Development of tunable multiwavelength fiber laser sources for photonic applications

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Development of Tunable Multiwavelength Fiber Laser Sources for Photonic Applications

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Summary

Wavelength division multiplexing (WDM) is an attractive technology that enables the transmission of multiple wavelength channels on the same large-bandwidth optical fiber, resulting in a huge increase in transmission capacity. For implementation of the next generation of optical networks to meet the ever increasing demand of the end-users, it is essential to develop low-cost WDM optical sources with tunable features for flexible control of the wavelength channels such as the ability to tune the center wavelengths and the wavelength spacings of the wavelength channels. Considering that the complexity and cost of the WDM optical sources will increase as the number of wavelength channels (or subscribers) increases, multiwavelength optical sources capable of simultaneously generating multiple lasing wavelengths are highly desirable in the WDM networks. Furthermore, multiwavelength optical sources have other useful applications, which include fiber-optic sensing, and test and measurement of WDM components.

This thesis documents the design and development of several novel tunable multiwavelength fiber lasers, such as a tunable multiwavelength fiber laser based on a fiber Sagnac loop filter, a tunable dual-wavelength fiber laser with tunable wavelength separation, and a tunable and switchable multiwavelength optical source. Exploring the elliptical-core feature of a polarization-maintaining erbium-doped fiber (PM-EDF) within the Sagnac loop filter, room-temperature multiwavelength lasing operation with tunable center wavelengths was achieved. Also a stable and tunable dual-wavelength fiber laser based on a fiber Bragg grating (FBG) written on a high-birefringence fiber with strain modulation was also developed, and dual-wavelength lasing operation with very narrow

Summary

linewidths of the two lasing lines (~ 2.5 kHz) and wavelength separation of as small as ~ 0.05 nm was achieved at room temperature. Using this developed tunable dual-wavelength fiber laser, a two-tap microwave photonic notch filter with tunable free spectral range was also developed. Furthermore, a novel thermally tunable and switchable comb filter based a linearly chirped fiber Bragg grating was also developed. Using this tunable and switchable comb filter, a novel switchable multiwavelength optical source with tunable features was developed.

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List of Abbreviations

ADC	Analog-to-digital conversion
AOFS	Acousto-optic frequency shifter
ASE	Amplified spontaneous emission
AWG	Array waveguide grating
CW	Clockwise
CCW	Counter-clockwise
DBR	Distributed Bragg reflector
DFB	Distributed feedback
DWDM	Dense wavelength division multiplexing
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
EDFL	Erbium-doped fiber laser
EMI	Electromagnetic interference
ESA	Electrical spectrum analyzer
FBG	Fiber Bragg grating
FSR	Free spectral range
Hi-Bi	High-birefringence
ITU	International Telecommunication Union
LAN	Local area network

List of Abbreviations

LCFBG	Linearly chirped fiber Bragg grating
LO	Local oscillator
LPG	Long period grating
MC	Mode converter
MEDFL	Multiwavelength erbium-doped fiber laser
MSSR	Main to secondary sidelobe ratio
MTI	Moving target interference
OSA	Optical spectrum analyzer
OSNR	Optical signal-to-noise ratio
PC	Polarization controller
PD	Photodetector
PHB	Polarization hole burning
PM	Polarization maintaining
PM-EDF	Polarization-maintaining erbium-doped fiber
PM-FBG	Polarization-maintaining fiber Bragg grating
PM-LCFBG	Polarization-maintaining linearly chirped fiber Bragg grating
RF	Radio frequency
RIN	Relative intensity noise
ROADM	Reconfigurable optical add/drop multiplexer

List of Abbreviations

SCFBG	Sampled chirp fiber Bragg grating
SFBG	Sampled fiber Bragg grating
SHB	Spectral hold burning
SLCFBG	Sampled linearly chirped fiber Bragg grating
SLED	Superluminescent light-emitting diode
SMF	Single mode fiber
SOA	Semiconductor optical amplifier
SOP	State of polarization
TMF	Two mode fiber
TOBF	Tunable optical bandpass filter
TOF	Time-of-flight
UV	Ultraviolet
WDM	Wavelength division multiplexing
WDR	Wavelength-dependent reflector

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1 Introduction

1.1 Background

The discovery of the light amplification process in rare-earth doped fibers dates back more than 40 years. In fact, research on optical fiber-based lasers has begun shortly after the famous proposal of the optical maser by Schawlow and Townes [1] in 1958 and the first demonstration of the laser effect by Maiman [2] in 1960. Due to the large attenuation of the glasses made at that time, the potential use of optical fibers for communications was not realized until the important paper published by Kao and Hockham [3] in 1966. Stone and Burrus [4], [5] reported the first silica-based fiber lasers in the early 1970s. Co-linearly pumped with the signal by semiconductor diode lasers and emitting continuously at room temperature, these fiber lasers showed good promise for fiber-optic telecommunications applications [6]. Since the discovery of practical rare-earth-based fiber amplifiers and lasers in the mid 1980s, these fiber lasers and amplifiers have attracted great interest for fiber-optic telecommunication applications, especially the fiber lasers based on the erbium ion, which has a radiative transition around $1.55\ \mu\text{m}$ that also corresponds to the lowest attenuation transmission window in silica fiber. Despite the fact

that its operating principle is based on a three-level laser system, the erbium ion in silica can be made into a very potent gain medium when it is implemented in fiber form. The lasing wavelength of a single-wavelength fiber ring laser can be tuned by adjusting the intra-cavity optical filter placed within the laser cavity. The erbium-doped fiber laser (EDFL) has many advantages over a bulk solid-state laser which include [7]:

- *High pump efficiency and power:* Since the core of the glass fiber can be made to only a few microns in diameter, the small mode-field diameter of the waveguided pump light can yield a much higher pump intensity in a fiber laser than that in a bulk solid-state device, resulting in a reduction in the lasing threshold.
- *Compact gain medium:* Although in fiber form, the doped fiber containing the gain medium can be quite long depending on the application requirements (e.g. output power); however, the EDFL is still more compact than the bulk solid-state laser.
- *Reducing cost and system complexity:* The fiber-based laser has an additional advantage over the bulk solid-state laser because it alleviates the need for an additional delivery fiber, thus reducing the system cost.
- *Low noise:* Fiber lasers inherently have very low levels of relative intensity noise (RIN).
- *Tunability:* The tuning range of the EDFLs can be much higher than that of the semiconductor lasers.
- *Large operation bandwidth:* The EDFL can be quite broadband because the erbium-doped fiber amplifier (EDFA) used in the fiber laser has a broad amplification bandwidth in the C-band and L-band.
- *Narrow linewidth:* A laser linewidth of as small as 750 Hz has been demonstrated [8].

Multiwavelength lasing operation can be achieved by using various approaches such as those based on semiconductor lasers and erbium-doped fiber technology. Gain-guided Fabry-Perot semiconductor lasers naturally generate a wavelength spectrum with multiple lasing lines; however, the output spectrum is not flat. Furthermore, the lasing wavelength spacing is fixed by the lengths of the cavities during fabrication of the semiconductor chip. Thus, it is very difficult to obtain accurate lasing wavelength spacing because the fabrication process requires a precision of the order of $0.1\ \mu\text{m}$, although temperature/current tuning of the laser can be taken into account.

A more direct approach to obtain a multiwavelength lasing operation with a uniform spectrum is to combine the lights from a laser array into the same fiber. Young et al. [9] have realised an array of sixteen distributed Bragg reflector (DBR) lasers, with each laser being followed by an electro-absorption modulator. A 16×1 multiplexer combines all the lasing signals into a semiconductor-based booster amplifier stage before the output. However, due to its complexity, this structure has very low yields and is costly. Furthermore, it can be very difficult to achieve the regularity of the channel spacing when the channel count is high.

Fiber lasers also offer great possibilities as multifrequency sources. Their ease of fabrication has yielded many ingenious designs. For multiwavelength fiber laser sources, they generally have two common characteristics: 1) a means of obtaining gain at several wavelengths simultaneously and 2) one or more filters are needed to define the lasing wavelengths. However, the biggest challenge in producing a multiwavelength lasing

output with an EDFL is the fact that the erbium ion saturates mostly homogeneously at room temperature, preventing stable multifrequency operation. One straightforward way to solve this problem is to use a single gain medium for every lasing wavelength, but this will increase the laser source's cost and complexity dramatically when the number of required lasing wavelengths is high. For the case of a single gain medium, a straightforward approach to solve the problem of homogeneous gain broadening is to cool the erbium-doped fiber (EDF) to 77 K with liquid nitrogen, thus rendering the gain medium inhomogeneous and allowing multifrequency operation to take place. But cooling the EDF down to 77 K is not practical due to the high cost incurred. Besides cooling the EDF down to the liquid nitrogen temperature, some other methods [10], [11] have been reported that can achieve multiwavelength lasing operation at room temperature. Poustie *et al.* [10] have achieved multiwavelength lasing output by using a spatial-mode beating filter to enhance the spatial-hole burning effect within the laser cavity. However, this method is not effective as the multimode optical fiber section introduces a large cavity loss to the laser source as the splice loss between the single mode fiber (SMF) and the multimode fiber is relatively high. Another method to overcome the EDF's homogeneous broadening at room temperature is to make the laser cavity inhomogeneous by enhancing the spectral hole burning (SHB) and polarization hole burning (PHB) [11]. However, liquid nitrogen will still be needed in order to obtain stable multifrequency lasing lines. Thus, new and stable multiwavelength fiber laser sources are needed to overcome the disadvantages of the designs mentioned above, and this forms the main motivation of this research project as described below.

1.2 Motivation

Multifrequency lasers are of great interest as head-end transmitters in wavelength-routed local area networks (LANs) [12]. Multiwavelength fiber lasers also have great potential in testing and measurement of wavelength division multiplexing (WDM) components and wavelength-selective sub-systems. Specific applications include testing of reconfigurable optical add/drop multiplexers (ROADMs), photonic switches, and embedded optical-performance monitors [13]. The multiwavelength laser source also enables per-channel gain and noise-figure measurements of optical amplifiers, and evaluation of full-channel system-loading effects [13]. In addition, for applications in research and development, this source offers significant cost and size reductions when compared to the more traditional banks of distributed feedback (DFB) lasers. The fact that all the lasing channels are available simultaneously provides the added advantage of reduced measurement time when compared to stepping a tunable laser across the channel spectrum.

Multiwavelength optical sources, especially those capable of emitting light at a number of well-defined wavelength channels at room temperature, are of great importance for the next generation of WDM networks. As the required transmission capacity increases, the number of wavelength channels required in optical communication systems also increases. The system complexity and cost will increase drastically when the dense wavelength division multiplexing (DWDM) networks' capacity increases. Multiwavelength fiber laser sources, which have a number of advantages as mentioned in Section 1.1, have

recently attracted extensive research worldwide, due to their enormous potential applications in fiber sensors and optical communications.

To achieve such a multiwavelength fiber laser source, a number of requirements need to be met. The requirements include a large number of channels over a large wavelength span, moderate output powers for all the wavelength channels (of the order of 100 μ W) with good optical signal-to-noise ratio (OSNR), spectral flatness, single-longitudinal mode operation of each lasing line, tuneability and accurate positioning on the International Telecommunications Union (ITU) frequency grid [14]. However, achieving all these requirements simultaneously is a very challenging task.

1.3 Objectives

The main objective of this thesis is to design and develop several multiwavelength fiber laser sources for applications in the optical communication applications. One aim of the thesis is to develop a multiwavelength fiber laser with both tunable center wavelength and wavelength spacing. First, a tunable room-temperature multiwavelength fiber laser based on a Sagnac loop filter is developed and it will be described in Chapter 3 [15]. The advantages offered by the fiber laser include all-fiber structure, low insertion loss, low cost and stable room-temperature operation. In order to investigate the effects of stability and polarization on the performance of the multiwavelength fiber laser, a stable dual-wavelength fiber laser with tunable wavelength spacing using an all polarization-maintaining (PM) cavity is also demonstrated and it will be described in Chapter 4 [16]. Due to its all-PM laser cavity, the dual-wavelength fiber laser is extremely stable under

room-temperature condition, and has useful application in microwave photonics, that is, a novel tunable microwave photonic notch filter based on this dual-wavelength fiber laser is proposed and it will be described in Chapter 5 [17].

Another aim of the thesis is to design and develop a thermally switchable and discretely tunable comb filter using a linearly chirped fiber Bragg grating (LCFBG) and it will be described in Chapter 6 [18]. As an important application of this tunable comb filter, a multiwavelength optical source is developed based on this comb filter as described in Chapter 6.

1.4 Major Contributions

The original contributions of this thesis are summarized below.

- A tunable multiwavelength fiber laser source based on a Sagnac loop filter is developed to realize room-temperature multifrequency lasing generation (see Chapter 3).
- A stable dual-wavelength fiber laser with tunable wavelength spacing based on an all-PM linear laser cavity is also developed (see Chapter 4).
- Implementation of a novel tunable microwave photonic notch filter with tunable free spectral range (FSR) based on the dual-wavelength fiber laser as described in Chapter 4. Development of a multiple-tap microwave photonic filter using a multiwavelength ring laser is also presented in Chapter 5.
- Design and development of a new thermally switchable and tunable comb filter

based on a LCFBG (see Chapter 6).

- Design and development of a novel switchable and tunable multiwavelength optical source based on the optical comb filter (see Chapter 6).

1.5 Thesis Outline

The introduction of EDFLs and FBGs is given in Chapter 2. First, the physics of amplification in erbium ions is introduced and the fundamentals of EDFA are described. Section 2.2 presents the mathematical modeling of EDFAs, which provide the optical gain in EDFLs. The theory, characteristics, and fabrication of fiber Bragg gratings (FBGs) are presented in Section 2.3. And the existing techniques of multiwavelength EDFLs (MEDFLs) are also briefly reviewed.

The lasing wavelengths of the MEDFLs are mainly determined by the wavelength-selection component within the laser cavity and the gain medium used to achieve a broad amplification bandwidth.

Chapter 3 presents a stable room-temperature multiwavelength fiber laser with tunable center wavelength using the Sagnac loop filter. The principle of the Sagnac loop filter is described in Section 3.2. The detailed description of the tunable multiwavelength fiber laser is presented in Section 3.3. The tunability of the laser's center wavelength and wavelength spacing is described.

Chapter 4 presents the proposed dual-wavelength fiber laser with tunable wavelength

spacing. The method used to measure the laser linewidth is described in Section 4.2. The detailed description of the dual-wavelength fiber laser is presented in Section 4.3. The wavelength-spacing tuning mechanism of the fiber laser is described.

Chapter 5 presents the application of the dual-wavelength fiber laser described in Chapter 4 in the implementation of a novel microwave photonic notch filter. Based on the proposed dual-wavelength fiber laser, a two-tap microwave photonic notch filter with tunable FSR is designed and developed and will be described in Section 5.3. The simulation results are confirmed by the experimental results. The relationship between the applied strain and the notch filter's FSR is described. Also, a multiple-tap microwave photonic filter based on a multiwavelength ring laser will be presented in Section 5.4.

Chapter 6 presents the design and development of a new switchable and tunable optical comb filter. The switching of the filter's transmission peaks and tuning of the wavelength spacing are described in Section 6.2. The use of heat sinks to improve the performance of the comb filter is discussed. The bandwidth and switching time of the optical comb filter are also described. And a multiwavelength optical source based on the proposed optical comb filter is presented. Section 6.3.2 describes the experimental setup of the multiwavelength optical source. The tuning and switching of the generated lasing wavelengths are described in Section 6.3.3.

Finally, Chapter 7 presents a summary of the thesis as well as the recommendations for future work.

2 Literature Review

In this chapter, the modeling of amplification from an EDF is presented. The physical process of amplification in the EDF will be described in detail, and the simulation algorithm will be highlighted. The theory, characteristics, and fabrication of FBGs are presented, and their applications in fiber lasers are reviewed. The various laser configurations of EDFLs are briefly introduced. And the existing techniques of MEDFLs are briefly reviewed. The fundamental background described in this chapter will be useful for the remaining chapters of the thesis.

2.1 The Physics of Amplification in Erbium-Doped Fiber

The performances of EDFLs and EDFAs are governed by the relevant electronic and optical characteristics which include the active ion, cross sections, spectral shapes of the emission and absorption bands, excited state lifetime, ion-ion interaction, as well as the static and dynamic ion-lattice interactions. Thus, the type of the active ion of the fiber laser's gain medium is a critical factor that determines the performance of the laser source. The importance of the erbium ion (Er^{3+}) as an active ion has been recognized

since the middle of 1980s. One reason for the important characteristic is shown in Fig. 2-1, which presents the Er^{3+} luminescence spectrum for a Ge/P-silica fiber [19]. The emission spectrum shows an optical gain of over 20 dB in the wavelength range of 1530 nm and 1560 nm, which corresponds to the lowest 1550 nm attenuation window in silica fiber. A critical factor that determines the successful application of EDFAs in optical communications is the long lifetime of the metastable state, which permits the required high-population inversions to be obtained under steady-state conditions using modest pump powers.

Figure 2-1: Measured emission spectrum of Er^{3+} -doped Ge/P-silica fiber [19].

Erbium is a transition metal of the rare-earth series. In a glass matrix, erbium forms trivalent ions with a $[Xe]4f^{11}5s^25p^6$ electronic structure. All visible and infrared erbium transitions come from electrons in the 4f layer [20]. Since this layer is partially isolated by the 5s and 5p layers, the erbium absorption and emission spectra are relatively unaffected by the type of glass matrix used. As for many rare-earth ions, the metastable level of erbium is well separated from the lower laser level, rendering non-radiative

transitions difficult and favoring fluorescence [20]. The principal energy levels of the erbium ion are illustrated in Fig. 2-2, where possible pump wavelengths and the nomenclature of energy levels in spectroscopic notation along with their lifetimes are indicated.

Figure 2-2: Schematic diagram of erbium ion's energy levels with the corresponding lifetimes [21].

Many different pump band levels exist and all are reachable with a known laser system. These lasers pump erbium ions from the fundamental level ($^4I_{15/2}$) up to an excited pump level (e.g. $^4I_{9/2}$ level for a pump in the 0.8 μm wavelength band). From there, ions will quickly and non-radiatively decay to the metastable level $^4I_{13/2}$. The very short lifetimes

of the pump levels relative to those of the metastable levels allow the accumulation of ions in the metastable level and the formation of a population inversion between the lower (fundamental) and (metastable) energy levels. However, since the erbium ions operate on a three-level laser system (i.e. the laser transition is between the metastable and fundamental levels), there is a need to counteract the signal absorption from the fundamental level before transparency is obtained. And this is not the case in four-level systems such as neodymium, where gain is observed at very low pump powers. The three-level nature also causes the erbium ion to be a gain medium with an optimal length, as will be discussed in the following sections.

The most direct treatment of the EDFA begins with a pure three-level atomic system [22]. The most important characteristics of the amplifier can be obtained from this simple model and its underlying assumptions. A detailed model for the simulation of a typical EDFA will be presented in Section 2.2.

2.2 Modeling of Erbium-Doped Fiber Amplifier

2.2.1 Amplification in Three-level Systems

A three-level system as depicted in Fig. 2-3, with a ground state denoted by 1, an intermediate state labeled as 3 (into which energy is pumped), and state 2 is considered here. Since state 2 often has a long lifetime in the case of a good amplifier, it is sometimes referred to as the metastable level. State 2 is the upper level of the amplifying transition and state 1 is the lower level. The populations of the levels are labeled N_1, N_2 ,

and N_3 . This three-level system is intended to represent that part of the energy level structure of Er^{3+} that is relevant to the amplification process. As is well known, in order to achieve amplification, a population inversion between states 1 and 2 is needed, and since state 1 is also the ground state, at least half of the total population of erbium ions needs to be excited to level 2 to achieve the population inversion.

Figure 2-3: The three-level system used for the amplifier model. The transition rates between levels 1 and 3 are proportional to the populations in those levels and to the product of the pump flux ϕ_p and the pump cross section σ_p . The transition rates between levels 1 and 2 are proportional to the populations in those levels and to the product of the signal flux ϕ_s and the signal cross section σ_s . The spontaneous transition rates of the ion (including radiative and nonradiative contributions) are given by Γ_{32} and Γ_{21} [23].

One can take a particular advantage, in the case of the EDFA, of the fact that the light fields are confined in the fiber core of very small dimension. The light intensities confined in the fiber core are thus very high, over long distances, and population inversion is achieved with relatively small pump powers. In the modeling process within this thesis, the problem is considered to be one dimensional. That is, the pump and signal

intensities as well as the erbium ion distribution are assumed to be constant in the transverse dimensions, over an effective cross-sectional area of the fiber.

The incident light intensity flux at the frequency corresponding to the 1 to 3 transition (in number of photons per unit time per unit area) is denoted by ϕ_p , which corresponds to the pump. The incident flux at the frequency corresponding to the 1 to 2 transition (in photons per unit time per unit area) is denoted by ϕ_s and corresponds to the signal field. The change in population for each level arises from absorption of photons from the incident light field, from spontaneous and stimulated emissions, and from other pathways for the energy to escape to a particular level. Here, the transition probability from level 3 to level 2 is denoted to be Γ_{32} . This is the sum of the nonradiative and radiative transition probabilities, and in practice, for the most typical cases, is mostly nonradiative. Γ_{21} is the transition probability from level 2 to level 1. In the case of the $^4I_{13/2}$ (level 2) to $^4I_{15/2}$ (level 1) transition of the Er^{3+} ion, Γ_{21} is mostly due to radiative transitions. This is due to the fact that there are, for Er^{3+} , no intermediate states between levels 1 and 2, to which ions excited to level 2 can relax. Here, the transition probability from level 2 to level 1 is defined to be $\Gamma_{21} = 1/\tau_2$, where τ_2 is the lifetime of level 2.

The absorption cross section for the level 1 to level 3 transition is denoted to be σ_p , and the emission cross section for the level 2 to level 1 transition by σ_s . The absorption and emission cross sections are assumed to be those for transitions between individual nondegenerate states and are thus equal. The rate equations for the population changes are written as [23]

$$\frac{dN_3}{dt} = -\Gamma_{32}N_3 + (N_1 - N_3)\phi_p\sigma_p \quad (2.1)$$

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + \Gamma_{32}N_3 - (N_2 - N_1)\phi_s\sigma_s \quad (2.2)$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1 - N_3)\phi_p\sigma_p + (N_2 - N_1)\phi_s\sigma_s \quad (2.3)$$

It is important to realize that, even in a simple one-dimensional model of the fiber amplifier, the transverse shape of the optical mode and its overlap with the transverse erbium-ion distribution profile are important. In general, this can be parameterized by a factor known as the overlap factor. Only the portion of the optical mode that overlaps with the erbium-ion distribution will stimulate absorption or emission from the Er^{3+} transitions. The entire mode, however, will experience gain or attenuation as a result of this interaction. For example, for a step index fiber, if the erbium is doped only in the fiber core, since part of the optical mode extends into the cladding, only that part of the optical mode that is in the core will experience the effect of the Er^{3+} presence, which can be used advantageously. By doping the erbium only in the very center of the fiber core, the erbium ions will only “see” the very high intensity portion of the optical mode and the pump can more easily invert the maximum number of Er^{3+} ions.

In the one-dimensional case, the light field intensities $I(z)$ are derived from the light field powers $P(z)$ by the following simplified relationship [23]:

$$I(z) = \frac{P(z)\Gamma}{A_{eff}} \quad (2.4)$$

where Γ is the overlap factor, representing the overlap between the erbium ions and the mode of the light field, A_{eff} is the effective cross-sectional area of the distribution of

erbium ions, and z is the distance along the EDF.

In fact, the energy levels of rare earth ions are composed of relatively well-separated multiplets, each of which is made up of a certain number of broadened individual levels. The pumping level 3 is assumed to belong to a multiplet different from that of level 2, and there is rapid relaxation from level 3 to level 2. For all practical purposes, the population in level 3 is then effectively zero and the rate equations involve only the two levels 1 and 2, with level 3 being involved only via the value of the pump absorption cross section from level 1 to level 3. In certain pumping configurations, level 3 can be identical to level 2 in the sense that the upper pump level and the upper amplifier level belong to the same multiplet.

Having reduced the three-level system to an effective two-level system, the rate equations involving only the total population densities of multiplets 1 and 2 can be written as [22], [22]

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_s^{(a)} - N_2\sigma_s^{(e)})\phi_s - (N_2\sigma_p^{(e)} - N_1\sigma_p^{(a)})\phi_p \quad (2.5)$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 + (N_2\sigma_s^{(e)} - N_1\sigma_s^{(a)})\phi_s - (N_1\sigma_p^{(a)} - N_2\sigma_p^{(e)})\phi_p \quad (2.6)$$

where $\sigma_s^{(a)}$, $\sigma_s^{(e)}$, $\sigma_p^{(a)}$, and $\sigma_p^{(e)}$ represent the signal and pump absorption and emission cross sections, respectively [24]. The McCumber relationship describes an accurate way of obtaining the emission cross section from the absorption cross section. Let us consider the absorption cross section of erbium ions in the 1.5 μm region. The McCumber relationship between the emission cross section, $\sigma^{(e)}$, and absorption cross section, $\sigma^{(a)}$,

is given as $\sigma^{(e)}(\nu) = \sigma^{(a)}(\nu)e^{(\varepsilon - h\nu)/kT}$, where ε represents the mean energy of the $^4I_{13/2}$ to $^4I_{15/2}$ transition, ν is the frequency of the light, h is the Planck's constant, k is the Boltzmann constant, and T is the temperature at which thermal equilibrium is reached. Note that the total population density N is given by [23]

$$N = N_1 + N_2 \quad (2.7)$$

2.2.2 Modeling of Gain and Amplified Spontaneous Emission

The erbium-ion concentration, the lifetime of the upper state of the amplifier transition, and the overlap integrals for the pump and signal modes are needed in the model. It is assumed that, for the present case, a very simple erbium-ion distribution across the fiber core where the distribution is uniform from $r = 0$ to $r = R$, where R is equal to or less than the core radius. In the so-called confined erbium-doped fibers, R will be smaller than the core radius. The intensities of the light fields will be averaged from $r = 0$ to $r = R$ to obtain an effective intensity that can be used in the one-dimensional model. This simplification of the transverse variation of the light intensity and the erbium-ion distribution will allow us to obtain a reasonably accurate model of the spectral shape of the amplified spontaneous emission (ASE) at the output end of the fiber.

From Section 2.2.1, the ion population density in the upper level N_2 as a function of the light-field intensities and the total ion density N is written as [23]

$$N_2 = \frac{\frac{\tau\sigma_s^{(a)}}{h\nu_s} I_s + \sum_j \frac{\tau\sigma_{\nu_j}^{(a)}}{h\nu_j} I_A(\nu_j) + \frac{\tau\sigma_p^{(a)}}{h\nu_p} I_p}{\frac{\tau(\sigma_s^{(a)} + \sigma_s^{(e)})}{h\nu_s} I_s + \sum_j \frac{\tau(\sigma_{\nu_j}^{(a)} + \sigma_{\nu_j}^{(e)})}{h\nu_j} I_A(\nu_j) + \frac{\tau(\sigma_p^{(a)} + \sigma_p^{(e)})}{h\nu_p} I_p + 1} N \quad (2.8)$$

where $I_A(v_j)$ is the ASE signal intensity at frequency v_j ($I_A(v_j) = \frac{P_A(v_j)\Gamma_{v_j}}{A}$, where A is the effective cross-sectional area of the distribution of erbium ions, $P_A(v_j)$ is the ASE power at frequency v_j , and Γ_{v_j} is the overlap factor of the ASE and the erbium distribution), h is the Planck's constant, τ is the lifetime of the upper level N_2 ($\tau = 1/\Gamma_{21}$) as we have reduced the three-level system into a two level system, and I_s ($I_s = h\nu_s\phi_s$) and I_p ($I_p = h\nu_p\phi_p$) are the signal and pump intensities, respectively. One signal and one pump are included here, which can either be copropagating or counterpropagating with the signal. It is assumed that the fiber is single moded and has the lowest-order mode for a step index fiber. The ASE is divided into components representing the power present in bandwidth Δv_j that is centered at frequency v_j .

