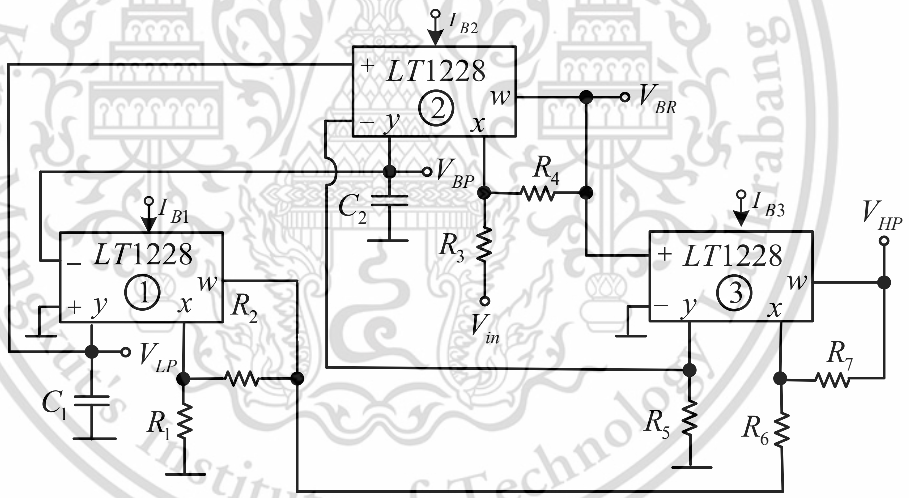


Fig. 5

a) f_0 = 20kHz, Q = 0.4 and the passband gain = 1.26

b) f_0 =150kHz, Q = 0.89 and the passband gain = 2.26

c) f_0 =200kHz, Q = 1 and the passband gain = 3.26

d) f_0 =250kHz, Q = 1.09 and the passband gain = 4.26

5. The input voltage is $50\text{mV}_{p\text{-}p}$, all resistors are 1kΩ and the three external DC bias currents are 50uA and capacitor $C_1 = C_2 = 1\text{nF}$. The voltage gain for the second order high pass response in Fig. 5 is as follows:

$$\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5 s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

i. the natural frequency, f_0 and

ii. the quality factor, Q

iii. the passband gain

a) f_0 = 69.6kHz, Q = 2 and the passband gain = 2

b) f_0 =79.6kHz, Q = 1 and the passband gain = 1

c) f_0 =89.6kHz, Q = 3 and the passband gain = 3

d) f_0 =99.6kHz, Q = 4 and the passband gain = 4

6. The input voltage is 50mV$_{p\text{-}p}$, f_l = 68.47kHz, f_h = 93.47kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:

$$\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

i. the natural frequency, f_0

ii. the quality factor, Q

iii. the passband gain

a) f_0 = 70 kHz, Q = 2.2, the passband gain = 0.4

b) f_0 = 80 kHz, Q = 3.2, the passband gain = 0.5

c) f_0 = 90 kHz, Q = 4.2, the passband gain = 0.6

d) f_0 = 100 kHz, Q = 5.2, the passband gain = 0.7

7. The input voltage is 50mV$_{p\text{-}p}$, f_l = 10kHz, f_h = 50kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band reject response in Fig. 5 is as follows:

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

i. the bandwidth, BW

ii. the natural frequency, f_0

iii. the passband gain

a) BW = 50kHz, f_0= 62.36 kHz, the passband gain = 0.2

b) BW = 70kHz, f_0 = 72.36 kHz, the passband gain = 0.4

c) BW = 40kHz, f_0 = 22.36kHz, the passband gain = 1

d) BW = 60kHz, f_0 = 52.36 kHz, the passband gain = 1.5

8. Design the second order low pass response using LT1228s to provide the natural frequency, f_0 = 70kHz and the pass-band gain = 2. The input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor C_1 = C_2 = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

i. the three external DC bias currents (Assume I_{B1} = I_{B2} = I_{B3} = I_B)

ii. the value of R_5

iii. the quality factor, Q

a) I_{B1} = I_{B2} = I_{B3} = 54µA, and R_5 =5.5kΩ, Q = 0.35

b) I_{B1} = I_{B2} = I_{B3} =44µA, and R_5 =4.5kΩ, Q = 0.25

c) I_{B1} = I_{B2} = I_{B3} = 34µA, and R_5 =3.5kΩ, Q = 0.15

d) I_{B1} = I_{B2} = I_{B3} =64µA, and R_5 =6.5kΩ, Q = 0.45

9. Design the second order band pass response using LT1228s to provide f_l= 58.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except

R_5) and C_1 = C_2 = 1nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:

$$\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

i. the natural frequency, f_0

ii. the bandwidth, BW

iii. the quality factor, Q

a) f_0 = 50kHz, BW= 5kHz, and Q = 0.8

b) f_0 = 60kHz, BW= 15kHz, and Q = 1.8

c) f_0 = 70kHz, BW= 25kHz, and Q = 2.8

d) f_0 = 30kHz, BW=35kHz, and Q = 3.8

10. Design the second order band reject response using LT1228s to provide f_l= 35.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except R_5) and C_1 = C_2 = 1nF. The voltage gain for the second order band reject response in Fig. 5 is as follows:

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

i. the natural frequency, f_0

ii. the passband gain

iii. he quality factor, Q

a) f_0 = 24.5kHz, the passband gain =4, and Q = 4.13

b) f_0 = 44.5kHz, the passband gain =3, and Q = 2.13

c) f_0 = 84.5kHz, the passband gain =2, and Q = 3.13

d) f_0 = 54.5kHz, the passband gain =1, and Q = 1.13

C-4.6Achievement test (solution)

	Field of Study: Engineering Education **Class: Second Year**	**Achievement test**

Section A

Questions 1 to 10

Choose the correct letter, **a, b, c, or d**. Circle the correct answer.

1. What is the transconductance equation for LT1228?

   a) $g_m = \frac{I_B}{2V_T}$

   b) $g_m = \frac{2I_B}{V_T}$

   c) $g_m = \frac{I_B}{10}$

   d) $g_m = 10I_B$

2. In ideal OTA part of LT1228, the current at *y* terminal is as follows:

   a) $I_y = g_m V_+$

   b) $I_y = g_m V_-$

   c) $I_y = g_m (V_+ - V_-)$

   d) $I_y = g_m (V_- - V_+)$

3. All the following statements show in which LT1228 can perform both functions.

   a) operational transconductance amplifier (OTA) and current feedback amplifier (CFA)

   b) operational amplifier (Op-amp) and current follower (CFA)

   c) operational transconductance amplifier (OTA) and voltage feedback amplifier (VFA)

   d) operational amplifier (Op-amp) and current feedback amplifier (CFA)

4. In ideal CFA part of LT1228, its output voltage can be seen as

a) $V_w = I_y R_w$

b) $V_w = I_x R_w$

c) $V_w = I_x R_T$

d) $V_w = I_y R_T$

5. Determine the OTA voltage gain when R = 1kΩ and I_B = 185μA?

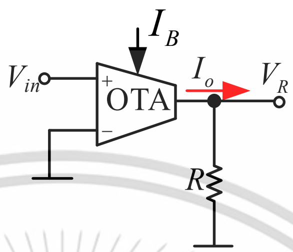


Fig. 1

a) 6.85

b) 4.85

c) 2.85

d) 1.85

6. Determine the CFA voltage gain when R_f = 1kΩ and R_1 =2kΩ.

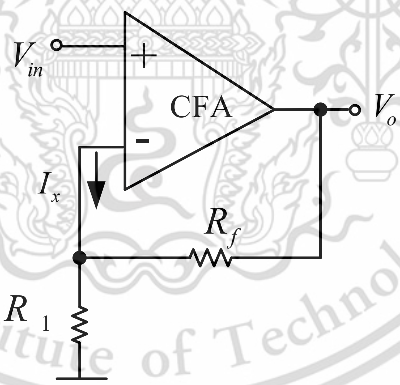


Fig. 2

a) 1.5

b) 2.5

c) 3.5

d) 4.5

7. The input voltage is 50mV$_{p\text{-}p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 150μA in Fig. 3?

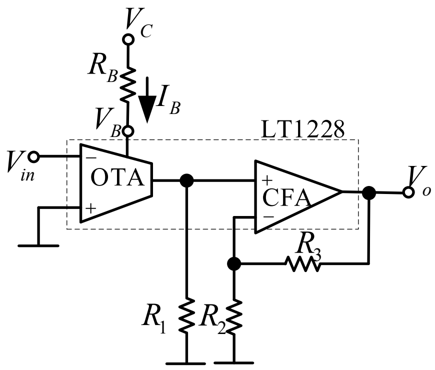


Fig. 3

a) -4

b) -3

c) -2

d) -1

8. Design the OTA voltage gain of 5 when I_B = 100μA in Fig. 1.

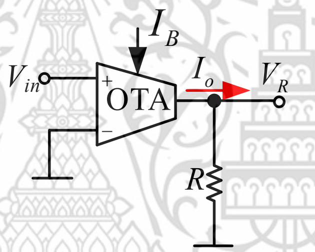


Fig. 1

a) R = 2kΩ

b) R = 3kΩ

c) R = 4kΩ

d) R = 5kΩ

9. Design the CFA voltage gain of 4 when R_f=1.2kΩ in Fig. 2.

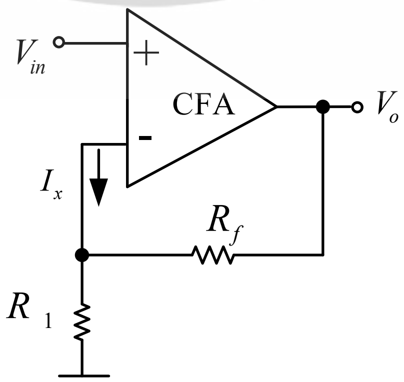


Fig. 2

a) $R_1 = 0.2\text{k}\Omega$

b) $R_1 = 0.3\text{k}\Omega$

c) $R_1 = 0.4\text{k}\Omega$

d) $R_1 = 0.5\text{k}\Omega$

10. Design the voltage gain amplifier using LT1228 to provide gain of -2 with external DC bias current is 100uA**.** The input voltage is $50\text{mV}_{p\text{-}p}$, and $R_3 = 1\text{k}\Omega$ and $R_2 = 1\text{k}\Omega$. Determine R_1 in Fig. 3**.**

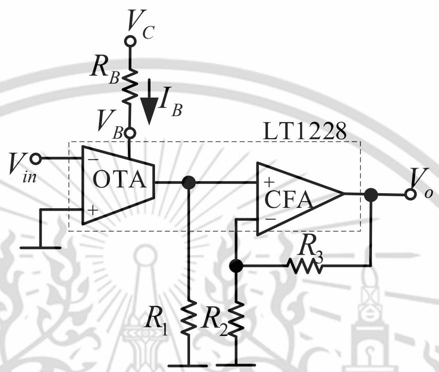


Fig. 3

a) $R_1 = 1\text{k}\Omega$

b) $R_1 = 3.5\text{k}\Omega$

c) $R_1 = 4\text{k}\Omega$

d) $R_1 = 6.5\text{k}\Omega$

Section B

Questions 11 to 20

Choose the correct letter, **a, b, c, or d**. Circle the correct answer.

11. The point at which the response drops –3 dB from the passband is called

a) Cutoff frequency

b) Natural frequency

c) Center frequency

d) All the above

11.

