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MICROWAVE GENERATION BASED ON FIBER BRAGG GRATING

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Acknowledgements

It was ever a sudden decision when I chose to pursue a PhD degree. However, I never felt regretful during my research period since I really learned a lot from my supervisor and my colleagues, not only in technical knowledge, but also in attitudes and the passion of life. There will be one day when I become old, the first memory script that will come to my mind, I believe, will be the beautiful days as a research student. The research experience will trigger me, encourage me, and excite me in my future work!

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Summary

Microwave generation in an optical way is of great interests since it has unique advantages over the traditional electrical methods. Using electric circuitry with several stages of frequency doubling to generate a microwave signal requires complicated and costly system setup. Moreover, the transmission of the electric signals also poses a problem due to large losses in the coaxial cables during data delivery. Optical fiber, because of its well-known advantages such as low transmission loss, light weight, immunity to electromagnetic interference, and low cost, has become an ideal medium to transfer data.

The main objective of this thesis is the optical generation of microwave signals, by heterodyning the output from a dual-wavelength laser at a photodetector. The dual-wavelength laser was realized by incorporating a fiber Bragg grating based dual-passband filter within a fiber laser cavity.

Fiber Bragg grating (FBG), a significant optical component for such microwave generation, has been widely utilized in fiber optics communication and fiber optics sensors since its first demonstration in 1978. Six different types of FBG structures, namely, uniform, apodized, chirped, phase-shifted, sampled, and tilted gratings have been well studied in the past three decades. In this thesis, a novel FBG structure which we name as inverse-Gaussian apodized FBG (IGAFBG) was designed and used as a dual-passband filter in a fiber laser. The principle, property, advantages, and application of the

IGA FBG are explained and explored in this report. Microwave at the designed frequency was realized using this IGA FBG filter.

In addition, frequency tunable microwave signals with a range of 20.16-24.196 GHz were also generated using IGA FBG by bonding the IGA FBG onto a cantilever and applying a displacement at the end of the cantilever, which forms a linear chirp to change the wavelength spacing of the two passbands in the filter. To obtain a higher microwave frequency tuning range of 8.835-24.36 GHz, phase-shifted FBG bonded onto a similar cantilever was used. To further extend the generated microwave frequency range beyond what the phase-shifted FBG mounted on the cantilever can achieve, a phase-shifted chirped FBG comprising a permanent π phase shift and a temporary π phase shift was used. The temporary π phase shift was induced by a platinum thin film heater. A tuning range from 6.88 to 36.64 GHz for the generated microwave signals was demonstrated. This range is limited only by the bandwidth of the stopband of the phase-shifted chirped FBG.

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List of Acronyms

CFBG	Chirped Fiber Bragg Grating
DWDM	Dense Wavelength Division Multiplexing
EDF	Erbium-Doped Fiber
EDFA	Erbium-Doped Fiber Amplifier
EPS-FBG	Equivalent Phase Shift Fiber Bragg Grating
ESA	Electrical Spectrum Analyzer
FBG	Fiber Bragg Grating
FFL	Feedback Fiber Loop
FP	Fabry-Perot
FSR	Free Spectral Range
IGA-FBG	Inverse-Gaussian Apodized Fiber Bragg Grating
OC	Optical Coupler
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
PC	Polarization Controller

PD	Photodetector
PM-FBG	Polarization-Maintaining Fiber Bragg Grating
PS-CFBG	Phase-Shifted Chirped Fiber Bragg Grating
PS-FBG	Phase-Shifted Fiber Bragg Grating
RI	Refractive Index
SA	Saturable Absorber
SCFBG	Sampled Chirped Fiber Bragg Grating
SLM	Single-Longitudinal-Mode
SOA	Semiconductor Optical Amplifier
TMM	Transfer Matrix Method
WDM	Wavelength Division Multiplexing

Chapter 1 Introduction

1.1 Background

Microwave, with frequencies ranging from 300 MHz to 300 GHz [1], or wavelengths from one meter to one millimeter, occupies a significant portion of the electromagnetic spectrum. Microwave has a huge number of applications in communication, radar, navigation, and power areas. For example, wireless Local Area Network (LAN) protocols such as Bluetooth and the IEEE 802.11 specifications use microwaves in the 2.4 GHz band. Many countries utilize licensed long-range Wireless Internet Access (WIA) services in the range of 3.5-4.0 GHz. Radar takes advantage of microwave radiation for air traffic control, weather forecasting, and navigation of ships. In addition, Global Navigation Satellite System (GNSS) such as the Global Positioning System (GPS) broadcasts navigational signals in a band between 1.2 GHz and 1.6 GHz. In power aspect, microwave oven is probably the most well-known invention that uses microwave for cooking or heating food. In this case, the microwave radiation operates at a frequency of around 2.45 GHz.

Microwave photonics, is an interdisciplinary topic combining the microwave and optical regimes, for applications such as sensor networks, instrumentation, radar, wireless communications [2-4] and so on. The combination takes advantage of low loss fiber component, reduced electromagnetic interference, broad bandwidth, and fast delivery of signal. Many research findings have been reported to study the functions of microwave photonics systems, which can be generally classified into four different categories [5]: 1.

use of optical fiber to transmit the microwave signals; 2. processing of microwave signals in the optical domain; 3, radio over fiber; 4, generation of microwave signals using optical heterodyning, as outlined in Fig. 1.1. Among these, optical generation of microwave is of numerous interests since it has advantages over the electrical method. The microwave generation using electric circuitry with several stages of frequency doubling [6] makes the entire system complicated and costly. Moreover, large loss of the electric signal transmission in the coaxial cables is not practical for remote delivery. It is well known that optical fiber has low transmission loss, light weight, is immune to electromagnetic interference, and supports the propagation of broad bandwidth waves. Hence, optically generating a microwave signal can provide significant convenience in data transfer and exchange, using the low-cost optical fiber as the transmission medium.

The principle of microwave generation in optical way is based on heterodyning of two optical waves with different frequencies at a photodetector, to produce an electrical signal with a frequency equal to the frequency difference of the two input waves. Two correlated optical wave sources are necessary to realize low phase noise microwave. To date, four major methods were used to optically generate a microwave signal, including optical injection locking [7,8], optical phase locked loop [9-13], external modulation [14-18], and dual-wavelength lasing [19-29]. Dual-wavelength laser is the focus of this research since the former three methods require an expensive microwave reference source and involve complicated setups. Two lasing lines from a single laser cavity can greatly reduce the system complexity and cost for microwave generation.

Fig. 1.1 The category of the applications of microwave photonics.

To achieve two lasing lines in a fiber laser, a good option is to incorporate a fiber Bragg grating filter in the laser cavity. Since its first demonstration by Hill *et al.* [30,31] in 1978, fiber Bragg grating (FBG), due to the permanent periodical refractive index modulation along the optical fiber core, has been intensely developed during past three decades. FBG has been widely employed in sensing applications, such as temperature and strain sensing [32,33], ultrasound sensing [34], current sensing [35,36], and so on, since the wavelength position of the narrow bandwidth reflected peak of FBG in spectrum is affected by the external perturbation. Also, FBG is an important optical element in fiber lasers, particularly acting as a filter to select a desired lasing wavelength.

Six different FBG structures [37] including uniform, chirped, apodized, phase-shifted, sampled, and tilted gratings, summarized in Fig. 1.2, have been well studied so

far, which will be explained in detail in chapter 2. To achieve a dual-passband filter for microwave generation, a novel FBG structure which is different from these six basic ones is particularly worth exploring, since this novel FBG structure has unique advantages compared to the other FBGs in producing two passbands, which will be illustrated in section 1.2.

Fig. 1.2 Classification of the structures of fiber Bragg grating.

1.2 Motivation

As mentioned in the previous section, a dual-wavelength laser is a good candidate to optically generate microwave signals. Each of the two wavelengths operating in single-longitudinal-mode (SLM) can be realized by incorporating a special structured FBG filter having two passbands in the fiber laser cavity, such as a phase-shifted (PS) FBG (PS-FBG) [20,21], an equivalent phase shift (EPS) FBG (EPS-FBG) [25,26], and an FBG pair [27-29]. In addition, an FBG inscribed in a polarization maintaining (PM) fiber to form

two reflected peaks [22-24] is an alternate choice. Unfortunately, all these FBG structures have some limitations. The fabrication of the PS-FBG requires a costly nanometer precision translation stage. The polarization maintaining FBG (PM-FBG) is inscribed in a PM fiber, which is more expensive than the standard single-mode fiber. An FBG pair owns a physical gap in the grating structure. Although an EPS-FBG only requires a relatively cheap translation stage with micrometer precision in fabrication, the sampling period of the grating in the experiment needs to be adjusted when compared to the calculated result. Also, there are physical gaps existing in the grating structure, which is not good in packaging due to the long grating length.

To overcome the above-mentioned limitations, a novel FBG structure needs to be developed, which is one primary motivation of this research. The proposed inverse-Gaussian apodized FBG (IGA-FBG) is a grating with no physical gaps in its structure. Moreover, only a relatively cheap micrometer precision translation stage is needed to vary the laser beam scanning speed. Furthermore, regular hydrogen loaded single-mode fiber is sufficient for the IGA-FBG fabrication.

Another major motivation of this research is to generate a frequency tunable microwave signal, based on an FBG tunable filter. So far, the reported works [20-23,25-28] can only generate a microwave signal at a certain fixed frequency, or a step-tunable frequency with very limited tuning range [29]. Continuous tunable microwave signal is significant in the applications of sensing and communication. Recently, one work [38] utilized three independent piezoelectric transducers to induce different phase-shift values on a single FBG, in which the wavelength spacing of the generated two lasing lines and thus the corresponding microwave frequency can be continuously tuned. However, three

costly piezoelectric transducers are required. Hence, it is necessary to explore some simple and low-cost setups to realize a tunable microwave signal. In this research, an IGAFBG, or a PS-FBG with two π phase shifts, bonded within a slanted slit of a cantilever which can provide a linear chirp, is proposed for tunable microwave generation. A phase-shifted chirped FBG (PS-CFBG) consisting of a permanent and a tunable π phase shift is also demonstrated to achieve a relatively large tuning range of the microwave frequency.

1.3 Objectives

Microwave generation using different structure FBGs including IGAFBG, PS-FBG, and PS-CFBG will be investigated.

One objective of the thesis is to investigate the physical principle of the IGAFBG when used as a passband filter. The spectral property of an IGAFBG is expected to be compared with those fundamental FBG structures, and its unique characteristic analyzed theoretically based on the simulation results. This new FBG structure will also be fabricated for testing in experiment.

Another aim of the project is to incorporate the IGAFBG with dual passbands in a fiber laser cavity, to generate dual-wavelength lasing. By heterodyning the dual wavelengths at a photodetector, a microwave signal at the desired frequency can be generated.

A frequency tunable microwave signal, based on an IGAFBG, or some other FBG structures such as PS-FBG and PS-CFBG, will also be explored in the project.

1.4 Major Contributions

Different from those traditional FBG structures such as uniform, apodized, chirped, phase-shifted, sampled, and tilted gratings, a novel FBG structure which we called the inverse-Gaussian apodized FBG (IGA FBG) is proposed. Instead of suppressing the sidelobes of a uniform FBG using a Gaussian apodization function, the sidelobes are enhanced by apodizing the grating with an inverse function. The number of the enhanced sidelobes in the reflection spectrum can be easily controlled by changing the grating length and the index modulation depth, and thus the number of the passbands in the corresponding transmission spectrum can be adjusted accordingly. The fabrication of the IGA FBG is a simple single-step scanning process using a standard phase-mask scanning technique, which shows its unique advantage over other FBG structures.

The IGA FBG with dual passbands was incorporated into a fiber laser cavity to generate dual-wavelength lasing. By heterodyning the two lasing wavelengths at a photodetector, a microwave signal was generated at a particular frequency. The proposed IGA FBG based dual-wavelength laser shows good stability and flexibility.

A frequency tunable microwave signal was achieved based on an IGA FBG bonded within the slanted slit of a cantilever. The cantilever provides a tunable linear chirp on the grating to change the wavelength spacing of the two passbands in the IGA FBG, and thus changing the microwave frequency.

A phase-shifted FBG consisting of two π phase shifts, bonded within the slanted slit of a cantilever, was also used to generate a tunable microwave signal. Through applying

different displacements on the cantilever, different chirp rates act on the grating to separate the wavelength spacing of the two passbands by different amounts.

To achieve a relatively large tuning range for the microwave, a phase-shifted chirped FBG with two π phase shifts is proposed, where one phase shift is permanently induced and the other is temporarily formed by a thermal head. A microwave signal with a tunable frequency ranging from 6.88 to 34.64 GHz is reported.

1.5 Organization of the Thesis

This thesis describes the author's progress and achievements during the research period. The content of the thesis is organized as follows.

Chapter 1 introduces the research background, motivation, objective and the contributions by the author.

Chapter 2 reviews the fundamental concept of FBG, including its filtering and sensing properties. Six basic and four advanced FBG structures were demonstrated, and their applications in fiber optics communication and fiber sensing are briefly described.

Chapter 3 describes the principle of microwave generation based on the optical heterodyning of two optical waves with different frequencies. The four major techniques used to produce low phase noise optical wave sources, including optical injection locking, optical phase locked loop, external modulation, and dual-wavelength lasing, are reviewed.

In chapter 4, a novel FBG structure, which is the inverse-Gaussian apodized FBG (IGAFBG), is proposed. The transmission and reflection spectra of an IGAFBG are

simulated, and the principle of an IGAFBG functioning as a dual-, triple-, and multi-passband filter is explained. The fabrication of an IGAFBG using a standard phase-mask scanning technique, employing a varying laser beam scanning speed, is illustrated, and some other inverse apodized FBGs, except IGAFBG is also discussed.

Chapter 5 describes the generation of a microwave signal from a dual-wavelength fiber laser, incorporating a dual-passband IGAFBG filter in the laser cavity. A dual-wavelength multi-longitudinal-mode erbium-doped fiber laser with a linear cavity was designed. To achieve an SLM operation for microwave generation, another erbium-doped fiber ring laser comprising an unpumped erbium-doped fiber (EDF) based saturable absorber was constructed. To further overcome the disadvantages of the saturable absorber, such as large loss within the EDF (greatly reduces the efficiency of the fiber laser), and careful control of the inherent power of the oscillating mode propagating into the EDF, a third laser cavity was built. In this cavity, we incorporated a semiconductor optical amplifier (SOA) operating in low-gain regime, to introduce inhomogeneous gain and to reduce gain competition, and a feedback fiber loop to ensure an SLM operation of each of the two lasing lines. In these three fiber lasers, IGAFBG serves as a dual-passband filter to generate dual-wavelength lasing.

Chapter 6 presents three different methods to obtain a frequency tunable microwave signal. One method is to provide a linear chirp on an IGAFBG to change the wavelength spacing of the two passbands in the grating. A cantilever was used to introduce a linear chirp and its operation principle is explained. A continuously tuned microwave signal from 20.16 GHz to 24.196 GHz, a tuning range of 4.036 GHz, was achieved. Instead of an IGAFBG that has a quite small tuning range, a phase-shifted FBG consisting of two π

phase shifts is used for tunable microwave generation. A cantilever is still utilized to provide a linear chirp on the phase-shifted FBG. As the applied chirp rate increases, the wavelength separation of the two passbands caused by the two phase shifts broadens, leading to an increase in the frequency of the generated microwave signal. Microwave signals ranging from 8.835 to 24.36 GHz with a tuning range of 15.525 GHz were obtained in experiment. To achieve a relatively large tuning range for the generated microwave, a dual-passband filter based on a phase-shifted chirped FBG is also proposed in chapter 6. One phase shift is permanently formed, while the other is temporarily generated by a thermal head. Due to the matching relationship between the position at the chirped grating and the wavelength of the thermal induced transmission peak, a wavelength spacing tunable filter is realized by scanning the thermal head along the grating. A continuously tuned microwave signal from 6.88 to 34.64 GHz, a tuning range of 27.76 GHz, was successfully obtained.

Chapter 7 summarizes the achievements of the research and makes recommendations for future extension of the work described in this thesis.

Chapter 2 Literature Review Part

One: Fiber Bragg Grating

2.1 Introduction

Fiber Bragg grating (FBG), which can be fabricated in the photosensitive fiber core of an optical fiber, has numerous applications in fiber optics communications and fiber optics sensors. In optical fiber communications, FBG can act as a dispersion compensator [39-41], a demultiplexer in wavelength division multiplexed (WDM) system [42], a tunable filter [43-46], and so on. This is due to the fact that the FBG possesses a narrow bandwidth reflected peak at the Bragg wavelength in its reflection spectrum. In fiber sensing applications, FBG can be used as a strain and temperature sensor [32,33,47,48], an ultrasound sensor [34,49], a current sensor [35,36], a refractive index sensor [50-55], and so on, since the reflected peak wavelength of the FBG is affected by external disturbances. Fig. 2.1 shows the schematic diagram of an FBG, in which a standard optical fiber consists of a core and a cladding, and the FBG is fabricated in the photosensitive fiber core by UV irradiation. A periodic refractive index modulation is created within the fiber core thus forming the grating structure. Lightwave can propagate within the fiber core by total internal reflection, since the refractive index of the fiber core is larger than that of the cladding. When a broad bandwidth lightwave is coupled into the FBG, some wavelengths will be reflected back, forming a narrow bandwidth reflection peak. The other wavelengths will pass through the grating and the transmission

spectrum will have a dip at the reflected wavelength, as shown in Fig. 2.1. Based on the coupled-mode theory at phase matching condition [56,57], the central wavelength λ_B in the reflection spectrum satisfies the following equation:

$$\lambda_B = 2n_{eff}\Lambda \quad (2.1)$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the propagated core mode, and Λ is the grating period.

Fig. 2.1 Schematic diagram of an FBG inscribed in an optical fiber and its operation principle.

2.2 Fundamental FBG Structures and Their Applications

FBGs have been classified broadly into the following six fundamental categories [37]: uniform, apodized, chirped, phase-shifted, superstructure, and tilted gratings. Each of these six fundamental FBG structures will be illustrated in the following sections.

2.2.1 Uniform FBG

Fig. 2.2(a) shows the variation of the effective refractive index along the length of a uniform FBG, which possesses a constant grating period and a constant index modulation depth. For the purpose of illustration, the grating period is not drawn to scale. Fig. 2.2(b) shows a reflection spectrum of a uniform FBG fabricated in the lab, using a 244 nm frequency-doubled argon laser and a uniform phase mask. It has a length of 1 cm, and a central wavelength of 1542.9 nm.

(a)

(b)

Fig. 2.2 (a) Variation of the effective refractive index along the length of a uniform FBG (not to scale); (b)

Experimentally measured reflection spectrum of a uniform FBG.