The population N_2 in equation (2.8) can now be written in terms of the field powers [23]

$$N_2 = \frac{\frac{\tau\sigma_s^a}{Ah\nu_s}\Gamma_s P_s + \sum_j \frac{\tau\sigma_{v_j}^a}{Ah\nu_j}\Gamma_{v_j} P_A(v_j) + \frac{\tau\sigma_p^a}{Ah\nu_p}\Gamma_p P_p}{\frac{\tau(\sigma_s^a + \sigma_s^e)}{Ah\nu_s}\Gamma_s P_s + \sum_j \frac{\tau(\sigma_{v_j}^a + \sigma_{v_j}^e)}{Ah\nu_j}\Gamma_{v_j} P_A(v_j) + \frac{\tau(\sigma_p^a + \sigma_p^e)}{Ah\nu_p}\Gamma_p P_p + 1} N \quad (2.9)$$

where the Γ_i (i.e. $\Gamma_s, \Gamma_{v_j}, \Gamma_p$) are the overlap factors between the light-field modes and the erbium distribution, P_s is the power of the signal ($P_s = Ah\nu_s\phi_s/\Gamma_s$); and P_p is the power of the pump ($P_p = Ah\nu_p\phi_p/\Gamma_p$), and $A = \pi R_c^2$ is the effective area of the erbium distribution, where R_c is the radius of the fiber core.

Each ASE power, $P_A(v_j)$, is composed of a forward-traveling ASE component, $P_A^+(v_j)$,

and a backward-traveling ASE component, $P_A^-(v_j)$, such that [23]

$$P_A(v_j) = P_A^+(v_j) + P_A^-(v_j) \quad (2.10)$$

The field propagating equations can be written in terms of the field powers. Only that part of the optical mode that overlaps with the erbium-ion dopant will experience gain and attenuation so that the overlapping parameters are also included in the propagation equations. The parameters of the fiber background loss for the pump, signal and ASE are assumed to be $\alpha_p^{(a0)}$, $\alpha_s^{(a0)}$ and $\alpha_{v_j}^{(a0)}$, respectively. The equations for the pump power P_p , signal power P_s and ASE power, $P_A^+(v_j)$ and $P_A^-(v_j)$ can be written as [23]

$$\frac{dP_p}{dz} = (N_2\sigma_p^{(e)} - N_1\sigma_p^{(a)})\Gamma_p P_p - \alpha_p^{(a0)} P_p \quad (2.11)$$

$$\frac{dP_s}{dz} = (N_2\sigma_s^{(e)} - N_1\sigma_s^{(a)})\Gamma_s P_s - \alpha_s^{(a0)} P_s \quad (2.12)$$

$$\frac{dP_A^+(v_j)}{dz} = (N_2\sigma_{v_j}^{(e)} - N_1\sigma_{v_j}^{(a)})\Gamma_s P_A^+(v_j) + N_2\sigma_{v_j}^{(e)}\Gamma_s h\nu_j \Delta v_j - \alpha_{v_j}^{(a0)} P_A^+(v_j) \quad (2.13)$$

$$\frac{dP_A^-(v_j)}{dz} = -(N_2\sigma_{v_j}^{(e)} - N_1\sigma_{v_j}^{(a)})\Gamma_s P_A^-(v_j) - N_2\sigma_{v_j}^{(e)}\Gamma_s h\nu_j \Delta v_j + \alpha_{v_j}^{(a0)} P_A^-(v_j) \quad (2.14)$$

Assume that the same overlapping parameters can be used for both the signal and ASE as they are both near the 1.5 μm wavelength. The ASE power in the channel centered at frequency v_j propagates as one signal with an input power of 0 at $z = 0$ for the forward-propagating ASE and another signal with an input power of 0 at $z = L$ (L is the length of the fiber) for the backward-propagating ASE. The model becomes more accurate, but it is more complex to treat numerically, when the frequency channel spacings, Δv_j are chosen to be very small such that the cross sections are essentially constant across Δv_j .

The objective of the simulation program is to compute the output spectrum of the EDFA over the wavelength range from λ_1 to λ_2 (where $\lambda_2 > \lambda_1$) with a spectral resolution of $\Delta\nu_j$. To do so, the program has been developed to solve these $2[(\lambda_2 - \lambda_1)/\Delta\nu_j + N_s + N_p]$, where N_s and N_p are the number of signal sources and pump sources used, coupled differential equations, that is, one differential equation for each spontaneous emission wavelength over a pre-defined wavelength range, one for each signal wavelength, and one for each pump, all in the forward and backward directions, as the signal/pump reflections at EDF ends caused by a reflector or by unwanted reflections are already taken into account. Since there is no way of knowing in advance the forward (+) and backward (-) ASE distributions along the fiber, the simulation program must make an assumption about the backward ASE at the signal input end ($z = 0$) if the signal is traveling along with the pump, in order to perform the integration of the equations over the length of the fiber with steps δz . Essentially, there are two ways to solve such a two boundary-value problem, namely the shooting method and the relaxation method. The boundary value is $P_A^+(z = 0) = 0$ but $P_A^+(z = L)$ is unknown, while $P_A^-(z = L) = 0$ and $P_A^-(z = 0)$ is unknown. The shooting method is a trial and error approach in which the backward ASE spectrum at $z = 0$ is first estimated before the system of equations is integrated from $z = 0$ to L . Since the backward ASE power must be null at the signal output end ($z = L$), it is possible to correct the first guess for $P_A^-(z = 0)$ and perform iteration until the boundary condition $P_A^-(z = L) = 0$ is met. The shooting method involves solving the equations by propagating the light fields forward and backward along the fiber, using the known boundary condition and a guess value of the unknown boundary condition for the signal, pump,

forward ASE and backward ASE, until a self-consistent solution is found. Thus, this method is not very practical and is very time consuming since its complexity, low convergence, and the results may be greatly influenced by the estimation method for solving the backward-ASE spectrum.

The relaxation method makes iterative adjustments to the solution. First, integration of the equations is performed along the signal propagation direction (from $z = 0$ to L) without considering the backward ASE. Then, considering the backward ASE, integration in the reverse direction (from $z = L$ to 0) is performed using the previously computed forward ASE distribution, and the first estimate of the backward ASE distribution is obtained. By performing the iteration this way with the boundary conditions of the previous iteration, it is possible to obtain a fast and precise convergence to a solution by the nature of the rate equations involved. The fact that the backward ASE was ignored in the first integration process overestimates the signal gain and the forward ASE, and underestimates the backward ASE in the second iteration process. However, in each iteration, the underestimation of the backward ASE decreases, and the solution is reached asymptotically, which is contrary to the shooting method that can lead to oscillations around the actual solution. The iteration process is stopped by adding an accuracy condition between iterations (e.g. a computed signal gain value changes by less than 0.001 dB).

In this study, the relaxation method has been used to calculate the EDFA gain with the help of the powerful software (Matlab 6.1), considering a frequency channel $\Delta\nu_j$ to be as small as 0.2 nm. The erbium-doped fiber's parameters are given as follows: the overlap

factor are $\Gamma = 0.40$ at 1530 nm and 1550 nm, and $\Gamma = 0.43$ at 1500 nm; the fiber length is 8 m; the fiber has a concentration of erbium ions of $N = 9.8 \times 10^{24} \text{ m}^{-3}$; the fiber has a numerical aperture of 0.23 and a cut-off wavelength of 900 nm. After iterating for about 20 times, the program converged to a solution with a satisfactory accuracy by setting an accuracy condition between iterations to be as small as 0.001 dB. A small input signal (-40 dBm) within the whole wavelength range (from $\lambda_1 = 1500 \text{ nm}$ to $\lambda_2 = 1600 \text{ nm}$) was used in the simulation. As an example to demonstrate the effectiveness of the simulation program, one simulation result of the EDFA is shown in Figure 2.4.

Figure 2-4: Simulation result of the erbium-doped fiber amplifier.

Finally, only a few adjustments are required to make the EDFA simulation program work in order to model the erbium-doped fiber laser operation. But a specific type of laser cavity must be taken into account. As in a linear cavity, instead of using the previously stated boundary conditions on the ASE distribution, the new boundary conditions would become $P_A^+(z=0) = R_1 \times P_A^-(z=0)$ and $P_A^-(z=L) = R_2 \times P_A^+(z=L)$, where R_1 and R_2 are

the reflectivities of the back and front reflectors, respectively.

2.3 Erbium-Doped Fiber Lasers

2.3.1 Single Frequency Fiber Lasers

An EDFL can be viewed as an EDFA operating in a particular regime, where coherent oscillation of ASE occurs due to some means of feedback. Thus, the EDFLs and the EDFAs are defined as follows. EDFLs are used as sources for coherent optical carriers, while EDFAs are used as traveling-wave amplifiers for coherent optical amplification. Continuous-wave, single-frequency lasers are required in a wide range of communication, sensor and spectroscopic applications. In addition, with system integration and miniaturization being emphasized, device compatibility with fiber and optic waveguide is essential. Although both semiconductor and miniaturized bulk solid-state lasers are viable optical sources, they require feedback and alignment insensitive integration into fiber/waveguide systems. Due to EDFL's inherent advantages which include all-fiber structure, high efficiency slope, broad operation bandwidth around the 1550 nm wavelength band, and full compatibility with the fiber-optic networks, EDFLs have attracted intensive interests all over the world since the early 1990s [44] ,[45]. Generally, the resonators within the EDFL are categorized into three structures, namely, linear cavity, ring cavity, and coupled cavity. Next, major developments in single-frequency EDFL technologies will be reviewed for these three kinds of laser cavities.

1. Linear cavity EDFL

The linear, or Fabry-Perot, cavity is the most common laser cavity structure. The fiber laser, in its most elementary form, can be described as a length of EDF enclosed by two reflectors. This simple resonator configuration is schematically illustrated in Fig. 2-5. In a forward-pumped linear cavity EDFL, the pump light is injected through a wavelength-dependent reflector (WDR) which is, ideally, perfectly transparent at the pump wavelength and perfectly reflective at the signal wavelength. The output coupler and the WDR mirror form the complete linear cavity. Note that the output coupler must be highly reflective at the pump wavelength to recycle the unused pump power back into the cavity, thus enhancing the laser's pump efficiency and ensuring no residual pump appearing at the output port. The output coupler reflectivity in the signal wavelength band can either be broadband, leading to a lasing wavelength determined by the gain curve of the EDF, or wavelength-selective, leading to a lasing wavelength selected, and possibly tuned, by the output coupler. The linear cavity configuration is interesting due to the engineering simplicity, increased efficiency, improved reliability, and low cost.

Figure 2-5: Schematic diagram of a linear cavity EDFL. M1: pump WDR mirror, M2: output coupler [25].

3. Ring cavity EDFL

The ring cavity design is the most common type of EDFL configuration found in the

literature. It is a simple cavity to build, and in its simplest form, the output of an EDFA is fed back into its input using a coupler to form a ring cavity laser as illustrated in Figure 2-6.

Figure 2-6: Schematic diagram of a typical ring cavity EDFL. LD: laser diode; PC: polarization controller, WDM coupler: wavelength division multiplexing coupler [25].

Besides its simplicity, a ring cavity that includes an optical isolator has the advantage of achieving traveling-wave operation, unlike the standing-wave operation of most linear cavity lasers. The traveling-wave operation is advantageous because it prevents the spatial hole burning from occurring. When a standing-wave pattern is established in a laser cavity, it will form a gain grating in the erbium-doped fiber. For the wave that forms this gain grating, the round-trip gain is reduced because the gain is locally saturated on the standing-wave pattern. Frequency hopping to other longitudinal cavity modes is possible since neighboring modes may have a higher (unsaturated) gain. Usually, when no cavity filters are used, linear cavity lasers are less stable in output power and frequency than those of ring cavity lasers. Wavelength selectivity can be achieved by using the optical filter within the ring cavity, using either a tunable optical bandpass filter or an FBG operating in the reflection mode. Ring cavity EDFLs use the gain provided by

the EDF more efficiently and have a FSR that is twice as large for the same cavity length, compared to the linear cavity lasers.

3. *Coupled cavity EDFL*

A typical coupled-cavity EDFL is the Fox-Smith resonator laser [26] as shown in Figure 2-7. The Fox-Smith resonator is a directional-coupler resonator with three mirrors creating two coupled cavities. Each of the cavities operating individually will produce a set of resonances. The first cavity is made of a dielectric mirror r_1 , which has a high reflection coefficient at the signal wavelength and is highly transparent at the pump wavelength, and a dielectric mirror r_4 . The second cavity is composed of the mirror r_1 (the common mirror) and a diffraction grating. The transmission of the complete resonator is high when both of the constituent cavities are at resonance and low when only one cavity is at resonance. If the cavity lengths are chosen to be in the ratio of two integers which are close, but not equal in value, the frequency spacing of the two transmission peaks will be made to be significantly further apart than the frequency spacing of either of the transmission peaks of the cavities acting individually. This is an example of the Vernier effect. When a gain medium, such as erbium dopant, is incorporated into the fiber, lasing will take place preferentially at frequencies which simultaneously satisfy the resonance conditions of both cavities. The lasing modes will then be sufficiently apart that one of them may be selected with the use of the diffraction grating.

Figure 2-7: Schematic diagram of a fiber Fox-Smith resonator laser [26].

The lasers described above all lase at a single wavelength, and some of them have the property of wavelength tuning. However, they are not good enough for applications in the DWDM lightwave systems because they cannot be directly applied to implement multi-wavelength optical sources with all the features as described in Chapter 1, which include a large number of lasing wavelengths over a broad bandwidth, high output power that is uniformly distributed across the lasing wavelengths, precise locations of the lasing wavelengths on the ITU frequency grid, and single frequency operation.

2.3.2 Multiwavelength Fiber Lasers

Room-temperature multiwavelength fiber lasers exploiting only one gain medium are mainly categorized by the gain medium into three different kinds: 1) multiwavelength EDFLs, 2) multiwavelength fiber Raman lasers, and 3) multiwavelength semiconductor optical amplifier (SOA) lasers, and they are briefly described below.

- *Multiwavelength EDFLs*: EDFLs that can simultaneously generate multiple lasing wavelengths have been investigated in order to develop simple compact sources for evaluation of WDM components [27], [28]. As the required transmission capacity of optical communication system increases, multiwavelength source technology becomes more important, considering that the complexity and cost of the source will increase as the number of WDM channel increases [28]. The laser cavity of the multiwavelength EDFL (see Fig. 2-8) normally consists of an EDFA and one or more wavelength-selective components such as fiber Bragg grating (FBG) based filters. The main advantages are their high efficiency and the broad amplification bandwidth of EDF in the 1550 nm window, which enable a large bandwidth (C+L band) for multiwavelength lasing operation and a large tunable bandwidth of the center wavelength with moderate peak power for each wavelength channels. The main limiting factor of multiwavelength EDFLs is the homogeneous linewidth broadening of EDF at room temperature which is the major barrier for achieving stable simultaneous oscillation of multiple lasing wavelengths. According to the conventional laser theory, each channel output of a laser containing a gain medium with homogeneous linewidth broadening becomes unstable due to the gain competition between the lasing wavelengths, and this is inevitable when two or more frequency components need to satisfy the laser oscillation condition [29]. A straightforward way to reduce the homogeneous linewidth broadening of EDF is to cool the EDF down to about 77 K. However, currently it is still difficult to achieve this even in the laboratory conditions. It is preferable to take some measures to make the EDF inhomogeneous or to greatly

reduce its homogeneous broadening linewidth so as to achieve room-temperature multiwavelength operation.

Figure 2-8: Multiwavelength EDFL configuration using in-fiber comb filters [28].

- Multiwavelength fiber Raman lasers:** Multiwavelength Raman fiber lasers have been investigated for room-temperature lasing operation because of its inhomogeneous broadening characteristics. A typical six-wavelength Raman fiber laser [30] is depicted in Fig. 2-9. The lasing wavelengths of the Raman fiber laser are determined by the six high reflectivities ($\sim 99\%$) of the FBGs as shown in Fig. 2-10. The most obvious advantages of the multiwavelength Raman fiber laser is the Raman amplifier's extremely wide gain bandwidth (covering both C and L telecommunication bands) with the use of several pumps at selected wavelengths and optical powers [30]. Also the wavelength spacing of the lasing output can be tuned by changing the physical parameters of the gratings [31]. However, the laser cavity lengths of most Raman fiber lasers are relatively long due to the low

nonlinear coefficient of the fiber used (which means a very long length, normally over 1 km, of fiber is required to generate enough Raman gain). Thus the laser cavity is relatively sensitive to the environment changes such as temperature, pressure, etc.

Figure 2-9: Schematic diagram of the six-wavelength Raman fiber laser [30].

- Multiwavelength SOA laser:** SOA is a competitive candidate for room-temperature multiwavelength fiber laser operation due to its inhomogeneous characteristics [32]. A recently reported multiwavelength fiber ring laser exploiting a SOA [33] is schematically shown in Fig. 2-10. The lasing wavelengths are determined by the comb filter (which is the delayed interferometer here) within the ring cavity. The main advantages of the SOA-based multiwavelength fiber laser are simple structure, small cavity length, and stable room-temperature operation. However, in this structure, normally more than one optical isolator is required in the ring laser cavity to ensure the unidirectional operation of the multiwavelength fiber laser, and more importantly to reduce the noise of the SOA. Due to the large noise caused by the SOA, SOA-based multiwavelength fiber lasers' output lasing lines will have lower signal-to-noise ratios than those of EDFLs. Also it is worth noting that proper splicing between an SOA waveguide and a fiber patch cord is needed to prevent the Fabry-

Perot resonance from occurring within the ring cavity.

Figure 2-10: Schematic diagram of the multiwavelength fiber ring laser using an SOA [33].

The important performance comparisons of these three kinds of multiwavelength fiber lasers are summarized in Table 2.1. Among these three kinds of multiwavelength fiber lasers, the multiwavelength EDFL is the most challenging one to develop due to the homogeneous linewidth broadening of Er^{3+} at room temperature, while the other two gain mediums will saturate inhomogeneously.

Table 2.1: Representative performance comparisons of three different type of multiwavelength fiber lasers.

Type of lasers (ref.)	Wavelength range (nm)	Number of lasing wavelengths	Pump	Cooled or uncooled	Type of comb filter
EDFL ([28])	7	11	980 nm 300 mW	Cooled	Chirped F-P filter, Sampled FBG
Raman laser ([31])	13.5	19	1064 nm 4.8-5.6 W	Uncooled	Cascaded LPGs
SOA laser ([33])	20	~ 50	125-275 mA	Uncooled	F-P filter

2.4 Fiber Gratings used in Lasers and Amplifiers

2.4.1 Principle of Fiber Bragg Gratings

The emergence of ultraviolet-written fiber gratings with both short and long periods as a reliable fiber technology has revolutionized the areas of passive and active fiber devices. Silica fibers doped with germanium can permanently have their optical properties changed when they are exposed to intense radiation from a laser operating in the blue or ultraviolet (UV) spectral region. This process is known as the photosensitive effect which can be used to induce periodic changes in the refractive index along the fiber length, resulting in the formation of an intracore FBG (see Fig. 2-11).

Figure 2-11: Schematic illustration of an example of a uniform fiber grating. Dark and light regions within the fiber core correspond to periodic variations of the refractive index of the fiber, Λ is the grating period.

The availability of UV-written fiber gratings [34] has resulted in a variety of important technological advances in fiber-based devices and systems. Fiber gratings have now become an enabling technology that provides convenient, cost-effective, and reliable solutions to a multitude of design problems in fiber systems, where the gratings have been used for applications such as optical feedback, wavelength control, filtering, sensing, and dispersion compensation [35]. Due to its inherent advantageous features such as ease of fabrication, spectral selectivity, low insertion loss, low polarization sensitivity and

ruggedness, the fiber grating technology has had a particularly strong impact on the design of active devices. For example, the fiber grating technology enables the fabrication of highly spectrally selective feedback elements directly into the fiber core, leading to extremely low loss resonators, a unique feature that many other technologies can not provide. Fiber gratings can be designed to operate over a wide range of wavelengths ranging from the ultraviolet to the infrared regions. The wavelength region near 1.5 μm is of particular interest because of its important application in fiber-optic communications. The fiber grating technology is now a well-developed and promising technique that can be used for the development of a variety of devices for applications in sensors and communications. Tunable optical components based on intracore uniform FBGs are one of the promising applications. To select and manipulate different WDM wavelength channels, tuning of the Bragg wavelength of the FBG is necessary. The Bragg wavelength of an FBG is given by

$$\lambda_B = 2n_{eff}\Lambda \quad (2.15)$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the silica fiber, and Λ is the grating period. According to Eq. (2.15), tuning of the Bragg wavelength can be realized by changing the grating period and the effective refractive index of the optical fiber. Hence, the change of the grating period and effective index can be achieved by applying strain to a section of the fiber due to the photoelastic effect. Also, it can be achieved by heating a section of the fiber that contains a Bragg grating due to the thermo-optic effect of the silica fiber.

A chirped FBG is an FBG with monotonically varying period and/or monotonically

varying refractive index. Figure 2-12 shows a schematic diagram of a chirped FBG with length L_g and chirped bandwidth $\Delta\lambda_{chirp}$. Similar to the uniform FBG described in Eq. (2.15), the local Bragg wavelength of a chirped FBG is given by

$$\lambda_B(z) = 2n_{eff}(z)\Lambda(z) \quad (2.16)$$

where z is the distance along the fiber. Hence, the total chirp of the grating period, $\Delta\Lambda_{chirp}$, is related to the chirped bandwidth of the grating as

$$\Delta\lambda_{chirp} = 2n_{eff} [\Lambda(L) - \Lambda(0)] = 2n_{eff} \Delta\Lambda_{chirp} \quad (2.17)$$

where $\Lambda(L)$ and $\Lambda(0)$ are the grating periods at the end and start positions, respectively.

Figure 2-12: A schematic diagram of a chirped FBG.

It is worth noting that the Bragg wavelength varies along the chirped FBG according to Eq. (2.16). That is, different wavelength components of an optical signal will be reflected at different positions along the chirped FBG.

The development of the long-period gratings (LPGs), which couples discrete wavelengths of the light into lossy cladding modes with extremely low levels of back reflection, has provided another useful tool for the design of various active fiber devices. Furthermore, specially designed FBGs can be used to develop tunable optical filters and even tunable

wavelength selective components such as tunable comb filters for multiwavelength generation.

2.4.2 Fabrication of Fiber Bragg Gratings

Since the fiber is doped with photosensitive germanium material, the refractive index of the fiber core can be changed by exposing it under the irradiation of UV laser light. Photosensitivity in optical fiber refers to a permanent change in the refractive index of the fiber core when exposed to light with characteristic wavelength and intensity that depend on the material of the fiber core. Photosensitivity was first observed in an optical fiber that was exposed to a 488-nm laser light launched into its core [36]. A transverse inscription method was later used to fabricate Bragg gratings using a direct excitation wavelength of 240 nm [34]. It was then discovered that photosensitivity could be improved by up to two orders of magnitude through hydrogenation of the optical fiber core before grating inscription [37]. The current consensus explains photosensitivity as being initiated through the formation of color centers [38] that gives way to compaction of the UV-irradiated glass [39].

FBGs can be distinguished into three main types depending on the types of fibers used, on the UV radiation bands, and on the UV radiation power. FBGs formed at low UV radiation intensities are generally referred to as Type I, which is characterized by a temporary refractive index change of $\Delta n > 0$ and its instability with temperature. Protracted UV exposure to Type I grating in some instances may result in complete or partial grating erasure, followed by the generation of Type IIA grating with a highly

negative Δn . When the UV irradiation at energy levels greater than 1000 mJ/cm^2 , the fiber core may be physically damaged [35], resulting in the generation of a Type II grating with a large refractive index change (of up to $\Delta n \approx 10^{-2}$). It is known that the Type II grating is the most stable grating against temperature change in these three types of FBGs.

Fiber gratings can be fabricated using various techniques, with each having its own merits and limitations. Among them, two commonly used techniques for fabricating the fiber gratings will be briefly described in this section, and they are the single-beam internal technique [36], and the phase mask technique [40].

In the single-beam internal technique, the grating formation is initiated by the light reflected from the far end of the fiber and propagating in the backward direction. The two counter-propagating waves interfere and create a standing wave pattern with periodicity of $\lambda/(2n)$, where λ is the laser wavelength and n is the mode index at that wavelength. The refractive index of silica is modified locally within the regions of high intensity, resulting in a periodic index variation along the fiber length. One disadvantage of the single-beam internal method is that the grating can be used only near the wavelength of the laser. A dual-beam holographic technique can solve this problem and is presented below.

The dual-beam holographic technique, as shown schematically in Fig. 2-13, makes use of an external interferometric scheme similar to that used for holography. Two optical beams obtained from the same laser operating in the ultraviolet region which make an angle of

2θ with respect to the beam axis, are made to interfere at the exposed core of an optical fiber. A cylindrical lens is used to expand the beam along the fiber length. Similar to the single-beam scheme as described previously, the interference pattern causes a change in the refractive index of the fiber, creating a fiber grating. The most important feature of the holographic technique is that the grating period Λ can be varied over a wide range by simply adjusting the angle θ (see Fig. 2-13).

Figure 2-13: Schematic illustration of a dual-beam holographic technique [35].

The phase mask technique uses a photolithographic process commonly employed for the fabrication of integrated electronic circuits. The basic idea is to use a phase mask with a periodicity related to the grating period. The main advantage of the phase mask method is that the demands on the temporal and spatial coherence of the ultraviolet beam are much less stringent than the single-beam internal technique because of the non-interferometric nature of the technique. The phase mask can also be used to form an interferometer using the setup shown in Fig. 2-14.

Figure 2-14: Schematic illustration of a phase mask interferometer technique used for making fiber gratings [35].

The UV laser beam falls normally on the phase mask and is diffracted into several beams in the Raman–Nath scattering regime. The two first-order diffracted beams interfere on the fiber surface and form a periodic intensity pattern. The grating period is exactly one-half of the phase mask period. There are several advantages of using the phase mask interferometer technique. The technique is insensitive to the lateral translation of the incident laser beam and is tolerant to any beam-pointing instability. This non-holographic scanning technique bypasses the need of a master phase mask and fabricates the grating directly on the fiber, period by period, by exposing short fiber sections of width w to the high-energy pulse. The fiber is moved by a distance, Λ (which is the grating period), before the next pulse arrives, resulting in a periodic index pattern such that only a fraction w/Λ in each period has a higher refractive index. The method is referred to as a point-by-point fabrication since a grating is fabricated period by period even though the period Λ is typically below $1\text{ }\mu\text{m}$. The point-by-point fabrication method is also suitable for the fabrication of long-period gratings in which the grating period exceeds $10\text{ }\mu\text{m}$ and can even be longer than $100\text{ }\mu\text{m}$, depending on the application. By using different types of

phase masks, such as a chirped phase mask or a sampled phase mask in the grating fabrication, special FBGs, such as a LCFBG or a sampled fiber Bragg grating (SFBG) can be obtained with the phase mask fabrication technique. In this thesis work, the phase mask fabrication method is employed for the fabrication of LCFBGs, which are used in comb filter and fiber laser design in Chapter 6 and 7.

2.4.3 Fiber Gratings Used in Active Fiber Devices

In fiber lasers and amplifiers, fiber gratings are becoming an integral part of fiber systems, for example, in EDFAs, the fiber gratings can provide practical solutions to a variety of important problems, such as gain-flattening, pump diode reflection and stabilization. And in single-longitudinal-mode fiber lasers, a promising alternative to DFB laser or DBR semiconductor laser, beside fiber grating-stabilized laser diodes, is the short-cavity fiber laser. The introduction of fiber gratings has greatly simplified the design of single-longitudinal-mode fiber lasers by reducing the number of required components to a minimum. Robust single-longitudinal-mode lasing operation can be obtained with a single phase-shifted grating written over the full length of the rare-earth doped fiber, a configuration which is similar to that of a DFB laser diode [41]-[43]. Single-longitudinal-mode fiber lasers have been shown to have high output power, narrow linewidth, low noise, and excellent wavelength stability and accuracy.

EDFLs have received a lot of attention because of their obvious compatibility with the 1.55 μm -based telecommunications systems. EDFLs can be pumped by 980 nm or 1480 nm laser diodes and can lase over much of the erbium gain band. EDFs, however, are not

well suited for designing single-longitudinal-mode lasers because of their relatively low pump absorption per unit length. Compared to other rare-earths, erbium ions have relatively low absorption cross-sections at the usual pump wavelengths, and they can only be doped in silica fibers at low concentrations to avoid problems due to clustering and ion-pair interactions. For the length of fiber required for robust single-longitudinal-mode laser operation (normally less than ~ 10 cm [44]), a typical erbium-doped fiber is only able to absorb a few milliwatts of pump power, which results in a $1.55\text{ }\mu\text{m}$ output power of a fraction of a few milliwatt. More efficient $1.55\text{ }\mu\text{m}$ single-longitudinal-mode lasers have been realized in fibers co-doped with erbium (Er) and ytterbium (Yb) [45], [46]. Er:Yb fibers are designed so that the ytterbium ions absorb most of the pump light and resonantly transfer the absorbed energy to erbium. As ytterbium does not suffer from the concentration-quenching problems experienced by erbium and has a larger absorption cross-section, it is possible to design fibers that can absorb tens of milliwatts of pump power using just a few centimeters of Yb-doped fiber. Although Er:Yb fibers are generally free of germania, it is possible to write strong fiber gratings directly into the Er:Yb doped fiber [47], which has lead to the development of a DFB fiber laser (Fig. 2-15). Owing to the availability of the fiber grating technology, single-frequency DFB fiber lasers with a number of unique features have been achieved. These features include the wavelength accuracy and stability characteristic of the fiber gratings as well as low noise and high fiber-coupled output power. Their very narrow laser linewidth, which can be as small as several kilohertz, also makes them extremely attractive for ultrahigh-resolution interferometric sensing [48]. However, one important drawback is that the DFB fiber lasers must be externally modulated due to the long lifetimes of the rare-earth ions.