12. Which filter rejects the low frequency and passes the high frequency.

a) All-pass filter

b) High pass filter

c) Low-pass filter

d) Band-stop filter

13. Which statements agree with the output and input voltages are equal in amplitude for all frequencies?

a) All-pass filter

b) High pass filter

c) Band-pass filter

d) Band-stop filter

14. The input voltage is $50mV_{p-p}$, all resistors are 1kΩ and the external DC bias current is 50uA and capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} \left(\because V_{in1} = V_{in}\right)$$

Determine

i. the natural frequency, f_0

ii. the passband gain

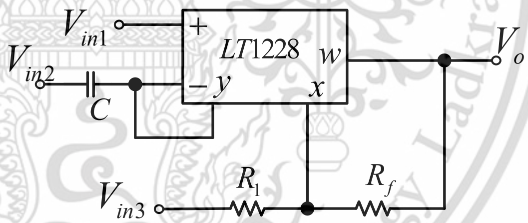


Fig. 4

a) f_0 = 25.7kHz, passband gain = 1

b) f_0 = 39.8kHz, passband gain = 2

c) f_0 = 45.7kHz, passband gain = 3

d) f_0 = 55.7kHz, passband gain = 4

15. The input voltage is $50mV_{p-p}$, the external DC bias current is 123 μA, all resistors are 1kΩ, capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}} \right) (\because V_{in2} = V_{in})$$

Determine the high pass phase response at f_0 = 98kHz.

a) 30º

b) 45º

c) 60º

d) 90º

16. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 μA, all resistors are 1kΩ, capacitor C = 2nF. The first order non-inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in2} = V_{in3} = V_{in})$$

Determine the non-inverting AP phase response at f_0 = 98kHz.

a) 45º

b) 60º

c) 90º

d) 180º

17. Design the first order multifunction filter using single LT1228 to provide the passband gain 5, the natural frequency, f_0 = 98kHz, the input voltage is 50mV$_{p\text{-}p}$, R_f =1kΩ, and capacitor C = 2nF in Fig. 4. The first order low pass voltage gain equation is as follows:

$$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$

Determine

i. the value of R_1

ii. the external DC bias currents

a) R_1 =0.25kΩ and I_B =123μA

b) R_1 =1kΩ and I_B =62μA

c) R_1 =2kΩ and I_B =50μA

d) R_1 =1kΩ and I_B =162μA

18. Design the first order multifunction filter using single LT1228 when the input voltage is 50mV$_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF in Fig. 4. The first order high pass voltage gain equation in Fig. 1 is as follows:

$$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}} \right) (\because V_{in2} = V_{in})$$

Determine the external DC bias current to provide its natural frequency, f_0 = 100kHz.

a) 25uA

b) 70uA

c) 125uA

d) 100uA

19. Design the first order multifunction filter using single LT1228 when the input voltage is 50mV$_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF, the external DC bias current is 123uA. The first order non-inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in2} = V_{in3} = V_{in})$$

Determine the frequency to provide its non-inverting AP phase response is 135 °.

a) 40 kHz

b) 90 kHz

c) 100kHz

d) 110kHz

20. Design the first order multifunction filter using single LT1228 when the input voltage is 50mV$_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order inverting AP voltage gain equation in Fig. 4 is as follows:

$$\frac{V_o}{V_{in}} = \frac{-\left(s - \frac{g_m}{C}\right)}{s + \frac{g_m}{C}} (\because V_{in1} = V_{in3} = V_{in})$$

Determine the frequency to provide its inverting AP phase response is -108°.

a) 135kHz

b) 98 kHz

c) 108kHz

d) 88kHz

Section C

Questions 21 to 30

Choose the correct letter, **a, b, c, or d**. Circle the correct answer.

21. The transfer function of second order low pass function is

$$\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

. What is the natural frequency for second order low pass function?

a) $\omega_0 = \frac{g_{m1}g_{m2}}{C_1C_2}$

b) $\omega_0 = \frac{g_{m1}}{C_2}$

c) $\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$

d) $\omega_0 = \frac{g_{m2}}{C_1}$

22. In band pass filter, the BW and Q relationship is

a) $f_0 = \frac{BW}{Q}$

b) $BW = \frac{Q}{f_0}$

c) $BW = \frac{f_0}{Q}$

d) $BW = f_0 \times Q$

23. Which statements describe the formula for the center frequency of band pass filter?

a) $f_0 = \frac{f_H + f_L}{2}$

b) $f_0 = \sqrt{f_H * f_L}$

c) $f_0 = \sqrt{f_H^2 + f_L^2}$

d) $f_0 = \sqrt{f_H - f_L}$

24. The input voltage is $50\text{mV}_{p\text{-}p}$, all resistors are 1kΩ, $I_{B1} = I_{B2} = I_{B3} =$ 100μA and capacitor $C_1 = C_2 =$ 10nF. The voltage gain for the second order low pass response is as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{\dfrac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \dfrac{2g_{m2}g_{m3}R_5}{C_2}s + \dfrac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

(iv) the natural frequency, f_0 and

(v) the quality factor, Q

(vi) the passband gain

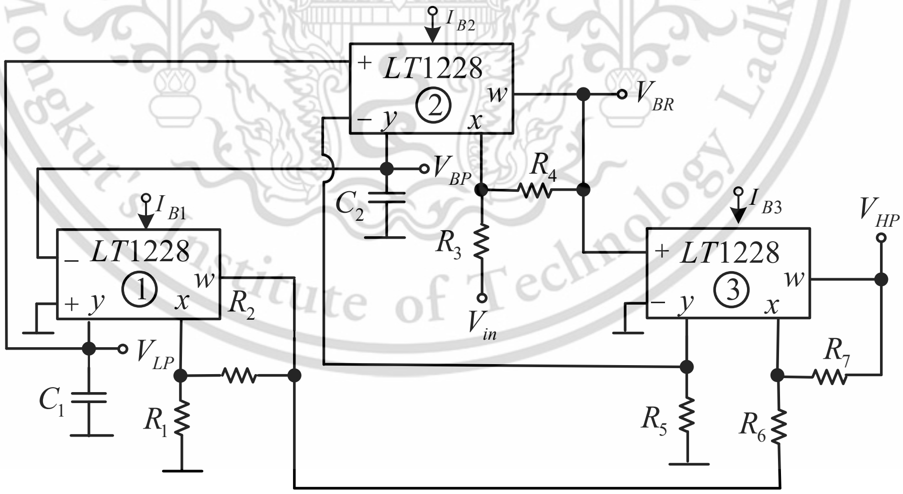


Fig. 5

a) f_0 = 16kHz, Q = 1 and the passband gain = 1

b) f_0 =56kHz, Q = 1.5 and the passband gain = 2

c) f_0 =66kHz, Q = 2.5 and the passband gain = 3

d) f_0 =76kHz, Q = 3.5 and the passband gain = 4

25. The input voltage is 50mV$_{p-p}$, all resistors are 1kΩ and the three external DC bias currents are 150uA and capacitor C_1 = C_2 = 1nF. The voltage gain for the second order high pass response in Fig. 5 is as follows:

$$\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5 s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

iv. the natural frequency, f_0 and

v. the quality factor, Q

vi. the passband gain

a) f_0 = 69.6kHz, Q = 2 and the passband gain = 2

b) f_0 =238.7kHz, Q = 0.3333 and the passband gain = 3

c) f_0 =89.6kHz, Q = 3 and the passband gain = 5

d) f_0 =99.6kHz, Q = 4 and the passband gain = 4

26. The input voltage is 50mV$_{p-p}$, f_l = 68.47kHz, f_h = 93.47kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:

$$\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

i. the bandwidth, BW

ii. the quality factor, Q

iii. the passband gain

a) BW = 15kHz, Q = 2.2, the passband gain = 0.4

b) BW= 25kHz, Q = 3.2, the passband gain = 0.5

c) BW = 35 kHz, Q = 4.2, the passband gain = 0.6

d) f_0 = 45 kHz, Q = 5.2, the passband gain = 0.7

27. The input voltage is 50mV$_{p-p}$, f_l = 20kHz, f_h = 60kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band reject response in Fig. 5 is as follows:

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate

i. the bandwidth, BW

ii. the natural frequency, f_0

iii. the passband gain

a) BW = 50kHz, f_0= 62.36 kHz, the passband gain = 0.2

b) BW = 70kHz, f_0 = 72.36 kHz, the passband gain = 0.4

c) BW = 40kHz, f_0 = 22.36kHz, the passband gain = 1

d) BW = 60kHz, f_0 = 52.36 kHz, the passband gain = 1.5

28. Design the second order low pass response using LT1228s to provide the natural frequency, f_0 = 70kHz and the pass-band gain = 2. The input voltage is 50mV$_{p-p}$, all resistors are 1kΩ (except R_5) and capacitor C_1 = C_2 = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

i. the three external DC bias currents (Assume I_{B1} = I_{B2} = I_{B3} = I_B)

ii. the value of R_5

iii. the quality factor, Q

a) I_{B1} = I_{B2} = I_{B3} = 44µA, and R_5 =4.5kΩ, Q = 0.25

b) I_{B1} = I_{B2} = I_{B3} = 54µA, and R_5 =5.5kΩ, Q = 0.35

c) I_{B1} = I_{B2} = I_{B3} = 34µA, and R_5 =3.5kΩ, Q = 0.15

d) I_{B1} = I_{B2} = I_{B3} = 64µA, and R_5 =6.5kΩ, Q = 0.45

29. Design the second order band pass response using LT1228s to provide f_l= 58.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except R_5) and C_1 = C_2 = 1nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:

$$\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

iv. the natural frequency, f_0

v. the bandwidth, BW

vi. the quality factor, Q

a) f_0 = 70kHz, BW= 25kHz, and Q = 2.8

b) f_0 = 50kHz, BW= 5kHz, and Q = 0.8

c) f_0 = 60kHz, BW= 15kHz, and Q = 1.8

d) f_0 = 30kHz, BW=35kHz, and Q = 3.8

30. Design the second order band reject response using LT1228s to provide f_l= 35.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except R_5) and C_1 = C_2 = 1nF. The voltage gain for the second order band reject response in Fig. 5 is as follows:

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Determine

iv. the natural frequency, f_0

v. the passband gain

vi. he quality factor, Q

a) f_0 = 24.5kHz, the passband gain =1, and Q = 4.13

b) f_0 = 44.5kHz, the passband gain =2, and Q = 2.13

c) f_0 = 54.5kHz, the passband gain =1.5, and Q = 1.13

d) f_0 = 84.5kHz, the passband gain =0.5, and Q = 3.13

C-5 Coding

```
int SWLP = 8;
int SWHP = 9;
int SWIAP = 10;
int SWNIAP = 11;
int SWUP_1 = 30;
int SWUP_2 = 32;
int SWDOWN_1 = 36;
int SWDOWN_2 = 34;
int LEDLP = 22;
int LEDHP = 24;
int LEDIAP = 28;
int LEDNIAP = 26;
int Vcontrol_1 = 6;
int Vcontrol_2 = 7;
int VIN1 = 2;
int VIN2 = 3;
int VIN3 = 4;
int VC1 = 0;
int VC2 = 0;

void setup() {
 pinMode(SWLP , INPUT);
 pinMode(SWHP , INPUT);
 pinMode(SWIAP , INPUT);
 pinMode(SWNIAP , INPUT);
 pinMode(SWUP_1 , INPUT);
 pinMode(SWUP_2 , INPUT);
 pinMode(SWDOWN_1 , INPUT);
 pinMode(SWDOWN_2 , INPUT);
 pinMode(LEDLP , OUTPUT);
 pinMode(LEDHP , OUTPUT);
 pinMode(LEDIAP , OUTPUT);
 pinMode(LEDNIAP , OUTPUT);
 pinMode(Vcontrol_1 , OUTPUT);
 pinMode(Vcontrol_2 , OUTPUT);
 pinMode(VIN1 , OUTPUT);
 pinMode(VIN2 , OUTPUT);
 pinMode(VIN3 , OUTPUT);

}

void loop()
{
  Vcontrol1 (VC1);
  Vcontrol2 (VC2);
 //analogWrite(Vcontrol_1, VC1);
 //analogWrite(Vcontrol_2, VC2);
```

```
if (!digitalRead(SWLP))
{
 while (!digitalRead(SWLP))
 {
  delay(2);
 }
 led_function(0);
 analogSwitch(0);
}
if (!digitalRead(SWHP))
{
 while (!digitalRead(SWHP))
 {
  delay(2);
 }
 led_function(1);
 analogSwitch(1);
}
if (!digitalRead(SWIAP))
{
 while (!digitalRead(SWIAP))
 {
  delay(2);
 }
 led_function(3);
 analogSwitch(3);
}
if (!digitalRead(SWNIAP))
{
 while (!digitalRead(SWNIAP))
 {
  delay(2);
 }
 led_function(2);
 analogSwitch(2);
}

if (!digitalRead(SWUP_1))
{
 while (!digitalRead(SWUP_1))
 {
  delay(2);
 }
 VC1++;
 if (VC1 > 10)
 {
  VC1 = 10;
 }
}
if (!digitalRead(SWDOWN_1))
```

```
 {
  while (!digitalRead(SWDOWN_1))
  {
   delay(2);
  }
  VC1--;
  if (VC1 < 0)
  {
   VC1 = 0;
  }
 }

 if (!digitalRead(SWUP_2))
 {
  while (!digitalRead(SWUP_2))
  {
   delay(2);
  }
  VC2++;
  if (VC2 > 10)
  {
   VC2 = 10;
  }
 }
 if (!digitalRead(SWDOWN_2))
 {
  while (!digitalRead(SWDOWN_2))
  {
   delay(2);
  }
  VC2--;
  if (VC2 < 0)
  {
   VC2 = 0;
  }
 }
}
void led_function(int ledmem)
{
 switch (ledmem)
 {
  case 0 :
   digitalWrite(LEDLP , HIGH);
   digitalWrite(LEDHP , LOW);
   digitalWrite(LEDIAP , LOW);
   digitalWrite(LEDNIAP , LOW);
   break;
  case 1 :
   digitalWrite(LEDLP , LOW);
   digitalWrite(LEDHP , HIGH);
```

```
      digitalWrite(LEDIAP , LOW);
      digitalWrite(LEDNIAP , LOW);
      break;
    case 2 :
      digitalWrite(LEDLP , LOW);
      digitalWrite(LEDHP , LOW);
      digitalWrite(LEDIAP , HIGH);
      digitalWrite(LEDNIAP , LOW);
      break;
    case 3 :
      digitalWrite(LEDLP , LOW);
      digitalWrite(LEDHP , LOW);
      digitalWrite(LEDIAP , LOW);
      digitalWrite(LEDNIAP , HIGH);
      break;
  }
}
void analogSwitch(int vinmem)
{
  switch (vinmem)
  {
    case 0 :
      digitalWrite(VIN1, HIGH);
      digitalWrite(VIN2, LOW);
      digitalWrite(VIN3, LOW);
      break;
    case 1 :
      digitalWrite(VIN1, LOW);
      digitalWrite(VIN2, HIGH);
      digitalWrite(VIN3, LOW);
      break;
    case 2 :
      digitalWrite(VIN1, HIGH);
      digitalWrite(VIN2, LOW);
      digitalWrite(VIN3, HIGH);
      break;
    case 3 :
      digitalWrite(VIN1, LOW);
      digitalWrite(VIN2, HIGH);
      digitalWrite(VIN3, HIGH);
      break;
  }
}
void Vcontrol1 (int Vc1)
{
  switch (Vc1)
  {
    case 0:
      analogWrite(Vcontrol_1, 0);
      break;
```

```
    case 1:
    analogWrite(Vcontrol_1, 56);
      break;
    case 2:
    analogWrite(Vcontrol_1, 83);
      break;
    case 3:
    analogWrite(Vcontrol_1, 103);
      break;
    case 4:
    analogWrite(Vcontrol_1, 117);
      break;
    case 5:
    analogWrite(Vcontrol_1, 128);
      break;
       case 6:
      analogWrite(Vcontrol_1, 139);
      break;
    case 7:
    analogWrite(Vcontrol_1, 152);
      break;
    case 8:
    analogWrite(Vcontrol_1, 172);
      break;
    case 9:
    analogWrite(Vcontrol_1, 201);
      break;
    case 10:
    analogWrite(Vcontrol_1, 254);
      break;
  }
}
void Vcontrol2 (int Vc2)
{
  switch (Vc2)
  {
    case 0:
      analogWrite(Vcontrol_2, 0);
      break;
    case 1:
    analogWrite(Vcontrol_2, 56);
      break;
    case 2:
    analogWrite(Vcontrol_2, 83);
      break;
    case 3:
    analogWrite(Vcontrol_2, 103);
      break;
    case 4:
    analogWrite(Vcontrol_2, 117);
```

```
  break;
case 5:
analogWrite(Vcontrol_2, 128);
  break;
   case 6:
  analogWrite(Vcontrol_2, 139);
  break;
case 7:
analogWrite(Vcontrol_2, 152);
  break;
case 8:
analogWrite(Vcontrol_2, 172);
  break;
case 9:
analogWrite(Vcontrol_2, 201);
  break;
case 10:
analogWrite(Vcontrol_2, 254);
  break;
}
}
```

