文章编号　1674-2915(2010)01-0064-06

All-fibre flat-top comb filter based on high-birefringence photonic crystal fibre loop mirror

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Abstract: A novel all-fibre flat-top comb filter based on a high birefringence photonic crystal fibre loop mirror is proposed and demonstrated. We simulate theoretically its output spectra and experimentally realize a flat-top output with a high extinction ratio. Compared to filters consisting of the conventional Panda polarization maintaining fibre, filters based on a high birefringence photonic crystal fibre loop mirror have better temperature stability. This kind of filter can be expected to be used widely in Wavelength-division-multiplexing (WDM) systems in the future.

Key words: flat-top comb filter; photonic crystal fibre; fibre loop mirror; temperature stability

1　Introduction

Wavelength-division-multiplexing (WDM) is an attractive fibre-optical communication technique. Optical comb filters are key components to control light signals for such techniques. Optical comb filters can be used for signal dropping or adding wavelengths in optical networks. The flat-top is one of the essential features for comb filters in high-speed optical communication systems. The smoother the top of the filter, the smaller the impact to the selected signal and thus the more stable the system becomes. A fibre Sagnac loop mirror filter, which has very good compatibility with fibre and stable performance, polarization independence and low dispersion, has attracted considerable interest in recent years due to its potential application in WDM systems[1,2], multiwavelength fiber lasers[3-6] and fibre amplifiers[7,8].

The flat-topped filter based on the fiber Sagnac loop mirror has been studied by other research groups. In Ref. [9], a flat-top comb filter was developed using a fifth-order Solc Sagnac filter which includes five sections of high birefringence fibre in a Sagnac fibre loop mirror. In Ref. [10], an all- fibre flat-top comb filter was fabricated by cascading two high birefringence Sagnac fibre loop mirrors. However, these schemes are difficult to construct. In addition, they are composed of conventional high birefringence fibre, whose temperature stability is not ideal.

In this paper, an all- fibre flat-top comb filter based on a high birefringence photonic crystal fibre loop mirror is proposed and demonstrated. The filter is composed of a 3 dB fibre coupler, single mode fibres and two sections of high birefringence photonic crystal fibres. Compared to the filters in Ref. [9,

Received date: 2009-10-11; Revised date: 2009-12-13.

Foundation item: supported by the "100 Projects" of Creative Research for the Undergraduates of Nankai University under Grant (BX6-224).

10], the proposed configuration is more compact. Furthermore, the filter has better temperature stability than the filters consisting of the conventional high birefringence fibre. The temperature sensitivity of the proposed filter based on the photonic crystal fibre is about 0.047 5 nm/℃, which is only 4.36% of the termerpatre sensitivity of the filter based on a Panda polarization maintaining fibre loop mirror.

2 Experiment setup and operation principle

Fig. 1 shows the experiment setup which consists of a Broadband Source(BBS), a fibre Sagnac loop mirror and an Optical Spectrum Analyzer(OSA) with a maximum resolution of 0.01 nm. The fiber Sagnac loop mirror is formed by a 3 dB fibre coupler, two Polarization Controllers (PC), and two sections of high birefringence photonic crystal fibres whose lengths are 2 m and 4 m, respectively. The beat length of the photonic crystal fibre is about 4.8 mm at 1 550 nm. The 3 dB fibre coupler and the PCs are all made of single mode fibre. The BBS has an operating wavelength range from 1 525 nm to 1 565 nm that provides the input and an OSA is used to measure the output spectrum of the filter.

In the fibre loop mirror, additional phase difference is generated between forward- and backward-propagating lights because of the birefringence effect. This accounts for coherent optical interference between the input and output.

