FAST AND SLOW LIGHT WITHIN MICRORING RESONATORS

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN APPLIED PHYSICS
FACULTY OF SCIENCE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
2009

KMIL-2009-SC-D-030-046

หัวข้อวิทยานิพนธ์ แสงเร็วและช้าในโพรงสั่นพ้องวงแหวนขนาดเล็ก
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บทคัดย่อ

วิทยานิพนธ์นี้เป็นการนำเสนอพฤติกรรมของแสงที่เกิดขึ้นจากโพรงสั่นพ้องวงแหวนขนาดเล็กแบบไม่เป็นเชิงเส้น ซึ่งจากพฤติกรรมดังกล่าว ทำให้สามารถแปลงสัญญาณแสง และสัญญาณไฟฟ้าไปอยู่ในรูปของความถี่ ความยาวคลื่น และโดเมนเวลาได้ โดยอาศัยคุณสมบัติของโพรงสั่นพ้องวงแหวนขนาดเล็กนี้ สร้างสัญญาณเคออสขึ้นมา และยังสามารถนำมาประยุกต์ใช้งานในด้านต่างๆ ได้มากมาย ซึ่งในวิทยานิพนธ์นี้ได้นำเสนอการประยุกต์ใช้งานใน 3 เรื่อง ดังนี้

เรื่องแรก เป็นการนำเสนอระบบการกำเนิดแสงเร็วอย่างง่าย โดยใช้สัญญาณอินพุทพัลซ์โซลิตอนป้อนเข้าไปในโพรงสั่นพ้องวงแหวนขนาดเล็กระดับไมโครเมตร ระบบดังกล่าวนี้สามารถสร้างสัญญาณพัลซ์ขนาดเล็กระดับออตโต้เซคคั่น และแคบกว่าได้ เพื่อใช้ในงานเขียนขนาดเล็กด้วยแสง หรือสวิตซ์ทางแสง และงานที่ต้องการความจุข้อมูลสูงๆ

เรื่องที่สอง เป็นการนำเสนอการออกแบบระบบอย่างง่าย และธรรมดา เพื่อนำพฤติกรรมของแสงที่เกิดขึ้นในรูปแบบต่างๆ ที่สัมพันธ์กัน นำมาประยุกต์ใช้งาน เช่น การกำเนิดแสงเร็ว แสงช้า การหยุดแสง และการเก็บแสงอย่างเป็นระเบียบ โดยใช้โพรงสั่นพ้องวงแหวนขนาดเล็กระดับไมโครเมตร และนาโนเมตร ผลลัพธ์ที่ได้ คือแบนด์วิดท์ที่มีขนาดใหญ่ และสามารถบีบอัด เพื่อเลือกความยาวคลื่น และยังสามารถนำไปประยุกต์ใช้เป็นหน่วยความจำทางแสงได้

เรื่องสุดท้าย เป็นการนำเสนอการออกแบบระบบใหม่ ของการจำลองการกำเนิดแสงเร็วและแสงช้า ซึ่งเกิดขึ้นโดยการใช้สัญญาณอินพุทพัลซ์โซลิตอนป้อนเข้าผ่านโพรงสั่นพ้องวงแหวนขนาดเล็กระดับไมโครเมตร ซึ่งสามารถกำเนิดสัญญาณได้ 2 สัญญาณ ให้ได้รับที่เวลาแตกต่างกัน เรียก สัญญาณจริง และสัญญาณหลอก โดยใช้แอ็คดรีอปเป็นตัวกรอง จากพฤติกรรมดังกล่าวนี้สามารถนำมาประยุกต์ เพื่อใช้สำหรับงานด้านความปลอดภัยทางการสื่อสารทางแสงได้

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Degree	Doctor of Philosophy
Program	Applied Physics
Year	2009
Thesis Advisor	Assoc. Prof. Dr. Preecha Yupapin

ABSTRACT

This thesis present the interesting results of nonlinear behaviors of light within a nonlinear ring resonator system, where optical and electrical signals conversion in frequency, wavelength and time domains can be made by using the chaotic signals generated within the micro ring system. There are three forms of applications using the chaotic behaviors are presented.

Firstly, A simple system of fast light generation by using a soliton pulse circulating in the integrated micro ring devices is proposed. Using such a system, an attosecond pulse and beyond can be easily generated and design ultra fast switching and lithography, including high capacity.

Secondly, The thesis propose a remarkably simple system of an all optical system that can be used to fast, slow, stop and store light coherently. The proposed system consist two micro and a nano ring resonators that can be integrated into a single system. The time independent optical gain is stored within the nano ring device, which is available for read only memory (ROM) application.

Finally, A new system of the simultaneous fast and slow light generation using a soliton pulse propagating within the nonlinear micro ring resonators for optical communication system. The other application is that the fast and slow light behaviors can be presented, which can be seen by using the add/drop multiplexers. In some cases, I can generate to obtain the two identical signals called “Signal” and “Ghost”, which is observed in different time frame.

ACKNOWLEDGEMENTS

First of all, I would like to express my greatest appreciation and my gratitude to my advisor, Assoc. Prof. Dr. Preecha Yupapin, for his generous support and guidance. His profound insight into physics and stimulated assignments helped me not only to understand but also to solve and move fast forward through many challenging problems.

I would like to thank my other committee members, Assoc. Prof. Dr. Thitinai Geawdang, Assoc. Prof. Ngamnit Wongcharoen, Assoc. Prof. Dr. Somsak Mitatha, Dr. Nithiroth Pornsuwancharoen for their assistance, helpful comments and insightful suggestions.

My co-workers at the Advanced Research Center for Photonic Laboratory have been key to this work, particularly Dr. Sappasit Thongmee, Dr. Narong Sangwaranatee, Chart Teeka and Khunthong Sarapat. Thanks are also due to friends, everyone for their conversation and helping everything.

I would also like to thank every members of the Department of Electronics Technology, Faculty of Science, Ramkhamhaeng University ; whose support has created a friendly environment.

Finally, and most importantly, I owe a debt of gratitude to my family - Mum and Dad, for all their love and support all my sisters Yuy and Ccc.

Sawatsakorn Chaiyasoonthorn

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CHAPTER 1

INTRODUCTION

Development of high capacity optical networks has accelerated because of emerging demands for world-wide communications. Information, interactive multimedia service, electronic commerce, and many other services are efficiently delivered online through the Internet. Optical fiber communication serves as the enabling technology to realize those Internet activities. Today several tens of gigabits-per-second of data traffic are carried over many thousands of kilometers through optical fiber communication systems. Terabits-per-second communication systems are rapidly being developed and will be the backbone for the global world interconnection in the foreseeable future.

Transmission of high capacity data and, more importantly, the management of that high capacity data are the keys to the realization of terabits-per-second global networks. Such rapid evolution in communication systems is creating enormous demands for optoelectronic components with capabilities beyond those currently available.

Since the first demonstration of femtosecond pulse generation in optical fiber lasers in 1990 [1,2], ultrafast fiber lasers have been a major topic of research in the ultrafast community. At the same time commercial ultrafast fiber lasers have also been firmly established in the optoelectronics industry. Currently, more than twenty commercial suppliers of femtosecond and picosecond fiber lasers exist and new companies are emerging all the time. During the last several years, ultrafast fiber lasers have made significant inroads in frequency metrology, where fiber lasers have reached a performance level similar to the more established.

Nonlinear fiber optics has continued to grow during the decade of 1990s, perhaps even more dramatically than anticipated. This growth is motivated by several recent advances in lightwave technology, the most important being the advent of high-capacity fiber-optic communication systems. In such systems, the transmitted signal is amplified periodically by using optical amplifiers to compensate for residual fiber losses. As a result, the nonlinear effects accumulate over long distances, and the effective interaction length can exceed thousands of kilometers.

1.1 Introduction to nonlinear optics

Nonlinear optics (NLO) is the branch of optics that describes the behavior of light in nonlinear media, that is, media in which the dielectric polarization (P) responds nonlinearly to the electric field (E) of the light. This nonlinearity is typically only observed at very high light intensities such as those provided by pulsed lasers.

Glass fibers for optical communications are made of fused silica, an amorphous material, to which dopant materials of various kinds can be added to produce changes in the refractive index. A number of third order nonlinear processes can occur; these can grow to appreciable magnitudes over the long lengths available in fibers, even though the nonlinear coefficients in the materials are relatively small. The effects are particularly important in single-mode fibers, in which the small mode field dimensions result in substantially high light intensities with relatively modest input powers.

Fiber nonlinearities fall into two general categories [3]. The first category of nonlinearities arises from modulation of the refractive index of silica by intensity changes in the signal (Kerr effect). This gives rise to nonlinearities such as self-phase modulation (SPM), whereby an optical signal alters its own phase; cross-phase modulation (CPM or XPM), where one signal affects the phases of all others optical signals and vice-versa, and four-wave mixing (FWM), whereby signals with different frequencies interact to produce mixing sidebands. The second category of nonlinearities corresponds to stimulated scattering processes, such as Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS), which are interactions between optical signals and acoustic or molecular vibrations in the fiber. These effects become important in long optical links operated at high optical power levels. In single-wavelength systems, SPM, SRS, and SBS can cause pulse distortion and attenuation. In addition to that, in DWDM systems, CPM, SRS, SBS, and FWM can cause crosstalk between optical channels.

Fiber nonlinearities have different influences on the communication systems. The SPM, for instance, leads to a change in the dispersion behavior in high-bit-rate transmission systems; the XPM, SRS, and SBS determine a decrease of the signal to noise ratio; the SRS and FWM will increase the crosstalk between different WDM channels [3]. On the other hand, the same nonlinear effects offer a variety of possibilities for ultrafast all-optical switching, amplification and regeneration [4]. The FWM, SRS, and SBS, for instance, are able to amplify optical signals in spectral ranges that can never be reached by erbium-doped fiber amplifiers. The FWM offers the possibility for a pure optical wavelength conversion and the realization of nonlinear optical phase conjugation, that can compensate completely the distortions of the optical pulses. Optical solitons offer the possibility of transmitting optical pulses over extremely large distances without distortion [5,6].

1.2 The Ring Resonator – History

The proposal to use an integrated ring resonator for a bandpass filter has been made in 1969 by E. A. Marcatili [7]. The layout of the channel dropping filter is shown in Fig. 1.1. The transmission properties of the used guide consisting of a dielectric rod with rectangular cross section, surrounded by several dielectrics of smaller refractive indices have been described by E. A. Marcatili in [8].

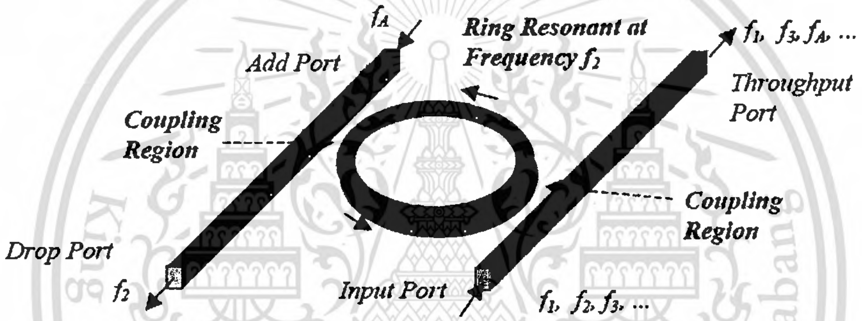


Fig. 1.1 Ring resonator channel dropping filter.

A general architecture for an autoregressive planar waveguide optical filter was demonstrated for the first time in 1996 [9]. The autoregressive lattice filters which were designed and fabricated consisted of one and two stages using Ge-doped silica waveguides.

A signal flow chart transformation for evaluating the filter transfer functions was demonstrated. Purely passive single ring resonator filters shown in Fig. 1.1 have been realized in the material system AlGaAs-GaAs [10, 11] and Si-SiO$_2$ [12] and Si$_3$N$_4$- SiO$_2$ [13]. The radius of the used ring resonators is between 5 μm and 30 μm and the Free Spectral Range (FSR) achieved is between 20 nm and 30 nm. Passive ring resonators in the form of a racetrack have been realized in the material system GaInAsP [14] and AlGaAs-GaAs [15]. The filter performance is limited by bending and scattering losses in the resonator. These losses could be compensated by using or adding an active material.

1.2.1 Fiber Ring Resonator

A ring resonator is simply a waveguide shaped into a ring structure as shown in Fig. 1.2. When an input electric field, E_i is coupled to the ring waveguide through an external bus waveguide, a positive feedback is induced and the field inside the ring resonator, E_r starts to build up. Coupling between the straight and the ring waveguide is achieved through the evanescent wave. Therefore, the gap and coupling length between them determine how much power is coupled from the straight waveguide to the ring waveguide and vice versa. The feedback mechanism is simply induced by the ring waveguide and therefore there is no need for any Bragg gratings, mirrors, or distributed feedback waveguides which are more difficult to fabricate. In such configuration, only certain wavelengths will be allowed to resonate inside the ring waveguide, thus frequency selectivity is obtained.