Appendix D

Data Analysis

1. Content validity of quizzes
2. Content validity of achievement test
3. Quality evaluation form of analog filter design
4. E_1/E_2 analysis

D-1 Content validity of quizzes

Behavioral objectives	Quizzes (Topic 1)	Expert's opinion					IOC	S.D.	Conclusion	Selected
		E1	E2	E3	E4	E5				
1	1	1	1	1	1	0	0.80	0.45	Ok	✓
	2	1	1	1	1	0	0.80	0.45	Ok	
	3	1	1	1	1	0	0.80	0.45	Ok	✓
	4	1	1	1	1	0	0.80	0.45	Ok	
	5	1	1	1	1	0	0.80	0.45	Ok	✓
	6	1	1	1	1	0	0.80	0.45	Ok	
	7	1	1	1	1	0	0.80	0.45	Ok	
	8	1	1	1	1	0	0.80	0.45	Ok	✓
2	9	0	1	1	1	0	0.60	0.55	Ok	✓
	10	1	1	0	1	0	0.60	0.55	Ok	✓
	11	1	1	0	1	1	0.80	0.45	Ok	✓
3	12	1	1	1	1	0	0.80	0.45	Ok	✓
	13	1	1	1	1	0	0.80	0.45	Ok	✓
	14	1	1	1	1	1	1.00	0.00	Ok	✓
	15	1	1	1	0	0	0.60	0.55	Ok	

Behavioral objectives	Quizzes (Topic 2)	Expert's opinion					IOC	S.D.	Conclusion	Selected
		E1	E2	E3	E4	E5				
1	1	1	1	1	1	0	0.80	0.45	Ok	
	2	1	1	1	-1	0	0.40	0.89	Can't use	*
	3	1	1	1	1	0	0.80	0.45	Ok	✓
	4	1	1	0	1	0	0.60	0.55	Ok	
	5	1	1	1	1	0	0.80	0.45	Ok	✓

	6	1	1	1	1	0	0.80	0.45	Ok	
	7	1	1	1	1	0	0.80	0.45	Ok	
	8	1	1	1	1	0	0.80	0.45	Ok	
	9	1	1	0	1	0	0.60	0.55	Ok	
	10	1	1	0	1	0	0.60	0.55	Ok	
	11	1	1	1	1	1	1.00	0.00	Ok	✓
2	12	1	1	1	1	1	1.00	0.00	Ok	
	13	1	1	1	1	0	0.80	0.45	Ok	
	14	1	1	1	1	0	0.80	0.45	Ok	✓
	15	1	1	1	1	0	0.80	0.45	Ok	✓
	16	1	1	1	1	0	0.80	0.45	Ok	
	17	1	1	1	1	0	0.80	0.45	Ok	✓
	18	1	1	1	1	0	0.80	0.45	Ok	✓
3	19	1	1	1	1	0	0.80	0.45	Ok	
	20	1	1	1	1	0	0.80	0.45	Ok	
	21	1	1	1	1	0	0.80	0.45	Ok	✓
	22	1	1	1	1	0	0.80	0.45	Ok	✓

Behavioral objectives	Quizzes (Topic 3)	Expert's opinion					IOC	S.D.	Conclusion	Selected
		E1	E2	E3	E4	E5				
	1	1	1	1	1	0	0.80	0.45	Ok	
	2	1	1	1	1	0	0.80	0.45	Ok	✓
	3	1	1	0	1	0	0.60	0.55	Ok	✓
1	4	1	1	1	1	0	0.80	0.45	Ok	✓
	5	1	1	1	1	0	0.80	0.45	Ok	
	6	1	1	1	1	0	0.80	0.45	Ok	
	7	1	1	0	-1	0	0.20	0.84	Can't use	
	8	1	1	0	1	0	0.60	0.55	Ok	

2	9	1	1	1	1	1	1.00	0.00	Ok	✓
	10	1	1	1	1	0	0.80	0.45	Ok	✓
	11	1	1	1	1	1	1.00	0.00	Ok	✓
	12	1	1	1	1	0	0.80	0.45	Ok	
	13	1	1	1	1	0	0.80	0.45	Ok	✓
	14	1	1	1	1	0	0.80	0.45	Ok	
3	15	1	1	1	1	0	0.80	0.45	Ok	✓
	16	1	1	1	1	0	0.80	0.45	Ok	
	17	1	1	1	1	0	0.80	0.45	Ok	
	18	1	1	1	1	0	0.80	0.45	Ok	
	19	1	1	1	1	0	0.80	0.45	Ok	✓
	20	1	1	1	1	0	0.80	0.45	Ok	
	21	1	1	1	1	0	0.80	0.45	Ok	✓
	22	1	1	1	1	0	0.80	0.45	Ok	

* refer to modified question that match with behavioral objectives and the experts' comments.

Quizzes

By

MS. May Phu Pwint Wai

Department of Engineering Education

Faculty of Industrial Education and Technology

King Mongkut's Institute of Technology Ladkrabang (KMITL)

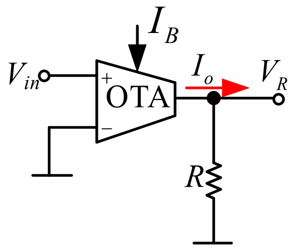
62603017@kmitl.ac.th

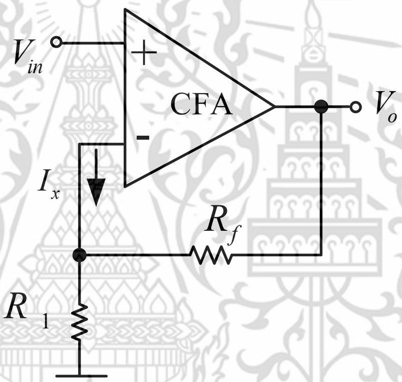
TABLE OF CONTENTS

	Field of Study: Engineering Education **Title: Basic concept of LT1228** **Class: Second Year**	**Quizzes**	**Page: 3/6**

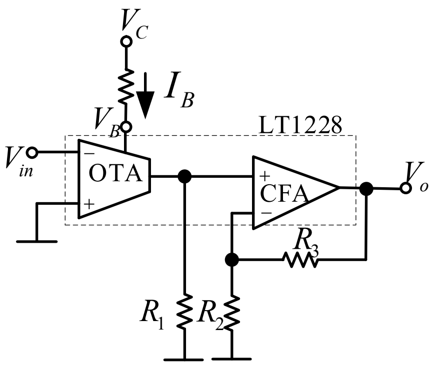
Behavioral Objective	**Questions**	**Consideration score**		
		+1	**0**	**-1**
	Section-1 **Questions 1 to 15** Choose the correct letter, a, b, c, or d. Circle the correct answer.			
1. Describes the basic features of LT1228.	1. Which of the following functions can perform LT1228? **a)** Operational amplifier (Op-amp) and current feedback amplifier (CFA) **b)** Operational transconductance amplifier (OTA) and current follower **c)** Operational transconductance amplifier (OTA) and current feedback amplifier (CFA) **d)** Operational amplifier (Op-amp) and current follower			
	2. Which terminals of OTA have high impedances, so the currents flow into these two terminals are zero? **a)** Non-inverting and inverting terminals **b)** *x* and *y* terminals **c)** Non-inverting and *y* terminals **d)** *x* and *w* terminals			
	3. In ideal OTA part of LT1228, the current at *y* terminal is as follows: **a)** $I_y = g_m(V_- - V_+)$ **b)** $I_y = g_m(V_+ - V_-)$ **c)** $I_y = g_m V_-$ **d)** $I_y = g_m V_+$			

	4. In ideal current feedback amplifier (CFA) part of LT1228, which terminals possess the same amount of voltage? **a)** *x* and *w* terminals **b)** *x* and *y* terminals **c)** *w* and *y* terminals **d)** *x* and *z* terminals			
	5. In ideal CFA part of LT1228, its output voltage can be seen as **a)** $V_w = I_x R_T$ **b)** $V_w = I_x R_w$ **c)** $V_w = I_y R_T$ **d)** $V_w = I_y R_w$			
	6. Which terminals of LT1228 possess high impedance output current and high impedance input voltages? **a)** *x*, V_+ and V_- terminals **b)** *w*, V_+ and *y* terminals **c)** *x*, V_+ and *y* terminals **d)** *y*, V_+ and V_- terminals			
	7. The *x* and *w* terminals possess **a)** low-impedance voltage output terminals **b)** low-impedance current output terminals **c)** low-impedance voltage input terminals **d)** high-impedance voltage output terminals			
	8. The transconductance, g_m is obtained by **a)** $g_m = \frac{I_B}{2V_T}$ **b)** $g_m = 10I_B$ **c)** $g_m = \frac{I_B}{10}$ **d)** $g_m = \frac{2I_B}{V_T}$			
	9. Determine the OTA voltage gain when R = 1kΩ and I_B = 50uA?			

<table>
<tr>
<td rowspan="3">2. Calculate the parameters of LT1228.</td>
<td>Fig. 1

a) 0.5
b) 1.5
c) 2.5
d) 3.5</td>
<td></td><td></td><td></td>
</tr>
<tr>
<td>10. Determine the CFA voltage gain for when R_f = 1kΩ and R_1 =5kΩ.
Fig. 2

a) 4.2
b) 3.2
c) 1.2
d) 0.2</td>
<td></td><td></td><td></td>
</tr>
<tr>
<td>**11.** The input voltage is 50mV$_{p\text{-}p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 300uA in Fig. 3?</td>
<td></td><td></td><td></td>
</tr>
</table>

<table>
<tr>
<td></td>
<td>
Fig. 3

a) -5
b) -6
c) -7
d) -8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Design the parameters of the voltage amplifier using LT1228.</td>
<td>12. Design the OTA voltage gain of 9 when I_B = 123.5μA in Fig. 1.

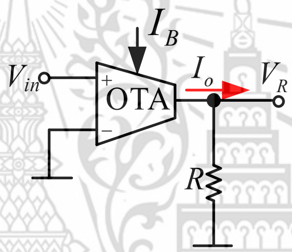



Fig. 1

a) R = 7.3kΩ
b) R = 6.8kΩ
c) R = 5.6kΩ
d) R = 4.7kΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13. Design the CFA voltage gain of 5 when R_f=1kΩ in Fig. 2.

