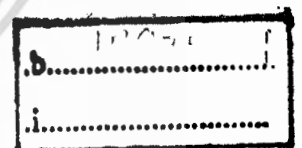


**STUDY OF NANO RESOLUTION MEASUREMENTS
BASED ON FIBER OPTICS**



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หัวข้อวิทยานิพนธ์	ศึกษาการวัดอย่างละเอียดระดับนาโนโดยใช้เส้นใยแก้วนำแสง
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บทคัดย่อ

วิทยานิพนธ์ฉบับนี้ นำเสนอศึกษาการวัดในระดับนาโนเมตร โดยใช้เส้นใยแก้วนำแสงชนิดเกรตติง เริ่มจากการตรวจวัดความเค้นในระดับนาโนเมตร โดยใช้การรบกวนทางความเค้นในระดับไมโครเมตร ระบบประกอบด้วยเส้นใยแก้วนำแสงชนิดเกรตติงครึ่งอยู่กับเฟียโซอิเล็กทริกซึ่งทำหน้าที่เป็นแหล่งกำเนิดการสั่นแบบมาตรฐาน ทำให้ความละเอียดในการวัดเพิ่มขึ้นจากการให้ความเค้นในระดับไมโครเมตรจนถึงระดับนาโนเมตร จากนั้นใช้การจำลองทางคอมพิวเตอร์และกระบวนการรบกวนอันดับสองบนเส้นใยแก้วนำแสงชนิดเกรตติง เพื่อหาความสัมพันธ์ระหว่างการเปลี่ยนความยาวคลื่นแบรกก์กับความยาวของเส้นใยแก้วนำแสงชนิดเกรตติงที่เพิ่มขึ้นจากความเค้น ผลลัพธ์ที่ได้แสดงให้เห็นความเป็นไปได้ในการใช้ระบบสำหรับการวัดความเค้นในระดับนาโนเมตร จากนั้นได้ศึกษาและวิเคราะห์ผลของความไม่เป็นเชิงเส้นในเส้นใยแก้วนำแสงชนิดเกรตติงที่มีต่อการวัดอย่างละเอียดในระดับนาโนเมตร ผลจากการจำลองทางคอมพิวเตอร์แสดงความสัมพันธ์ระหว่างค่าสัมประสิทธิ์การสะท้อนและความยาวคลื่นแบรกก์ที่เปลี่ยนไป ส่วนสุดท้ายศึกษาการประยุกต์ใช้การวัดระดับนาโนเมตร โดยใช้เส้นใยแก้วนำแสงชนิดเกรตติงกับเทคนิคอินเตอร์เฟอโรมิเตอร์เพื่อเพิ่มความละเอียดในการวัด

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ABSTRACT

This thesis presents a study of the nano-scale measurements based on fiber optics. Initially, a new concept of nano-strain monitoring using μ -strain perturbation is proposed, the a system consists of a fiber Bragg grating and a standard vibration source. The measurement resolution is increased from μ -strain to n-strain regime, using the second order perturbation method on the fiber grating stretching length. The change in Bragg wavelength due to the change in fiber stretching length is simulated. Results obtained have shown the feasibility of using such a proposed system to monitor small strain and vibration in the nano-scale range. Secondly, the nonlinear effect in fiber grating to nano-scale measurement resolution is analyzed. The simulation results obtained have shown the relations between the reflectivity and Bragg wavelength, which is neglected. The last one, the self calibration of the nano-scale measurement between fiber Bragg grating and New Generation Interferometry is proposed and analyzed. The increasing in measurement resolution in term of optical path difference (OPD).

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Piyawadee Yabosdee

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CHAPTER 1

INTRODUCTION

1.1 Statement and Significance of the Problems

Fiber grating has been widely used in broad areas of applications and very important elements for both the optical fiber communications and sensor systems. As tactile sensor using optical fiber sensor which capable of detecting contact force, vibration, texture, and temperature [1]. Fiber grating are applied for health monitoring of the oil production offshore platform which is located in the Bohal sea, East China [2]. Optical fiber grating appears to be useful for a variety of applications. For instance, in order to measure in both parameters, i.e. simultaneous measurements (strain and temperature) at the same time and location, the techniques have been combined the use of a pair of fiber grating for their applications [3]. The others use the fiber interferometrically interrogated techniques [4,5], long period gratings [6], or a new stress-sensing technique based upon measurement of light scattering produced by an array of birefringent waveguides [7].

Vibration sensors using fiber optic have also been interested in various applications such as study of the measurement flow-induced structural vibrations [8], A broadband nanometer amplitude modulation fiber optic vibrometer with nanometric accuracy is reported [9], The use of a fiber grating microphone has been developed and tested in the audible frequency range [10]. The use of a fiber grating which is configured as a Fabry-Perot interferometer in fiber-optic vibration sensing is also investigated [11], especially, the capable performance in the small scale measurement, i.e. nano-scale regime. This thesis presents the model of nano-scale vibration using fiber grating stretching, where the small increment of grating length stretching is simulated and discussed. The linear stretching of fiber grating is simulated relatively to the change in vibration frequency of the ceramic piezoelectric device, which is changed respecting to the applied voltage. The potential of using such a device for

nano-scale sensor and vibration is studied and discussed. The feasibility of simultaneous measurement of strain and temperature within the same range is discussed.

Although most applications of fiber grating have focused on the linear properties but some nonlinear properties becomes very importance for the development of optical devices in present such as Hojoon Lee studied the optical pulses transmitted though fiber grating using phase-shifted grating and nonlinear effect to compare their performance in optical switching [12]. When high pump laser light is launched into fiber grating, optical Kerr effects are induced and modified depending on signal power. The results are optical switching of signal light by intense pump light [13]. Pedro M. Ramos *et al.* studied the influence of the Kerr-like nonlinearity on the pulse propagation in two types of fiber gratings which are uniform and raised-cosine apodized gratings. H. Alatas *et al.* studied the result of solitons which propagated in nonlinear Bragg grating, the result shown that the bifurcation is induced and soliton energy is varied [14]. Yosia *et al.* shown the Cross Phase Modulation (XPM) effect between CW probe and strong Gaussian pump in a fiber grating. The result appeared three potential nonlinear switching applications as optical switching, optical inverter and optical limiter [15]. For the fabrication of nonlinear fiber grating such as H. Liu *et al.* proposed a novel and flexible method for controlling the chirp rate of a linearly chirped fiber Bragg grating and nonlinearly chirped FBG by adhering a uniform FBG onto a plastic plate with a pre-calculated curvature and applying an axial force on the plate [16]. R.T. Zheng *et al.* reported a novel fabrication method to generate continuous chirp in a fiber Bragg grating using a uniform phase mask. The result of method has a nonlinear group delay response and an asymmetric bandpass spectrum [17].

From previous paragraph shown widely used of fiber grating and its nonlinear applications. Thus this thesis studies the nonlinear effect in fiber grating for the

improvement of the measurement resolution. The results will be shown the relation between the characteristics of the fiber grating and the optical Kerr effects.

Nonlinear behaviors of light in a ring resonator have been widely investigated by Yupapin et al [18]. While more details of nonlinear behaviors in fiber optic with some benefits are also described by Ferreira [19]. They have shown that the nonlinear penalties such as chaos, bifurcation and bistability which introduce the system degradation become benefits. Yupapin and Suwancharoen [20, 21] have proposed the use of nonlinear behavior where the information security using the chaotic signals in the micro ring device can be made. In principle, the chaotic codes could be generated and cancelled between the specific clients. By this technique, the capacity of the transmission data can be secured and increased when the chaotic packet switching is employed. They have also shown that the telephone networks can be included in the secure communication unit within the system. Alternatively, Yupapin and Suchat [22, 23] have demonstrated that the use of nonlinear behavior known as four-wave mixing (FWM) of light in a fiber optic ring resonator could be used to generate a pair of the entangled photons. The advantage of such a system is that there is no optical pumping part and component included in the system (i.e. an all fiber optic scheme), which is a remarkably simple arrangement, and it is easy to implement in the practical applications. However, the problem of the fiber optic property known as a fiber birefringence could affect the optimum entangled state visibility after traveling within a length of the fiber. Trojek et al [24] have analyzed the timing-walk off on the entangled photons in fiber optic, which could be compensated by using the phase retardation device. To shift the polarization orientation angle, therefore, the polarization controller device is recommended to use for adjusting and preserving the entangled states along the fiber optic length. Moreover, Fietz and Shvets [25] have reported that the polarized entangled photons can be generated by using a micro ring device, which is associated with the practical devices which have been fabricated. Recently, Yang et al. [26] have shown the promising results when the enhanced

second-harmonic generation in AlGaAs micro ring resonators is obtained. In Chapter 5, we have shown that two ultra high resolution interferometers have been proposed, which is a classical interferometer, the other is a quantum interferometer. The increasing in measurement resolution in term of optical path difference (OPD).

1.2 Goal of the Thesis

The aim of this thesis is the study nano-scale measurements based on fiber optics. The applications are the new concept of nano-strain monitoring using micro strain perturbation and nonlinear effects in fiber grating to nano-scale measurement resolution. The last one, it is to proposed a concept of a new generation interferometric technique.

1.3 Scope of the Thesis

This thesis studies the nano-scale measurements based on fiber optics. It focuses on the uniform fiber grating and nano measurements resolution. In this thesis presents such system design that is a model of the nano-scale vibration measurement system can be performed and simulated using mathematical modeling.

