Novel Tunable Fiber Optic Edge Filter Based on Modulating Chirp Rate of π-Phase-Shifted Fiber Bragg Grating

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***Abstract*-We propose and experimentally demonstrate a novel tunable fiber optic edge filter based on modulating the chirp rate of a π-phase-shifted fiber Bragg grating (FBG) operated in reflection mode. The phase shift induced notch in the reflection spectrum is utilized as the edge filter. The dependence of the π-phase-shifted FBG's spectral response on the chirp rate has been numerically studied in detail and experimentally confirmed for the first time. The linear wavelength range of this edge filter can be tuned by changing the chirp rate of FBG. A fiber optic edge filter is further obtained experimentally and tested as a wavelength interrogator, which is in a good agreement with numerical results. The proposed edge filter has advantages of simple-structure, cost-effectiveness, high sensitivity, and flexible tunable, thus opening up some applications, especially as wavelength interrogator in small wavelength range.**

I. Introduction

Fiber optic edge filters have been investigated for applications in interrogation of wavelength modulation based fiber optic sensor such as fiber Bragg grating (FBG) sensors, long period grating (LPG) sensors and Fabry-Perot (F-P) sensors based on the principle of converting wavelength shift detection into optical intensity measurement [1-7]. Furthermore, fiber optic edge filters have been utilized widely for power equalization among different wavelength channels in an erbium-doped fiber amplifier [8].

Recently, many theoretical and experimental investigations on design and fabricating fiber optic edge filters have been reported [1-9]. Using LPGs [4,7], high birefringence fiber Sagnac loop mirror (HBF Sagnac LM) [5] and FBGs [1,2,6], fiber optic edge filters have been successfully realized, respectively. However, in despite of the low insertion loss and relatively high slope efficiency, LPGs are too sensitive to bending and environmental conditions. Moreover, it is very difficult to tailor LPGs' spectral response in the process of fabrication. As a result, LPGs as the edge filters are imposed some constraints in some applications [4,7]. For the HBF Sagnac LM based fiber optic edge filters, the HBF Sagnac LM is sensitive to temperature, and the shift of wavelength for an uncompensated HBF Sagnac LM with the temperature is very wide, leading to the instability of the practical systems [5]. In contrast, FBGs are relatively more suitable to application of fiber optic edge filters in most conditions. The tilted chirp FBGs are usually utilized as edge filters [1,6]. However, compared with uniform FBGs, it is more complicated to fabricate the tilted chirp FBGs and it is more difficult to tune the spectrum of tilted chirp FBGs.

In this paper, a novel fiber optic edge filter based on modulating the chirp rate of π-phase-shifted FBG is proposed and demonstrated experimentally. The wavelength response range of the filter is tunable by varying the chirp rate of π-phase-shifted FBG.

II. Design And Operational Principles

For the study on FBG, phase-shifted FBGs have drawn considerable research interests. By introducing a discrete, localized phase shift into the FBG, the spectral responses will have an extremely narrow notch within the pass band in the reflection spectrum of the FBG.

As an all fiber optical band pass filter device, the phase-shifted FBG has many potential applications in fiber optic source and sensor systems due to the unique advantages of all fiber geometry, low insertion loss, low polarization sensitivity, compact size and low cost.

In general, the phase-shifted FBG with a π-phase shift in the center of the grating is used quite widely because the notch with lowest reflectivity in the centre of the reflection spectrum can be obtained. However, few investigations have been attempted to the spectral response of phase shift FBG on the chirp rate, which is focused on in this work.

The phase-shifted FBG can be numerically described by the transfer matrix method (TMM) based on the coupled mode theory [10].