Figure 2-15: A typical design of high-power (> 5 mW) single-longitudinal-mode fiber lasers at $1.55 \mu\text{m}$ based on erbium: ytterbium doped fibers [46].

FBG-based filters can also be designed as wavelength-selective components for multiwavelength fiber laser sources. Chow *et al.* [28] reported multiwavelength fiber ring lasers using a transmissive wideband Bragg grating based Fabry-Perot resonator [49] and a reflective sampled Bragg grating [50]. By incorporating two LCFBGs and a tunable filter with 6 nm tuning range, a periodic comb-like spectrum was obtained with this transmissive Fabry-Perot filter [49]. Due to the comb filter's all fiber structure, the insertion loss of the filter is relatively small, which was measured to be $\sim 3\text{dB}$, compared with those of the bulk dielectric filters. The other type of comb filter is a reflective SFBG, which is structurally simple and thus reduces the system complexity and cost. However, the insertion loss of the SFBG was approximately 7 dB, which is dominated by the insertion loss of the 3 dB coupler which was used instead of a circulator to enable the reflective Bragg filter to be used in the ring laser cavity. For both laser configurations using these two types of grating filters, simultaneous multiwavelength lasing outputs with different wavelength spacing (0.65-1.8 nm) have been achieved at room temperature [28]. The grating-based comb filter is the key component of a room-temperature multiwavelength fiber laser source, which defines the center wavelength and the wavelength spacing of the fiber laser. Gu has proposed a multiwavelength EDFL using cascaded LPGs [51], where the first LPG couples part of the core mode into a cladding

mode, and the second LPG combines the two modes, resulting in sharp interference fringes. By using two cascaded LPGs separated by tens of centimeters as an optical comb filter, up to 21 equally-spaced lasing wavelengths over a bandwidth of 30 nm were obtained at room temperature. Thus, by applying the FBG-based techniques into the design of the optical comb filters, multiwavelength fiber lasers can be designed with greater flexibility.

2.5 Summary

In this chapter, the physics of the EDF amplification has been discussed. One popular modeling method of the EDFA has been briefly described. The operating principle and fabrication process of the FBG have been described. Due to the inherent advantageous features such as spectral selectivity, low insertion loss, low polarization sensitivity, and all-fiber structure, FBG technique can be applied to the design and fabrication of active fiber devices, especially the all-fiber lasers. Several laser configurations of the EDFLs have been briefly reviewed. And different gain mediums used in the development of multiwavelength fiber lasers have been summarized. Specially designed optical comb filters with short or long-period fiber gratings can be used as the wavelength selective components for multiwavelength lasing operation at room temperature.

3

Tunable Multiwavelength Fiber Laser

In this chapter, a tunable multiwavelength laser source based on a Sagnac loop filter is proposed and demonstrated experimentally. In this EDFL, the Sagnac loop filter consists of a segment of polarization-maintaining erbium-doped fiber (PM-EDF) that acts as a high-birefringent component within the loop filter as well as an optical gain medium for the laser source. Room-temperature multiwavelength operations with 50 GHz and 100 GHz wavelength spacings have been achieved with this fiber laser. The center wavelengths of the output lasing lines can be tunable by adjusting the polarization controller (PC) within the laser cavity. This laser configuration has a simple structure, and does not require any optical isolators compared to other reported fiber lasers.

Section 3.1 gives a brief literature review on the multiwavelength fiber laser sources. Section 3.2 introduces the principle of the Sagnac loop filter and presents the experimental results of the Sagnac loop filter which is used in the fiber laser source. The experimental results and discussion of the proposed multiwavelength fiber laser source are presented in Section 3.3. A summary of this chapter is given in Section 3.4. Part of the work presented here has already been published [15].

3.1 Introduction

Multiwavelength fiber laser sources, capable of emitting light at several well-defined wavelengths simultaneously, are useful for WDM optical communication systems, especially as head-end transmitters in wavelength-routed local area networks (LANs) [12]. Multiwavelength fiber lasers can be used for this purpose, and several schemes have been developed [27], [28], [52]-[55] in recent years. Generally, in order to achieve multiple-frequency lasing operation, multiwavelength fiber lasers must have two common characteristics: 1) a means of obtaining gains for several lasing wavelengths simultaneously and 2) one or more filters are needed to define the locations of the lasing wavelengths. A dual-frequency fiber laser was demonstrated in 1993 by using a coupled-cavity configuration [52]. Since then, a fiber laser that can simultaneously generate up to 29 wavelengths has been realized by cooling the doped fiber to 77 K using liquid nitrogen [27]. The cavity length can be quite small (~ 1 mm or so) since the spacing between the lasing wavelengths is governed by the longitudinal-mode spacing. A 1-mm cavity length corresponds to about 100 GHz wavelength spacing. Such fiber lasers operate as standard multimode lasers. Cooling of the EDF helps reduce the homogeneous broadening of the gain spectrum to below 0.5 nm. The gain spectrum is then predominantly inhomogeneously broadened, resulting in multiwavelength lasing operation through the spectral hole burning (SHB) effect. Long cavities with several meters of doped fibers can also be used. Wavelength selection can then be made using an intra-cavity comb filter such as the Fabry-Perot interferometer [28]. In a dual-filter approach, using a tunable comb filter in combination with a set of fiber gratings enables a

multiwavelength source to be switchable on a microsecond timescale to precise pre-selected wavelengths [53]. However, the need to cool the EDF using the liquid nitrogen is not an effective solution for most practical applications.

3.1.1 Room Temperature Operation of Multiwavelength Laser Sources

To obtain multifrequency lasing operations, there are two main methods. One method involves the use of multiple independent gain mediums. In a manner similar to semiconductor laser arrays, it is quite straightforward to create multiwavelength EDFLs that use a single gain medium for each lasing wavelength [56]-[58]. In 1994, Takahashi *et al.* [56] demonstrated a multifrequency ring EDFL oscillating simultaneously over four wavelengths that were spaced 1.6 nm apart by using an 8×8 array waveguide grating (AWG) and four EDFAs. Later, Miyazaki and his co-workers [57] showed a ring EDFL that can lase on 15 lines separated by 1.6 nm, and the laser consists of 15 EDFAs placed between two 16×16 AWGs. One interesting scheme using a single-pump laser was proposed by Kim *et al.* [58] and is depicted in Fig. 3-1. The light from a 1480 nm pump laser is evenly distributed to N fiber segments by a $1 \times N$ broadband coupler. Each segment is composed of a piece of EDF followed by an optical isolator, a tunable optical filter and variable attenuator. By adjusting each attenuator, it is possible to establish multifrequency oscillation in this ring laser cavity. Independent wavelength tuning of each lasing line is the unique feature of this structure. However, the system complexity and cost will be high, because multiple gain mediums are needed to achieve multiwavelength operation.

Figure 3-1: Schematic diagram of a multifrequency EDFL using a single pump [58].

Another popular method to construct a multiwavelength fiber laser source involves the use of a single gain medium. The very first attempt [59] to achieve room-temperature operation of multifrequency EDFLs using a single-gain stage shows great potential of these sources. Later, Hübner and his co-workers [60] proved that a multifrequency EDFL can be obtained by writing a series of DFB fiber gratings in a single erbium-doped fiber. In their approach, which is similar to the DFB semiconductor lasers, a Bragg grating is formed directly into the erbium-doped fiber that provides gain. Phase-shifted DFB lasers have also been made by creating a small region in the middle of the doped fiber without a grating. Multiple gratings with slightly different Bragg wavelengths can also be formed into the same doped fiber, resulting in several DFB lasers cascaded together, and this can provide five lines over a 4.2 nm range. The use of specially-doped fibers has also led to

very elegant designs. A twin-core EDF was used by Graydon *et al.* [61] as an inhomogeneous gain medium in a multifrequency ring EDFL. In this twin-core fiber, wavelength-dependent periodic coupling between the two fiber cores partially decouples the available gain for each wavelength, because the two cores interact with a different subset of erbium ions. Poustie *et al.* [10] used a multimode fiber to create a periodic frequency filter based on spatial mode beating to generate four lasing lines that are spaced by 2.1 nm. In 1992, Abraham *et al.* [62] showed a multifrequency hybrid laser that consists of a 980 nm pump laser diode with anti-reflection coating coupled to an EDF with a fiber mirror, and the laser produced an output spectrum with six lines spaced by 0.44 nm. In 1997, Zhao *et al.* [63] demonstrated that the control of optical feedback in a modified S-type cavity allowed stable multifrequency operation. A very interesting scheme to realize room-temperature operation of a multifrequency EDFL was demonstrated by Sasamori *et al.* [64], where they used an acousto-optic modulator to prevent the laser from reaching the steady-state operation (see Figure 3-2), which effectively reduced the homogeneous broadening of the erbium-doped fiber.

Figure 3-2: Schematic diagram of a multifrequency EDFL based on an acousto-optic modulator, (a) ring cavity, (b) multiwavelength optical bandpass filter, and high-gain EDFA [64].

3.1.2 Multiwavelength Erbium-doped Fiber Laser Cooled by Liquid Nitrogen

For room-temperature operation, the most obvious way to achieve multifrequency operation from an EDFL using a single-gain medium is to cool the EDF by immersing the EDF in a bath of liquid nitrogen at a typical temperature of 77 K. At this temperature, the erbium ions become inhomogeneous, and multifrequency operation can be achieved more easily. However, this inconvenient and unreliable approach is not practical for many field applications. Nonetheless, many potent experimental results have been published using this method [11], [28], [65]. In 1996, Chow *et al.* [28] published results concerning a multifrequency ring EDFL using two different types of periodic frequency filters. They obtained eleven laser peaks spaced by 0.65 nm using a Fabry-Perot filter based on chirped fiber Bragg gratings [49], and five laser peaks spaced by 1.8 nm with a sampled

fiber Bragg grating.

That same year, Yamashita *et al.* [27] proposed a single-polarization linear-cavity multifrequency EDFL. This laser does not use PM fiber and operates in a traveling-wave mode, thus preventing spatial hole burning from occurring, since cavity feedback is provided by a Faraday mirror. Also a Fabry-Perot etalon was used as a periodic frequency filter. A polarizer and a Faraday rotator were placed on each side of the etalon to prevent parasitic reflections from happening. With this setup, they obtained simultaneous oscillation over 17 wavelengths spaced by 0.8 nm. Simultaneous lasing of up to 24 wavelengths has also been demonstrated by Park *et al.* [11] using controlled polarization evolution in a ring cavity and liquid nitrogen cooling to enhance SHB, PHB, and polarization selectivity. A polarizer and a polarization controller were placed before a piece of PM fiber to form a Lyot filter with a FSR of 1.1 nm. Furthermore, Yamashita *et al.* [27] realized a multiwavelength Er:Yb Fabry-Perot micro-laser with 29 lines spaced 0.4 nm apart. But cooling the erbium-doped fiber to the temperature of liquid nitrogen (77 K) is not practical in most circumstances. Thus, this chapter will present a new multiwavelength laser configuration using some special EDFs to obtain multiwavelength lasing operation under room-temperature conditions without the use of liquid nitrogen.

3.2 Sagnac Loop Filter

To obtain multiple wavelength operation, a robust optical filter with low insertion loss and periodic spectrum is needed to define (and even tune) the lasing wavelengths of the fiber laser. Several kinds of filters have been constructed (as discussed in Section 2.3.3)

for the selection of the fiber laser's wavelengths, which include AWGs, Mach-Zehnder interferometers, in-fiber comb filters, and spatial mode beating filters. This section presents a fiber Sagnac loop filter with a very wide operation bandwidth and tunable FSR.

3.2.1 Theory of the Sagnac Loop Filter

A fiber-based Sagnac loop filter is based on the Sagnac interferometer and the non-reciprocity of the fiber's birefringence to the polarization states of the light. Compared with the Mach-Zehnder interferometer-based filters, the Sagnac loop filters are more tolerant against environmental changes because the two light beams split and then combined by the fiber coupler travel along the same path.

Figure 3-3 shows the schematic diagram of a fiber Sagnac loop filter which is formed by connecting a segment of fiber to the two ports of a 3-dB fiber coupler to form a loop. The input optical power is assumed to be small (e.g. < 30 dBm), so that the filter is operating in the linear region. If nothing is added into the fiber loop and a normal 3-dB fiber coupler is used, the Sagnac loop will act as a perfect fiber loop mirror because the transmittivity will be zero. The loop filter appears to function like a fiber-ring resonator but it behaves quite differently because of two crucial differences. First, there is no feedback mechanism in the Sagnac loop filter since the light entering the input port exits from the resonator after a single round trip. Second, the input optical field is split into two counter-propagating parts that share the same optical path and interfere at the coupler coherently. Thus, the fiber Sagnac loop filter is much more stable than the Mach-Zehnder interferometer-based filter which has two different optical paths.

Figure 3-3: Schematic setup of a typical fiber-based Sagnac loop filter.

When a section of high-birefringence (Hi-Bi) fiber (with length L and birefringence B) and a PC are incorporated into the loop, the filter will generate a periodic comb-like spectrum which can be used for wavelength selection in EDFLs. The Jones matrix describing the birefringent elements within the loop is denoted as J . Such configuration is depicted in Fig. 3-4.

Figure 3-4: Schematic diagram of the Sagnac loop filter with J being the Jones matrix describing the birefringent loop.

For only one input electric-field amplitude E_1 , the output field amplitude E_2 is given by [66]:

$$\begin{pmatrix} E_{2x} \\ E_{2y} \end{pmatrix} = \begin{pmatrix} (2k-1)J_{xx} & (1-k)J_{xy} + kJ_{yx} \\ -kJ_{xy} - (1-k)J_{yx} & (1-2k)J_{xx} \end{pmatrix} \begin{pmatrix} E_{1x} \\ E_{1y} \end{pmatrix} \quad (3.1)$$

Here k is the coupling ratio of the fiber coupler, and x, y are the two principle axes of the Hi-Bi fiber within the fiber loop. It is assumed that the energy in the system is conserved,

so $J_{yx} = -J_{xy}^*$, and $k = 0.5$ (considering a 3-dB coupler here), then Eq. (3.1) can be simplified to

$$\begin{pmatrix} E_{2x} \\ E_{2y} \end{pmatrix} = \frac{1}{2}(J_{xy} - J_{xy}^*) \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} E_{1x} \\ E_{1y} \end{pmatrix} \quad (3.2)$$

where J_{xy}^* is the complex conjugate of J_{xy} . The Jones matrix for the loop with a Hi-Bi fiber can be represented by a product of three matrices, namely, U_L , U_R and D . The matrices U_L and U_R take into account the linear and circular birefringence of the coupler and orientation of the principal axes of a Hi-Bi fiber at the ports 3 and 4, they can generally be written as follows:

$$U = \begin{pmatrix} U_{xx} & U_{xy} \\ -U_{xy}^* & U_{xx}^* \end{pmatrix} \quad (3.3)$$

where U_{xx} and U_{xy} are complex numbers, and the condition $|U_{xx}|^2 + |U_{xy}|^2 = 1$ must be satisfied. The Jones matrix D describing linear birefringence of the Hi-Bi fiber is given as

$$D(\omega, L) = \begin{pmatrix} e^{i\Delta\beta(\omega)L/2} & 0 \\ 0 & e^{-i\Delta\beta(\omega)L/2} \end{pmatrix} \quad (3.4)$$

where $i = \sqrt{-1}$, $\Delta\beta(\omega) = \beta_x(\omega) - \beta_y(\omega)$ is the difference between the two propagation constants of the Hi-Bi fiber that supports two linearly orthogonal fundamental modes, and ω is the angular frequency of the lightwave. For the two linearly orthogonal modes ($\beta_x(\omega)$ and $\beta_y(\omega)$), the following condition holds $\beta(\omega) = \frac{2\pi}{\lambda}n(\omega)$ where λ is the wavelength of the light and $n(\omega)$ is the refractive index of the Hi-Bi fiber. Thus the following relationship is obtained

$$\Delta\beta(\omega) = \frac{2\pi}{\lambda} B \quad (3.5)$$

where the Hi-Bi fiber's birefringence $B = n_x - n_y$ (n_x and n_y are the refractive indices of the Hi-Bi fiber along the two principle axes, respectively). It should be noted that a common average phase shift of $e^{i\overline{\beta}(\omega)L}$ is omitted in Eq. (3.4) because the Sagnac interferometer can not distinguish the common phase term for the clockwise (CW) propagating beam and the counter-clockwise (CCW) propagating beam.

Using Ref. [66] and Eqs. (3.1)- (3.4), the intensity transfer function, T_1 , for the reciprocal port 1 can be derived as

$$T_1 = 1 - \sin^2(\Delta\beta(\omega) \times L/2) \quad (3.6)$$

Because the system is assumed to be energy conservative, the transmittivity of port 2 will satisfy $T_2 = 1 - T_1$. Using Eqs. (3.5) and (3.6), the intensity transfer function of port 2 is given by

$$T_2 = \sin^2\left(\frac{\pi BL}{\lambda}\right) \quad (3.7)$$

The spacing of the interfered fringes from the output port 2 of the Sagnac loop filter or the filter's FSR, $\Delta\lambda$, is given by

$$\Delta\lambda = \frac{\lambda^2}{BL} \quad (3.8)$$

According to Eq. (3.7), the output spectrum of the Sagnac loop filter is a periodic comb-like profile with a FSR, $\Delta\lambda$, defined by Eq. (3.8).

3.2.2 Characterization of the Fiber Sagnac Loop Filter

Figure 3-5 depicts the experimental setup of the fiber Sagnac loop filter, which is based on the principle of the Sagnac interferometer. The filter consists of a 50:50 single-mode fiber coupler, a polarization controller (PC), and a 6-m segment of “panda” Hi-Bi fiber.

Figure 3-5: Experimental setup of the fiber Sagnac loop filter with a 50:50 fiber coupler, a polarization controller (PC) and 6 meter of Hi-Bi fiber (with birefringence $B \approx 5.167 \times 10^{-4}$ at the wavelength of 1550 nm).

The input light entered the input port is equally split into two counter-propagating beams (i.e. the CW and CCW beams) by the coupler, and these CW and CCW lightwaves recombine at the coupler after propagating through the whole fiber loop. The Hi-Bi fiber in the loop introduces a phase difference between the two orthogonally polarized parts of the two light beams traveling in the loop.

There are mainly two types of PM fiber [67]. One fiber type, such as the tiger PM fiber, has a non-cylindrical symmetry of the fiber core, making the core elliptical in shape. And the amount of birefringence created by this technique is typically $B \sim 10^{-6}$ at the wavelength of 1550 nm. Another PM fiber type, such as the Panda PM fiber, makes use of stress-induced birefringence with $B \sim 10^{-4}$ at the wavelength of 1550 nm. Apparently, the stress-induced PM fiber has larger birefringence than that of the tiger PM fiber. The

birefringence value depends on the location and the thickness of the stress-induced elements. Such fibers are often named after the shape of the stress-induced elements, resulting in whimsical names such as “panda” and “bow-tie” fibers. Here in this thesis only the stress-induced birefringent fiber is considered, where the effective index of each polarization is influenced mainly by the stress alone. Thus, the phase difference between the two linearly orthogonal modes introduced by the Hi-Bi fiber, δ , is given by $\delta = \Delta\beta(\omega)L$, where $\Delta\beta(\omega)$ relates to the modal birefringence B as defined by Eq. (3.5).

The slow and fast axes of the Hi-Bi fiber are denoted as x axis and y axis, respectively. The polarization controller is set to produce a rotation of 90° in relation to the principle axes of the Hi-Bi fiber for beams coming from both directions. Thus, the x -axis component of the CW propagating beam is changed to the y -axis component by the polarization controller and then travels through the Hi-Bi fiber as the fast mode. On the other hand, the x -axis component of the CCW propagating beam after traveling through the Hi-Bi fiber as the slow mode will change to the y -axis mode as the fast mode after passing through the PC. The x -axis components of the two counter-propagating beams will interfere when they are recombined at the 3 dB coupler, with the phase difference δ , and then exit the coupler. The same interference mechanism applies to the y -axis components of the two beams. This mechanism suggests that the transmittivity of the Sagnac loop filter depends on the phase difference δ and is therefore a periodic function of wavelength, λ , according to Eq. (3.7).

The transmittivity of the Hi-Bi fiber loop filter is independent of the state of polarization

of the input beam as described above [66]. And maximum contrasts of the interfered fringes from the output port of the coupler can be achieved when the PC is adjusted to rotate the linearly polarized components of the two counter-propagating beams by 90° . If the rotational angle is not set to 90° , only part of the beams will interfere and the contrast of the fringes will decrease.

3.3 Tunable Multiwavelength Fiber Laser

3.3.1 Spectral Response of the Fiber Sagnac Loop Filter

Figure 3-6 shows part of the spectral response of the loop filter which was characterized with a tunable laser source (ANDO AQ4321D), and measured with an OSA. The laser source was set at 0 dBm, and was tunable through the whole 100 nm wavelength range (from 1520 to 1620 nm). From Fig. 3-6, it can be seen that the insertion loss of the filter was around 5 dB, which was mainly caused by the losses of the 3-dB fiber coupler and the two splice points between the single-mode fiber and the Hi-Bi fiber. The figure also shows that the extinction ratios of the spectral peaks are about 25 dB, and that the transmission spectrum is very flat within this 10 nm range. The spacing between the spectral peaks, $\Delta\lambda$, is about 0.85 nm, which can be determined from Eq. (3.8) (where $L = 6$ m) with the birefringence $B = \lambda / L_B$ (where L_B is the beat length of the PM fiber and $B \sim 5 \times 10^{-4}$ at $\lambda = 1550$ nm).

Figure 3-6: Measured spectral response of the Sagnac loop filter from 1540 nm to 1550 nm within the C-band using a tunable laser source.

Figure 3-7 shows the measured spectral response of the loop filter from 1520 nm – 1620 nm). Figure 3-7 (a) shows the spectral response of the multiwavelength comb filter within the C-band (1520 nm – 1570 nm), where the power variation in the entire 50 nm wavelength range is very small (within 1 dB).

Figure 3-7: Measured spectral responses of the filter with a FSR of about 0.85 nm: (a) In the whole C-band (from 1520 nm to 1570 nm), (b) In the wavelength range of 1590 nm–1600 nm, (c) In the whole L-band (from 1570 nm to 1620 nm).

Figures 3-7 (a), (b) and (c), show that, within the entire 100 nm wavelength range, the spectrum of the Sagnac loop filter is a periodic comb-like grid with very small power variation (less than 1 dB) and an extinction ratio of over 25 dB, thus these filter characteristics are very suitable for the implementation of multiwavelength fiber lasers. This kind of fiber Sagnac loop filter has many advantages such as all-fiber geometry, ease of connection with other fiber-optic components and optical communication systems, large operating band (> 100 nm), very low insertion loss, polarization independence, and stability.

The center wavelengths of the spectral peaks of the periodic comb-like spectrum can be tuned by changing the state of the polarization controller manually. This method allows the spectral peaks of the comb filter to be precisely set on the ITU frequency grid, however, at the same time the extinction ratio of the filter spectrum also changes when

the center wavelengths of the spectral peaks of the filter are tuned. Thus, with this filter and fine adjustment of the PC within the loop, a periodic comb-like spectrum with a frequency separation or FSR of ~ 100 GHz or 50 GHz can be achieved, and this is required in DWDM optical communication systems. The FSR of the filter can be reduced by increasing the length L of the Hi-Bi fiber (see Eq. (3.8)). With this tunable feature, the Sagnac loop filter is very suitable for use in the design of multiwavelength fiber laser sources with lasing wavelengths precisely set on the ITU frequency grid.

3.3.2 Experimental Setup of the Proposed Multiwavelength Fiber Laser

Figure 3-8 shows the experimental setup of the proposed multiwavelength fiber laser using the Sagnac loop filter. The laser cavity is formed by a fiber loop and a fiber mirror as a reflector, and consists of a 3-dB fiber coupler, a 1480/1550 nm WDM coupler, and two polarization controllers (PC1 and PC2). The fiber mirror has a reflectivity greater than 96% at 1550 nm and 15 m of PM-EDF. The PM-EDF is an elliptical-core EDF with a numerical aperture of 0.26, a birefringence of $B \approx 2.40 \times 10^{-4}$ at 1550 nm and an erbium ion concentration of $3 \times 10^{24} \text{ m}^{-3}$. The pump laser is a stable laser diode with a power of 180 mW at 1480 nm. As the PM-EDF also has the property of high birefringence, the fiber coupler, PC1 and the PM-EDF form a fiber Sagnac loop filter [68], [69]. The birefringence of the PM-EDF produces a wavelength-dependent phase difference between the fast and slow components of the CW and CCW beams propagating in the loop, namely, $\delta = (2\pi BL)/\lambda$, where B is the modal birefringence of the PM-EDF and L

is the length of the PM-EDF, and λ is the operation wavelength. This is because the two counter-propagating light waves travel along different axes of the PM-EDF when PC1 is set to generate a 90° rotation of the polarization state of the light in both directions. Note that this Sagnac loop filter is much less sensitive to environmental changes since both the counter-propagating lights travel in the same optical path before being recombined at the fiber coupler. As the phase difference between these two counter-propagating light waves is wavelength dependent, the intensity transfer function of the loop is described by Eq. (3.7). The wavelength separation (or FSR) between two transmission peaks of the Sagnac loop filter's spectrum depends on the modal birefringence B and length L of the PM-EDF, which is given by $\Delta\lambda = \frac{\lambda^2}{BL}$ according to Eq. (3.8). Thus, the spacing between two transmission peaks can be changed by using different length of the PM-EDF within the laser cavity or using the method described in Section 3.2.1. The total cavity length is about 20 meters and the total cavity loss is about 6 dB, which is mainly caused by the loss of the 3-dB fiber coupler.

Figure 3-8: Schematic diagram of the proposed multiwavelength fiber laser based on the Sagnac loop filter.

Figure 3-9 shows a photograph of the proposed multiwavelength EDFL. Here the PM-EDF serves as the active gain medium in the laser cavity as well as the Hi-Bi fiber in the Sagnac loop filter due to the high birefringence of the PM-EDF. Thus the laser cavity and the Sagnac loop can be coupled together with a fiber mirror to provide feedback of light in the cavity. As the PM-EDF being explored here is an elliptical-core EDF [69], [70], it can support single-mode operation along the minor axis and multimode operation along the major axis. And this can generate multiple lasing wavelengths in a very simple manner under room temperature conditions. By changing the setting of the PC2 to adjust the polarization-dependent loss and polarization state of the light within the cavity, tunable multiple lasing lines can be obtained from the output port of the fiber coupler.

Figure 3-9: A photograph of the proposed multiwavelength EDFL.

3.3.3 Experimental Results and Discussion

The output spectrum of the proposed multiwavelength EDFL measured with an ANDO OSA is shown in Fig. 3-10, where the two lasing lines are generated at 1557.22 nm and 1558.52 nm, with a wavelength spacing of 1.3 nm ($\sim 2 \Delta\lambda_1$). Here the wavelength spacing of the fiber Sagnac loop filter is given by $\Delta\lambda_1 \approx 0.667$ nm, when the length of the PM-EDF is 15 m according to Eq. (3.8). The power levels of the lasing lines are both about 300 μ W.

Figure 3-10: Two lasing wavelengths generated at the output port of the fiber laser.