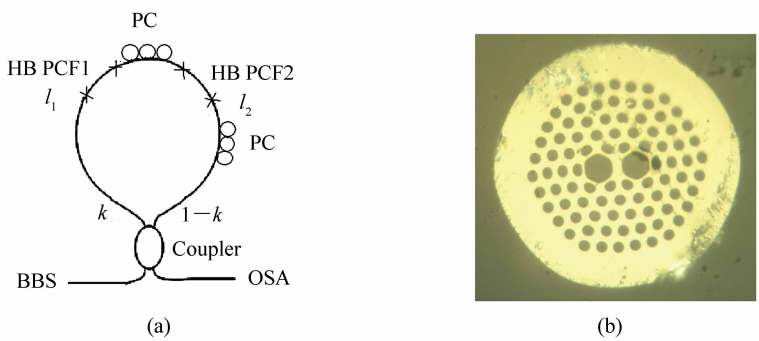


Fig. 1　(a) Schematic illustration of two-section HiBi-FLM, (b) Cross-section of high birefringence photonic crystal fibre.

When there are two sections of birefringence fibre in the fibre loop mirror (Fig. 1), the transmittivity can be calculated as[11]

$$T = (1 - 2k)^2 + 4k(1 - k)A^2, \qquad (1)$$

where $A = \cos\left(\frac{\beta_1 + \beta_2}{2}\right)\sin(\theta_1 + \theta_3)\cos\theta_2 + \cos\left(\frac{\beta_1 - \beta_2}{2}\right)\cos(\theta_1 + \theta_3)\sin\theta_2$, $\beta_i = -\frac{2\pi l_i(n_o - n_e)}{\lambda}$, $i = 1, 2$. θ_1, θ_2 and θ_3 denote the rotation angles of the optical signals in the single mode fibres and polarization controllers, l_i is the length of HBF(i), n_o and n_e are the refractive indices of the ordinary (o) and extraordinary (e) light, λ is the wavelength and k is the power-splitting ratio of the coupler.

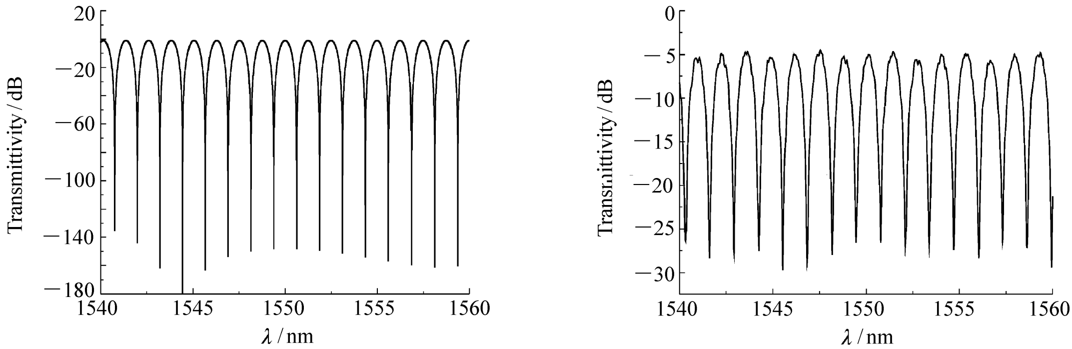
For the 3 dB coupler, we have

$$T = \left[\cos\left(\frac{\beta_1 + \beta_2}{2}\right)\sin(\theta_1 + \theta_3)\cos\theta_2 + \cos\left(\frac{\beta_1 - \beta_2}{2}\right)\cos(\theta_1 + \theta_3)\sin\theta_2\right]^2, \qquad (2)$$

It can be seen from Eq. (2) that the lengths of the fibre used in the fibre loop mirror and θ_i determine the transmittivity. After the lengths are determined by adjusting the state of PCs, different θ_i can be produced, so that different filter characteristics can be achieved. Under certain circumstances, we may achieve a flat-top comb filter.