This thesis is formed by six chapters and began with a brief introduction to the overall review of the research background in Chapter 1, including the goal and objectives, scope and significance of the study. The literature review of fiber grating fundamental, theory, properties, external characteristics of fiber grating and nonlinear effects in the fiber grating are described subsequently in Chapter 2. In Chapter 3 will show the result of simulation related to the modeling of the nano-strain monitoring according to the properties and characteristics required. Chapter 4 will explain mathematical modeling of nonlinear effect in the fiber grating and the numerical results. Chapter 5, we firstly propose a concept of a new generation interferometric technique. Finally, a summary of this thesis and future work will be presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

Fiber optics technology is finding increasing in the field of distributed and sensors in applications. Much of the work in sensors has been in the development of the fiber grating.

Over the years there have been several techniques developed to inscribe grating into optical fiber. In 1978, at the Communication Research Centre, Department of Communications, Ottawa, Ontario, Canada[27]. The grating in an optical fiber was first demonstrated by Hill et al. They are launching intense Argon ion laser radiation into Ge-doped core fiber and observed refractive index changes when UV light launched into the fiber core. Three years later, Lam and Garside [28] showed the relationship between the photo-induced refractive index and the power of the exposure UV light. This discovery a new writing technology for fiber grating, side-writing technique by Meltz et al. in 1989 [29]. Meltz's technique demonstrated external fabrication of fiber grating in Ge-doped core fiber. Fiber grating technology developed rapidly after UV light side-writing technology was developed. The new techniques have removed the complexity in the manufacturing process of fiber grating. Fiber grating are the keys to modern optical fiber communications and sensor systems. The commercial products of fiber grating have been available since early 1995.

Advances of fiber optic technologies are having a significant impact on the development of optical instrumentation systems for sensor and telecommunication applications , including their application in temperature sensing. An fiber grating temperature sensor with a grating period of 1550 nm was designed and fabricated by Ramesh and coworkers in 1999. Excellent linearity was observed in the range $-60\text{ }^{\circ}\text{C}$ to $+150\text{ }^{\circ}\text{C}$ between the shift in center wavelength and temperature.

In this chapter, we will review the mathematical model and the physics of fiber grating, which will be helpful in modeling them. General characterization and behavior of fiber grating are also briefly discussed. Finally, this chapter review nonlinear effects in fiber grating.

2.1 Fiber Grating

Normal optical fibers possess uniform refractive index along their lengths. However, it is possible to make the refractive index of the core glass vary periodically along the length of a fiber, rising and falling, then rising again. Such fibers are called fiber grating, because the refractive index variations scatter light passing through the fiber. Each time the light hits a region of higher refractive index, a bit is scatter from each high-index zone interfere constructively, producing strong reflection as shown in Figure 2.1. The high-index regions also scatter light at other wavelengths, but the scattered wave differ in phase so they cancel each other by destructive interference, thus these non-resonant wavelengths are transmitted through the grating with low loss [30]. Fiber grating are defined as periodic perturbations of the refractive index along the length of the core of an optical fiber waveguide. Thus, fiber grating provide modulation of core refractive index of a single mode fiber. The grating are induced by exposing the fiber core to a periodic pattern of UV light over an extended time. The prolonged exposure results in a permanent refractive index change in the core of the fiber. [31]

Fiber grating are passive optical components, which selectively reflect and transmit light of certain wavelengths. So far they are the most important example of optical fibers designed to serve the function of optical components.

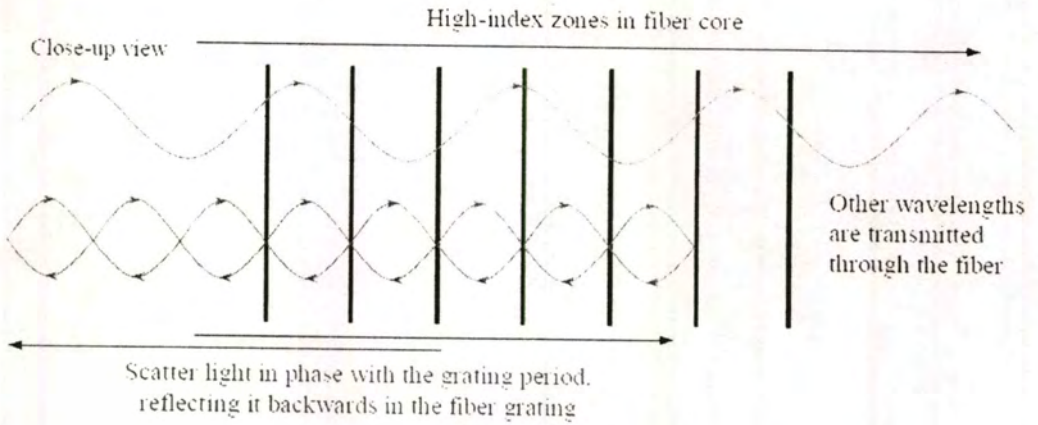


Figure 2.1 FBG reflects light at wavelengths that match the grating period and transmits other wavelengths

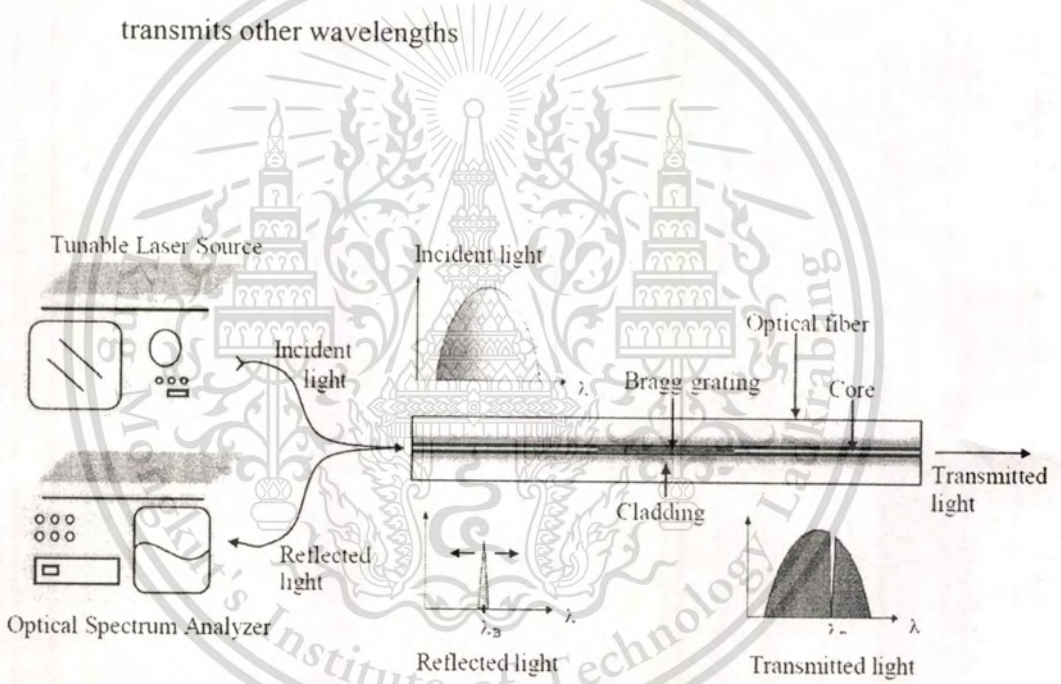


Figure 2.2 The Fiber grating system

2.2 Reflection and Transmission in the Fiber Grating

The reaction of the light traveling through the fiber grating depends on its wavelength. Each line in the fiber grating reflects a little bit of the light at all wavelengths. If the wavelength in the glass is exactly twice the spacing/period of the “lines” written in the fiber, all the scattered light is in phase, so the light waves interfere constructively. That wavelength is reflected. The more lines the more uniform the spacing, and the more strongly they are written, the stronger the reflection. The wavelength selected is twice the distance between the lines written into the fiber because the light wave has to go through the region between them twice, once into the fiber grating, and once when reflected back. The wavelength that counts is the wavelength in the glass, which is shorter than the wavelength in air. This means the refractive index enters the equation if we want the results in terms of the wavelength in air (which is the usual way of denoting wavelength).

Other wavelengths that do not meet this criterion are not reflected in phase, so the scattered light waves do not add constructively. The reflected light averages out to zero, so they are transmitted essentially unaffected. The result is a simple line reflection filter, which reflects the selected wavelength and transmits other wavelengths. No optical device behaves perfectly, and in practice reflection increases strongly over a range of wavelengths, with peak reflection at the selected wavelength. FG can be made to have peak reflection across a narrow band, with nearly square sides as shown in Figure 2.3 for a grating with peak reflection in a band centered at 1538.19 nm. The reflection curve shows the fraction of light (in dB) reflected at that wavelength, while the transmission plot shows the transmission loss at that wavelength. The rest of the light outside the selected band passes through unaffected.