Note from Fig 2.2(b) that apart from the central wavelength, the reflected spectrum also contains other secondary peaks. These are called sidelobes and are a result of a finite grating length with abrupt beginning and ending of the refractive index variation in the fiber core (rectangular function). The Fourier transform of the “rectangular” function gives a *sinc* function and hence the reflected spectrum shown.

2.2.2 Gaussian apodized FBG

Since a uniform FBG has a finite grating length with an abrupt beginning and ending in the fiber core, the Fourier transform of this “rectangular” function yields a *sinc* function, leading to a reflection spectrum shown in Fig. 2.2(b). Apart from the desired central wavelength, the reflection spectrum also comprises multiple sidelobes, which may cause crosstalk problem when a series of uniform FBGs with nearby Bragg wavelengths are multiplexed. To suppress the sidelobes, a Gaussian apodization function can be employed on the uniform FBG, since the Fourier transform of a Gaussian function is still Gaussian. Therefore, the crosstalk problem can be solved. Fig. 2.3(a) shows the variation of the effective refractive index along the length of a Gaussian apodized FBG (not to scale), and Fig. 2.3(b) shows an experimentally measured reflection spectrum of a Gaussian apodized FBG with the sidelobes greatly suppressed, as an example.

(a)

(b)

Fig. 2.3 (a) Variation of the effective refractive index along the length of a Gaussian apodized FBG (not to scale); (b) Experimentally measured reflection spectrum of a Gaussian apodized FBG.

2.2.3 Chirped FBG

Linearly chirped FBG has a linear period variation along the grating length and can reflect a relatively broad bandwidth lightwave. Due to the matching relationship between the reflected wavelength and the grating position, a certain transverse load applied on the grating will create a corresponding ripple in the spectrum, and thus the chirped FBG can be used as a transverse strain sensor. Also, the chirped FBG is a well-known optical element for dispersion compensation [58-61] in fiber communication systems. Fig. 2.4(a) shows the variation of the effective refractive index along the length of a chirped FBG

(not to scale), while Fig. 2.4(b) shows an experimentally measured reflection spectrum of a 6 cm long chirped FBG, with a chirp rate of 2.25 nm/cm. It can be seen that, the bandwidth of the reflection spectrum is more than 18 nm, which is much broader than that of a uniform FBG shown in Fig. 2.2(b). Several techniques have been reported to fabricate a chirped FBG, such as utilizing a chirped phase mask [62], applying a varying strain on the fiber [63,64], bending the fiber [65], shifting the fiber with a varying speed during the UV beam scanning process [66], providing a gradient of temperature along the fiber [67], and changing the sampling period of a sampled FBG in a chirped way [68] .

(a)

(b)

Fig. 2.4 (a) Variation of the effective refractive index along the length of a chirped FBG (not to scale); (b) Experimentally measured reflection spectrum of a chirped FBG.

2.2.4 Phase-shifted FBG

Phase-shifted FBG is an FBG with a “phase jump” in its grating structure, as illustrated in Fig. 2.5(a). This type of FBG produces an ultra-narrow bandwidth passband in the stopband of the transmission spectrum. Normally a π phase shift is created by moving the fiber of $\Lambda/2$ in the center of the grating to form a passband in the middle of the stopband, where Λ is the grating period. The phase shift can be realized by either a special phase-shifted phase mask [69], UV post-processing [70], or thermal post-processing [71]. This type of grating has found applications in low-power all-optical switching [72], strain sensing [73], transverse load sensing [74], and distributed feedback lasing [75]. Fig. 2.5(b) shows an experimentally measured transmission spectrum of a phase-shifted FBG, in which an ultra-narrow passband is observed in the stopband window of the spectrum. The bandwidth of a PS-FBG can be as small as 0.4 pm [73].

(a)

(b)

Fig. 2.5 (a) Variation of the effective refractive index along the length of a phase-shifted FBG (not to scale);

(b) Experimentally measured transmission spectrum of a phase-shifted FBG.

2.2.5 Superstructure FBG

Superstructure FBG (or sampled FBG) consists of a series of sub-gratings of equal lengths, separated by identical physical gaps between the adjacent sub-grating sections, as illustrated in Fig. 2.6(a). The reflection spectrum of a sampled FBG comprises multiple reflection peaks of equal wavelength spacings. Fig. 2.6(b) shows a measured reflection spectrum of a sampled FBG, fabricated using the phase-mask scanning technique. A 5 cm long amplitude mask having a pitch of 450 μm is positioned between a photosensitive fiber and a phase mask with a pitch of 1066 nm. A gap of approximately 0.5 mm is set between the phase mask and the amplitude mask to ensure that the phase mask is not damaged in the fabrication process. The amplitude mask, which is made from a thin metal plate, is placed in contact with the photosensitive fiber. Since the sampled

FBG has multiple reflected peaks, it has been incorporated in a fiber laser cavity to generate multi-wavelength lasing [76].

(a)

(b)

Fig. 2.6 (a) Variation of the effective refractive index along the length of a sampled FBG (not to scale); (b) Experimentally measured reflection spectrum of a sampled FBG.

2.2.6 Tilted FBG

Tilted FBG is a grating having a tilt angle of θ with respect to the cross section of the optical fiber, as illustrated in Fig. 2.7(a). The nominal grating period satisfies the

following equation $\Lambda_g = \Lambda \cos \theta$, where Λ is the grating period along the fiber axis. This tilt structure brings a strong coupling of the forward propagating core mode and numerous backward propagating cladding modes, but provides a reduced coupling of the counter propagating core modes. The backward coupled cladding modes attenuate rapidly and thus the resonance wavelengths cannot be observed in the reflection spectrum, while occurring in the transmission spectrum. Fig. 2.7(b) shows the measured transmission spectrum of a tilted FBG with a tilt angle of 6° . Core mode resonance and numerous cladding mode resonances can be easily observed. Since the cladding mode index is affected by the refractive index (RI) of the medium surrounding the fiber, the tilted FBG can be used as an ambient RI sensor. Fig. 2.7(c) shows an extracted spectrum of Fig. 2.7(b) within a wavelength span of 3 nm. The blue line is the transmission spectrum of the tilted FBG in air, while the green line is the transmission spectrum when the grating is immersed in water. It can be seen that, there is a red shift of the cladding mode resonances when the ambient RI changes from 1 (in air) to 1.33 (in water).

(a)

(b)

(c)

Fig. 2.7 (a) Schematic diagram of a tilted FBG. Experimentally measured transmission spectrum of the grating with a tilt angle of 6° immersed (b) in air (within a wavelength span of 20 nm), and (c) in air and water (within a wavelength span of 3 nm).

2.3 Advanced FBG Structures and Their Applications

In previous sections 2.2.1-2.2.6, six fundamental FBG structures and their applications have been described. In recent years, some other novel advanced FBG structures have also been reported and will be briefly discussed here.

2.3.1 FBG pair

An FBG pair is a grating structure consisting of two identical sub-gratings of length L , having a physical gap, ΔL , between the two sub-gratings, as shown in Fig. 2.8(a). The refractive index modulation profile of an FBG pair is shown in Fig. 2.8(b). For illustration purpose, please note that the grating period is not drawn to scale. An FBG pair was fabricated, with L of 2 mm and ΔL of 10 mm, whose transmission spectrum is shown in Fig. 2.8(c). The identical and separated sub-gratings act as two reflectors, similar to the two massive mirrors in a bulk Fabry-Perot (FP) etalon. Due to the FP effect, a comb-like spectrum is formed. The free spectral range (FSR) of an FBG pair can be changed by selecting appropriate L and ΔL values under certain UV beam power. The FBG pair has been used as a multi-passband filter in a multi-wavelength laser [27,28].

Fig. 2.8 (a) Schematic diagram, (b) refractive index modulation profile (not to scale), and (c) measured transmission spectrum of an FBG pair.

2.3.2 Equivalent phase shift FBG

In section 2.2.4, a phase-shifted FBG was described. The fabrication of a phase-shifted FBG requires a high resolution (normally several nanometer precision) piezoelectric transducer to generate the phase shift in the grating structure. Another FBG structure, which is called the “equivalent phase shift FBG (EPS-FBG)”, was designed to generate a phase shift, but requires only a submicrometer precision controller during fabrication and thus the setup cost can be greatly reduced. By changing one of the sampling periods to 1.5 times the original sampling period of a sampled FBG, as shown in Fig. 2.9(a), an equivalent phase-shift can be formed in the stopband of the odd Fourier order reflection peaks [77]. Fig. 2.9(b) shows the refractive index modulation profile (not drawn to scale) of an EPS-FBG. Fig. 2.9(c) shows a measured spectrum of an EPS-FBG given in Ref. [77]. The detailed structure analysis can be found in Ref. [77] as well. Generally, the EPS in the -1 order Fourier reflection peak has the largest reflectivity, compared to the ones in the other odd Fourier reflection peaks, and no EPS exists in the peaks with even Fourier orders [77]. This can be clearly observed in Fig. 2.9(c). The dip caused by the EPS in the -1 order peak cannot be resolved due to the limited resolution of the optical spectrum analyzer (OSA). Hence, EPS-FBG is an alternate way to generate a phase shift in the stopband of a grating. Due to the ultra-narrow bandwidth passband, the EPS-FBGs can ensure single-longitudinal-mode operation for each of the lasing wavelengths from fiber lasers [25,26].

Fig. 2.9 (a) Schematic diagram, (b) refractive index modulation profile (not to scale), and (c) measured transmission spectrum (given in [77]) of an equivalent phase shift FBG.

2.3.3 Sampled chirped FBG

Instead of using a uniform phase mask to fabricate a sampled FBG, a chirped phase mask can be utilized to generate a sampled chirped FBG (SCFBG). Fig. 2.10(a) shows the refractive index modulation profile (not drawn to scale) of an SCFBG. The SCFBG has an advantage of decoding the position information, since there is a matching relationship between the wavelength of the reflected peaks and the grating position. The reason is that, an SCFBG can be treated as a series of small gratings with varying periods, leading to different wavelength peaks in spectrum, as shown in Fig. 2.10(b) which is an experimentally measured spectrum of an SCFBG. The chirped phase mask used in this case has a length of 3 cm and a chirp rate of 2.25 nm/cm. The sampling period of the grating, which is defined as $L + \Delta L$ in Fig. 2.10(a), is 6 mm. In each sampling, there is a 2 mm grating section followed by a 4 mm blank section. The SCFBG has found applications in a multi-wavelength laser [78], pressure mapping at the prosthetic knee joint [79], a load and position sensor [48], and so on.

(a)

Fig. 2.10 (a) Refractive index modulation profile (not to scale) and (b) experimentally measured reflection spectrum of a sampled chirped FBG.

2.3.4 Phase-shifted chirped FBG

Finally, another variation of the six standard FBG structures is the phase-shifted chirped FBG (PS-CFBG). This FBG structure incorporates a π phase shift within a chirped FBG, as shown in Figs. 2.11(a) and (b), creating an ultra-narrow bandwidth passband in the stopband of the chirped grating. The phase shift can be realized by three different methods, such as providing a displacement between the fiber and the phase mask during the UV light scanning process [80], UV post-processing [70], and thermal post-processing [43]. Fig. 2.11(c) shows a measured transmission spectrum of a PS-CFBG, in which the phase shift is caused by the heat from a thermal head. This type of FBG has been used as a tunable filter in a tunable fiber laser [81].

Fig. 2.11 (a) Schematic diagram and (b) refractive index modulation profile (not to scale) of a phase-shifted chirped FBG; (c) Measured transmission spectrum of the chirped FBG with a phase shift caused by the heat from a thermal head.

The above-mentioned PS-FBG, FBG pair, and EPS-FBG have already been used to generate microwave signals [20,21,25-29], acting as dual-passband filters in fiber lasers. However, the fabrication of the PS-FBG requires a costly nanometer precision translation stage to ensure that a correct and precise phase shift is inscribed in the grating. An FBG pair owns a physical gap in the grating structure. For the EPS-FBG, the sampling period of the grating in the experiment needs to be adjusted when compared to the calculated result, and there are also physical gaps existing in the grating structure, which is not good in packaging due to the long grating length. It is necessary to develop a novel FBG structure to overcome these limitations. By comparison, the proposed inverse-Gaussian apodized FBG (IGA-FBG) is a grating structure with no physical gaps, and only a relatively cheap micrometer precision translation stage is needed to vary the laser beam scanning speed. The detailed study of the IGA-FBG will be described in chapter 4.

2.4 Chapter Summary

In this chapter, the concept and operation principle of FBG have been described. In addition, six fundamental FBG structures and their applications have also been introduced, including uniform, apodized, chirped, phase-shifted, superstructure, and tilted gratings.

Apart from these commonly used FBG structures, some other advanced FBG structures, such as an FBG pair, an equivalent phase shift FBG, a sampled chirped FBG, and a phase-shifted chirped FBG, have also been illustrated. These various FBG structures were designed and investigated by the various groups for specific applications.

In this thesis, I will introduce a novel FBG structure that has not been investigated thus far. The need of a new structure arises from the need to optically generate a microwave signal precisely using a simple and low cost technique. This new FBG structure will be described in detail in chapter 4 of this thesis.

Chapter 3 Literature Review Part

Two: Optical Generation of

Microwave Signals

3.1 Introduction

Optical generation of microwave signals is of great interests since it has unique advantages over the electrical method of generating microwave signals, in that the electric circuitry needed to generate the signals requires several stages of frequency doubling [6], making the entire system complicated and costly. Moreover, large losses of the electric signal transmitted through the coaxial cables make remote delivery of the electrical signal impractical. As known, optical fiber has low transmission loss, light weight, is immune to electromagnetic interference, and supports the propagation of broad bandwidth light waves. Therefore, optically generating a microwave signal can provide significant convenience in data transfer, using the low-cost optical fiber as the transmission medium.

The principle of optical microwave generation is based on heterodyning of two optical waves with different frequencies at a photodetector. An electrical signal with a frequency equal to the frequency difference of the two input waves can be generated, which will be explained in detail in section 3.2. To realize low phase noise microwave

signal, two correlated optical wave sources are needed. In section 3.3, I will review the four major techniques used to produce correlated optical wave sources, including optical injection locking, optical phase locked loop, external modulation, and dual-wavelength lasing.

3.2 Principle of Microwave Generation by Optical Heterodyning

Microwave signals can be generated by optical heterodyning, in which two optical waves at slightly different wavelengths are made to beat at a photodetector, as illustrated in Fig. 3.1.

Fig. 3.1 Operation principle for optical heterodyne generation employing a high-frequency photodetector.

The frequencies of the two optical input waves are in the infrared region near 200 THz, whereas the difference frequency of the generated output signal is much lower and in the microwave region.

For simplicity of analysis, let us assume that these two optical input waves are linearly polarized monochromatic plane waves propagating in the $+z$ direction. The complex electrical field vectors of the two waves can be expressed as [82]:

$$\mathbf{E}_1 = E_1 e^{j(\omega_1 t - k_1 z + \varphi_1)} \mathbf{e}_1 \quad (3.1)$$

$$\mathbf{E}_2 = E_2 e^{j(\omega_2 t - k_2 z + \varphi_2)} \mathbf{e}_2 \quad (3.2)$$

where E_1 and E_2 are the field amplitudes, ω_1 and ω_2 are the angular frequencies, k_1 and k_2 are wave numbers, φ_1 and φ_2 are the phases, and $\mathbf{e}_1$ and $\mathbf{e}_2$ are the unit vectors determining the orientation of the two electrical field vector of the input waves, respectively.

The intensity of the superimposed wave of the two input waves is given by the magnitude of their Poynting vectors that are described by [82]:

$$I_1 = \frac{1}{2} \sqrt{\frac{\varepsilon_r \varepsilon_0}{\mu_0}} |\mathbf{E}_1|^2 \quad (3.3)$$

$$I_2 = \frac{1}{2} \sqrt{\frac{\varepsilon_r \varepsilon_0}{\mu_0}} |\mathbf{E}_2|^2 \quad (3.4)$$

where ε_0 and ε_r are the permittivities of free space and the medium, respectively, and μ_0 is the permeability of free space.

If the two input waves are ideal plane waves with the same polarization, i. e., $\mathbf{e}_1 = \mathbf{e}_2$, the resulting electric field will be the sum of the two input fields, expressed as:

$$\mathbf{E}_0 = \mathbf{E}_1 + \mathbf{E}_2 \quad (3.5)$$

By squaring the absolute value of both sides, we have

$$\begin{aligned} |\mathbf{E}_0|^2 &= |\mathbf{E}_1 + \mathbf{E}_2|^2 = |\mathbf{E}_1|^2 + |\mathbf{E}_2|^2 + \mathbf{E}_1 \mathbf{E}_2^* + \mathbf{E}_1^* \mathbf{E}_2 \\ &= |\mathbf{E}_1|^2 + |\mathbf{E}_2|^2 + 2|\mathbf{E}_1||\mathbf{E}_2| \cos[(\omega_2 - \omega_1)t - (\varphi_2 - \varphi_1)] \end{aligned} \quad (3.6)$$

Hence, the intensity of the superimposed wave can be written as [82]:

$$I_0 = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[(\omega_2 - \omega_1)t - (\varphi_2 - \varphi_1)] \quad (3.7)$$

When the optical interference wave incidences on a photodetector, the generated photocurrent can be expressed as [82]:

$$i = \eta_0 \frac{q}{hf_1} P_1 + \eta_0 \frac{q}{hf_2} P_2 + 2\eta_{fc} \frac{q}{h} \sqrt{\frac{P_1 P_2}{f_1 f_2}} \cos[(\omega_2 - \omega_1)t - (\varphi_2 - \varphi_1)] \quad (3.8)$$

where q is the charge of an electron, h is the planck constant, f_1 and f_2 are the frequencies of the input waves, P_1 and P_2 denote the power levels of the two optical input waves, and η_0 and η_{fc} are the DC and high-frequency quantum efficiencies of the photodetector, respectively. It should be noted that, the transit time limitations, or microwave losses affect the high-frequency performance of the photodetector, and typically the DC efficiency η_0 , is much larger than the high-frequency efficiency η_{fc} [82]. In addition, the frequencies of the two input waves are normally close to each other, i. e., $(f_1 \approx f_2) = f_{eq}$, and are far larger than their difference frequency ($f_c = f_1 - f_2$). For instance, if the input waves are operating at $\lambda_1 = 1550 \text{ nm}$ and $\lambda_2 = 1550.2 \text{ nm}$, their corresponding frequencies are $f_1 = 193.4 \text{ THz}$ and $f_2 = 193.375 \text{ THz}$. The frequency difference is only $f_c = 25 \text{ GHz}$,

which is many orders of magnitude smaller than the frequency that corresponds to 1550 nm or 1550.2 nm.