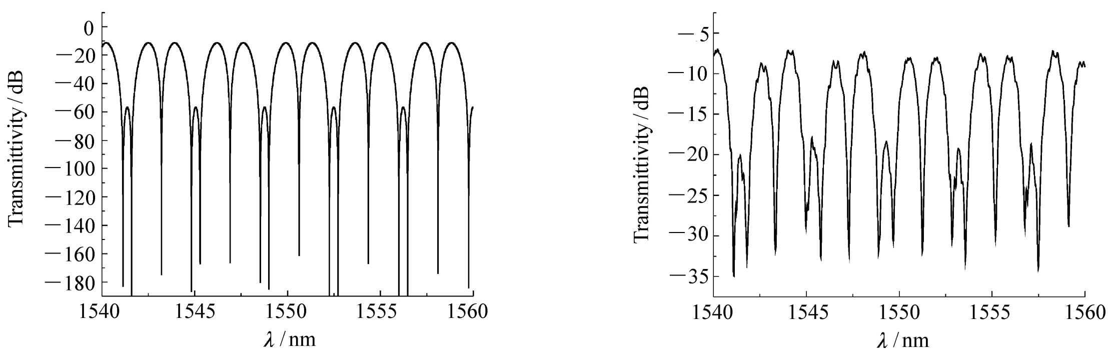
3 Results and discussion

From Fig. 2 to Fig. 6, we present the numerical simulation results calculated from Eq. (2) and corresponding experimental results. It can be seen that different types of filters can be realized with different values of θ_i. It follows from Fig. 6(a) and Fig. 6(b) that when $\theta_1+\theta_3=0.08\pi$ and $\theta_2=0.64\pi$, and the results correspond to a flat-top comb filter with an extinction ratio of about 20 dB. It also follows that the experimental and numerical results are in good agreement.



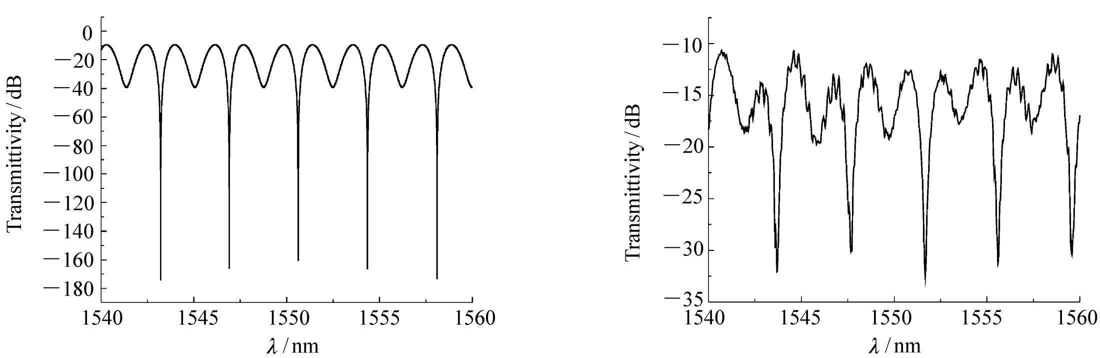
(a) Numerical simulation (b) Experiment result

Fig. 2 Transmittivity of high birefringence fibre loop mirror when $\theta_1+\theta_3=0.5\pi$, $\theta_2=0.1\pi$.



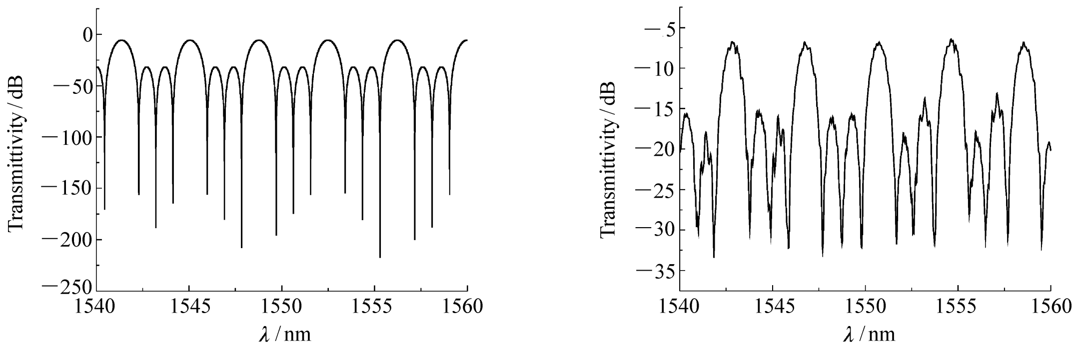
(a) Numerical simulation (b) Experiment result

