Hybrid fiber grating-based optical comb filters with changeable channel numbers

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An in-fiber Mach-Zehnder interferometer filter based on a pair of long-period fiber gratings (LPFGs) has been operated in the reflection mode by incorporating a broadband chirped-fiber Bragg grating (CFBG) or an optical fiber mirror reflector. As a result, the extinction ratio has been nearly doubled and, by tuning chirp rate, i.e. reflection bandwidth of the CFBG using a beam-bending method, channel number of the formed optical comb filter can be easily changed. In our experiment, two comb filters with channel numbers being changed from 1 to 5 and 3 to 9 have been achieved, respectively.

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1. Introduction

Optical fiber grating filters have been studied extensively due to their several important advantages such as the low insertion loss and the inherent compatibility to the optical fiber networks. Their versatility and unique capabilities have generated a large number of applications in the optical fiber communication and sensor systems. In recent years, an in-fiber Mach-Zehnder interferometer (MZI) by using a pair of long-period fiber gratings (LPFGs) written in series along a fiber has attracted considerable research interest [1,2]. In such a device the first LPFG couples part of the core mode intensity into one or several cladding modes (i.e. high order modes) and the second LPFG combines the core and cladding modes again. Due to the differential refractive index of the optical fiber, an in-fiber MZI is therefore formed where the core and the cladding of the fiber between the two LPFGs act as the two arms. Such devices may act as a cost-efficient wavelength-division-multiplexing (WDM) filters with very low insertion loss [1]. The channel wavelengths can be tuned by applying strain, varying temperature, or changing the differential refractive index of the fiber by introducing nonlinear effect [3-5]. And the fringe spacing can be easily adjusted by changing the separation between the two LPFGs during grating fabrication process [2]. These LPFG-based MZI filters may play an important role in fiber lasers and sensors [6,7]. However, extinction ratio of these filters is dependent on wavelength due to the wavelength-dependent coupling efficiency of the individual LPFGs. High extinction ratio can be only achieved in a relatively narrow band where the optical intensity is nearly equally separated into the core and cladding modes, corresponding to the wavelength bands where the notch depth for the individual LPFGs is around 3 dB. For rest parts of the involved wavelength band, especially for the both band edges, the extinction ratio is low. This is a serious disadvantage for these LPFG-based MZI filters.

In this paper, LPFG-based MZI filters have been operated in the reflection mode by incorporating a broadband chirped-fiber Bragg grating (CFBG) or an optical fiber mirror reflector. For the first case (with a CFBG), we call it “hybrid fiber grating-based comb filter” because two kind of fiber gratings (CFBG and LPFG) are used and only channels located within the reflection wavelength range of the CFBG can been seen at the output port. Compared with the previous designs operated in transmission mode, the proposed filters show nearly doubled extinction ratios, which greatly enhances the flexible selectivity of the spectral band of these devices, though the extinction ratio is still dependent on wavelength. Furthermore, by tuning chirp rate, i.e. reflection bandwidth of the CFBG reflector, channel number of the so-called “hybrid fiber grating-based comb filter” can be easily adjusted. This allows us to select those channels with high extinction ratios only, while it is not possible for the original designs operated in transmission mode. In our experiment, two comb filters with extinction ratios over 15 dB, changeable channel numbers of 1 to 5 and 3 to 9 have been achieved respectively.

2. Design and principle

The LPFG-based MZI consists of two identical LPFGs fabricated in series along a single-mode fiber with the polymer jacket of the fiber between gratings stripped off. The first LPFG couples part of the core mode intensity into a cladding mode and these two modes combine again in the second LPFG. The core and cladding of the fiber therefore act as two arms of the MZI and their difference in propagating constant introduces the optical path difference. Interference fringes can be observed within each stop band of the LPFGs, with a fringe spacing being described as