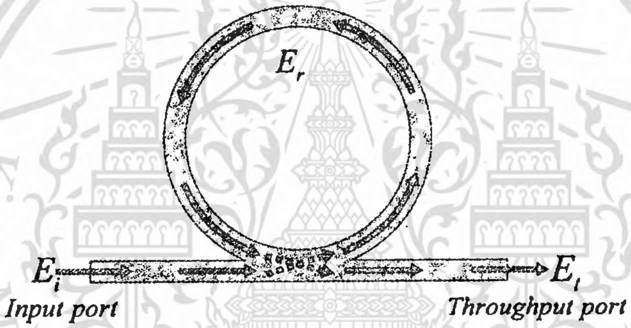


Fig. 1.2 Schematic diagram for a ring resonator coupled to a single waveguide.

1.2.2 Microring Resonators

Now can summarize the advantages attained by microring resonators over other conventional optical cavities:

- **Geometry:**

The ring geometry by itself is unique. The ring waveguide supports a traveling wave rather than a standing wave. Hence, coupling can be at any point on the ring circumference. Furthermore, it allows more than one waveguide to be coupled to the ring. Therefore, multiplexing, demultiplexing, and routing can be achieved with no need for external circulators.

- **Simplicity:**

Fabrication of microring resonators is straightforward. There is no need for any mirrors, Bragg Gratings, or distributed feedback waveguides to achieve the positive feedback.

- **Materials:**

There is no need for any exotic materials to fabricate microring resonators. Semiconductors fabrications are well developed and their high refractive indices allow smaller radii bends to be feasible. Bending losses decrease exponentially with increasing core-cladding refractive index contrast. This made high index contrast a fundamental requirement for Very Large Scale Integration (VLSI) photonics [7]. A 2 μm microring resonator with a finesse of 100 will have a cavity lifetime of 10 ps. Therefore, 100 GHz data can be processed by such a device. Semiconductors also allow micro rings to be integrated with other optoelectronics devices such as micro lasers, amplifiers, and detectors.

1.2.3 Integrated Ring Resonator System

The basic type of autoregressive moving average (ARMA) planar waveguide filter is a single ring resonator connected to one coupler provides no path back to the input port. This filter is called all-pass or, in the absence of loss, unit transmittance networks [16], because the magnitude of their transmission factor is unity on the whole spectrum, independent of wavelength. Although lossless all-pass filters do not display magnitude filter characteristics, their phase response is frequency dependent. Therefore, they can be configured for group delay equalization and dispersion compensation [17–19], polarization mode dispersion compensation [20], and other applications based on their phase-frequency characteristics such as band-pass filtering when used in conjunction with other optical components. There have been growing interests in tunable dispersion compensators (TDC) for high-speed wavelength division multiplexed (WDM) networks. This is because the chromatic dispersion of transmission path can be changed frequently in a dynamically re-configurable WDM networks. The TDC based on ring resonator all-pass filter is one of the key components in these networks. Optical ring resonator all-pass filters (RRAPF) can be realized using multi-stage in either cascading single stages or using lattice architectures [15]. In this thesis, multi-stage ring resonator all-pass filters for dispersion compensation is proposed and analyzed. Desired group delay shape, which has a larger value and sharper, can be tuned by the amount of power coupling to the ring.

1.3 Behavior of light in Ring Resonator

Optical Soliton has been recognized as a nonlinear solitary wave for years. Since then, it has been widely investigated in several subjects such as in Physics, Mathematics and Communication, especially, in optical communication. Generally, the common property of a soliton known as Self-Phase Modulation (SPM) and Cross Phase Modulation (CPM) are the challenged behaviors. Furthermore, the non-dispersion behavior of the soliton is the key advantageous, which is capable the use in long-haul communication where the long distance link without a repeater can be employed. The other interesting soliton behavior is the localization where the soliton pulse can be trapped and stored within the periodic medium, which is useful in many areas of applications. Theoretically, a soliton pulse can be recovered when the balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as self-phase modulation, which it occurs when the matching between the soliton property and localized media is provided. When the generation of the localized soliton pulse is achieved, it is available for applications in many areas of research in science and technology. One of the interesting applications is that the high speed computer, i.e. quantum computer) which can be reversely processed. However, the problem remains where the memory for quantum computer is required, is the ability to drastically slow down the propagation speed of light, and to coherently stop and store optical pulses, hold the key to ultimate control of light. It has profound implication for optical communication [21] and quantum information processing [22, 23]. There are two major approaches, employing either electronics or optical resonant. However, most of the system imposes severe constraints. One of the recent works was reported, where the general analysis for the criteria to stop and store light coherently using array micro cavities (waveguides) was proposed by Yanik and Fan [24, 25]. They have shown that light could be stopped and stored coherently under adiabatic condition with all optical system. However, the system is still complicated, which is difficult to make a realistic implementation. Therefore, the searching for the suitable devices and technologies are still necessary. Recently, the use of a chaotic soliton to form a fast light generation within a tiny device known as a micro ring resonator (waveguide) has been reported by Yupapin et al [26]. They have shown that the large bandwidth can be compressed coherently with a small group velocity. In practice, such devices have been fabricated and used in various applications [27-30]. In this thesis, we show that the large bandwidth of light pulse is generated and compressed within the nonlinear micro and nano ring system. The selected (tuned) pulse is coherently stopped and stored within the nano ring device. In applications, we can use the tuned light pulse to perform the required applications such as optical memory, quantum repeater and quantum logic gate. We have also discussed that when the coherent pulse is in the stopping situation, the output gain is constant, which is allowed to store light pulse to be stored coherently within the device.

1.4 Fast and Slow Light

A remarkably simple system of an all optical system that can be used to fast and slow light coherently is proposed. A system consists of ring resonators that can be integrated into a single system, whereas the large bandwidth signal is generated by a soliton pulse within a Kerr type nonlinear medium. The balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as Self-Phase Modulation (SPM).

The speed and performance of the chips, their associated packages, and, hence, the computer systems are dictated by the lithographic minimum printable size. Lithography, which replicates a pattern rapidly from chip to chip, wafer to wafer, or substrate to substrate, also determines the throughput and the cost of electronic systems. A lithographic system includes exposure tool, mask, resist, and all of the processing steps to accomplish pattern transfer from a mask to a resist and then to other devices. The demand of using the ultra short light pulses in broad areas has been rapidly increased. Which means it is recognized as the important tool for fast improvement of frontier research in the areas. For examples, the areas of applications such as high small scale lithography, high density compact disk writing and reading, high resolution interferometer and surface roughness, high speed switching and communication, high speed optical and quantum computer are included. However, in practice, the more flexible and reliable device and system are still required to use in realistic application. The extended details of nonlinear benefits of light. Further, the theoretical investigations of such devices in other areas of applications have also been increased, where the areas such as optical communication system.

In this thesis, the applications such as high capacity, fast and slow light, ultra-fast switching, communication security, optical memory, and extremely narrow pulse lithography are described. For example, an extremely narrow ultraviolet (UV) pulse width generation for pico-lithography technology using a nonlinear ring resonator system is described, whereas a system consists of three micro and a nano optical ring resonators which can be used to generate the 50 pm (10^{-12} m) optical spectral width at the ultraviolet wavelength.

1.5 Goal of the Thesis

A variety of nonlinear optical signal processing functions in microring resonator can be realized in many applications. For examples, the Kerr effect can be used to communication high microwave frequency (THz) and the add/drop multiplexing can be used cancellation chaotic signal and the chaos of nonlinear system can be chaotic communication.

Microring resonators with these applications are thus need careful and exact design for their correct operation. A direct result of the progress in fabrication techniques is the increased need of the accurate models for characterizing the nonlinear devices. For very simple devices, analytical tools provide a framework for quick low cost feasibility studies and allow for design optimization before devices are fabricated.

The primary goal of this thesis is to investigates the design and simulation nonlinear characteristics of ring resonator architectures. Secondary goal is the generation of a very narrow full width at half maximum (FWHM) and sharp tip using the Kerr effect nonlinear type of soliton in a microring resonator for communication security application. Finally, to design a new system of signal security using the nonlinear micro ring resonators for optical communication system.

1.6 Scope of the Thesis

With the growing importance of micro ring resonators for a variety of applications, it becomes necessary to devise a model which is directly interpretable in physical terms, and which is essentially free of any fit parameters. In this thesis, the chaos signal cancellation approach to design and analyze nonlinear optical add/drop ring resonator filters. I can generate of a very narrow full width at half maximum (FWHM) and sharp tip for optical lithography. I created to the chaotic signal for communication security using the nonlinear micro ring resonators. The present analysis is restricted to directional couplers and waveguides characterized by various parameters, the power coupling coefficient, power coupling loss, the radius of the ring waveguide and attenuation coefficient.

1.7 Organization of the Thesis

This thesis presents a novel design and simulated characteristics for characterizing nonlinear optical ring resonator filters. The organization is as follows:

- The current chapter gives an introduction to the subject of the thesis; Introduction to Nonlinear Optics, Ring Resonator, Behavior of light in Ring Resonator and Fast and Slow Light in Microring Resonators
- Chapter 2 describes some of nonlinear optics in waveguide which is used to characterize nonlinear devices and theoretical background nonlinearity, Optical chaotic communication, Optical Soliton, Optical Add/Drop Ring Resonator Filter.
- Chapters 3,4 and 5 describe the design of nonlinear devices by using nonlinear behavior in microring resonator filters and all essential parameters describing the nonlinear characteristics.
- Finally, Chapter 6 presents a conclusion of the results of the thesis and a discussion of future research.

CHAPTER 2

NONLINEAR OPTICS IN WAVEGUIDE

For an understanding of the nonlinear optics in waveguide, it is necessary to consider the theory of electromagnetic wave propagation in dispersive nonlinear media. The objective of this chapter is to obtain discuss fiber characteristics, fiber nonlinearities and basic equation that governs propagation of optical pulses in single mode fibers. I discuss nonlinear in optical fiber ring resonator such as Kerr Effect , Optical chaotic communication, Optical Soliton and Optical Add/Drop Ring Resonator Filter

In this chapter, we will discuss different nonlinear processes that affect the performance of semiconductor microring resonators.

2.1 Introduction

2.1.1 Nonlinear Susceptibility

Nonlinear optics is the study of phenomena that occur as a consequence of the modification optical properties of a material under intense illumination. Typically, only laser light is sufficiently intense to modify the optical properties of a material. Nonlinear optical phenomena are nonlinear in the sense that the induced material polarization is nonlinear in the electric field [31]. The general equation that describes the optical field evolution in a dielectric material is given by

$$\nabla^2 \mathrm{E} - \frac{1}{c^2}\frac{\partial^2 \mathrm{E}}{\partial t^2} = -\mu_0 \frac{\partial^2 \mathrm{P}(\mathrm{E})}{\partial t^2} \tag{2.1}$$

where the polarization $\vec{\mathrm{P}}$ characterizes the medium and it is a function of the electric field. In the case of weak nonlinear behavior of the medium, the polarization can be expressed by a Taylor polynomial as

$$\vec{\mathrm{P}} = \underbrace{\varepsilon_0\vec{\mathrm{E}} + \varepsilon_0\chi^{(1)} : \vec{\mathrm{E}}}_{linear\ P_L} + \underbrace{\varepsilon_0\chi^{(2)} :: \vec{\mathrm{E}}\cdot\vec{\mathrm{E}} + \varepsilon_0\chi^{(3)} ::: \vec{\mathrm{E}}\cdot\vec{\mathrm{E}}\cdot\vec{\mathrm{E}} + \ldots,}_{nonlinear\ P_{NL}} \tag{2.2}$$

where dielectric dispersion is ignored. $\chi^{(1)}$ is the linear susceptibility, :represents the inner tensor product and the second and the third-order tensor $\chi^{(2)}$and $\chi^{(3)}$ are responsible for the second harmonic generation, and the third-order harmonic generation, respectively.

2.1.2 Optical Kerr Effect

Nonlinear effect in optical fibers is due either to changes in the refractive index with optical power or to scattering phenomenal. The power dependence of refractive index is responsible for the Kerr effect. Depending on the shape of the input signal, the Kerr nonlinearity manifests itself by different effect, such as self-phase modulation, cross-phase modulation, Nonlinear behaviors of light traveling in fiber optic are commonly induced by the effects such as Kerr effects, four-wave mixing, and the external nonlinear pumping power. The device characteristics that suit to implement in the practical communication system has seen. To meet the practical applications, the micro ring and Add/drop parameters are needed to make them satisfy the usual fabrication. The analogy of chaotic signal generation using fiber ring resonator and the related behaviors are described.