By further assuming the power levels of the two input waves are similar, i. e., $P_1 = P_2 = P_{opt}$, Eq. (3.8) can be simplified as [82]:

$$i = 2s_0P_{opt} + 2s_{f_c}P_{opt} \cos[2\pi f_c t - \Delta\varphi] \quad (3.9)$$

in which,
$$s_0 = \eta_0 \frac{q}{hf_{eq}} \quad (3.10)$$

$$s_{f_c} = \eta_{f_c} \frac{q}{hf_{eq}} \quad (3.11)$$

where s_0 and s_{f_c} are the DC and high frequency responsivities of the photodetector, and $\Delta\varphi = \varphi_2 - \varphi_1$.

The first term in Eq. (3.9) is the DC photocurrent generated by the constituent optical input waves, and the second term is the desired electrical signal oscillating at the frequency of f_c , which represents the frequency of the generated microwave signal. This resultant frequency can then be monitored by an electrical spectrum analyzer.

To realize low phase noise in the microwave signal, two correlated optical wave sources will be needed. Several different techniques can produce these two correlated optical wave sources, and they will be illustrated in section 3.3.

3.3 Optical Microwave Generation Using Different Techniques

The principle of microwave generation based on optical heterodyning has been described in section 3.2. A microwave signal can be obtained by beating two optical waves of different wavelengths at a photodetector. However, using two free-running laser diodes, even if their polarization plane matches, will produce a microwave signal with high phase noise, since the two input optical waves are not correlated. To obtain a low phase noise microwave signal, four major techniques have been explored in recent years, including optical injection locking [7,8], optical phase locked loop [9-13], external modulation [14-18], and dual-wavelength lasing [19-29].

3.3.1 Optical injection locking

To achieve two coherent optical waves, an optical injection locking system was built by Goldberg *et al.* [7], as shown in Fig. 3.2. In his setup, a reference oscillator is used to modulate the master laser, whose output is injected into two slave lasers. The wavelengths of the two slave lasers are locked to the +2 and -2 order sidebands of the master laser. Hence, the output wavelengths from the two slave lasers are phase correlated with one another.

Fig. 3.2 Optical injection locking system with a master laser and two slave lasers. [7]

3.3.2 Optical phase locked loop

Optical phase locked loop [5] is another technique used to achieve phase coherence between two light waves. As shown in Fig. 3.3, the phase of laser 1 is locked to that of laser 2 electrically via a feedback loop circuit. A heterodyned beat signal at a photodetector is obtained, whose phase is compared with an RF reference at a mixer which is then connected to an amplifier followed by a low-pass loop filter. Under a proper feedback loop gain and response time, the phase of the beat signal can be locked to the external RF reference signal.

Fig. 3.3 Optical phase lock loop setup. [5]

3.3.3 External modulation

Two coherent optical wave sources can also be achieved, through the external modulation approach [17]. Fig. 3.4 shows the block diagram of the experimental setup by the external modulation approach [17]. A laser beam is passed through a Mach-Zehnder modulator, whereby the odd-order sidebands are suppressed. The optical carrier wavelength is filtered by the notch filter leaving only the +2 and -2 order sidebands at the output. A beat signal can be obtained by heterodyning the two lasing lines at +2 and -2 order sidebands using a photodetector.

Fig. 3.4 Microwave generation based on external modulation technique. [17]

3.3.4 Dual-wavelength lasing

As can be seen from sections 3.3.1-3.3.3, a microwave reference source is needed in the system setup to generate the two correlated light waves for microwave generation. At the point of writing this thesis, a regular microwave reference source typically costs US\$ 30k or more. In recent years, researchers have used dual-wavelength lasers to generate microwave signals [19-24,26,27,29]. The advantage of this method is that no microwave source is needed in the system which will lead to significant reduction of the system cost. Although the dual lasing lines from a dual-wavelength laser are not phase locked, the two wavelengths come from the same laser cavity, and thus the phase correlation between them is generally much better than the case of using two free-running lasers.

Fig. 3.5 shows a schematic diagram of a dual-wavelength fiber laser that can generate microwave signals, as proposed by Chen *et al* [25]. In the laser ring cavity, a semiconductor optical amplifier (SOA), instead of erbium doped fiber (EDF), is used as the gain medium to avoid homogeneous line broadening. FBG1 is an equivalent-phase-shift FBG (EPS-FBG) with two ultra-narrow bandwidth passbands. FBG2 comprises of two superimposed regular FBGs having two different center wavelengths and hence, two reflection peaks. This superimposed FBG is used to filter out the two passbands of FBG1. A polarization controller (PC) is used to fine tune the cavity birefringence. The laser output is captured by an optical spectrum analyzer (OSA), and a microwave signal is obtained by heterodyning the dual lasing lines at a photodetector (PD) and monitored by an electrical spectrum analyzer (ESA). The measured wavelength spacing of the dual lasing lines is 0.147 nm, corresponding to a microwave signal of ~18.4 GHz frequency.

Instead of using the EPS-FBG as FBG 1 in Fig. 3.5, PS-FBG with two π phase shifts [21] can also be used as an alternate way to form dual-wavelength lasing.

Fig. 3.5 Schematic diagram of the fiber ring laser to generate microwave using an EPS-FBG. [25]

Another method to generate dual-wavelength lasing is to incorporate an FBG pair into a linear cavity [27]. As shown in Fig. 3.6, a section of EDF acts as the gain medium. The pump light from a laser diode is injected into the linear cavity through a wavelength division multiplexer (WDM). The FBG pair comprising two uniform FBGs (FBG1 and FBG2) is connected between port 1 and port 3 of an optical circulator. The FBG pair serves as a dual-passband filter, and FBG3 is a uniform FBG to filter out the two passbands of the FBG pair. A microwave signal at 9.616 GHz was achieved by heterodyning the dual-lasing lines at a photodetector [27].

Fig. 3.6 Schematic diagram of the fiber laser to generate microwave using an FBG pair. [27]

To incorporate polarization-maintaining FBGs (PM-FBGs) in the linear cavity of a fiber laser, dual-wavelength lasing lines can also be achieved [23]. Fig. 3.7 shows the configuration of the dual-wavelength laser. The cavity consists of two wavelength matched PM-FBGs that are written in a PM-EDF with high erbium concentration. FBG1 has a length of 12 mm, reflectivity of 80%, and 3 dB bandwidth of around 0.1 nm. FBG2 has a length of 8 mm, reflectivity of 99%, and 3 dB bandwidth of around 0.3 nm. PM-FBG exhibits two reflected peaks with orthogonal polarization modes, since the refractive indices along the fast and slow axes of the PM fiber are different. Hence, dual-wavelength lasing can be formed in the distributed-Bragg-reflector laser. The obtained wavelength spacing of the two lasing wavelengths is 0.374 nm.

Fig. 3.7 Schematic diagram of the fiber laser to generate microwave using two PM-FBGs. [23]

As illustrated above, researchers had incorporated a PS-FBG [20,21], an EPS-FBG [25,26], an FBG pair [27-29], or a PM-FBG [22,23] in the fiber laser cavity, to achieve dual-wavelength lasing. However, each of these FBG structures has some drawbacks. The fabrication of the PS-FBG requires a nanometer precision translation stage (thus high cost). The PM-FBG was inscribed in a PM fiber, which is more expensive than the standard single-mode fiber. An FBG pair includes a physical gap in the grating structure. Although an EPS-FBG requires only a relatively cheap translation stage with micrometer precision in fabrication, the sampling period of the grating in the experiment needs to be adjusted when compared to the calculated result. Also, there are physical gaps in the grating structure, which is not good in packaging due to the long grating length.

To overcome the above-mentioned drawbacks, a novel FBG structure called inverse-Gaussian apodized FBG (IGAFBG) was proposed and will be introduced in chapter 4. The fabrication of the IGAFBG is a simple one-step scanning process. Moreover, the IGAFBG was inscribed in a low cost standard hydrogen loaded fiber and there is no physical gap in its structure.

3.4 Chapter Summary

In this chapter, I have laid out the principle of microwave generation based on optical heterodyning of two optical waves with different frequencies. The four major methods used to produce correlated optical wave sources, including optical injection locking, optical phase locked loop, external modulation, and dual-wavelength lasing, have been reviewed. Among the four methods, dual-wavelength lasing has an advantage in that no microwave reference source is required and thus the system cost can be greatly

reduced. Several dual-wavelength fiber lasers using EPS-FBG, PS-FBG, FBG pair, or PM-FBG, have been studied.

In the next chapter, I will introduce a new FBG structure which we named as “inverse-Gaussian apodized fiber Bragg grating (IGA-FBG)”. As it turns out, this new FBG structure can be used effectively for dual-wavelength lasing, which when heterodyned at the photodetector, will generate microwave signals.

Chapter 4 Inverse-Gaussian

Apodized Fiber Bragg Grating

4.1 Introduction

A uniform FBG is the simplest type of FBGs that is characterized by a narrow bandwidth reflection spectrum at the Bragg wavelength. However, a normal uniform FBG has large sidelobes due to its finite grating length. For certain applications, these sidelobes pose a problem. For example, in Dense Wavelength Division Multiplexing (DWDM) applications where multiple wavelength light signals are transmitted through the optical fiber, these sidelobes limit the number of optical wavelengths that can be used if cross-talk is to be avoided. Hence for this application, it is desirable that the sidelobes are significantly suppressed. The sidelobes can be suppressed using a commonly used apodization function which is generally a Gaussian function [37], since the Fourier transform of the Gaussian function yields a Gaussian-like reflection spectrum. To date, no group has explored the applications for the case where the sidelobes are enhanced. This is understandable since sidelobes are a nuisance in DWDM application and play no part in sensor application. My interest to explore sidelobe enhancement arises from the motivation of this thesis, which is to optically generate microwave signals in an effective way. Sidelobes are secondary wavelength peaks in the reflection spectrum of an FBG. After enhancing the sidelobes we can obtain a corresponding transmission spectrum with multi passband peaks which are caused by the gaps between the lobes in the reflection

spectrum, and the wavelength separation of the passband peaks corresponds closely to the microwave signal frequency. Hence if these sidelobes can be enhanced, it would be possible for us to develop a closely-spaced and ultra-narrow dual-passband filter that, when incorporated into a fiber laser system, can be used to generate microwave signals as described in chapter 3.

To enhance the sidelobes of an FBG, I employed the same technique used to suppress the sidelobes except that, instead of using a Gaussian apodization function, I have used an inverse-Gaussian function. I have termed the new FBG structure as the inverse-Gaussian apodized FBG (IGAFBG). As it turns out, the number of the sidelobes that can be enhanced in an IGAFBG can be flexibly controlled during the fabrication process, by controlling the laser beam power and the grating length. It is also established that, in its transmission spectrum, the IGAFBG does form dual (non-identical or identical) ultra-narrow bandwidth passbands with a flexible designed wavelength spacing, or multi passbands with varied “free spectral ranges (FSRs)”. In the next few sections, I will present the simulation results of IGAFBG, and demonstrate the fabrication of the IGAFBG. In section 4.7, I will also briefly introduce some other types of the inverse apodized FBGs.

4.2 Spectrum Simulation of IGAFBG Using the Transfer Matrix Method

Transfer matrix method (TMM) is chosen to do the spectrum simulation due to its efficiency compared to the Runge-Kutta numerical integration method [37]. An FBG

structure fabricated using UV interference possesses a periodical refractive index variation that can be expressed as [37]:

$$\delta n_{eff}(z) = \overline{\delta n_{eff}}(z) \left\{ 1 + v \cos \left[\frac{2\pi}{\Lambda} z + \Phi(z) \right] \right\} \quad (4.1)$$

where $\overline{\delta n_{eff}}$ is the “dc” index change spatially averaged over a grating period, also referred as the index modulation depth, v is the fringe visibility of the index change, Λ is the nominal grating period, and $\Phi(z)$ describes grating chirp.

The electric fields of the electromagnetic waves propagating within an FBG can be separated into a forward and a backward propagating component with amplitudes of R and S , respectively. With TMM we divide the grating into m uniform sub-sections, using R_i and S_i to represent the field amplitudes of the forward and backward propagating components of the electromagnetic waves after traversing the i^{th} section of the FBG. At the end of the grating, $R_0 = R\left(\frac{L}{2}\right) = 1$, and $S_0 = S\left(\frac{L}{2}\right) = 0$, assuming the grating to span from $-\frac{L}{2}$ to $\frac{L}{2}$ in the z direction. The relationship of the field magnitudes between two adjacent sub-sectional gratings is described by:

$$\begin{bmatrix} R_i \\ S_i \end{bmatrix} = F_i \begin{bmatrix} R_{i-1} \\ S_{i-1} \end{bmatrix} \quad (4.2)$$

from which the matrix can be expressed as:

$$F_i = \begin{bmatrix} \cosh(\gamma_B \Delta z) - i \frac{\sigma}{\gamma_B} \sinh(\gamma_B \Delta z) & -i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) \\ i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) & \cosh(\gamma_B \Delta z) + i \frac{\sigma}{\gamma_B} \sinh(\gamma_B \Delta z) \end{bmatrix} \quad (4.3)$$

where Δz is the length of i^{th} sub-sectional grating, σ is the “dc” self-coupling coefficient, κ is the “ac” coupling coefficient, and $\gamma_B = \sqrt{\kappa^2 - \sigma^2}$.

For a single-mode fiber,

$$\sigma(z, \lambda) = 2\pi n_{\text{eff}} \left(\frac{1}{\lambda} - \frac{1}{\lambda_D} \right) + \frac{2\pi}{\lambda} \overline{\delta n_{\text{eff}}}(z) - \frac{1}{2} \frac{d\Phi}{dz} \quad (4.4)$$

$$\kappa(z) = \frac{\pi}{\lambda} v \overline{\delta n_{\text{eff}}}(z) \quad (4.5)$$

where $\lambda_D \equiv \lambda_B$ is the designed wavelength for an infinitesimally weak Bragg grating ($\delta n_{\text{eff}} \rightarrow 0$).

Based on Eqs. (4.2)-(4.5), R_m and S_m can be calculated from:

$$\begin{bmatrix} R_m \\ S_m \end{bmatrix} = F \begin{bmatrix} R_0 \\ S_0 \end{bmatrix}; \quad F = F_m F_{m-1} \dots F_i \dots F_1 \quad (4.6)$$

From Eq. (4.6), $m \sim 100$ is sufficient for most apodized and chirped gratings. It should be noted that coupled mode theory is not valid when the sub-sectional grating length is only a few grating periods long [37].

The reflectivity of the grating can then be calculated as:

$$r = \left| \frac{S_m}{R_m} \right|^2 \quad (4.7)$$

The transmittivity of the grating is thus:

$$t = 1 - r \quad (4.8)$$

One more thing should be pointed out is that, for an apodized grating with a linear chirp, the “dc” self-coupling coefficient can be expressed as [37]:

$$\sigma(z, \lambda) = 2\pi n_{\text{eff}} \left(\frac{1}{\lambda} - \frac{1}{\lambda_D} \right) + \frac{2\pi}{\lambda} \overline{\delta n_{\text{eff}}}(z) + \frac{4\pi n_{\text{eff}} z (cr)}{\lambda_D^2} \quad (4.9)$$

in which,

$$\overline{\delta n_{\text{eff}}}(z) = \overline{\delta n_{\text{eff}}} A(z) \quad (4.10)$$

where $A(z)$ is defined as the apodization function, and cr is the chirp rate of the grating.

A commonly used apodization function for DWDM application to suppress the sidelobes is a Gaussian function given by:

$$A(z) = \exp \left[\frac{-4(\ln 2) z^2}{(L/3)^2} \right] \quad (4.11)$$

To enhance the sidelobes, we employed a function as follows:

$$A(z) = 1 - \exp \left[\frac{-4(\ln 2) z^2}{(L/3)^2} \right] \quad (4.12)$$

This function is an inverse of a Gaussian function.

4.3 IGAFBG as a Dual-Wavelength Passband Filter

4.3.1 Principle of IGAFBG

Using the TMM, the reflection and transmission spectra of an IGAFBG can be simulated, as shown in Fig. 4.1. In calculation, $n_{eff} = 1.45$, $L = 1.2$ cm, $\lambda_D = 1550$ nm, and $\overline{\delta n_{eff}} = 2.5 \times 10^{-4}$ were used, and $A(z)$ is given in Eq. (4.12). Fig. 4.2 shows the effective refractive index variation along the fiber axis of an IGAFBG, in which the average index variation (dashed line) has an inverse-Gaussian distribution. Note that the grating period is not drawn to scale. It can be seen from Fig. 4.2 that, the grating structure of the IGAFBG is different from those fundamental ones described in chapter 2.

(a)

(b)

Fig. 4.1 (a) Calculated reflection spectrum of an IGAFBG described by Eq. (4.12); (b) the corresponding transmission spectrum of this IGAFBG. In simulation, $n_{eff} = 1.45$, $L = 1.2$ cm, $\lambda_D = 1550$ nm, and

$$\overline{\delta n_{eff}} = 2.5 \times 10^{-4}.$$

Fig. 4.2 Effective refractive index variation along the fiber axis of an IGAFBG, the dashed line is an inverse-Gaussian distribution.

To fully appreciate the special property of an IGAFBG, the reflection spectra of a uniform FBG and a Gaussian apodized FBG are also simulated with the same parameter

values as the IGAFBG, but with $A(z) = 1$ and $A(z) = \exp\left\{\left[-4(\ln 2)z^2\right]/(L/3)^2\right\}$, as shown in Figs. 4.3 and 4.4, respectively. It can be seen from Fig. 4.3 that, the uniform FBG possesses sidelobes at both the short-wavelength and long-wavelength side of the Bragg wavelength, with the main lobe saturated since this is a strong grating. In a traditional Gaussian apodized grating, as shown in Fig. 4.4, the average refractive index is not uniform along the length of the grating. Sidelobes are still present on the short-wavelength side of the Bragg wavelength, but no sidelobe on the long-wavelength side is observed. This is due to the non-uniform “dc” index change caused by the Fabry-Perot effect [83]. Singh *et al.* [84] explained that the suppression of sidelobes on the short wavelength side of the Bragg wavelength is not pronounced because of the self-induced chirp between the two ends of the grating, decreasing the resonant wavelengths on both ends of the grating rather than the resonant wavelength in the central part of the grating. Hence, sidelobes only exist on the short-wavelength side of the spectrum. The inverse-Gaussian apodization function is equal to unity minus the commonly used Gaussian apodization function. In this case, the resonant wavelengths on both ends of the grating are larger than the resonant wavelength in the central portion of the grating, and hence, the sidelobes on the long-wavelength side of the spectrum become enhanced, while no sidelobe enhancement occurs on the short-wavelength side of the Bragg wavelength, as shown in Fig. 4.1(a).