$$S = \frac{2\pi\lambda}{(\beta_{core} - \beta_{clad})L}, \quad (1)$$

where λ is wavelength, L is the center-to-center separation between the two LPFGs, β_{core} and β_{clad} are the propagating constants of the core and the cladding modes, respectively. The envelope curves of the interference fringes are determined by the minimum and maximum transmissivity, which are given respectively by

$$T^{\min} = [T_s - \alpha(1 - T_s)]^2, \quad (2)$$

$$T^{\max} = [T_s + \alpha(1 - T_s)]^2, \quad (3)$$

where $T_s = \cos^2 sd + (\Delta\beta / 2s)^2 \sin^2 sd$, is transmissivity of a single LPFG, d is the grating length, s is defined by $s^2 = \kappa\kappa^* + (\Delta\beta/2)^2$ with κ being the coupling coefficient of the grating and $\Delta\beta$ being the detuning parameter defined by $\Delta\beta = \beta_{core} - \beta_{clad} - 2\pi/\Lambda$ (Λ is the grating period); and α ($0 \le \alpha \le 1$) denotes the loss on the cladding modes. If there is no loss on the cladding modes, $\alpha = 1$, $T_{pair}^{\max}$ will equal to 1, namely, no loss will happen for the transmission channels.

If an optical fiber mirror reflector or a broadband CFBG reflector with very high reflectivity of 100% is used to reflect the transmitted light and make it pass the LPFG pair again, the minimum and maximum transmissivity of the reflected light will be described as

$$T_R^{\min} = \gamma[T_s - \alpha(1 - T_s)]^4, \quad (4)$$

$$T_R^{\max} = \gamma[T_s + \alpha(1 - T_s)]^4, \quad (5)$$

where $0 \le \gamma \le 1$ is the reflectivity of the mirror (or reflector). Eqs. (4) and (5) indicate that the extinction ratio of interference fringes will be greatly improved. For example, if $\alpha = \gamma = 1$, i.e. no loss introduced during light propagating in fiber cladding and reflection, and $T_s = 0.8$ (corresponding to ~1 dB transmission loss of a single LPFG), we will get $T^{\max} = T_R^{\max} = 1$, $T^{\min} = 0.36$, and $T_R^{\min} = 0.13$. The corresponding extinction ratios are 4.43 and 8.86 dB for the cases of without and with reflector, respectively. That is to say, extinction ratio of the LPFG-based MZI filter will be doubled by using the beam reflector.

3. Experimental results and discussion

Several samples of LPFG pair-based MZI filter and CFBGs were fabricated by using a 244 nm laser beam (frequency-doubled Argon laser) in a hydrogen-loaded single-mode fiber with a beam-scanning method. After fabrication, the gratings were annealed at 100 °C for ~15 hours. The period and length for each LPFG were 475 μm and 12 mm, respectively. The transmission minimum (or notch depth) of the LPFGs can be adjusted by changing power of the argon laser. In this work, the transmission minimum taking place at around 1560 nm was around 4.5 dB, relatively larger than 3 dB so that the highest extinction ratio of the formed MZIs happened at both sides of the center wavelength (corresponding to the two 3-dB-transmission-loss parts). The center to center grating separations were different so that different fringe spacings from 1.1 to 4.35 nm were achieved. The bandwidth-tunable CFBG reflector, with a center wavelength of 1555 nm and high reflectivity of over 20 dB, was chirp rate-tuned by using a special cantilever beam-bending method, which was previously reported in [8]. The experimental measurement setup is shown in Fig. 1. A tunable laser source (TLS) and an optical spectrum analyzer (OSA) were used, incorporated with an optical circulator, to measure optical spectra of the fiber gratings and their formed filters.