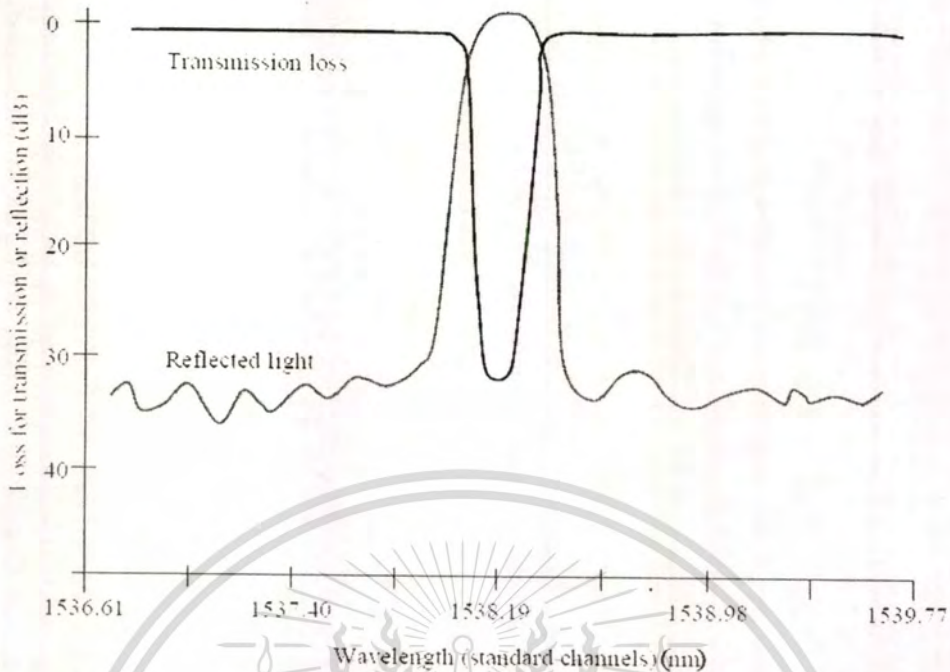


Figure 2.3 Reflection and transmission in the fiber grating

The variation of the reflectivity with the wavelength depends of the grating. Fine, thin, evenly spaced lines tend to concentrate reflection at a narrow range of wavelengths. Turning up exposures to make a stronger grating will increase reflectivity and broaden the range of reflected wavelengths. Commercial devices using this design select a range of wavelengths as narrow as a few tenths of a nanometer and ranging up to several nanometers wide. The narrow ranges are well matched to the requirements of wavelength division multiplexing in the 1550 nm band.

2.3 Mathematical Model of the Fiber Grating

This section intends develop a mathematical model that represents the model of fiber grating that will help in the design. The purpose are the discussion on fiber grating which will being an overview of Bragg condition, Refractive index modulation and Refractive index perturbation.

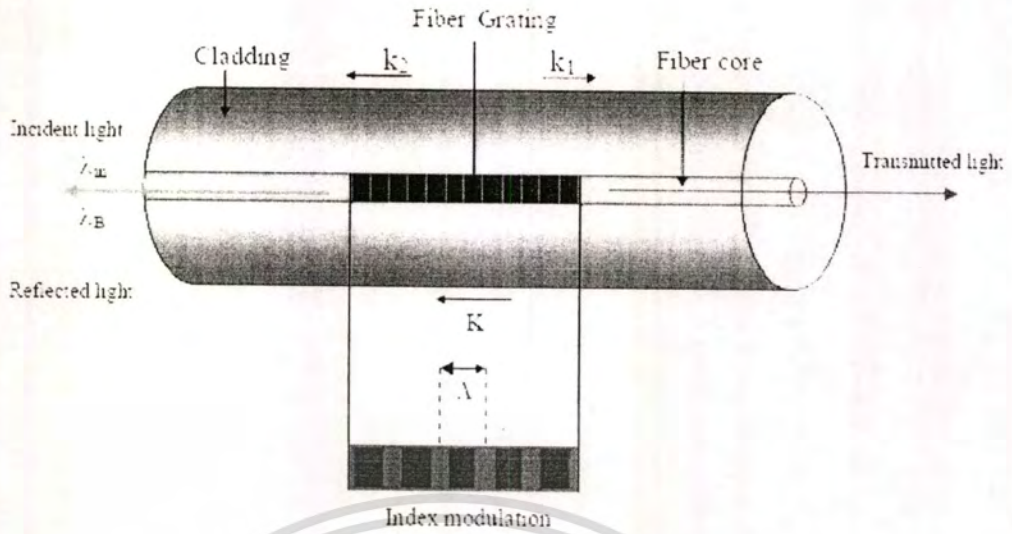


Figure 2.4 Schematic of fiber grating

When a guided fiber mode at the Bragg condition is incident upon a fiber grating, a certain percentage of the incident light will be scattered at each grating plane. Certain directions may be discovered where wavelets created at each plane are in phase. If these directions correspond to a mode of the fiber, then a resonant condition is satisfied. In this case, the forward wave momentum (proportional to \vec{k}_1 , the forward-propagating modal wavevector) is reflected by the grating momentum \vec{K} . Conservation of momentum dictates that

$$\vec{k}_2 = \vec{k}_1 + \vec{K} \quad (2.1)$$

where \vec{k}_1 is the modal wavevector of the forward-propagating wave, \vec{k}_2 is the modal wavevector of the backward-propagating wave, both defined as $k_\alpha = 2\pi/\lambda_\alpha$ and \vec{K} is the grating momentum $k_g = 2\pi/\Lambda$

As the photon frequencies are identical for the two propagating waves, $\lambda_1 = \lambda_2 = \lambda_B$, therefore from eq.(2.1) we get

$$2 \left(\frac{2\pi n}{\lambda_B} \right) = \frac{2\pi}{\Lambda} \quad (2.2)$$

Which simplifies to the first-order Bragg condition $\lambda_B = 2n_{\text{eff}} \Lambda$

The fiber grating is an optical diffraction grating. When broadband light is launched into a fiber grating, the major wavelength is transmitted but a specific wavelength is reflected. A specific wavelength is called the Bragg wavelength (λ_B) and will be reflected from the Bragg grating, as illustrated in Figure 2.4, which depends on the grating period and effective refractive index (n_{eff}) and Λ is the grating period, which is given by

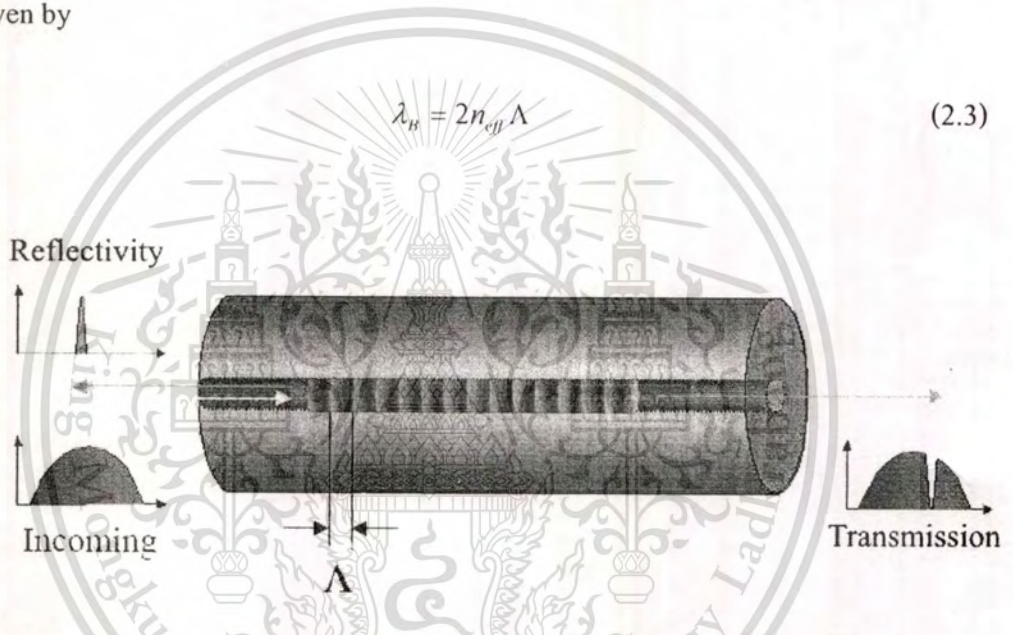


Figure 2.5 Schematic of fiber grating with reflectivity and transmission

Normally the effective refractive index and the grating period are constant for the uniform fiber grating. Using the coupled-mode theory, the reflectivity at Bragg wavelength can be given by

$$R(L, \lambda) = \frac{\kappa^2 \sinh^2(sL)}{\Delta\beta^2 \sinh^2(sL) + s^2 \cosh^2(sL)} \quad (2.4)$$

Where $R(L, \lambda)$ is the reflectivity, which is a function of the grating length and wavelength, L is the grating length, κ is the coupling coefficient, $\Delta\beta$ is the detuning wavevector and $s = (\kappa^2 - \Delta\beta^2)^{1/2}$. At the center wavelength of the fiber grating the wavevector detuning is zero, therefore the equation (2.4) becomes

$$R(L, \lambda) = \tanh^2(\kappa L) \quad (2.5)$$

2.3.1 Refractive index modulation

Consider a uniform fiber grating consists of an average refractive index n_0 and a periodic modulation of refractive index in the fiber core. Thus the refractive index profile can be given by equation (2.4) and shown in Figure 2.6

$$n(z) = n_0 + \Delta n \cdot \cos\left[\frac{2\pi}{\Lambda} z\right] \quad (2.6)$$

where z is the distance along the longitudinal fiber axis,
 Δn is refractive index perturbation.

