Multi-channel notch filter based on a phase-shifted phase-only-sampled fiber Bragg grating

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Abstract: We propose a novel method for the implementation of a tunable multi-channel notch filter based on a thermally induced phase-shift phase-only sampled fiber Bragg grating (FBG). The proposed method is numerically and experimentally demonstrated. A 51-channel notch filter with a bandwidth (FWHM) of 0.026 nm and a tuning range of 0.6 nm has been achieved. This proposed technique offers the potential applications to the multiwavelength fiber laser and multi-channel all optical logic devices.

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OCIS codes: (060.3735) Fiber Bragg gratings; (120.2440) Filters; (230.1480) Bragg reflectors; (050.5080) Phase shift; (060.2340) Fiber optics components.

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1. Introduction

Recently, with the increasingly demands for the broad-band and high-speed fiber transmission link, multi-channel optical filter has received significant attention due to its unique properties, such as the low cost, the low insertion-loss, and the high-quality of the channel performances capable of being used as either a chromatic dispersion compensator [1-2] or the key device for the implementation of multiwavelength fiber lasers [3]. To date, several kinds of multi-channel fiber Bragg gratings (FBGs) have been proposed and demonstrated, such as the sinc-sampled FBG, the superimposed FBG, the Talbot-effect based FBG, and the phase-only...
sampled FBG. In particular, the phase-only sampled FBG has attracted much more interest due to the minimum index-modulation requirement and the smooth refractive-index profile, which is especially compatible with the robust side-writing phase-mask technique [1-2].

Phase-shifted FBG is one of the critical fiber passive components which has been widely used in, for example, the narrow band-pass filter, fiber lasers emitted with a narrow linewidth, and the all-optical logic devices [4-9]. A phase-shift can be permanently inscribed into the FBG by using either the phase-shift phase-mask technique or the UV postprocessing technique. In addition, a temporary phase-shift can be introduced into the FBG by thermal or mechanical methods [8-9]. The distinct advantage of the tunability makes the temporarily inscribed phase-shift technique more attractive for the implementation of tunable or switchable all-optical devices. Ngo et al. have proposed and demonstrated a simple method for the development of a tunable narrow band-pass filter based on a temporary phase-shift introduced by a wire heater [8]. Latterly, they employed this method to make an eight-wavelength fiber laser using eight wire heaters [9]. However, due to the thermal diffusion effect between each wires and the difficulty to determinate the positions of heating wires located, the method is not available for the implementation of multi-channel narrow filter with a high-count channel number.

In this paper, we propose a novel technique for the realization of a multi-channel notch filter, where only one thermally induced phase-shift is inserted into the phase-only sampled FBG with a channel number up to 51. Besides the intrinsic properties of the thermally induced phase-shift FBG, including a continuously tuning range, easy control, low cost, narrow bandwidth, and low polarization sensitivity, this technique offers an extraordinary advantage that all the notch channel are simultaneously realized by controlling the phase-shift at only one-point of the FBG. The proposed method has the potential applications to the development of a multiwavelength fiber laser with high channel-count, and the multi-channel all optical logic devices, such as all-optical switch, temporal differentiator and integrator, and the pulse shaper.

2. Principle and simulation results for the phase-shifted phase-only-sampled FBG

As is generally known, the phase-only sampled FBG is the product of a single-channel seed grating with the phase-only sampling function in spatial domain. In general, the refractive index-modulation $\Delta n(z)$ can be expressed as

$$\Delta n(z) = \text{Re} \left\{ \Delta n_0 + \frac{\Delta n_i(z)}{2} \cdot \exp \left( \frac{2\pi i}{A(z)} \right) \cdot s(z) \right\},$$

where $\Delta n_i(z)$ is the maximum index-modulation, $z$ is the position along the grating, $\Delta n_0$ denotes the “dc” part of the index-modulation, $A(z)$ is the local pitch of a seed grating and it can be expressed as $A(z) = A_0 (1 - C_z \times z)$ for a linearly chirped FBG, where $A_0$ is the period at the beginning position of grating and $C_z$ is the chirp rate of the grating period. $s(z)$ denotes the phase-only sampling function [1]. As a phase shift $\theta$ is introduced in the sampled FBG at the position of $z_0$, the index modulation can be equivalently written as