Fig. 3 Transmittivity of high birefringence fibre loop mirror when $\theta_1+\theta_3=0.38\pi$, $\theta_2=0.64\pi$.



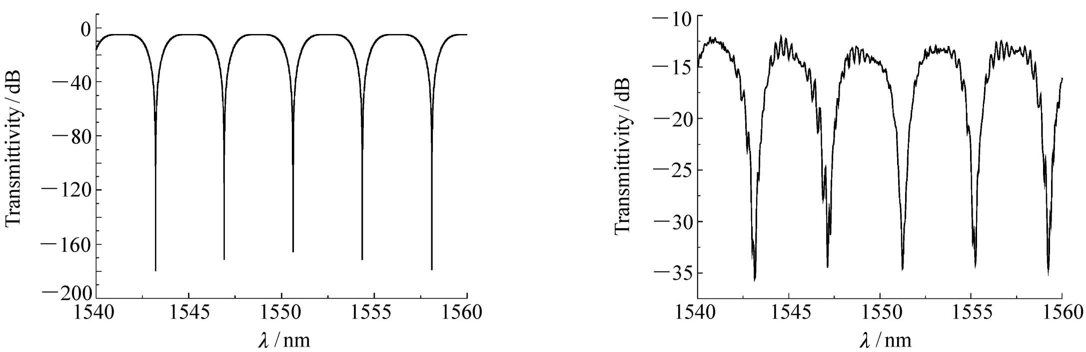
(a) Numerical simulation (b) Experiment result

Fig. 4 Transmittivity of high birefringence fibre loop mirror when $\theta_1+\theta_3=0.32\pi$, $\theta_2=0.64\pi$.



(a) Numerical simulation　　(b) Experiment result

Fig. 5　Transmittivity of high birefringence fibre loop mirror when $\theta_1 + \theta_3 = 0.64\pi$, $\theta_2 = 0.64\pi$.



(a) Numerical simulation　　(b) Experiment result

Fig. 6　Transmittivity of high birefringence fibre loop mirror when $\theta_1 + \theta_3 = 0.08\pi$, $\theta_2 = 0.64\pi$.

The difference between the experiment results and the numerical simulation results, such as larger insertion loss, unsmooth spectra and deflections of peak/notch wavelengths may be due to: 1) low power light source; 2) loss and interference caused by splicing points; and 3) return loss.

For the case of flat-top filter, we also investigate its stability at room temperature. The spectra of the filter are repeatedly scanned by the OSA over intervals of 5 min at room temperature and are shown in Fig. 7. The excellent stability of this flat-top filter at room temperature can be seen from the spectra as almost identical.

Since the photonic crystal fibre has excellent temperature stability, we expect that the proposed flat-top filter will also have excellent temperature stability. The filter was placed in a temperature controlled oven and the wavelength shift of the notch

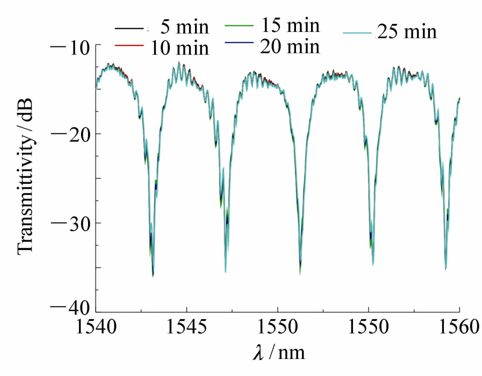


Fig. 7　Spectra of flat-top comb filter based on high birefringence photonic crystal fibre loop mirror recorded every 5 min at room temperature.

around 1 550 nm was recorded, and the results are shown in Fig. 8.