Fig. 4.3 Calculated reflection spectrum of a typical uniform FBG without apodization, which means $A(z) =$

1. In simulation, $n_{eff} = 1.45$, $L = 1.2$ cm, $\lambda_D = 1550$ nm and $\overline{\delta n_{eff}} = 2.5 \times 10^{-4}$.

Fig. 4.4 Calculated reflection spectrum of a Gaussian apodized FBG. In simulation, $n_{eff} = 1.45$, $L = 1.2$ cm,

$$\lambda_D = 1550 \text{ nm}, \overline{\delta n_{eff}} = 2.5 \times 10^{-4}, \text{ and } A(z) = \exp\left\{\left[-4(\ln 2) z^2\right] / (L/3)^2\right\}.$$

For the reflection spectrum of the IGAFBG as shown in Fig. 4.1(a), three lobes (main lobe, +1, and +2 order lobes) with high and almost-equal reflectivity occur.

Comparing with Fig. 4.3, Fig. 4.1(a) shows that the main lobe becomes narrower and its 3 dB bandwidth (BW) is decreased to about 1/3 of the unapodized reflection spectrum shown in Fig. 4.3. This suggests that the IGAFBG not only enhances the reflection spectral sidelobes but also squeezes the main lobe of a typical uniform FBG. The sidelobes are enhanced in such a way that the gaps between the lobes form two deep and ultra-narrow passbands, as shown in Fig. 4.1(b). The 3 dB bandwidths of the two passbands are calculated to be around 4.6 pm and 5.7 pm respectively, and the wavelength spacing between peak 1 and peak 2 is approximately 0.137 nm.

4.3.2 Adjustment of the wavelength spacing of an IGAFBG

It was found that, by changing the grating length L or the index modulation depth $\overline{\delta n_{eff}}$, the 3 dB bandwidths of the two passbands and the wavelength spacing between them can be changed. As shown in Fig. 4.5, where $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, $\overline{\delta n_{eff}} = 2 \times 10^{-4}$, the 3 dB bandwidths of the two passbands decrease and the wavelength spacing also decreases, as L increases from 1.4 cm to 1.9 cm. For example, the 3 dB bandwidths are calculated to be 5.19 pm (peak 1) and 6.64 pm (peak 2), respectively, and the wavelength spacing is around 0.114 nm when L is 1.4 cm; while the 3 dB bandwidths are 1.92 pm (peak 1) and 1.28 pm (peak 2) and the wavelength spacing is 0.096 nm when L is 1.9 cm. It should be noted that, when L is less than 1.4 cm and at a modulation depth of 2×10^{-4} , the sidelobes cannot be enhanced enough to form two high transmittivity passbands. In contrast, when L is greater than 1.9 cm, a triple-channel filter or a multi-channel filter can be realized as more sidelobes are enhanced due to the increased grating length. This will be discussed in detail in section 4.4. In Fig. 4.6, when $n_{eff} = 1.45$, $\lambda_D =$

1550 nm, $L = 1.5$ cm, it can be seen that, the 3 dB bandwidths of the two transmission bands decrease and the wavelength spacing increases as $\overline{\delta n_{eff}}$ increases from 2×10^{-4} to 2.5×10^{-4} .

Fig. 4.5 3 dB bandwidths of peak 1 (solid line with diamond joints) and peak 2 (solid line with square joints) and wavelength spacing between these two peaks (dashed line) versus L of an IGAFBG. In

simulation, $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, and $\overline{\delta n_{eff}} = 2 \times 10^{-4}$.

Fig. 4.6 3 dB bandwidths of peak 1 (solid line with diamond joints) and peak 2 (solid line with square joints) and wavelength spacing between these two peaks (dashed line) versus $\overline{\delta n_{eff}}$ of an IGAFBG. In

simulation, $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, and $L = 1.5$ cm.

Another unique advantage of the IGAFBG is that it can produce identical dual-passband filters [85] via a simpler scanning method during the grating fabrication process. As seen from Fig. 4.5, at crossing point “M”, the two transmission peaks (peak 1 and peak 2) will have the same 3 dB bandwidths of 3.1 pm and a wavelength spacing of 0.104 nm with $L = 1.62$ cm. The transmission spectrum for this condition is shown in Fig. 4.7(a). The reason for an IGAFBG to produce identical passbands is explained as follows. At a specific index modulation depth of 2×10^{-4} for example, if the grating length is less than a threshold value of 1.62 cm, the +2 order sidelobe is not sufficiently enhanced, and the gap between the +1 and the +2 order sidelobes is not as deep as the gap between the main lobe and the +1 order lobe, and hence the two passbands are not identical. However, when the grating length is equal to the threshold value of 1.62 cm, both the +1 and +2 order sidelobes are enhanced to such a state that the +2 order sidelobe has almost the same reflectivity as the main lobe, and hence identical passbands can form, as shown in Fig. 4.7(a). Similarly, identical passbands can also occur when L is 1.5 cm and $\overline{\delta n_{eff}}$ is 2.16×10^{-4} , which is indicated by “N” in Fig. 4.6, and the corresponding transmission spectrum is shown in Fig. 4.7(b). The wavelength spacing for this case is 0.113 nm and the 3 dB bandwidths of the two passbands are 3.5 pm. It should be noted that, the wavelength spacing between the two identical passbands of an IGAFBG filter can be flexibly changed by selecting a proper grating length and a proper index modulation depth. For example, when $\overline{\delta n_{eff}}$ is 3.25×10^{-4} and L is 1 cm, the wavelength spacing becomes 0.17 nm, and the 3 dB bandwidths of the two passbands are 5 pm, as shown in Fig. 4.7(c).

Fig. 4.7 Calculated transmission spectra of three different IGAFBGs having two identical passbands with varied wavelength spacings. (a) wavelength spacing of 0.104 nm and 3 dB bandwidths of 3.1 pm (see “M” in Fig. 4.5); (b) wavelength spacing of 0.113 nm and 3 dB bandwidths of 3.5 pm (see “N” in Fig. 4.6); (c) wavelength spacing of 0.17 nm and 3 dB bandwidths of 5 pm, when $\overline{\delta n_{eff}}$ is 3.25×10^{-4} and L is 1 cm.

4.4 IGAFBG as Triple-Wavelength and Multi-Wavelength Passband Filters

By selecting the proper index modulation depth and grating length of an IGAFBG, the number of the sidelobes in the reflection spectra to be enhanced can be controlled. Hence a triple-wavelength and even a multi-wavelength passband filter can be produced. For example, a triple-wavelength passband filter based on an IGAFBG is shown in Fig. 4.8. In simulation, I have set $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, $\overline{\delta n_{eff}} = 3 \times 10^{-4}$, $L = 1.5$ cm, with the apodization function given in Eq. (4.12). The 3 dB bandwidths of the three transmission bands λ_1 , λ_2 , and λ_3 are approximately 1.8, 0.6, and 1.6 pm, respectively. The wavelength spacings $\Delta\lambda_{12}$, $\Delta\lambda_{23}$, and $\Delta\lambda_{34}$ are 0.13, 0.096, and 0.07 nm, respectively.

Fig. 4.8 Calculated transmission spectrum of an IGAFBG with three passbands. In simulation, $n_{eff} = 1.45$, L

$$= 1.5 \text{ cm}, \lambda_D = 1550 \text{ nm}, \text{ and } \overline{\delta n_{eff}} = 3 \times 10^{-4}.$$

Similarly, multi-wavelength passband filter with varied “FSRs” can also be obtained based on an IGAFBG. By choosing $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, $\overline{\delta n_{eff}} = 4 \times 10^{-4}$, and $L = 2$ cm, the simulation result is shown in Fig. 4.9, where the +1 order dip has a wavelength spacing of “FSR1”, and the +2 order dip has “FSR2” and so on. It should be noted that, “FSR” (FSR with a quotation mark) in the IGAFBG is not the normal definition of FSR but refers to the relevant wavelength spacing between adjacent passbands. The 3 dB bandwidths of λ_1 , λ_2 , λ_3 , λ_4 , λ_5 , and λ_6 are 0.021, 0.017, 0.026, 0.119, 0.681, and 2.979 pm, respectively. “FSR1”, “FSR2”, “FSR3”, “FSR4”, and “FSR5” are 0.098, 0.081, 0.066, 0.053, and 0.041 nm, corresponding to ~12.25, ~10.125, ~8.25, ~6.625, and ~5.125 GHz frequency, respectively.

Fig. 4.9 Calculated transmission spectrum of an IGAFBG having multi passbands with varied “FSR” values. The +1 order dip has “FSR1”, and the +2 order dip has “FSR2” and so on. In simulation, $n_{eff} = 1.45$, $L = 2$ cm, $\lambda_D = 1550$ nm, and $\overline{\delta n_{eff}} = 4 \times 10^{-4}$.

One possible application of this IGAFBG is in a fiber laser whereby the IGAFBG can be incorporated in the cavity to generate a step-tunable microwave signal [29], using only a uniform FBG (e. g., having a 3 dB bandwidth of 0.1 nm) that is tuned by applying a strain along its fiber axis to select the desired adjacent dual wavelengths.

4.5 Chirped IGAFBG as a Dual-Passband Filter with a Tunable Wavelength Spacing

In section 4.4, it was demonstrated that the IGAFBG with various “FSRs” can act as a step-tunable filter. Furthermore, the wavelength spacing between the two passbands of an IGAFBG can, in principle, be continuously tuned by applying a strain gradient along the IGAFBG which introduces a linear chirp along the length of the grating [86]. By applying different strain distributions on the IGAFBG, varying chirp rates of 0, 0.1, 0.15, and 0.2 nm/cm were obtained, giving wavelength spacings of 0.164, 0.158, 0.15, and 0.14 nm, respectively, as shown in Fig. 4.10. In simulation, $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, $\overline{\delta n_{eff}} = 3 \times 10^{-4}$, $L = 1$ cm, and the apodization function given in Eq. (4.12). Due to the incorporated chirp on the IGAFBG, the shape of the transmission spectrum changes slightly, and this can be seen in Figs. 4.10(a)-(d). The 3 dB bandwidths of the two passbands also increase slightly and the transmittivity of the two peaks decreases a little, as shown in Table 4.1. However, this will not affect the IGAFBG as a dual-passband filter. Only a regular uniform FBG whose 3 dB bandwidth covering the wavelength spacing $\Delta\lambda$ of the two passbands is needed to pick out the desired dual channels.

Fig. 4.10 Calculated transmission spectra of IGAFBGs at (a) 0 (b) 0.1 (c) 0.15, and (d) 0.2 nm/cm chirp

rate. In simulation, $n_{eff} = 1.45$, $\lambda_D = 1550$ nm, $\overline{\delta n_{eff}} = 3 \times 10^{-4}$, and $L = 1$ cm.

Table 4.1 Calculated parameters of an IGAFBG under different chirp rates (see Fig. 4.10)

Chirp rate (nm/cm)	Wavelength Spacing (nm)	3 dB BW of peak 1 (pm)	3 dB BW of peak 2 (pm)	Transmittivity of peak 1 (dB)	Transmittivity of peak 2 (dB)
0	0.164	5.95	6.76	0	0
0.1	0.158	8.15	8.7	-1	-1.3
0.15	0.15	11.89	11.89	-2	-2.5
0.2	0.14	11.89	17.3	-3.5	-3.5

Since the wavelength spacing of the two passbands can be continuously tuned, it is believed that a continuously tunable microwave signal can be generated by incorporating such an IGAFBG in a linear [28] or a ring [87] laser cavity. The generated microwave frequency ranges from ~20.5 GHz (0.164 nm wavelength spacing) to ~17.5 GHz (0.14 nm wavelength spacing) in this case. The tuning range can be easily changed by using a different IGAFBG with a different wavelength spacing.

4.6 Fabrication of IGAFBG

The simulation result of an IGAFBG has been well studied in sections 4.3-4.5. In this section, the realization of an IGAFBG in experiment will be demonstrated.

4.6.1 Experimental setup to fabricate an IGAFBG

A standard phase mask scanning technique is utilized in the fabrication of an IGAFBG. The experimental setup is shown in Fig. 4.11.

Fig. 4.11 Experimental setup of the fabrication of an IGAFBG. The blue line is the UV beam from a 244-nm frequency-doubled argon laser, and the red arrow marks the scanning direction of the translation stage.

Fig. 4.12 Phase mask used in the fabrication of an IGAFBG.

The UV light (blue line) from a 244-nm frequency-doubled argon laser is focused through a cylindrical lens and a uniform phase mask (see Fig. 4.12) onto the core of a single-mode fiber. The fiber is hydrogen-loaded for several days to obtain

photosensitivity. The inverse-Gaussian apodization function can be realized by varying the scanning speed of the laser beam. A high scanning speed yields a low index modulation depth (low UV light exposure). By adjusting the laser beam power, beam size, and the position of the fiber relative to the phase mask, different index modulation depths can be achieved. It is also noted that the type of the fiber used and the duration of the hydrogen loading process affect the effective refractive index of the grating. After several trials of different scanning speed distributions, the scanning speed profile expressed as:

$$V(z) = \frac{0.03}{A(z) + 0.1} \text{ mm/s} \quad (4.13)$$

and shown in Fig. 4.13, was chosen to best fit the inverse-Gaussian apodization function $A(z)$ given in Eq. (4.12).

Fig. 4.13 Scanning speed profile of the UV light used in the fabrication of an IGAFBG. Solid line, experimental speed distribution; dashed line, ideal $V(z)$ function.

4.6.2 Experimental results of the IGAFBG fabrication

A series of experiments for the IGAFBG fabrication was conducted, and the results are shown as follows.

4.6.2.1 IGAFBG based dual-passband filter with an adjustable wavelength spacing

To fabricate an IGAFBG with dual passbands having a wavelength spacing of 0.1 nm, a 60 mW argon laser with a scanning speed profile $V(z)$ given in Eq. (4.13) was applied to a 18 mm long grating. The experimentally measured (solid line) and the numerically calculated (dashed line) transmission spectra of this IGAFBG are shown in Fig. 4.14, which shows good agreement with each other. In simulation, n_{eff} is 1.447, L is 18 mm, λ is 532.85 nm, and $\overline{\delta n_{eff}}$ is 2.3×10^{-4} .

Fig. 4.14 Transmission spectra of an IGAFBG with a wavelength spacing of 0.1 nm. Solid line, measured spectrum; dashed line, calculated spectrum. In simulation, $n_{eff} = 1.447$, $L = 18$ mm, $\lambda = 532.85$ nm and

$$\overline{\delta n_{eff}} = 2.3 \times 10^{-4}.$$

Narrower wavelength spacing of the two transmission bands can be realized by increasing the grating length and decreasing the argon laser power. A 50 mW argon laser was used to fabricate a 25 mm long IGAFBG. The dual passbands have a wavelength spacing of 0.07 nm, as shown in Fig. 4.15, where the solid line is the experimental result and the dashed line is the simulation result. In simulation, n_{eff} is 1.447, L is 25 mm, Λ is 532.85 nm, and $\overline{\delta n_{eff}}$ is 1.4×10^{-4} . The small discrepancy between the experiment result and the simulation result may be due to the unavoidable misalignment of the fiber relative to the phase mask.

Fig. 4.15 Transmission spectra of an IGAFBG with wavelength spacing of 0.07 nm. Solid line, measured spectrum; dashed line, calculated spectrum. In simulation, $n_{eff} = 1.447$, $L = 25$ mm, $\Lambda = 532.85$ nm, and

$$\overline{\delta n_{eff}} = 1.4 \times 10^{-4}.$$

Figs. 4.14 and 4.15 show the spectra of two IGAFBGs with non-identical dual passbands. Fig. 4.16 shows the transmission spectra of an IGAFBG with identical dual passbands having a wavelength spacing of approximately 0.144 nm. The length of the

grating is 12 mm and the argon laser output power is set at 66 mW. The experimental result (solid line) and the simulated result (dashed line) are again in a good agreement with each other. In simulation, $n_{eff} = 1.447$, $L = 12$ mm, $\overline{\delta n_{eff}} = 2.7 \times 10^{-4}$, and $\Lambda = 532.85$ nm.

Fig. 4.16 Transmission spectra of an IGAFBG with two identical passbands. Solid line, measured spectrum (the argon laser output power used is 66 mW and the grating length is 12 mm); dashed line, calculated spectrum. In simulation, $n_{eff} = 1.447$, $L = 12$ mm, $\Lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 2.7 \times 10^{-4}$.

4.6.2.2 IGAFBG based multi-passband filter with varied “FSRs”

A multi-wavelength passband filter with varied “FSRs” based on an IGAFBG can also be obtained in experiment. The laser output power of 80 mW and a scanning speed profile of $V(z)$ given in Eq. (4.13) were used in this case to fabricate a 17 mm long IGAFBG. The experimentally measured transmission spectrum is shown in Fig. 4.17(a) and the matched simulation result is shown in Fig. 4.17(b). In Fig. 4.17(a), the sharp

transmission peaks are not fully resolved due to the limited 0.01 nm resolution of the OSA, and the ripples occurring in the dips are due to the high transmittivity of the passbands producing unavoidable electrical noise in the spectrum. In simulation, $n_{eff} = 1.447$, $L = 17$ mm, $\overline{\delta n_{eff}} = 4.5 \times 10^{-4}$, and $\lambda = 532.85$ nm. The experimental and theoretical “FSR” values are given in Table 4.2, and they agree with each other. As shown in Table 4.2, the fabricated IGAFBG has varied “FSR” values of 0.129, 0.098, 0.068, and 0.051 nm, corresponding to ~16.125, ~12.25, ~8.5 and ~6.375 GHz in frequency, respectively.

(a)

(b)

Fig. 4.17 Transmission spectra of an IGAFBG with varied “FSRs” as a multi-wavelength passband filter. (a) measured spectrum (the argon laser output power used is 80 mW and the grating length is 17 mm); (b) simulated spectrum. The +1 order dip has “FSR1”, and the +2 order dip has “FSR2” and so on. In

simulation, $n_{eff} = 1.447$, $L = 17$ mm, $\lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 4.5 \times 10^{-4}$.

Table 4.2 “FSRs” of an IGAFBG as a multi-wavelength filter (see Fig. 4.17).