The TMM to modeling fiber Bragg grating is based on identifying 2×2 matrices for each uniform section of the grating, and then multiplying all of these together to obtain a single 2×2 matrix that describes the whole grating. The FBG is divided into M uniform sections and define R_i and S_i to be the field amplitudes after traversing the section i. Thus for FBGs, the propagation $\mathbf{F}_i$ through each uniform section is described by a matrix defined such that:

$$\begin{bmatrix} R_i \\ S_i \end{bmatrix} = \mathbf{F}_i \begin{bmatrix} R_{i-1} \\ S_{i-1} \end{bmatrix} \quad (1)$$

Once all of the matrices for the individual uniform sections are obtained, the output amplitudes can be calculated by:

$$\begin{bmatrix} R_M \\ S_M \end{bmatrix} = \mathbf{F} \begin{bmatrix} R_0 \\ S_0 \end{bmatrix} \tag{2}$$

$$\mathbf{F} = \mathbf{F}_M \cdot \mathbf{F}_{M-1} \cdot \ldots \cdot \mathbf{F}_i \cdot \ldots \cdot \mathbf{F}_1 \tag{3}$$

For phase-shifted FBGs, a phase-shifted matrix $\mathbf{F}_{pi}$ is inserted between the factors $\mathbf{F}_i$ and $\mathbf{F}_{i+1}$ in the product in (3) for a phase shift after the *i*th section. For FBGs the phase-shifted matrix is of the form:

$$\mathbf{F}_{pi}^{B} = \begin{bmatrix} \exp(\frac{-i\phi_i}{2}) & 0 \\ 0 & \exp(\frac{i\phi_i}{2}) \end{bmatrix} \tag{4}$$

Here, ϕ_i is the shift in the phase of the grating for discrete phase shifts. The TMM is suitable for the numerical simulation of the FBG because of high precision, efficiency and convenience. The next simulations are mainly made in Matlab software. The parameters used in the simulations are presented in the table I.

The calculated reflection spectrums of π-phase-shifted FBG with chirp rate of 0, 0.5 and 2.0 nm/cm are illustrated in Fig. 1. It is worth to be noted that for the π-phase-shifted FBG with chirp rate 2.0 nm/cm, the spectrum is too wide to be shown completely here.

In Fig. 2 it is clearly indicated that the bandwidth of the notch increases as well as the bandwidth of the whole spectrum when the chirp rate increases. In particular, the reflection spectrum of 1 cm long π-phase-shifted FBG with chirp rate 2.0 nm/cm is shown detailedly in Fig. 2 as an ensample. We clearly observe that for a 1 cm long π-phase-shifted FBG, when the chirp rate is about 2.0 nm/cm, each of the two fringe lines of the notch can be used as a fiber optic edge filter.

With the purpose of analysis and optimization the performance of edge filter based on the π-phase-shifted FBG, the linear wavelength range, the wavelength sensitivity and the peak reflectivity are investigated as the most important parameters which determine the dynamic range, the precision of wavelength interrogation and the signal amplitude respectively.

In more detail, Fig. 3 depicts the change in the linear wavelength range of the notch with the chirp rate of the π-phase-shifted FBG. It is clearly that the linear wavelength range of the notch is approximatively proportional to the chirp rate. The disagreement between the relation described in the Fig. 3 and the ideal linear function is due to the distortion of the notch compared with the normative beeline shape.

TABLE I

PARAMETERSPE USED IN SIMULATIONS

Denotation	Explanation	Value
n_0	Refractive index of fiber core	1.449
L	Grating length	1 cm
Λ	Grating period	536 nm
Δn	Index modulation depth	2.19×10^{-4}

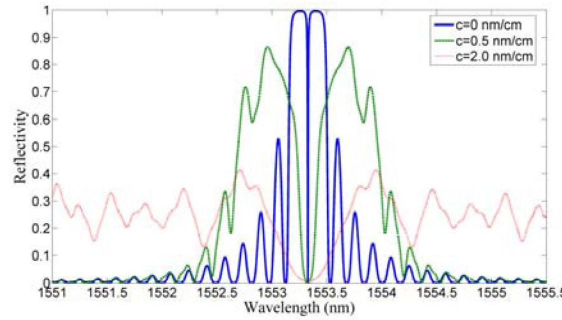

Fig. 1. Reflection spectrums of π-phase-shifted FBG when chirp rate (c) is 0, 0.5 and 2.0 nm/cm respectively.