By tuning the PC2 within the laser cavity, which effectively changes the polarization state of the fiber laser, multiwavelength lasing operation with three lasing lines (Fig. 3-11 (a)), five lasing lines (Fig. 3-11 (b)), six lasing lines (Fig. 3-11 (c)), and seven lasing lines (Fig. 3-11 (d)) can be achieved. Figures 3-11(a)-(d) show the monitored spectra of different number of lasing lines at different settings of PC2. Figure 3-11 (a) shows three lasing lines at 1557.04 nm, 1558.34 nm and 1559.64 nm, with separation of 1.3 nm ($\sim 2\Delta\lambda_1$). The 3-dB linewidth of each lasing line is less than 50 pm, which is restricted by the resolution of the OSA. Figure 3-11 (b) shows simultaneously five lasing lines at 1555.76 nm, 1557.06 nm, 1557.71 nm, 1558.37 nm and 1559.01 nm, and the wavelength spacings between the lines are 1.3 nm ($\sim 2\Delta\lambda_1$), 0.65 nm ($\sim \Delta\lambda_1$), 0.66 nm ($\sim \Delta\lambda_1$), 0.64 nm ($\sim \Delta\lambda_1$), respectively. Figure 3-11 (c) shows six lasing lines at 1555.13 nm, 1555.78 nm, 1556.43 nm, 1557.73 nm, 1558.38 nm and 1559.68 nm. Through carefully changing the setting of the PC2 to adjust the state of polarization and the total loss of the laser cavity, seven simultaneous lasing wavelengths can be also obtained as shown in Fig. 3-11 (d). The

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OSNRs of all these lasing lines are very large (over 30 dB). And all the lasing lines have an optical power greater than 100 μ W.

Figure 3-11: Measured spectra of the multiwavelength fiber laser with different settings of the PC. (a) Three lasing lines with a wavelength spacing of ~ 1.3 nm. (b) Five lasing lines (the four lasing lines on the right side have a wavelength spacing of ~ 0.65 nm). (c) Six lasing lines (the center three lasing lines have a wavelength spacing of ~ 0.66 nm). (d) Seven lasing lines (the six lasing lines on the right side have a wavelength spacing of ~ 0.64 nm).

Figure 3-12 shows stable lasing output spectra measured over 30 minutes with different wavelength spacings by changing the setting of PC2 at room temperature. The power fluctuation of the lasing lines within half an hour is very small (less than 1 dB), showing the laser stability. The OSNRs of all the lasing lines are greater than 40 dB. And the laser

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linewidths of all the lasing lines are ~ 50 pm.

Figure 3-12: Stable lasing lines from the multiwavelength fiber laser. (a) Two lasing lines at 1557.17 nm and 1559.13 nm. (b) Three lasing lines at 1557.17 nm, 1558.50 nm and 1559.80 nm. Both measurements were taken at a regular interval of 30 seconds.

It is worth noting that the gain medium we used in the proposed multiwavelength fiber laser is an elliptical-core erbium-doped fiber, which has polarization anisotropic gain effects [25]. The elliptical-core erbium-doped fiber has two principle polarization axes. If the polarization of the pump is appropriately adjusted, it can support single mode

operation along the minor axis and multimode operation along the major axis. Thus, stable multiple wavelength lasing operation could be achieved under room temperature conditions.

The wavelength spacing of the multiwavelength fiber laser can be changed by using different length of the PM fiber within the fiber Sagnac loop filter. In Figures 3-10, 3-11, and 3-12, the length of the PM-EDF within the laser cavity is 15 m. When using a longer length of the PM-EDF, the separation between two neighboring lasing lines will decrease according to Eq. (3.8). In Figures 3-13(a) and (b), a longer length of 25 m of the PM-EDF was used within the laser cavity. As shown in Figure 3-13 (a), two nearest lasing lines have a wavelength separation of $\sim 0.8 \text{ nm}$ ($\sim 2 \Delta\lambda_2$). Here the wavelength spacing of the fiber Sagnac loop filter is given as $\Delta\lambda_2 \approx 0.4 \text{ nm}$, when the length of the PM-EDF is 25 m according to Eq (3.8). And in Fig. 3-13 (b), the number of lasing lines increases to eight, while the smallest wavelength spacing between two neighboring lasing lines is about 0.4 nm ($\sim \Delta\lambda_2$). Because the wavelength spacing depends on the physical parameters of the PM-EDF, such as the length and the birefringence of the PM-EDF, the longer the length of the PM-EDF, the smaller the channel spacing of the generated lasing wavelengths will be.

Note that the wavelength spacings of all the output lasing lines shown in Figures 3-10, 3-11, 3-12 and 3-13 are not uniform mainly due to the intense mode competition of the EDF at room temperature, which could prevent a certain wavelength from lasing. Thus the obtained wavelength spacings of the output lasing lines are not always uniform and, in some cases, they could be a multiple of the fiber Sagnac loop's wavelength spacing or

FSR, which is defined in Eq (3.8).

Figure 3-13: Measured output spectra of the multiwavelength fiber laser with a longer length of PM-EDF (i.e. $L = 25$ m). (a) Three lasing lines at 1559.95 nm, 1561.87 nm and 1562.67 nm. (b) Maximum number of lasing lines.

Compared with the reported work [27], the proposed multiwavelength fiber laser using the polarization-maintaining Sagnac loop filter has several unique advantages such as stable room-temperature operation without the need to cool the EDF with liquid nitrogen, tunable lasing wavelengths, simple structure with less optical components compared with

reference [28] due to the fact that the PM-EDF functioned as both the gain medium and the PM fiber within the Sagnac loop filter at the same time, and changeable wavelength spacing by using different length of the PM fiber within the Sagnac loop filter. A similar approach has been reported in reference [71], in which a fiber-grating-based Sagnac loop filter was used as the wavelength-selection component in the laser cavity. However, the center wavelengths of the lasing lines were all fixed and liquid nitrogen was also required to cool the EDF to 77 K to ensure stable room-temperature operation. The disadvantage of the proposed multiwavelength fiber laser is that the wavelength separations of the output lasing wavelengths are not always uniform due to the EDF's mode competition at room temperature.

3.4 Summary

A novel tunable multiwavelength EDFL based on a fiber Sagnac loop filter has been presented. The elliptical-core PM-EDF placed within the Sagnac loop filter provides optical gain for the laser cavity and can also be used as the wavelength-selective component of the multiwavelength EDFL. By changing the setting of PC2 within the laser cavity, two, three and four stable lasing lines in the C-band, and five, six, seven and even eight lasing lines were obtained at room temperature. Wavelength spacings of 0.8 nm or 0.4 nm (i.e. 100 GHz or 50 GHz) can be achieved by using different length of PM-EDF within the laser cavity's Sagnac loop filter. The linewidth of the lasing lines is as small as 50 pm. The output lasing lines from the multiwavelength EDFL was found to be fairly stable for an observation over an hour under room temperature conditions, without using any additional measures to stabilize the fiber laser. The OSNR of all the lasing lines

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are greater than 40 dB and the total output power of the fiber laser is over 3 mW. This laser configuration has many unique advantages such as simple structure, low cost, without the need to use optical isolators and multiple lasing wavelengths with changeable wavelength spacing. Using different length of the PM-EDF, both C-band and L-band lasing operations can be achieved.

4

A Stable Dual-Wavelength Fiber Laser with Tunable Wavelength Spacing

This chapter presents the proposed design and development of a stable dual-wavelength fiber laser with tunable wavelength spacing using a polarization-maintaining (PM) linear cavity. This fiber laser with an all-PM linear cavity can generate two stable lasing lines with both tunable center wavelengths and variable wavelength spacing at room temperature. Due to the two orthogonally polarized reflection peaks generated by the PM fiber Bragg grating (PM-FBG) in the laser cavity, two stable lasing lines with a wavelength separation of 0.22 nm are obtained. By stretching the PM-FBG, dual-wavelength lasing operation with a wavelength separation of as small as 0.05 nm is achieved. This laser configuration has such unique advantages as stable room-temperature lasing operation, very narrow linewidth, small variation of the lasing wavelengths, small power fluctuation of the lasing lines, low cavity loss, and simple all-fiber structure compared with many other techniques.

Section 4.1 gives a brief review on dual-wavelength fiber lasers and their applications. Section 4.2 describes the commonly used measurement methods for laser linewidth measurements. And Section 4.3 presents the proposed dual-wavelength fiber laser and the

experimental results. A summary of the chapter is given in Section 4.4. Part of the work presented here has already been published [16].

4.1 Introduction

Dual-wavelength and multiwavelength lasers that can generate short pulses have attracted much interest over the years because of their important applications such as in time-division-multiplexed optical based communication systems [73]-[78]. Actively mode-locked EDFLs such as multiwavelength lasers with tunable wavelength features using fiber gratings are reported in [73]-[77]. However, for such a laser to operate stably, special means of overcoming mode competition between the lasing lines due to the large homogeneous broadening of the EDF (such as using temporal-spectral multiplexing of the pulses [75] and separately pumped EDF cavities [77]) must be utilized, which inevitably increases the complexity and cost of the laser.

External-cavity semiconductor lasers using FBGs have been proposed as stabilized continuous-wave laser sources, and as tunable laser sources [79]. These lasers have narrow linewidths (~ 50 MHz) and could be a viable cost-effective alternative to DFB laser diodes and DBR laser diodes. Dual-wavelength lasers have also been the subject of considerable research interest as sources capable of producing beat signals at microwave frequencies, which is desirable for wide band electronic signal-processing systems [80]-[82]. Beat signal frequencies in the microwave and millimeter range have been previously demonstrated using separate laser cavities [81]-[82]. However, these systems employing separate cavities can suffer from phase noise and phase drift, thus making a

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single-cavity dual-wavelength preferable for producing stable beat signal frequencies. Furthermore, a dual-wavelength fiber laser source can also generate solitons with high repetition rate [83]. One recently reported technique proposes the use of a continuous wave signal from two frequency modes of two separate lasers for the generation of a soliton pulse train at a repetition frequency in the gigahertz range [83], [84]. The transformation of the generated beat signal from the laser into a train of solitons and subsequent soliton compression results from nonlinear effects in a fiber with slow amplification or dispersion decreasing along the length, where the frequency period of the generated soliton pulse train is the frequency difference between the two modes [83], [84]. Theoretical analysis has shown that, using this technique, a continuous wave train of high-quality and sufficiently separated soliton pulses can be generated with extremely small pedestal components in the pulses. Thus, a stable and simple single-cavity dual-wavelength fiber laser will be useful for the generation of the beat signal frequencies which can be used in various applications as described above.

It is preferable that a dual-wavelength fiber laser source has the following important features:

- Stable room-temperature operation;
- Narrow laser linewidth;
- Only two longitudinal modes to ensure stable room-temperature operation;
- Tunable center wavelengths of the two lasing lines;
- High output power (of the order of tens of milliwatts);
- Simple design, easy construction and low cost;

- Large OSNR;
- Tunable wavelength separation (if possible).

Till to date, most reported dual-wavelength fiber lasers do not meet all the described features listed above. The proposed dual-wavelength fiber laser with tunable wavelength spacing is presented in Section 4.3 in detail.

4.2 Laser Linewidth Measurement

In this section, several methods for laser linewidth measurement and characterization of fiber lasers are introduced. Laser linewidth is often defined in terms of the full width at half maximum (FWHM) of the optical intensity power spectrum. Grating-based OSAs do not offer the measurement resolution required for the measurement of small laser linewidth, thus alternative characterization methods must be used to measure the very narrow linewidths of fiber lasers. These alternative methods include the optical heterodyne method, the delayed self-homodyne method, and the delayed self-heterodyne method [85]. These methods can provide extremely high resolution required for laser linewidth measurements. The delayed self-heterodyne method was used for the measurement of the proposed dual-wavelength fiber laser's linewidth and it is described below.

The delayed self-heterodyne technique provides a simple way to perform laser linewidth measurements without the requirement of a separate local oscillator (LO) laser, which is needed in the other two methods as described above. Taking advantage of the large optical delays provided by the optical fiber, Okoshi and co-workers demonstrated that

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linewidth measurements could be performed with a simple optical interferometer [86]. The delayed self-heterodyne concept is shown in Fig. 4-1 (a), where an incident light is split into two paths by the interferometer. The optical frequency of one arm is offset with respect to the other. If the delay, τ_o , of one path exceeds the coherence time, τ_c , of the source, the two combining beams will interfere as if they were originated from two independent lasers with a frequency offset or shift by $\delta\nu$ as shown in Fig. 4-1(b). Thus the system performs similarly to the optical heterodyne measurement method [85]. The beat tone produced is displaced from 0 Hz by the frequency shifter by $\delta\nu$. An electrical spectrum analyzer (ESA) displays the beat tone which is broadened by the laser linewidth. The translation of linewidth information from optical frequencies to low frequencies where electronics instrumentation operates is shown in Fig. 4-2. As with the optical heterodyne case [85], the spectrum displayed by the ESA is a result of the convolution of the individual power spectra of the interfering waves (see Fig. 4-2).

Figure 4-1: Delayed self-heterodyne method. (a) Optical measurement setup. (b) Equivalent circuit when the delay time of the interferometer is larger than the coherence time of the signal.

Figure 4-2: The delayed self-heterodyne mixing of the laser field with a frequency shifted replica.

When the incoherent mixing requirement is satisfied, the photocurrent spectrum of the delayed self-heterodyne method (which is similar to the case of the optical heterodyne method) consists of two parts. One part is the direct detection and the other is the self-heterodyne spectrum, which is the desired mixing product which is given as [85]:

$$S_i(f) \approx \Re^2 \left\{ S_d(f) + 2 \left[S_s(\nu - \delta\nu) \otimes S_s(-\nu) \right] \right\} \quad (4.1)$$

(ESA $\Rightarrow$ direct direction + self-heterodyne spectrum)

where $\delta\nu$ is the frequency shift applied to the field traversing one arm of the interferometer, ν is the frequency of the laser under test, $\otimes$ denotes the convolution operation, $S_d(f)$ is the ordinary direct detection that could be measured with just a photodetector and ESA, $S_i(f)$ is the interfered detection, $S_s(\nu)$ is the self-heterodyne spectrum, and $\Re$ is the detector responsivity. Since the mixing term is essentially the laser spectrum under test convolved with itself (see Fig. 4-2) and displaced in frequency by $\delta\nu$,

the displayed lineshape will always be symmetrical, even if the original lineshape had important asymmetries.

Laser sources exhibiting frequency jitter will yield larger measured linewidths in a similar way as the heterodyne technique [85]. In this case, the measured linewidth will vary with the interferometer delay [87], and a larger delay will yield a larger linewidth. For Lorentzian lineshapes, the 3-dB linewidth must be inferred from measurements taken further down on the displayed lineshape as with the heterodyne case. The relationship between the measured FWHM linewidth using the delayed self-heterodyne method and the actual laser linewidth ($\Delta\nu$) is shown in Table 4.1, assuming that the optical field of the laser under test has a Lorentzian profile.

Table 4.1: Linewidth relations using the delayed self-heterodyne method.

Measured Full-Width Point	Corresponding Actual Laser Linewidth
-3 dB	$2\Delta\nu$
-10 dB	$2\sqrt{9}\Delta\nu$
-20 dB	$2\sqrt{99}\Delta\nu$
-30 dB	$2\sqrt{999}\Delta\nu$

4.3 Proposed Dual-Wavelength Fiber Laser with Tunable Wavelength Spacing

Dual-wavelength fiber lasers are very suitable for the generation of soliton pulse trains in

an optical fiber [88], generation of beat signals at microwave frequencies for electronic signal processing systems [89], generation of optical millimeter wave [90] and multiwavelength differential-absorption-lidar (DIAL) measurement of trace gases [91]. In recent years, several multiwavelength EDFLs have been reported using, for example, cascaded FBG cavities [92], polarization-dependent-loss elements [93], and multimode fibers [94]. To overcome the homogeneous broadening of the EDF at room temperature, the EDF was cooled to 77 K with liquid nitrogen [28] and the effect of polarization-hole burning could also be used to make the gain medium inhomogeneous [95]. However, all the previously reported on EDFLs are polarization dependent and thus polarization controller(s) (and hence the high cost incurred) were usually used to minimize the system instability. In addition, most of the previously reported EDFLs have a fixed wavelength separation and are thus limited in applications.

This work describes the proposal and experimental demonstration of a stable and wavelength-spacing tunable dual-wavelength fiber laser with an all-PM linear cavity, which is formed by a uniform PM-FBG and a PM linearly chirped FBG (PM-LCFBG). The wavelength separation between the two lasing lines can be tuned from 0.22 nm down to 0.05 nm by applying an axial strain on the PM-FBG through stretching. A stable dual-wavelength lasing output with a 3-dB linewidth of as small as ~ 2.5 kHz was obtained at room temperature as described below.

4.3.1 Experiment Setup of the Proposed Dual-Wavelength Fiber Laser

The experimental setup of the proposed dual-wavelength fiber laser is depicted in Fig. 4-

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3. Pump light from a 980-nm pump laser is coupled into the laser cavity through a 980/1550 nm WDM coupler. The linear laser cavity consists of an 8-m long PM-EDF, a uniform PM-FBG with a section of strain modulation and a PM-LCFBG, both of which were fabricated on the Hi-Bi fiber. The PM-EDF with a birefringence of 2.4×10^{-4} at 1550 nm and a concentration of erbium ions of $3 \times 10^{24} \text{ m}^{-3}$ is spliced (instead of using connectors to reduce the cavity loss) to the PM-FBG and PM-LCFBG. The Hi-Bi fiber used to fabricate the PM-FBG and PM-LCFBG were hydrogen-loaded for two weeks to increase their photosensitivity.

Figure 4-3: Experimental configuration of the proposed stable all-PM dual-wavelength fiber laser with tunable wavelength spacing.

The PM-FBG fabricated with a phase mask method has two reflection peaks at 1544.54 nm and 1544.76 nm with over 30 dB reflectivity. The 60-mm long PM-LCFBG fabricated with a phase mask (with a chirp rate of 2.25 nm/cm) has a stopband of about 17 nm in the transmission mode, which is centered at 1545.5 nm and has a reflectivity of ~90%. Instead of using a bulk dielectric mirror, the PM-LCFBG used here can be easily spliced with other components, thus making the laser cavity an all fiber structure. As the linear laser cavity is formed by the PM-FBG and PM-LCFBG, the lasing wavelengths are defined by the reflection peaks of the PM-FBG. It is worth noting that, except for the WDM coupler, the whole fiber laser cavity is all PM. The polarization state of the light

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within the laser cavity can thus be maintained, resulting in stable lasing wavelengths at the laser output under room temperature conditions. And Fig. 4-4 shows the photograph of the proposed dual-wavelength fiber laser source.

Figure 4-4: photograph of the proposed dual-wavelength fiber laser source.

4.3.2 Principle of the Proposed Dual-Wavelength Fiber Laser

Polarization properties are important features of fiber lasers. Birefringence properties of the fibers and components used in the laser cavity have to be considered in order to understand the characteristics of the fiber laser. Bragg gratings used as mirrors in the laser cavity are ideal components for the realization of all-fiber and compact devices that can be pumped with pigtailed laser diodes. When Bragg gratings are used as reflectors in

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a fiber laser cavity, the oscillating frequency of the laser is fixed by the resonance wavelength of the grating, which is related to the refractive index of the fiber by the Bragg condition (described in Chapter 2). The PM-FBG used in the proposed laser cavity has two reflection peaks in the reflection mode, with orthogonal polarization states, separated by the strain-optic effect in the Hi-Bi fiber due to its high birefringence [96], [97]. The Bragg wavelength λ_B of the PM-FBG is given by Eq. (2.15) as described in Chapter 2, where n_{eff} is the effective refractive index of the fiber core and Λ is the grating pitch. The normalized birefringence of the Hi-Bi fiber is given by $B = n_x - n_y$, where n_x and n_y are the refractive indices of the fiber's slow and fast axes, respectively. From these expressions of λ_B and B , the wavelength separation of the two reflection peaks of the PM-FBG is given as

$$\Delta\lambda = 2B\Lambda \quad (4.2)$$

This laser configuration exploits the difference in the wavelengths of the Bragg reflection of lights propagating along orthogonally linearly polarized axes of the Hi-Bi fiber. The PM-FBG (with $\Lambda = 1.045 \text{ } \mu\text{m}$) written on a segment of the Hi-Bi fiber with a birefringence of $B = 2.2 \times 10^{-4}$ at 1550 nm has two reflection peaks with a wavelength separation of $\sim 0.23 \text{ nm}$ (as calculated from Eq. (4.2)).

Both ends of the PM-FBG are mounted and fixed on a 3D stage, and the axial strain is applied to the PM-FBG by stretching the fiber with a micrometer. When the axial strain is applied to the PM-FBG, the grating pitch Λ is elongated, resulting in the shift of the reflection peaks to the longer wavelength range. When the PM-FBG is stretched, the

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birefringence of the Hi-Bi fiber is also reduced due to the deformation of the fiber core, which is changed from an elliptical core to a circular core. In general, the normalized birefringence of the Hi-Bi fiber, B , comprises of a stress anisotropy component B_s and a waveguide shape component B_G that is proportional to the ellipticity of the fiber [98]. When the Hi-Bi fiber's ellipticity is reduced due to the applied axial strain, the waveguide shape component B_G also decreases. Using the applied strain $\varepsilon = \Delta L / L$, where L is the length of the fiber and ΔL is the change of the fiber length due to stretching, and Eq. (4.2), the wavelength spacing after stretching can be derived as

$$\Delta\lambda = 0.22 \left[1 - \left(\frac{1}{1 - b/a} \right) \frac{100\varepsilon}{1 + 100\varepsilon} \right] \quad (4.3)$$

where a and b represent the lengths of the fiber core's long axis and short axis, respectively. Neglecting the effect of temperature change, it is assumed that when the PM-FBG is stretched, the volume of the stretched fiber does not change and thus the ellipticity of the fiber core decreases accordingly. Therefore, the birefringence B of the Hi-Bi fiber decreases and the wavelength separation between the two lasing lines is reduced according to Eq. (4.2).

4.3.3 Dual-Wavelength Fiber Laser with Tunable Wavelength Spacing

The output spectrum of the fiber laser was measured using an OSA with a resolution of 0.01 nm. Figure 4-5 shows two simultaneous lasing lines at 1544.54 nm and 1544.76 nm with a wavelength separation of 0.22 nm at a pump power of 85 mW when no strain was

applied to the PM-FBG. The OSNR of each lasing line is over 40 dB.

Figure 4-5: Measured laser spectrum showing two lasing lines centered at 1544.54 nm and 1544.76 nm which are separated by $\Delta\lambda = 0.22$ nm. The pump power used was 85 mW. No strain was applied to the PM-FBG.

The FWHM linewidth of the dual-wavelength fiber laser was measured using the delayed self-heterodyne technique, which has been discussed in Section 4.2. Since the grating-based OSAs can not provide the measurement resolution required for laser linewidth measurement and the proposed dual-wavelength fiber laser has a very small linewidth (which is much smaller than the resolution of the OSA), an alternative characterization method must be employed. There are three commonly used methods for the measurement of laser linewidth (see Section 4.2): 1) the optical heterodyne method, 2) the delayed self-homodyne method, and 3) the delayed self-heterodyne method. However, the first and second laser linewidth measurement methods are not suitable for our application. That is because the optical heterodyne method needs a LO with a linewidth much smaller than that of the laser under test, which is not available in our laboratory, and the photodetector in our laboratory has a weak response from 0 to 1 GHz. The optical setup for the

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linewidth measurement of the proposed fiber laser using the delayed self-heterodyne method is schematically shown in Fig. 4-6. The laser output from the dual-wavelength fiber laser was filtered out by a tunable bandpass filter to select only one lasing wavelength for linewidth measurement. And then the filtered light was split into two optical paths with the same optical power by a 3 dB optical coupler. In one arm, the fiber delay τ_o was introduced to the light through an 80-km single-mode fiber (SMF) to ensure the incoherent mixing of the light in two arms, and one PC was used to optimize the state of polarization (SOP) of the incident light. And, in the other arm, an acousto-optic frequency shifter (AOFS) was used to introduce a 100 MHz frequency shift to the light. Another 3 dB coupler was used to form the interferometer, and the mixed optical signal was fed into a 25 GHz photodetector (New Focus IR photodetector 1414) followed by an ESA (Agilent E4470B) to display the beat tone, from which the actual laser linewidth can be determined.

Figure 4-6: The experimental setup for the laser linewidth measurement of the proposed dual-wavelength fiber laser using the delayed self-heterodyne technique [85].

The measured beat tone is shown in Fig. 4-7, which has a 3 dB FWHM linewidth of about 5 kHz. According to the relationship of the measured FWHM linewidth using the

delayed self-heterodyne method and the actual laser linewidth as shown in Table 4-2, the laser linewidth of the dual-wavelength fiber laser is half of that of the FWHM linewidth displayed in the ESA. Thus, the actual linewidth of each lasing line is ~2.5 kHz, which is much smaller than the linewidths of most DFB lasers.

Figure 4-7: Measured beat tone of the linewidth of one lasing wavelength of the dual-wavelength fiber laser using an ESA with the optical delayed self-heterodyne technique.

Tuning of the wavelength separation of the dual-wavelength fiber laser is implemented by applying an axial strain to the PM-FBG within the laser cavity. When applying the axial strain to the PM-FBG, the center wavelengths of the lasing lines will shift to the longer wavelength region due to the elongated grating pitch as explained in Section 4.3.2. The tunable range of the lasing lines' center wavelengths is about 2~3 nm. The total output power of the fiber laser is about 0.25 mW, and the oscillation or output efficiency is 0.33%, which is limited by the low transmission of the PM-LCFBG.

Compared to the case with no axial strain applied to the PM-FBG where the wavelength

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separation is 0.22 nm (see Fig. 4-5), when an axial strain was applied to the PM-FBG, Figures 4-8 (a) and (b) show that the wavelength separation between the two lasing lines can be reduced to 0.15 nm and 0.076 nm, respectively. By stretching the PM-FBG further, a stable dual-wavelength lasing output with a wavelength spacing of as small as 0.05 nm was obtained (see Fig. 4-9 (d)).

Figure 4-8: Output spectra of the dual-wavelength fiber laser with different wavelength spacings, when different amount of axial strain was applied to the PM-FBG. (a) Wavelength spacing is $\Delta\lambda = 0.15$ nm. (b) Wavelength spacing is $\Delta\lambda = 0.076$ nm.

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To the author’s knowledge, this is the smallest wavelength separation of a stable dual-wavelength fiber laser at room temperature that is ever achieved. The stability of the dual-wavelength fiber laser was studied by performing repeated scanning of the fiber laser’s output spectra as shown in Fig. 4.9, where the power fluctuation of the lasing wavelengths was estimated to be < 0.5 dB, and the frequency variation of the lasing wavelengths was estimated to be < 0.01 nm, which is limited by the resolution of the OSA.

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Figure 4-9: Spectra of a stable dual-wavelength lasing output with a wavelength spacing of (a) 0.22 nm; (b) 0.124 nm; (c) 0.079 nm; (d) 0.050 nm when different amount of axial strain was applied to the PM-FBG. The measurements were taken at one-minute intervals over half an hour.

PHB effect, whose origin is due to the polarization dependence of the emission cross section of the erbium ions in the silica host, leads to polarization hole-burning with a hole depth which depends on the degree of amplifier compression. Note that the laser cavity of the proposed dual-wavelength fiber laser consists of all PM components (except for the WDM coupler). The enhanced polarization-hole-burning effect will increase the

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inhomogeneous loss of the laser cavity, which leads to multiwavelength lasing operation at room temperature. Furthermore, the cavity length of the linear laser cavity is small, which makes it less susceptible to environmental changes. Therefore, stable room-temperature dual-wavelength lasing operation can be achieved with the proposed fiber laser.

The Hi-Bi fiber, on which the PM-FBG was fabricated, has an elliptical fiber core, and when it is being stretched, the birefringence of the Hi-Bi fiber will change due to the deformation of the fiber core under axial strain. When the fiber is stretched, the ellipticity of the fiber core will decrease, which causes the birefringence of the Hi-Bi fiber to decrease. Hence, the wavelength separation between the two lasing wavelengths will decrease as a result of a reduced fiber birefringence because the birefringence of the Hi-Bi fiber is proportional to the ellipticity of the fiber core [98]. Thus, the wavelength separation of the two lasing lines is inversely proportional to the applied axial strain (in microstrain), according to Eq. (4.2).

The experimental results agree well with the simulation results as calculated from Eq. (4.3) (see Fig. 4-10). The wavelength separation between the two lasing lines can be tuned from 0.22 nm down to 0.05 nm (as shown in Fig. 4-5 and Fig. 4-9 (d), respectively). This relationship between the wavelength separation and the axial strain has potential applications in fiber-optical strain sensors, which has an obvious advantage due to the high OSNR of laser-based fiber sensors.

Figure 4-10: The relationship between the wavelength separation of the two lasing lines and the applied axial strain on the PM-FBG. The solid line and the data points are the simulation result and experimental result, respectively.