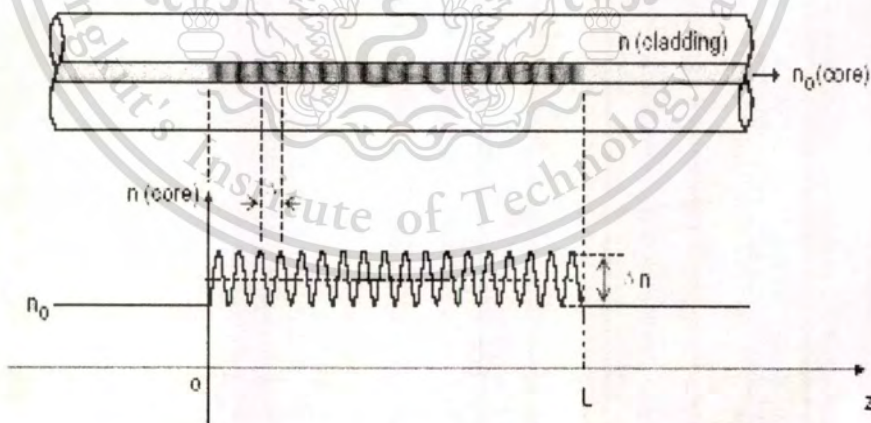


Figure 2.6 Refractive index modulation of fiber grating

2.3.2 Refractive index perturbation

The refractive index perturbation (Δn) is the amplitude of the induced refractive index perturbation (typically 10^{-5} to 10^{-3}) can be expanded in a Taylor series about z_0 as

$$\Delta n(z) = \Delta n_0 + (z - z_0) \left(\frac{\Delta n}{\Delta z} \right) \Big|_{z=z_0} + \frac{1}{2!} (z - z_0)^2 \left(\frac{\Delta^2 n}{\Delta z^2} \right) \Big|_{z=z_0} + \frac{1}{3!} (z - z_0)^3 \left(\frac{\Delta^3 n}{\Delta z^3} \right) \Big|_{z=z_0} + \dots \quad (2.7)$$

2.4 External characteristics of the Fiber grating

2.4.1 Strain sensitivity

For application, when the strains is applied on the fiber grating by the expand it. This is the perturbation of the grating period (Λ) and the effectively refractive index (n_{eff}). Then the central Bragg wavelength (λ_B) is changed to $\Delta\lambda_B$. Such the $\Delta\lambda_B$ is depended on the strain changes, is given by

$$\Delta\lambda_B = 2 \left(\Lambda \frac{\partial n_{eff}}{\partial l} + n_{eff} \frac{\partial \Lambda}{\partial l} \right) \Delta l + 2 \left(\Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T} \right) \Delta T \quad (2.8)$$

The first term in equation (2.8) represents the strain effect on fiber grating. This corresponds to change in the grating period (Λ) and the effectively refractive index (n_{eff}). The above strain effect term may be expressed as

$$\Delta\lambda_B = \lambda_B (1 - p_e) \varepsilon \quad (2.9)$$

where p_e is an effective strain-optic constant, ε is longitudinal strain is given by $\Delta l/l$. The equations (2.9) are related to the applied strains on the fiber grating with the change of Bragg wavelength. Table 2.1 summarizes different values of Poisson's ratio, ν , and P_e for different wavelengths and materials [32-37].

Table 2.1 Photo-elastic Coefficients

Reference	λ (nm)	n_{eff}	P_e	ν	Material
Yariv [32]	630	1.46	0.20	0.21	Fused silica
Primak [33]	589.2	1.458	0.164	0.219	Vitreous silica
Borrelli [34]	632.8	1.457	0.207	0.168	Fused silica
Bertholds [35]	633	1.458	0.206	0.16	Optical fiber
Xu [36]	1533.3	1.465	0.218	0.17	Optical fiber
Hocker [37]	633	1.456	0.216	0.17	Optical fiber

2.4.2 Temperature sensitivity

Thermal expansion or contraction changes the period of the grating and thus the Bragg wavelength, and the effective refractive index n_{eff} is also temperature dependent (thermo-optic effect). Therefore change in Bragg wavelength for a given change in temperature is given by

$$\Delta\lambda_B = 2 \left(\Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T} \right) \Delta T \quad (2.10)$$

Substitution of $\frac{\partial n_{eff}}{\partial T} = n_{eff} \alpha_n$ Where α_n is the thermo-optic coefficient, and where $\frac{\partial \Lambda}{\partial T} = \Lambda \alpha_\Lambda$ is α the thermal expansion coefficient of the fiber, into equation (2.10) gives

$$\Delta\lambda_B = 2n_{eff} \Lambda \alpha_n \Delta T + 2n_{eff} \Lambda \alpha_\Lambda \Delta T \quad (2.11)$$

which, upon substitution of the Bragg condition gives

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha_\Lambda + \alpha_n) \Delta T$$

$$\Delta\lambda_B = \lambda_B (\alpha_\Lambda + \alpha_n) \Delta T$$

The second term in equation (2.8) represents the effect of temperature on fiber grating. A shift in the Bragg wavelength due to thermal expansion can be changed the grating length and the refractive index of fiber core. This fractional wavelength shift can be written as

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \quad (2.12)$$

where α_Λ is the thermal expansion coefficient (approximately 0.55×10^{-6} for silica), α_n is the thermo-optic coefficient (approximately 8.6×10^{-6} for silica). From equation (2.12) the expected sensitivity for a 1550 nm Bragg grating is approximately $0.0014 \text{ nm}^\circ\text{C}$

2.5 Nonlinear Effects in the Fiber grating

2.5.1 Optical Kerr Effect

When the high power laser is launched into fiber grating, the optical Kerr effect are induced in grating region and the refractive index profile changed which is proportion to the intensity of light, thus equation (2.6) can be rewritten as

$$n(z) = n_0 + \Delta n \cdot \cos\left[\frac{2\pi}{\Lambda}z\right] + n_2 |E(z)|^2 \quad (2.13)$$

where $E(z)$ is the electric field, n_2 is the nonlinear Kerr coefficient. equation (2.13) consists of the first term is average refractive index in fiber core, the second term is the refractive index perturbation and the last term is nonlinear Kerr effect. The third term in equation (2.13) is the main parameter to effect the change of Bragg wavelength, which is discussed.

CHAPTER 3

NANO-STRAIN MONITORING USING μ -STRAIN PERTURBATION

We propose a new design of the nano-scale strain monitoring system, which consists of a fiber Bragg grating and a standard vibration source. The measurement resolution is increased from μ -strain to nano-strain, Using the perturbation method on the fiber grating stretching length. The change in Bragg wavelength due to the change in fiber stretching Length is simulated. Results obtained have shown the feasibility of using such a proposed system to monitor small strain and vibration in the nano-scale range. The relationships between temperature and strain on the one hand, and Bragg wavelength on the other hand are plotted. This is shown as it has a potential of being used in simultaneous measurement.

This chapter presents the model of nano-scale vibration using fiber grating stretching, where the small increment of grating length stretching is simulated and discussed. The linear stretching of fiber grating is simulated relative to the change in vibration frequency of the ceramic piezoelectric device, which is changed with respect to the applied voltage. The potential of using such a device for nono-scale sensor and vibration is studied and discussed. The feasibility of simultaneous measurement of strain and temperature within the same range is also discussed.

3.1 System Design of the Nano-Strain Monitoring

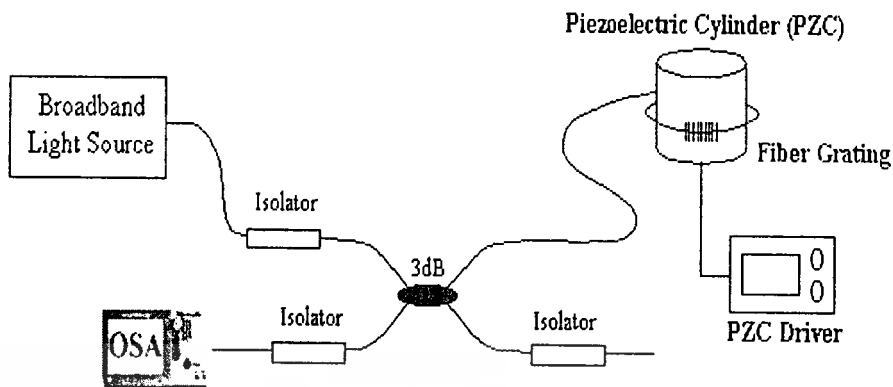


Figure 3.1 A schematic diagram of a nano-scale vibration monitoring system.

A model of the proposed nano-scale vibration measurement system is shown in Figure 3.1. When broadband light source is launched into the fiber grating that is wound around the piezoelectric cylinder (PZC). The PZC is connected to its driver. When the signal from PZC driver is supplied into the PZC. It expanded in the radius direction that is given by $\Delta r = Vd$, where $d \approx 4.00 \times 10^{-10} \text{ m/V}$ is piezoelectric coefficient and V is applied voltage. The amplitude of expansion can be adjusted by the DC level from PZC driver. Since the fiber grating is wrapped and stretched to the PZC. Its expansion follows the expansion of PZC. The extension of fiber grating is given by $\Delta l = 2\pi L \Delta r / t$, where L is the length of the windings on the cylinder and t is the diameter of fiber core. It is about $\Delta l \approx 0.402 \mu\text{m/Volt}$. Then the longitudinal strain is given by $\Delta l / l$. Equation (3.1), We obtain the relation between $\Delta \lambda_B$ and applied strains that can be changed by vibration of PZC. Normally the PZC can be vibrated in nanometer scale. Such the system design can be used nano-scale vibrometer and the amplitude of vibration can be detected by the shift of central Bragg wavelength from OSA. The nano-scale relationship between strain (n-strain) and Bragg wavelength can be formed. For sinusoidal variations of the index perturbation the coupling coefficient, κ is given by

$$\kappa = \frac{\pi \Delta n}{\lambda} (1 - V^{-2}) \quad (3.1)$$

Where V is the normalized frequency of the fiber, given by $V = (2\pi a / \lambda) \sqrt{n_{co}^2 - n_{cl}^2}$, a is the core radius, n_{co} and n_{cl} are the core and cladding indices respectively.

Table 3.1 The parameters used in the proposed system design.