The optical Kerr Effect (i.e. nonlinear refraction index) results from the third order nonlinear susceptibility $\chi^{(3)}$, which is a fourth rank tensor.

An optical wave is a real quantity and usually expressed as

$$\vec{\mathrm{E}}(t) = \mathrm{Re}\left\{\vec{\mathrm{E}} \exp j(\vec{k} \cdot \vec{r} + \omega t)\right\} \tag{2.3}$$

or similarly as

$$\vec{\mathrm{E}}(t) = \frac{1}{2}\vec{\mathrm{E}} \exp j(\vec{k} \cdot \vec{r} + \omega t) + c.c. \tag{2.4}$$

where c.c. represents the complex conjugate of the preceding term. Thus, an x-polarized optical wave, propagating in the z-direction in an isotropic medium, is represented mathematically as

$$\vec{\mathrm{E}}(t) = \frac{1}{2}\mathrm{E}_x \hat{x} \exp j(kz + \omega t) + c.c. \tag{2.5}$$

The third order polarization (mediated by $\chi^{(3)}$) in a material leads to a nonlinear intensity dependent contribution to its refractive index; i.e., the refractive index of the material changes as the incident intensity on the material changes. The susceptibility tensors in isotropic material can be further simplified as $\chi^{(2)} = 0$, due to inversion symmetry; the third order nonlinear susceptibility will only have one contributing term χ_{xxxx} since the light is x-polarized and there are no means for sourcing additional polarization components.

The linear and nonlinear induced polarizations are

$$P_L = \varepsilon_0(1+\chi^{(1)})E, \tag{2.6}$$

$$\begin{aligned} P_{NL} &= P^{(3)} \\ &= \varepsilon_0 \chi_{xxxx}(\omega;-\omega,\omega,\omega)E^{*}EE \\ &\quad + \varepsilon_0 \chi_{xxxx}(\omega;\omega,-\omega,\omega)EE^{*}E \\ &\quad + \varepsilon_0 \chi_{xxxx}(\omega;\omega,\omega,-\omega)EEE^{*} \\ &= 3\varepsilon_0 \chi_{xxxx}|E|^2 E \\ &= \frac{3}{4}\varepsilon_0 \chi_{xxxx}|E_x|^2 E \end{aligned} \tag{2.7}$$

respectively. Hence,

$$P = P_L + P_{NL} = \varepsilon_0\left(1+\chi^{(1)}+\frac{3}{4}\varepsilon_0\chi_{xxxx}|E_x|^2\right)E$$

The total dielectric constant is

$$\varepsilon_r^{tot} = \varepsilon_r + \Delta\varepsilon_r$$

where $\varepsilon_r = 1+\chi^{(1)} = n_o^2$ and $\Delta\varepsilon = \frac{3}{4}\chi_{xxxx}|E_x|^2$ after comparing with the expression for P. The refractive index is related to the dielectric constant as:

$$n = \sqrt{\varepsilon_r + \Delta\varepsilon_r} \approx \sqrt{\varepsilon_r} + \frac{\Delta\varepsilon_r}{2\sqrt{\varepsilon_r}} = n_0 + \frac{3\chi_{xxxx}}{8n_0}|E_x|^2 \tag{2.8}$$

The intensity dependent refractive index for a nonlinear material is given by

$$n = n_0 + n_2|E|^2 \tag{2.9}$$

Comparing Eq.(2.8) and Eq.(2.9), the nonlinear refractive index is directly determined by the third-order susceptibility as

$$n_2 = \frac{3\chi_{xxxx}}{8n_0} = \frac{3\chi^{(3)}}{8n_0} \tag{2.10}$$

which characterizes the strength of the optical nonlinearity. The intensity I of an optical wave is proportional to $|E|^2$ as $I = \frac{1}{2\eta}|E|^2$ where η is the impedance of the medium. When comparing the optical response in the same medium, $I = |E|^2$ is taken for simplification.

2.1.3 Self-Phase Modulation

The change in refractive index due to the Kerr effect determines a corresponding change in the propagation constant. As a consequence, the phase of a signal propagating through the fiber varies with distance according to the equation:

$$\phi = n_0 k_0 z + \gamma P(t) z \tag{2.11}$$

where $\gamma = n_2 k_0 / A_{eff}$. The first term in Eq. (2.11) represents the linear phase shift due to signal propagation; the second term represents the nonlinear phase shift. When the incident wave is a pulse with a power variation given by *P*(*t*), the output pulse is chirped. This phenomenon is called self-phase modulation (SPM), since the power variation within the pulse leads to its own phase modulation. In the leading edge of the pulse, where $dP/dt > 0$, the instantaneous frequency is downshifted from the central frequency, whereas in the trailing edge, where $dP/dt < 0$, the instantaneous frequency is upshifted. The chirping due to nonlinearity leads to increased spectral broadening.

In the presence of dispersion, the spectral broadening due to SPM determines two situations qualitatively different. In the normal dispersion region (where the wavelength is shorter than the zero dispersion wavelength, λ_{ZD}) the chirping due to dispersion is to downshift the leading edge and to upshift the trailing edge of the pulse, which is a similar effect as that due to SPM. Thus, in this regime the chirping due to dispersion and SPM add. On the other hand, in the anomalous dispersion region, the chirping due to dispersion is opposite to that due to SPM. Consequently, nonlinearity and dispersion induced chirpings can partially or even completely cancel each other. When this cancellation is total, the pulse neither broadens in time nor in its spectrum and such pulse is called a soliton. Much research effort has been devoted to the study of optical solitons and their application in telecommunication systems because they have the peculiar behaviour of preserving their shape during propagation [6,32]

2.1.4 Cross-Phase Modulation

When two or more signals having different carrier frequencies are transmitted simultaneously inside an optical fiber, the nonlinear phase evolution of the signal at frequency ω_i depends also on the power of the other signals. This nonlinear phenomenon is known as cross-phase modulation (XPM) and it is due also to the intensity dependence of the refractive index. The nonlinear phase shift of the signal at ω_i becomes:

$$\phi_i^{NL} = \gamma z\left[P_i + 2\sum_{i \neq j} P_j\right] \tag{2.12}$$

Where P_j is the power of the signal at ω_j. The first term in the square brackets represents the contribution of SPM, while the second term is the contribution from the XPM. The factor 2 in Eq. (2.12) indicates that XPM is twice as effective as SPM for the same amount of power.

From Eq. (2.12) it can be deduced that XPM is effective only when the interactive signals are superimposed in time. In the presence of finite dispersion, two pulses at different frequencies will move with different velocities and thus the pulses will walk off from each other. Obviously, larger dispersion will reduce the walk off length and hence the XPM effects.

Due to XPM, the phase of each channel in a WDM system is affected by both the average power and the bit pattern of all other channels. Fiber dispersion converts phase variations into amplitude fluctuations that affect the signal-to-noise ratio (SNR) and introduce jitter. In these circunstances, an understanding of the interplay between XPM and GVD is very important for WDM systems [33].

2.2 Optical Chaotic Communication

The appearance in the year of 1990 of two seminal papers involving fundamentals of chaotic systems to generated a tremendous amount of interest and work with subsequent applications in synchronization and control of chaos. In particular, the peculiar features of chaotic systems well explored [34,35] (synchronization capability and sensitivity to initial condition), opened up a whole new field for using chaotic signals as information carriers. It is currently accepted that chaotic systems provide a rich mechanism for signal design and generation, with promising potential applications to communications and signal processing. Since chaotic signals are typically broadband, noise like and difficult to predict they can be used in various contexts for masking information-bearing waveforms. They can also be used as modulating waveforms in spread spectrum systems, like Code Division Multiple Access (CDMA) that is becoming very popular in many fields of telecommunication. Two fundamental characteristics of chaos in physical systems are the complexity of the dynamics and the sensitivity of the time evolution to small perturbations. The sensitivity of chaos to small perturbations has been seen for a long time as merely a barrier to prediction, and not as a useful property. Major developments in the area of controlling chaos using small perturbations have proved otherwise: the sensitivity to small perturbations exhibited by chaotic systems allows controlling them using

Chaos communications is an application of chaos theory which is aimed to provide security in the transmission of information performed through telecommunications technologies. By secure communications, one has to understand that the contents of the message transmitted are inaccessible to possible eavesdroppers.

In chaos communications security is based on the complex dynamic behaviors provided by chaotic systems. Some properties of chaotic dynamics, such as complex behaviors, noise-like dynamics (pseudorandom noise) and spread spectrum, are used to encode data. On the other hand, being chaos a deterministic phenomenon, it is possible to decode data using this determinism. In practice, implementations of chaos communications devices resort to one of two chaotic phenomena: synchronization of chaos, or control of chaos. The implement chaos communications using such properties of chaos, two chaotic oscillators are required as a transmitter (or master) and receiver (or slave). At the transmitter, a message is added on to a chaotic signal and then, the message is masked in the chaotic signal. As it carries the information, the chaotic signal is also called chaotic carrier.

When chaos synchronization is used, a basic scheme of a communications device (Cuomo and Oppenheim 1993) is made by two identical chaotic oscillators. One of them is used as the transmitter, and the other as the receiver. They are connected in a configuration where the transmitter drives the receiver in such a way that identical synchronization of chaos between the two oscillators is achieved. For the purpose of transmission of information, at the transmitter, a message is added as a small perturbation to the chaotic signal that drives the receiver. In this way, the message transmitted is masked by the chaotic signal. When the receiver synchronizes to the transmitter, the message is decoded by a subtraction between the signal sent by transmitter and its copy generated at the receiver by means of the synchronization of chaos mechanism. This works because, whilst the transmitter output contains the chaotic carrier plus the message, the receiver output is made only by a copy of the chaotic carrier without the message. The electrical signals with a power far below the one produced by the chaotic system itself. Thus, the complexity of chaos and its sensitivity to small perturbations can be combined harmoniously by using the sensitivity to control (and take advantage of) the complexity. As a consequence, it is currently recognized by many engineers that the fact that chaos provides complex behavior from simple systems can be exploited to obtain technological advantages over conventional means for information transmission.

Optical Chaos is observed in many nonlinear optical systems. One of the most common examples is a ring resonator. One of the most seminal works is published by Ikeda (Physical Review Letters, 1982) where chaotic behavior in a ring resonator was proposed and experimentally confirmed. Optical Chaos was an exciting field of research in mid-1980s and was expected at that time to lead to production of all optical devices including all optical computers. Researchers realized later the inherent limitation of the optical systems due to the non-localized nature of photons compared to highly localized nature of electrons. Research in Optical Chaos has seen a recent resurgence in the context of studying synchronization phenomena, and in developing techniques for secure optical communications. [36,37]

2.3 Optical Soliton

How can we make beams that maintain their shape and size along propagation? As explained in the previous section, the phase between the different plane waves constructing the beam should be invariant along propagation. In a linear medium, the phase between the different plane waves depends solely on the propagation angle. It is clear then, that if all the plane wave components have the same angles, they will also have the same phase velocity and no phase difference will be acquire during propagation. If we represent the propagation direction of these plane waves by arrows, these arrows will creates a cone in space. The associated beam will propagate in this linear medium with no broadening while it maintain it's shape and dimensions. This type of beams is called "Bessel beams" since their field is described by Bessel function.

In a nonlinear medium, however, each plane wave is influenced by all the others. This is because the index change is a function of the total intensity. For some nonlinearities it is possible to find an ensemble of plane waves which will delay the phase velocity of the on axis components (in comparison with the of axis components) Consequently, the phase delay between the different propagating plane waves (explained in the previous section) will be compensated by the other waves via the medium nonlinearity.

If the nonlinearity is such that the index at the beam center is higher than in the dark regions, then the plane wave that propagate on axis will experience the highest index and will propagate slower from those off axis. This high index experienced by the on axis wave can compensate for it's linear tendency to propagate faster (because it is on axis). One example in which the index of refraction fully compensates for the shorter trajectory is a hyperbolic secant solution in a Kerr type mediem. The plane waves that construct the hyperbolic secant index profile (induced by the beam via the nonlinearity) have all the same phase velocity along propagation, and hence their interference (the hyperbolic secant shape) also maintains its shape and size as it propagates.

One can also look on solitons from the mathematical perspective. One has to find a stationary wave solution of governing nonlinear wave equation. The mathematical aspects of solitons are out of the scope of this thesis. Hence, here I will give just the final solution. For the exact mathematical derivation, the reader may refer to [38-40].