It is indicated that the linear wavelength range increases when increasing the chirp rate, which means that the dynamic range of the proposed edge filter can be widen by adding the value of chirp rate. In addition, the relation between the wavelength sensitivity and the chirp rate of the π-phase-shifted FBG is shown in the Fig. 4 in detail for analyzing the precision of the proposed edge filter. Fig. 4 illustrates that the wavelength sensitivity of the proposed edge filter undergoes the digression when chirp rate increases. The difference of the curve in Fig. 4 from accurate linear relation is also caused by the distortion of the notch.

To evaluate the influence of chirp rate on the signal amplitude of the proposed edge filter, we represent in Fig. 5 the dependence of the peak reflectivity on the chirp rate. It is provided that the peak reflectivity of the π-phase-shifted FBG decreases when chirp rate increases, which means that the signal amplitude of the proposed edge filter is a decreasing function of chirp rate.

By synthesizing the response of linear wavelength range, wavelength sensitivity and the peak reflectivity on the chirp rate, it is revealed that the dynamic range, sensitivity and the signal amplitude of the edge filter are restricted by each other and need a tradeoff design to obtain the excellent performance for application in a given condition.

III. EXPERIMENT

In our experiment, a uniform 1 cm long FBG is fabricated at first by the phase mask scanning technique, where the UV radiation from a frequency doubled Argon laser is focused by a cylindrical lens trough a phase mask onto the core of a photosensitive optical fiber.

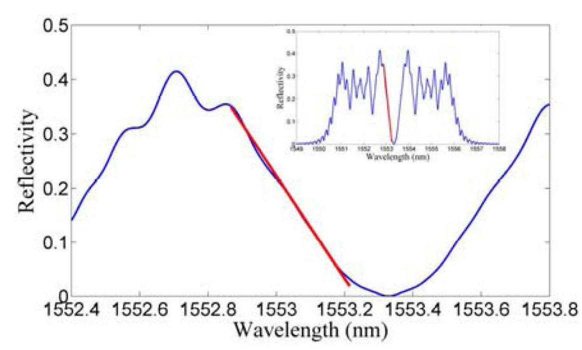

Fig. 2. Reflection spectrum of 1 cm long π-phase-shifted FBG with chirp rate of 2.0 nm/cm.

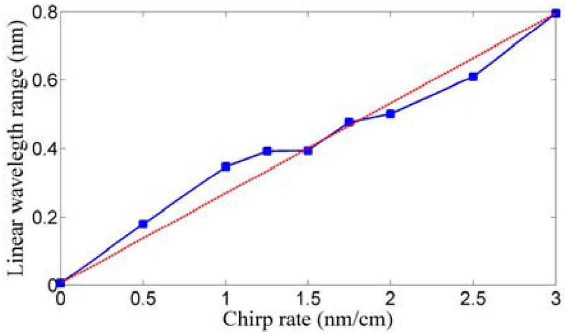

Fig. 3. The relation between the linear wavelength range of the proposed edge filter and the chirp rate of the π-phase-shifted FBG.

Then, the π-phase-shifted FBG is produced by means of the UV post-processing technique, where the uniform UV light is irradiated on the centre of FBG after forming the original conventional FBG. The UV post-processing technique is easy to implement, and the amount of phase shift can be monitored by observing the change of reflection spectrum.

The reflection spectrum of the fabricated π-phase-shifted FBG is monitored by a tunable laser source and an optical spectrum analyzer. A small amount of the laser radiation is sent to the FBG through an optical circulator. The reflection spectrum is therefore available at the optical circulator output and is monitored using optical spectrum analyzer.