	“FSR1”	“FSR2”	“FSR3”	“FSR4”
Measured	0.129 nm	0.098 nm	0.068 nm	0.051 nm
Simulated	0.122 nm	0.094 nm	0.07 nm	0.057 nm

4.6.2.3 Comparison of IGAFBG and FBG pair in spectral shape

Since an FBG pair can also act as a multi-passband filter, it is necessary to compare the IGAFBG with the FBG pair with respects to their spectral properties. Fig. 4.18 shows the calculated transmission spectrum of an FBG pair. In simulation, the length of each sub-grating is 5 mm, the separation between the two FBGs is 7 mm (total length of the FBG pair is 17 mm), n_{eff} is 1.447, Λ is 532.85 nm, and $\overline{\delta n_{eff}}$ is 4.5×10^{-4} . This FBG pair has the same length and index modulation depth as the IGAFBG shown in Fig. 4.17(b). The calculated “FSR” values of the FBG pair are given in Table 4.3. It can be seen from Table 4.3 that, the central “FSR” (“FSR3”) is larger than the others, and the reason has already been explained in Refs. [88] and [89], and will also be briefly explained as follows. The identical and separated FBGs act as two reflectors. The “FSR” of an FBG pair varies with wavelength λ as [88]:

$$FSR(\lambda) = \frac{c}{2n_{eff}(\lambda)L_{eff}(\lambda)} \quad (4.14)$$

where c is the light velocity in vacuum, and L_{eff} is the effective cavity length. The effective refractive index n_{eff} can be treated as a constant within a small wavelength range. Off resonance, one can imagine that the grating reflectivity and the Bragg scattering are weaker than those in the resonance condition, so that the light penetrates farther into gratings [88]. Hence, L_{eff} increases as resonance wavelength increases to the red edges and decreases to blue edges in the spectrum. Therefore, FSR on resonance is larger than the others.

Fig. 4.18 Simulated transmission spectrum of an FBG pair. In simulation, $n_{eff} = 1.447$, $\Lambda = 532.85$ nm, $\overline{\delta n_{eff}} = 4.5 \times 10^{-4}$, the length of each sub-grating is 5 mm, and the separation between these two sub-gratings is 12 mm. The numbers 1, 2, 3, 4 and 5 in the figure do not mean the dip order, and they refer to “FSR1”, “FSR2”, “FSR3”, “FSR4”, and “FSR5” only.

Table 4.3 “FSRs” of an FBG pair (see Fig. 4.18).

	“FSR1”	“FSR2”	“FSR3”	“FSR4”	“FSR5”
Simulated	0.0865 nm	0.0989 nm	0.1011 nm	0.1003 nm	0.0938 nm

The objective behind IGAFBG is to enhance the sidelobes. The enhanced +1 order sidelobe may have the shortest effective cavity length, leading to the largest “FSR”, followed by the +2, +3, +4, and other higher order sidelobes (see Figs. 4.8, 4.9 and 4.17). Hence, we have “FSR1” > “FSR2” > “FSR3” > “FSR4” in Fig. 4.17(b), which is different from the case of an FBG pair as illustrated above.

4.7 Other Inverse Apodized FBGs

IGA FBG is just one type of inverse apodized FBGs. The reflection spectra of some other types of inverse apodized FBG were also simulated and will be discussed in this section.

Apart from the IGA FBG, six other inverse apodization functions, whose expressions are summarized in Table 4.4, were also used in simulation. Fig. 4.19 shows the profiles of these functions, including the IGA FBG. These functions were chosen as their corresponding apodization expressions are well-known window functions employed in filter designs [90] to suppress the sidelobes in the rejection band.

Fig. 4.19 The profiles of the inverse apodization functions summarized in Table 4.4 when $L = 10$ mm. (a) Inverse Gaussian; (b) Inverse Hamming with $k_0 = 1$ and $H = 1$; (c) Inverse Blackman with $k_0 = 1$ and $B = 0.18$; (d) Inverse Tanh with $k_0 = 0.5$, $\alpha = 3$, and $\beta = 4$; (e) Inverse Sinc with $k_0 = 1$, $A = 10$, and $B = 2$; (f) Inverse Cauchy with $k_0 = 1$ and $C = 0.5$; and (g) Absolute Sine.

Table 4.4 Different types of inverse apodization functions, where L is the grating length and the other characteristic constants can be found in the captions of Fig. 4.19.

Name of inverse apodization function	Description	Equation number
Inverse Hamming	$A(z) = 1 - k_0 \frac{\left(1 + H \cos \frac{2\pi z}{L}\right)}{1 + H}$	(4.15)
Inverse Blackman	$A(z) = 1 - k_0 \frac{1 + (1 + B) \cos\left(\frac{2\pi z}{L}\right) + B \cos\left(\frac{4\pi z}{L}\right)}{2 + 2B}$	(4.16)
Inverse Tanh	$A(z) = 1 - k_0 \left\{ 1 + \tanh \left[\beta \left(1 - 2 \left \frac{2z}{L} \right ^\alpha \right) \right] \right\}$	(4.17)
Inverse Sinc	$A(z) = 1 - k_0 \operatorname{sinc}^A \left[\frac{1}{2} \left(\frac{2z}{L} \right)^B \right]$	(4.18)
Inverse Cauchy	$A(z) = 1 - k_0 \frac{1 - \left(\frac{2z}{L}\right)^2}{1 - \left(\frac{2Cz}{L}\right)^2}$	(4.19)
Absolute Sin	$A(z) = \left \sin \frac{\pi z}{L} \right $	(4.20)

The simulated reflection spectra corresponding to the apodization functions in Table 4.4 are shown in Figs. 4.20 to 4.25. The characteristic values used in the simulations are as follows: $n_{eff} = 1.45$, $L = 1$ cm, and $\overline{\delta n_{eff}} = 3 \times 10^{-4}$. It can be seen that, the inverse Tanh apodized FBG (see Fig. 4.22) has a similar reflection spectrum as an FBG pair. This is reasonable because the transition in the apodization function is sharp, and there is also a physical gap in the grating structure (see curve d in Fig. 4.19 in the region of $z = -3$ to $z =$

3 mm). The other inverse apodized FBGs have a similar spectrum as the IGAFBG, but with slightly different “FSR” distributions. To fabricate a particular varying-“FSR” multi-passband filter, the appropriate inverse apodization function can be selected, together with the corresponding scanning speed profile of the UV light, illustrating the flexibility of the proposed technique.

Fig. 4.20 Calculated reflection spectrum of a grating with an inverse Hamming apodization function

$$A(z) = 1 - k_0 \frac{\left(1 + H \cos \frac{2\pi z}{L}\right)}{1 + H}, \text{ where } k_0 = 1, \text{ and } H = 1.$$

Fig. 4.21 Calculated reflection spectrum of a grating with an inverse Blackman apodization function

$$A(z) = 1 - k_0 \frac{1 + (1 + B) \cos\left(\frac{2\pi z}{L}\right) + B \cos\left(\frac{4\pi z}{L}\right)}{2 + 2B}, \text{ where } k_0 = 1, \text{ and } B = 0.18.$$

Fig. 4.22 Calculated reflection spectrum of a grating with an inverse Tanh apodization function

$$A(z) = 1 - k_0 \left\{ 1 + \tanh \left[\beta \left(1 - 2 \left| \frac{2z}{L} \right|^\alpha \right) \right] \right\}, \text{ where } k_0 = 0.5, \alpha = 3, \text{ and } \beta = 4.$$

Fig. 4.23 Calculated reflection spectrum of a grating with an inverse Sinc apodization function

$$A(z) = 1 - k_0 \text{sinc}^A \left[\frac{1}{2} \left(\frac{2z}{L} \right)^B \right], \text{ where } k_0 = 1, A = 10, \text{ and } B = 2.$$

Fig. 4.24 Calculated reflection spectrum of a grating with inverse Cauchy apodization function

$$A(z) = 1 - k_0 \frac{1 - \left(\frac{2z}{L} \right)^2}{1 - \left(\frac{2Cz}{L} \right)^2}, \text{ where } k_0 = 1, \text{ and } C = 0.5.$$

Fig. 4.25 Calculated reflection spectrum of a grating with an absolute *sine* apodization function

$$A(z) = \left| \sin \frac{\pi z}{L} \right|.$$

4.8 Chapter Summary

In this chapter, a novel FBG structure (inverse-Gaussian apodized FBG) which is different from the traditional ones as shown in chapter 2, has been proposed and analyzed. The transmission and reflection spectra of an IGAFBG have been simulated using the transfer matrix method.

It has been found that, by changing the grating length and the index modulation depth, the number of sidelobes enhanced in the reflection spectrum of an IGAFBG can be controlled, so that the number of the passbands in the corresponding transmission spectrum can be controlled. This IGAFBG can act as a dual-, triple-, and multi-passband filter.

In simulation, it has been verified that, for an IGAFBG based dual-passband filter, the spacing of the two passbands can be changed by applying different strain profiles, i. e., different linear chirp rates, along the length of the grating. Hence, in principle a dual-passband IGAFBG filter with a tunable wavelength spacing can be achieved.

The fabrication of an IGAFBG using the phase-mask scanning technique has been illustrated. An IGAFBG with two non-identical passbands, two identical passbands, three passbands, and multi passbands consisting of varied “FSRs”, has been demonstrated.

In addition, instead of using an inverse-Gaussian apodization function, some other inverse apodization functions, such as inverse Hamming, inverse Blackman, inverse Tanh and so on, have been used to enhance the sidelobes of an FBG, and their reflection spectra were simulated and discussed.

Chapter 5 Application of IGAFBG for Dual-Wavelength Fiber Laser and Microwave Generation

5.1 Introduction

Multi-wavelength fiber lasers have attracted a lot of interests for their potential applications in optical instrumentation, wavelength-division-multiplexing communications, optical sensing systems, and microwave photonic generation. However, due to the long cavity length, an enormous number of densely spaced longitudinal modes around the central lasing mode always exist, which is undesirable in some applications since they are prone to mode hopping. Therefore, single-longitudinal-mode (SLM) operations are desirable, particularly for microwave generation.

FBG is an important optical element for dual-wavelength lasing. To overcome the limitations of PS-FBG, EPS-FBG, FBG pair, and PM-FBG, IGAFBG was proposed and presented in chapter 4. The fabrication of the IGAFBG is a simple one-step scanning process. Moreover, the IGAFBG was inscribed in a low cost standard hydrogen loaded fiber with no physical gap in its structure. It has been illustrated that, the IGAFBG can act as a dual-passband filter due to the fact that the sidelobes are greatly enhanced in the reflection spectrum. In this chapter, the application of an IGAFBG in a dual-wavelength

fiber laser will be introduced. Several dual-wavelength fiber lasers for microwave generation using an IGAFBG filter will also be discussed.

5.2 Dual-Wavelength Multi-Longitudinal-Mode Fiber Laser Based on an IGAFBG

5.2.1 Design of IGAFBG filter

For this experiment, an IGAFBG with a length of 1.2 cm was fabricated, using the phase-mask scanning technique as explained in section 4.6. A 70 mW UV light from a 244-nm frequency-doubled argon laser is focused through a cylindrical lens and a uniform phase mask with a pitch of 1065.7 nm, onto the core of a single-mode fiber that is hydrogen-loaded for five days. The scanning speed profile utilized is $V(z)$ as given in Eq. (4.13) to best fit the inverse-Gaussian apodization function $A(z)$ as given in Eq. (4.12). The experimentally measured (solid line) and the numerically calculated (dashed line) transmission spectra are shown in Fig. 5.1. Two passbands with very narrow 3 dB bandwidths were observed in the spectrum. Due to the limited resolution (0.01 nm) of the optical spectrum analyzer (OSA) used in the experiment, the true 3 dB bandwidths of the two transmission bands cannot be exactly determined. However, they are estimated to be 3.25 pm (peak 1 at 1542.257 nm) and 2.85 pm (peak 2 at 1542.403 nm) based on the simulation result. The wavelength spacing between the two channels is approximately 0.146 nm. In simulation, $n_{eff} = 1.447$, $L = 12$ mm, $\lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 3 \times 10^{-4}$.

Fig. 5.1 Transmission spectra of the proposed IGAFBG with a wavelength spacing of 0.146 nm (peak 1 at 1542.257 nm and peak 2 at 1542.403 nm). Solid line, measured spectrum; dashed line, calculated spectrum.

In simulation, $n_{eff} = 1.447$, $L = 12$ mm, $\Lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 3 \times 10^{-4}$.

5.2.2 Dual-wavelength lasing based on the designed IGAFBG

The two narrow peaks in the transmission spectrum of the IGAFBG gave us the idea that such grating can be used as a dual-channel filter for dual-wavelength fiber laser emission. To demonstrate this, a linear cavity fiber laser was constructed, and schematically shown in Fig. 5.2. The laser cavity consists of a uniform FBG which couples the output of the pump laser into the cavity which simultaneously acts as one of the two cavity mirrors of the laser, a 4.3 m long erbium-doped fiber (EDF) as the gain medium, a polarization controller (PC) to fine tune the cavity birefringence, an IGAFBG as the dual-channel filter (its transmission spectrum is shown in Fig. 5.1), and a chirped FBG (CFBG) that forms the other cavity mirror of the laser, and concurrently the output coupler. All the gratings used (uniform FBG, IGAFBG, and CFBG) in this system were fabricated using the same standard single-mode hydrogen loaded fibers. The uniform

FBG has a length of 1 cm with reflectivity of 33 dB, a 3 dB bandwidth of 0.22 nm, and a Bragg wavelength at 1542.33 nm. The CFBG has a length of 3 cm, whose Bragg wavelength is centered at 1545.5 nm (chirp rate is 4.5 nm/cm) with a stopband of approximately 18 nm in the transmission mode, and reflectivity of approximately 94%.

Fig. 5.2 Schematic diagram of the dual-channel fiber laser with an IGA-FBG filter in its linear all-fiber cavity. EDF, erbium-doped fiber; PC, polarization controller; IGA-FBG, inverse-Gaussian apodized fiber Bragg grating; CFBG, chirped fiber Bragg grating; OSA, optical spectrum analyzer.

By adjusting the polarization controller carefully, the output spectrum of the laser as shown in Fig. 5.3(a) was obtained, and measured under a pump power of 300 mW. The laser emits simultaneously at 1542.257 and 1542.403 nm with a wavelength separation of 0.146 nm, which exactly matches the two passbands of the IGA-FBG shown in Fig. 5.1. The optical signal-to-noise ratio (OSNR) for these two lasing lines is around 45 dB. Fig. 5.3(b) shows the repeated scans of the two ultra-narrow lasing lines at two-minute intervals over half an hour at room temperature. The dual-wavelength lasing parameters, including the central wavelength, the wavelength spacing, the 3 dB spectral bandwidths, and the OSNR, are all observed to be reasonably unchanged, indicating good stability of the lasing output.

(a)

(b)

Fig. 5.3 Output laser spectra. (a) two lasing lines at 1542.257 and 1542.403 nm (within 4.5 nm wavelength domain); (b) repeated scans of the two lasing lines at two-minute intervals over half an hour at room temperature (within 1 nm wavelength domain).

It should be noted that, a change in the temperature of the laser, however, will shift the two lasing lines simultaneously since the reflection spectrum of the uniform FBG, IGAFBG and CFBG are all temperature sensitive, and drift approximately by the same amount. This, however, will not affect the wavelength spacing and stability of the emission spectra of the fiber laser.

5.3 Dual-Wavelength Erbium-Doped Fiber Laser Based on an IGAFBG and a Saturable Absorber

It has been demonstrated in section 5.2 that dual-wavelength lasing can be achieved using an IGAFBG filter, based on a simple linear cavity fiber laser structure, which only requires some basic optical components such as FBG filters, isolator, polarization controller, and EDF. However, it is a multi-longitudinal-mode operation at each lasing wavelength due to the long cavity length. In this section, a dual-wavelength fiber laser with each lasing oscillation operating in SLM is realized by incorporating an IGAFBG together with a saturable absorber (SA).

5.3.1 Design of IGAFBG filter

A 20 mm long IGAFBG was fabricated using the phase-mask scanning technique using a 53 mW UV light. The phase mask has a pitch of 1065.7 nm. The scanning speed profile of the translation stage is $V(z)$ as given in Eq. (4.13), where $A(z)$ is given in Eq. (4.12). Fig. 5.4 shows the measured (solid line) and the simulated (dashed line) transmission spectra of the IGAFBG. The two spectra show good agreement with each other. In simulation, $n_{eff} = 1.447$, $L = 20$ mm, $\lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 1.6 \times 10^{-4}$. Two

transmission bands at 1542.995 and 1543.077 nm with ultra-narrow 3 dB bandwidths are observed in Fig. 5.4. Due to the limited 0.01 nm resolution of the OSA used in the experiment, the true 3 dB bandwidths of the two transmission bands cannot be accurately resolved. The wavelength spacing between the two channels is approximately 0.082 nm.

Fig. 5.4 Transmission spectra of an IGAFBG filter with a wavelength spacing of 0.082 nm (two peaks are at 1542.995 and 1543.077 nm). Solid line, measured spectrum; dashed line, simulated spectrum.

5.3.2 Dual-wavelength fiber ring laser incorporating the designed IGAFBG

The schematic diagram of the proposed dual-wavelength fiber ring laser is shown in Fig. 5.5. As is well known, both EDF and semiconductor optical amplifier (SOA) biased in the large-gain regime can act as the gain medium in a fiber laser. However, the latter has disadvantages of high noise, low saturated power, and undesirable nonlinear effect, and hence EDF is used in this experiment. The EDF has a length of 4 m, pumped with a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer (WDM).

An IGAFBG of length 20 mm, and whose transmission spectrum is shown in Fig. 5.4, acts as a dual-wavelength passband filter with a wavelength spacing of 0.082 nm. A uniform FBG with a Bragg wavelength at 1542.75 nm, extinction ratio of 35 dB in transmission, and a 3 dB bandwidth of around 0.16 nm, was tuned by applying a strain along the fiber axis, to select and reflect the two transmission bands of the IGAFBG. Fig. 5.6 shows the experimentally measured transmission spectrum of the uniform FBG. A 2 m long unpumped EDF with an absorption coefficient of 5.2 dB/m at 1530 nm serves as a saturable absorber (SA) while the PC is used to fine tune the cavity birefringence. Laser output was coupled out via the 10% port of the 90/10 optical coupler (OC), of which 10% of it was monitored by an OSA while the other 90% output power was channeled to the photodetector (PD) after amplification by an erbium-doped fiber amplifier (EDFA). The microwave signal at the output of the photodetector was monitored using an electrical spectrum analyzer (ESA).

Fig. 5.5 Schematic diagram of the proposed fiber ring laser.

Fig. 5.6 Experimentally measured transmission spectrum of the uniform FBG.