We start from the Maxwell equations with the following assumptions:

- The electric field in the propagation direction is negligible in comparison with the transverse electric field (paraxial approximation).
- The elecro-magnetic wave is monochromatic and its frequency is ω.
- The transverse electric field is $E(x,y,z,t)=\psi(x,y,x)\exp[j(\omega t-kz)]$ where the slowly varying field $\psi(x,y,x)$ changes much slower than $\exp[j(\omega t-kz)]$ **.
- The change in the refractive index is much smaller than one.

For beams in Kerr-type medium (for which the index of refraction is the following function of the intensity: $n(I) = n_0 + n_2 I$, one can start from the Maxwell equations and derive the nonlinear Schrödinger equation:

$$\frac{\partial}{\partial z}\psi(x,y,z) = \left[\frac{j}{2k}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{jkn_2}{n_0}\left|\psi(x,y,z)\right|^2\right]\psi(x,y,x) \tag{2.16}$$

Here, z is the propagation direction, k is the wave vector, and ψ is the slowly-varying amplitude of the electric field. Among all solutions for Equation (2.16) there is one family of particular interest:

$$\psi = \sqrt{\psi_0}\,\sec h\left[\frac{x}{W_0}\right]\exp\left[j\left(\frac{z}{4z_0}\right)\right] \tag{2.17}$$

Here $W_0 = \sqrt{\frac{2n_0}{n_2}\frac{1}{k\psi_0}}$ and $Z_0 = \frac{kW_0^2}{2}$. We can see that the intensity of this subfamily ($I(x,y) = |\psi|^2$) is z independent. For any chosen peak power, ψ_0, we can find a sech solution with appropriate width (the width, W_0, is a function of the peak intensity and is wider for lower peak intensities). All solutions of this sub-family (equation (2.17) will keep their shape and size invariant along propagation. Yet, in order to observe such solitons in nature, it is not enough to have a steady state mathematical solution in hand: one should also check for the stability of this steady state solution to noise and to deviations from ideal initial condition. If the solution exemplifies a state of stationary propagation-only then it can be considered as a soliton.

2.4 Optical Add/Drop Ring Resonator Filter

Unlike Fabry-Perot cavities, Bragg gratings, and distributed feedback waveguide devices, the ring geometry permits more than one waveguide to be coupled to the ring resonator. This in return allows multiple input/output accessibility and no need for external circulators to manipulate the input, reflected and throughput data streams. For instance, if one more waveguide is coupled to the filter, an optical add/drop filter is obtained, as shown in Figure 2.1

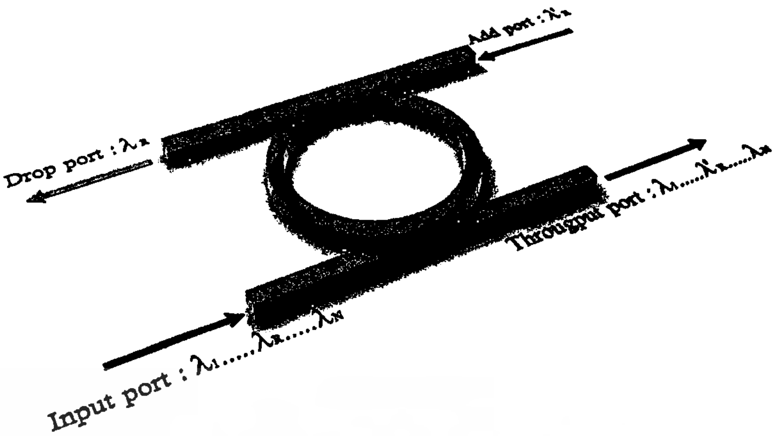


Fig. 2.1 Schematic diagram for a ring resonator coupled to two waveguides, in an add/drop filter configuration.

An incident optical signal composed of multiple wavelengths ($\lambda_1,\ldots,\lambda_R,\ldots,\lambda_N$) at the input port coupled into the ring and for a resonant wavelength (λ_R), the energy builds up in the resonator despite the small coupling and eventually the signal is coupled into the drop port. Symmetrically, a new signal at resonant wavelength (λ_R') at the add port couples to the output port through the ring. As a result, such a configuration constitutes a very compact add/drop filter where a channel can be dropped from the WDM spectrum and replaced by a new signal on the same channel. Note that waves with a wavelength away from resonance will not repeat themselves in the ring and the coupled field interferes destructively with the wave in the resonator leading to little energy in the resonator and little dropped power. Residual dropped power at non-resonant wavelengths is possible due to imperfections and can induce inter-band crosstalk that is detrimental to WDM applications. Moreover, if the input channel at λ_R is not completely extinguished, intra-band crosstalk will result. These issues will be studied and can be theoretically overcome by varying coupling parameters, inducing loss/gain in the ring and inserting additional rings between the two waveguides.

2.4.1. Design Approaches

Optical filter design is typically approaches with electromagnetic field equations where the fields are solved in the frequency or time domain. These techniques are required for characterizing ring resonator performances and directional couplers. However, they can become cumbersome and non-intuitive for filter design. Therefore, a different analytical method of signal processing including the scattering matrix method [15,41], the transfer matrix/chain matrix algebraic method [42,43,44] have been developed for determining optical filter transfer functions in Z-domain. The other approach in order to enable us to analyze the complex photonic circuit and fast calculation of the optical transfer functions is using a graphical approach. It is also called the *Signal Flow Graph method (SFG)* proposed by S. J. Mason [45]. This method is originally used in the electrical circuits, which is not widely used in the analysis of optical circuits.

The requirements of optical filters are considered to be satisfied are:

1. Linearity of all optical components.
2. Time invariance of all optical components.
3. Optical components must be lumped (i.e. not distributed).

The effects such as backscatter of light along the length of an optical fiber or waveguide, or saturation of an optical amplifier are therefore not considered here (the former is a distributed phenomenon; the latter is a nonlinear effect).

2.5 CONCLUSIONS

This chapter introduced the fundamental concepts of different nonlinear optics in waveguide include soliton signal which used as the input for launching into micro ring resonator. Consequently, we understand of the behaviors and enable design for the nonlinear devices as mention in chapter 3, 4 and 5. In the next chapter we design nonlinear optical devices by using nonlinear behavior in microring resonator filters and all essential parameters describing the nonlinear characteristics.

CHAPTER 3

FAST LIGHT GENERATION

In this chapter, I design the optical devices result from nonlinear optics in waveguide based microring resonator. The results obtained have shown that the generation of a very narrow full width at half maximum (FWHM) and sharp tip is achieved. With some selected parameters such as ring radii, coupling coefficients and nonlinear refractive indices, the extremely short pulse is generated. Which means fast light is generated from ns to zs and beyond by using the simple system.

3.1 Introduction

Ultra short light pulses have been the broad areas of research and investigation in many subjects, which is recognized as the important tool for fast improvement of frontier research in the areas. For examples, the areas of applications such as high small scale lithography, high density compact disk writing and reading, high resolution interferometer and surface roughness, high speed switching and communication, high speed optical and quantum computer are included. The sub femtosecond light pulse generations have been reported [46,47], especially, when the ultra short pulse of few hundreds attosecond pulse was generated and realized. Recently, Yiping Hou et al [48] have shown that a single attosecond pulse with pulse width of 40 as could be generated in the multicycle-driver regime by adding a weak second-harmonic field. However, in practice, the more flexible and reliable device and system are still required to use in realistic application. Recently, Yupapin et al have shown the promising idea that the nonlinear effects of light in fiber optic and micro ring resonators [49, 50] could be used in several applications. In principle, the nonlinear effects of light in the device known as Kerr effects and four-wave mixing have shown the potential of applications. The extended details of nonlinear benefits of light were described by Mario [51]. In practice, the micro ring device with the radius of few microns has been constructed [52, 53, 54], where the micro ring devices with radii ranging from 3-15 microns could be fabricated. Further, the theoretical investigations of such devices in other areas of applications have also been increased, where the areas such as chaotic communication [50] and polarized photons generation [55] have been proposed.

In this thesis, the simple system of the attosecond pulse generation using the integrated optic devices known as the multi-stage micro ring resonators is proposed. The ring parameters used are ring radii, R= 5-10 μm, couple coefficients, K = 0.25 – 0.5. The temporal soliton pulse with peak power of 12 W is input into the serial micro ring resonators (multi-stage), where the generation of the attosecond pulse with the full width at half maximum (FWHM) of 50 as is achieved. The advantage of the proposed system is that the generation of the attosecond pulse and beyond is plausible by using the remarkably simple system, where the feasibility of using such a design for zeptosecond pulse and beyond generation has shown in good results.

3.2 Chaotic Soliton Generation

An optical soliton is recognized as a powerful laser pulse, which can be used to enlarge the optical bandwidth when propagates within the nonlinear micro ring resonator [58]. Moreover, the soliton self-phase modulation (SPM) keeps the large output gain. When the soliton pulse is introduced into the multi-stage micro ring resonators as shown in Fig. 3.1, the input optical field (E_{in}) is given by

$$E_{in} = A\operatorname{sec}h\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right] \tag{3.1}$$

Where A and z are the optical field amplitude and propagation distance, respectively. *T* is a soliton pulse propagation time in a frame moving at the group velocity, $T = t-\beta 1_1 {}^* z$, where β_1 and β_2 are the coefficients of the linear and second order terms of Taylor expansion of the propagation constant. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. The frequency shift of the soliton is ω_0. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When a soliton peak intensity $\left(\left|\beta_2 / \Gamma T_0^2\right|\right)$ is given, then T_o is known. For the soliton pulse in the micro ring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length ($L_{NL}= (1/\Gamma\phi_{NL})$, where $\Gamma = n_2 * k_0$, is the length scale over which dispersive or nonlinear effects makes the beam becomes wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths, hence $L_D = L_{NL}$.

When light propagates within the nonlinear material (medium), the refractive index *(n)* of light within the medium is given by

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P, \tag{3.2}$$

where n_0 and n_2 are the linear and nonlinear refractive indexes, respectively. I and P are the optical intensity and optical power, respectively. The effective mode core area of the device is given by A_{eff}. For the micro ring and nano ring resonators, the effective mode core areas range from 0.50 to 0.1 μm^2 [59].

When a soliton pulse is input and propagated within a micro ring resonator as shown in Fig. 3.1, which can be a series micro ring resonators. The resonant output is formed, thus, the normalized output of the light field can be expressed as [73]

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\left[1 - \frac{(1-(1-\gamma)x^2)\kappa}{(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2 + 4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\phi}{2})}\right] \tag{3.3}$$

The close form of equation (3.3) indicates that a ring resonator in the particular case to very similar to a Fabry-Perot cavity, which has an input and output mirror with a field reflectivity, $(1-\kappa)$, and a fully reflecting mirror. Where κ is the coupling coefficient, and $x = \exp(-\alpha L/2)$ represents a roundtrip loss coefficient, $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_{In}|^2$ are the linear and nonlinear phase shifts, $k = 2\pi/\lambda$ is the wave propagation number in a vacuum. Where L and α are a waveguide length and linear absorption coefficient, respectively.

3.3 Generalized Fast Light Generation

The remarkably simple system of the attosecond pulse generation using a serial micro ring resonator is shown in Fig. 3.1. When a soliton pulse is input into the nonlinear Kerr effects medium, the nonlinear behavior of light traveling in a micro ring resonator is introduced. To make the system associate with the practical device [56], the parameters of the system are fixed to $\lambda_0 = 1.55\ \mu m$, $n_0 = 3.34$ (InGaAsP/InP), $A_{eff} = 50\ \mu m^2$, $\alpha = 0.02$ dBkm^{-1}, $\gamma = 0.1$, and $R_1 = 10\ \mu m$. The coupling coefficient of the micro ring resonator is fixed at $\kappa = 0.25$-0.5. The nonlinear refractive index is $n_2 = 2.2 \times 10^{-13}$ m^2/W [50], and the plot of 20,000 iterations are operated.

The system of the attosecond pulse generation consist the multi-stage micro ring resonators, where the ring radii are 10, 5 and 10 microns, respectively. The soliton pulse is coupled into the system with $\kappa = 0.25$-0.5.The selected input pulse widths are 50 ns, 50 ps and 50 fs, with wavelength of 1550 nm. After the first micro ring resonator, there is some of the optical power coupled into the second and third ring resonator, respectively. The wave guided loss of 0.5 dBmm^{-1} is noted.