Parameter	Variable	Value
Refractive index of fiber core	n_1	1.461
Refractive index of fiber cladding	n_2	1.457
Core radius	a	5 μm
Grating length	l	150 μm
Grating period	Λ	334.69 nm
Central Bragg wavelength	λ_B	977.30 nm
effective strain-optic constant	p_e	0.227

3.2 Numerical Results

Using equation (2.4), the simulation results of the reflectivity which is seen by the optical spectrum analyzer, are shown in Figure 3.2. The central Bragg wavelength shifts with the applied strain of the fiber grating wavelength at 977.30 nm. There are eight peaks of the reflected signals at the corresponding Bragg wavelengths, and this the parameter of Table 3.1 are used. Shifts in Bragg wavelength from 977.30 nm to 1000 nm and they can be experimentally detected by using the optical spectrum analyzer.

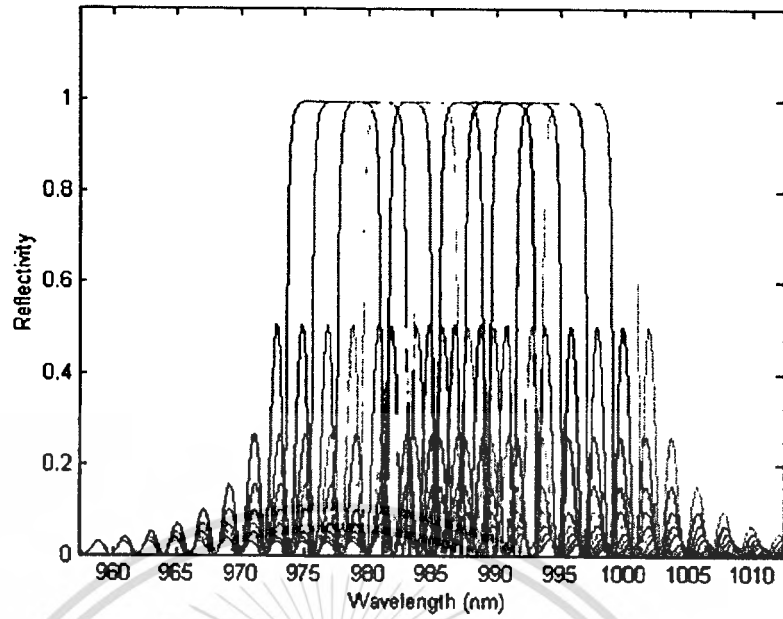


Figure 3.2 The relation between central Bragg wavelength and the reflectivity of light on a fiber grating.

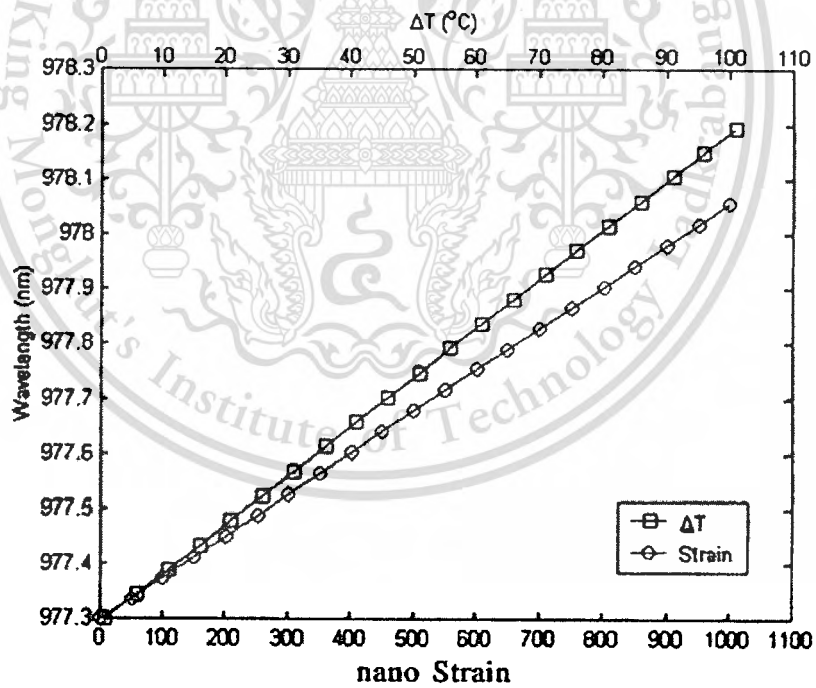


Figure 3.3 The central Bragg wavelength related to the applied strains and temperature on a fiber grating.

The simulation data obtained by using the perturbation terms in Chapter 2. Because the applied strain on the fiber grating that is wrapped and stretched to the PZC, which can be changed by the applied voltage from the PZC driver, the relationship between the central Bragg wavelength and applied strain can be monitored, which is shown in Figure 3.3. Similarly, the thermal expansion is introduced, the relationship between the change in Bragg wavelength and temperature.

The nano-strain measurement in Figure 3.3 is obtained by using the perturbation method, where the small increment can be formulated and simulated. The required data can be obtained by a term truncation method (3rd-order perturbation), and the good linearity and resolution can be seen. Strain and temperature sensitivities for a 977.30 nm Bragg grating are plotted. In application, instrument resolution becomes the measurement limitation. Applied strains and temperature are varied from 0 to 1,000 $\mu\epsilon$ and from 0 to 100 C, respectively. However, in practice, the practical ranges of strains and temperature are to be specified.

3.3 Conclusion

According to the mathematical simulation results, the nano-scale strain measurement system has been designed using the small perturbation of the micro strain, which is based on fiber grating and standard PZC. The small vibration amplitude of PZC is introduced by the applied voltage, which could introduce the small change in Bragg wavelength. Thus the simulation results obtained have shown the feasibility of using such a proposed system to make a measurement relationship between the strain (small vibration) and Bragg wavelength in the nano-scale range. The plausibility of simultaneously measuring temperature and strain has been simulated and discussed. However, the errors in the simulated data might have occurred because of the difference in the presence wavelength at 1550nm. Further, the nonlinear effects on the sensing unit investigated in the Chapter 4. The relationship between the change in nano-strain and vibration will be the subject of our future investigation.

CHAPTER 4

NONLINEAR EFFECTS IN FIBER GRATING TO NONO-SCALE MEASUREMENT RESOLUTION

We propose the results of optical Kerr effects in fiber grating for the measurement resolution. When the high power laser is launched into fiber grating, optical Kerr effects are induced in grating region then the effective refractive index is changed depending on the input power. The results that are given by the mathematical simulation, have shown the relation between the reflectivity and Bragg wavelength. All results can be used to analyze and improve the resolution of measurement system for fiber grating sensors and its applications. This chapter 4 studies the nonlinear effect in the fiber grating for the improvement of the measurement resolution. The results will be shown the relation between the characteristics of the fiber grating and the optical Kerr effects.

4.1 Mathematical Modeling of Nonlinear Effect in Fibre Grating

Consider a uniform fiber grating consists of an average refractive index n_0 and a periodic modulation of refractive index in the fiber core. Thus the refractive index profile can be given by equation (2.6). When the high power laser is launched into fiber grating, the optical Kerr effect are induced in grating region and the refractive index profile changed which is proportion to the intensity of light, thus equation (2.6) can be rewritten as equation (2.13)

$$n(z) = n_0 + \Delta n \cdot \cos\left[\frac{2\pi}{\Lambda} z\right] + n_2 |E(z)|^2 \quad (2.13)$$

Equation (2.13) consists of the first term is average refractive index in fiber core, the second term is the refractive index perturbation and the last term is nonlinear Kerr

effect. The third term is the main parameter to effect the change of Bragg wavelength, which is discussed.

4.2 Numerical Results

Consider the uniform fiber grating with Bragg wavelength at 1550 nm can be plotted the spectrum reflectivity is as shown in Figure 4.1.

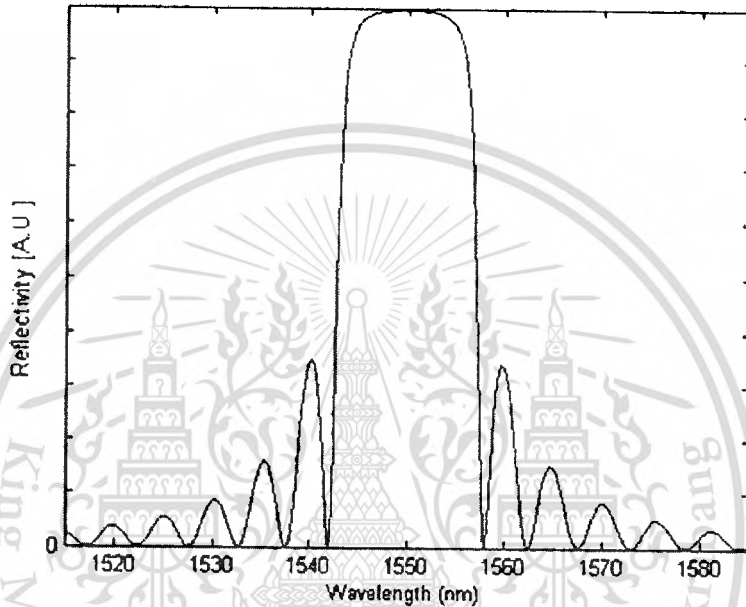


Figure 4.1 Spectrum reflectivity of the uniform fiber grating with Bragg wavelength at 1550 nm.

From equation (2.3) shown the refractive index which consists of an average refractive index (n_0) and a refractive index perturbation (Δn). Because of n_0 is constant thus the refractive index is depending on Δn which is slowly varying.