The monitored reflection spectrum is shown in Fig. 7 (a). Compared with the reflection spectrum of the conventional FBG, there is a notch in the centre of the spectrum due to the π phase shift.

After fabrication of the π-phase-shifted FBG, modulating the chirp rate is realized next. The experimental setup for modulating the chirp rate of the fabricated π-phase-shifted FBG is presented in Fig. 6. As shown in Fig. 6, the π-phase-shifted FBG is bonded at a slant onto the lateral surface of the beam with the center located just at the beam's neutral surface. When the beam is bent, a strain field with respect to thickness forms. The FBG thus undergoes a bend induced strain, which brings on modulation of the chirp rate, and the chirp rate is proportional to the curvature of the beam [11].

In Fig. 7, the reflection spectrums with different chirp rate values induced by several curvatures are illustrated.

Because it is difficult to measure the accurate absolute value of the chirp rate, the values of chirp rate are normalized to the maximum, as 0, 0.2, 0.5, and 1.

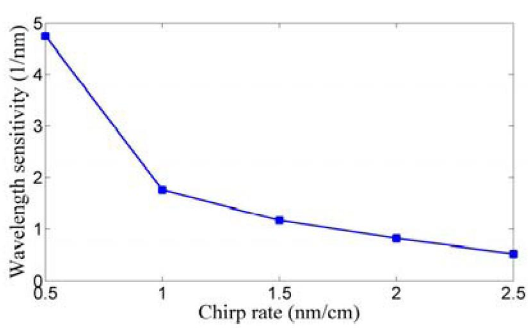

Fig. 4. The relation between the wavelength sensitivity of the proposed edge filter and the chirp rate of the π-phase-shifted FBG.

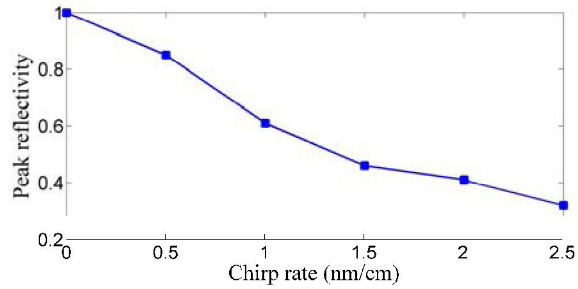

Fig. 5. The relation between the peak reflectivity and the chirp rate of π-phase-shifted FBG.

For investigating the spectral response of the π-phase-shifted FBG on the chirp rate, there is no remarkable difference between representing the normalized and absolute chirp rate.

From Fig.7, it is clear that the spectral response of the π-phase-shifted FBG on chirp rate is accord to the numerical simulation results, however, it should be noted that the wavelength shift in the spectrum due to the different curvatures is induced by the remnants radial strain to the FBG when bending. The setup of bending FBG for modulating the chirp rate to get the reflection spectrum illustrated in Fig. 7 (d) is fixed and the π-phase-shifted FBG with this spectral response is used as the fiber optic edge filter for the next experiment. The proposed fiber optic edge filter is tested as a wavelength interrogator, and the experimental setup is composed of a tunable laser source, a 3-port optical circulator, a photodetector, and the chirped π-phase-shifted FBG based edge filter, as shown in Fig. 8. The CW radiation of the laser goes to the π-phase-shifted FBG through the optical circulator and the light reflected from π-phase-shifted FBG within its spectrum goes to the photodetector through another port of optical circulator. In the experiment, input wavelength is tuned from 1547.35 to 1547.65 nm. Fig. 9 shows the normalized output of the photodetector is an approximately linear function of input wavelength in the range of 1547.35 to 1547.65 nm with the wavelength resolution better than 0.04 nm without amplifier operation. The higher wavelength resolution can be obtained by making the original output of the photodetector be amplified.