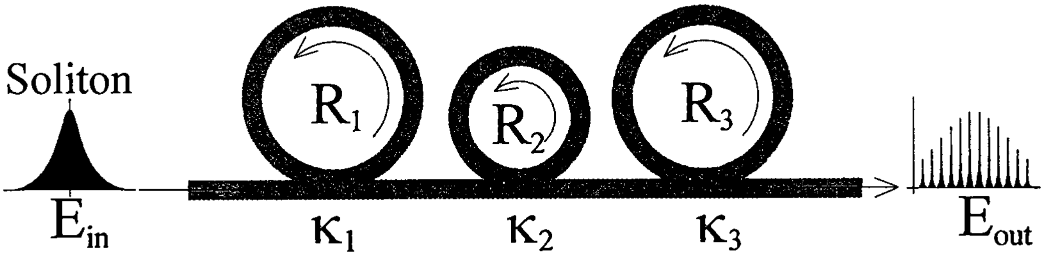


Fig. 3.1 Schematic of the attosecond pulse generation using the multi-stage microring resonators.

The simulation results with different input peak powers of 7.5, 12.0 and 20.0 W, with pulse widths of 50 ns, ps, fs, as, and zs are investigated. The simulation results of the output signals at the resonant peak power with 20,000 roundtrips are shown in Figs. (3.2)-(3.6). One set of the simulation results has shown that the clear single attosecond pulse could be generated as shown in Fig. 3.3(b), by using the simulation parameters as followings: ring radii 5-10 microns, input power 12 W, pulse width 50 fs, coupling coefficient K = 0.5. However, all parameters may be changed to investigate more behaviors and characteristics of the devices. The plot of two different input powers and coupling coefficients are shown in Figs. 3.7 and 3.8, which is found that the generation of the clear single attosecond peak is achieved when the input peak power is 12 W with K=0.5 as shown in Figs.3.4 (d) and 3.8(c), where the used parameters can be used to generate the single attosecond pulse, which the others could not properly be generated the attosecond pulse. In Fig. 3.9, the generated attosecond pulse width of 50 as at FWHM is expanded within 20,000 roundtrips, which the one roundtrip is 2.9 x 10^{-12} sec. The input pulse width of 50 fs is applied into the system as shown in Fig. 3.8(c). Where the other pulses are interfered and lost within the device. The time lack of those pulses is presented by the link between the devices, which is neglected. The detection of the specific output is specified by time difference. However, the output peak is amplified by the Kerr nonlinear effect within the ring devices. The resonant peak is obtained by the superposition which is called four-wave mixing type. In practice, the input power is used the commercial laser diode [57], which is available in the commercial market.

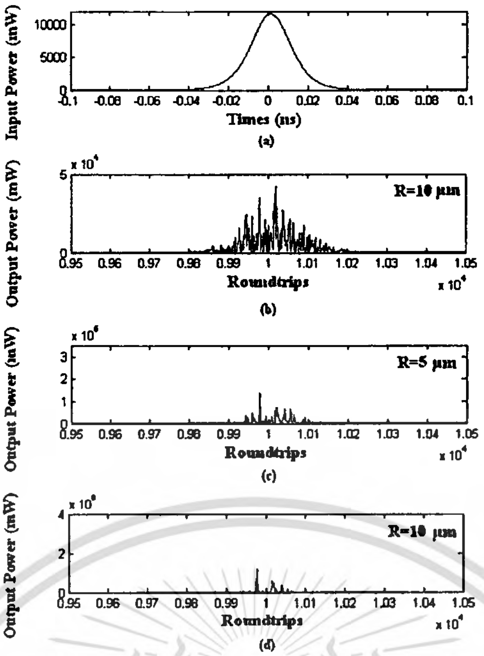


Fig. 3.2 The attosecond switching pulse generated by using the multi-stage micro ring devices with 50 ns (a) input pulse, coupling constant K = 0.5, where the ring radii are 10 μm (b), 5 μm (c) and 10 μm (d).

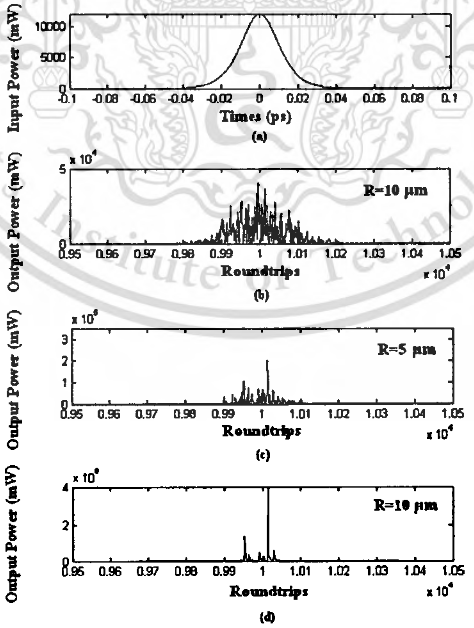


Fig. 3.3 The attosecond switching pulse generated by using the multi-stage micro ring devices with 50 ps (a) input pulse (a),coupling constant K= 0.5, where the ring radii are 10 μm (b), 5 μm (c) and 10 μm (d).

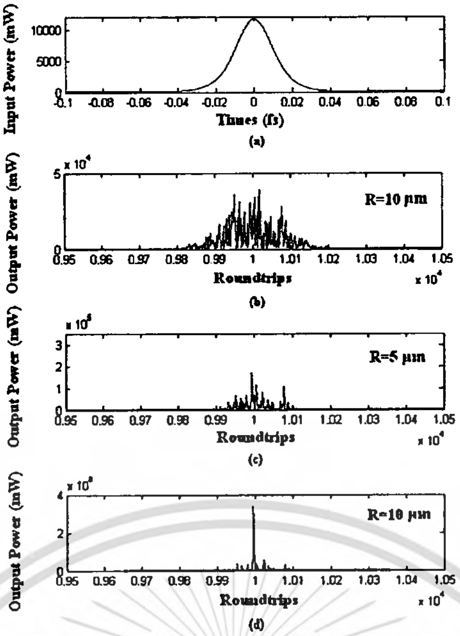


Fig. 3.4 The attosecond switching pulse generated by using the multi-stage micro ring devices with 50 fs (a) input pulse (a), coupling constant K = 0.5, where the ring radii are 10 μm (b), 5 μm (c) and 10 μm (d).

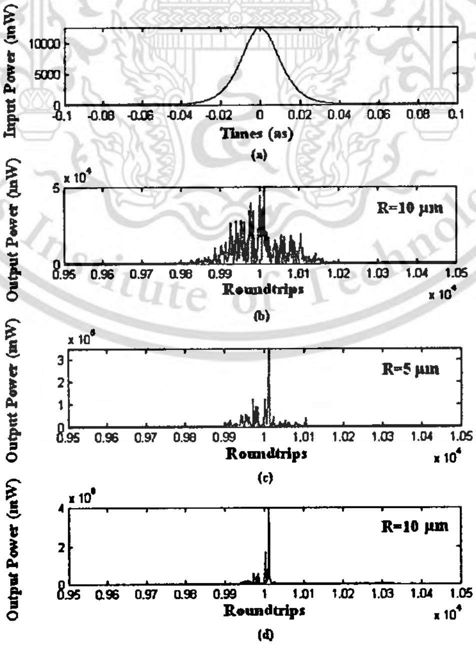


Fig. 3.5 The attosecond switching pulse generated by using the multi-stage micro ring devices with 50 as (a) input pulse (a), coupling constant K = 0.5, where the ring radii are 10 μm (b), 5 μm (c) and 10 μm (d).

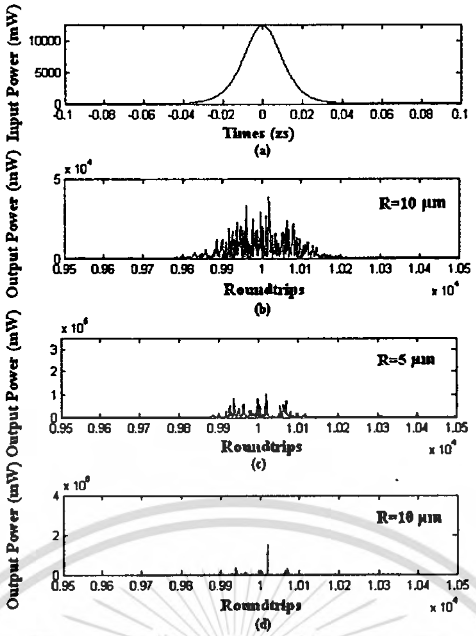


Fig. 3.6 The attosecond switching pulse generated by using the multi-stage micro ring devices with 50 zs input pulse (a), coupling constant K = 0.5, where the ring radii are 10 μm (b), 5 μm (c) and 10 μm (d).

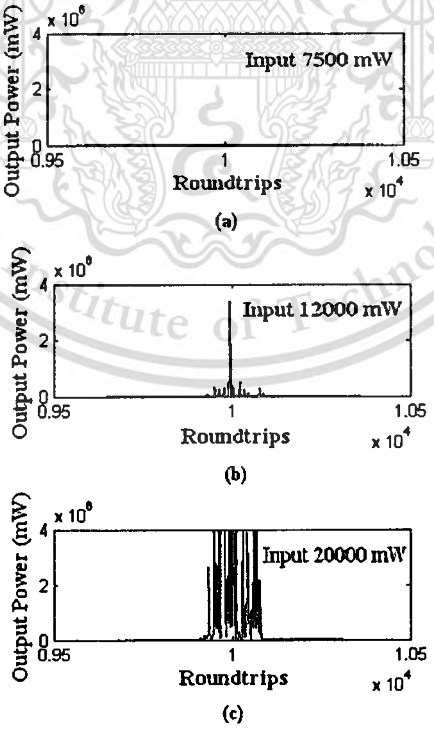


Fig. 3.7 The relationship between the output pulse and roundtrips (time) with a 50 fs input pulse, the coupling constant K = 0.5, where the input powers are (a) 7.5, (b) 12.0 and (c) 20.0 W.

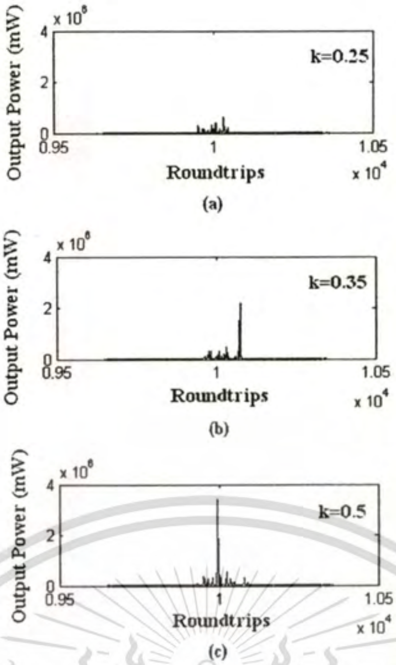


Fig. 3.8 Plot of the relationship between the output pulse and roundtrips (time) with a 50 fs input pulse, the different coupling constants are (a) 0.25, (b) 0.35 and (c) 0.5, the ring radii are 10 μm, 5 μm and 10 μm.

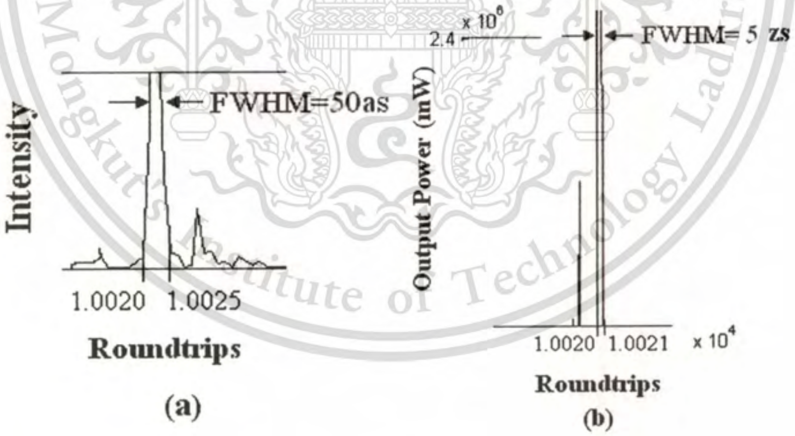


Fig. 3.9 Pulse width expansion of the output pulse in Fig. 3.4 (d) and 3.5(d) with the fraction of time of 10^{-3} of the input power.

In applications, the exact roundtrips time at the resonant peak power can be controlled and selected, where the required pulse width can be selected and used. Further, the pulse width beyond the zeptosecond pulse width can also be generated with the same principle. This is available for the applications such as new generation of ultra fast switching and lithography, including high capacity compact disk processing, high resolution image construction, and high resolution interferometer.