As the laser cavity is an all-PM linear cavity, the output spectrum from the fiber laser is very stable. Figures 4-9 (a)-(d) show the repeated scans of the laser output spectra with different wavelength spacings at one-minute intervals over half an hour. The power fluctuation of the two lasing lines is very small (less than 0.5 dB) and the wavelength shift is within 0.002 nm. From Fig. 4-9, it is apparent that the dual-wavelength operation is very stable at room temperature even with wavelength separations smaller than 0.5 nm [29], due to the enhanced polarization hole burning of the laser cavity. In this all-PM linear laser cavity structure, the two lasing lines oscillate along two orthogonally linearly polarization modes which are separated by the reflection peaks of the PM-FBG, and this greatly reduces the mode competition between the lasing lines.

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One of the important applications of the proposed dual-wavelength fiber laser is to generate a high frequency microwave signal by beating the two output lasing wavelengths [90], [99]. Therefore, a 25-GHz photodetector and an ESA were employed to optically heterodyne the two amplified output lasing wavelengths, and the schematic diagram of the measurement setup is shown in Fig. 4-11. The output spectrum from the proposed dual-wavelength fiber laser was split by a 10/90 fiber coupler, whereby 10% of the output spectrum was monitored by an OSA, while the remaining 90% of the output laser spectrum was fed into a 25-GHz photodetector (which is followed by an ESA) to monitor the generated beat signal. An EDFA was used to boost the lasing wavelengths' output power before it was fed into the photodetector.

Figure 4-11: Schematic diagram of the measurement setup of the beat signal generated by the proposed dual-wavelength fiber laser.

Since the two lasing wavelengths are generated from the same laser cavity, the relative phase fluctuations between the two lasing wavelengths are low because two wavelengths will change simultaneously with the environmental changes. The dual-wavelength fiber laser operation was found to be stable with a maximum peak power difference of the two lasing wavelengths of < 0.5 dBm. Note that this power difference between the two lasing wavelengths is due to the unequal reflectivities of the PM-FBG's two reflection peaks,

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which determines the lasing wavelengths of the fiber laser. However, this power difference between the two lasing wavelengths can be reduced by inserting a PC (with an optimized setting) in the laser cavity.

Fig. 4-12 (a) shows that the frequency of the beat signal generated by the two lasing wavelengths was measured to be ~ 9.41 GHz when the wavelength separation of the dual-wavelength fiber laser was ~ 0.076 nm. This is as expected because the optical heterodyning method requires that the wavelength difference between the two lasing wavelengths corresponds to the frequency of the generated beat signal. Similarly, Fig. 4-12 (b) shows that, when the wavelength separation of the two lasing wavelengths was ~ 0.15 nm, the frequency of the beat signal generated by the dual-wavelength fiber laser was measured to be ~ 18.03 GHz. Thus the proposed technique provides a unique advantage in that the frequency of the generated beat signal can be tuned to a desired value in practice to meet practical application requirements by adjusting the wavelength spacing between the two lasing wavelengths. In Fig. 4-12, the 3-dB beat linewidths were both estimated to be < 50 MHz, and the frequency drifts of the two beat signals (which were measured over 10 minutes) were estimated to be < 5 MHz, which was limited by the resolution of the ESA.

Fig. 4-12: Measured beat signal of the proposed dual-wavelength fiber laser. (a) when the wavelength separation is ~ 0.076 nm; (b) when the wavelength separation is ~ 0.15 nm.

The phase noise of the beat signal (close to the carrier frequency) is ~ -58 dBc/Hz. The beat signal has a relatively large phase noise and a relatively broad 3-dB linewidth because the phases of the two lasing wavelengths were not correlated with each other. However, the phase noise of the beat signal can be greatly reduced by phase-locking the

two lasing modes [99]. Note that the microwave power of the generated beat signal is relatively low, which was probably caused by the low response of the photodetector and the non-uniform power levels of the two lasing wavelengths.

4.4 Summary

A novel wavelength-spacing tunable dual-wavelength fiber laser with an all-PM linear laser cavity structure has been presented. Taking advantages of the PM-FBG, two stable lasing lines with a wavelength separation of 0.22 nm were obtained. By stretching the PM-FBG, the two lasing lines' center wavelengths can be tuned and different wavelength spacing (of as small as 0.05 nm) can be obtained. The maximum tunable range of the laser's center wavelength is about 3 nm. And the wavelength separation of the two lasing lines can be tuned from 0.22 nm down to as small as 0.05 nm, which is the smallest wavelength separation ever achieved, to the best of the author's knowledge, for a room-temperature dual-wavelength fiber laser source. The OSNRs of the two lasing wavelengths are over 40 dB. This dual-wavelength fiber laser configuration has such unique advantages as stable lasing operation at room temperature, very narrow linewidth (~ 2.5 kHz), very small wavelength variation (< 0.01 nm) and power variation (< 0.5 dB), low cavity loss, and simple structure compared with many other techniques. The developed dual-wavelength fiber laser has potential applications in many areas such as fiber-optic strain and temperature sensors, generation of high bit-rate soliton trains and generation of microwave beat frequency. In particular, the proposed dual-wavelength fiber laser has useful applications in the implementation of tunable microwave photonic notch filter (see Chapter 5).

5

Microwave Photonic Filters Using Multiwavelength Laser Sources

Using the developed dual-wavelength fiber laser with tunable wavelength spacing as described in Chapter 4 and a multiwavelength semiconductor optical amplifier (SOA) ring laser, this chapter presents the development of multiple-tap microwave photonic filters. Exploiting the incoherent operation of the lasing lines coming from the stable room-temperature multiwavelength laser source, two microwave photonic filters are implemented with a phase modulator and a segment of single-mode fiber (SMF) as a dispersive device. For the two-tap microwave notch filter, when stretching the PM-FBG to tune the wavelength separation of the two lasing lines from the dual-wavelength fiber laser, a tunable microwave photonic notch response with a rejection ratio greater than 35 dB was achieved. This kind of filter has several unique advantages such as the use of a single laser source to implement a multiple-tap microwave photonic filter, tunable FSR (for the two-tap microwave filter), elimination of the need to use fiber delay lines or fiber Bragg gratings in the filter part to achieve tunability, and reconfigurability.

Section 5.1 gives a general introduction of microwave photonic filters. The operating principle of the proposed tunable two-tap microwave photonic notch filter is presented in

Section 5.2. The simulation and experimental results of the proposed tunable microwave photonic notch filter are presented in Section 5.3. And Section 5.4 describes the multiple-tap microwave photonic filter. Part of the work presented here has already been published [17].

5.1 Introduction

Microwave photonic filters, see for example, references [100]-[106], are photonic subsystems designed to perform equivalent functionality to that of a conventional microwave filter within a radio frequency (RF) system or link, because they can provide supplementary advantages that are inherent to photonics technologies such as low attenuation, large bandwidth, immunity to electromagnetic interference (EMI), tunability, reconfigurability, and light weight. A simple example of the concept of a microwave photonic filter is presented here.

Figure 5-1 depicts a typical application of a microwave photonic filter in a moving target identification (MTI) ground radar system [107]. The MTI radar exploits the Doppler effect to separate the targets of interest from a clutter (such as land, sea water, and rain). To achieve this objective, the radar sends a pulse sequence with pulse width τ and interpulse period $PRI=1/PRF$, where PRF is the pulse repetition frequency. Any moving object will generate a Doppler frequency shift $\Delta\nu$ from the radar's signal central frequency f_o according to its speed (dR/dt) , where $R(t)$ designates the time-varying distance from the target to the radar. The spectral signature of each object repeats periodically in the spectrum with a period given by the PRF , which obviously sets the

limit on determining an unambiguous Doppler shift.

Figure 5-1: Example of a microwave photonic filter used in a ground MTI radar [107].

Thus, it is sufficient to obtain all the information of the moving targets and the clutter by focusing on a spectral region from f_o to $f_o + PRF$. Signal processing on the detected signal is normally needed to filter out the clutter and noise (the unwanted signals) from the target(s). This signal processing process is usually performed, as shown in Fig. 5-2 (a), by frequency down-converting the detected signal to a baseband signal, which is then converted to a digital signal by an analog-to-digital converter (ADC). In order to distinguish the small signal reflected from the target and the large signal generated by the fixed objects, high-performance ADCs (with 14-bit to 18-bit resolution) are normally required, which is a major bottleneck in the system. If the clutter can be removed before the down-conversion frequency process, then the high-resolution requirements on the

ADCs can be removed, but this process is difficult to achieve and is costly in the microwave domain. However, this difficult and costly process can be easily overcome if the RF signal is modulated onto an optical carrier and then processed directly in the optical domain by using a microwave photonic filter (see Fig. 5-2 (b)).

Figure 5-2: (a) A typical signal processing configuration in an MTI radar system. (b) Modified and efficient signal processing configuration with a microwave photonic filter prior to the down-conversion process [108].

A modified and more efficient signal processing method of the RF signal is illustrated in Fig. 5-3. The detected signal from the RF antenna is modulated onto an optical carrier, and is then directly processed in the optical domain by a microwave photonic filter based on fiber-optic or integrated-optic devices, which offer a number of unique advantages such as large bandwidth, low attenuation and immunity to EMI as described in Section 5.1. This more efficient photonic's method by using microwave photonic filters is to replace the traditional RF signal processing approach (see Fig. 5-4), where the RF signal from an antenna is directly fed to an RF processing circuit, which is usually at an intermediate frequency band after the down-conversion operation.

Figure 5-3: Schematic diagram of the signal processing configuration of the RF signal using a microwave photonic filter [108].

Figure 5-4: Schematic diagram of the traditional RF signal processing configuration [108].

Obviously, by adding more photonic components, the system complexity will increase, however, the photonic technologies using fiber delay lines or FBGs can provide many unique advantages [109]-[112]. Optical delay lines have very low attenuation, very large time-bandwidth products, are immune to EMI, lightweight, and can provide very short delays that can result in very high-speed sampling frequencies. And the use of FBGs can also provide tunability for the microwave photonic filters. Furthermore, photonic approaches provide the possibility of achieving parallel signal processing in the spatial and wavelength domains using WDM techniques.

However, it is important to reduce the complexity and hence cost of the microwave photonic filter by using, for example, a simple optical source as the optical carrier in the system (see Fig. 5-3). This chapter presents a novel two-tap tunable microwave photonic

notch filter using a simple dual-wavelength fiber laser which has been presented in Chapter 4. The tunable microwave photonic notch filter has a tunable FSR. In the proposed approach, RF signal processing is achieved without increasing the filter complexity (or adding additional photonic components) by using the dual-wavelength fiber laser source (see Chapter 4) as the optical carrier in the RF signal processing system. This filter configuration has many advantages such as simple structure, less number of optical components, multiple-tap response with one single optical source, tunable FSR, and low cost. The system configuration is described in Section 5.2. And the simulation and experimental results are presented in Section 5.3.

5.2 Configuration and Principle of Proposed Tunable

Microwave Photonic Notch Filter

5.2.1 Experimental Setup of the Proposed Tunable Microwave Photonic Notch Filter

The experimental setup of the proposed tunable microwave photonic notch filter based on a tunable dual-wavelength fiber laser (as presented in Chapter 4) is depicted in Fig. 5-5. In the tunable dual-wavelength fiber laser, pump light from a 980-nm laser diode is coupled into the laser cavity through a 980/1550 nm WDM coupler. The linear laser cavity consists of an 8-m long PM-EDF, a uniform FBG with a section for strain modulation and a LCFBG, both of which were fabricated on the Hi-Bi fiber (see Chapter 4 and Ref. [16]). The PM-EDF with a birefringence of 2.4×10^{-4} at 1550 nm and a

concentration of erbium ions of $3 \times 10^{24} \text{ m}^{-3}$ are spliced (instead of using connectors to reduce the cavity loss) to the PM-FBG and the PM-LCFBG. The Hi-Bi fiber, with a beat length of 4 mm at 1550 nm, was hydrogen loaded for two weeks to enhance its photosensitivity before fabrication of the PM-FBG and PM-LCFBG. The PM-FBG was fabricated with a uniform phase mask (with a grating pitch of $1.045 \text{ } \mu\text{m}$), and has two reflection peaks near 1545 nm. The 60-mm long PM-LCFBG was fabricated with a phase mask (with a chirp rate of 2.25 nm/cm), and has a stopband of about 18 nm in the transmission mode which is centred at 1546.5 nm (see Fig. 5-6).

Figure 5-5: Experimental setup of the proposed tunable microwave photonic notch filter.

The measured transmission spectra of the PM-LCFBG and PM-FBG are shown in Figures 5-6 (a) and (b), respectively. Instead of using a bulk dielectric mirror, the PM-LCFBG used here can be easily spliced with other fiber-optic components, thus making the laser cavity an all-fiber structure. As the linear laser cavity is formed by the PM-FBG

and the PM-LCFBG, the lasing wavelengths are defined by the reflection peaks of the PM-FBG. The wavelength separation of the PM-FBG's two reflection peaks is determined by the birefringence of the Hi-Bi fiber used as described in Chapter 4.

Figure 5-6: Monitored transmission spectrum of (a) the PM-LCFBG, (b) the PM-FBG used in the tunable dual-wavelength fiber laser.

It is worth noting that, except for the WDM coupler, the whole laser cavity is all PM. The

polarization state of the light within the laser cavity is thus maintained, resulting in a stable lasing operation from the laser's output port under room temperature conditions. The two output lasing wavelengths from the dual-wavelength fiber laser are then amplified by an EDFA, and the amplified laser light goes into a 10/90 fiber coupler which is monitored by an OSA.

The proposed tunable microwave photonic notch filter is implemented by modulating the amplified light from the tunable dual-wavelength fiber laser (as described in Chapter 4) using a 10 GHz phase modulator (see Fig. 5-5). The photonic microwave bandpass filter proposed here is realized by eliminating the baseband resonance using the 10 GHz phase modulator. The phase modulated light then goes through a 50 km segment of SMF as a dispersive device to eliminate the baseband resonance of the notch filter as well as to introduce a time delay to the optical signal. The output from the SMF is then fed into a 12 GHz photodetector (PD) (New Focus 1544B), which is followed by a vector network analyzer (Anritsu 37369C). The phase modulator is driven by the microwave signal to be processed by the photonic filter. As the tunable dual-wavelength fiber laser source, which can generate two lasing wavelengths with tunable wavelength separation, is used as the optical source, a two-tap transversal microwave photonic notch filter with tunable FSR can be achieved. Note that the two lasing wavelengths from the tunable dual-wavelength fiber laser are uncorrelated with each other, thus the proposed tunable microwave photonic notch filter is free from coherent interference or is operating in the incoherent region.

5.2.2 Principle of the Proposed Tunable Microwave Photonic Notch Filter

The input optical field ($\tilde{E}_i(\omega_m)$) and the output optical field ($\tilde{E}_o(\omega_m)$), as shown in Fig. 5-3, are linearly related to each other by

$$\tilde{E}_o(\omega_m) = \tilde{E}_i(\omega_m) H_o(\omega_m) \quad (5.1)$$

where $H_o(\omega_m)$ is the transfer function of the microwave photonic filter depicted in Fig. 5-5, which can be shown to be given by

$$H_o(\omega_m) \propto \sin\left(\frac{\pi D(\lambda_1 + \lambda_2)^2 f_m^2 L}{4c}\right) \cos(\Delta\tau\omega_m / 2) \quad (5.2)$$

In Eq. (5.2), f_m ($f_m = \frac{\omega_m}{2\pi}$) denotes the modulating frequency of the microwave signal,

D and L represent the chromatic dispersion parameter ($D = 17$ ps/nm/km here) and the length of the SMF ($L = 50$ km here), $\Delta\tau$ is the time delay due to the 50 km SMF, λ_1 and λ_2 are the two lasing wavelengths ($\lambda_2 > \lambda_1$) of the dual-wavelength fiber laser, and c is the speed of light in vacuum. The time delay (or sampling period) $\Delta\tau$ of the microwave photonic notch filter can be expressed as

$$\Delta\tau = DL\Delta\lambda \quad (5.3)$$

where $\Delta\lambda = \lambda_2 - \lambda_1$ is the wavelength separation between the dual-wavelength fiber laser's two output lasing wavelengths. The corresponding FSR of the microwave photonic notch filter is given by

$$FSR = 1 / \Delta\tau \quad (5.4)$$

Using Eqs. (5.2) and (5.3), the simulation results of the microwave photonic notch filter's

amplitude response using two different values of $\Delta\lambda$ ($\Delta\lambda = \lambda_2 - \lambda_1 = 1553.909 \text{ nm} - 1553.78 \text{ nm} = 0.129 \text{ nm}$ and $\Delta\lambda = \lambda_2 - \lambda_1 = 1544.76 \text{ nm} - 1544.54 \text{ nm} = 0.22 \text{ nm}$) are shown in Figures 5-7 (a) and (b), respectively. From Figures 5-7 (a) and (b), it can be seen that, by applying some axial strain to the PM-FBG within the dual-wavelength fiber laser (see Fig. 5-5) to tune the wavelength separation $\Delta\lambda$ of the two lasing wavelengths, the FSR of the proposed tunable microwave photonic notch filter can be tuned. According to Eqs. (5.3) and (5.4), the smaller the wavelength separation $\Delta\lambda$, the larger the FSR of the microwave photonic notch filter will be. When the wavelength separation is $\Delta\lambda = 0.129 \text{ nm}$, the calculated microwave photonic notch filter's FSR is 9.2 GHz (see Fig. 5-7 (a)); and when the wavelength separation is tuned up to $\Delta\lambda = 0.22 \text{ nm}$, the calculated FSR is 4.72 GHz (see Fig. 5-7 (b)). When no axial strain was applied to the PM-FBG (i.e. $\Delta\lambda = 0.36 \text{ nm}$), the calculated frequency response with an FSR of 3.22 GHz is shown in Fig. 5-8. Thus, by tuning the wavelength separation of the dual-wavelength fiber laser's two lasing lines, a two-tap microwave photonic notch filter with tunable FSR can be achieved as shown in Figures 5-7 and 5-8. The experimental results of the tunable microwave photonic notch filter are presented in Section 5.3.2.

Figure 5-7: Simulated amplitude response of the microwave photonic notch filter for two different wavelength separations $\Delta\lambda$. (a) $\Delta\lambda = \lambda_2 - \lambda_1 = 1553.909 \text{ nm} - 1553.78 \text{ nm} = 0.129 \text{ nm}$ and the filter's FSR is 9.2 GHz; (b) $\Delta\lambda = \lambda_2 - \lambda_1 = 1544.76 \text{ nm} - 1544.54 \text{ nm} = 0.22 \text{ nm}$ and the filter's FSR is 4.72 GHz.

Figure 5-8: Simulated amplitude response of the microwave photonic notch filter when dual-wavelength fiber laser's wavelength separation is $\Delta\lambda = 0.36$ nm and the filter's FSR is 3.22 GHz.

It is worth noting that, in the proposed microwave photonic notch filter, a phase modulator instead of an intensity modulator was used. When implementing the microwave photonic notch filter using an intensity modulator, the modulated signal at the output will have two sidebands in phase. However, when using a phase modulator to implement a microwave photonic notch filter, the output signal will have two sidebands that are π out of phase. If the phase modulated signal is directly detected using a photodetector, the microwave signal cannot be recovered since the beating of the carrier and the two out-of-phase sidebands would cancel out with each other. Thus, a certain length of the SMF was placed after the modulator to serve as a dispersive device so as to effectively rotate the two sidebands of the phase modulated signal to make them in phase by using the dispersion of the SMF. Then the phase modulated signal may be recovered when this dispersive optical signal is fed to a photodetector.

5.3 Microwave Photonic Notch Filter Based on the Dual-Wavelength Fiber Laser

5.3.1 Dual-Wavelength Fiber Laser with Tunable Wavelength Separation

The monitored output spectra of the tunable dual-wavelength fiber laser source are shown in Fig. 5-9. Two lasing wavelengths with a wavelength separation of $\Delta\lambda \sim 0.36$ nm are shown in Fig. 5-9 (a), when no strain was applied to the PM-FBG in the laser cavity. The OSNR of these two lasing lines are more than 45 dB. When some axial strain was applied to the PM-FBG within the laser cavity, Fig. 5-9 (b) shows that dual-wavelength lasing operation with a reduced wavelength separation of $\Delta\lambda = 0.22$ nm was obtained as described in Chapter 4. By further stretching the PM-FBG, the wavelength separation of the dual-wavelength fiber laser can be tuned down to $\Delta\lambda = 0.129$ nm (see Fig. 5-10) and even as small as $\Delta\lambda = 0.05$ nm (see Chapter 4). For all the lasing wavelengths shown in Figures 5-9 and 5-10, the OSNRs are very large (i.e. > 40 dB), and the laser linewidths are ~ 2.5 kHz as described in Chapter 4.

Figure 5-9: Output spectra of the dual-wavelength fiber laser monitored by the OSA. (a) Without stretching the PM-FBG and $\Delta\lambda = 0.36$ nm. (b) The wavelength separation was reduced to $\Delta\lambda = 0.22$ nm when some axial strain was applied to the PM-FBG.

Figure 5-10: Measured output spectrum of the dual-wavelength fiber laser when the PM-FBG was further stretched to reduce the wavelength separation to $\Delta\lambda = 0.129$ nm.

Due to the homogeneous broadening of the EDF, it is normally difficult to achieve a stable dual-wavelength lasing operation with wavelength separation smaller than 0.5 nm under room temperature conditions [29]. However, in the design described here, due to the enhanced PHB and SHB in the saturated PM-EDF, stable room-temperature dual-wavelength operation with a small wavelength separation was achieved. The dual-wavelength lasing operation was observed to be very stable over one-hour duration. The repeated scan of the laser output is shown in Fig. 5-11 over half an hour at 60 second intervals.

Figure 5-11: Repeated scan of the dual-wavelength fiber laser's output spectrum for half an hour when the wavelength separation is 0.129 nm.

5.3.2 Tunable Microwave Photonic Notch Filter

The measured amplitude responses of the tunable microwave photonic notch filter with different FSRs are shown in Figures 5-12 (a)-(c) when the dual-wavelength fiber laser's wavelength separation was adjusted by stretching the PM-FBG as described in Section 5.3.1. From the simulation results (see Fig. 5-7 and Fig. 5-8) described in Section 5.2.2, it can be seen that the corresponding experimental results agree well with the simulation results. That is, compare Fig. 5-7 (a) with Fig. 5-12 (a), Fig. 5-7 (b) with Fig. 5-12 (b), and Fig. 5-8 with Fig. 5-12 (c), where the simulation and experimental results are similar. The notch rejection ratios of the microwave filter with three different FSRs are all greater than 35 dB (see Figures 5-12 (a)-(c)). The wavelength separations between the two lasing lines are 0.129 nm, 0.22 nm and 0.36 nm as shown in Figures 5-9 (a), (b) and Fig. 5-10, respectively, and the corresponding measured filter responses with three different FSRs

of 9.46 GHz, 4.952 GHz, and 3.175 GHz, when different amount of strain was applied to the PM-FBG, are shown in Figures 5-12 (a)-(c), respectively. To the author’s knowledge, this is the first proposal of a dual-wavelength fiber laser with tunable wavelength spacing that is used to implement a tunable microwave photonic notch filter.

Figure 5-12: Measured filter responses of the tunable microwave photonic notch filter with a vector network analyzer for different wavelength separation $\Delta\lambda$ of the two output lasing wavelengths from the dual-wavelength fiber laser. (a) $\Delta\lambda = 0.129$ nm. (b) $\Delta\lambda = 0.22$ nm. (c) $\Delta\lambda = 0.36$ nm. (The low frequency part of Fig. 5-12 (c) is not very clear due to the weak response of the 12 GHz photodetector from 0-2 GHz.)

The simulation results and the experimental data of the tunable microwave photonic notch filter's time interval $\Delta\tau$ (according to Eq. (5.3)), the applied strain to the PM-FBG ε (see Chapter 4), and the dual-wavelength fiber laser's wavelength separation $\Delta\lambda$ are shown in Fig. 5-13. The experimental results shown in Fig. 5-13 (where $\square$ represents the measured notch filter's time interval $\Delta\tau$ (or $1/\text{FSR}$) and Δ represents the axial strain applied to the PM-FBG) clearly show that they agree well with the simulation results (solid lines in Fig. 5-13). When the strain applied to the PM-FBG increases, the birefringence of the PM-FBG will decrease, and this results in a reduction of the wavelength separation of the dual-wavelength fiber laser [98]. According to Eqs. 5.3 and 5.4, the smaller the wavelength separation $\Delta\lambda$, the smaller the microwave notch filter's time interval $\Delta\tau$ will be, and this, in turn, results in a larger FSR of the filter. Thus, a

tunable two-tap microwave photonic notch filter with tunable FSR can be achieved by adjusting the wavelength separation of the tunable dual-wavelength fiber laser.

Figure 5-13: Simulation results (solid line) of the relationships among the notch filter's time interval $\Delta\tau$, applied axial strain ϵ to the PM-FBG within the laser cavity and the wavelength separation $\Delta\lambda$ of the dual-wavelength fiber laser. Measured experimental results of $\Delta\tau$ and ϵ are shown in $\square$ and Δ , respectively.

Taking advantage of the tunable dual-wavelength fiber laser described in Chapter 4, the proposed microwave photonic notch filter has several unique features such as simple structure with very few optical components in the filter part compared with [104], [105], the use of only a single and yet tunable dual-wavelength fiber laser source instead of a number of DFB lasers [104], and the filter's FSR can be easily tuned through tuning the wavelength separation of the dual-wavelength fiber laser.

5.4 Microwave Photonic Bandpass Filter Using a Multiwavelength Ring Laser

An all-optical microwave photonic bandpass filter is proposed and demonstrated using a multiwavelength semiconductor optical amplifier (SOA) based ring laser, an optical phase modulator, and a segment of single-mode fiber (SMF). Experimental results show a multiple-tap bandpass microwave filter by using the multiwavelength SOA ring laser with equalized output power as the optical source. Two laser configurations, one with a linearly chirped fiber Bragg grating (LCFBG) to compensate for the dispersion of the laser cavity and one without the LCFBG, are used to compare their multiwavelength laser outputs and the corresponding microwave filters' responses. The maximal main to secondary sidelobe ratio (MSSR) of the microwave filter is over 10 dB.

5.4.1 System Configuration and Operating Principle

The experimental configuration of the proposed microwave photonic bandpass filter is shown in Fig. 5-14 (a), which basically consists of two parts, namely, the multiwavelength SOA ring laser (the left side of the figure), and a microwave bandpass filter. The multiwavelength ring-cavity laser consists of a SOA (Kamelian OPA), two polarization-independent fiber isolators, one polarization controller (PC), one 10:90 fiber coupler, and a 3-port circulator with a sampled linearly chirped fiber Bragg grating (SLCFBG) connected to one of the circulator's ports. The two isolators within the laser cavity ensure the unidirectional operation of the ring laser, and the PC is used to optimize the state of polarization (SOP) of the light within the ring laser as the SOA is polarization dependent. The SLCFBG combined with the 3-port circulator serves as the wavelength-selective component in the ring laser. The SLCFBG was designed to generate a high channel-count comb in the C-band and its transmission spectrum is shown in Fig. 5-14

(b). And the measured wavelength spacing of the SLCFBG is about 100 GHz. The SLCFBG with high channel-count comb is achieved by choosing a chirp phase mask with an appropriate values as well as an amplitude mask in the grating fabrication process [113]. To obtain lasing wavelengths with equalized peak power level from the ring laser, a LCFBG, whose transmission spectrum is shown in Fig. 5-14 (c), is connected with the SLCFBG to serve as a bandpass filter to limit the wavelength range of the SLCFBG and, more importantly, to compensate for the dispersion induced by the SLCFBG so as to reduce the power differences of the output lasing wavelengths. The output lasing wavelengths from the SOA ring laser are then amplified by an in-line EDFA (Optolink-MP) to compensate for the loss of the dispersive SMF in the microwave filter. An RF signal (with modulating frequency of 500 MHz to 10 GHz) drives a phase modulator (Avanex), which is used to modulate the amplified lasing wavelengths of the multiwavelength SOA ring laser after having passed through the inline EDFA and a PC. The phase modulated optical signal is launched into a 60 km or 40 km SMF, which is then fed into a photodetector (PD) and followed by a network analyzer (Anritsu). The working principle of the multiple-tap microwave photonic filter described here is quite similar to that of the two-tap microwave photonic notch filter as described in Section 5.2. The amplified optical signal is modulated by the phase modulator, and delayed by a segment of SMF before it is being monitored by a network analyzer. Taking advantages of the multiwavelength SOA ring laser's simultaneous multiwavelength lasing operation, the number of optical components required within the microwave photonic filter part is reduced.

Figure 5-14: (a) Experimental configuration of the microwave photonic bandpass filter based on the multiwavelength SOA ring laser (60 km SMF). (b) Measured reflection spectrum of the SLCFBG. (c) Measured transmission spectrum of the LCFBG. PC: polarization controller; SOA: semiconductor optical amplifier; PD: photodetector; SMF: single-mode fiber.