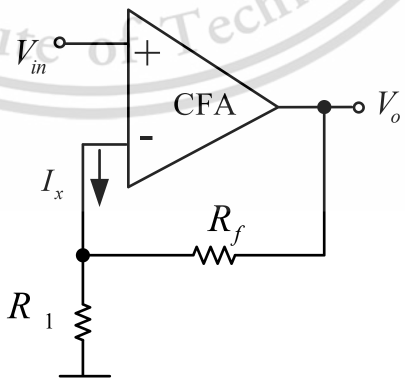
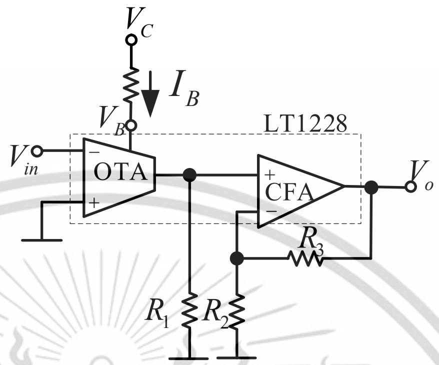



Fig. 2

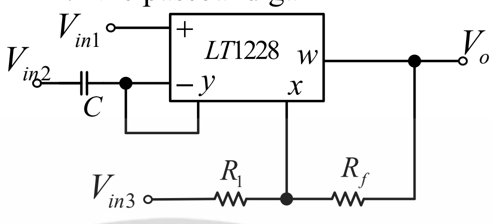
a) R_1 =2kΩ
b) R_1 =3.5kΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
</table>

	c) R_1 =0.25kΩ **d)** R_1 =5.2kΩ			
	14. Design the voltage gain amplifier using LT1228 to provide gain of -5 with external DC bias current is 100uA**.** The input voltage is 50mV$_{p-p}$, and R_3 = 1kΩ and R_2 =1kΩ. Determine R_1 in Fig. 3**.**  Fig. 3 **a)** R_1 =2.5kΩ **b)** R_1 =3.5kΩ **c)** R_1 =4.5kΩ **d)** R_1 =5.5kΩ			
	15. Design the voltage gain amplifier using LT1228 to provide gain of -5. The input voltage is 50mV$_{p-p}$, and R_1 = 1kΩ and R_2 =1kΩ and R_3 = 1kΩ. Determine the external DC bias current in Fig. 3**.** **a)** I_B =300μA **b)** I_B =567μA **c)** I_B =166.67μA **d)** I_B =250μA			

	Field of Study: Engineering Education **Title: First order multifunction filter using single LT1228** **Class: Second Year**	**Quizzes**	**Page: 7/12**

Behavioral Objectives	**Questions**	**Consideration score**		
		+1	**0**	**-1**
	Questions 1 to 22 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.			
	1. What is the roll of rate of the first order low pass filter? **a)** 20dB/decade **b)** 40dB/decade **c)** 80dB/decade **d)** 60dB/decade			
	2. The point at which the response drops –3 dB from the passband is called **a)** Cutoff frequency **b)** Natural frequency **c)** Center frequency **d)** All the above			
1. Describes the first order multifunction filter using single LT1228.	3. Which filter rejects the low frequency and passes the high frequency. **a)** Low-pass filter **b)** High pass filter **c)** All-pass filter **d)** Band-stop filter			
	4. What is the purpose of a low pass filter? **a)** To attenuate the signal at low frequency **b)** To amplify the signal at low frequency **c)** To attenuate the signal at high frequency **d)** To amplify the signal at high frequency			
	5. Which statements agree with the output and input voltages are			

	equal in amplitude for all frequencies? **a)** High pass filter **b)** Band-pass filter **c)** All-pass filter **d)** Band-stop filter			
	6. In a first order low pass filter, frequencies lower than cutoff frequencies are called as **a)** Stop band frequency **b)** Pass band frequency **c)** Center band frequency **d)** None of the mentioned			
	7. Which filter rejects all frequencies within a specified band and passes all those outside this band. **a)** low pass **b)** high pass **c)** band-pass **d)** band-stop			
	8. Name the filter that has two stop bands? **a)** Band-reject filter **b)** Band-pass filter **c)** High pass filter **d)** Low pass filter			
	9. Which filter performs exactly the opposite to the band-stop filter? **a)** Band-pass filter **b)** Band-elimination filter **c)** Low pass filter **d)** None of the above			
	10. Which filter passes the low frequency and rejects the high frequency. **a)** High pass filter **b)** Low pass filter **c)** All-pass filter **d)** Band-stop filter			
2. Calculate the parameters of the first order multifunction	**11.** The input voltage is $50mV_{p\text{-}p}$, all resistors are 1kΩ and the external DC bias current is 60μA and capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 1 is as follows:			

filter using single LT1228.	$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1}=V_{in})$ Determine i. the natural frequency, f_0 ii. the passband gain  Fig. 1 **a)** f_0 = 20kHz, passband gain = 1 **b)** f_0 = 30kHz, passband gain = 1.5 **c)** f_0 = 47.7kHz, passband gain = 2 **d)** f_0 = 50kHz, passband gain = 2.5			
	12. The input voltage is $50mV_{p-p}$, all resistors are 1kΩ and the external DC bias current is 80μA and capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right)(\because V_{in2}=V_{in})$ Determine i. the natural frequency, f_0 ii. the passband gain a) f_0 = 63.6kHz, passband gain = 2 b) f_0 = 53.6kHz, passband gain = 1.5 c) f_0 = 43.6kHz, passband gain = 1 d) f_0 = 33.6kHz, passband gain = 0.5			
	13. The input voltage is $50mV_{p-p}$, the external DC bias current is			

	123µA, all resistors are 1kΩ, capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$ Determine the low pass phase response at f = 500kHz. **a)** -39º **b)** -69º **c)** -79º **d)** -90º			
	14. The input voltage is 50mV$_{p-p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right) (\because V_{in2} = V_{in})$$ Determine the high pass phase response at f = 50kHz. **a)** 33º **b)** 63º **c)** 93º **d)** 103º			
	15. The input voltage is 50mV$_{p-p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order non-inverting AP voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in2} = V_{in3} = V_{in})$$ Determine the non-inverting AP phase response at f = 500kHz. **a)** 42º **b)** 52º **c)** 62º **d)** 22º			
	16. The input voltage is 50mV$_{p-p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C =			

	2nF. The first order inverting AP voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{-\left(s-\frac{g_m}{C}\right)}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in3} = V_{in})$$ Determine the inverting AP phase response at f = 50kHz. **a)** - 54º **b)** -44º **c)** -64º **d)** -84º			
3. Design the parameters of the first order multifunction filter using single LT1228.	**17.** Design the first order multifunction filter using single LT1228 to provide passband gain 1.5, the natural frequency, f_0 = 40kHz, the input voltage is $50mV_{p-p}$, R_f=1kΩ, and capacitor C = 2nF in Fig. 1. The first order low pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$ Determine i. the external DC bias currents ii. the value of R_1 **a)** I_B =162µA, and R_1 =3kΩ **b)** I_B =50µA, and R_1 =2kΩ **c)** I_B =123µA and R_1 =1kΩ **d)** I_B =62µA and R_1 =1kΩ			
	18. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF in Fig. 1. The first order high pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right) (\because V_{in2} = V_{in})$$ Determine the external DC bias current at f_0 = 80 kHz. **a)** 25uA **b)** 70uA			

	c) 125uA **d)** 100uA			
	19. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor $C = 2nF$, and the external DC bias current is 123uA. The first order low pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$ Determine the frequency to provide its LP phase response is -45°. **a)** 135 kHz **b)** 98kHz **c)** 88kHz **d)** 108 kHz			
	20. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor $C = 2nF$, and the external DC bias current is 123uA. The first order high pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right) (\because V_{in2} = V_{in})$$ Determine the frequency to provide its HP phase response is 45°. **a)** 98kHz **b)** 88kHz **c)** 108kHz **d)** 135kHz			
	21. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor $C = 2nF$, and the external DC bias current is 123uA. The first order non-inverting AP voltage gain equation in Fig. 1 is as follows:			

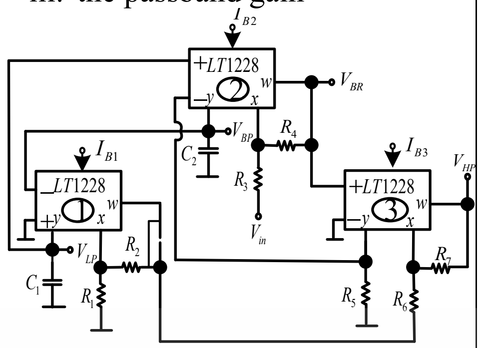
	$$\frac{V_o}{V_{in}}=\frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}}(\because V_{in2}=V_{in3}=V_{in})$$ Determine the frequency to provide its non-inverting AP phase response is 135º. **a)** 40kHz **b)** 90kHz **c)** 100kHz **d)** 110kHz			
	22. Design the first order multifunction filter using single LT1228 when the input voltage is 50mV$_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order inverting AP voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}}=\frac{-\left(s-\frac{g_m}{C}\right)}{s+\frac{g_m}{C}}(\because V_{in1}=V_{in3}=V_{in})$$ Determine the frequency to provide its inverting AP phase response is -90º. **a)** 118kHz **b)** 98 kHz **c)** 108kHz **d)** 88kHz			

	Field of Study: Engineering Education **Title: Second order multifunction filter using LT1228s** **Class: Second Year**	**Quizzes**	**Page: 13/20**

Behavioral Objectives	**Questions**	**Consideration score**		
		+1	**0**	**-1**
	Questions 1 to 22 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.			
1. Describe the basic features of the second order universal filter using three LT1228s.	1. What is the roll of rate of the second order high pass filter? **a)** 20dB/decade **b)** 40dB/decade **c)** 60dB/decade **d)** 80dB/decade			
	2. The transfer function of second order low pass function is $\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$. What is the natural frequency for second order low pass function? **a)** $\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$ **b)** $\omega_0 = \frac{g_{m1}g_{m2}}{C_1C_2}$ **c)** $\omega_0 = \frac{g_{m1}}{C_2}$ **d)** $\omega_0 = \frac{g_{m2}}{C_1}$			
	3. The transfer function of second order high pass function is			

	$T(s) = \dfrac{-2s^2 g_{m3} R_5}{\left(s^2 + \dfrac{2g_{m2} g_{m3} R_5}{C_2} s + \dfrac{g_{m1} g_{m2}}{C_1 C_2}\right)}$. What is the quality factor for second order high pass function? **a)** $Q = \dfrac{1}{K}\sqrt{\dfrac{C_2 g_{m1}}{C_1 g_{m2}}}$ **b)** $Q = \dfrac{1}{K}\sqrt{\dfrac{C_1 g_{m2}}{C_2 g_{m1}}}$ **c)** $Q = \dfrac{1}{2K}\sqrt{\dfrac{C_1 g_{m2}}{C_2 g_{m1}}}$ **d)** $Q = \dfrac{1}{2K}\sqrt{\dfrac{C_2 g_{m1}}{C_1 g_{m2}}}$			
	3. In band pass filter, the BW and Q relationship is **a)** $BW = \dfrac{f_0}{Q}$ **b)** $f_0 = \dfrac{BW}{Q}$ **c)** $BW = \dfrac{Q}{f_0}$ **d)** $BW = f_0 \times Q$			
	4. Which statements describe the formula for the center frequency of band pass filter? **a)** $f_0 = \dfrac{f_H + f_L}{2}$ **b)** $f_0 = \sqrt{f_H * f_L}$ **c)** $f_0 = \sqrt{f_H^2 + f_L^2}$ **d)** $f_0 = \sqrt{f_H - f_L}$			
	5. What is the phase shift of a second order band pass filter at natural frequency? **a)** -180º **b)** -45º **c)** -90º **d)** 0º			
	6. What is the Q factor of a second order band stop filter?			