$$\Delta n'(z) = \begin{cases} 
\text{Re} \left\{ \Delta n_0 + \frac{\Delta n_i(z)}{2} \cdot \exp \left( \frac{2\pi i}{A(z)} \right) \cdot s(z) \right\} & \text{when } z \leq z_0 \\
\text{Re} \left\{ \Delta n_0 + \frac{\Delta n_i(z)}{2} \cdot \exp \left( \frac{2\pi i}{A(z)} \right) \cdot \exp(\theta) \cdot s(z) \right\} & \text{when } z > z_0
\end{cases}.$$
It is obviously seen from Eq. (2) that the phase-shift phase-only sampled FBG is equivalent to a phase-shift single channel FBG (also called the seed grating) multiplied by a sampling function in spatial domain. Therefore, the reflection spectrum resulted from a phase-shifted seed grating should be copied simultaneously through all the sampled channels. Figure 1 shows the simulation results for the reflection spectrum of 51-channel FBG in which a $\pi$ phase shift is inserted at its central position. Here the original 51-channel FBG (without phase-shift inserted) is a linearly chirped grating designed for the simultaneous dispersion and dispersion-slope compensation in optical communication system, which has a channel-spacing of 0.8 nm and a grating length of 12 cm [1-2,10]. It can be seen from the Fig. 1(b) (i.e., the three channels spectra near the central of Fig. 1(a)) that a narrow band-stop (notch) filter with a bandwidth (full width at half maximum (FWHM)) of 0.028 nm is obtained through all the channels. To verify the tunability of this kind of notch filter, some numerical simulations about the influences of the magnitude and position of the phase-shift on the reflection response of the phase-only sampled 51-channel FBG are further investigated. Figure 2(a) shows the reflection spectra (in the central channel) of the FBG with 7 different phase shifts ranged from 0 to $\pi$. It can be seen that the bandwidth of the notch filter is decreasingly changed as the phase shift is gradually increased. Meanwhile, with increase of the phase shift, the strength and the peak wavelength of the notch filter are increased also. Figure 2(b) shows the reflection spectra in the central channel, in which the $\pi$ phase shift is introduced at 7 different positions. As is well-known, for a linearly chirped FBG, the reflective wavelength is only determined by the fiber effective index and the local pitch $\Lambda(z)$, which is linearly changed along the grating. As is shown in Fig. 2(b), the peak wavelength of the resulted notch filter changes linearly with the length of $z_0$ where the phase shift is inserted. Therefore, if we mechanically change the phase-shift position along the phase-only sampled linearly chirped FBG, a tunable notch filter can be obtained and the tunable range is determined by the channel bandwidth, which is 0.6 nm in this paper. Moreover, the above simulation results offer us the potentials for the implementation of a continuously tunable multi-channel optical switching and all-optical logic devices by thermally engineering the profile of the notch filter.
Fig. 2. Numerical results for the reflection spectra in the central channel of the 51-channel FBG. (a) The reflection spectra in which 7 different phase shifts ranged from 0 to $\pi$ are introduced at the central position of FBG, and (b) the reflection spectra in which a $\pi$ phase shift is introduced at 7 different positions of the grating.

3. Experimental results

The schematic diagram of the proposed multi-channel notch filter is shown in Fig. 3, where the phase-only sampled FBG is vertically placed on a NiCr wire heater which is fixed in a V-groove. The V-groove is fabricated on a heat-insulating material. Because of the thermo-optical effect, the refractive index of the fiber will change with the temperature of the wire heater (i.e., NiCr wire, its diameter is about 0.3mm). Hence, the temperature change in a local small section of the fiber will introduce a phase shift at that point [9]. An amplified spontaneous emission (ASE) is used as the broadband light source (BLS). As shown in Fig. 3, a simple circuit including a variable resistor and a direct current source is employed to control the temperature of the NiCr wire. A heat sink made from a thin copper plank is placed over the crossing area to dissipate the unwanted heat conduction.

Once the temperature of NiCr wire is heated up, the phase shift is increased and can be expressed as [8]

$$\theta = \frac{2\pi L}{\lambda} \kappa \cdot \Delta T,$$

(3)
where $\kappa$ is the thermo-optical coefficient of the silica fiber ($8.6 \times 10^{-6} \text{ K}^{-1}$ for silica fiber), $\Delta T$ is the temperature change, and $L$ is the width of the heated region (related to the diameter of NiCr wire). The temperature change related to a $\pi$ phase shift is about 300K. A linearly chirped phase-only sampled 51-channel FBG with channel bandwidth of 0.6 and spacing of 0.8 nm has been employed here [2]. Figure 4 shows the experimental measurement for the reflection spectrum, it is seen that the characteristics are almost the same with the designed one used in the above section. However, as shown in the inset of Fig. 4(a), there exists a small oblique on the top of reflection curve, which may be attributed to the existence of the cladding-mode coupling [11]. The dispersion spectrum is illustrated in Fig. 4(b) where the dispersion in the central channel is -1815 ps/nm and the dispersion slope equals to -6.7 ps/nm$^2$ which is measured by using phase-shift method (PSM) under the modulation frequency of 250 MHz [2]. From Eq. 3, by carefully adjusting the variable resistor, the minimum bandwidth of the notch filter can be obtained in the reflection spectrum which should be related to the $\pi$ phase shift. Figure 5 shows the reflection spectrum of the 51-channel FBG with $\pi$ phase shift, which is measured by using optical spectrum analyzer (OSA). The reflection spectrum of central three channels is shown in Fig. 5(b). The FWHM of the notch filter is about 0.026 nm at the central channel which agrees well with the numerical results in the above section. Note that, seen from Fig. 5(b), the two sidebands beside the notch are non-symmetric, i.e. the left-side is lower and the right side is higher. It is caused by the small oblique existing on the top of reflection spectrum (as shown in Fig. 4(a)). Moreover, the ripples on its reflection bandwidth are caused by the inserted $\pi$ phase shift which effectively forms a Fabry-Perot cavity in the FBG. These ripples will reduce the signal-to-noise ratio (SNR) of the notch filter. It is expected to eliminate or reduce the ripples by designing an appropriate phase profile of the phase-shift in the future.