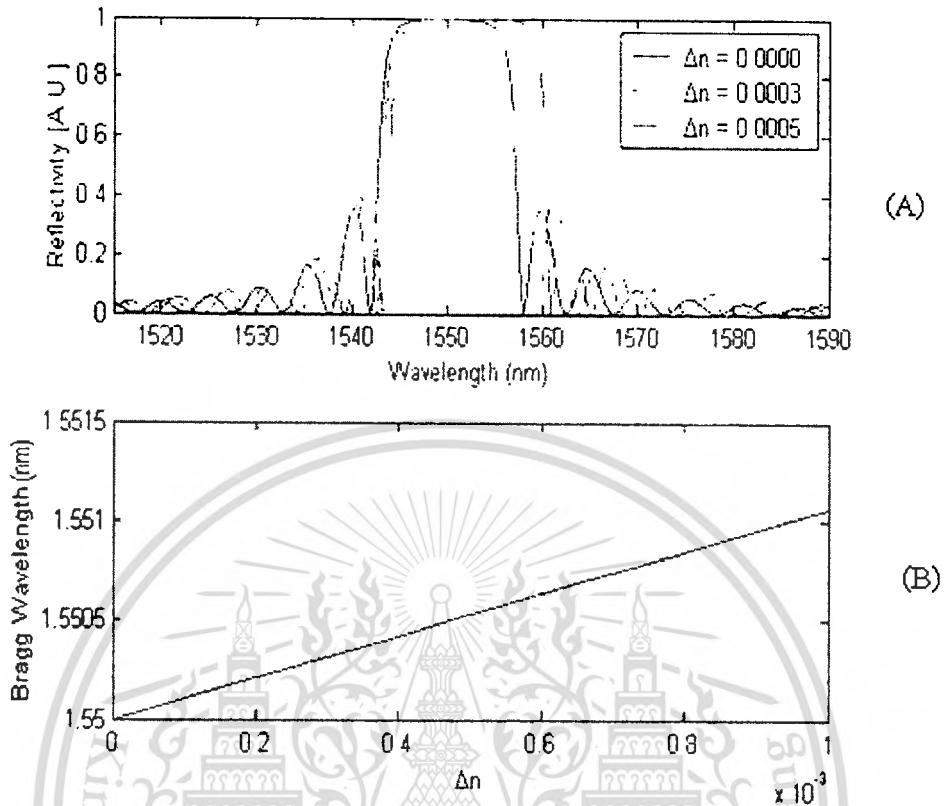


Figure 4.2 Spectrum reflectivity of the uniform fiber grating with Bragg wavelength at 1550 nm. with the variation of the refractive index perturbations.

Figure 4.2(A) shows the spectrum reflectivity of the uniform fiber grating with the three refractive index perturbations. The Bragg wavelength is linearly shifted with Δn in Figure 4.2(B).

Normally, a fiber grating has a refractive index perturbation, thus the effective refractive index of the fiber grating is constant, therefore a fiber grating has a Bragg wavelength which is a specific characteristic of the fiber grating.

When a high power laser is launched into a fiber grating, optical Kerr effects are induced in the grating region. This effect causes a change in the effective refractive index, which is shown in equation (2.13) and consists of the refractive index and

nonlinear Kerr effect term. Thus the relation between the variation of Bragg wavelength and optical Kerr effects can be plotted in Figure 4.3.

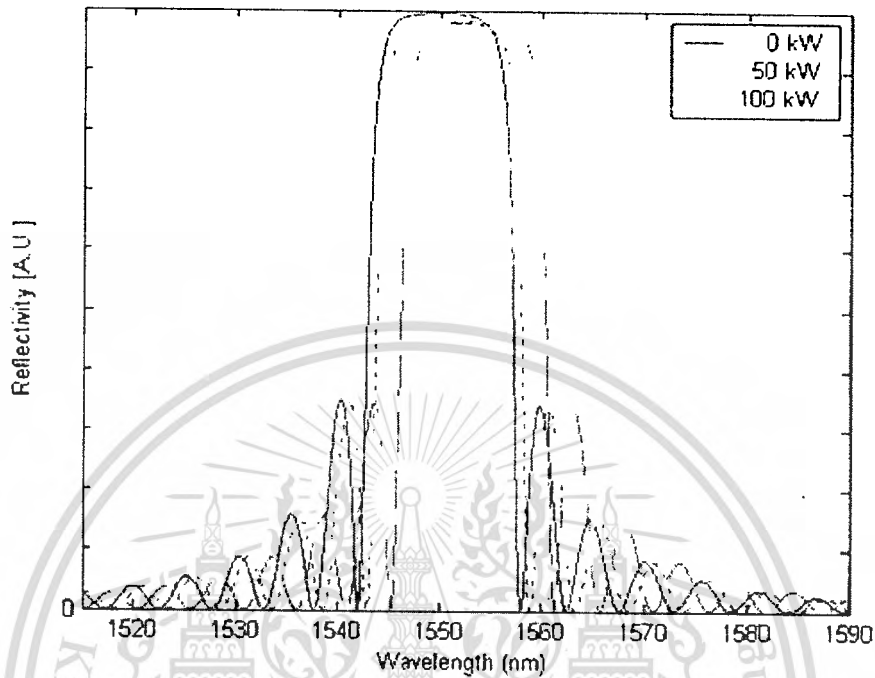


Figure 4.3 Spectrum reflectivity of the uniform fiber grating with Bragg wavelength at 1550 nm changes due to optical pump power 0 kW, 50 kW, 100 kW respectively.

Figure 4.3, Bragg wavelength shift when input power is increased because nonlinear term in equation (2.13) is changed, thus the effective refractive index is changed too. Besides Bragg wavelength is changed, the reflectivity of fiber grating is decreased, can be shown in Figure 4.4.

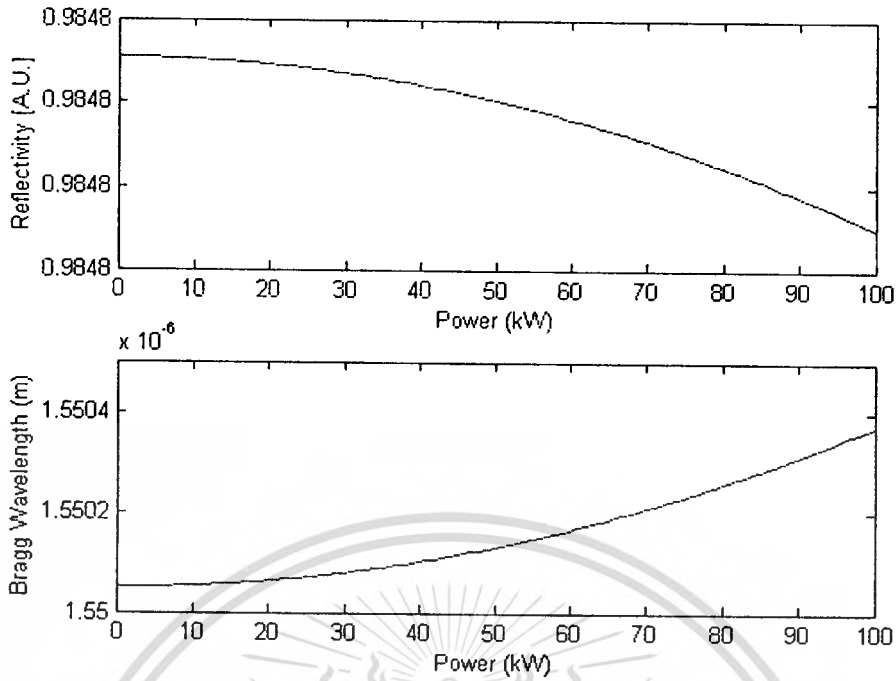


Figure 4.4 Reflectivity and Bragg Wavelength of the uniform fiber grating changes due to optical pump power.

Figure 4.4, when input power is continually increased. Bragg wavelength is nonlinearly increased and reflectivity is nonlinearly decreased. Therefore reflectivity and Bragg wavelength is nonlinearly changed when the optical Kerr effect is appeared. However, in practice, the fiber grating sensors are required the linear measurement and high accuracy so the nonlinear effects in fiber grating may be limited the measurement resolution. In opposite, some optical communication systems are required the nonlinear phenomenon such as optical switching required many state of switching which can be created by nonlinear effect, nonlinear effect can be expanded optical bandwidth etc.

4.3 Conclusion

According to the simulation results, the measurement resolution for fiber grating sensors are reduced by nonlinear effects. The simulation results obtained have shown the relation of the characteristics fiber grating as reflectivity and Bragg wavelength are nonlinear changed when Kerr effect is induced. All results can be used to analyze and introduce the problems and factors are impacted to the resolution of measurement system.



CHAPTER 5

THE CONCEPT OF A NEW GENERATION INTERFEROMETRY

We firstly propose a concept of a new interferometric technique, where the ultra narrow spectral width of light pulse generated by using the micro ring resonators can be used to perform the ultra high resolution interferometer. The use of such systems for quantum interferometer, high resolution interferometer and surface characterization are described.

5.1 The Concept of A New Generation Interferometry.

When the entangled photons generate and enter into the fiber optic system, the amount of the walk-off on the entangled photons depends on the location where the photon pairs are within the fiber. This position is completely random due to the coherent nature of light in fiber optic. To compensate the longitudinal timing-walk off effect, a polarization controller is recommended to ensure that the polarization rotation is the same on both photons from the entangled pair. Additionally the compensator fiber is used to change the relative phase ϕ of the states of the polarized light. Because of the change in birefringence, the tilting of the compensator allows to apply a phase shift to the entangled states of the two photons, which are given by equation (5.1) [38].

$$|\psi\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1 \otimes |V\rangle_2 + e^{i\phi}|V\rangle_1 \otimes |H\rangle_2) \quad (5.1)$$

In applications, the walk-off entangled state parameters involving in the measurement are related to the changes in the applied physical parameters such as force, stress, strain, heat, pressure etc. However, the interested parameters in these

proposed systems are concerned the fiber optic birefringence related parameters, which can be given by

$$\Delta \phi = \frac{2 \pi (n_x - n_y) L_w}{\lambda} \quad (5.2)$$

Where $\Delta n = (n_x - n_y)$ is the fiber optic birefringence, L_w is named as the entangled states walk-off length, and λ is the light source wavelength.