5.4.2 Experimental Results and Discussion

The photosensitive fiber was hydrogen loaded at 80 °C for more than two weeks to increase its photosensitivity before grating fabrication. The SLCFBG was UV written using a 5 cm long chirped phase mask (with a chirp rate of 4.8 nm/cm) together with an amplitude mask. When the reflective LCFBG (which serves as a bandpass filter) was not connected to the SLCFBG (see Fig. 5-14 (a)), seven lasing wavelengths between 1557 nm and 1563 nm with wavelength spacings of about 0.8 nm were generated from the output port of the ring laser as shown in Fig. 5-15 (a). By adjusting the PC to change the polarization state of the light within the ring laser, four lasing lines ranging from 1560 nm to 1563 nm with ~ 0.8 nm wavelength spacing, an OSNR greater than 40 dB, and small peak power difference are obtained as shown in Fig. 5-15 (a). The output lasing

wavelengths of the SOA ring laser are very stable at room temperature over a 30-minute repeated scan.

Figure 5-15: (a) Measured output spectrum from the multiwavelength SOA ring laser when the LCFBG was not connected in the laser cavity. (b) Measured bandpass filters' response with 40 km SMF as the dispersion component.

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As each of the lasing wavelengths is used to implement only one tap of the microwave photonic filter, there is no correlation among the different taps, so there is no limitation on the minimum time delay or maximum FSR. By feeding these lasing wavelengths to the phase modulator and a 40-km SMF as a dispersive device (see Fig. 5-4 (a)), a four-tap bandpass filter is then obtained, as shown in Fig. 5-15 (b) as the multiwavelength ring laser generates four lasing wavelengths within the 3 dB spectrum bandwidth. The FSR of the four-tap microwave bandpass filter is about 1.85 GHz.

In order to generate more lasing wavelengths from the multiwavelength ring laser (within the 3 dB spectral bandwidth) and hence achieve a microwave photonic filter with more taps (and hence narrower bandwidth), a reflective LCFBG was spliced to the SLCFBG as a bandwidth-limiting filter to limit the wavelength range of the SLCFBG's comb-like spectrum and, more importantly, to compensate for the dispersion in the SLCFBG in order to flatten the output power levels of the multiwavelength ring laser's output lasing lines. The 6-cm long LCFBG was fabricated with the phase mask method, and has a ~ 25 dB deep stopband from 1546 nm to 1564 nm (see Fig. 5-14 (c)). The chirp phase mask has a chirp rate of 2.25 nm/cm and a grating pitch of 1067 nm. As shown in Fig. 5-16 (a), with the reflective LCFBG, a larger number of lasing wavelengths with more uniform peak power levels were generated from the multiwavelength SOA ring laser. Seven lasing wavelengths within the 3 dB spectral bandwidth and channel spacings of ~ 0.8 nm are obtained between 1549 nm and 1559 nm at room temperature. The OSNRs of the seven lasing lines are all above 40 dB. By appropriately adjusting the PC within the laser cavity, a maximum number of eight lasing wavelengths within the 3 dB spectral bandwidth between 1549 nm and 1558 nm were achieved at room temperature as shown in Fig. 5-16

(a). The power flatness of the eight lasing lines is within 1 dB. The linewidths of all the lasing lines, which are determined by the 3 dB bandwidths of the SLCFBG's passbands, were measured to be ~ 5 GHz, which is large enough to enable the microwave filter to operate in the incoherent regime. Since each of the lasing wavelengths is used to implement only one tap of the microwave photonic filter, an eight-tap microwave bandpass filter (here the length of the SMF is 60 km) was developed and the measured filter's response by the network analyzer is shown in Fig. 5-16 (b). The FSR of the eight-tap microwave photonics filter is about 1.26 GHz. Comparing the results of the two SOA-based ring laser configurations (with the LCFBG and without the LCFBG), we observe that the number of lasing lines from the SOA ring laser with the LCFBG is much larger than that of the SOA ring laser without the LCFBG. The reason is that the LCFBG compensates for the dispersion of the SOA ring laser considerably, which will improve the output performance of the multiwavelength SOA ring laser, and this will hence improve the performance of the multiple-tap microwave filter. This is because the performance of the microwave filter such as the number of taps, phase noise, and side-mode rejection ratio is mainly affected by the output of the multiwavelength SOA-based source.

Figure 5-16: (a) Measured output spectrum from the multiwavelength SOA ring laser when the LCFBG was connected to the SLCFBG. (b) Measured bandpass filter's response with 60 km SMF as the dispersive component.

Two multiple-tap microwave photonic filters based on a multiwavelength SOA ring laser, a phase modulator and a segment of SMF have been presented. By adjusting the setting of the PC within the multiwavelength SOA ring laser, multiwavelength operation with four and eight lasing wavelengths was obtained, which were used for the implementation

of four-tap and eight-tap microwave photonic bandpass filters with FSRs of ~ 1.85 GHz and ~ 1.26 GHz, respectively.

5.5 Summary

In this chapter, two multiple-tap microwave photonic filters using multiwavelength laser sources have been presented. Stable room-temperature dual-wavelength and multiwavelength lasing operations have been achieved using the dual-wavelength fiber laser and the multiwavelength SOA-based ring laser, respectively. Based on the linear-cavity dual-wavelength fiber laser, a two-tap microwave photonic notch filter with tunable FSR was implemented. The light from the dual-wavelength fiber laser and from the multiwavelength SOA-based ring laser goes into a phase modulator (followed by a dispersive device) to form a microwave photonic notch filter. The FSR of the two-tap microwave photonic notch filter can be tuned from 3.175 GHz to 9.46 GHz by changing the wavelength separation between the dual-wavelength fiber laser's two lasing wavelengths. The rejection ratio of the notch is greater than 35 dB. Also a multiple-tap photonic bandpass filter was demonstrated using a multiwavelength SOA ring laser. Four-tap and eight-tap microwave photonic bandpass filters with FSRs of ~ 1.85 GHz and ~ 1.26 GHz were achieved.

The proposed microwave photonic filters have several unique advantages compared with other approaches. First, the filters have a simple structure with less optical components required. Second, the filters do not require two or more tunable DFB lasers [104], [105], [114], which increase the complexity and cost of the filters. Moreover, another advantage

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of the proposed tunable microwave photonic notch filter is that the wavelength separation of the dual-wavelength fiber laser can be easily tuned by stretching the PM-FBG; allowing the implementation of a tunable microwave photonic notch filter.

6

Tunable Comb Filter and Tunable Multiwavelength Optical Source

This chapter presents the design and fabrication of a switchable and tunable comb filter based on a thermally-induced linearly chirped fiber Bragg grating (LCFBG). The proposed technique involves writing a LCFBG with a depth of over 30 dB in the stopband from 1537 nm to 1554 nm. By using a heated resistance wire in contact with a particular point on the LCFBG, perturbation to the fiber's refractive index was introduced at that point. When the LCFBG was heated, a transmission spectral peak appeared within the stopband of the LCFBG operating in the transmission mode, and the location of the spectral peak was determined by the position of the heating point on the LCFBG. Through the application of multiple controllable resistance wires to heat the LCFBG at different points, a tunable and switchable comb filter was achieved. To demonstrate the effectiveness of this comb filter, multiple transmission peaks with different wavelength spacings were obtained.

This chapter is organized as follows. Section 6.1 gives a literature review on various kinds of tunable optical bandpass filters (TOBFs) and comb filters. The proposed tunable comb filter is presented in detail in Section 6.2. Section 6.3 presents the tunable

multiwavelength optical source based on the proposed tunable comb filter. A summary of this chapter is given in Section 6.4. Part of the work presented here has already been published in Ref. [18].

6.1 Introduction

With the advanced developments of WDM technology in recent years, there is a strong increasing demand for the large bandwidth for the transmission of exponentially increasing internet traffic. The next generation of reconfigurable optical networks that are capable of dynamically selecting and manipulating WDM channels is thus of great interest. In particular, there is considerable interest in the development of multiwavelength optical sources for the next generation of optical networks, see for example, references [71], [115]-[119]. Several multiwavelength erbium-doped fiber lasers have been reported using various types of optical filters, such as a sampled chirped fiber Bragg grating (SCFBG) [115], a Mach-Zehnder interferometer [116], a Fabry-Perot filter with an acousto-optic frequency shifter [117], a Sagnac loop filter [71], a segment of polarization-maintaining (PM) fiber based on the concept of polarization mode coupling [118], and superimposed chirped fiber Bragg gratings [119]. However, these optical filters cannot meet all the requirements of a multiwavelength fiber laser source, which include tunable center wavelengths, tunable wavelength spacings, switchable wavelength channels, and narrow bandwidths of the spectral peaks.

6.1.1 Tunable Optical Bandpass Filters Based on Fiber Bragg Gratings

One possible solution to meet some of the requirements of a multiwavelength fiber laser as mentioned above is to utilize one or more flexible wavelength-selection components such as tunable optical bandpass filters (TOBFs). FBG is one of the most promising components used for the development of optical filters due to its inherent advantages such as all-fiber geometry, low polarization sensitivity, low insertion loss, flexibility in tuning of the reflective Bragg wavelength, small size and low cost. In reference [28], a Fabry-Perot filter combined with a bandwidth-limiting filter was used for the generation multiple spectral peaks, however, the wavelength channels can neither be tuned nor switched. Moreover, using an additional optical filter will introduce more insertion loss and increase the complexity and cost [28]. A sampled chirp fiber Bragg grating (SCFBG) together with a 3-dB fiber coupler working in the reflection mode has only a limited number of wavelength channels from the laser [115]. Wavelength tuning is achieved by tuning the strain gradient of the SCFBG, which is surface-mounted at a slant onto one lateral side of a plate so that each spectral peak of the SCFBG will experience an equal strain increment when an external force is applied to the plate. However, an FBG operating in the transmission mode is a band-rejection filter, and it thus needs to be combined with an expensive optical circulator or fiber coupler which introduces insertion loss to operate in the reflection mode. Thus, an optical comb filter with flexibility for adjusting the wavelength channels is desirable for the development of the next generation of multiwavelength optical sources.

Figure 6-1: The experimental setup of the tunable multiwavelength fiber ring laser [115].

6.1.2 Optical comb filters

Another filtering method used in the development of multiwavelength fiber laser sources is to use an optical comb filter (or multiwavelength filter) as a wavelength-selection component within the laser cavity. Three main kinds of optical comb filters have been reported in the literature as described below.

(1) Sagnac loop filter and Mach-Zehnder filter

The Sagnac loop filter normally consists of a four-port 3-dB fiber coupler, a polarization controller (PC), which is set to generate a 90° rotation of the two lights traveling in two opposite directions within the fiber loop, and a segment of PM fiber (which is also known as a high-birefringence fiber) with length L and birefringence B , see Fig. 6-2 (a). As the two counter-propagating lights on different polarization axes experience different optical

path lengths due to the setting of the PC, wavelength-dependent spectrum is obtained at the output port of the 3-dB coupler. According to the theory of the Sagnac loop filter as described in Chapter 3 (assuming the optical power of the light within the fiber loop is below 30 dBm, that is, the filter is operating in the linear region), the FSR the Sagnac loop filter's transmission spectrum is $\Delta\lambda = \lambda^2 / (BL)$, where λ is the filter's operating wavelength. The operating bandwidth of the Sagnac loop filter is determined by the 3-dB optical coupler's bandwidth. By using a wideband 3-dB coupler, an operating bandwidth of over 100 nm can be easily achieved with good periodicity.

From Fig. 6-2 (b), the Mach-Zehnder filter is formed by connecting two four-port 3-dB fiber couplers to form two different optical paths (i.e. $L_1 \neq L_2$ and $L_2 > L_1$), and this results in the filter's transmission spectrum being wavelength dependent. And the FSR of the filter's transmission spectrum is given as $\Delta\lambda = \lambda^2 / (n\Delta L)$, where λ is the operating wavelength, n is the effective refractive index of the fiber, and $\Delta L = L_2 - L_1$ is the difference of the two optical paths. Also the filter's operating bandwidth is mostly determined by the bandwidths of the two 3-dB fiber couplers. Due to the two different optical paths, the stability of the Mach-Zehnder filter is not as good as that of the Sagnac loop filter in which two optical signals travel through the same optical path.

Figure 6-2: Schematic diagrams of the optical comb filters. (a) Sagnac loop filter [120], where CW and CCW stand for clockwise and counter clockwise, respectively. (b) Mach-Zehnder filter [116].

These two kinds of optical comb filters with similar working principle have the merits of periodic spectrum with a wide operating bandwidth, polarization independence, tunability of center wavelength and large extinction ratio (> 25 dB). Furthermore, the filter's wavelength spacing (or FSR) can be changed by using PM fiber with different length for the fiber Sagnac loop filter and by changing the optical length difference for the Mach-Zehnder filter. However, the bandwidth of each spectral peak of these filters is very large, which is about half of the FSR (i.e. $\Delta\lambda / 2$). This is because the bandwidth and FSR of these two filters' output spectra are all determined by the product of the birefringence and

PM fiber's length for the Sagnac filter and by the optical path difference for the Mach-Zehnder filter. However, it is difficult to make the spectral peaks of these comb filters switchable.

(2) Acousto-optic tunable filter

Acousto-optic frequency shifters (AOFSSs) can also be used to form an optical comb filter by connecting two AOFSSs with a segment of two-mode fiber (TMF) [121]. As shown in Fig. 6-3(a), two AOFSSs are separated by a TMF with length L . Due to the fiber's different refractive indices of the two modes, LP_{01} and LP_{11} within the TMF, a periodic wavelength-dependent transmission spectrum can be obtained.

Figure 6-3: (a) Schematic diagram of the optical comb filter [121]. (b) All-fiber comb filter with tunable comb-spacing. (TMF: two-mode fiber; FS: frequency shifter; MS: mode stripper; MC: mode converter)

When the coupling efficiencies of the two AOFSSs are set to 50%, the filter operates just like a Mach-Zehnder interferometer. Tunable wavelength spacing (comb spacing) can be achieved by placing two mode converters (MCs) at two particular positions of the TMF to flexibly control the optical path length difference ($L_1 + L_3 - L_2$), as shown in Fig. 6-

3(b). And the center wavelength of the comb filter can be tuned by changing the frequency of the RF signal that drives the AOFS. The rejection ratios of the transmission peaks are more than 24 dB. However, the operating bandwidth of this kind of comb filter is as small as ~ 35 nm, and the bandwidth of each transmission peak is as large as ~ 0.3 nm.

(3) Long period grating pairs

A pair of LPGs (which is also known as cascaded LPGs) can also be used to generate comb-like transmission spectrum. As shown in Fig. 6-4, two LPGs are inscribed on two different locations of the fiber core that are separated by a distance of D . The first LPG couples part of the core mode of the incoming optical signal to the cladding, then the two modes (core and cladding modes) will interfere at the second LPG, and spectral fringe patterns are generated. Thus, by exploiting the optical path difference between the core mode and the cladding mode, a periodic transmission spectrum can be obtained. The advantages of this kind of optical comb filter are all-fiber structure, low insertion loss, simple structure, and tunable wavelength spacing by controlling the separation D between the two LPGs, grating length, and refractive index of the fiber cladding between the two LPGs. However, LPGs are very sensitive to the environmental temperature change, which makes this kind of comb filter unstable. Also the bandwidth of each generated spectral peak is relatively large (typically > 0.4 nm). Besides, it is difficult to make this type of optical comb filter switchable, and spectral peaks' center wavelengths tunable, and the filter also has a limited operating bandwidth.

Figure 6-4: Schematic diagram of the optical comb filter based on a pair of LPGs [31].

Other comb filter techniques including Fabry-Perot filter [28], PM fiber combining with a polarizer [118], and delayed interferometer [33] are also capable of generating multiple transmission peaks simultaneously. But these techniques do not provide the flexibility for manipulating the wavelength spacing (or FSR) and the center wavelengths of the generated wavelength channels, thus, these kinds of filters can only have multiwavelength lasing operation with fixed wavelength spacing and fixed center wavelength. The performance comparisons of various optical comb filters are shown in Table 6.1. Thus, a more flexible and versatile comb filter is needed to for the design of a tunable multiwavelength laser source.

Table 6.1: Performance comparisons of various optical comb filters.

Type of comb filters	Operating bandwidth (nm)	Bandwidth of spectral peak (nm)	Rejection ratio (dB)	Insertion loss (dB)	FSR
Sagnac loop filter	> 100	> 0.2	> 30	~ 3.5	tunable
Mach-Zehnder filter	> 80	> 0.4	> 25	6-7	tunable
Acousto-optic filter	35-40	> 0.3	~ 24	2-3	tunable
Cascaded LPG pairs	25-30	> 0.1	~ 13	1-2	difficult to tune
Fabry-Perot filter	> 150	> 0.25	15-20	< 1	fixed

6.2 Thermally Switchable and Tunable Comb Filter

This section presents the issues involved in the design and development of a switchable and tunable comb filter based on a LCFBG. The issues include the thermally-induced temporary phase shift, the grating used in the filter design, the heat-insulated stage, and means to induce multiple temporary phase shifts and the heat sinks used to reduce the heat conduction.

6.2.1 Temporary Phase Shift in Fiber Gratings

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A temporary phase shift can be introduced into an FBG by various means such as heating [122], applying tension [123], and applying pressure [124]. The temporary phase shift created can be removed from the FBG when the external disturbance is removed. The principle of temporary phase shift is presented in this section.

Due to the elastic-optical effect, the refractive index of the fiber changes with the applied external strain. Hence, the external strain applied to a small section of the fiber by means of stretching introduces a phase shift at that point. Using this technique, Xu have demonstrated a TOBF based on a phase-shifted FBG, in which a piezoelectric stack was used to change the local strain in order to introduce a temporary phase shift at different points along the LCFBG, which in turn results a tunable transmission peak within the grating's stopband [123]. But their filter cannot be continuously tuned in wavelength, and the control mechanism is complicated and expensive. Moreover, the rejection ratio of their filter is only 10.6 dB. These disadvantages make it unsuitable for use in multiwavelength optical laser sources.

Similarly, heating a small region of the FBG will introduce perturbation to the spectrum of the grating since the refractive index of the fiber changes with temperature [125]. The fiber's refractive index in this small heated region will be perturbed when the fiber is heated at this point due to the thermo-optical effect. When heating the fiber at a certain point, the change in the fiber's length can be neglected compared with the thermally-induced phase shift because the thermal expansion coefficient is much smaller than the thermal-optical coefficient of the fiber [126]. Due to the thermo-optical effect, the

refractive index of the fiber will change when a phase shift is introduced at this heating point. The thermally introduced phase shift, ϕ , is given as [124]

$$\phi = \frac{2\pi L}{\lambda} \beta \Delta T \quad (6-1)$$

where L is the length of the heated region, ΔT is the temperature change, λ is the operating wavelength, and β is the thermo-optical coefficient ($\sim 8.6 \times 10^{-6} \text{ K}^{-1}$ for silica fiber). Theoretically, a 100% transmission peak within the stopband of the fiber grating operating in the transmission mode can be obtained with a $\phi = \pi$ phase shift. For a LCFBG, the Bragg wavelength will shift linearly with the heating position along the LCFBG [35]. The simulation results of the heated LCFBG are shown in Fig. 6-5. It can be seen that the center wavelengths of the transmission peaks are determined by the positions of the heating points, where the phase shifts are introduced. By simultaneously heating the LCFBG at different points, multiple transmission peaks will be created within the stopband of the LCFBG (see Fig. 6-5(b)). Furthermore, if the thermally-induced perturbations to the LCFBG can be independently controlled, a switchable and tunable comb filter will be developed.

Figure 6-5: Simulation results of (a) reflection spectrum and (b) transmission spectrum of a 6-cm long LCFBG with a π phase shift at five different points of the LCFBG. This figure is obtained from reference [125].

To introduce a thermally-induced temporary phase shift on a LCFBG, it is important to control the heating temperature because a high temperature of over 600 K can create a permanent phase shift in the grating which is not a reversible process as reported in reference [122]. To investigate the effects of temporary phase shift and permanent phase shift on the grating performance, a 28-mm long FBG was put inside a tightly fitted loop of NiCr wire with a diameter of 250 μm , which was used as the heating element. The grating was then thermally bonded to a Peltier-effect heat pump, which was used to keep the unprocessed region of the fiber grating at a constant temperature. For a temperature of less than 570 K, no permanent changes in the FBG's reflection spectrum were observed, even after hours of continuous heat treatment. But, for temperature > 600 K, permanent changes were observed in the grating spectrum, and for temperature approaching 1000 K, the change in the spectrum was rapid and saturated within minutes. In summary, to achieve a reversible or non-permanent temporary phase shift to the FBG, the applied

temperature change must be less than 570 K.

6.2.2 Linearly Chirped Fiber Bragg Grating

As described above, a bandpass filter can be achieved by introducing a phase shift into the uniform FBG when the FBG operates in the transmission mode. However, this method creates some unwanted transmission outside the stopband of the FBG. In WDM communication systems, the unwanted transmission may introduce significant crosstalk between the operating wavelength channels. And in laser applications, the unwanted side modes might not be easily eliminated from the laser output. Based on this consideration, a grating filter with a high rejection bandwidth and a large stopband is highly preferred. Among all the different types of fiber gratings, the LCFBG (as described in Chapter 2) has a large stopband in the transmission mode, which can be as large as 100 nm by using a phase mask with longer length and larger chirp rate in the grating fabrication.

More importantly is that the local Bragg wavelength of the LCFBG in the transmission mode monotonically relates to the position of the grating. Exploiting this advantageous feature of LCFBG, tuning of the generated transmission peak's center wavelength can be achieved by changing the heated position of the grating at which the temporary phase shift is created. Thus, tunable multiple transmission peaks can be easily obtained by adjusting the individual heating positions on the LCFBG. Moreover, a LCFBG with a local Bragg wavelength linearly related to the grating position is desirable for the development of flexible wavelength-selection components with simple tuning mechanism. The local Bragg wavelength relates to the position of a LCFBG is given as [127]

$$\lambda_B(z) = 2n_{eff}\Lambda(z) = 2n_{eff}(\Lambda_o + \Lambda_1 z) \quad (6-2)$$

where $\Lambda(z)$ is the local period of the grating as a function of the grating position z , n_{eff} is the effective refractive index of the fiber, Λ_o is the grating period at the beginning of the LCFBG, Λ_1 is the chirp rate, and z is the distance along the fiber.

The photosensitive fiber used for grating fabrication was hydrogen loaded for over three weeks at 80° to increase the fiber's photosensitivity. The 6-cm long LCFBG has a ~ 18.6 nm stopband, in which the depth is over 25 dB when operating in the transmission mode as shown in Fig. 6-6. A deep stopband of the LCFBG is desirable in order to obtain transmission peaks with higher rejection ratios. Due to the long length (6 cm in this design) of the LCFBG (and hence larger width of the stopband), which was fabricated using a phase mask with 2.25 nm/cm chirp rate, it is easier to introduce multiple temporary perturbations to the grating. And different wavelength spacings (comb spacings) can also be possibly achieved with the proposed filter based on the 6-cm long LCFBG as described below.

Figure 6-6: Measured transmission spectrum of the 6-cm LCFBG.

6.2.3 Design of Optical Comb Filter

The LCFBG (as described in Sections 6.2.1 and 6.2.2) was designed to be a tunable and switchable comb filter. A stage, which is made of heat-insulated materials, was designed to mount the LCFBG with the resistance wires in contact with the LCFBG at multiple positions in a controllable manner. A photograph of the stage (25 cm $\times$ 33 cm) mounting the tunable and switchable comb filter is shown in Fig. 6-7. Two electric connector arrays are placed on the top and bottom of the stage. In the center of the stage, there is a platform with forty (40) V-grooves, where the LCFBG and all the resistance wires are fixed in the grooves. The horizontal center groove in the middle of the platform is used to fix the LCFBG with two fiber holders. 40 V-grooves (with each having a diameter of 0.3 mm) separated by 1.25 mm are used to hold the resistance wires as external perturbations to the LCFBG. Two fiber holders on the two sides of the platform are used to hold the

LCFBG so that the grating is in complete contact with the resistance wires. In this particular design, nine NiCr resistance wires, with each having a diameter of 0.2 mm, are fixed in the V-grooves of the stage to heat the grating at nine points.

Figure 6-7: Photograph of the stage for mounting the proposed tunable and switchable comb filter.

The schematic diagram of the filter design is shown in Fig. 6-8. The heating element consists of nine 0.2 mm thick, ~8 cm long resistance wires, with each wire having a resistivity of $37.5 \Omega/\text{m}$. Each of the resistance wires is connected to a variable resistor (0–100 k Ω) for independent control of the electrical power consumed by the resistance wire, which in turn controls the temperature change at each of the heating points. By tuning the variable resistor to its minimum or maximum resistance value, the transmission peaks within the stopband of the LCFBG can be switched on or off, respectively.

Figure 6-8: Schematic diagram of the proposed thermally switchable and tunable comb filter based on a LCFBG with multiple heated resistance wires. OSA: optical spectrum analyzer.

Also, the center wavelengths of the generated transmission peaks within the stopband of the LCFBG can be changed by moving the resistance wires to different V-grooves in order to heat the grating at different positions. This is because the center wavelength of the transmission peak varies linearly with the position of the heating point (as described in Section 6.2.2). In this design, the V-grooves on the stage are spaced 1.25 mm apart, which corresponds to a ~ 0.4 nm wavelength difference between the center wavelengths of the transmission peaks. With this method, the center wavelengths and the wavelength spacings of the transmission peaks can be discretely tuned in steps of 0.4 nm over the whole stopband of the LCFBG. Fig. 6-9 shows the relationship between the allowable wavelength spacing of the generated transmission peaks and the distance between the two resistance wires. The slope of the line shown in Fig. 6-9 is ~ 0.32 nm/cm according to Eq. (2.17) as shown in Chapter 2. The tunable range of the comb filter is only limited by the

bandwidth of the LCFBG's stopband, which can be increased by using a longer phase mask with a higher chirp rate during the grating fabrication.

Figure 6-9: Relationship between the thermally induced transmission peak's wavelength spacing and the corresponding separation between the two resistance wires (solid line is the simulation result, the dotted points “•” is the experiment result).

6.2.4 Testing of Tunable Comb Filter

A broadband source (C+L band) was used as the light source to measure the spectrum of the comb filter, which was monitored by an OSA. When heating all the nine resistance wires, all of which are separated by 5 mm, nine transmission peaks with a wavelength spacing of ~ 1.6 nm were obtained within the stopband of the LCFBG as shown in Fig. 6-10.

Figure 6-10: Measured transmission spectrum of the switchable and tunable comb filter, which shows nine spectral peaks within the stopband of the LCFBG.

All the thermally-induced transmission peaks have a rejection ratio of more than 25 dB. The power flatness of all the transmission peaks is within 1 dB, which can be controlled by adjusting the electric power applied to the corresponding resistance wires. The transmission losses of the peaks are all ~ 5 dB due to the deep stopband of the LCFBG (see Fig. 6-10). The current of the power supply is less than 2 A, and the electrical power consumed is less than 8 W.

Each of the transmission peaks can be switched on and off by controlling the current supplied to the corresponding variable resistor which is connected to each resistance wire. When the resistance of the fourth resistor was adjusted to its maximum value to remove the thermal perturbation at the fourth heating point, eight transmission peaks (with the fourth transmission peak switch off) with wavelength separations of 1.6 nm and 3.2 nm within the stopband were achieved as shown in Fig. 6-11. Using this method, a

switchable optical comb filter with switchable transmission peaks can be achieved.

Figure 6-11: Measured transmission spectrum of the tunable comb filter when eight resistance wires were heated simultaneously.

When heating a small section of the LCFBG without using heat sinks, due to heat conduction (the length of the heating region is equal to the resistance wire's diameter, which is about 0.2 mm), the fiber region along the two sides of the resistance wire will also be heated, which will then change the temperature of the fiber in this small region. As the fiber grating is very sensitive to temperature changes, the Bragg wavelength at this relatively broad heated section will also shift to the long-wavelength range. As a result, some broad spectral disturbance will appear in the spectrum of the grating. This undesirable broad spectral perturbation will broaden the bandwidth of the spectral peak, which will degrade the performance of the comb filter. Thus, it is important to reduce the heat conduction in order to generate transmission peaks with a very narrow bandwidth. In the design, heat sinks are placed along the fiber's two sides of each resistance wire to dissipate the unwanted heat that causes the spectral perturbations in the short-wavelength

range (see Fig. 6-12).

Figure 6-12: Schematic diagrams showing the temperature distribution along the fiber grating that is heated by resistance wires without heat sink (a) and with heat sinks (b).