	a) It is a measure of the filter's gain at a specific frequency b) It is a measure of the filter's attenuation at a specific frequency c) It is a measure of the filter's phase shift at a specific frequency d) It is a measure of the filter's bandwidth at a specific frequency			
	7. What is the purpose of second order band pass filter? a) To isolate and amplify a narrow range of frequency while attenuating outside of this frequency range b) To isolate and amplify a specific frequency range while attenuating outside of this frequency range c) To amplify low frequency while attenuating unwanted frequency range d) To amplify high frequency signals while attenuating unwanted frequency range			
	8. What is the purpose of the second order band stop filter? a) To amplify a narrow range of frequency b) To attenuate a narrow range of frequency c) To amplify low frequency d) To amplify high frequency			
2.Calculate the parameters of the second order universal filter using three LT1228s.	9. The input voltage is $50mV_{p-p}$, all resistors are 1kΩ, $I_{B1} = I_{B2} = I_{B3} = 125.66\mu A$ and capacitor $C_1 = C_2 = 10nF$. The voltage gain for the second order low pass response is as follows: $\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the natural frequency, f_0			

	ii. the quality factor, Q iii. the passband gain  Fig. 5 a) f_0 = 20kHz, Q = 0.4 and the passband gain = 1.26 b) f_0 =150kHz, Q = 0.89 and the passband gain = 2.26 c) f_0 =200kHz, Q = 1 and the passband gain = 3.26 d) f_0 =250kHz, Q = 1.09 and the passband gain = 4.26				
	10. The input voltage is 50mV$_{p-p}$, all resistors are 1kΩ and the three external DC bias currents are 50uA and capacitor C_1 = C_2 = 1nF. The voltage gain for the second order high pass response in Fig. 5 is as follows: $\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5 s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the natural frequency, f_0 and ii. the quality factor, Q iii. the passband gain				

	a) f_0 = 69.6kHz, Q = 2 and the passband gain = 2 **b)** f_0 =79.6kHz, Q = 1 and the passband gain = 1 **c)** f_0 =89.6kHz, Q = 3 and the passband gain = 3 **d)** f_0 =99.6kHz, Q = 4 and the passband gain = 4			
	11. The input voltage is 50mV$_{p-p}$, f_l = 68.47kHz, f_h = 93.47kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows: $\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$ Calculate i. the natural frequency, f_0 ii. the quality factor, Q iii. the passband gain **a)** f_0 = 70 kHz, Q = 2.2, the passband gain = 0.4 **b)** f_0 = 80 kHz, Q = 3.2, the passband gain = 0.5 **c)** f_0 = 90 kHz, Q = 4.2, the passband gain = 0.6 **d)** f_0 = 100 kHz, Q = 5.2, the passband gain = 0.7			
	12. The input voltage is 50mV$_{p-p}$, the natural frequency, f_0 = 70kHz, the quality factor, Q = 3.7333, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:			

$$\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$$

Calculate

i. the bandwidth, BW
ii. the lower end of natural frequency, f_l
iii. the higher end of natural frequency, f_h

a) BW = 28.75kHz, f_l = 81.25 kHz, f_h = 50 kHz
b) BW = 38.75kHz, f_l = 71.25 kHz, f_h = 60 kH,
c) BW = 48.75kHz, f_l = 51.25 kHz, f_h = 90 kHz
d) BW = 18.75kHz, f_l = 61.25 kHz, f_h = 80 kHz

13. The input voltage is 50mV$_{p-p}$, f_l = 10kHz, f_h = 50kHz, all resistors are 1kΩ and $C_1 = C_2$ = 10nF. The voltage gain for the second order band reject response in Fig. 5 is as follows:

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$$

Calculate

i. the bandwidth, BW
ii. the natural frequency, f_0
iii. the passband gain

a) BW = 50kHz, f_0= 62.36 kHz, the passband gain = 0.2

	b) BW = 70kHz, f_0 = 72.36 kHz, the passband gain = 0.4 **c)** BW = 40kHz, f_0 = 22.36kHz, the passband gain = 1 **d)** BW = 60kHz, f_0 = 52.36 kHz, the passband gain = 1.5			
	14. The input voltage is 50mV$_{p-p}$, the natural frequency, f_0 = 30kHz, the quality factor, Q = 6, all resistors are 1kΩ and C_1 = C_2 = 1nF. The voltage gain for the second order band reject response in Fig. 5 is as follows: $\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the three external DC bias currents (Assume I_{B1} = I_{B2} = I_{B3} = I_B) ii. the lower end of natural frequency, f_l iii. the higher end of natural frequency, f_h **a)** I_{B1} = I_{B2} = I_{B3} = 18.8uA, f_l = 27.6kHz, f_h = 32.6kHz **b)** I_{B1} = I_{B2} = I_{B3} = 28.8uA, f_l = 0.6 kHz, f_h = 42.6kHz **c)** I_{B1} = I_{B2} = I_{B3} = 38.8uA, f_l = 7.6kHz, f_h = 82.6kHz **d)** I_{B1} = I_{B2} = I_{B3} = 8.8uA, f_l = 17.6kHz, f_h = 52.6 kHz			
3. Design the parameters of the	15. Design the second order low pass response using LT1228s to provide the natural			

second order universal filter using three LT1228s.	frequency, f_0 = 70kHz and the pass-band gain = 2. The input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows: $\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the quality factor, Q **a)** $I_{B1} = I_{B2} = I_{B3}$ = 54µA, and R_5 =5.5kΩ, Q = 0.35 **b)** $I_{B1} = I_{B2} = I_{B3}$ =44µA, and R_5 =4.5kΩ, Q = 0.25 **c)** $I_{B1} = I_{B2} = I_{B3}$ = 34µA, and R_5 =3.5kΩ, Q = 0.15 **d)** $I_{B1} = I_{B2} = I_{B3}$ =64µA, and R_5 =6.5kΩ, Q = 0.45			
	16. Design the second order low pass response using LT1228s to provide the natural frequency, f_0 = 105kHz and the quality factor, Q = 0.25. The input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows:			

	$$\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the pass-band gain **a)** $I_{B1} = I_{B2} = I_{B3} = 65.9\mu A$, $R_5 = 3k\Omega$, and the passband gain = 2 **b)** $I_{B1} = I_{B2} = I_{B3} = 35.9\mu A$, $R_5 = 2k\Omega$, and the passband gain = 1 **c)** $I_{B1} = I_{B2} = I_{B3} = 25.9\mu A$, $R_5 = 1k\Omega$, and the passband gain= 4 **d)** $I_{B1} = I_{B2} = I_{B3} = 15.9\mu A$, $R_5 = 5k\Omega$, and the passband gain= 3			
	17. Design the second order high pass response using LT1228s to provide the natural frequency, f_0= 50kHz and the pass-band gain = 2. The input voltage is $50mV_{p-p}$, all resistors are $1k\Omega$ (except R_5) and capacitor $C_1 = C_2 = 1nF$. The voltage gain for the second order high pass response in Fig. 5 is as follows: $$\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5			

		iii. the quality factor, Q **a)** $I_{B1} = I_{B2} = I_{B3} = 52\mu A$, $R_5 = 3k\Omega$, and $Q = 0.45$ **b)** $I_{B1} = I_{B2} = I_{B3} = 42\mu A$, $R_5 = 4.5k\Omega$, and $Q = 0.35$ **c)** $I_{B1} = I_{B2} = I_{B3} = 32\mu A$, $R_5 = 6k\Omega$, and $Q = 0.25$ **d)** $I_{B1} = I_{B2} = I_{B3} = 62\mu A$, $R_5 = 5.5k\Omega$, and $Q = 0.15$			
		18. Design the second order high pass response using LT1228s to provide the natural frequency, $f_0 = 85kHz$ and the quality factor, $Q = 1.5$. The input voltage is $50mV_{p-p}$, all resistors are $1k\Omega$ (except R_5) and capacitor $C_1 = C_2 = 1nF$. The voltage gain for the second order high pass response in Fig. 5 is as follows: $\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5 s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g}{C_1C}}$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the pass-band gain **a)** $I_{B1} = I_{B2} = I_{B3} = 53.4\mu A$, $R_5 = 0.62k\Omega$, and the passband gain = 0.66 **b)** $I_{B1} = I_{B2} = I_{B3} = 43.4\mu A$, $R_5 = 0.32k\Omega$, and the passband gain =0.22			

	c) $I_{B1} = I_{B2} = I_{B3} = 33.4\mu A$, $R_5 = 0.42k\Omega$, and the passband gain = 0.11 **d)** $I_{B1} = I_{B2} = I_{B3} = 23.4\mu A$, $R_5 = 0.62k\Omega$, and the passband gain = 0.44			
	19. Design the second order band pass response using LT1228s to provide f_l= 58.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except R_5) and $C_1 = C_2$ = 1nF. The voltage gain for the second order band pass response in Fig. 5 is as follows: $\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m}}{C_1C}}$ Determine **i.** the natural frequency, f_0 **ii.** the bandwidth, BW **iii.** the quality factor, Q **a)** f_0 = 50kHz, BW= 5kHz, and Q = 0.8 **b)** f_0 = 60kHz, BW= 15kHz, and Q = 1.8 **c)** f_0 = 70kHz, BW= 25kHz, and Q = 2.8 **d)** f_0 = 30kHz, BW=35kHz, and Q = 3.8			
	20. Design the second order band pass response using LT1228s to provide f_l = 8kHz, f_h = 12.5kHz, all resistors are 1kΩ (except R_5) and $C_1 = C_2$ = 1nF. The voltage gain (dB) for the second order band pass response in Fig. 5 is as follows: $\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m}}{C_1C}}$			

	Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the quality factor, Q iii. the value of R_5 **a)** $I_{B1} = I_{B2} = I_{B3} =$ 5.28μA, Q = 1.2, and R_5 =2.6kΩ **b)** $I_{B1} = I_{B2} = I_{B3} =$ 6.28μA, Q = 2.2, and R_5 =3.6kΩ **c)** $I_{B1} = I_{B2} = I_{B3} =$ 7.28μA, Q = 3.2, and R_5 =4.6kΩ **d)** $I_{B1} = I_{B2} = I_{B3} =$ 8.28μA, Q = 4.2, and R_5 =5.6kΩ			
	21. Design the second order band reject response using LT1228s to provide f_l= 35.6kHz, f_h = 83.6kHz, all resistors are 1kΩ (except R_5) and $C_1 = C_2 =$ 1nF. The voltage gain for the second order band reject response in Fig. 5 is as follows: $\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine **i.** the natural frequency, f_0 **ii.** the passband gain **iii.** he quality factor, Q **a)** f_0 = 24.5kHz, the passband gain =1, and Q = 4.13 **b)** f_0 = 44.5kHz, the passband gain =2, and Q = 2.13 **c)** f_0 = 84.5kHz, the passband gain =0.5, and Q = 3.13			

	d) f_0 = 54.5kHz, the passband gain =1.5, and Q = 1.13			
	22. Design the second order band reject response using LT1228s to provide f_l = 6kHz, f_h = 15kHz, all resistors are 1kΩ (except R_5) and C_1 = C_2 = 1nF. The voltage gain (dB) for the second order band reject response in Fig. 5 is as follows: $$\frac{V_{BR}}{V_{in}}=\frac{-\left(s^2+\frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$$ Determine **i.** the three external DC bias currents (Assume I_{B1} = I_{B2} = I_{B3} = I_B) **ii.** the quality factor, Q **iii.** the val			

	ue of R_5 **a)** $I_{B1} = I_{B2} = I_{B3}$ =5.96µA, Q = 1.05, and R_5 =8kΩ **b)** $I_{B1} = I_{B2} = I_{B3}$ =6. 96µA, Q = 2.05, and R_5 =9kΩ **c)** $I_{B1} = I_{B2} = I_{B3}$ =7. 96µA, Q = 3.05, and R_5 =10kΩ **d)** $I_{B1} = I_{B2} = I_{B3}$ =8. 96µA, Q = 4.05, and R_5 =11kΩ			

D-2 Content validity of achievement test

Behavioral objectives	Achievement Test	Expert's opinion E1	E2	E3	E4	E5	IOC	S.D.	Conclusion	Selected
Topic 1 Question (1 to 15)										
	1	1	1	-1	-1	0	0.00	1.00	Can't use	*
1	2	1	1	1	-1	0	0.40	0.89	Can't use	
	3	1	1	1	1	0	0.80	0.45	Ok	✓
	4	1	1	1	1	0	0.80	0.45	Ok	
	5	1	1	1	0	0	0.60	0.55	Ok	
	6	1	1	1	1	0	0.80	0.45	Ok	✓
	7	1	1	1	1	0	0.80	0.45	Ok	✓
	8	1	1	1	1	0	0.80	0.45	Ok	
2	9	1	1	0	-1	0	0.20	0.84	Can't use	*
	10	1	1	-1	1	0	0.40	0.89	Can't use	*
	11	1	1	0	1	1	0.80	0.45	Ok	✓
	12	1	1	0	0	1	0.60	0.55	Ok	
	13	1	1	1	1	0	0.80	0.45	Ok	✓
	14	1	1	1	1	0	0.80	0.45	Ok	✓
3	15	1	1	0	1	1	0.80	0.45	Ok	✓
Topic 2 Question (1 to 22)										
	1	1	1	1	1	0	0.80	0.45	Ok	
	2	1	1	1	-1	0	0.40	0.89	Can't use	*
1	3	1	1	1	1	0	0.80	0.45	Ok	✓
	4	1	1	0	1	0	0.60	0.55	Ok	