IV. CONCLUSION

This paper presents a novel tunable fiber optic edge filter based on modulating the chirp rate of a π-phase-shifted FBG. The spectral response of π-phase-shifted FBG on the chirp rate is numerical simulated in detail. The simulation results show that the notch of reflection spectrum can be used as a fiber optic edge filter when the chirp rate is tuned to a certain value, and the linear wavelength range of the filter can be tuned in a range by changing the chirp rate.

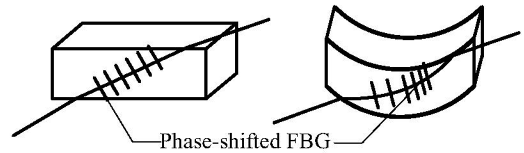

Fig. 6 Schematic diagram of the experimental setup for modulation the chirp rate of π-phase-shifted FBG.

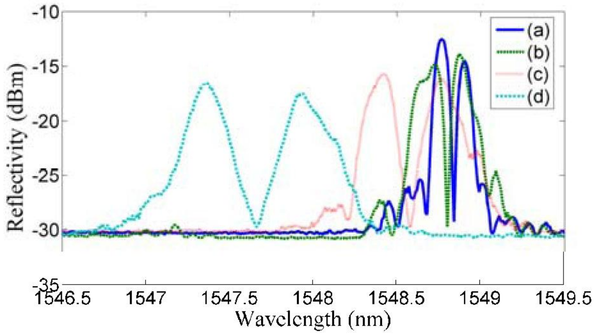

Fig. 7 Reflection spectrums of π-phase-shifted FBG with different chirp rates changed by the bend. Normalized chirp rates: 0 (a), 0.2 (b), 0.5 (c) and 1 (d).

The π-phase-shifted FBG is fabricated and its spectral response on chirp rate is investigated experimentally, which confirms the simulation results. The proposed edge filter is realized experimentally and tested as a wavelength interrogator, by which the wavelength range from 1547.35 nm to 1547.65 nm is demodulated with the wavelength resolution better than 0.04 nm. The numerical and experimental results indicate that this proposed fiber optic edge filter is effective and available for potential practical application. Finally, it is worth noting that the linear wavelength range of the proposed edge filter is limited by the reflectivity and wavelength sensitivity, therefore, it is especially applicable to the cases where the small response range, high precision and adjustability are required. However, it is worth to solve the limitation of the linear wavelength range to make it more feasible for practical application in more conditions. Furthermore, this work seems promising not only to provide an interesting solution for the fiber optic edge filter but also to widen the application field in design and fabrication of phase shifted FBGs based devices, further studies on which will be summarized in our next study.

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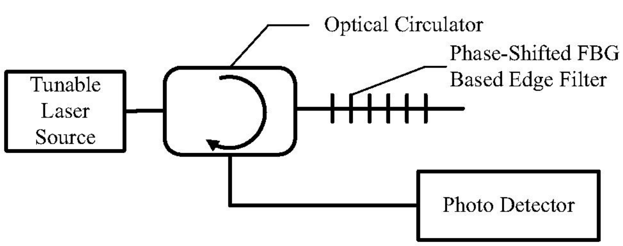

Fig. 8. Schematic diagram of experimental setup for the test of proposed fiber optic edge filter used as the wavelength interrogator.

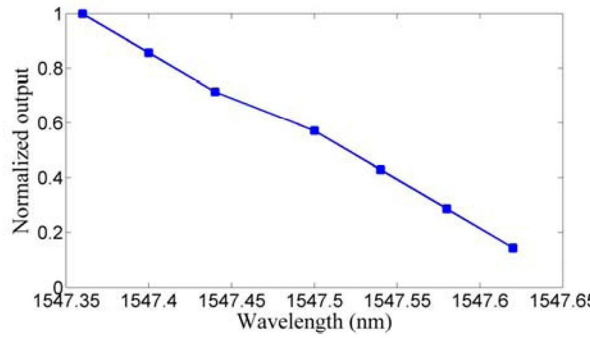

Fig. 9. Normalized output of photo detector with different input wavelength.

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