By adjusting the PC carefully under a 230 mW pump power, we obtained a stable dual-wavelength lasing. Fig. 5.7(a) shows the repeated scans of the two lasing lines at a 6-minute interval over an hour at room temperature. The laser emits simultaneously at 1542.996 and 1543.078 nm with a wavelength separation of 0.082 nm, which match the two transmission bands of the IGAFBG shown in Fig. 5.4. The optical signal-to-noise ratio (OSNR) for these two lasing lines is more than 30 dB. The laser output power fluctuation is shown in Fig. 5.7(b), which gives a maximum power fluctuation at the dual wavelengths of less than 1 dB, illustrating good stability in the output power of the fiber laser. Any small wavelength variation that may have occurred in the system and shown in Fig. 5.7(c) is beyond the resolution limit of the OSA, and hence not noticeable. A microwave signal was observed in the ESA and Fig. 5.8(a) shows the spectrum in a 20 GHz span with a resolution of 1 MHz. Only one beat frequency was observed, which suggests that each of the two lasing wavelengths is operating in SLM. Fig. 5.8(b) shows the result in a 2 MHz span with a resolution of 10 kHz. The central frequency of the microwave signal is approximately 10.502 GHz, corresponding to a wavelength separation of 0.082 nm of the two lasing lines. The central frequency shift is within 1 MHz, and shows good stability with time. The 3 dB bandwidth of the microwave signal is less than 10 kHz. This was monitored for 30 mins and no noticeable mode hopping was observed in the ESA, indicating good quality of the generated microwave signal. In literature, the generated microwave signal has a bandwidth of less than 5 kHz using the optical injection locking method [7], less than 1 MHz using the optical phase locked loop method [12], and less than 10 kHz or 20 kHz using the dual-wavelength lasing method

[19,20,27]. It can be seen that, the quality of the generated microwave signal in our proposed technique is comparable to the other published techniques.

(a)

(b)

(c)

Fig. 5.7 (a) Lasing spectra taken at a 6-min interval over one hour with dual-wavelength at 1542.996 and 1543.078 nm. (b) Output power fluctuation and (c) emitting wavelength variation with scanning time.

(a)

(b)

Fig. 5.8 Electrical spectrum of the beat signal. (a) 20 GHz span with resolution of 1 MHz (b) 2 MHz span with resolution of 10 kHz

It should be noted that, without the injection of the unpumped EDF as an SA, the SLM operation cannot be obtained in such a long cavity laser. The reason is explained as follows. In the experimental setup, the total cavity length of the fiber ring laser is approximately equal to 15 m when the SA is removed. Therefore, the FSR of the laser cavity will be close to 13.3 MHz. To achieve an SLM operation for each lasing wavelength, the 3 dB bandwidth of any of the two passbands in the IGAFBG must be smaller than twice the cavity FSR, which is around 26.6 MHz, corresponding to a 0.21 pm bandwidth of the passband. However, the 3 dB bandwidths of the two passbands are not less than 0.21 pm, in which case SLM operation cannot be achieved. With the SA incorporated into the ring cavity, we were able to obtain an SLM operation for each wavelength oscillation successfully.

It is well known that, a large absorption coefficient of an EDF corresponds to a small optical power within the fiber laser and vice versa. When lightwave propagates into the unpumped EDF, a standing wave can form within the fiber, which then distributes the spatial optical power periodically along the full length of the unpumped EDF. This leads to a periodic variation of the absorption coefficient along its length and hence a periodic refractive index variation along the unpumped EDF based on the Kramers-Kronig relation [91], thus inducing a weak FBG. In our experiment, the unpumped EDF has a low Er ion concentration of $3 \times 10^{18} \text{ Er}^{3+}/\text{cm}^3$ and the average injection power is less than 20 mW, so that the average refractive index change is estimated to be less than 3×10^{-7} [92]. The 3 dB bandwidth of the induced FBG can then be calculated using [93,94]:

$$\Delta f = (c / \lambda) \left[2\Delta n / (n_{\text{eff}} \lambda) \right] \sqrt{(\Delta n / 2n_{\text{eff}})^2 + (\Lambda / L_g)^2} \quad (5.1)$$

where c is the speed of light in vacuum, and $\Lambda = \lambda / (2n_{\text{eff}})$ is the grating period. Here we used a wavelength $\lambda = 1540 \text{ nm}$, a grating length $L_g = 2 \text{ m}$, an effective refractive index $n_{\text{eff}} = 1.48$, and an average refractive index change $\Delta n < 3 \times 10^{-7}$ to estimate the 3 dB bandwidth of the self-induced FBG. The estimated 3 dB bandwidth is $\Delta f < 14.3 \text{ MHz}$. With the cavity length of the fiber laser being approximately 19 m after incorporating the SA, which corresponds to a 10.5 MHz cavity FSR, it is obvious that the 3 dB bandwidth of the induced weak FBG is less than twice the laser cavity's FSR and hence an SLM operation for each of the two lasing lines is guaranteed. It should be pointed out that, 2-m long unpumped EDF was chosen in the experiment, for the reason that if the unpumped EDF is too short, based on Eq. (5.1), the bandwidth of the induced FBG will be too broad and thus SLM operation cannot be guaranteed. On the other hand, if the unpumped EDF

is too long, the absorption effect of the EDF will be dominant and large losses will occur in the laser system, in which case lasing oscillation cannot be formed.

If the SA is removed from the laser configuration, an SLM operation can only be realized by shortening the laser cavity length, and thus to ensure a sufficiently large cavity FSR. This can be achieved by shortening the length of the pumped EDF. However, such shortening will lead to an unexpected drop in the round-trip medium gain of the laser, resulting in a loss of lasing with time. One way to compensate for this loss of gain due to the shortened EDF is to replace it with a highly doped EDF. Such EDF has a high absorption coefficient which will cause its inherent temperature to increase thus affecting the stability of the fiber laser.

5.4 Switchable Dual-Wavelength Erbium-Doped Fiber Laser Using an IGAFBG Filter and a Low-Gain Semiconductor Optical Amplifier

In section 5.3, an SLM operation for each of the dual lasing wavelengths was achieved in a fiber ring laser, by incorporating an IGAFBG filter, and an unpumped EDF based saturable absorber. One disadvantage of using the unpumped EDF is its large loss (typically in the order of 4-6 dB/m), which greatly reduces the efficiency of the fiber laser. Another problem is that, the power of the oscillating mode propagating into the unpumped EDF must be carefully controlled. This is due to the fact that the unpumped EDF produces an induced FBG with ultranarrow bandwidth, which can only select the desired single mode oscillation under a proper inherent power. If the inherent power is

too low, the induced FBG is too weak and cannot form a self-tracking filter. However, if the inherent power is too high, the bandwidth of the induced FBG is too broad and multimode operation may result. One more limitation of using the unpumped EDF is that, since the induced FBG is a passive filter, its resonance frequency will change once mode hopping occurs, and there is no mechanism available to pull the oscillating mode back to the original mode, hence affecting the stability of the laser wavelength.

To overcome the above-mentioned limitation of the incorporated unpumped EDF based SA, a new fiber ring laser will be demonstrated in this section to achieve a dual-wavelength operation. It is well known that the pumped EDF as a gain medium in a fiber laser has a homogeneous broadening characteristic, and hence an SOA operating in low-gain regime was incorporated in the cavity, to introduce inhomogeneous gain and reduce gain competition [95,96]. In addition, a feedback fiber loop (FFL) [97] was added into the cavity to guarantee SLM operation at each wavelength oscillation of the proposed dual-wavelength fiber laser. No unpumped EDF-based SA exists in the system and thus there is no need for accurate control of the pump power.

5.4.1 Design of IGAFBG filter

In this experiment, a standard phase-mask scanning technique was used to fabricate an 18 mm long IGAFBG. The UV laser power was set at 60 mW and the pitch of phase mask used is 1065.7 nm. The fiber was hydrogen loaded for five days to make it photosensitive. The scanning speed profile of the translation stage $V(z)$ as given in Eq. (4.13) was used to best fit the $A(z)$ profile given in Eq. (4.12). Fig. 5.9 shows the experimentally measured (solid line) and the numerically calculated (dashed line)

transmission spectra of the IGAFBG, and they agree with each other. The calculated result is based on the transfer matrix method. In simulation, $n_{eff} = 1.447$, $L = 18$ mm, $\Lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 2.3 \times 10^{-4}$. Two transmission bands at 1542.2 and 1542.3 nm with ultra-narrow 3 dB bandwidths were observed in the spectra. The true 3 dB bandwidths of the two transmission bands cannot be accurately measured owing to the limited resolution (0.01 nm) of the OSA used in the experiment, and are estimated to be approximately 1.47 pm and 0.86 pm, respectively, based on the simulation result. The wavelength spacing between the two channels is approximately 0.1 nm.

Fig. 5.9 Transmission spectra of an IGAFBG with a wavelength spacing of 0.1 nm. Solid line, measured spectrum; dashed line, calculated spectrum. In simulation, $n_{eff} = 1.447$, $L = 18$ mm, $\Lambda = 532.85$ nm, and $\overline{\delta n_{eff}} = 2.3 \times 10^{-4}$. The reflection peak of a uniform FBG can be tuned at positions *a*, *b*, and *c* to achieve dual-wavelength switching.

5.4.2 Switchable dual-wavelength erbium-doped fiber laser incorporating the designed IGAFBG

The schematic diagram of the proposed dual-wavelength fiber ring laser is shown in Fig. 5.10. In Ring-1, a 4 m long erbium-doped fiber (EDF) serves as the gain medium, pumped with a 1480 nm laser diode (200 mW) through a 1480/1550 nm WDM. An 18 cm long IGAFBG whose transmission spectrum is shown in Fig. 5.9, acts as a dual-wavelength passband filter with a wavelength spacing of 0.1 nm. An SOA operating in its low-gain regime provides the inhomogeneous gain and reduces gain competition. The SOA has a maximum operating current of 250 mA, a small signal gain of 22 dB, and a saturation output power of 9.5 dBm. A uniform FBG with a Bragg wavelength at 1542 nm, extinction ratio of 30 dB in transmission, and a 3 dB bandwidth of around 0.15 nm, was bonded onto a translation stage so that it can be tuned by strain along the fiber axis. A feedback fiber loop (Ring-2) constructed with a 3 dB optical coupler (OC), combines with the IGAFBG filter to ensure an SLM operation. The lengths of Ring-1 and Ring-2 are about 16 and 0.9 m, corresponding to 12.5 MHz and 222.22 MHz FSRs, respectively. Owing to the Vernier effect, the value of the effective FSR becomes the least common multiple number of the two Rings' FSRs [98]. A PC was used to fine tune the cavity birefringence. The laser output was coupled out by the 10% port of the 90/10 optical coupler, and 10% of the output power was monitored by an OSA. The other 90% of the output power was coupled to a PD after amplification by an EDFA, and the microwave signal was detected by an ESA.

Fig. 5.10 Schematic diagram of the proposed fiber ring laser. EDF, erbium doped fiber; IGAFBG, inverse-Gaussian apodized fiber Bragg grating; OC, optical coupler; SOA, semiconductor optical amplifier; PC, polarization controller; OSA, optical spectrum analyzer; EDFA, erbium-doped fiber amplifier; PD, photodetector; ESA, electrical spectrum analyzer.

The uniform FBG can be tuned by a translation stage at three different strains, corresponding to positions *a*, *b*, and *c* in spectrum shown in Fig. 5.9. When the reflection peak of the uniform FBG overlaps with the two transmission peaks of the IGAFBG (position *b* in Fig. 5.9), a dual-wavelength lasing was established at 1542.2 and 1542.3 nm with a wavelength spacing of 0.1 nm. Fig. 5.11(a) shows the repeated scans of the two lasing lines at 3 min intervals over half an hour at room temperature, which exactly matches the two passbands of the IGAFBG shown in Fig. 5.9. The OSNR for these two lasing lines is around 40 dB. The detailed output power variation of the laser is shown in Fig. 5.11(b). It can be seen that, the maximum power fluctuation at the two wavelengths is only around 1 dB, illustrating good stability in output power of the dual-wavelength

laser. Fig. 5.12(a) shows a single wavelength emission at 1542.2 nm, when the reflection peak of the uniform FBG moves to position *a* in Fig. 5.9. The OSNR of this single lasing line is approximately 42 dB. Similarly, another single wavelength emission at 1542.3 nm is shown in Fig. 5.12(b), when the reflection peak of the uniform FBG moves to position *c* in Fig. 5.9, whose OSNR is around 42 dB.

(a)

(b)

Fig. 5.11 (a) Lasing spectra taken at a 3-min interval with dual-wavelength at 1542.2 and 1542.3 nm. (b)

Output power fluctuation at each lasing line within half an hour.

(a)

(b)

Fig. 5.12 Single wavelength operation of the proposed fiber laser at (a) 1542.2 nm and (b) 1542.3 nm.

Microwave signal at 12.51 GHz was achieved by beating the two lasing lines at a photodetector, when the reflection peak of uniform FBG moves to position *b* in Fig. 5.9. Fig. 5.13(a) shows the measured result in a 20 GHz span with a resolution of 1 MHz. Only one beat frequency exists, proving that each of the two lasing wavelengths is operating in SLM. Fig. 5.13(b) shows the result displayed in a 10 MHz span with a

resolution of 100 kHz. The central frequency of the microwave signal is around 12.51 GHz, corresponding to a wavelength separation of 0.1 nm of the two lasing lines. The central frequency shift is within 1 MHz, which suggests good stability in the generated microwave signal, and the 3 dB bandwidth of the microwave signal is less than 100 kHz.

(a)

(b)

Fig. 5.13 Electrical spectrum of the beat signal when the reflection peak of the uniform FBG is tuned to location b. a) 20 GHz span with resolution of 1 MHz b) 10 MHz span with resolution of 100 kHz.

When the reflection peak of the uniform FBG moves to position a or c in Fig. 5.9, single lasing line at 1542.2 or 1542.3 nm occurs. The SLM operation of the single wavelength emission is also verified. Choosing an output lasing line at 1542.2 nm as an example [see Fig. 5.12(a)], the RF spectrum of the laser output is shown in Fig. 5.14. The 400 MHz frequency range is wide enough to capture the beat signals between the main lasing mode and the possible adjacent modes. Obviously, the single wavelength emission operates in SLM since no beat signal exists in Fig. 5.14.

Fig. 5.14 Electrical spectrum of the beat signal when the reflection peak of the uniform FBG is tuned to location a .

Both the FFL and the SOA (operating in low-gain regime) are important for the performance of the dual-wavelength laser. It was found that, by removing the FFL and SOA from the ring cavity, unexpected multi-longitudinal-mode operation was obtained. In addition, dual-wavelength lasing is not stable even if we fine tune the PC, since the two lasing lines at 1542.2 and 1542.3 nm compete with each other. This is due to the long cavity length and the homogeneous gain of the pumped EDF in conjunction with mode hopping.

When a low-gain SOA was incorporated into the cavity without the FFL, stable dual-wavelength lasing was obtained when the drive current of SOA was increased to 75 mA (5mA above the transparency current). The output spectrum obtained is similar to the one shown in Fig. 5.11(a). Under this low-gain regime, the SOA introduces inhomogeneous gain and reduces gain competition among the different modes, resulting in stable dual-wavelength emission. It should be noted that, tuning of the PC in this case has no obvious effect on the stability of the lasing output. Due to the long ring cavity length, however, SLM operation cannot be obtained. The RF spectra obtained by beating the dual wavelengths (at 1542.2 and 1542.3 nm) and the single wavelength (at 1542.2 nm) are shown in Figs. 5.15 and 5.16, respectively. Fig. 5.16 shows that the frequency spacing between the adjacent beat signals is around 13.4 MHz, corresponding to a cavity length of about 15 m. The estimated 3 dB bandwidths of the two passbands in the IGAFBG are 1.47 pm and 0.86 pm, and this correspond to around 183.8 MHz and 107.5 MHz in frequency, both of which are greater than twice the cavity FSR (13.4 MHz). In this case, multi-longitudinal-mode operation was obtained.

Fig. 5.15 Electrical spectrum of the beat signal when the reflection peak of the uniform FBG is tuned to location b , but the FFL is removed from the cavity.

Fig. 5.16 Electrical spectrum of the beat signal when the reflection peak of the uniform FBG is tuned to location a , but the FFL is removed from the cavity.

By incorporating both the FFL and the low-gain SOA into the cavity, stable SLM operation at each wavelength oscillation of the dual-wavelength fiber laser was achieved. The short cavity length of Ring-2 provides a much larger FSR compared to Ring-1. Due

to the Vernier effect, the effective FSR becomes the least common multiple number of the FSRs of the two rings [98]. Hence the FFL is critical for mode suppression in a long length cavity. Besides, the incorporated IGAFBG filter has ultra-narrow transmission bands, and combining this characteristic with Ring-1 and Ring-2, we obtained SLM operation. Since only low-gain regime is preferred for SOA, the drive current of the SOA must be properly controlled. It was found that the drive current of the SOA should be restricted to 70-105 mA. Below 70 mA, the SOA is not activated enough to provide inhomogeneous gain, while above 105 mA, the SOA provides too much gain, leading to high noise and undesirable nonlinear effects [95], and SLM operation is not guaranteed.

5.5 Chapter Summary

In this chapter, the application of an IGAFBG in fiber lasers has been illustrated. An erbium-doped fiber laser with a linear cavity, incorporating an IGAFBG as a dual-passband filter, has been realized to emit dual-wavelength lasing. Unfortunately, it is a multi-longitudinal-mode operation due to the long cavity length.

To achieve a single-longitudinal-mode operation at each of the two lasing wavelengths, an erbium-doped fiber ring laser has been constructed. In the ring cavity, an IGAFBG acts as a dual-passband filter, and an unpumped EDF based saturable absorber induces an ultra-narrow bandwidth FBG to guarantee an SLM operation.

Due to the fact that the unpumped EDF based saturable absorber has some limitations such as large loss, and the requirement of a proper inherent power, another erbium-doped fiber ring laser was set up, incorporating an IGAFBG as a dual-passband filter, an SOA operating in low-gain regime to introduce inhomogeneous gain and reduce

gain competition, and a feedback fiber loop to ensure an SLM operation. With this setup, a switchable dual-wavelength laser with a wavelength spacing of 0.1 nm was achieved. The OSNR of the dual-wavelength lasing is approximately 40 dB, and a microwave signal at 12.51 GHz was generated by beating the two lasing lines at a photodetector.

Chapter 6 Tunable Microwave Generation Using FBG-Based Filters

6.1 Introduction

In chapter 5, I have described two setups to obtain microwave signals at particular frequencies of 10.502 and 12.51 GHz, using EDF lasers that incorporated IGAFBG based dual-passband filters. However, in some applications such as broadband surveillance radar, spread-spectrum, software-defined radio and so on, a tunable microwave generation scheme is desirable. As can be noted from chapter 5, the frequency of the microwave signal generated is determined by the wavelength spacing of the two lasing lines from the fiber laser, which in turn depends on the wavelength spacing of the two transmission bands in the filter. Hence in principle, the tuning of the microwave frequency can be realized by tuning the wavelength spacing of the two passbands in the filter. In this chapter, tunable microwave generation is realized in three different ways, by using the same Er-doped fiber laser system, but with different tunable FBG filters in each method, namely, IGAFBG, phase-shifted FBG, and phase-shifted chirped FBG.