![Reflection spectrum](a)

![Dispersion spectrum](b)

Fig. 4. (a) Reflection spectrum of the 51-channel phase sample FBG, and (b) its dispersion spectrum.
To confirm the above numerical analysis, the experimental investigations about the influences of the magnitude and the position of the phase shift on the reflection spectrum are carried out. By appropriately controlling and decreasing the variable resistor, we introduce seven different magnitudes of the phase shifts labeled by the number 1 to 7 at the central position of the 51-channel FBG. The corresponding results are shown in Fig. 6(a). Compared with Fig. 2(a), it can be seen that the experimental results agree well with the numerical ones. Figure 6(b) shows the reflection spectra (within the central channel) corresponding to the phase shifts at three different positions: 4, 6, and 7 cm from the beginning of the grating. The obtained results is also in accordant with the ones as is shown in Fig. 2(b), which in turn verifies that the peak wavelength of the notch filter can be easily controlled by moving the grating or the heating wire along the grating direction. On the other hand, for the practical application of this multi-channel notch filter, the spectral stability is one of the critical parameters to be considered. Generally, it is believed that two main factors may cause the instability of the filter: 1) thermal diffusion effect of the NiCr wire, and 2) the drift of the FBGs’ reflection spectrum as a result of the environmental perturbation. In our experiment, the thermal diffusion effect may be alleviated by making use of the heat sink. Meanwhile, all the measuring experiment is implemented in an isolated environment to eliminate the environmental perturbation. To verify this, we repeatedly measure the spectrum by scanning the OSA 7 times in every other 5 minute. The result is illustrated in Fig. 6(c). It can be seen that there are no peak-wavelength shift to be visible. Note that, the copper sink is located above the fiber which is in contact with the fiber. As described above, the thermal diffusion will affect the stability of this notch filter. The stable performance of this filter is partly attributed to the use of the heat sink. Moreover, the reflection spectra with the \( \pi \) phase shift at different channels (i.e., the central wavelength of the four channels are 1530.20 nm, 1540.50 nm, 1550.04 nm, and 1560.50 nm, respectively) are illustrated in Fig. 6(d). Besides of the intrinsic difference of channel bandwidth of the 51-channel FBG caused by the dispersion slope (since the phase-only sampled FBG is designed and fabricated to compensate the dispersion and dispersion slope) [10], the four reflection spectra agree well with each other, which in return means that the proposed setup works pretty stable.
Fig. 6. (a) Reflection spectra with different phase shifts (the 7th phase shift is $\pi$), (b) central channel’s reflection spectra of the 51-channel FBG with the phase shifts at three different positions, (c) seven central channel reflection spectra scanned every other 5 minutes, and (d) the reflection spectra of four channels with different central wavelengths (i.e., 1530.20 nm, 1540.50 nm, 1550.04 nm, and 1560.50 nm).

4. Conclusions

A novel approach for the implementation of a tunable multi-channel notch filter has been demonstrated. This method offers an unprecedented characteristic that the resulted notch filters are thermally tunable and all the channels are simultaneously obtained by inserting only one thermally induced phase-shift in FBG. Several key parameters, such as the magnitude and the position of the phase shift inserted, are numerically and experimentally investigated. A tunable notch filter with a FWHM of 0.026 nm, a tuning range of 0.6 nm, and a channel number up to 51 has been obtained. It is expected that various potential applications, such as the multiwavelength fiber laser, the multichannel all optical logic devices (including multichannel switching, temporal differentiator and integrator, pulse shaping etc.) can be developed by using this kind of filter.

Acknowledgments

This work was supported by the Grant-in-Aid for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan. This work was also partly supported by the Kurata Memorial Hitachi Science and Technology Foundation in Japan.