We begin with the first proposed system which is as shown in Figure 5.1. A pair of the entangled photons is formed after light pulses circulating in a fiber ring resonator (EPR source), and the polarization controller applied. Such a system of an optical fiber interferometer incorporating the entangled states generation setup is as shown schematically. The entangled photons are generated by the first part of the setup, which was well confirmed by Yupapin and Suchat[39]. This generates two pairs of the entangled photons which one is entered into the sensing and the other into the reference arm where both arms are coated to obtain the maximum reflected powers. There are only the signal and idler photons entered into a 2x2 coupler with the 50/50 coupling ratio and detected by two detectors (D1 and D2). The difference between the round-trip times of two arms is set at Δt . As a result, we can obtain the following polarization entangled state, which is given by

$$|\Phi\rangle = |2, H\rangle_s |2, H\rangle_i + \exp [i(\phi_s + \phi_i)] |2, V\rangle_s |2, V\rangle_i \quad (5.3)$$

The subscript (s, i) identifies whether the state is the signal (s) or the idler (i) state. The center wavelength of the signal is reflected and interfered being detected by detectors D1 and D2 and seen by using the interferometric technique. The entangled photons are interfered and recombined by a polarization combiner after reflected back from the fiber ends of the same coupler. The applied physical parameter that performs on the sensing arm will change the fiber birefringence, which will be recovered by

rotating the Polarization Controllers. The change in rotation angle then can be related to the change in fiber birefringence, i.e. physical parameter, which is given in equation (5.2).

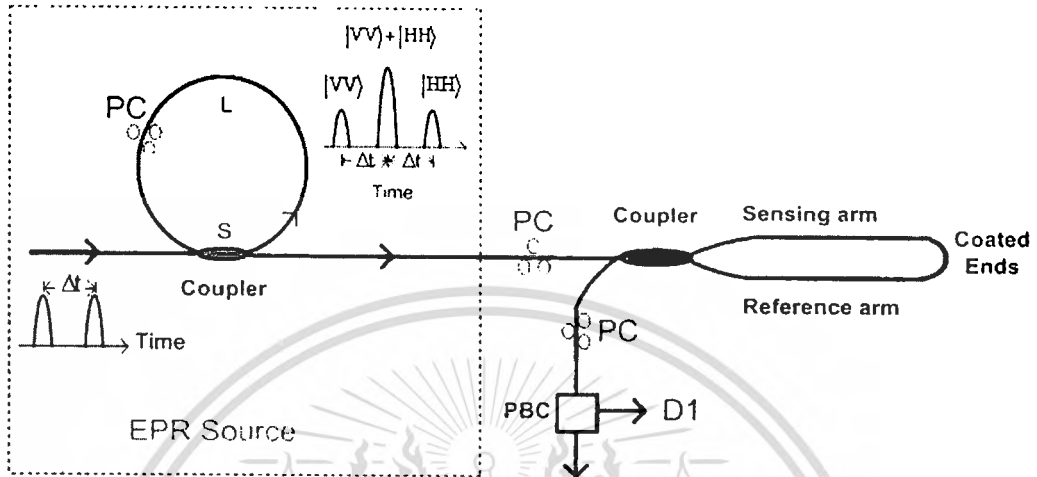


Figure 5.1 Schematic diagram of the quantum interferometric system.

LD: Laser Diode, PCs: Polarization Controllers, Ds: Detectors, PBC: Polarization Beam Combiner. S and L are stands for short and long fiber lengths.

For example, the entangled photons probability is as shown in term of the optical output intensity, i.e. entangled photon visibility. It was generated by using the first part of the system, when the phase difference $\phi = 0^\circ$ is as shown in Figure 5.2(a) [5]. This is the optimum entangled photon visibility. Figure 5.2(b) presents the optical intensity at the output of the polarization output, when the phase difference of the signal peak and the delay peak of the nonlinear fiber ring resonator is $\phi = 45^\circ$. The interference signal of the center wavelength signal can be presented in the form of the output intensity, i.e. visibility, when the PBC is replaced by a beam splitter and visibility is plotted. This is named as a general interferometric technique. The interference of the entangled photons is measured by the change in phase of the

optimum entangled photon visibility, where the self calibration and simultaneous measurement between the classical (optical visibility) and quantum (entangled photon visibility) respecting to the same physical parameter can be realized.

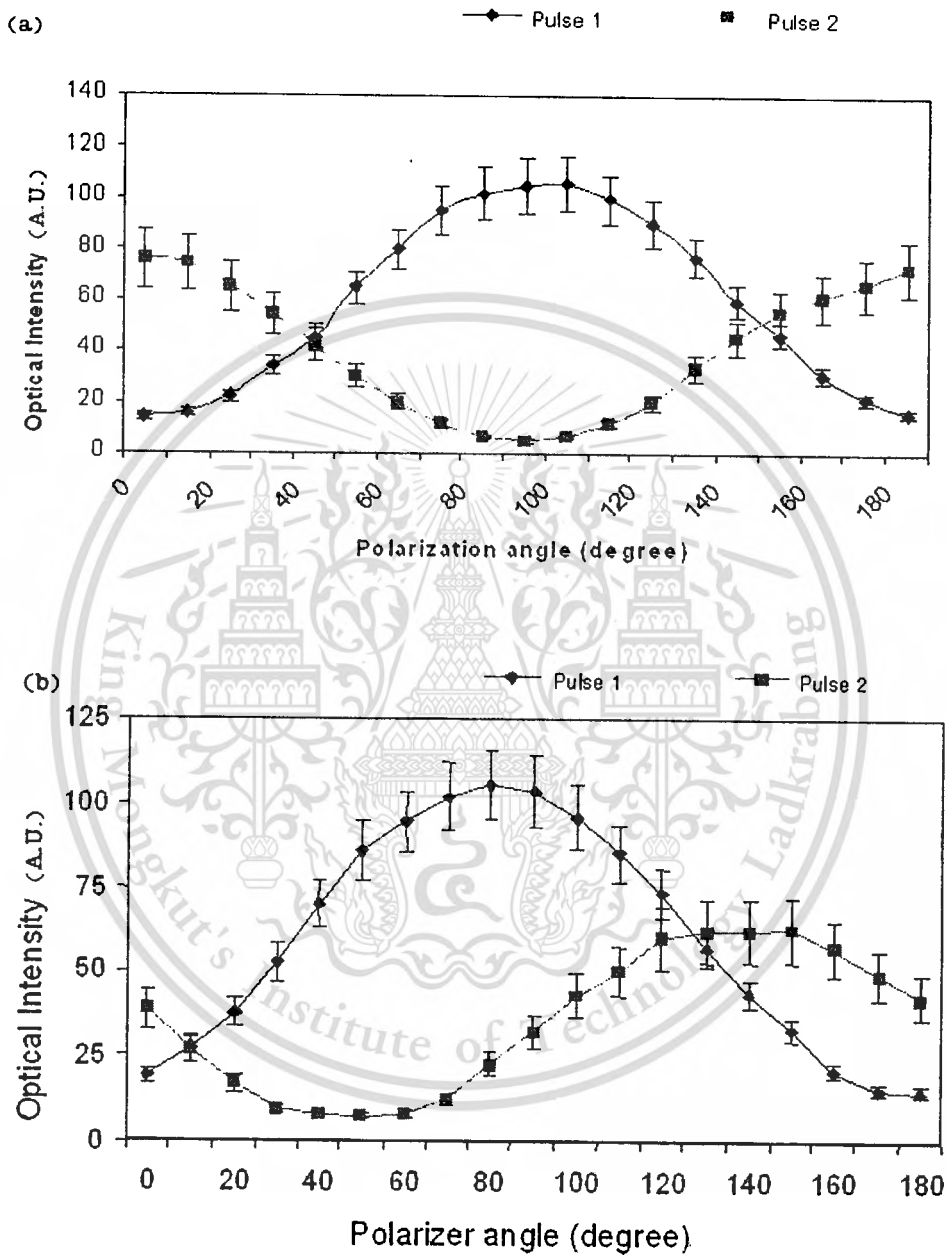


Figure 5.2 Graphs of the measured optical signals: (a) $\phi = 0^\circ$ and (b) $\phi = 45^\circ$ at room temperature, where pulse 1 and pulse 2 were detected by D1 and D2 respectively.

The entangled photons enter into a 90:10 fiber coupler, where more input power (90 %) is entered into a sensing part (fiber Bragg grating). The Bragg grating resonance, which is the center wavelength of light back reflected from a Bragg grating depends on the effective index of refraction of the core and the periodicity of the grating. The effective index of refraction, as well as the periodic spacing between the grating planes, will be affected changes in strain and temperature. The shift in the Bragg grating center wavelength due to strain and temperature changes is given by

$$\Delta\lambda_{\text{Bragg}} = 2\left(\Lambda \frac{\partial n}{\partial l} + n \frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda \frac{\partial n}{\partial T} + n \frac{\partial \Lambda}{\partial T}\right)\Delta T \quad (5.4)$$

where T is temperature and l is length of strain effect and Λ is the periodicity of the reflective index variation n is the effective refractive index of the core. The first term in equation (5.4) represents the strain effect on an optical fiber. This corresponds to a change in the grating spacing and the strain optic induced change in the refractive index. The second term in equation (5.4) represents the temperature effect on an optical fiber. A shift in the Bragg wavelength due to thermal expansion changes the grating spacing and changes the index of refraction. This fractional wavelength shift for temperature change ΔT may be written as $\Delta\lambda_{\text{Bragg}} = \lambda_{\text{Bragg}}(\alpha_{\Lambda} + \alpha_n)\Delta T$ equation (2.12)

Where $\frac{\partial n_{\text{eff}}}{\partial T} = n_{\text{eff}}\alpha_n$ and $\frac{\partial \Lambda}{\partial T} = \Lambda\alpha_{\Lambda}$

α_{Λ} is the thermal expansion coefficient (approximately 0.55×10^{-6} for silica)

α_n is the thermo-optic coefficient (approximately 8.6×10^{-6} for silica).