I have proposed the remarkably simple scheme for fast light pulse generation, where light pulse with switching time of attosecond and beyond is generated, using the multi-stage nonlinear micro ring devices. I found that the generation of the extremely short pulse in the range of 50 zeptosecond and beyond is plausible. In practice, the temporal mode detection of such a narrow pulse (i.e. short response time) is the problem in the realistic application due to the optical material bandwidth limitation, therefore, the detection technique is become the subject of investigation rather than the device material. However, the use the spatial mode is useful, where the new generation optical lithography with a very fine pen will be the next generation lithography.

3.4 CONCLUSIONS

In chapter 3, I have proposed the use of a microring resonator to design ultra fast switching and lithography, including high capacity compact disk processing, high resolution image construction, and high resolution interferometer. Where the chaotic signals can be generated using nonlinear effect.

CHAPTER4

SLOW LIGHT GENERATION

In this chapter, I propose a remarkably simple system of an all optical system that can be used to fast, slow, stop and store light coherently. A system consists of ring resonators that can be integrated into a single system, whereas the large bandwidth signal is generated by a soliton pulse within a Kerr type nonlinear medium. The balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as self-phase modulation(SPM), which introduces the optical output (i.e. gain) constant, which means that light pulse can be trapped, i.e. stopped coherently within the ring-waveguide. The time independent optical gain is stored within the nano ring device, which is available for read only memory (ROM) application. The applications such as optical memory, multiplexed sensors, frequency converters, quantum key distribution and extremely narrow pulse lithography are described.

4.1 Introduction

The ability to slow down the speed of light, and to coherently stop and store optical pulses, holds the key to ultimate control of light and has shown potential for optical communications and quantum information processing [22, 23]. There are two major approaches, employing either electronics or optical resonant, however, most of the system impose severe constraints. One of the recent works was proposed, where the general analysis for the criteria to stop and store light coherently using array micro cavities was proposed by Yanik and Fan [24, 25]. However, the system is still complicated, which is difficult to make the realistic implementation. Therefore, the searching for the suitable devices and technologies are still required. Recently, Yupapin et al [60] have shown that the large bandwidth light pulses can be generated and compressed coherently, whereas the use of such a proposed device in various applications has been reported [28, 29,30]. Since, the use of a chaotic soliton to form a fast light generation within a tiny device known as a micro ring resonator (waveguide) has been reported by Yupapin et al [60]. They have shown that the large bandwidth can be compressed coherently with a small group velocity. In practice, there are such devices have been fabricated and used in various applications. Optical Soliton has been recognized as a nonlinear solitary wave for years [61, 62]. Since then, it has been widely investigated in several subjects such as in physics, mathematics and communication, especially, in optical communication. Generally, the common property of a soliton known as self-phase modulation (SPM) and cross phase modulation(CPM) are the challenged behaviors. Furthermore, the non-dispersion behavior of the soliton is the key advantageous. This is capable the use in long-haul communication, where the long distance link without a repeater can be employed. The other interesting soliton behavior is the localization, where the soliton pulse can be trapped and stored within the periodic medium, which is useful in many areas of applications. Generally, the soliton pulse can be recovered, when the balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as self-phase modulation, it occurs when the matching between the soliton property and localized media is provided. When the generation of the localized soliton pulse is achieved, it is available for applications in many areas of research in science and technology.

4.2 Stop and Store Light within a Nano-waveguide

In order to coherently stop a pulse with a given bandwidth, the following criteria must be satisfied; (i) the system must process an initial state with a sufficiently large bandwidth, and (ii) the modulation accomplishes coherent frequency conversion for all spectral components and reversibly compresses the pulse bandwidth. In operation, the large bandwidth within the micro ring device can be generated by using a soliton pulse input into the nonlinear micro ring resonator.

The schematic diagram of the proposed system is as shown in Fig. 4.1, a soliton pulse with 20 ns pulse width, peak power at 500 mW is input into the system. By using the suitable ring parameters, for instance, ring radii R_1= 10 μm, R_2= 5 μm, and R_3= 2.5 μm. To make the system associate with the practical device, the selected parameters of the system are fixed to λ_0 = 1.55 μm, n_0 = 3.34 (InGaAsP/InP), A_{eff} = 0.50, 0.25 μm^2 and 0.12 μm^2 for a micro ring and nano ring respectively, α = 0.5 dBmm^{-1}, γ = 0.1. The coupling coefficient (kappa, κ) of the micro ring resonator is ranged from 0.50 to 0.975. The nonlinear refractive index is $n_2 = 2.2 \times 10^{-17}$ m^2/W. In this case, the wave guided loss used is 0.5dBmm^{-1}. As shown in

Fig. 4.2, the signal is chopped (sliced) into a smaller signal spreading over the spectrum as shown in Fig. 4.2 (a), which is shown that the large bandwidth is formed within the first ring device. The compress bandwidth with smaller group velocity is obtained within the ring R_2. The amplified gain is obtained within a nano ring device (i.e. ring R_3). The stopping light pulse situation can be formed by using the constant gain condition, where a small group velocity is seen. The attenuation of the optical power within a nano ring device is required in order to keep the constant output gain, where the next round input power is attenuated and kept the same level with the R_2 output, which they are 30 and 40 mW respectively as shown in Fig. 4.2. This means that the remaining power of the stopped (stored) light pulse can be absorbed the coupling loss and distributed into the employed system.

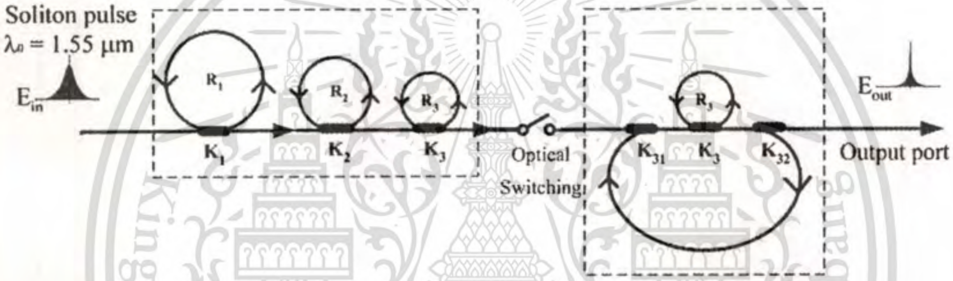
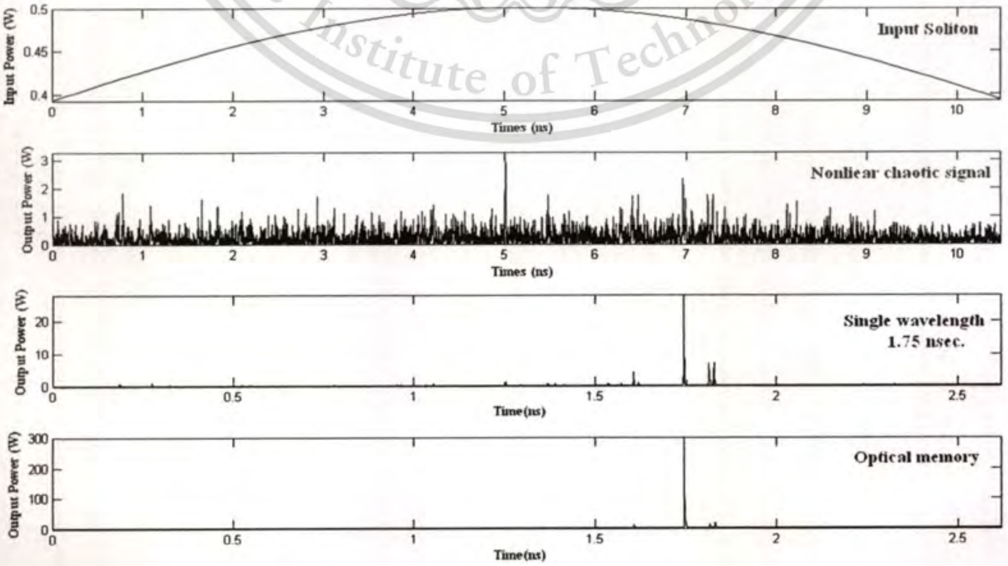
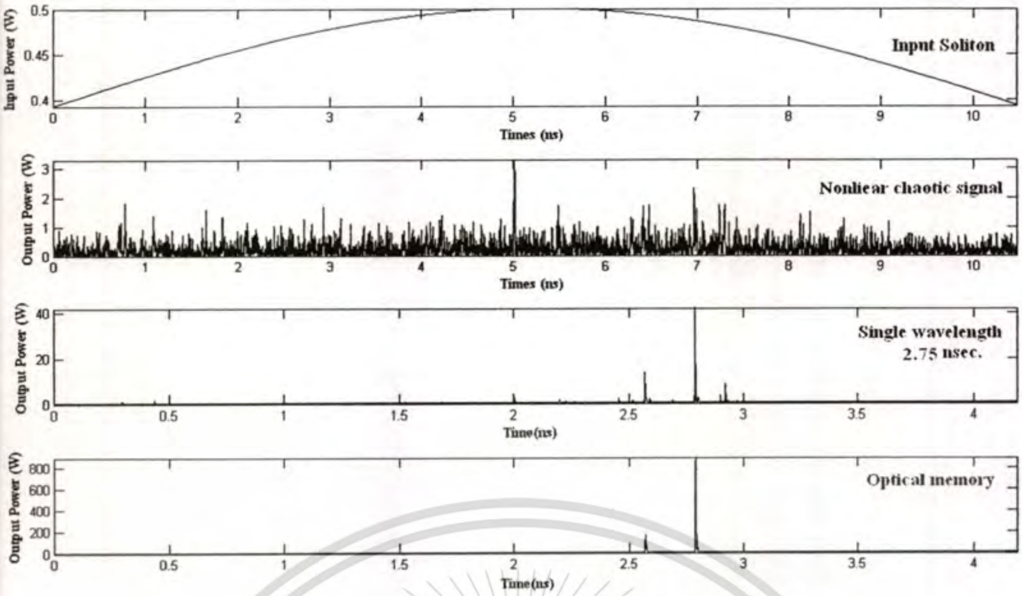


Fig. 4.1 Schematic of an all optical stopped and stored light pulse system, R_s: ring radii, κ_s: coupling coefficients, κ_{31} and κ_{32} are coupling losses.



(a)



(b)

Fig. 4.2. Results obtained when a soliton pulse is input into a ring resonator system, where the parameters used are (a) R_1= 10 μm, R_2= 5 μm, R_3= 2.5 μm, center wavelength at 1,550 nm, and (b) R_1= 10 μm , R_2= 5 μm , R_3=4 μm, center wavelength at 1,550 nm, with 50,000 roundtrips.

The other interesting property of the stop light pulse is that the adiabatic behavior of the stopped light pulse is occurred when the roundtrip time is vanished (i.e. stopped) or the stored light pulse switching time is vanished(small group velocity). The stop light concept is formed when the constant gain of the tuned light pulse is achieved as shown in Fig. 4.3. Since, we have found that the tuned light pulse gain recovery can be obtained by connecting the nano ring device into the system (i.e. R_2), therefore, the coupling loss is included due to the different core effective areas between micro and nano ring devices, which is given by 0.1dB. However, we have already described that the other ring parameters are also very important to keep stopping light pulse behavior. We can conclude that the tuned light pulse can be stored or stopped in the nano ring device when the output gain is reached a constant value which is time independence, as shown in Figs. 4.2 and 4.3. By using equation (3.3), the output gain of light pulse within a ring R_3 is obtained. The output gain of a ring R_3 can be attenuated and reached the value that can be used for the next storing input power, which is shown in Fig. 4.3(d). The main parameters that can provide the constant are κ_{31}, κ_{32} and the output power.

In principle, the soliton behavior known as SPM is performed when the balance between the dispersion and nonlinear length phase shift is presented, which is induced the soliton pulse gain recovery is occurred. When light pulse is slow down and completely stopped within a ring R_3, the stopped and stored light pulse time of 1ps (10^{-12} s) is achieved. In application, the memory (ROM) time can be increased by expanding the gain constant time. Furthermore, the adiabatic fashion of light pulse is seen when the number of roundtrip (circulation time) is small comparing to the switching time, for instance, when the pulse is stopped while the switching pulse reaches the switching time at ps, fs, as, zs, etc. The switching time is not a negative value, i.e. positive, therefore, the number of roundtrip of stopping light pulse that can be stored light within the nano ring resonator (waveguide) is vanished, which is induced the ratio of number of roundtrip and switching time is vanished(i.e. time is vanished). This is the concept of cold light when the adiabatic and reversible pulse bandwidth compression process is introduced.