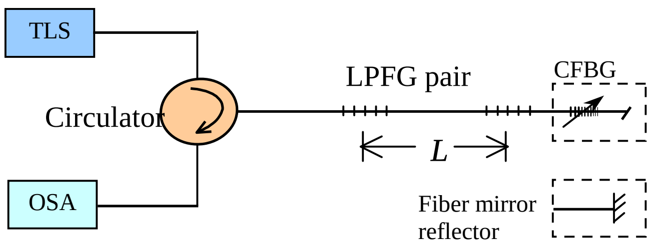
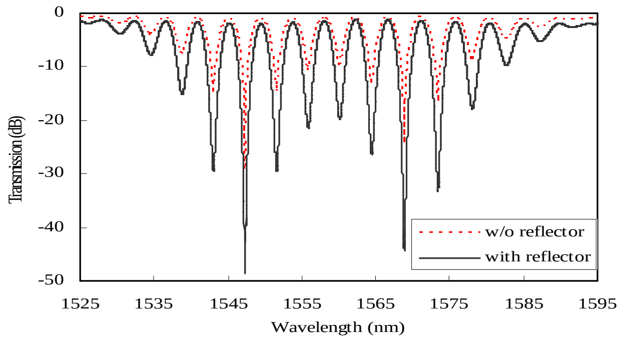


Fig. 1. Design and measurement setup of the proposed optical comb filter based on an LPFG pair and a bandwidth-tunable CFBG. TLS, tunable laser source; OSA, optical spectrum analyzer.

First, a fiber mirror reflector was used to verify the effect of extinction ratio enhancement by reflecting optical light and making it pass the LPFG-based MZI again. Figure 2 shows the measured filter spectra of two LPFG pair-based MZIs with and without a fiber mirror reflector. The LPFG center-to-center separations for these two MZIs were 12 and 49 cm, respectively. The corresponding fringe spacings are 4.35 and 1.1 nm, respectively. It is obviously that the extinction ratio was greatly enhanced. The maximum notch depth increased from 29 to 49 dB and from 22 to 43 dB for the two MZIs, respectively. As one of the benefits, effective channel number, with enough high extinction ratio, of the MZI filter is also increased. If 10-dB is set as a threshold, channel numbers of the two filters are increased from 8 to 10 and 34 to 42, respectively. The measured improvements in extinction ratio are not as high as the theory analysis predicted in Part 2, mainly caused by the inevitable measurement errors of the OSA arising from the relatively large wavelength resolution (0.02 nm).



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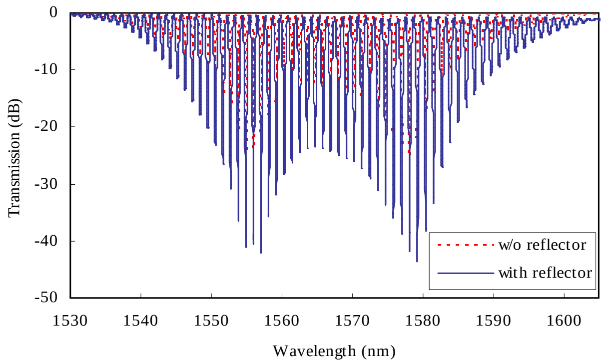

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Fig. 2. Optical spectra of LPFG pair-based MZIs with and without incorporating with a fiber mirror reflector. The fringe spacings are (a) 4.35 and (b) 1.1 nm, respectively.

Optical fiber comb filters can be achieved by combining this LPFG-based MZI with a broadband CFBG reflector. And by changing bandwidth of the CFBG, channel number of the hybrid-fiber-grating-based comb filter can be controlled independently. An effective fiber grating chirp-rate tuning method, which we reported previously in [8], was used to change the reflection bandwidth of the CFBG. In this method, the CFBG was glued, in a slant direction, onto the lateral surface of a specially-designed, equal-strength cantilever beam. Chirp-rate (or bandwidth) tuning of the CFBG was achieved by changing deflection of the cantilever beam. Fig. 3 shows the measured transmission spectra of the hybrid fiber grating-based comb filter, as well as the corresponding reflection spectra of the CFBG when its bandwidth was changed. With increasing bandwidth of the CFBG from 5 nm to ~20 nm, comb filters with a 4.35-nm channel spacing and channel number of 1 to 5 have been achieved in turn. In another experiment, channel number of 3 to 9 was achieved by using a LPFG-based MZI with a 2.4-nm fringe spacing. The measured spectra were shown in Fig. 4. Due to the high initial reflectivity of the CFBG reflector, no obvious reduction in reflectivity was observed even when the bandwidth was further broadened.