6.2 Tunable Microwave Generation Using an IGAFBG

In this section, a method of using a cantilever to provide a linear chirp to change the wavelength spacing of the two passbands in an IGAFBG will be illustrated, and a continuously tunable microwave generation with a range of 20.16-24.196 GHz is realized.

6.2.1 Principle of cantilever induced chirp on a grating

A cantilever can provide a linear chirp for an FBG. As shown in Fig. 6.1(a), an FBG is glued within the slanted slit at the lateral side of a cantilever. The lengths of the two lateral sides are L and d , and the thickness of the cantilever is h , as marked in the figure. The center of the grating overlaps with the crossing point (red dot) of the fiber axis and the neutral axis of lateral side (dash-dot line). When a force or a displacement is applied to the free end of the cantilever [see Fig. 6.1(b)], half of the grating will experience tension while the other half will experience compression, with the strain at the crossing point (red dot) being zero [99]. Neglecting the small effect from the transverse moment, the curvature on the neutral axis of the cantilever beam at a given point z ($0 < z < L$) can be expressed as [99]:

$$\kappa(z) = \frac{12LF}{Eh^3b_0} = \frac{2f}{L^2} \quad (6.1)$$

where E is the Young modulus, F and f are the applied force and displacement, respectively.

The axial strain at each position along the grating is proportional to the curvature κ and the distance x that is between the given point on the grating and the crossing point at

the neutral axis [99], where $-l/2 < x < l/2$ and l is the grating length. At a certain displacement on the cantilever, there is a corresponding determined κ value based on Eq. (6.1). Hence, the axial strain along the grating is linearly distributed relative to distance x . In this way, a linear chirp can be formed along the grating.

Fig. 6.1 A cantilever bonded with an FBG when (a) no displacement, and (b) certain displacement is applied at the free end.

6.2.2 Chirped IGAFBG with a tunable wavelength spacing

IGAFBG is a grating structure that enhances the sidelobes of a uniform FBG to form two passbands in the stopband in its transmission spectrum. Using the transfer matrix method as illustrated in section 4.2, the transmission spectrum of an IGAFBG can be simulated and the result is shown in Fig. 6.2(a). In the simulations, n_{eff} is set at 1.44717, $\overline{\delta n_{eff}}$ is set at 3.6×10^{-4} , Λ is set at 532.5 nm, L is set at 9 mm, and the inverse apodization function used is given by Eq. (4.12). The wavelength spacing of the two passbands in the IGAFBG is found to be 0.192 nm, and by introducing a linear chirp in the grating, the wavelength spacing can be changed. As shown in Figs. 6.2(b)-(d), when different chirp rates of 0.1, 0.2, and 0.25 nm/cm are applied onto the IGAFBG, the wavelength spacings become 0.181, 0.17, and 0.16 nm, respectively. It can also be observed that the shape of the transmission spectrum changes slightly, which is a combined effect of the added chirp and the inverse apodization structure of the grating.

Fig. 6.2 Calculated transmission spectra of IGAFBGs at (a) 0 (b) 0.1 (c) 0.2, and (d) 0.25 nm/cm chirp rate, with different wavelength spacings. In simulation, $n_{eff} = 1.44717$, $\Lambda = 532.5\text{ nm}$, $\overline{\delta n_{eff}} = 3.6 \times 10^{-4}$, and $L = 9\text{ mm}$.

To verify the simulation results, a 9 mm long IGAFBG was fabricated using the standard phase mask scanning technique. A 73 mW UV light from a 244-nm frequency-doubled argon laser was focused through a cylindrical lens and a uniform phase mask with a pitch of 1065 nm, onto the core of a single-mode fiber that was hydrogen loaded for eight days. To realize the inverse-Gaussian apodization function $A(z)$ as given in Eq. (4.12), a scanning speed profile expressed in Eq. (4.13) was chosen for the UV light beam.

After the grating fabrication, the IGAFBG was glued, using the epoxy gel, into the slanted slit at the lateral side of a right-angle triangular cantilever (see the inset of Fig. 6.3). The cantilever has a length L of 18 cm, a width d of 3 cm, and a thickness h of 0.8 cm. The center of the IGAFBG was positioned at the point where the slanted slit crosses the neutral axis of the cantilever. With a displacement applied at the free end of the cantilever, a linearly chirped strain is obtained along the length of the grating, as explained in section 6.2. Hence, the strain induced chirp applied on the grating can be continuously tuned by adjusting the magnitude of the displacement at the end of the cantilever.

The measured transmission spectrum of the IGAFBG is shown in Fig. 6.4(a), in the case when no displacement was applied on the cantilever. Two passbands were observed at 1541.473 and 1541.665 nm, with a wavelength spacing of 0.192 nm. As the applied displacement on the cantilever increases, the wavelength spacing of the two passbands decreases. Three out of a series of measured wavelength spacing values of 0.182, 0.17, and 0.16 nm, are shown in Figs. 6.4(b)-(d), respectively, and are shown to match the simulated results in Fig. 6.2. It can be seen that, the experimental results in Fig. 6.4 are in

a good agreement with the simulated results in Fig. 6.2. There is a slight blue shift of the measured spectrum, compared to the simulated ones. This could be due to the fact that the grating is not glued onto the cantilever at a perfect position.

Fig. 6.3 Schematic diagram of the proposed fiber ring laser. The inset is the mechanism structure of the right-angle triangular cantilever with an IGAFBG bonded on it.

Fig. 6.4 Measured transmission spectra of IGAFBGs under different displacements applied on the free end of the cantilever, with wavelength spacings of (a) 0.192 nm, (b) 0.182 nm, (c) 0.17 nm, and (d) 0.16 nm of the dual passbands.

6.2.3 Tunable microwave generation from a dual-wavelength fiber laser

The schematic diagram of the proposed dual-wavelength fiber laser is shown in Fig. 6.3. In the fiber ring cavity, a section of EDF with a length of 4 m, pumped with a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer (WDM), acts as the gain medium. An IGAFBG whose spectrum is shown in Fig. 6.4(a), is bonded onto a cantilever to serve as a wavelength spacing tunable filter. A uniform FBG having a Bragg wavelength of 1540.7 nm, reflectivity of 99%, and a 3 dB bandwidth of around 0.3 nm, was tuned by applying a strain along the fiber axis, to filter out the two passbands of the IGAFBG. A 2 m long unpumped EDF with an absorption coefficient of 5.2 dB/m at 1530 nm serves as an SA. A polarization controller (PC) was used to fine tune the cavity birefringence. Laser output was coupled out via the 10% port of the 10:90 optical coupler (OC). 10% of the output power was monitored by an OSA, while the other 90% was connected to a photodetector (PD) after amplification by an erbium-doped fiber amplifier (EDFA). The microwave signal was observed using an electrical spectrum analyzer (ESA).

Fig. 6.5 Measured output laser spectra when different displacements are applied on the free end of the cantilever, giving wavelength spacings of (a) 0.192 nm, (b) 0.182 nm, (c) 0.17 nm, and (d) 0.16 nm of the two lasing lines.

By properly adjusting the PC under a pump power of 210 mW, dual-wavelength lasing was obtained, as shown in Fig. 6.5(a). The two lasing lines at 1541.477 and 1541.669 nm were obtained from the laser, with a wavelength spacing of 0.192 nm,

which matches the two passbands of the IGAFBG as shown in Fig. 6.4(a). The optical signal-to-noise ratio (OSNR) for these two lasing lines is approximately 36 dB. Repeated scans of the two wavelengths at a 6 minute interval within one hour are shown in Fig. 6.6(a), and the output power fluctuation of the laser is shown in Fig. 6.6(b). It can be seen that, the maximum power fluctuation at each of the two lasing wavelengths is less than 2 dB, illustrating good stability in the output power of the fiber laser. Fig. 6.7(a) shows the microwave signal captured by the ESA, within a 40 GHz span with a resolution of 3 MHz, and Fig. 6.7(b) shows the detail of the signal within a 10 MHz span with a resolution of 100 kHz. With only one beating frequency observed in the ESA suggests that each of the two lasing lines is in SLM operation. The generated microwave signal has a central frequency of approximately 24.196 GHz, corresponding to a wavelength spacing of 0.192 nm of the two lasing lines. The central frequency shift is within 1 MHz, which shows good stability of the microwave signal.

(a)

(b)

Fig. 6.6 (a) Lasing spectra taken at a 6 min interval within one hour when no displacement is applied on the cantilever (b) Output power fluctuation at each lasing wavelength.

(a)

(b)

Fig. 6.7 Electrical spectrum of the beat signal. (a) 40 GHz span with resolution of 3 MHz (b) 10 MHz span with resolution of 100 kHz.

As demonstrated earlier, a displacement applied onto the free end of the cantilever induces a linear chirp in the grating. A greater displacement brings a larger chirp rate, and vice versa. As a result, the wavelength spacing of the dual passbands of the IGAFBG will vary and can be adjusted accordingly. Therefore, the wavelength separation of the dual lasing lines can be tuned, to generate microwave signals with tunable frequencies. Increasing the displacement on the cantilever, the microwave frequency decreases to a smaller value. As shown in Figs. 6.5(b)-(d), under different displacements, the wavelength separation of the two lasing lines were tuned to be 0.182, 0.17, and 0.16 nm [matching the wavelength spacing in the IGAFBG filter shown in Figs. 6.4(b)-(d)], corresponding microwave frequencies of 22.96, 21.44, and 20.16 GHz, respectively, as shown in Fig. 6.8. That is to say, a microwave signal with a continuously tunable frequency, ranging from 24.196 GHz down to 20.16 GHz, was successfully achieved. It should be noted that, an unpumped EDF based SA was incorporated in the laser cavity since it can induce an ultra-narrow bandwidth FBG [94], which ensures the SLM operation in each of the two lasing lines, even when the bandwidth of the two passbands in the IGAFBG becomes broadened under a relatively large chirp.

Fig. 6.8 Electrical spectra of the beat signals at 24.196, 22.96, 21.44, and 20.16 GHz, corresponding to the wavelength spacings as shown in Fig. 6.4.

6.3 Tunable Microwave Generation Using a Phase-Shifted FBG

In section 6.2, linear chirp was introduced to an IGAFBG attached to the side of a triangular cantilever, by bending the cantilever. In doing so, the wavelength spacing between the two passbands of the IGAFBG can be varied from 0.16 to 0.192 nm, which corresponds to a frequency tuning range of 20.16 GHz - 24.2 GHz. However, the tuning range of the wavelength spacing is relatively small, since the added chirp also changes the entire shape of the transmission spectrum of the IGAFBG. Under a relatively large chirp rate, the insertion loss of the two passbands is too large and both passbands disappear. In this case, the IGAFBG cannot act as a dual-passband filter any more.

To obtain a wider tuning range, a method of using a phase-shifted FBG with two π -phase shifts attached to the side of a triangular cantilever, will be illustrated. The wavelength spacing between the two passbands of the phase-shifted FBG can be tuned from 0.07 to 0.188 nm by bending the cantilever.

6.3.1 Phase-shifted FBG bonded on a triangular cantilever to provide a tunable wavelength spacing

6.3.1.1 Principle of phase-shifted FBG with two π phase shifts

Apart from IGAFBGs, phase-shifted FBGs (PS-FBG) can also generate two ultra-narrow passbands in the stopband of the transmission spectrum. A conventional PS-FBG normally consists of a π phase shift in the center of the uniform grating structure, to form a passband within its stopband, which was illustrated in section 2.2.4. If two π phase shifts are positioned such that they are separated by a distance of ΔL with its center coinciding with the center of the grating, as shown in Fig. 6.9, it can be shown that the wavelength spacing of two transmission bands can be expressed as [80]:

$$\Delta\lambda = \frac{\lambda^2}{8n \cdot \Delta L} \quad (6.2)$$

where n is the effective refractive index of the fiber, λ is the Bragg wavelength of the grating, and ΔL is the separation distance between the positions of the two π -phase shifts. Hence, by setting the appropriate distance ΔL between the positions of the two phase shifts, a desirable wavelength spacing of the two passbands can be achieved. A dual-wavelength laser can be formed by incorporating such a dual-passband filter in the laser cavity. By beating the two wavelengths from the dual-wavelength fiber laser at a

photodetector, a microwave signal can be generated, and the beat frequency is given by:

$$f \cong \frac{c\Delta\lambda}{\lambda^2} \quad (6.3)$$

Fig. 6.9 Schematic diagram of a PS-FBG with two π -phase shifts.

6.3.1.2 Fabrication of a phase-shifted FBG with two π phase shifts

The standard phase-mask scanning technique was employed to fabricate the PS-FBG. The UV light from a 244-nm frequency-doubled argon laser was focused, through a cylindrical lens and a uniform phase mask of pitch 1064 nm, onto the core of a single-mode fiber. The fiber was hydrogen loaded for seven days to enhance its photosensitivity. By detuning a relative position by $\lambda/2$ between the phase mask and the fiber during the laser beam scanning process at a selected grating position, using a precision piezoelectric transducer, a π phase shift can be realized. A PS-FBG with a length of 13 mm was fabricated, whose transmission spectrum is shown in Fig. 6.10. The separation distance between the positions of the two phase shifts in the grating is 3 mm, corresponding to a wavelength spacing of 0.07 nm in the spectrum, calculated using Eq. (6.2). These two transmission peaks cannot be exactly resolved due to the fact that the OSA has a limited 0.01 nm resolution.

Fig. 6.10 Experimentally measured transmission spectrum of a PS-FBG with two phase shifts having a wavelength spacing of 0.07 nm.

6.3.1.3 Tuning the wavelength spacing in a phase-shifted FBG with two π phase shifts

To realize tunability of the wavelength spacing, the fabricated PS-FBG was bonded onto a triangular cantilever, as shown in Fig. 6.11, the same as the arrangement described in section 6.2.1. The grating was glued using an epoxy gel into a slanted slit that is at the lateral side of a triangular cantilever beam, with the center of the grating positioned at the neutral axis of the beam. When the cantilever is bent by applying a displacement at the free end, half of the grating above the neutral axis will experience tension while the other half below the neutral axis will experience compression [99]. The strain at the centre of the grating that crosses the neutral axis remains zero. As a result, a tunable linear chirp, corresponding to different displacements applied on the cantilever beam, can be obtained with the center wavelength unchanged. Using this cantilever method, a uniform PS-FBG

with two π -phase shifts turns into a chirped PS-FBG with two π -phase shifts. When a displacement is applied on the free end of the cantilever, leading to a linear chirp on the grating, the π -phase shifted grating that is in tension will have its transmission peak shifting to the longer wavelength end of the spectrum, while the π -phase shifted grating that is in compression will have its transmission peak shifting to the shorter wavelength end of the spectrum. In this way, the wavelength spacing between the two passbands can be varied depending on the displacement applied to the free end of the cantilever. Fig. 6.12 shows the measured transmission spectra of the PS-FBG under four different applied displacements, and the increase in the wavelength separation can be obviously observed. The wavelength spacings in these four cases are 0.070, 0.083, 0.110, and 0.188 nm, respectively. It can be seen that, as the transmission bands become broadened, the transmission peaks can be more easily resolved.

Fig. 6.11 A cantilever bonded with a PS-FBG to provide a linear chirp on the grating.

Fig. 6.12 Experimentally measured transmission spectra of a PS-FBG under four different displacements.

6.3.2 Dual-wavelength erbium-doped fiber laser using a phase-shifted FBG on a triangular cantilever

The schematic diagram of the proposed dual-wavelength EDF ring laser employed for the microwave generation is shown in Fig. 6.13. In the fiber laser ring cavity, a section of EDF with a length of 4.3 m was used as the gain medium, pumped by a 1480 nm laser diode at a power of 200 mW. A PS-FBG with a length of 13 mm that is bonded on the cantilever, serves as the wavelength spacing tunable filter. The separation distance between the positions of the two phase shifts in the grating is 3 mm, corresponding to a wavelength spacing of 0.07 nm in spectrum (see Fig. 6.10). A uniform FBG with a Bragg wavelength of 1540.7 nm, a 3 dB bandwidth of 0.3 nm, and reflectivity of 99% was incorporated to filter out the two transmission bands provided by the two phase shifts. A 2 m long unpumped EDF serves as an SA, ensuring that each of the two lasing

wavelengths operates in SLM. A PC was employed to fine tune the birefringence of the laser cavity. Laser output was coupled out via a 10:90 coupler where 10% of the output was connected to an OSA for lasing monitoring, and 90% to an ESA through an EDFA and a PD to capture the generated microwave signal.

Fig. 6.13 Schematic diagram of the proposed fiber ring laser. The inset is the mechanism structure of the triangular cantilever with a PS-FBG bonded on it. EDF, erbium doped fiber; PS-FBG, phase-shifted fiber Bragg grating; OC, optical coupler; PC, polarization controller; OSA, optical spectrum analyzer; EDFA, erbium-doped fiber amplifier; PD, photodetector; ESA, electrical spectrum analyzer.

Fig. 6.14 shows the repeated scans of the dual-wavelength laser output every 6 min within one hour, during which no strain was applied on the cantilever beam. The optical

signal-to-noise ratio (OSNR) is approximately equal to 35 dB, and the maximum power fluctuation of the two wavelengths was observed to be less than 2.2 dB, as shown in Fig. 6.15, illustrating good stability of the laser. Microwave signal was obtained by heterodyne photodetection of the two lasing lines. As shown in Fig. 6.16, in a measurement range of 20 GHz and a resolution of 3 MHz, only one beating frequency at 8.835 GHz (corresponding to a wavelength spacing of 0.07 nm) was observed as expected, verifying that each wavelength oscillation is indeed in SLM operation. The inset of Fig. 6.16 shows the display of the beat signal in a range of 10 MHz with a resolution of 100 kHz. The frequency shift was observed to be stable within 1 MHz in the free-running mode.

Fig. 6.14 Measured output spectra of the dual-wavelength SLM laser every 6 min during one hour.

Fig. 6.15 Fluctuation of the output power at the two lasing lines.

Fig. 6.16 Electrical spectrum of the microwave signal observed in the ESA within a span of 20 GHz. The inset shows the detail of the beat signal within a span of 10 MHz.

Various displacements were applied to the free end of the triangular cantilever beam using a vertical linear stage, as shown in Fig. 6.11. The wavelength spacing of the PS-FBG increases as the displacement increases, as illustrated in Fig. 6.12, enabling the frequency of the generated microwave signal to be tuned towards a higher value. Four of a series of continuously tunable microwave signals at frequencies of 8.835, 10.200, 13.600, and 24.365 GHz, corresponding to wavelength spacings of 0.070, 0.083, 0.110, and 0.188 nm (see Fig. 6.12), respectively, were captured by the ESA, as shown in Fig.