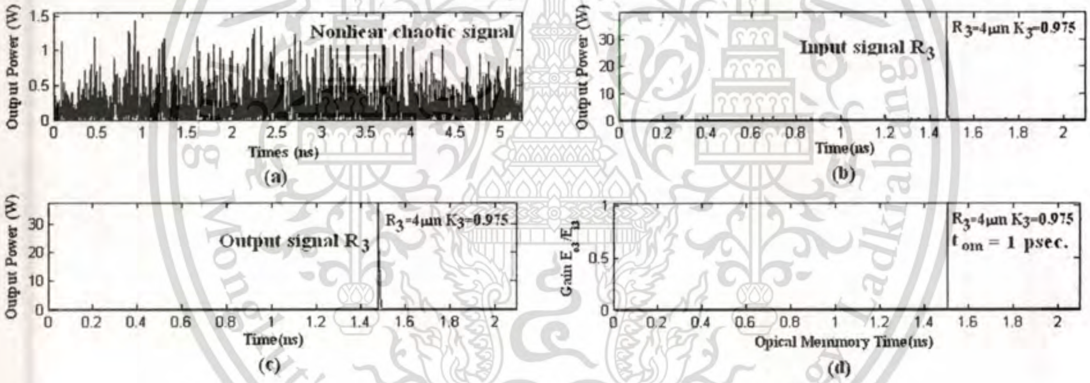


Fig. 4.3 Results obtained when light is stored within a nano ring device with 25,000 roundtrips, the ring radii are $R_1 = 10\ \mu m$, $R_2 = 5\ \mu m$, $R_3 = 4\ \mu m$, optical memory time (t_{om}) is 1.505-1.506 ns.

4.3 CONCLUSIONS

In chapter 4, I have shown that a large bandwidth of the arbitrary wavelength of light pulse can be compressed and tuned to store within a nano-waveguide. The tuned pulse can be slow down and stopped coherently when the matching between dispersion and nonlinear length is exhibited, whereas the soliton SPM pulse exhibits the gain constant within the soliton period. The selected light pulse can be trapped and used to perform the memory. The adiabatic storing pulse process to preserve the coherent information encoded can also be performed. The key advantages of the system are the reversely compress bandwidth and the maintaining power, which can be tuned to obtain the arbitrary pulse for optical/quantum memory (**ROM**). By using the proposed system, the applications such as quantum repeater, quantum entangled photon source and quantum logic gate can also be available, which can be fulfilled the concept of computer by light i.e. quantum computer being realized.

CHAPTER 5

FAST AND SLOW LIGHTT GENERATION FOR COMMUNICATION SECURITY

In this chapter, I propose a new system of signal security using the nonlinear micro ring resonators for optical communication system. When a soliton pulse is input into the system, the chaotic signal is generated and multiplexed into the optical link. The chaotic waveform can be cancelled by using an add/drop device connecting into the transmission link. By using the appropriate ring parameters, the original signal can be retrieved. The other application is that the fast and slow light behaviors can be presented, which can be seen by using the add/drop multiplexers. In some cases, we can generate to obtain the two identical signals called "Signal" and "Ghost", which is observed in different time frame. In application, the communication security can be performed when the required information is multiplexed and performed the link by using chaotic signal, fast and slow light and signal and ghost, where the original signal can be retrieved by the known clients.

5.1 Introduction

An optical ring resonator has become a promising device for optical signal processing applications, where the nonlinear behavior of light traveling within the device has been widely investigated [63-65]. Mario has described the nonlinear behaviors of light within an optical fiber [54], where the nonlinear properties of light including soliton have been described. The use of a micro ring device to form the nonlinear behaviors with various applications has been proposed [66, 67]. The use of nonlinear behaviors of light for communication security has been one of the popular research areas in communication for years. The key point is that the system with perfect security is needed in the realistic application. Several signal security techniques such as digital encoding [53], chaotic noise generation and cancellation [68], chaotic encoding [69], quantum chaotic encoding [70] and quantum encoding [71] have been proposed. More details of such techniques have also been described by reference [67]. In principle, quantum technique is recommended to use for perfect security, however, the problem remains due to the difficulty of implementation. Up to date, there is no dominant technique has been used for communication security. The searching of such a technique that can be served the security requirement and the realistic system remains is required. Recently, Yupapin et al [60] have reported the interesting results when the ultrafast pulse with pulse width of attosecond (as) can be easily generated by using a soliton pulse travelling in the nonlinear micro ring resonators (NMRRs). The interesting idea is that the system is very small which is capable to implement within the communication device and system. The device fabrication in such a scale is confirmed by reference [72]. In this work, we propose the system that can be used to generate the fast and slow light behaviors and signal and ghost concept. Firstly, the chaotic signal is generated within a nonlinear micro ring device which can be cancelled by using the designed add/drop multiplexer. Secondly, we propose the concept of fast and slow lights, where fast light in the form of a soliton pulse can be performed the signal in the slower time frame, which can be detected by using the add/drop multiplexer. In some cases, it is found that there are two identical signals with different time frame, i.e. Signal and Ghost. Using this scheme, a pair of the same signals is generated and separated by the certain time interval, where one signal is in front called "signal", the other is in behind called "ghost". Both signals are generated by using a soliton pulse input into a nonlinear micro ring resonator. The involved parameters are ring radius, coupling coefficient and refractive index. In principle, when the signal transmission is in the network, the control parameters are known by the specific clients. Results obtained have shown that the optical power left after dropping is still valid for long distance link. In application, we can use the proposed system to form the communication security system, where the chaotic noise, fast and slow light, and signal and ghost can be easily generated and retrieved by the specified users.

5.2 Operating Principle

Optical soliton is recognized as a powerful laser pulse, which is used to generate the chaotic filter characteristics, especially, when it propagates within the nonlinear microring resonators [73]. When the soliton pulse is input into the multi-stage microring resonators as shown in Fig. 5.1

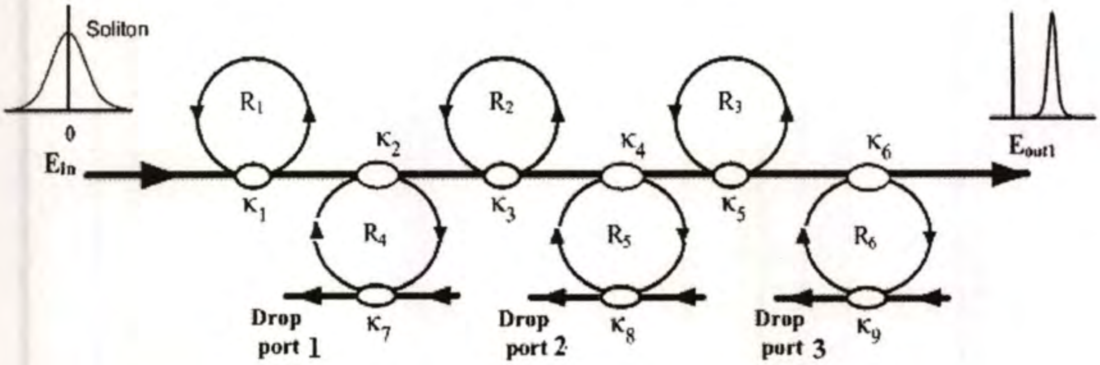


Fig. 5.1 Schematic diagram of micro ring devices and add/drop multiplexers in the communication link.

In this thesis, the iterative method is introduced to obtain the results,as shown in Eq.(3.3) and similarly, when the output field is connected and input into the other ring resonators.

The input optical field as shown in Eq. (3.1), i.e. a soliton pulse, is input into a nonlinear micro ring resonator. By using the appropriate parameters, the chaotic signal is obtained by using Eq. (3.3). To retrieve the signals from the chaotic noise, we propose to use the add/drop device with the appropriate parameters. This is given in details as followings. The two complementary optical circuits of ring-resonator add/drop filters can be given by the Eqs. (5.1) and (5.2) [73].

$$\left|\frac{E_t}{E_{in}}\right|^2 = \frac{(1-\kappa_1) - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_n L) + (1-\kappa_2)e^{-\alpha L}}{1+(1-\kappa_1)(1-\kappa_2)e^{-\alpha L} - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_n L)} \tag{5.1}$$

and

$$\left|\frac{E_d}{E_{in}}\right|^2 = \frac{\kappa_1\kappa_2 e^{-\frac{\alpha}{2}L}}{1+(1-\kappa_1)(1-\kappa_2)e^{-\alpha L} - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_n L)} \tag{5.2}$$

where E_t and E_d represents the optical fields of the throughput and drop ports respectively. κ_1 and κ_1 are coupling coefficients. $\beta = kn_{eff}$ is the propagation constant, n_{eff} is the effective refractive index of the waveguide and the circumference of the ring is $L = 2\pi R$, here R is the radius of the ring. In the following, new parameters will be used for simplification: $\phi = \beta L$ is the phase constant. The chaotic noise cancellation can be managed by using the specific parameters of the add/drop device, which the required signals can be retrieved by the specific users. κ_1 and κ_2 are coupling coefficient of add/drop filters, $k_n = 2\pi / \lambda$ is the wave propagation number for in a vacuum, and where the waveguide (ring resonator) loss is α = 0.5 dBmm^{-1}. The fractional coupler intensity loss is γ = 0.1. In the case of add/drop device, the nonlinear refractive index is neglected.

In operation as shown in Fig. 5.1, the proposed system can be used to generate the chaotic signal by using the first micro ring resonator, and the cancellation of the chaotic signal can be achieved by using the add/drop filter (multiplexer) with the appropriate parameters. To obtain more power which is suitable for long distance link, the soliton pulse is recommended to use for chaotic signal generation. The chaotic signal cancellation can be obtained by using the add/drop filters at drop ports 1, 2 and 3 of the add/drop filters R_4, R_5 and R_6.

5.3 Signal and Ghost Generation for Communication security

When the optical power in the form of soliton pulse is input into the first ring of the system as shown in Fig. 5.1, the nonlinear behaviour occurs, which is induced the noisy signal called chaotic signals. In this case, the optical power of 5W is input into the first micro ring device, where the other parameters are λ_0 = 1.55 μm, n_0 = 3.34, A_{eff} = 0.25 μm^2. The waveguide ring resonator loss is α = 0.5 dBmm^{-1}. The practical bending loss of the waveguide fabricated by InGaAsP/InP is confirmed by Yupapin and Suwancharoen [50], the propagation loss as low as 1.3±.02 dBmm^{-1} at 1.55 μm. The fractional coupler intensity loss is γ = 0.1, and R_1 =R_2=R_3= 10 μm The nonlinear refractive index used is n_2 = 2.2 x 10^{-17} m^{2}W^{-1}, and the data of 20,000 iterations which is approximately equal to 29x 10^{-12} second (29 ps). We assume that ϕ_L = 0 for simplicity, however, the change in phase is slightly altered the optical output, which means the dispersion can be neglected when the resonant output is occurred. After the soliton pulse of 5W at the time To = 5 ns is input into the first ring as shown in Fig. 5.2(a), the chaotic signal is generated as shown in Fig. 5.2(b). The coupling coefficient κ_1 is 0.5. The chaotic cancellation is obtained by using the add/drop filter at drop port 1 as shown in Fig. 5.2(c), when κ_2=κ_7=0.3, and the radius ring resonator R_4 = 12 μm. The drop signal obtained is slower in time than the original input signal, which can be named as fast (input) and slow (output) light behaviors. From the result, this is confirmed that the remaining optical power is available for long distance link.