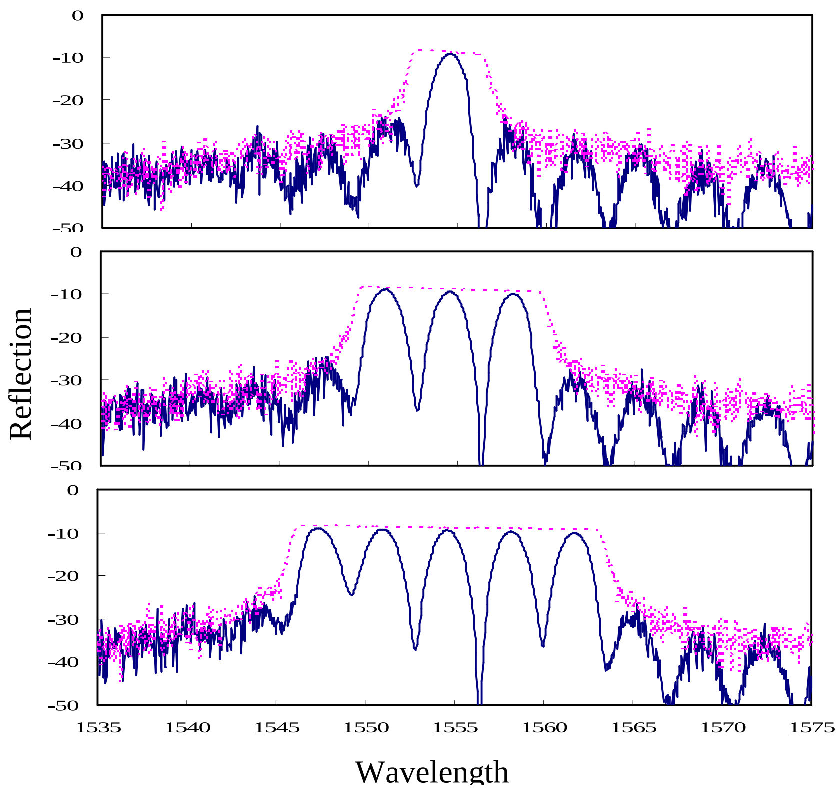

Fig. 3. Optical spectra of the hybrid fiber grating-based comb filter with a channel spacing of 4.35 nm (solid lines) and corresponding reflection spectra of the CFBG reflector (dashed lines).