6.17. That is to say, microwave signals ranging from 8.835 to 24.36 GHz were successfully obtained.

Fig. 6.17 Captured electrical spectra of the tunable microwave signals at 8.835, 10.200, 13.600, and 24.360 GHz; the inset shows the corresponding optical spectra of the PS-FBG when different displacements were applied on the cantilever beam (measured by OSA).

6.4 Tunable Microwave Generation Using a Phase-Shifted Chirped FBG

Providing a tunable chirp on a phase-shifted FBG is just one way to tune the wavelength spacing of the two passbands within the stopband of a phase-shifted grating, as discussed in section 6.3. The tuning range of the wavelength spacing is limited by the bandwidth of the stopband as well as the mechanical property of the cantilever on which

the grating is adhered to. It is well known that a chirped FBG has a significantly larger stopband as compared to a uniform FBG. Hence, a larger tuning range can be expected when a phase-shifted chirped FBG is utilized in place of the phase-shifted FBG within the laser cavity.

In this section, a dual-wavelength fiber ring laser incorporating a phase-shifted chirped FBG (PS-CFBG) will be presented. The PS-CFBG consists of two passbands caused by two π phase shifts, where one is permanently fabricated within the grating, while the other is temporarily induced through the heat from a thermal head. The wavelength spacing of the two passbands can be continuously tuned by scanning the thermal head along the PS-CFBG. A tunable microwave signal with a frequency ranging from 6.88 to 36.64 GHz is obtained by heterodyning the two output lasing wavelengths at a photodetector. In principle, the tuning range of the microwave can be further increased by using a relative larger chirp rate grating or a longer grating with the same chirp rate, and a microwave signal with tens of GHz and even up to THz could be realized based on this proposed technique.

6.4.1 PS-CFBG tunable filter

A temporary π phase shift in a uniform FBG or a CFBG generated by heating a small section of the grating has been well studied in [43,100]. By scanning a thermal head along a CFBG, the wavelength of the thermal induced passband can be continuously tuned due to the matching relationship between the passband wavelength and the grating position. By inserting another permanent phase shift in the CFBG and tuning the position of the thermal-induced phase shift, the wavelength spacing of the two passbands caused

by the two phase shifts can then be continuously tuned. As shown in Fig. 6.18(a), a PS-CFBG comprising two π phase shifts, where one is permanently fabricated at the long wavelength end of the grating and the other induced by the heat from a thermal head at the short wavelength end of the grating. The heating element used is a platinum film resistor of 800 ohm. Unlike the NiCr resistance wire heater that requires a heat sink to suppress the thermal perturbation [43,100], the platinum film resistor has a more focused heating region and almost acts as a point heater which generates very weak thermal disturbance to the neighbor grating sections. Fig. 6.18(b) shows the image of the platinum film resistor observed under an optical microscope. The platinum film resistor consists of a serpentine distribution structure, forming a rectangle with a width of 570 μm and a length of 1000 μm . The substrate holding the platinum film is made of SiO_2 . Once the thermal head is scanned along the CFBG, the wavelength spacing of the two passbands $\Delta\lambda$ can be continuously tuned.

(a)

(b)

Fig. 6.18 (a) Operation principle of a PS-CFBG with a tunable thermal-induced phase shift and a permanent phase shift. (b) Microscope image of the platinum film resistor based thermal head.

We fabricated a PS-CFBG with a permanent π phase shift using the standard phase-mask scanning technique. An 80 mW UV light from a 244-nm frequency-doubled argon laser was focused through a cylindrical lens and a linearly chirped phase mask with a chirp rate of 0.073 nm/cm, onto the core of a Ge-doped single-mode fiber that had been hydrogen loaded for ten days. By detuning the relative position equivalent to half of the grating period at a selected grating position between the phase mask and the fiber, using a piezoelectric transducer during the UV beam scanning process, a permanent π phase shift was generated in a CFBG. The upper curve of Fig. 6.19 shows the measured transmission spectrum of a fabricated 5 cm long PS-CFBG with a permanent phase shift at a wavelength of 1560.806 nm. This PS-CFBG has a bandwidth of ~ 0.456 nm and an extinction ratio of 25 dB for its transmission response. To introduce another temporary phase shift in the PS-CFBG, a platinum film resistor, driven at a dc voltage of 0.54 V,

bonded on a 2D translation stage, and positioned just behind the fiber, was scanned along the length of the grating. It was found that, if the position of the temporary phase shift is too near to the permanent one, the two passbands cannot be distinguished and only one peak is observed in the spectrum. Two stable separated passbands can only be obtained if their wavelength separation is at least 0.06 nm, as shown in the middle curve of Fig. 6.19 (an offset is employed for the spectrum for easy observation). A larger wavelength separation of the two passbands were obtained by moving the thermal head farther away from the position of the permanent phase shift. The lower curve of Fig. 6.19 shows an example in which the wavelength separation is 0.204 nm. It should be noted that, the sharp peaks in Fig. 6.19 cannot be exactly resolved due to the limited 0.01 nm resolution of the OSA.

Fig. 6.19 Transmission spectra of the PS-CFBG with one passband caused by the permanent phase shift (upper curve), two passbands with 0.06 nm wavelength spacing (middle curve), and two passbands with 0.204 nm wavelength spacing (lower curve).

6.4.2 Tunable microwave generation based on a PS-CFBG

Fig. 6.20 shows the schematic diagram of the proposed dual-wavelength fiber laser. In the fiber ring cavity, a section of erbium-doped fiber (EDF) with a length of 2.6 m, pumped with a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer (WDM), acts as the gain medium. A PS-CFBG with two passbands generated by a permanent and a temporary thermal-induced phase shift serves as a tunable dual-passband filter. A CFBG having a similar spectrum as the PS-CFBG but without inserting any phase shift in the grating structure was used to filter out the two passbands of the PS-CFBG. A 2 m long unpumped EDF with an absorption coefficient of 5.2 dB/m at 1530 nm serves as an SA. A polarization controller (PC) was used to adjust the cavity birefringence. Laser output was coupled out via the 10% port of the 10:90 optical coupler (OC). 10% of the output power was monitored by an OSA, and the other 90% was connected to a PD after amplification by an EDFA. The microwave signal detected at the PD was displayed on an ESA.

Fig. 6.20 Schematic diagram of the proposed fiber ring laser.

By scanning the thermal head along the PS-CFBG, a series of dual wavelength lasing with a continuously tunable wavelength spacing was obtained. Fig. 6.21 shows six of the many measured results (an offset is employed in the spectra display for easy observation), with different wavelength separations of 0.06, 0.096, 0.16, 0.21, 0.238, and 0.298 nm, when the distances between the thermal head and the position of the permanent phase shift are 5, 7.8, 13.2, 16.7, 19.3, and 24 mm, correspondingly. To verify the stability of the generated dual wavelength lasing, repeated scans of the two wavelengths with a wavelength spacing of 0.06 nm were recorded at a 6 minute interval over a one-hour period, as shown in Fig. 6.22(a). The optical signal-to-noise ratio (OSNR) for these two lasing lines is around 30 dB. Fig. 6.22(b) shows the output power fluctuation of the laser. Notice that the maximum fluctuation at each of the two lasing wavelengths is less than 2

dB, which illustrates good stability in the output power of the fiber laser. Fig. 6.23 shows the captured microwave signals in the ESA within a 40 GHz span and a resolution of 3 MHz, at frequencies of 6.88, 10.86, 18.24, 24.88, 29.36, and 36.64 GHz, corresponding to the dual wavelength lasing with different wavelength spacings in Fig. 6.21. The only one beating frequency in the ESA verifies that each of the two lasing wavelengths is in SLM operation. The detail of the signal at 6.88 GHz within a 10 MHz span and a resolution of 100 kHz is shown in Fig. 6.24, corresponding to a wavelength spacing of 0.06 nm of the two lasing lines. The central frequency shift is within 1 MHz, which shows good stability of the generated microwave.

It should be noted that, the tuning range of the beat signal spans from 6.88 to 36.64 GHz in our current setup. This range is limited only by the bandwidth of the stopband of the PS-CFBG. In practice, the tuning range can be easily increased by using a relative larger chirp rate FBG or a longer FBG with the same chirp rate.

Also, we noticed that the optical output power stability of the various laser configurations described in chapters 5 and 6 varies from 1 dB to 2.2 dB. In literature, the output power fluctuation of the dual-wavelength laser has been reported to be 0.6 dB [21,22], 0.5 dB [24], and 2 dB [28], which is comparable to our proposed technique. To further stabilize the lasing output, the EDF can be cooled to 77 K in liquid nitrogen to reduce the homogeneous broadening of the fiber [101].

Fig. 6.21 Lasing spectra with tunable wavelength spacings of 0.06, 0.096, 0.16, 0.21, 0.238, and 0.298 nm.

(a)

(b)

Fig. 6.22 (a) Lasing spectra with a wavelength spacing of 0.06 nm taken at a 6-min interval over a one hour period. (b) Output power fluctuation at each lasing line.

Fig. 6.23 Electrical spectra of the captured microwave signals with tunable frequencies within 40 GHz span under a resolution of 3 MHz.

Fig. 6.24 Electrical spectrum of the beat signal at 6.88 GHz within 10 MHz span under a resolution of 100 kHz.

6.5 Chapter Summary

In this chapter, frequency tunable microwave signals have been realized in three different ways, based on the same EDF laser system, but different FBG filters incorporated in the laser cavity. The three different FBG filters used are IGAFBG, phase-shifted FBG, and phase-shifted chirped FBG.

Using the IGAFBG bonded on a cantilever, a tunable microwave signal with a range of 20.16-24.196 GHz has been achieved by bending the cantilever. This is due to the fact that, the cantilever can provide a linear chirp to change the wavelength spacing of the two passbands in the IGAFBG, thus changing the wavelength spacing of the two output lasing lines, which in turn change the frequency of the generated microwave signal.

The tuning range of the microwave signal using the IGAFBG is relatively small, since the added chirp not only changes the wavelength spacing of the two passbands, but also changes the entire spectral shape. The insertion loss of the two passbands will be too large and both passbands will disappear when the added chirp is beyond a certain value. In this case, dual-wavelength lasing is not achievable. Hence, another method of using a phase-shifted FBG with two π phase shifts bonded on a same cantilever has been explored to obtain a larger tuning range, which is from 8.835 to 24.36 GHz.

As is known, the tuning range of the microwave signal depends on the tuning range of the wavelength spacing between the two passbands in the grating, and the wavelength spacing is limited by the bandwidth of the stopband. To increase the tuning range, a phase-shifted chirped FBG, which has a larger bandwidth stopband compared to IGAFBG and phase-shifted FBG, has been used to generate a microwave signal with a range of 6.88 to 36.64 GHz. The phase-shifted chirped FBG possesses two π phase shifts. One phase shift is permanently fabricated in the grating while the other is temporarily thermal induced. The wavelength spacing of the two passbands caused by the two phase shifts is continuously tuned by scanning the thermal head along the grating. In principle, a microwave signal of tens of GHz or even up to THz could be realized based on this technique, if a larger chirp rate FBG or a longer FBG with the same chirp rate is used.

Chapter 7 Conclusions and Recommendations for Future Work

7.1 Conclusions

Dual-wavelength lasing has a unique advantage in microwave generation since it does not require an expensive microwave reference source. To achieve dual-wavelength lasing, several different structured FBGs including inverse-Gaussian apodized FBG, phase-shifted FBG, and phase-shifted chirped FBG, were used to act as dual-passband filters in this work.

The fundamental concept and working principle of FBG had been reviewed. Six different types (i.e., uniform, apodized, chirped, phase-shifted, superstructure, and tilted FBGs) and four advanced FBG structures (i.e., FBG pair, equivalent-phase-shift FBG, sampled chirped FBG, and phase-shifted chirped FBG), and their applications in fiber optics communication and fiber sensing had also been demonstrated.

The principle of microwave generation based on optical heterodyning had been explained. Four different techniques namely optical injection locking, phase locked loop, external modulation, and dual-wavelength lasing to generate microwave signals had been introduced, in which dual-wavelength lasing is the focus of this research, since the other three techniques require a costly reference source.

Inverse-Gaussian apodized FBG, which is a novel FBG structure, has been proposed. Such a FBG structure has unique advantages over PS-FBG, EPS-FBG, FBG pair, and PM-FBG, which were used for microwave generation in recent years. The fabrication of the IGAFBG involves a simple single-step scanning process. Also, the IGAFBG is inscribed in a low cost standard hydrogen loaded fiber and there is no physical gap in its structure. The principle of IGAFBG acting as a dual-, triple-, and multi-passband filter has been explained, based on the simulation results. The fabrication of an IGAFBG using a phase-mask scanning technique has been illustrated.

Using this new IGAFBG, a dual-wavelength multi-longitudinal-mode erbium-doped fiber laser with a linear cavity was demonstrated. Two lasing lines with a wavelength spacing of 0.146 nm were obtained. However, due to the long cavity length, only multi-longitudinal-mode operation was achieved. To achieve an SLM operation for each wavelength oscillation of the two lasing lines, another erbium-doped fiber ring laser comprising an unpumped erbium-doped fiber based saturable absorber was constructed. The saturable absorber serves as an ultra-narrow bandwidth FBG, whose bandwidth is less than twice the cavity FSR, thus ensuring SLM operation. A microwave signal at 10.502 GHz was obtained in this setup. However, unpumped EDF based saturable absorber has some drawbacks, such as large loss within the EDF (greatly reduces the efficiency of the fiber laser), and careful control of the inherent power of the oscillating mode propagating into the unpumped EDF is needed. To overcome these disadvantages, a laser cavity incorporating a semiconductor optical amplifier (SOA) that operates in low-gain regime to introduce inhomogeneous gain and reduce gain competition, and a

feedback fiber loop to ensure an SLM operation, was proposed. A microwave signal at 12.51 GHz was obtained in this fiber laser configuration.

By creating a linear chirp using a cantilever on an IGAFBG, the wavelength spacing between the two passbands of the grating can be tuned, which is a combination of the effect of the inverse apodized and chirped grating structures. Thus the frequency of the beat signal can be tuned and continuously tuned microwave signals from 24.196 GHz down to 20.16 GHz were demonstrated experimentally.

The tunability of the frequency of the generated microwave signal using an IGAFBG is limited. This is due to the fact that, as the applied chirp rate increases, the entire shape of the transmission spectrum changes. Up to a certain chirp rate, the two passbands of the IGAFBG will disappear and the IGAFBG cannot act as a dual-passband filter. Hence, dual-wavelength lasing is not available in this case. Instead of an IGAFBG, a phase-shifted FBG consisting of two π phase shifts was also used for frequency tunable microwave generation using a cantilever to provide a linear chirp similar to the previous case with IGAFBG. As the chirp rate increases with the application of a larger displacement, the transmission peak corresponding to the phase shift located in the section of the grating that is under tension will shift towards to a longer wavelength, while the transmission peak corresponding to the phase shift located in the section of the grating that is under compression will shift towards to a shorter wavelength. Hence, the wavelength separation of the two passbands broadens, and thus the frequency of the generated microwave signal increases. Microwave signals ranging from 8.835 to 24.36 GHz were obtained using a PS-FBG with two π phase shifts.

The tuning range of the wavelength spacing of a PS-FBG with two π phase shifts is limited by the bandwidth of the stopband of the phase-shifted grating. To increase the tuning range, a chirped FBG with significantly larger bandwidth stopband was considered. A dual-wavelength fiber ring laser, based on a phase-shifted chirped FBG with a permanent and a temporary thermal induced phase shift, was proposed to realize a relatively large tuning range for the generated microwave signals. By scanning a thermal head along the length of the grating, the wavelength spacing of the two lasing lines can be changed. A microwave signal continuously tuned from 6.88 to 36.64 GHz was successfully generated. In practice, the tuning range can be further increased by using either a larger chirp rate FBG or a longer FBG with the same chirp rate. A microwave signal of tens of GHz or even up to THz could be realized based on this proposed technique in principle.

In summary, the physical principle, spectral property, structure advantages, and practical application of the newly proposed IGAFBG have been investigated, based on the simulation and experimental results. Frequency tunable microwave generations have been realized optically using different types of FBGs, namely, IGAFBG, PS-FBG, and PS-CFBG.

7.2 Recommendations for Future Work

Research is an ongoing process. Although I have demonstrated some new and interesting results pertaining to optical microwave signal generation using FBGs, there will always be new areas that can be explored. In the following, I will highlight some additional work that future researchers may consider exploring.

1. To add a linear chirp on an IGAFBG, the wavelength spacing of the two passbands in the grating was tuned, as explained in chapter 6. However, the tuning range is relatively small. By adding a non-linear chirp provided by a non-uniform shaped cantilever in an IGAFBG, the tuning range may be increased.
2. The application of IGAFBG in a fiber laser has been explored. The IGAFBG may be used in fiber sensing applications. It has been proved that, by increasing the displacement on the free end of a cantilever holding an IGAFBG, the wavelength spacing of the two passbands can be decreased. Based on this principle, the IGAFBG can be used as a sensor to measure the displacement applied on the free end of the cantilever.
3. The PS-FBG with two π phase shifts attached on a cantilever was used as a tunable filter, as illustrated in section 6.3. The wavelength spacing of the two passbands caused by the two phase shifts increases as the displacement applied on the free end of the cantilever increases. Hence, the setup can be used to sense the displacement on the cantilever. In addition, the proposed PS-FBG is a uniform grating. Pushing or pulling the free end of the cantilever will increase the chirp rate to increase the wavelength spacing of the passbands. To substitute the PS-FBG with a PS-CFBG consisting of two π phase shifts, pushing and pulling the free end of the cantilever will increase and decrease the wavelength spacing, respectively. This phenomenon can be used in sensing to detect the direction of the applied displacement on the cantilever.
4. The PS-CFBG with a permanent and a temporary thermal-induced π phase shift has a relatively large tuning range for the generated microwave. However, when the

positions of the two phase shifts are too close, the heat from the thermal head will disturb both passbands, and thus there is a lower limit for the microwave frequency. To overcome this, a thermal head with a smaller dimension and higher heating efficiency can be used. This will extend the lower limit of the tuning frequency and hence increase the tuning range of the microwave signal.

5. The optical methods of generation of the microwave signals using different FBG filters in dual-wavelength fiber lasers have been discussed in this thesis. The usefulness and the efficiency of the generated microwave signals in transmission are expected to be further explored in a practical system in collaboration with another research group.

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Journal Papers

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Conference Papers

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