	5	1	1	1	1	0	0.80	0.45	Ok	✓
	6	1	1	1	1	0	0.80	0.45	Ok	
	7	1	1	1	1	0	0.80	0.45	Ok	
	8	1	1	0	0	0	0.40	0.55	Can't use	
	9	1	1	0	1	0	0.60	0.55	Ok	
	10	1	1	0	1	0	0.60	0.55	Ok	
2	11	1	1	1	1	1	1.00	0.00	Ok	✓
	12	1	1	1	1	0	0.80	0.45	Ok	
	13	1	1	1	1	0	0.80	0.45	Ok	
	14	1	1	1	1	0	0.80	0.45	Ok	✓
	15	1	1	1	1	0	0.80	0.45	Ok	✓
	16	1	1	1	1	0	0.80	0.45	Ok	
3	17	1	1	1	1	0	0.80	0.45	Ok	✓
	18	1	1	1	1	0	0.80	0.45	Ok	✓
	19	1	1	1	1	0	0.80	0.45	Ok	
	20	1	1	1	1	0	0.80	0.45	Ok	
	21	1	1	1	1	0	0.80	0.45	Ok	✓
	22	1	1	1	1	0	0.80	0.45	Ok	✓
Topic 3 Question (1 to 23)										
1	1	1	1	1	1	0	0.80	0.00	Ok	
	2	1	1	1	1	0	0.80	0.00	Ok	✓
	3	1	1	1	1	0	0.80	0.00	Ok	
	4	1	1	0	1	0	0.60	0.50	Ok	✓
	5	1	1	1	1	0	0.80	0.00	Ok	✓
	6	1	1	1	1	0	0.80	0.00	Ok	
	7	1	1	1	-1	0	0.40	1.00	Can't use	
	8	1	1	0	-1	0	0.20	0.96	Can't use	
	9	1	1	0	1	0	0.60	0.50	Ok	
	10	1	1	1	1	0	0.80	0.00	Ok	✓

2	11	1	1	1	1	0	0.80	0.00	Ok	✓
	12	1	1	1	1	0	0.80	0.00	Ok	✓
	13	1	1	1	1	0	0.80	0.00	Ok	
	14	1	1	1	1	0	0.80	0.00	Ok	✓
	15	1	1	1	1	0	0.80	0.00	Ok	
3	16	1	1	1	1	0	0.80	0.00	Ok	✓
	17	1	1	1	1	0	0.80	0.00	Ok	
	18	1	1	1	1	0	0.80	0.00	Ok	
	19	1	1	1	1	0	0.80	0.00	Ok	
	20	1	1	1	1	1	1.00	0.00	Ok	✓
	21	1	1	1	1	0	0.80	0.00	Ok	
	22	1	1	1	1	0	0.80	0.00	Ok	✓
	23	1	1	1	1	0	0.80	0.00	Ok	

* refer to modified questions that is match with behavioral objectives and the experts' comments.

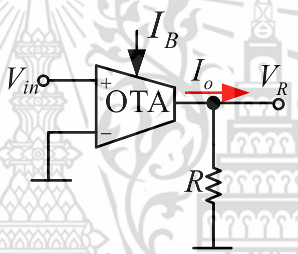
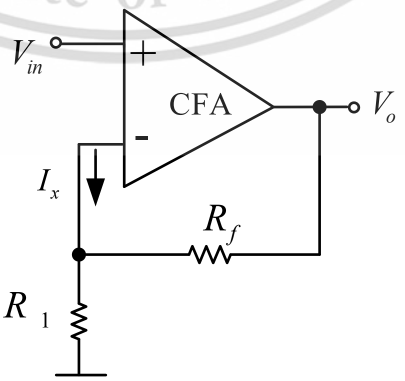
Achievement Test

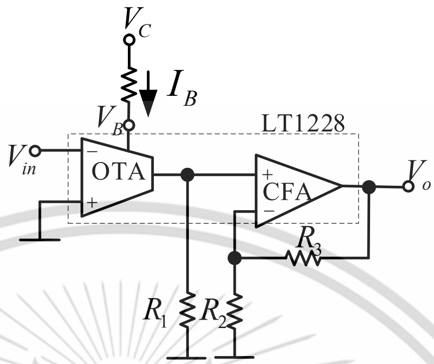
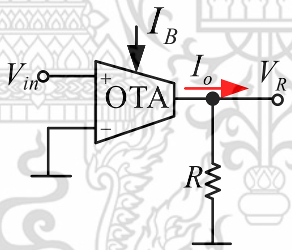
By
MS. May Phu Pwint Wai
Department of Engineering Education
Faculty of Industrial Education and Technology
King Mongkut's Institute of Technology Ladkrabang (KMITL)
62603017@kmitl.ac.th

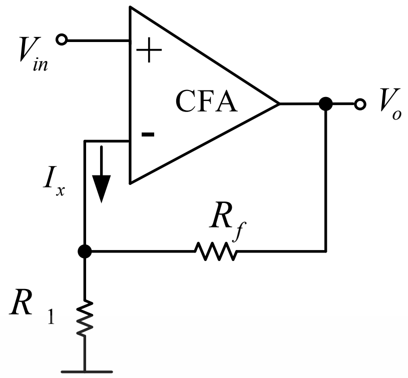
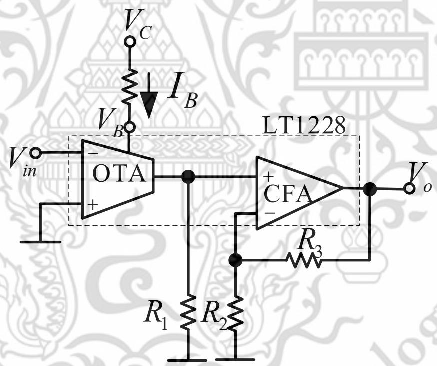
TABLE OF CONTENTS

	Field of Study: Engineering Education Title: Basic concept of LT1228 Class: Second Year	Achievement Test	Page: 3/12

Behavioral Objective	Questions	Consideration Score		
		+1	0	-1
	Questions 1 to 10 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.			
1. Describes the basic features of LT1228.	**1.** What is the transconductance equation for LT1228? **a)** $g_m = \frac{I_B}{2V_T}$ **b)** $g_m = \frac{2I_B}{V_T}$ **c)** $g_m = \frac{I_B}{10}$ **d)** $g_m = 10I_B$			
	2. In ideal OTA part of LT1228, the current at *y* terminal is as follows: **a)** $I_y = g_m V_+$ **b)** $I_y = g_m V_-$ **c)** $I_y = g_m (V_+ - V_-)$ **d)** $I_y = g_m (V_- - V_+)$			
	3. All the following statements show in which LT1228 can perform both functions. **a)** operational transconductance amplifier (OTA) and current feedback amplifier (CFA) **b)** operational amplifier (Op-amp) and current follower (CFA)			

	c) operational transconductance amplifier (OTA) and voltage feedback amplifier (VFA) **d)** operational amplifier (Op-amp) and current feedback amplifier (CFA)			
	4. In ideal CFA part of LT1228, its output voltage can be seen as **a)** $V_w = I_y R_w$ **b)** $V_w = I_x R_w$ **c)** $V_w = I_x R_T$ **d)** $V_w = I_y R_T$			
2. Calculate the parameters of LT1228.	5. Determine the OTA voltage gain when R = 1kΩ and I_B = 185µA?  Fig. 1 **a)** 6.85 **b)** 4.85 **c)** 2.85 **d)** 1.85			
	6. Determine the CFA voltage gain for when R_f = 1kΩ and R_1 =2kΩ.  Fig. 2 **a)** 1.5 **b)** 2.5			

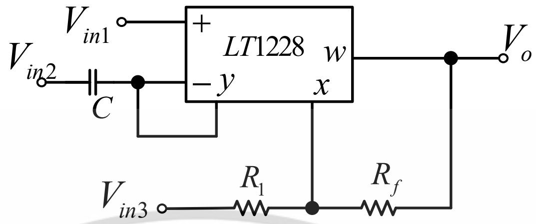
	c) 3.5 **d)** 4.5			
	7. The input voltage is 50mV$_{p-p}$, and all resistors are 1kΩ. Determine the LT1228 voltage gain when its external DC bias current is 150μA in Fig. 3?  Fig. 3 **a) -4** **b) -3** **c) -2** **d) -1**			
3. Design the parameters of voltage gain amplifier using LT1228.	8. Design the OTA voltage gain of 5 when I_B= 100μA in Fig. 1.  Fig. 1 **a)** R_1 =2kΩ **b)** 3kΩ **c)** 4kΩ **d)** 5kΩ			
	9. Design the CFA voltage gain of 4 when R_f =1.2kΩ in Fig. 2.			

	 Fig. 2 **a)** 0.2kΩ **b)** 0.3kΩ **c)** 0.4kΩ **d)** 0.5kΩ			
	10. Design the voltage gain amplifier using LT1228 to provide gain of -2 with external DC bias current is 100uA. The input voltage is 50mV$_{p-p}$, and R_3 = 1kΩ and R_2 =1kΩ. Determine R_1 in Fig. 3.  Fig. 3 **a)** R_1 =1kΩ **b)** R_1 = 3.5kΩ **c)** R_1 = 4kΩ **d)** R_1 = 6.5kΩ			

	Field of Study: Engineering Education **Title: First order multifunction filter using single LT1228** **Class: Second Year**	**Achievement Test**	**Page: 8/13**

Behavioral Objectives	**Questions**	**Consideration score**		
		+1	**0**	**-1**
1. Describe the basic features of the first order multifunction filter using single LT1228.	1. The gain of the first order low pass filter **e)** Increases at the rate 20dB/decade **f)** Increases at the rate 40dB/decade **g)** Decreases at the rate 20dB/decade **h)** Decreases at the rate 40dB/decade			
	2. The point at which the response drops –3 dB from the passband is called a) Cutoff frequency b) Natural frequency c) Center frequency 2. d) All the above			
	3. Which filter rejects the low frequency and passes the high frequency. **a)** All-pass filter **b)** High pass filter **c)** Low-pass filter **d)** Band-stop filter			
	4. What is the purpose of a low pass filter? a) To attenuate high frequency signals b) To amplify low frequency signals c) To attenuate low frequency signals d) To amplify high frequency signals			
	5. Which statements agree with the output and input voltages are equal in amplitude for all frequencies? **a)** All-pass filter **b)** High pass filter **c)** Band-pass filter **d)** Band-stop filter			

	6. In a first order low pass filter, frequencies lower than cutoff frequencies are called as **a)** Stop band frequency **b)** Center band frequency **c)** Pass band frequency **d)** None of the mentioned			
	7. Which filter rejects all frequencies within a specified band and passes all those outside this band. **a)** band-stop **b)** low pass **c)** high pass **d)** band-pass			
	8. Name the filter that has two stop bands? a) Band-reject filter b) High pass filter c) Low pass filter d) Band-pass filter			
	9. Which filter performs exactly the opposite to the band-stop filter? a) Band-elimination filter b) Low pass filter c) Band-pass filter d) None of the above			
	10. Which filter passes the low frequency and rejects the high frequency. a) High pass filter b) All-pass filter c) Band-stop filter d) Low pass filter			
2. Calculate the parameters of the first order multifuncti	11. The input voltage is $50mV_{p-p}$, all resistors are 1kΩ and the external DC bias current is 50uA and capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 1 is as follows:			

on filter using single LT1228.	$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1}=V_{in})$ Determine i. the natural frequency, f_0 ii. the passband gain  Fig. 1 a) f_0 = 25.7kHz, passband gain = 1 b) f_0 = 39.8kHz, passband gain = 2 c) f_0 = 45.7kHz, passband gain = 3 d) f_0 = 55.7kHz, passband gain = 4			
	12. The input voltage, V_{in2} is 50mV$_{p-p}$, all resistors are 1kΩ and the external DC bias current is 70µA and capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right)(\because V_{in2}=V_{in})$ Determine i. the natural frequency, f_0 ii. the passband gain a) f_0 = 55.7kHz, passband gain = 2 b) f_0 = 63.6kHz, passband gain = 1.5 c) f_0 = 73.6kHz, passband gain = 1 d) f_0 = 83.6kHz, passband gain = 0.5			
	13. The input voltage is 50mV$_{p-p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order low pass voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1}=V_{in})$			

	Determine the low pass phase response at f_0 = 98kHz. **a)** -30º **b)** -45º **c)** -60º **d)** -0º			
	14. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order high pass voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right)(\because V_{in2}=V_{in})$ Determine the high pass phase response at f_0 = 98kHz. **a)** 30º **b)** 45º **c)** 60º **d)** 90º			
	15. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order non-inverting AP voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}}(\because V_{in2}=V_{in3}=V_{in})$ Determine the non-inverting AP phase response at f_0 = 98kHz. **a)** 45º **b)** 60º **c)** 90º **d)** 180º			
	16. The input voltage is 50mV$_{p\text{-}p}$, the external DC bias current is 123 µA, all resistors are 1kΩ, capacitor C = 2nF. The first order inverting AP voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}} = \frac{-\left(s-\frac{g_m}{C}\right)}{s+\frac{g_m}{C}}(\because V_{in1}=V_{in3}=V_{in})$ Determine the inverting AP phase response at f_0 = 98kHz. **a)** -45º			

	b) - 90º **c)** -60º **d)** -180º			
3. Design the parameters of the first order multifunction filter using single LT1228.	17. Design the first order multifunction filter using single LT1228 to provide the passband gain 5, the natural frequency, f_0 = 98kHz, the input voltage is $50mV_{p-p}$, R_f =1kΩ, and capacitor C = 2nF in Fig. 1. The first order low pass voltage gain equation is as follows: $$\frac{V_o}{V_{in}} = \frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}} (\because V_{in1} = V_{in})$$ Determine i. the value of R_1 ii. the external DC bias currents a) R_1 = 0.25kΩ and I_B = 123µA b) R_1 = 1kΩ and I_B = 62µA c) R_1 = 2kΩ and I_B = 50µA d) R_1 = 1kΩ and I_B = 162µA			
	18. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF in Fig. 1. The first order high pass voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right) (\because V_{in2} = V_{in})$$ Determine the external DC bias current to provide its natural frequency, f_0=100kHz. a) 25uA b) 70uA c) 125uA d) 100uA			
	19. Design the first order multifunction filter using single LT1228 when the input voltage is $50mV_{p-p}$, all resistors are 1kΩ, capacitor C = 2nF, the external DC bias current is 123uA. The first order low pass voltage gain equation in Fig. 1 is as follows:			