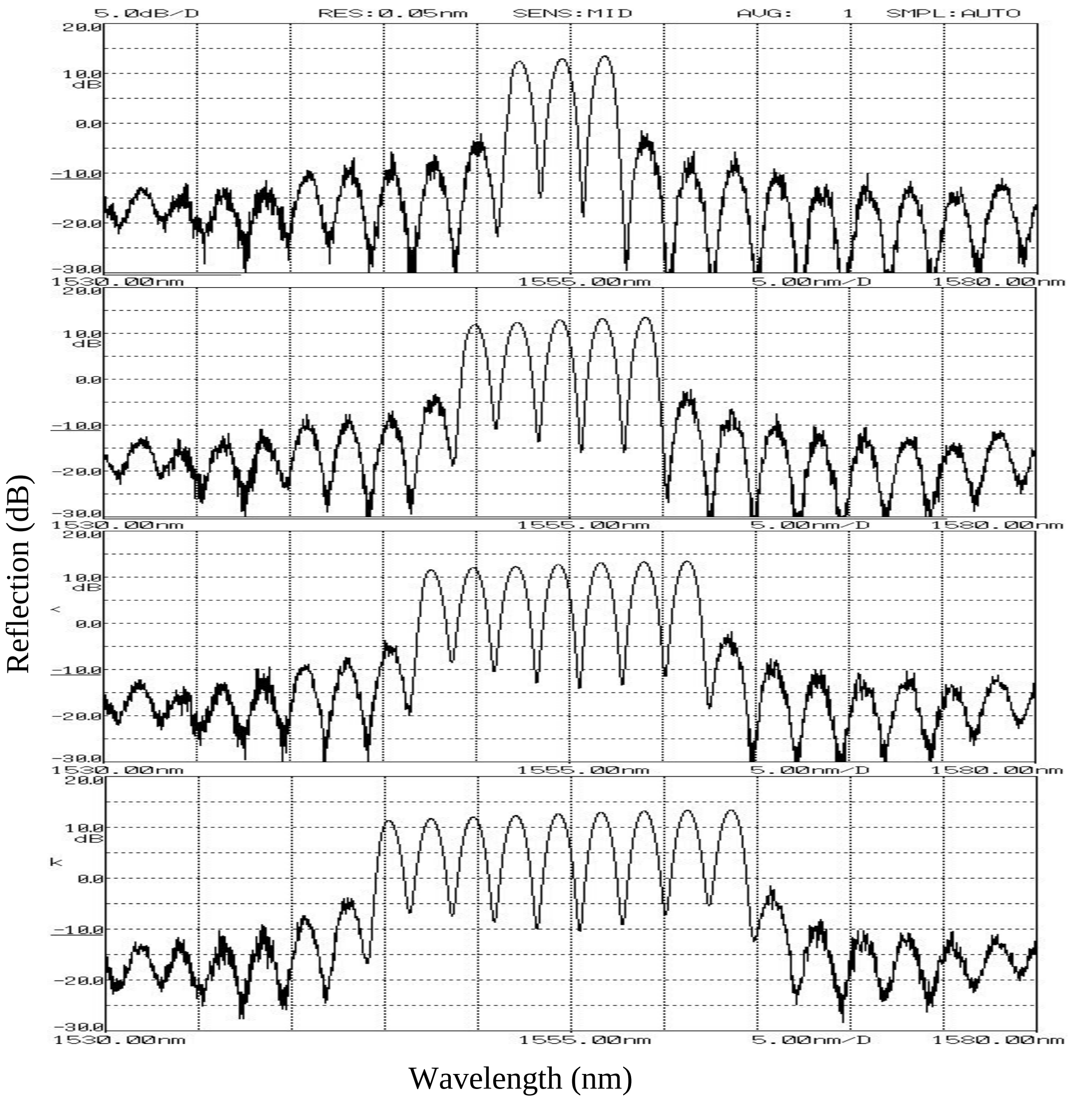

Fig. 4. Optical spectra of the hybrid fiber grating-based comb filter with a channel spacing of 2.4 nm.

Based on our previous study on chirp-rate tunable CFBG [9], bandwidth tuning with high reflectivity being maintained is achievable in a large range of 1.8-37.8 nm. With such a large tunable bandwidth range of CFBG, hybrid fiber grating-based optical comb filters with a more variable channel number will be available. Furthermore, wavelengths of both the LPFG-based MZI and the CFBG reflector can be tuned by applying strain on them or changing the temperature. These advantages make the hybrid fiber grating-based comb filter a very flexible and useful fiber-optic device. Its relatively long length arising from the long LPFG separation, which decides the channel spacing, could be reduced by using some fiber with a higher differential refractive index.

4. Conclusions

Hybrid fiber grating-based optical comb filters, which were based on a pair of long-period fiber gratings and a broadband CFBG reflector, have been proposed and demonstrated experimentally. The extinction ratio has been doubled and, furthermore, the channel number can be easily changed in a large range by tuning the chirp rate, i.e. bandwidth of the CFBG reflector. In the experiment, optical fiber comb filters with wavelength spacing of 4.35 and 2.4 nm, and changeable channel numbers of 1 to 5 and 3 to 9 have been achieved, respectively.

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