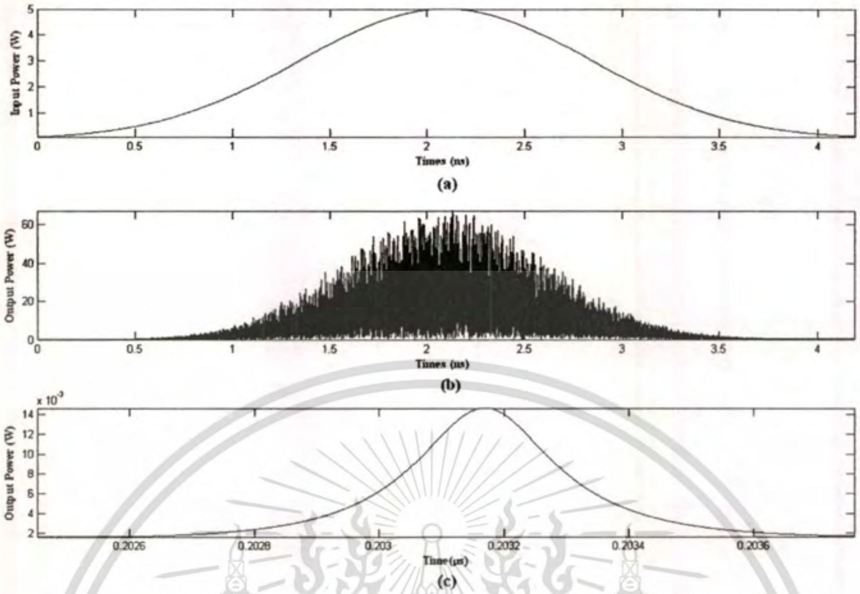


Fig. 5.2 Chaotic and the filter signals obtained at R_1 and R_4 respectively, (a) input signal (fast light), (b) chaotic signal, (c) drop port signal (slow light)

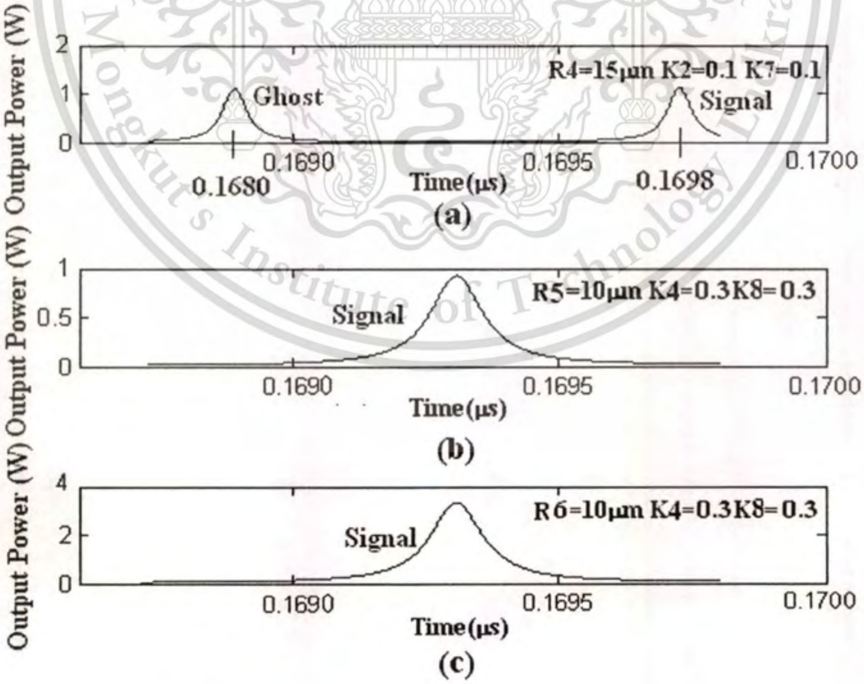


Fig. 5.3 Output signals obtained at drop port R_4, R_5 and R_6, (a) Ghost and Signal, (b) signal and (c) signal.

In Fig. 5.3, the output signals at the drop ports of R_4, R_5 and R_6 are seen. There are two forms of the signals, which one is obtained by the bandstop filter, the other is bandpass filter. Where the ring radius $R_4 = 15\ \mu m$, and the coupling coefficient $\kappa_2 = \kappa_7 = 0.1$ is as shown in Fig. 5.3(a). There are the identical signals with the separation time of 18 ns. We have named these two signals as "Ghost" and "Signal" for faster and slower in times respectively. Fig. 5.3(b) is the output signal obtained when $\kappa_4=\kappa_8=0.3$, the ring radius (R_5) is 10 μm. Fig. 5.3(c) shows the signal after the cancellation (i.e. bandpass filter) with the parameters used are $R_6 = 10\ \mu m$ and the coupling coefficients $\kappa_6 = \kappa_9 = 0.3$.

In Fig. 5.4, the input power waveform with the center peak at 2 ns is shown in Fig. 5.4(a), where the relationship between the input and output power is shown in Fig. 5.4(b). The slower chaotic signals are seen in Fig. 5.4(c), 5.4(e) and 5.4(g), where the corresponding drop port signals are shown in Fig. 5.4(d), 5.4(f) and 5.4(h). The parameters used are $R_1=R_3=R_4=15$ μm, $R_2=R_5=10\ \mu m$, $R_6=21\ \mu m$, $\kappa_2=\kappa_7=0.1$, $\kappa_4=\kappa_8=0.3$ and $\kappa_6=\kappa_9=0.1$. The bandstop filter signals are obtained in Fig. 5.4(d) and 5.4(h), where the bandpass filter signal with slower time (μs) is obtained in Fig. 5.4(f). The separation time of the ghost and signal of 1.7 and 1.3 ns are obtained in Fig. 5.4(d) and 5.4(h), respectively.

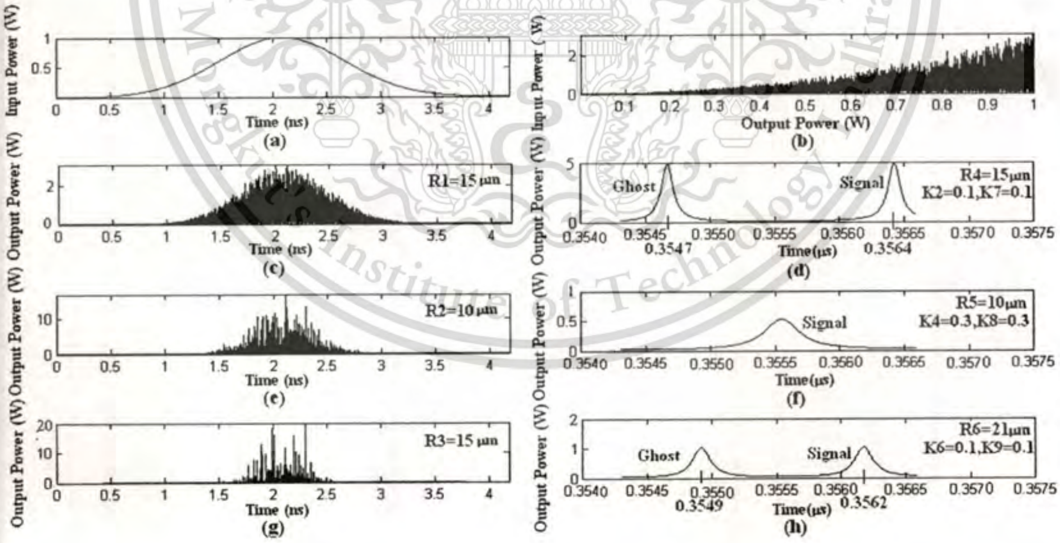


Fig. 5.4 Chaotic signals generated by R_1, R_2 and R_3 and the output signals at drop ports R4, R_5 and R_6, (a) input signal, (b) input and output power, (c) chaotic signal, (d) Ghost and Signal, (e) chaotic signal, (f) drop port signal, (g) chaotic signal, (h) Ghost and Signal.

In applications, the communication security can be performed in the networks. By using the proposed system, the chaotic signals can be generated and transmitted into the optical communication link, whereas the specified users along the networks who know the corrected details of the add/drop device can retrieve the required information. However, there are two schemes in the proposed system. Firstly, the chaotic cancellation can be made by using the fast and slow light method. Secondly, a pair of signal and ghost can be used to confirm each other by using the specified separation time. In practice, two key points of this application are the secret parameters, and the proposed device is now fabricated and available, which will be implemented in the near future.

5.4 CONCLUSIONS

The chaotic signal generation using a soliton pulse in the nonlinear micro ring resonators is presented. The secure information with high coupling power of soliton pulse can be used to perform the communication security for long distance link. I have proposed the two techniques called "fast and slow lights" and "ghost and signal", which can be used to performed the signal security. Using this proposed scheme, the communication security can be employed incorporating the transmission data in the communication system. Therefore, the communication security requirement is plausible. The advantage of the system is that the clear signal can be retrieved by the specific add/drop filter, which is now commercially made.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

A remarkably simple system of an all optical system that can be used to fast and slow light is proposed. A system consists of ring resonators that can be integrated into a single system, whereas the large bandwidth signal is generated by a soliton pulse within a Kerr type nonlinear medium. The balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as self-phase modulation (SPM), which introduces the optical output (i.e. gain) constant. The applications such as optical lithography extremely narrow pulse lithography and communication security are described in three topics.

Firstly, the Generalized Fast Light Generation the simple scheme for fast light pulse generation has been proposed, where light pulse with switching time of attosecond and beyond is generated, using the multi-stage nonlinear micro ring devices. The result found that the generation of the extremely short pulse in the range of 50 zeptosecond and beyond is plausible. In practice, the temporal mode detection of such a narrow pulse (i.e. short response time) is the problem in the realistic application due to the optical material bandwidth limitation, therefore, the detection technique is become the subject of investigation rather than the device material. However, the use the spatial mode is useful, where the new generation optical lithography with a very fine pen will be the next generation lithography.

Secondly, the Stop and Store Light within a Nano-waveguide a remarkably simple system of an all optical system that can be used to fast, slow, stop and store light optically is proposed. The system consists of two micro and a nano ring resonators that can be integrated into a single system, which can be employed to overcome the problem of bandwidth delay constraints with small group velocities. The large bandwidth is generated by a soliton pulse within a Kerr type nonlinear medium where an all optical adiabatic and reversible pulse bandwidth compression can be performed. The balance between dispersion and nonlinear lengths of the soliton pulse exhibits the soliton behavior known as self-phase modulation, which introduces the optical output (i.e. gain) constant, which means that light pulse can be trapped, i.e. localized coherently within the nano-waveguide. The time independent optical gain is stored within the nano ring device, which is available for trapping either spatial or temporal soliton.

Finally, the Fast and Slow Light Generation for communication security this chaotic signal generation using a soliton pulse in the nonlinear micro ring resonators is presented. The secure information with high coupling power of soliton pulse can be used to perform the communication security for long distance link. This thesis have proposed the two techniques called "fast and slow lights" and "ghost and signal", which can be used to performed the signal security. Using this proposed scheme, the communication security can be employed incorporating the transmission data in the communication system. Therefore, the communication security requirement is plausible. The advantage of the system is that the clear signal can be retrieved by the specific add/drop filter, which is now commercially made.

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APPENDIX

LIST OF PUBLICATIONS

Publication in 2009

1. S. Chaiyasoonthorn, N. Pornsuwancharoen, P.P. Yupapin, **An extremely narrow UV pulse generation using a micro and nano ring system for pico-lithographic resolution**, Optik - International Journal for Light and Electron Optics, 2009. (Impact Factor:2007:0.383) (Article in press)

2. S. Mitatha, S. Chaiyasoonthorn and P.P. Yupapin, **Dark-Bright Optical Solitons Conversion via an Optical Add/Drop Filter**, Microwave and Optical Technology Letter, Vol. 51(7), 2009. (Article in press)

3. K. Sarapat, S. Chaiyasoonthorn, S. Thongmee, P.P.Yupapin, **Dark-bright optical solitons conversion via an optical add/drop filter for signals and networks security applications**, Optik - International Journal for Light and Electron Optics, 2009. (Impact Factor:2007:0.383) (Article in press)

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1. W. Suwancharoen, S. Thongmee and S. Chaiyasoonthorn and P.P. Yupapin, **Chaotic Signal Filtering Device using a Serial Connection of Micro-Ring Resonators**, JNOPM, Special Issue Volume, November, 2008. (Impact Factor 2006:0.496)

2. P.P. Yupapin, S. Chaiyasoonthorn and N. Pronsuwancharoen, **Fast Light with the Micro Ring Devices for New Generation Optical Lithography**, Optical Resonators : Research, Technology and Applications, NOVA Science Publisher, 2008. (Article in press)

3. S. Mitatha, K. Dejhan, S. Chaiyasoonthorn and P.P. Yupapin, **Atto Second Pulse and Its Beyond Generation Based on Muti-stage Micro Ring Resonators,** Advanced Materials Research, Vol. 55-57, 2008, pp. 485-488.

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6. P.P. Yupapin, S. Chaiyasoonthorn, and O. Saneochit, **A new generation optical lithography using a third harmonic pulse generated by micro ring resonators**, International Journal of Light and Electron Optics, 2008. DOI : 10.1016/j.ijleo.2008.09.012 (Impact Factor:2007:0.383)

7. N. Pornsuwancharoen, S. Chaiyasoonthorn and P.P. Yupapin, **Fast and Slow Lights Generation using Chaotic Signals in the Nonlinear Micro Ring Resonators for Communication Security**, Optical Engineering, 2008. (Impact Factor:2008:0.757) (Article in press)

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1. P.P. Yupapin, W. Suwancharoen, S. Chaiyasoonthorn and S. Thongmee, **An Optical Tunable Band-pass Filter using Chaotic Signals in a Nonlinear Micro Ring Resonator**, SPIE -Volume 6793, 2007.

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