When the heat sink was not placed along the two sides of each resistance wire, the measured filter's transmission spectrum is shown in Fig. 6-13 (a). It can be seen that some broad spectral perturbations occur in the short-wavelength side of the generated transmission peak due to the heat conduction. When heat sink was used to reduce the heat conduction from each resistance wire, the broad spectral perturbation was significantly reduced. Hence, the bandwidth and the rejection ratio of the generated transmission peak are greatly improved as shown in Fig. 6-13 (b). The rejection ratio of the transmission

peak was greater than 25 dB with the use of the heat sink, but the rejection ratio was only 16 dB when no heat sink was used.

Figure 6-13: Measured transmission spectra of the tunable comb filter when only one resistance wire was heated. (a) Without using the heat sink. (b) With the heat sink.

Using heat sinks to reduce the heat conduction, a tunable optical comb filter with a transmission peak's bandwidth of as small as ~ 10 pm was achieved. By changing the

positions of the resistance wires (which are separated by about 2.5 mm) on the stage, the smallest wavelength spacing of this comb filter is found to be ~ 0.8 nm as shown in Fig. 6-14.

Figure 6-14: Measured output spectrum of the tunable comb filter with two transmission peaks separated by 0.8 nm.

When only two of the resistance wires, which were separated by 5 mm in the center of the stage, were switched on, two transmission peaks with a wavelength separation of ~ 1.6 nm were obtained as shown in Fig. 6-15. Through this way, the comb filter's wavelength spacing can be discretely tuned from 0.8 nm to as large as 16 nm. Note that this tunable range can be increased by using a LCFBG that is fabricated with a phase mask with longer length and higher chirp rate.

Figure 6-15: Measured transmission spectrum of the tunable comb filter when only two resistance wires, which were separated by 5 mm, were heated.

Figure 6-16: Transmission spectrum of the tunable comb filter when only one resistance wire was heated.

Furthermore, the number of generated transmission peaks can be flexibly controlled by adjusting the resistances of the variable resistors. When only one variable resistor was adjusted to its minimum resistance value, the resistance wire was heated and one point on the LCFBG was perturbed externally by the temperature change. Thus, a single

transmission peak was generated within the stopband of the LCFBG as shown in Fig. 6-16. When two, three, and even nine resistance wires were switched on by adjusting the variable resistors, two, three and nine transmission peaks were obtained as shown in Fig. 6-17 (a), (b) and Fig. 6-10, respectively. Using this technique, the number of transmission peaks of the tunable optical comb filter can be adjusted or controlled.

Figure 6-17: Measured transmission spectra of the tunable comb filter. (a) When two resistance wires were heated, the wavelength separation is ~ 1.6 nm. (b) When three resistance wires were heated, the wavelength separation is ~ 1.6 nm.

6.3 Tunable Multiwavelength Optical Source Using Tunable Comb Filter

This section reports a novel, switchable and wavelength-spacing tunable multiwavelength optical source using the developed tunable comb filter as presented in Section 6.2. By using the tunable comb filter to slice a broadband light source, eight switchable wavelength channels with tunable wavelength spacing were achieved. The proposed tunable multiwavelength optical source has the unique advantages of simple structure, switchable wavelength channels, tunable wavelength spacing, narrow lasing linewidth, stable room-temperature operation, and low cost.

Section 6.3.1 briefly reviews several methods used in the development of the multiwavelength optical source. Section 6.3.2 describes the principle and experimental setup of the proposed tunable multiwavelength optical source. Experimental results and discussion of the tunable and switchable multiwavelength optical source are presented in Section 6.3.3.

6.3.1 Introduction

Technologies of multiwavelength fiber lasers have advanced significantly in recent years due to their enormous potential applications such as in optical communications [117], fiber-optic sensors [128], implementation of microwave photonic filters [129], [130]

measurement of fiber chromatic dispersion [131], measurement of the polarization mode dispersion of the fiber [132], and optical sources for the passive optical networks [133], [134]. A number of approaches using a single-gain medium such as EDFAs [29], [115], [135], [136] and SOAs [137], [138] to achieve multiwavelength lasing operations have been demonstrated in the past few years. However, it is more difficult to develop EDFA-based multiwavelength lasers that can operate stably under room-temperature condition due to the intrinsic homogeneous gain broadening of the erbium ion of the EDF, unless cooling of the erbium-doped fiber down to 77 K with liquid nitrogen [11] is employed, which is not practical. And the SOA-based multiwavelength ring lasers require at least one optical isolator, which increases the complexity and cost of the system, to ensure unidirectional operation in the ring laser cavity. Furthermore, the SOA-based ring lasers have such disadvantages as small operating bandwidth, polarization dependence, large noise figure, and large cavity loss due to the non-fiber structure. Moreover, most of the multiwavelength lasers reported so far lack the flexibility to allow simultaneous tunability of the wavelength spacing as well as switching of the individual wavelength channels to be achieved, which is one of the most important desirable features of multiwavelength lasers.

Multiwavelength optical sources can also be developed using various filtering techniques in the laser cavity which include the use of FBGs operating in the reflective mode [129], arrayed waveguide gratings (AWGs) to slice the broadband optical source [130], [133], or wavelength grating router [8]. The multiwavelength source reported in reference [129] consists of a broad-band superluminescent LED (SLED) with a 40-nm bandwidth, two

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fiber gratings (FBG1 and FBG2), and a 2×2 fiber coupler. Both FBGs were fabricated using the phase mask technique, and one of the FBGs was mounted on a stage to achieve strain modulation. Two wavelength channels with tunable wavelength separation were achieved with this optical source by tuning the Bragg wavelength of one of the FBGs by applying strain on the FBG. By adding the number of uniform fiber gratings connecting to the fiber coupler, more wavelength channels can be generated with this technique. However, the 3-dB fiber coupler connecting the fiber gratings has a high insertion loss, and only a limited number of wavelength channels can be obtained with this method. Furthermore, the generated wavelength channels cannot be made to be switchable and the tuning mechanism employed is not flexible.

In [130], the generated wavelength channels can be switchable and the wavelength spacing can also be made to be tunable, but the center wavelengths of the wavelength channels cannot be tuned. Also, the insertion losses of the AWGs are very large, ~ 12 dB, which is obviously undesirable for the multiwavelength optical source. Besides the use of the AWGs in the design of multiwavelength optical sources increases the cost and complexity of the optical source, high insertion losses of AWGs also lead to low output power, which in turn requires the use of optical amplifiers such as EDFAs and SOAs (and hence increasing the cost and complexity) to boost the power of the generated wavelength channels.

This section presents the review of two existing techniques used in the development of the multiwavelength optical sources. The performances of these two types of optical

sources are compared. In the following sections, a novel switchable multiwavelength optical source with tunable wavelength spacing based on a thermally tunable comb filter with a LCFBG (as presented in Section 6.2) is presented.

6.3.2 Principle and Experimental Setup of Multiwavelength Optical Source

The experimental setup of the proposed multiwavelength optical source is schematically shown in Fig. 6-18. The multiwavelength slicing optical source consists of a broadband light source (which is centered at 1555 nm and has a 40 nm bandwidth), a thermally tunable comb filter based on a LCFBG (LCFBG2 in Fig. 6-19) as described in Section 6.2 and Ref. [18], a 3-port circulator, and a LCFBG1. The output spectrum of the multiwavelength optical source is monitored by an OSA. The two chirped gratings (LCFBG1 and LCFBG2) were fabricated with the phase mask technique, where the phase mask has a grating spacing of 1.067 μm , and a chirp rate of 2.25 nm/cm. The photosensitive fiber (Fibercore PS1500) used in the grating fabrication was hydrogen-loaded at 80° for over three weeks to increase its photosensitivity. The transmission spectrum of the LCFBG2 as depicted in Fig. 6-19 shows a stopband with a rejection ratio of over 30 dB from 1536.56 nm to 1555.38 nm. The LCFBG1, which has an identical transmission spectrum as that of LCFBG2, is combined with the 3-port circulator to form a bandwidth-limiting filter to suppress any broadband light outside the stopband of the LCFBG2. It is worth noting that LCFBG1 and LCFBG2 are placed in opposite directions with each other in order to cancel out the dispersions introduced by these two chirped

gratings (i.e., the grating spacing of the LCFBG1 increases along its length while the grating spacing of the LCFBG2 decreases along its length).

Figure 6-18: Schematic diagram of the proposed tunable multiwavelength optical source.

Figure 6-19: Measured transmission spectrum of the fabricated LCFBG2 with an OSA.

The tunable comb filter, as described in Section 6.2, is formed by a 6-cm long LCFBG (LCFBG2 in Fig. 6-18), which is fixed in the middle of a stage that is made of a heat-insulated material as shown in the inset of Fig. 6-18. The tunable comb filter also has eight independently controlled resistance wires (with each having a diameter of 0.2 mm), which are connected to two electric connector arrays on the top and bottom sides of the stage, which are used to heat the LCFBG2 with controlled flexibility. The tunable comb filter is used as a flexibly controlled filter in the multiwavelength optical source. The heating element consists of eight 0.2 mm-thick, ~ 8-cm long resistance wires, with a resistivity of $37.5 \Omega/\text{m}$ each. Each of the resistance wires is connected to a variable resistor (0-100 k Ω) for independent control of the electrical power supplied to the resistance wire, which in turn controls the temperature change at each heating point.

Due to the thermo-optical effect, the refractive index of the fiber changes with the temperature change. Hence, the temperature change in a small section of the fiber will

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introduce a phase shift at that heating point. In the experiment, when the variable resistor connected to the resistor wire was adjusted to $0\ \Omega$, a phase shift was introduced into the LCFBG2 due to the temperature change. The value of the phase shift, ϕ , created at a heating point due to the thermo-optical effect can be determined by Eq (6.1). When the created phase shift is equal to $\phi = \pi$, a transmission peak will appear within the stopband of the LCFBG2. As long as ΔT is less than 570 K, the heating of the LCFBG2 is a non-destructive process because the spectral thermal disturbance is not permanent within the stopband of the chirped grating [124]. When each variable resistor is tuned to its maximum value of 100 k Ω (i.e. smallest power supplied to the resistance wire), the temperature change will be negligible and the passband peak will disappear. Thus, by appropriately controlling the variable resistors connected to the resistance wires, switchable transmission peaks can be obtained within the stopband of the LCFBG2. The V grooves on the stage are spaced at 1.25 mm apart, which corresponds to a ~ 0.4 nm wavelength difference between two adjacent transmission peaks. With this method, one can tune the center wavelengths of the generated wavelength channels and also discretely tune the wavelength spacing between the channels by controlling the electric power applied to the resistance wires as described in Section 6.2. Combining this tunable comb filter with a bandwidth-limiting filter (i.e. the circulator and LCFBG1) to filter out the unwanted transmission spectrum outside the stopband of the LCFBG2, a tunable multiwavelength optical source with switchable lasing wavelengths and tunable wavelength spacing can be achieved and its experimental results are presented below.

6.3.3 Tunable and Switchable Multiwavelength Optical Source

Figures 6-20 (a) and (b) show the output spectra of the proposed multiwavelength optical source when only two resistance wires were heated at two different V-grooves. In Fig. 6-20 (a), two wavelength channels were obtained with a wavelength separation of ~ 4 nm, an OSNR of ~ 20 dB, and a peak power of over 0.1 mW when no heat sinks were placed on the LCFBG2. From Fig. 6-20 (a), it can be seen that there are some broad spectral perturbations in the short-wavelength side of the main spectral peaks. This is because when the LCFBG2 was heated at a certain point; both sides of this point (due to the 0.2 mm finite diameter of the resistance wire) were also heated due to heat conduction. Since the LCFBG2 is sensitive to the temperature change, the reflected Bragg wavelength at the heating point will shift to the long-wavelength range.

As a result, broad spectral perturbations will be introduced into the short-wavelength side of the main spectral peaks [126]. By placing heat sinks on the two sides of each resistance wire, the broad spectral perturbations of the spectral peak in the short-wavelength range can be reduced (as shown in Fig. 6-20 (b)). The wavelength separation between the two wavelength channels shown in Fig. 6-20 (b) was also tuned to a smaller value of ~ 1.6 nm by just changing the position of one of the resistance wires. The SNRs of the two wavelength channels are improved to over 25 dB, the 3 dB linewidth of each wavelength channel is reduced to as small as ~ 10 pm, which is defined by the bandwidth of the tunable comb filter's passband.

Figure 6-20: Output spectra of the multiwavelength optical source. (a) When two resistance wires spaced 12.5 mm apart (without heat sinks) were switched on, and the wavelength separation is ~ 4 nm. (b) When two resistance wires spaced 5 mm apart (with heat sinks) were switched on, and the wavelength separation is ~ 1.6 nm.

Figure 6-21 (a) shows the output spectrum of the multiwavelength optical source when four of the eight resistance wires were switched on. Each of the four wavelength channels has a peak power of ~ 0.1 mW and an OSNR of over 20 dB, and the wavelength spacings

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among the four lasing lines are ~ 1.6 nm. Figure 6-21 (b) shows the output spectrum of the multiwavelength optical source when all the eight resistance wires were heated, and eight wavelength channels with a wavelength spacing of ~ 1.6 nm, a peak power of ~ 0.1 mW, and a SNR of more than 20 dB were achieved.

Figure 6-21: Measured output spectra of the multiwavelength optical source. (a) When four resistance wires (with 5 mm separation) were tuned on. (b) When eight resistance wires (with 5 mm separation) were tuned on.

The current of the power supply used was less than 2 A, and the electrical power consumed was ~ 8 W, when all the eight resistance wires were switched on. The power levels of all the generated lasing wavelength peaks shown in Figures 6-21 (a) and (b) are almost identical. The power fluctuation is very small of ~ 1 dB. Moreover, increasing the width of the LCFBG2's stopband by using a phase mask with a longer grating length and larger chirp rate will enable the number of wavelength channels to be increased.

The switching time of the multiwavelength optical source is mainly determined by the switching time of the tunable comb filter as described in Section 6.2. The switching time of the tunable comb filter is about 0.5 second, which is relatively large due to the time required to heat up the resistance wire. Furthermore, the center wavelengths of the generated wavelength channels can also be tunable by changing the positions of the LCFBG2 [18].

6.4 Summary

A novel thermally switchable and tunable comb filter based on a LCFBG that used controllable multiple heated resistance wires has been experimentally demonstrated. With the use of nine resistance wires, which were controlled by nine variable resistors that were powered by a DC power supply and were attached to the V-grooves of the stage, nine switchable and tunable transmission peaks with a very narrow bandwidth of ~ 10 pm were obtained within the stopband of the 6-cm LCFBG. Heat sinks were placed on the two sides of each resistance wire to reduce the heat conduction. This tunable and

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switchable comb filter has many unique advantages, which include switchable transmission peaks, tunable center wavelengths, variable wavelength spacings, narrow bandwidth of each spectral peak, low polarization sensitivity, low power consumption, simple structure with few optical components, and low cost. The proposed tunable comb filter has many potential applications such as a tunable wavelength-selective device for use in multiwavelength fiber laser sources, wavelength division multiplexing networks, and implementation of microwave photonic filters with multiple taps.

The tunable comb filter described here was also used as a wavelength-selective device in the laser cavity of a multiwavelength optical source as described in Section 6.3. Based on a thermally tunable comb filter together with a bandwidth-limiting filter, eight wavelength channels with a wavelength spacing of ~ 1.6 nm were achieved at room temperature with the tunable multiwavelength optical source. By changing the positions of the resistance wires on the tunable comb filter, multiple wavelength channels with tunable wavelength spacing (1.6 nm – 9.6 nm) were achieved. By controlling the temperature changes at certain points on the tunable comb filter with the variable resistors, the wavelength channels can be made to be switchable. The 3-dB linewidth of each wavelength channel is very small (~ 10 pm). The heat conduction effect can be effectively removed by placing heat sinks on both sides of each resistance wire. Table 6.1 summarizes the important parameters of the tunable multiwavelength source presented in this chapter. The proposed tunable multiwavelength optical source has great potential for such applications as in wavelength-division multiplexing systems, fiber-optic sensors, implementation of microwave photonic filters, and measurement of the chromatic

dispersion and polarization-mode dispersion of the fiber.

Table 6.2: Performance parameters of the developed multiwavelength optical source.

Switchable wavelength channle	Tunable wavelength spacing range	OSNR	3 dB Linewidth	Tunable center wavelength
Yes	1.6 nm-9.6 nm	25 dB	~ 10 pm	Yes

7

Conclusions and Recommendations for Future Work

This chapter presents conclusions of the thesis with special emphasis on the results.

Some suggestions on future work are also given.

7.1 Conclusions

This thesis has presented the investigations of several multiwavelength and dual-wavelength fiber lasers based on various filtering techniques, which include fiber-based Sagnac loop filter, PM-FBG with strain modulation, SCLFBG, and thermally tunable comb filter. To demonstrate the effectiveness of the proposed laser configurations, several room-temperature multiwavelength fiber laser sources have been developed and tested and they are listed below.

- A tunable multiwavelength fiber laser based on the Sagnac loop filter
- A tunable dual-wavelength fiber laser with tunable wavelength spacing
- A tunable multiwavelength optical source using the thermally tunable comb filter

- A two-tap microwave photonic notch filter with tunable FSR using a dual-wavelength fiber laser
- A multiple-tap microwave photonic bandpass filter based on the multiwavelength ring laser

In Chapter 2, the basic theory of the EDFA and the characteristics of FBGs have been presented, and the existing technologies of EDFLs and multiwavelength lasers have been briefly discussed.

In Chapter 3, a novel tunable multiwavelength EDFL based on a fiber Sagnac loop filter has been presented. By adjusting the setting of PC2 within the laser cavity, two, three and four stable lasing lines in the C-band, and five, six, seven and even eight lasing lines with different wavelength spacings were obtained at room temperature. Wavelength spacings of 0.8 nm or 0.4 nm (i.e. 100 GHz or 50 GHz) can be achieved by using different length of PM-EDF of the Sagnac loop filter within the laser cavity. The output lasing lines from the multiwavelength EDFL were found to be fairly stable over an hour under room temperature conditions, without using any additional measures to stabilize the fiber laser. The OSNR of all the lasing lines are greater than 40 dB and the total output power of the fiber laser is over 3 mW. This laser configuration has several unique advantages such as simple structure, low cost, no optical isolators are needed, and multiple lasing wavelengths with tunable wavelength spacings.

In Chapter 4, a novel wavelength-spacing tunable dual-wavelength fiber laser with an all-PM linear laser cavity structure has been presented. Taking advantages of the PM-FBG, two stable lasing lines with a wavelength separation of 0.22 nm have been obtained. By stretching the PM-FBG, the two lasing lines' center wavelengths can be tuned, and dual-wavelength operation with different wavelength spacings (of as small as 0.05 nm) can be obtained. And the wavelength separations of the two lasing lines can be tuned from 0.22 nm down to as small as 0.05 nm, which is the smallest wavelength separation, to the best of our knowledge, ever achieved for a room-temperature dual-wavelength fiber laser source. The OSNR of the lasing wavelength is over 40 dB. This fiber laser configuration has the advantages of stable lasing operation at room temperature, very narrow linewidth (3 dB FWHM linewidth of ~ 2.5 kHz), very small wavelength variation (< 0.002 nm) and power variation (< 0.5 dB), low cavity loss and simple structure compared with many other techniques.

In Chapter 5, a novel two-tap microwave photonic notch filter with tunable FSR using the wavelength-spacing tunable dual-wavelength fiber laser has been presented. Based on the linear-cavity dual-wavelength fiber laser, a two-tap microwave photonic notch filter was implemented. The FSR of the tunable microwave photonic notch filter can be tuned from 3.175 GHz to 9.46 GHz by changing the wavelength separation between the dual-wavelength fiber laser's two lasing wavelengths, and the rejection ratio of the notch is greater than 35 dB. The proposed tunable microwave photonic

notch filter has many advantages compared with other approaches, which include simple structure with less optical components in the filter part, two or more tunable DFB lasers are not needed (and thus reduce the system's cost), and easily tunable wavelength separation of the fiber laser by stretching the PM-FBG.

In Chapter 6, a novel thermally switchable and tunable comb filter based on a LCFBG that uses controllable multiple heated resistance wires has been presented. With nine resistance wires, which are controlled by nine variable resistors powered by a DC power supply and are attached to the V-grooves of the stage, nine switchable and tunable transmission peaks with a very narrow bandwidth of ~ 10 pm were obtained within the stopband of the 6-cm LCFBG. Heat sinks were placed in the fiber region to reduce heat conduction of the resistance wires. This tunable and switchable comb filter has many unique advantages, which include switchable transmission peaks, tunable center wavelengths and wavelength spacings, narrow bandwidths of the spectral peaks, low polarization sensitivity, low power consumption, simple structure with few optical components, and low cost. Section 6.3 presents a novel multiwavelength slicing optical source with switchable wavelength channels and tunable wavelength spacings based on the thermally tunable comb filter (as described in Section 6.2) together with a bandwidth-limiting filter. Eight wavelength channels with a wavelength spacing of ~ 1.6 nm were achieved at room temperature with the multiwavelength optical source. By changing the positions of the resistance wires on the tunable comb filter, multiple wavelength channels with tunable wavelength

spacing (1.6 nm – 9.6 nm) were achieved. By controlling the temperature changes at certain points on the tunable comb filter with the variable resistors, all the wavelength channels can be made to be switchable. The 3-dB linewidth of each wavelength channel is less than ~ 10 pm. The heat conduction effect can be effectively removed by placing heat sinks on both sides of each resistance wire. This multiwavelength fiber laser has the unique advantages of simple structure, switchable wavelength channels, tunable wavelength spacing, very narrow linewidth, stable room-temperature operation, and low cost.

7.2 Recommendations for Future work

The multiwavelength fiber laser presented in Chapter 3 utilized the fiber Sagnac loop filter as the wavelength-selective component within the laser cavity. However, the fiber loop length and the birefringence of the PM fiber are sensitive to environmental changes (e.g. changes with the temperature and pressure). One suggested improvement is to use other type of PM fibers that are not sensitive to the outside temperature changes, and this will improve the temperature stability of the multiwavelength fiber laser source.

In Chapter 4, a dual-wavelength fiber laser with tunable wavelength spacing has been presented. One interesting point to note is that the proposed linear laser cavity can show the relationship between the amount of applied axial strain and the wavelength

separation of the fiber laser. Note that the Bragg wavelength of the PM-FBG is also influenced by the temperature change. The proposed dual-wavelength fiber laser, after appropriate implementation, can thus be used as a simultaneous strain and temperature fiber sensor. Due to its high OSNR, this fiber laser based optical sensor will be useful in remote sensing applications. As the optical source and the sensor part are all integrated in one laser cavity, the number of components required for the sensor system will be reduced.

A tunable optical comb filter based on a LCFBG has been presented in Chapter 6. Using the currently available phase mask, the total tunable range of the filter is limited by the bandwidth of the LCFBG's stopband, which is ~ 16.5 nm. Using a longer phase mask or a phase mask with a larger chirp rate, a tunable comb filter with larger tunable range of the wavelength spacing can be developed. By fixing the resistance wires' positions while moving the LCFBG in the longitudinal direction, a comb filter with continuous tunable spectral peaks can be obtained. Furthermore, by precisely controlling the DC voltage applied to the resistance wires, the attenuation of the spectral peaks can be adjusted.

In Chapter 6, a novel multiwavelength optical source with tunable wavelength spacing and switchable wavelength channels has also been presented. The proposed multiwavelength fiber laser can be used for the measurement of the chromatic dispersion of the optical fiber based on the time-of flight (TOF) or pulse-delay

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technique. Due to its simplicity and high speed, the TOF measurement method is an interesting application for the measurement of dispersion in already-deployed fiber links. While the TOF measurements obtained so far are fairly accurate, the complexity associated with the multiwavelength source and the lack of tunability of the wavelength spacing are the main limiting factors. It should be noted that the proposed multiwavelength optical source is very suitable for this kind of application due to its stability and tunability of the wavelength spacing.

AUTHOR'S PUBLICATIONS

The publications shown below result from the work of this thesis

Journal Papers

- [1] N. Q. Ngo, **D. Liu**, X. Y. Dong, L. N. Binh, S. C. Tjin, and S. Y. Li, "Spacing-tunable multiwavelength fiber laser source using a Sagnac loop filter," *SPIE Optical Engineering*, vol. 44, pp. 014202-1-014202-5, 2005.
- [2] **D. Liu**, N. Q. Ngo, X. Y. Dong, S. C. Tjin, and P. Shum, "A stable dual-wavelength fiber laser with tunable wavelength spacing using a polarization-maintaining linear cavity," *Applied Physics B: Lasers and Optics*, vol. 81, pp. 807–811, 2005.
- [3] N. Q. Ngo, **D. Liu**, S. C. Tjin, X. Dong, and P. Shum, "Thermally switchable and discretely tunable comb filter with a linearly chirped fiber Bragg grating," *Opt. Lett.*, vol. 30, pp. 2994–2996, 2005.
- [4] **D. Liu**, N. Q. Ngo, H. N. Chan, C. K. Teu, and S. C. Tjin, "A switchable triple-wavelength erbium-doped fiber laser with a linear laser cavity," *Microwave and Optical Technology Letters*, vol. 48, pp. 632–635, 2006.
- [5] **D. Liu**, N. Q. Ngo, G. Ning, and S. C. Tjin, "Tunable microwave photonic notch filter using a dual-wavelength fiber laser with phase modulation," *Opt. Commun.*, vol. 266, pp. 240-248 2006.
- [6] **D. Liu**, N. Q. Ngo, and S. C. Tjin, "Microwave photonic bandpass filter using a multiwavelength semiconductor-optical amplifier ring laser," *SPIE Optical Engineering*, vol. 46. pp. 054304-1-054304-4, 2007.

- [7] **D. Liu**, N. Q. Ngo, S. C. Tjin, and X. Dong, "A dual-wavelength fiber laser sensor system for measurement of temperature and strain," *IEEE Photon. Technol. Lett.*, vol. 19, pp. 1148-1150, 2007.

Conference Papers

- [8] **D. Liu**, N. Q. Ngo, X. Y. Dong, K.T. V. Grattan, T. Sun, L. Binh, S. C. Tjin, and S. Y. Li, "A discretely tunable multiwavelength fiber laser source with an elliptical core fiber Sagnac loop filter," *Proc. Of APOC'04, Beijing China, November, 2004*.

The publications shown below result from collaborations with other members in NTU.

Journal Papers

- [9] X. Yu, **D. Liu**, P. Shum, H. Dong, X. Dong, and N. Q. Ngo, "A multiwavelength fiber laser with temperature stability by using a HiBi-PCF Sagnac loop filter," *SPIE Optical Engineering.*, vol. 45, pp. 044201-1–044201-4, 2006.
- [10] G. Ning, P. Shum, S. Aditya, **D. Liu**, Y. Gong, N. Q. Ngo, and M. Tang, "Multiwavelength Raman fiber lasers with equalized peak power using a sampled chirped fiber Bragg grating," *Applied Physics B: Lasers and Optics.*, vol. 83, pp.249–253, 2006.

Bibliography

- [1] A. L. Schawlow and C. H. Townes, "Infrared and optical masers," *Phys. Rev.*, vol. 112, pp. 1940-1949, 1958.
- [2] T. H. Maiman, "Stimulated optical radiation in ruby," *Nature*, vol. 187, pp. 493-494, 1960.
- [3] K. C. Kao and G. A. Hockham, "Dielectric-fiber surface waveguide for optical frequencies," *Proceedings of the Institute of Electrical Engineers*, vol. 117, pp. 1151-1158, 1966.
- [4] J. Stone and C. A. Burrus, "Neodymium-doped silica lasers in end-pumped fiber geometry," *Appl. Phys. Lett.*, vol. 23, pp. 388-389, 1973.
- [5] J. Stone and C. A. Burrus, "Neodymium-doped fiber lasers: room-temperature cw operation with an injection laser pump," *Appl. Opt.*, vol. 13, pp. 1256-1258, 1974.
- [6] J. C. Fletcher, C. Elachi, G. A. Evans, and C. Yeh, "Fiber distributed feedback laser," *United States Patent*, No. 3958188, pp. 9, 1976.
- [7] P. W. France, *Optical fiber lasers and amplifiers*, CRC Press, Boca Raton, 1991.
- [8] Y. W. Song, S. A. Havstad, D. Starodubov, Y. Xie, A. E. Willner, and J. Feinberg, "40-nm-wide tunable fiber ring laser with single-mode operation using a highly stretchable FBG," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1167-1169, 2001.
- [9] M. G. Young, U. Koren, B. I. Miller, M. A. Newkirk, M. Chien, M. Zirngibl, C. Dragone, B. Tell, H. M. Presby, and G. Raybon, "A 16×1 wavelength division multiplexer with integrated distributed Bragg reflector lasers and electroabsorption modulators," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 908-910, 1993.