	$\frac{V_o}{V_{in}}=\frac{\left(1+\frac{R_f}{R_1}\right)\frac{g_m}{C}}{s+\frac{g_m}{C}}(\because V_{in1}=V_{in})$ Determine the frequency to provide its LP phase response is -54º. a) 108kHz b) 135kHz c) 88kHz d) 98kHz			
	20. Design the first order multifunction filter using single LT1228 when the input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order high pass voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}}=\left(\frac{\left(1+\frac{R_f}{R_1}\right)\times s}{s+\frac{g_m}{C}}\right)(\because V_{in2}=V_{in})$ Determine the frequency to provide its HP phase response is 36º. a) 98kHz b) 135kHz c) 88kHz d) 108kHz			
	21. Design the first order multifunction filter using single LT1228 when the input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF, the external DC bias current is 123uA. The first order non-inverting AP voltage gain equation in Fig. 1 is as follows: $\frac{V_o}{V_{in}}=\frac{s-\frac{g_m}{C}}{s+\frac{g_m}{C}}(\because V_{in2}=V_{in3}=V_{in})$ Determine the frequency to provide its non-inverting AP phase response is 135 º. a) 40kHz b) 90 kHz c) 100kHz d) 110kHz			
	22. Design the first order multifunction filter using single LT1228			

	when the input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ, capacitor C = 2nF, and the external DC bias current is 123uA. The first order inverting AP voltage gain equation in Fig. 1 is as follows: $$\frac{V_o}{V_{in}} = \frac{-\left(s - \frac{g_m}{C}\right)}{s + \frac{g_m}{C}} \left(\because V_{in1} = V_{in3} = V_{in}\right)$$ Determine the frequency to provide its inverting AP phase response is -108º. a) 135kHz b) 98 kHz c) 108kHz d) 88kHz			

	Field of Study: Engineering Education **Title: Second order universal filter using three LT1228s** **Class Second Year**	**Achievement Test**	**Page: 14/21**

Behavioral Objectives	**Questions**	**Consideration score**		
		+1	**0**	**-1**
	Questions 1 to 10 Choose the correct letter, **a, b, c, or d**. Circle the correct answer.			
1. Describe the basic features of the second order universal filter using three LT1228s.	1. What is the roll of rate of the second order high pass filter? a) 20dB/decade b) 40dB/decade c) 60dB/decade d) 80dB/decade			
	2. The transfer function of second order low pass function is $\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$. What is the natural frequency for second order low pass function? a) $\omega_0 = \frac{g_{m1}g_{m2}}{C_1C_2}$ b) $\omega_0 = \frac{g_{m1}}{C_2}$ c) $\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$ d) $\omega_0 = \frac{g_{m2}}{C_1}$			
	3. The transfer function of second order high pass function is $\frac{V_{HP}}{V_{in}} = \frac{-2as^2}{s^2+\frac{2ag_{m2}}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}} (where \bullet a = g$. What is the quality factor for second order high pass function?			

	a) $Q=\frac{1}{a}\sqrt{\frac{C_2 g_{m1}}{C_1 g_{m2}}}$ b) $Q=\frac{1}{2a}\sqrt{\frac{C_2 g_{m1}}{C_1 g_{m2}}}$ c) $Q=\frac{1}{a}\sqrt{\frac{C_1 g_{m2}}{C_2 g_{m1}}}$ d) $Q=\frac{1}{2a}\sqrt{\frac{C_1 g_{m2}}{C_2 g_{m1}}}$			
	4. In band pass filter, the BW and Q relationship is a) $f_0 = \frac{BW}{Q}$ b) $BW = \frac{Q}{f_0}$ c) $BW = \frac{f_0}{Q}$ d) $BW = f_0 \times Q$			
	5. Which statements describe the formula for the center frequency of band pass filter? a) $f_0 = \frac{f_H + f_L}{2}$ b) $f_0 = \sqrt{f_H * f_L}$ c) $f_0 = \sqrt{f_H^2 + f_L^2}$ d) $f_0 = \sqrt{f_H - f_L}$			
	6. What is the phase shift of a second order band pass filter at natural frequency? a) -45^{o} b) -90^{o} c) -180^{o} d) 0^{o}			
	7. What is the Q factor of a second order band stop filter? a) It is a measure of the filter's bandwidth at a specific frequency b) It is a measure of the filter's gain at a specific frequency			

	c) It is a measure of the filter's attenuation at a specific frequency d) It is a measure of the filter's phase shift at a specific frequency			
	8. What is the purpose of the second order band pass filter? a) To isolate and amplify a narrow range of frequency while attenuating outside of this frequency range b) To amplify low frequency while attenuating unwanted frequency range c) To amplify high frequency signals while attenuating unwanted frequency range d) To isolate and amplify a specific frequency range while attenuating outside of this frequency range			
	9. What is the purpose of the second order band stop filter? a) To attenuate a narrow range of frequency b) To amplify a narrow range of frequency c) To amplify low frequency d) To amplify high frequency			
2.Calculate the parameters of the second order universal filter using three LT1228s.	10. The input voltage is $50mV_{p-p}$, all resistors are 1kΩ, $I_{B1} = I_{B2} = I_{B3} =$ 100µA and capacitor $C_1 = C_2 =$ 10nF. The voltage gain for the second order low pass response is as follows: $\frac{V_{LP}}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the natural frequency, f_0 ii. the quality factor, Q iii. the passband gain			

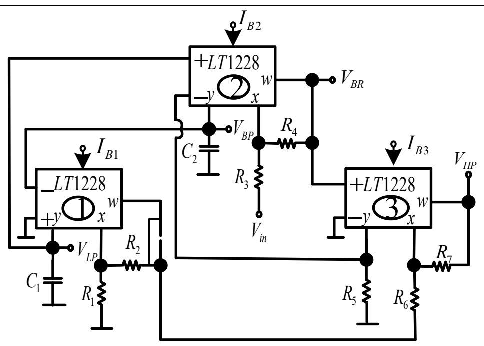
<table>
<tr><td></td><td>


Fig. 5

a) f_0 = 16kHz, Q = 1 and the passband gain = 1
b) f_0 =56kHz, Q = 1.5 and the passband gain = 2
c) f_0 =66kHz, Q = 2.5 and the passband gain = 3
d) f_0 =76kHz, Q = 3.5 and the passband gain = 4
</td><td></td><td></td><td></td></tr>
<tr><td></td><td>
11. The input voltage is 50mV$_{p\text{-}p}$, all resistors are 1kΩ and the three external DC bias currents are 150uA and capacitor C_1 = C_2 = 1nF. The voltage gain for the second order high pass response in Fig. 5 is as follows:

$$\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5 s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$

Calculate
i. the natural frequency, f_0
ii. the quality factor, Q
iii. the passband gain

a) f_0 = 69.6kHz, Q = 2 and the passband gain = 2
b) f_0 =238.7kHz, Q = 0.3333 and the passband gain = 3
c) f_0 =89.6kHz, Q = 3 and the passband gain = 5
d) f_0 =99.6kHz, Q = 4 and the passband gain = 4
</td><td></td><td></td><td></td></tr>
<tr><td></td><td>
12. The input voltage is 50mV$_{p\text{-}p}$, f_l = 68.47kHz, f_h = 93.47kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows:
</td><td></td><td></td><td></td></tr>
</table>

	$\dfrac{V_{BP}}{V_{in}} = \dfrac{\dfrac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \dfrac{2g_{m2}g_{m3}R_5}{C_2}s + \dfrac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the bandwidth, BW ii. the quality factor, Q iii. the passband gain a) BW = 15kHz, Q = 2.2, the passband gain = 0.4 b) BW= 25kHz, Q = 3.2, the passband gain = 0.5 c) BW = 35 kHz, Q = 4.2, the passband gain = 0.6 d) f_0 = 45 kHz, Q = 5.2, the passband gain = 0.7			
	13. The input voltage is 50mV$_{p\text{-}p}$, the natural frequency, f_0 = 70kHz, the quality factor, Q = 3.7333, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order band pass response in Fig. 5 is as follows: $\dfrac{V_{BP}}{V_{in}} = \dfrac{\dfrac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \dfrac{2g_{m2}g_{m3}R_5}{C_2}s + \dfrac{g_{m1}g_{m2}}{C_1C_2}}$ Calculate i. the bandwidth, BW ii. the lower end of natural frequency, f_l iii. the higher end of natural frequency, f_h a) BW = 28.75kHz, f_l = 81.25 kHz, f_h = 50 kHz b) BW = 38.75kHz, f_l = 71.25 kHz, f_h = 60 kH, c) BW = 18.75kHz, f_l = 61.25 kHz, f_h = 80 kHz d) BW = 48.75kHz, f_l = 51.25 kHz, f_h = 90 kHz			
	14. The input voltage is 50mV$_{p\text{-}p}$, f_l = 20kHz, f_h = 60kHz, all resistors are 1kΩ and C_1 = C_2 = 10nF. The voltage gain for the second order			

	band reject response in Fig. 5 is as follows: $$\frac{V_{BR}}{V_{in}}=\frac{-\left(s^2+\frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$$ Calculate i. the bandwidth, BW ii. the natural frequency, f_0 iii. the passband gain a) BW = 50kHz, f_0= 62.36 kHz, the passband gain = 0.2 b) BW = 70kHz, f_0 = 72.36 kHz, the passband gain = 0.4 c) BW = 40kHz, f_0 = 22.36kHz, the passband gain = 1 d) BW = 60kHz, f_0 = 52.36 kHz, the passband gain = 1.5				
	15. The input voltage is 50mV$_{p-p}$, the natural frequency, f_0 = 30kHz, the quality factor, Q = 6, all resistors are 1kΩ and C_1 = C_2 = 1nF. The voltage gain for the second order band reject response in Fig. 5 is as follows: $$\frac{V_{BR}}{V_{in}}=\frac{-\left(s^2+\frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$$ Calculate i. the three external DC bias currents (Assume I_{B1} = I_{B2} = I_{B3} = I_B) ii. the lower end of natural frequency, f_l iii. the higher end of natural frequency, f_h a) I_{B1} = I_{B2} = I_{B3} = 28.8uA, f_l = 0.6 kHz, f_h = 42.6kHz b) I_{B1} = I_{B2} = I_{B3} = 38.8uA, f_l = 7.6kHz, f_h = 82.6kHz c) I_{B1} = I_{B2} = I_{B3} = 8.8uA, f_l = 17.6kHz, f_h = 52.6 kHz d) I_{B1} = I_{B2} = I_{B3} = 18.8uA, f_l = 27.6kHz, f_h = 32.6kHz				
	16. Design the second order low pass response using LT1228s to provide				

	the natural frequency, f_0 = 70kHz and the pass-band gain = 2. The input voltage is $50mV_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows: $$\frac{V_{LP}}{V_{in}}=\frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the quality factor, Q **a)** $I_{B1} = I_{B2} = I_{B3}$ =44µA, and R_5 =4.5kΩ, Q = 0.25 **b)** $I_{B1} = I_{B2} = I_{B3}$ = 54µA, and R_5 =5.5kΩ, Q = 0.35 **c)** $I_{B1} = I_{B2} = I_{B3}$ = 34µA, and R_5 =3.5kΩ, Q = 0.15 **d)** $I_{B1} = I_{B2} = I_{B3}$ =64µA, and R_5 =6.5kΩ, Q = 0.45			
3. Design the parameters of the second order universal filter using three LT1228s.	17. Design the second order low pass response using LT1228s to provide the natural frequency, f_0 = 105kHz and the quality factor, Q = 0.25. The input voltage is $50mV_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order low pass response in Fig. 5 is as follows: $$\frac{V_{LP}}{V_{in}}=\frac{\frac{-g_{m1}g_{m2}g_{m3}R_5}{C_1C_2}}{s^2+\frac{2g_{m2}g_{m3}R_5}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}$$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the pass-band gain			

	a) $I_{B1} = I_{B2} = I_{B3}$ = 35.9µA, R_5 =2kΩ, and the passband gain = 1 **b)** $I_{B1} = I_{B2} = I_{B3}$ = 65.9µA, R_5 =3kΩ, and the passband gain = 2 **c)** $I_{B1} = I_{B2} = I_{B3}$ = 25.9µA, R_5 =1kΩ, and the passband gain = 4 **d)** $I_{B1} = I_{B2} = I_{B3}$ = 15.9µA, R_5 =5kΩ, and the passband gain = 3			
	18. Design the second order high pass response using LT1228s to provide the natural frequency, f_0 = 50kHz and the pass-band gain = 2. The input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order high pass response in Fig. 5 is as follows: $\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the quality factor, Q **a)** $I_{B1} = I_{B2} = I_{B3}$ = 52µA, R_5 =3kΩ, and Q = 0.45 **b)** $I_{B1} = I_{B2} = I_{B3}$ =42µA, R_5 =4.5kΩ, and Q = 0.35 **c)** $I_{B1} = I_{B2} = I_{B3}$ = 32µA, R_5 =6kΩ, and Q = 0.25 **d)** $I_{B1} = I_{B2} = I_{B3}$ =62µA, R_5 =5.5kΩ, and Q = 0.15			
	19. Design the second order high pass response using LT1228s to provide the natural frequency, f_0 = 85kHz and the quality factor, Q = 1.5. The input voltage is 50m$V_{p\text{-}p}$, all resistors are 1kΩ (except R_5) and capacitor $C_1 = C_2$ = 1nF. The voltage gain for the second order high pass response in Fig. 5 is as follows:			