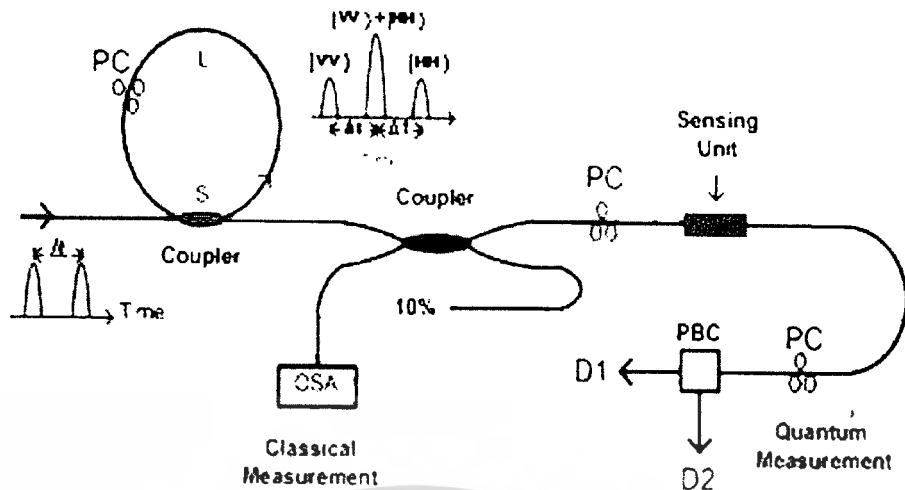


Figure 5.3 A schematic diagram of the simultaneous classical-quantum measurement system. LD: Laser Diode, PCs: Polarization Controllers, Ds: Detectors, OSA: Optical Spectrum Analyzer, PBC: Polarization Beam Combiner. S and L are stands for short and long fiber lengths.

In operation, the measurement of the change in the entangled states can be formed by the change in the optimum entangled state visibility, and the changed in walk-off length or phase, i.e. birefringence is measured. Then the fiber optic sensing self calibration system using the entangled photon in fiber optic ring resonator is realized, where the applied physical parameters can be simultaneously measured and the self calibration applied. In the system, a pair of the entangled photons (signal and idler) is randomly generated via a fiber ring resonator, which is now easy to generate. Then the optical signals with the entangled photons enter into the system and sensing unit, i.e. fiber grating. The center wavelength signal is blocked by the fiber grating property and reflected back and detected by the OSA. The change in Bragg wavelength and the entangled photon states walk-off are measured relatively to the change in physical parameter on the sensing unit. Which means, the simultaneous measurement and the self calibration between the change in the entangled photon

states walk-off, and Bragg wavelength are simultaneously self calibration. The change in phase i.e. birefringence of the entangled photon visibility is obtained. For instance, the entangled states of a pair of photon with and without the thermal effects are shown in Figure 5.1 and 5.3 respectively. When the sensing unit is put into a thermal control environment, the physical parameters such as pressure, strain or force and the thermal sensitivity can be measured both by using equation (2.12), the sensitivity of temperature and the change in the optimum entangled photon visibility respecting to temperature is as shown in Figure 5.3 where the applied temperatures were ranged from 30 °C to 80 °C.

To obtain the optimum measurement performance with the weak coupled into a reference arm. The resonant signal in fiber grating (sensing unit) is reflected back to the same coupler with the coupling ratio 90:10 to the optical spectrum analyzer. The optical isolator is also recommended to protect the optical feedback into the operating source. The signal and idler (quantum signal) are entered into a fiber grating and then entering into a polarization combiner and through the detectors. The simultaneous measurement is performed respecting to the same applied physical parameter.

The measurement resolution is one of the advantages of these schemes. For example, if we set the parameters of Equation (2.12) as followings. Given light source wavelength is 800 nm, then we have the relation which is expressed by

$$\Delta \phi = 3.92 \times 10^6 (n_x - n_y) L_w \quad (5.5)$$

We set L_w is a constant value, the linear relationship between the fiber birefringence and the entangled photons phase shift is measured. To obtain the maximum entangled photon visibility as the initial states before the measurement, then the polarization device is rotated to obtain the optimum photon visibility. The resolution of measurement depends on the angle rotation device resolution that can be retrieved by the change in sensing birefringence, i.e. Δn . When one of the physical

parameters such as strain or heat is applied on the fiber grating, then the measurement between the entangled states walk-off length and Bragg wavelength can be made simultaneously, the self calibration of the system between the interested physical parameter, Bragg wavelength and walk-off phase shift is also validity.

5.2 Conclusion

In practice, a fiber ring resonator as shown in Figure 5.1 and Figure 5.3 can be replaced by a micro ring device. The same principle can be operated to form the ultra high resolution interferometer. The advantage is that the device is now smaller and more compact system, while the ultra narrow spectral width is introduced the increasing in measurement resolution. For instance, the pulse spectral width within the range of nm and beyond is plausible. In conclusion, we have proposed the new concept of the interferometer, where the ultra high measurement using the very short pulse generated by the micro ring device has shown the promising application. The potential applications for quantum interferometer and simultaneous measurement sensing systems are proposed.

CHAPTER 6

SUMMARY

This thesis is the study nano-scale measurements based on fiber optics. The applications are the new concept of nano-strain monitoring using micro-strain perturbation and nonlinear effects in fiber grating to nano-scale measurement resolution. Finally, a concept of a new generation interferometric technique.

The first, a new design of the nano-scale strain monitoring system, which consists of a fiber Bragg grating and a standard vibration source. The measurement resolution is increased from micro-strain to nano-strain. Using the perturbation method on the fiber grating stretching length. The change in Bragg wavelength due to the change in fiber stretching length is simulated. Results obtained have shown in the Figure 3.2 and Figure 3.3. The proposed system to monitor small strain and vibration in the nano-scale range. The plausibility of simultaneously measuring temperature and strain has been simulated and discussed. However, errors in simulated data might have occurred because of the difference in the presented wavelength at 1550nm.

The second, the results of optical Kerr effects in fiber grating for the measurement resolution. When the high power laser is launched into fiber grating, optical Kerr effects are induced in grating region then the effective refractive index is changed depending on the input power. The results that are given by the mathematical simulation, have shown the relation between the reflectivity and Bragg wavelength. All results can be used to analyze and improve the resolution of measurement system for fiber grating sensors and its applications. According to the simulation results, the measurement resolution for fiber grating sensors are reduced by nonlinear effects. The simulation results obtained have shown the relation of the characteristics fiber grating as reflectivity and Bragg wavelength are nonlinear changed when Kerr effect is induced. All results can be used to analyze and introduce the problems and factors are

impacted to the resolution of measurement system. However, the error from simulated data may be occurred by the determination of fiber grating parameters but the trend isn't difference. Further, the nonlinear effects on the optical switching by fiber grating will be investigated in the future work.

The finally, we firstly propose a concept of a new interferometric technique, where the ultra narrow spectral width of light pulse generated by using the micro ring resonators can be used to perform the ultra high resolution interferometer. The use of such systems for quantum interferometer, high resolution interferometer and surface characterization are described. The concept of a new interferometric technique as shown in Figure 5.1 and Figure 5.3 can be replaced by a micro ring device. The same principle can be operated to form the ultra high resolution interferometer. The advantage is the device that is now smaller and more compact system, while the ultra narrow spectral width is introduced the increasing in measurement resolution. In conclusion, we have proposed the new concept of the interferometer, where the ultra high measurement using the very short pulse generated by the micro ring device has shown the promising application. The potential applications for quantum interferometer and simultaneous measurement sensing systems are proposed.

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APPENDIX

LIST OF PUBLICATIONS

- P. Yabosadee ,P. Phipithirankarn and P.P. Yupapin. **A new concept of nano-strain monitoring using m-strain perturbation**, Light and Electron Opt, (2008)
doi:10.1016/j.ijleo.2008.07.032
- P.P. Yupapin and P. Yabosdee, **Optimum entangled photon generation by micro ring resonators for new generation interferometry use**, Light and Electron Optics, 2008 doi:10.1016/j.ijleo.2008.09.011
- P.P. Yupapin, P. Yabosdee, and P. Phipithirankarn. **Entangled Photon Generation in a Nonlinear Micro Ring Resonator for Birefringence Based Sensing Applications**, Light and Electron Opt, 2008 doi:10.1016/j.ijleo.2008.03.004
- P. Phipithirankarn, P. Yabosdee, W. Suwanchaoen and P.P. Yupapin. **Novel Design of a Micro Gyroscope Based Birefringence Measurement for Sensor Applications**, Advanced Materials Research, vol. 55-57, 2008, pp 521-524.
- P. Phipithirankarn, P. Yabosadee, and P.P. Yupapin. **Nonlinear Effects in fiber grating to Nano-scale Measurement Resolution**. Journal of Nonlinear Optical Physics & Materials .Special Issue Volume, November, 2008.
- S.Pipatsart, P. Yabosdee and P.P.Yupapin. **Human Hair Shiny Characterization by Light for Shampoo Industry Applications** . The Second National Conference on Optics and Applications, 2004.

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