-
- [10] A. J. Poustie, N. Finlayson, and P. Harper, "Multiwavelength fiber laser using a spatial mode beating filter," *Opt. Lett.*, vol. 19, pp. 716-718, 1994.
- [11] N. Park and P. F. Wysocki, "24-line multiwavelength operation of erbium-doped fiber-ring laser," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1459-1461, 1996.
- [12] M. Zirngibl, C. H. Joyner, L. W. Stulz, C. Dragone, H. M. Presby, and I. P. Kaminow, "LARNet, a local access router network," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 215-217, 1995.
- [13] H. J. R. Dutton, *Understanding optical communications*, Prentice Hall PTR, New Jersey, 1998.
- [14] Optical interfaces for multichannel systems with optical amplifiers, *International Telecommunication Union (ITU-U)*, recommendation G.692, pp. 40, 1998.
- [15] N. Q. Ngo, D. Liu, X. Y. Dong, L. N. Binh, S. C. Tjin and S. Y. Li, "Spacing-tunable multiwavelength fiber laser source using a Sagnac loop filter," *Opt. Eng.*, vol. 44, pp. 014202-1-014202-5, 2005.
- [16] D. Liu, N. Q. Ngo, X. Y. Dong, S. C. Tjin and P. Shum, "A stable dual-wavelength fiber laser with tunable wavelength spacing using a polarization-maintaining linear cavity," *Appl. Phys. B*, vol. 81, pp. 807-811, 2005.
- [17] D. Liu, N. Q. Ngo, G. Ning, P. Shum, and S. C. Tjin, "Tunable microwave photonic notch filter using a dual-wavelength fiber laser with phase modulation," *Opt. Commun.*, vol. 266, pp. 240-248, 2006.
- [18] N. Q. Ngo, D. Liu, S. C. Tjin, Xinyong Dong, and P. Shum, "Thermally switchable and discretely tunable comb filter with a linear chirped fiber Bragg grating," *Opt. Lett.*, vol. 30, pp. 2994-2996, 2005.

-
- [19] W. J. Miniscalco, "Erbium-doped glasses for fiber amplifier at 1550 nm," *J. Lightwave Technol.*, vol. 9, pp. 234-250, 1991.
- [20] P. W. France, *Optical fiber lasers and amplifier*, CRC, Boca Raton, pp. 259, 1991.
- [21] R. Larose, *Réalisation et applications d'un laser à fibre à l'erbium monofréquence*, Ph. D. Thesis, Université Laval, Sainte-Foy, Canada, pp. 173, 1995.
- [22] E. Desurvire, J. R. Simpson, and P. C. Becker, "High gain erbium-doped traveling-wave fiber amplifier," *Opt. Lett.*, vol. 12, pp. 888-890, 1987.
- [23] P. C. Becker, *Erbium-doped fiber amplifiers: fundamentals and technology*, Academic Press, San Diego, 1999.
- [24] B. Pedersen, A. Bjarklev, J. H. Povlsen, K. Dydbal, and C. C. Larsen, "The design of erbium-doped fiber amplifier," *J. Lightwave Technol.*, vol. 9, pp. 1105-1112, 1991.
- [25] A. E. Siegman, *Lasers*, University Science Books, Mill Valley, 1980.
- [26] P. Barnsley, P. Urquhart, C. Millar, and M. Brierley, "Fiber Fox-Smith resonators: application to single-longitudinal-mode operation of fiber lasers," *Journal of the Optical Society of America A*, vol. 5, pp. 1339-1346, 1988.
- [27] S. Yamashita, K. Hsu, and W. H. Loh, "Miniature erbium: ytterbium fiber Fabry-Perot multiwavelength lasers," *IEEE J. Sel. Topics in Quantum Electron.*, vol. 3, pp. 1058-1064, 1997.
- [28] J. Chow, G. Town, B. J. Eggleton, M. Isben, K. Sugden, and I. Bennion, "Multiwavelength generation in an erbium-doped fiber laser using in-fiber comb filter," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 60-62, 1996.
- [29] K. Zhou, D. Zhou, F. Dong, and N. Q. Ngo, "Room-temperature multiwavelength

- erbium-doped fiber ring laser employing sinusoidal phase-modulation feedback,” *Opt. Lett.*, vol. 28, pp. 893-895, 2003.
- [30] M. D. Mermelstein, C. Horn, J. -C. Bouteiller, P. Steinvurzel, C. Headley, and B. J. Eggleton, “Six wavelength Raman fiber laser for C + L band Raman amplification,” *OFC’02*, CThJ, pp. 478, 2002.
- [31] Y. -G. Han, C. -S. Kim, J. U. Kang, U. -C. Paek, and Y. Chung, “Multiwavelength Raman fiber-ring laser based on tunable cascaded long-period fiber gratings,” *IEEE Photon. Technol. Lett.*, vol. 15, pp. 383-385, 2003.
- [32] K. K. Qureshi, H. Y. Tam, W. H. Chung, and P. K. A. Wai, “Multiwavelength laser source using linear optical amplifier,” *IEEE Photon. Technol. Lett.*, vol. 17, pp. 1611-1613, 2005.
- [33] H. Dong, G. Zhu, Q. Wang, H. Sun, N. K. Dutta, J. Jaques, and A. B. Piccirilli, “Multiwavelength fiber ring laser source based on a delayed interferometer,” *IEEE Photon. Technol. Lett.*, vol. 17, pp. 303-305, 2005.
- [34] G. Meltz, W. W. Morey, and W. H. Glenn, “Formation of Bragg gratings in optical fibers by a transverse holographic method,” *Opt. Lett.*, vol. 14, pp. 823-825, 1989.
- [35] A. Othonos and K. Kalli, *Fiber Bragg gratings: fundamentals and application in telecommunications and sensing*, Artech House, 1999.
- [36] K. O. Hill, Y. Fujii, D. Johnson, and B. Kawasaki, “Photosensitivity in optical fiber waveguides: application to reflection filter fabrication,” *App. Phys. Lett.*, vol. 32, pp. 647-649, 1978.
- [37] P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, “High pressure H₂ loading as a technique for achieving ultrahigh UV photosensitivity and

- thermal sensitivity in GeO₂ doped optical fibers,” *Electron. Lett.*, vol. 29, pp. 1191-1193, 1993.
- [38] D. P. Hand and P. St. J. Russell, “Photoinduced refractive-index changes in germanosilicate fibers,” *Opt. Lett.*, vol. 15, pp. 102-104, 1990.
- [39] H. G. Limberger, P. -Y. Fonjallaz, R. P. Salathé, and F. Cochet, “Compaction and photoelastic-index changes in fiber Bragg gratings,” *App. Phys. Lett.*, vol. 68, pp. 3069-3071, 1996.
- [40] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, “Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask,” *App. Phys. Lett.*, vol. 62, pp. 1035-1037, 1993.
- [41] J. T. Kringlebotn, J. L. Archambault, L. Reekie, and D. N. Payne, “Er³⁺ : Yb³⁺ co-doped fiber DFB laser,” *Opt. Lett.*, vol. 19, pp. 2101-2103, 1994.
- [42] W. H. Loh and R. I. Laming, “1.55 μ m phase-shifted distributed feed-back fiber laser,” *Electron. Lett.*, vol. 31, pp. 1440-1442, 1995.
- [43] Z. E. Harutjunian, W. H. Loh, R. I. Laming, and D. N. Payne, “Single polarization twisted distributed feedback fiber laser,” *Electron. Lett.*, vol. 32, pp. 346-348, 1996.
- [44] G. A. Ball and W. H. Glenn, “Design of a single-mode linear-cavity erbium fiber laser utilizing Bragg reflectors,” *J. Lightwave Technol.*, vol. 10, pp. 1338-1343, 1992.
- [45] J. T. Kringlebotn, P. R. Morkel, L. Reekie, J. L. Archambault, and D. N. Payne, “Efficient diode-pumped single-frequency erbium: ytterbium fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1162-1164, 1993.

-
- [46] J. T. Kringlebotn, J. L. Archambault, L. Reekie, J. E. Townsend, G. C. Vienne, and D. N. Payne, "Highly efficient, low-noise grating-feedback $\text{Er}^{3+} : \text{Yb}^{3+}$ codoped fiber laser," *Electron. Lett.*, vol. 30, pp. 972-973, 1994.
- [47] J. L. Archambault, L. Reekie, L. Dong, and P. S. Russell, "High reflectivity photorefractive Bragg gratings in germania-free optical fibers," in *CLEO'94 Tech. Dig.*, Anaheim, CA, p. 242, 1994.
- [48] K. P. Koo and A. D. Kersey, "Fiber laser sensor for ultra-high strain resolution using interferometric interrogation," *Electron. Lett.*, vol. 20, pp. 1180-1182, 1996.
- [49] G. E. Town, K. Sugden, J. Williams, I. Bennion, and S. B. Poole, "Wide band Fabry-Perot-like filters in optical fibers," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 78-80, 1995.
- [50] B. J. Eggleton, P. A. Krug, L. Poladian, and F. Ouellette, "Long periodic superstructure Bragg gratings in optical fibers," *Electron. Lett.*, vol. 30, pp. 1620-1622, 1994.
- [51] X. J. Gu, "Wavelength-division multiplexing isolation fiber filter and light source using cascaded long-period fiber gratings," *Opt. Lett.*, vol. 23, pp. 509-510, 1998.
- [52] S. V. Chernikov, R. Kashyap, P. F. McKee, and J. R. Taylor, "Dual frequency all fiber grating laser source," *Electron. Lett.*, vol. 29, pp. 1089-1091, 1993.
- [53] N. J. C. Libatique and R. K. Jain, "Precisely and rapidly wavelength-switchable narrow linewidth 1.5- μm laser source for wavelength division multiplexing applications," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1584-1586, 1999.
- [54] Y. -G. Han, T. V. A. Tran, and S. B. Lee, "Wavelength-spacing tunable multiwavelength erbium-doped fiber laser based on four-wave mixing of

- dispersion-shifted fiber,” *Opt. Lett.*, vol.31, pp. 697-699, 2006.
- [55] F. Ahmed, N. Kishi, T. Miki, “Multiwavelength erbium-doped fiber Fabry-Perot laser and its uniform spectral lines power operation,” *IEEE Photon. Technol. Lett.*, vol. 17, pp. 753-755, 2005.
- [56] H.Takahashi, H. Toba, and Y. Inoue, “Multiwavelength ring laser composed of EDFAs and an arrayed waveguide wavelength multiplexer,” *Electron. Lett.*, vol. 30, pp. 44-45, 1994.
- [57] T. Miyazaki, N. Edagawa, S. Yamamoto, and S. Akiba, “A multiwavelength fiber ring-laser employing a pair of silica-based arrayed-waveguide-gratings,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 910-912, 1997.
- [58] K. -H. Kim, H. -K. Lee, S. -Y. Park, and E. -H. Lee, “Wavelength-varying multiwavelength optical filter laser using a single pump light source.” *United States Patent*, No. 5524118, pp. 6, 1996.
- [59] N. Park, J. W. Dawson, and K. J. Vahala, “Multiwavelength operation of an Er-doped fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 4, pp. 540-542, 1992.
- [60] J. Hübner, P. Varming, and M. Kristensen, “Five wavelength DFB fiber laser source for WDM systems,” *Electron. Lett.*, vol. 33, pp. 139-140, 1997.
- [61] O. Graydon, W. H. Loh, R. I. Laming, and L. Dong, “Triple-frequency operation of an Er-doped twincore fiber loop laser,” *IEEE Photon. Technol. Lett.*, vol. 8, pp. 63-65, 1996.
- [62] D. Abraham, R. Nagar, M. N. Ruberto, G. Eisenstein, J. L. Zyskind, D. DiGiovanni, U. Koren, and G. Raybon, “Intracavity-diode-pumped erbium doped fiber laser,” *Electron. Lett.*, vol. 28, pp. 1830-1832, 1992.

-
- [63] Y. Zhao, C. Shu, S. P. Li, H. Dong, and K. T. Chang, "Multiple wavelength operation of a unidirectional Er-doped fiber ring laser with optical feedback," *Technical Digest of CLEO '97*, paper CThL65, pp. 396, 1997.
 - [64] H. Sasamori, K. Isshiki, H. Watanabe, and K. Kasahara, "Multi-wavelength erbium-doped ring light source with fiber grating filter," *Technical Digest of Optical Amplifiers and Their Applications (OAA'97)*, paper WC3, pp. 235-238, 1997.
 - [65] S. Yamashita and K. Hotate, "Multiwavelength erbium-doped fiber laser using intracavity etalon and cooled by liquid nitrogen," *Electron. Lett.*, vol. 32, pp. 1298-1299, 1996.
 - [66] X. Fang, H. Ji, C. T. Allen, K. Demarest, and L. Pelz, "A compound high-order polarization independent birefringence filter using Sagnac interferometers," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 458-460, 1997.
 - [67] G. P. Agrawal, *Nonlinear fiber optics*, third edition, Academic Press, 2001.
 - [68] X. Fang and R. O. Claus, "Polarization-independent all-fiber WDM based on a Sagnac interferometer," *Opt. Lett.*, vol. 20, pp. 2146-2148, 1995.
 - [69] B. Srinivasan, S. Gupta, and R. K. Jain, "Polarization anisotropic gain behavior in elliptical core rare earth doped fibers," *Doped Fiber Devices and Systems, Proc. SPIE*, vol. 2289, pp. 51-55, 1994.
 - [70] J. H. Cordero, V. A. Kozlov, A. L. G. Carter, and T. F. Morse, "Polarization effects in a high birefringence elliptical fiber laser with a Bragg grating in a low birefringence fiber," *Appl. Opt.*, vol. 39, pp. 972-977, 2000.
 - [71] X. Shu, S. Jiang, and D. Huang, "Fiber grating Sagnac loop and its

-
- multiwavelength-laser application,” *IEEE Photon. Technol. Lett.*, vol. 12, pp. 980-982, 2000.
- [72] X. P. Dong, S. Li, K. S. Chiang, M. N. Ng, and B. C. B. Chu, “Multiwavelength erbium-doped fiber laser based on a high-birefringence fiber loop mirror,” *Electron. Lett.*, vol. 36, pp. 1609-1610, 2000.
- [73] S. Li and K. T. Chan, “Electrical wavelength tunable and multiwavelength actively mode-locked fiber ring laser,” *Appl. Phys. Lett.*, vol. 72, pp. 1954-1956, 1998.
- [74] K. L. Lee and C. Shu, “Alternate and simultaneous generation of 1-GHz dual-wavelength pulses from an electrically tunable harmonically mode-locked fiber,” *IEEE Photon. Technol. Lett.*, vol. 12, pp. 624-626, 2000.
- [75] G. E. Town, L. Chen, and P. W. E. Smith, “Dual wavelength modelocked fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1459-1461, 2000.
- [76] S. Li and K. T. Chan, “A novel configuration for multiwavelength actively mode-locked fiber laser using cascaded fiber Bragg grating,” *IEEE Photon. Technol. Lett.*, vol. 11, pp. 179-181, 1999.
- [77] D. Pudo, L. R. Chen, D. Giannone, L. Zhang, and I. Bennion, “Actively mode-lock tunable dual-wavelength erbium-doped fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 14, pp. 143-145, 2002.
- [78] Y. Yao, X. Chen, Y. Dai, and S. Xie, “Dual-wavelength erbium-doped fiber laser with a simple linear cavity and its application in microwave generation,” *IEEE Photon. Technol. Lett.*, vol. 18, pp. 187-189, 2006.
- [79] F. N. Timofeev, I. A. Kostko, P. Bayvel, O. Berger, R. Wyatt, R. Kashyap, I. F.

-
- Lealman, and G. D. Maxwell, "10 Gbit/s directly modulated, high temperature-stability external fiber grating laser for dense WDM network," *Electron. Lett.*, vol. 35, pp. 1737-1739, 1999.
- [80] A. Ezbiri and R. P. Tatam, "Passive signal processing technique for miniature Fabry-Perot interferometric sensor with a multimode laser diode source," *Opt. Lett.*, vol. 20, pp. 1818-1820, 1996.
- [81] N. Onodera, "THz optical beat frequency generation by modelocked semiconductor lasers," *Electron. Lett.*, vol. 32, pp. 1013-1015, 1996.
- [82] F. N. Timofeev, S. Benett, R. Griffin, P. Bayvel, A. J. Seeds, R. Wyatt, R. Kashyap, and M. Robertson, "High spectral purity millimeter-wave modulated optical signal generation using fiber grating lasers," *Electron. Lett.*, vol. 34, pp. 668-669, 1998.
- [83] P. V. Mamyshev, S. V. Chernikov, and E. M. Dianov, "Generation of fundamental soliton trains for high bit rate optical fiber communication lines," *IEEE J. Quantum Electron.*, vol. 27, pp. 2347-2355, 1991.
- [84] E. M. Dianov, P. V. Mamyshev, A. M. Prokhorov, and S. V. Chernikov, "Generation of a train of fundamental soliton at a high repetition rate in optical fiber," *Opt. Lett.*, vol. 14, pp. 1008-1010, 1989.
- [85] D. Derickson, *Fiber optic test and measurement*, Prentice Hall PTR, New Jersey, 1998.
- [86] T. Okoshi, K. Kikuchi, and A. Nakayama, "Novel method for high frequency resolution measurement of laser output spectrum," *Electron. Lett.*, vol. 16, pp. 630-631, 1980.

- [87] L. B. Mercer, "1/f frequency noise effects on self-heterodyne linewidth measurement," *J. Lightwave Technol.*, vol. 9, pp. 485-493, 1991.
- [88] S. V. Chernikov, J. R. Taylor, P. V. Mamyshev, and E. M. Dianov, "Generation of soliton pulse train in optical fiber using two CW singlemode diode lasers," *Electron. Lett.*, vol. 28, pp. 931-932, 1992.
- [89] Y. Matsui, M. D. Pelusi, S. Arahira, and Y. Ogawa, "Beat frequency generation up to 3.4 THz from simultaneous two-mode lasing operation of sampled-grating DBR laser," *Electron. Lett.*, vol. 35, pp. 472-474, 1999.
- [90] Y. Lai, W. Zhang, J. A. R. Williams, and I. Bennion, "An optical millimeter wave fiber laser," *OFC'03, TuL5*, pp. 238-239, 2003.
- [91] A. J. Ruggiero, M. W. Bowers, and R. A. Young, "Mini-AM DIAL system," *Laser and Electro-Optics (CLEO'99)*, CFE6, pp. 523, 1999.
- [92] Q. Mao and J. W. Y. Lit, "Switchable multiwavelength erbium-doped fiber laser with cascaded fiber grating cavities," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 612-614, 2002.
- [93] Y. W. Lee and B. Lee, "Wavelength-switchable erbium-doped fiber ring laser using spectral polarization-dependent loss element," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 795-797, 2003.
- [94] X. Feng, Y. Liu, S. Fu, S. Yuan, and X. Dong, "Switchable dual-wavelength ytterbium-doped fiber laser based on a few-mode fiber grating," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 762-764, 2004.
- [95] J. Sun, J. Qiu, and D. Huang, "Multiwavelength erbium-doped fiber lasers exploiting polarization hole burning," *Opt. Commun.*, vol. 182, pp. 193-197, 2000.

-
- [96] J. H. Cordero, V. A. Kozlov, A. L. G. Carter, and T. F. Morse, "Fiber laser polarization tuning using a Bragg grating in a Hi-Bi fiber," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 941-943, 1998.
- [97] Y. Liu, K. S. Chang, and P. L. Chu, "Generation of dual-wavelength picosecond pulses from a self-seeded Fabry-Perot laser diode and a polarization-maintaining fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1742-1744, 2004.
- [98] R. B. Dyott, J. R. Cozens, and D. G. Morris, "Preservation of polarization in optical fiber waveguides with elliptical cores," *Electron. Lett.*, vol. 15, pp. 380-382, 1979.
- [99] D. Wake, C. R. Lima, and P. A. Davies, "Optical generation of millimeter-wave signals for fiber-radio systems using a dual-mode DFB semiconductor laser," *IEEE Trans. Microw. Theory Tech.*, vol. 43, pp. 2270-2276, 1995.
- [100] A. Seeds, "Microwave photonics," *IEEE Trans. Microw. Theory Tech.*, vol. 50, pp. 877-887, 2002.
- [101] J. Capmany, B. Ortega, D. Pastor, and S. Sales, "Discrete-time optical processing of microwave signals," *J. Lightwave Technol.*, vol. 23, pp. 702-723, 2003.
- [102] J. Capmany, D. Pastor, and B. Ortega, "Microwave signal processing using optics," in *Proc. Optical Fiber Conf. (OFC)*, Anaheim, CA, pp. 23-76, 2005.
- [103] K. Jackson, S. Newton, B. Moslehi, M. Tur, C. Cutler, J. Goodman, and H. J. Shaw, "Optical fiber delay-line signal processing," *IEEE Trans. Microw. Theory Tech.*, vol. 33, pp. 193-204, 1985.
- [104] F. Zeng and J. Yao, "All-optical bandpass microwave filter based on an electro-optic phase modulator," *Optics Express*, vol. 12, pp. 3814-3819, 2004.

- [105] J. Mora, J. Capmany, A. Loayssa, and D. Pastor, "Novel technique for implementing incoherent microwave photonic filters with negative coefficients using phase modulation and single sideband selection," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1943-1945, 2006.
- [106] H. Zmuba and E. N. Toughlian, *Photonics Aspects of Modern Radar*. Boston, MA: Artech House, 1994.
- [107] D. B. Hunter and R. A. Minasian, "Reflectively tapped fiber optic transversal filter using in-fiber Bragg gratings," *Electron. Lett.*, vol. 31, pp. 1010-1012, 1995.
- [108] J. Capmany, B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *J. Lightwave Technol.*, vol. 24, pp. 201-209, 2006.
- [109] G. A. Ball, W. H. Glenn, and W. W. Morey, "Programmable fiber optic delay line," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 741-743, 1994.
- [110] D. B. Hunter and R. A. Minasian, "Tunable transversal filter based on chirped gratings," *Electron. Lett.*, vol. 31, pp. 2205-2207, 1995.
- [111] W. Zhang, J. A. R. Williams, L. A. Everall, and I. Bennion, "Fiber-optic radio frequency notch filter with linear and continuous tuning by using a chirped fiber grating," *Electron. Lett.*, vol. 34, pp. 1770-1772, 1998.
- [112] J. Capmany, D. Pastor, and B. Ortega, "New and flexible fiber-optic delay line filters using chirped Bragg gratings and laser arrays," *IEEE Trans. Microw. Theory Tech.*, vol. 47, pp. 1321-1327, 1999.
- [113] Y. Dai, X. Chen, X. Xu, C. Fan, and S. Xie, "High channel-count comb filter based on chirped sampled fiber Bragg grating and phase shift," *IEEE Photon. Technol. Lett.*, vol. 17, pp. 1040-1042, 2005.

-
- [114] D. Pastor and J. Capmany, "Fiber optic transversal filter using laser array and linearly chirped fiber grating," *Electron. Lett.*, vol. 34, pp. 1684-1685, 1998.
- [115] J. L. Yang, S. C. Tjin, and N. Q. Ngo, "Multiwavelength tunable fiber ring laser based on sampled chirp fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1026-1028, 2004.
- [116] H. L. An, X. Z. Lin, E. Y. B. Pun, and H. D. Liu, "Multi-wavelength operation of an erbium-doped fiber ring laser using a dual-pass Mach-Zehnder comb filter," *Opt. Commun.*, vol. 169, pp. 159-165, 1999.
- [117] A. Bellemare, M. Karasek, M. Rochette, S. LaRochelle, and M. Tetu, "Room temperature multifrequency erbium-doped lasers anchored on the ITU frequency grid," *J. Lightwave Technol.*, vol. 18, pp. 825-831, 2000.
- [118] S. Yamashita and T. Baba, "Spacing-tunable multiwavelength fiber laser," *Electron. Lett.*, vol. 37, pp. 1015-1017, 2001.
- [119] X. Dong, P. Shum, C. C. Chan, and X. Yang, "FSR-tunable Fabry-Pérot filter with superimposed chirped fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 184-186, 2006.
- [120] N. J. C. Libatique and R. K. Jain, "A broadly tunable wavelength-selectable WDM source using a fiber Sagnac loop filter," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1283-1285, 2001.
- [121] I. K. Hwang, S. H. Yun, and B. Y. Kim, "All-fiber tunable comb filter with nonreciprocal transmission," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1437-1439, 1998.
- [122] M. Janos and J. Canning, "Permanent and transient resonances thermally induced

- in optical fiber Bragg gratings,” *Electron. Lett.*, vol. 31, pp. 1007-1009, 1995.
- [123] M. G. Xu, A. T. Alavie, R. Maaskant, and M. M. Ohn, “Tunable fiber bandpass filter based on a linearly chirped fiber Bragg grating for wavelength demultiplexing,” *Electron. Lett.*, vol. 32, pp. 1918-1919, 1996.
- [124] C. J. S. de Matos, P. Torres, L. C. G. Valente, W. Margulis, and R. Stubbe, “Fiber Bragg grating characterization and shaping by local pressure,” *J. Lightwave Technol.*, vol. 19, pp. 1206-1211, 2001.
- [125] S. Y. Li, N. Q. Ngo, S. C. Tjin, P. Shum, and J. Zhang, “Thermally tunable narrow-bandpass filter based on a linearly chirped fiber Bragg grating,” *Opt. Lett.*, vol. 29, pp. 29-31, 2004.
- [126] S. Sandgren, B. Sahlgren, A. Asseh, W. Margulis, F. Laurell, R. Stubbe, and A. Lidgard, “Characterization of Bragg gratings in fibers with the heat-scan technique,” *Electron. Lett.*, vol. 31, pp. 665-666, 1995.
- [127] R. Kashyap, *Fiber Bragg gratings*, Academic Press, 1999.
- [128] H. B. Yu, W. Jin, Y. B. Liao, G. Stewart, B. Culshaw, H. L. Ho, and Y. H. Li, “A novel fiber-optic intra-cavity sensing network using a mode-locked fiber ring laser,” *Optical Fiber Sensors Conference (OFS)*, Portland OR, USA, vol. 1, pp. 507-510, 2002.
- [129] D. Pastor, J. Capmany, and B. Ortega, “Broad-band tunable microwave transversal notch filter based on tunable uniform fiber Bragg gratings as slicing filter,” *IEEE Photon. Technol. Lett.*, vol. 13, pp. 726-728, 2001.
- [130] D. Pastor, B. Ortega, J. Capmany, S. Sales, A. Martinez, and P. Munoz, “Optical microwave filter based on spectral slicing by use of arrayed waveguide gratings,”

- Opt. Lett.*, vol. 28, pp. 1802-1804, 2003.
- [131] J. -N. Maran, R. Slavik, S. L. LaRochelle, and M. Karasek, "Chromatic dispersion measurement using a multiwavelength frequency-shifted feedback fiber laser," *IEEE Trans. Instrum. Meas.*, vol. 53, pp. 67-71, 2004.
- [132] S. Yamashita, T. Baba, and Y. Namihiro, "Measurement of polarization mode dispersion (PMD) with a multiwavelength fiber laser," *IEICE Trans. Electron.*, vol. 86, pp. 59-62, 2003.
- [133] K. H. Han, E. S. Son, H. Y. Choi, K. W. Lim, and Y. C. Chung, "Bidirectional WDM PON using light-emitting diodes spectrum-sliced with cyclic arrayed-waveguide grating," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 2380-2382, 2004.
- [134] D. K. Jung, H. Kim, K. H. Han, and Y. C. Chung, "Spectrum-sliced bidirectional passive optical network for simultaneous transmission of WDM and digital broadcast video signals," *Electron. Lett.*, vol. 37, pp. 308-309, 2001.
- [135] D. S. Moon, U. -C. Paek, and Y. Chung, "Multi-wavelength lasing oscillations in an erbium-doped fiber laser using few-mode fiber Bragg grating," *Opt. Express*, vol. 12, pp. 6147-6152, 2004.
- [136] X. Feng, H. Y. Tam, and P. K. A. Wai, "Switchable multiwavelength erbium-doped fiber laser with a multimode fiber Bragg grating and photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1088-1090, 2006.
- [137] L. R. Chen, "Tunable multiwavelength fiber ring lasers using a programmable high-birefringence fiber loop mirror," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 410-412, 2004.
- [138] H. Chen, "Multiwavelength fiber ring laser by use of a semiconductor optical

Bibliography

amplifier,” *Opt. Lett.*, vol. 30, pp. 619-621, 2005.