	$\frac{V_{HP}}{V_{in}} = \frac{-2g_{m3}R_5s^2}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the value of R_5 iii. the pass-band gain **a)** $I_{B1} = I_{B2} = I_{B3} = 43.4\mu A$, $R_5 = 0.32k\Omega$, and the passband gain $= 0.22$ **b)** $I_{B1} = I_{B2} = I_{B3} = 53.4\mu A$, $R_5 = 0.62k\Omega$, and the passband gain $= 0.66$ **c)** $I_{B1} = I_{B2} = I_{B3} = 33.4\mu A$, $R_5 = 0.42k\Omega$, and the passband gain $= 0.11$ **d)** $I_{B1} = I_{B2} = I_{B3} = 23.4\mu A$, $R_5 = 0.62k\Omega$, and the passband gain $= 0.44$			
	20. Design the second order band pass response using LT1228s to provide $f_l = 58.6kHz$, $f_h = 83.6kHz$, all resistors are $1k\Omega$ (except R_5) and $C_1 = C_2 = 1nF$. The voltage gain for the second order band pass response in Fig. 5 is as follows: $\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine **i.** the natural frequency, f_0 **ii.** the bandwidth, BW **iii.** the quality factor, Q **a)** $f_0 = 70kHz$, BW= 25kHz, and $Q = 2.8$ **b)** $f_0 = 50kHz$, BW= 5kHz, and $Q = 0.8$ **c)** $f_0 = 60kHz$, BW= 15kHz, and $Q = 1.8$ **d)** $f_0 = 30kHz$, BW=35kHz, and $Q = 3.8$			
	21. Design the second order band pass response using LT1228s to provide $f_l = 8kHz$, $f_h = 12.5kHz$, all			

	resistors are 1kΩ (except R_5) and $C_1 = C_2 = 1$nF. The voltage gain (dB) for the second order band pass response in Fig. 5 is as follows: $\frac{V_{BP}}{V_{in}} = \frac{\frac{g_{m2}g_{m3}R_5}{C_2}s}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the quality factor, Q iii. the value of R_5 **a)** $I_{B1} = I_{B2} = I_{B3} = 5.28\mu A$, $Q = 1.2$, and $R_5 = 2.6k\Omega$ **b)** $I_{B1} = I_{B2} = I_{B3} = 6.28\mu A$, $Q = 2.2$, and $R_5 = 3.6k\Omega$ **c)** $I_{B1} = I_{B2} = I_{B3} = 7.28\mu A$, $Q = 3.2$, and $R_5 = 4.6k\Omega$ **d)** $I_{B1} = I_{B2} = I_{B3} = 8.28\mu A$, $Q = 4.2$, and $R_5 = 5.6k\Omega$			
	22. Design the second order band reject response using LT1228s to provide f_l= 35.6kHz, f_h= 83.6kHz, all resistors are 1kΩ (except R_5) and $C_1 = C_2 = 1$nF. The voltage gain for the second order band reject response in Fig. 5 is as follows: $\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$ Determine **i.** the natural frequency, f_0 **ii.** the passband gain **iii.** the quality factor, Q **a)** f_0 = 24.5kHz, the passband gain =1, and Q = 4.13 **b)** f_0 = 44.5kHz, the passband gain =2, and Q = 2.13 **c)** f_0 = 54.5kHz, the passband gain =1.5, and Q = 1.13 **d)** f_0 = 84.5kHz, the passband gain =0.5, and Q = 3.13			

	23. Design the second order band reject response using LT1228s to provide $f_l = 6$kHz, $f_h = 15$kHz, all resistors are 1kΩ (except R_5) and $C_1 = C_2 = 1$nF. The voltage gain (dB) for the second order band reject response in Fig. 5 is as follows: $$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + \frac{2g_{m2}g_{m3}R_5}{C_2}s + \frac{g_{m1}g_{m2}}{C_1C_2}}$$ Determine i. the three external DC bias currents (Assume $I_{B1} = I_{B2} = I_{B3} = I_B$) ii. the quality factor, Q iii. the value of R_5 **a)** $I_{B1} = I_{B2} = I_{B3}$ =6. 96µA, Q = 2.05, and R_5 =9kΩ **b)** $I_{B1} = I_{B2} = I_{B3}$ =5.96µA, Q = 1.05, and R_5 =8kΩ **c)** $I_{B1} = I_{B2} = I_{B3}$ =7. 96µA, Q = 3.05, and R_5 =10kΩ **d)** $I_{B1} = I_{B2} = I_{B3}$ =8. 96µA, Q = 4.05, and R_5 =11kΩ			

D-3 Quality Evaluation form of analog filter design

Assessment Items	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Total	Average	S.D.
1. Lesson plan based on the MIAP learning model								
1.1.Behavioral objectives are clear.	5	5	5	4	5	24	4.8	0.45
1.2. The time spent on each activity is appropriate to the level of the student.	5	4	4	4	4	21	4.2	0.45
1.3. The sorting of activities is appropriate.	5	5	4	4	4	22	4.4	0.55
1.4. Teaching activities are consistent with the behavioral objectives.	5	5	4	4	4	22	4.4	0.55
1.5. Teaching media are consistent with behavioral objectives.	5	5	3	4	5	22	4.4	0.89
1.6. Learning activities develop the students' self-learning and problem-solving skills.	5	5	4	4	5	23	4.6	0.55
Average							**4.47**	**0.57**
2. Laboratory sheets								
2.1. The content of the laboratory sheets is correct	5	5	4	5	4	23	4.6	0.55
2.2. The content of the laboratory sheets is consistent with the teaching 5objectives.	5	5	5	5	4	24	4.8	0.45
2.3. The content of the laboratory sheets is difficult and easy, suitable for the student's level.	5	5	4	4	4	22	4.4	0.55
2.4. The language used in the laboratory sheets is appropriate.	5	5	4	4	4	22	4.4	0.55

2.5. The clarity of the figures, tables, or graphs on the laboratory sheets is appropriate.	5	4	4	5	4	22	4.4	0.55
2.6. The order of the experimental steps in the laboratory sheets is appropriate.	5	5	4	5	4	23	4.6	0.55
2.7. The experimental procedures in the laboratory sheets are described in detail and clearly.	5	5	4	5	5	24	4.8	0.45
Average							**4.52**	**0.52**
3. PowerPoints								
3.1. The content of the PowerPoints is correct, interesting, and appropriate.	5	4	3	3	5	20	4	1.00
3.2. The content of the PowerPoints is consistent with the teaching objectives.	5	5	4	4	4	22	4.4	0.55
3.3. The content of the PowerPoints is difficult and easy, suitable for the student's level.	4	5	4	4	4	21	4.2	0.45
3.4. The font colors and font sizes on the PowerPoints are appropriate.	4	4	3	5	4	20	4	0.71
3.5. The clarity of the figures, tables, or graphs on the PowerPoints is appropriate.	5	4	3	5	4	21	4.2	0.84
3.6. The content of the PowerPoints encourages learning.	4	5	4	5	4	22	4.4	0.55
Average							**4.2**	**0.68**

4. Experimental set								
4.1. The color and size of the experimental set are appropriate.	5	5	5	5	4	24	4.8	0.45
4.2. The font colors and font sizes on the experimental set are appropriate.	5	4	5	5	4	23	4.6	0.55
4.3. The placement of the devices on the experimental set is appropriate.	5	5	5	5	4	24	4.8	0.45
4.4. The position of the devices on the experimental set makes it convenient to conduct experiments.	5	5	4	5	4	23	4.6	0.55
4.5. The use of the experimental set is easy and safe.	5	5	4	4	4	22	4.4	0.55
4.6. The ease of transport and storage of the experimental set is appropriate.	5	5	5	4	4	23	4.6	0.55
Average							**4.63**	**0.51**
5. Achievement test and quizzes								
5.1. The questions in the achievement test and quizzes are consistent with the teaching objectives.	5	5	4	4	4	22	4.4	0.55
5.2. The questions in the achievement test and quizzes are difficult and easy, suitable for the student's level.	4	5	4	4	4	21	4.2	0.45

5.3. The number of questions in the achievement test and quizzes is appropriate.	5	4	4	4	4	21	4.2	0.45
5.4. The nature of the question format is clear and simple to comprehend.	5	5	4	4	4	22	4.4	0.55
Average							**4.30**	**0.50**
Total average							**4.42**	**0.56**

D-4. E_1/E_2 analysis

Student	Quizzes			Sum (Total=30 points)
	Q1	Q2	Q3	
1	**7**	9	9	25
2	**9**	9	10	28
3	8	9	10	27
4	10	9	8	27
5	8	10	10	28
6	9	10	9	28
7	8	9	10	27
8	9	9	6	24
9	10	10	9	29
10	9	10	10	29
11	9	9	10	28
12	10	10	9	29
13	9	10	10	29
14	8	10	10	28
15	10	10	8	28
16	9	10	9	28
17	9	8	9	26
18	10	10	10	30
19	10	10	9	29
20	8	10	10	28

Student	Quizzes (Total=30 points)	Achievement test (Total=30 points)
1	25	28
2	28	27
3	27	28
4	27	26
5	28	26
6	28	26
7	27	28
8	24	25
9	29	29
10	29	27
11	28	28
12	29	29
13	29	28
14	28	26
15	28	24
16	28	26
17	26	24

18	30	29
19	29	28
20	28	28
Sum	$\sum X$=555	$\sum Y$ =540

The efficiency obtained from the scores from the achievement tests in observed after teaching all topics is as follows:

$$E_2 = \frac{540}{30} \times 100 = 90\%$$

The efficiency obtained from the scores from the quizzes in observed after teaching each topic is as follows:

$$E_1 = \frac{\frac{555}{20}}{30} \times 100 = 92.5\%$$

AUTHOR BIOGRAPHY

Author: Ms. May Phu Pwint Wai

Degree: Doctor of Philosophy of Education

Date of Birth: 01st May 1986

Place of Birth: Meiktila, Myanmar

Undergraduate and Graduate Education:

Doctor of Philosophy of Education in Engineering Education,
King Mongkut's Institute of Technology Ladkrabang, Bangkok, 2022

Master of Engineering (Electronics),
Yangon Technological University (YTU), Yangon, Myanmar, in 2010

Bachelor of Engineering (Electronics),
Yangon Technological University (YTU), Yangon, Myanmar, in 2007

Major: Engineering Education

Presentations and Publications:

M. P. P. Wai, Jaikla W., Chaichana, A., Suwanjan, P., Chanapromma C., and Sunthonkanokpong, W., (2020) "Voltage-Mode Biquad Filter Using Three LT1228s with Independent and Electronic Control of Center Frequency and Quality Factor," Engineering Letters, 31, 1-8.

M. P. P. Wai, Jaikla W., Siripongdee, S., Chaichana, A., and Suwanjan, P., (2020) "Electronically Tunable TISO Voltage-Mode Universal Filter Using Two LT1228s," International Journal of Engineering and Technology Innovation, 12, 62-74.

M. P. P. Wai, Suwanjan. P., Jaikla, W., and Chaichana, A., (2021) "Electronically and Orthogonally Tunable SITO Voltage-Mode Multifunction Biquad Filter Using LT1228s," Elektronika Ir Elektrotechnika, 27, 1-7.

M. P. P. Wai, Jaikla W., Siripongdee, S., Chaichana. A., and P. Suwanjan. P., (2021) "One Input Voltage and Three Output Voltage Universal Biquad Filters with Orthogonal Tune of Frequency and Bandwidth," International Journal of Electrical and Computer Engineering (IJECE), 11, 2962-2973.

M. P. P. Wai, Jaikla W., Suwanjan, P., and Sunthonkanokpong, W., (2020) "Single Input Multiple Output Voltage Mode Universal Filters with Electronic Controllability Using Commercially Available ICs," 17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications, and Information Technology (ECTI-CON), 607-610.