Within the range of temperature change of 16 ℃, the notch wavelength shifts by only 0.76 nm corresponding to a temperature sensitivity of about

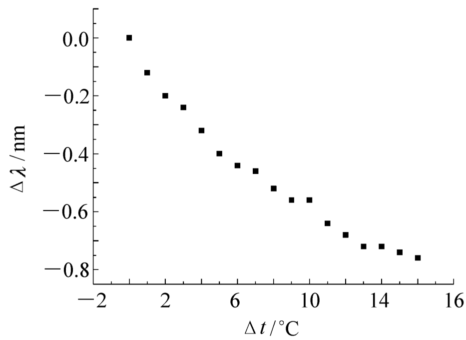


Fig. 8 Wavlength shift of flat-top comb filter based on high birefringence photonic crystal fibre loop mirror due to the change of temperature.

0.047 5 nm/℃.

In order to compare the temperature stability of a flat-top filter based on a conventional high birefringence fibre loop mirror with a high birefringence photonic crystal fibre loop mirror, a fibre loop mirror with two sections of Panda polarization maintaining fiber was assembled. The lengths of Panda polarization maintaining fibre were 2.9 m and 5.8 m. The beat length of the Panda polarization maintaining fibre is about 2.9 mm at 1 550 nm. After the careful adjustment, the fibre loop mirror shows the following flat-top filter characteristics(Fig. 9).

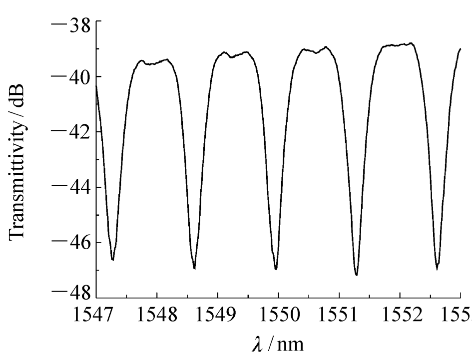


Fig. 9 Spectrum of flat-top comb filter based on Panda polarization maintaining fibre loop mirror.

Through experiment observation, the stability of the flat-top filter based on a Panda polarization-maintaining fibre loop mirror at room temperature is found to be less stable. The spectra of the filter were repeatedly scanned by the OSA with an interval of 5 min at room temperature and the results are shown in Fig. 10. It can be seen that the spectrum has large fluctuations.

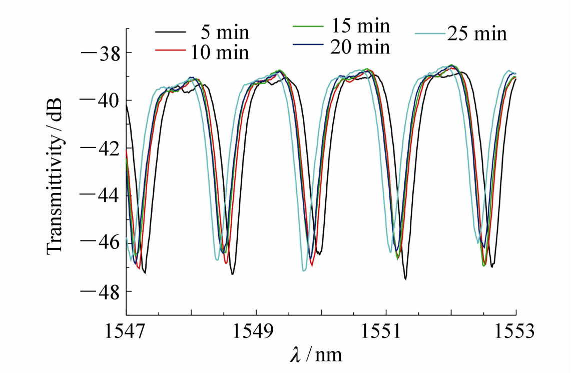


Fig. 10 Spectra of flat-top comb filter based on Panda polarization maintaining fibre loop mirror recorded every 5 min at room temperature.

Similarly, the temperature stability of the filter based on the Panda polarization maintaining fibre loop mirror was also measured and the experimental resuts are shown in Fig. 11. Within a range of temperature change of less than 8 ℃, the notch wavelength shifts 8.72 nm, so that the temperature sensitivity of the filter is 1.09 nm/℃. The lack of temperature stability will affect any signal tranmission significantly and hence this filter cannot be directly used in a practical fibre-optical communication system. Compared with a flat-top filter based on a conventional high birefringence fibre loop mirror,

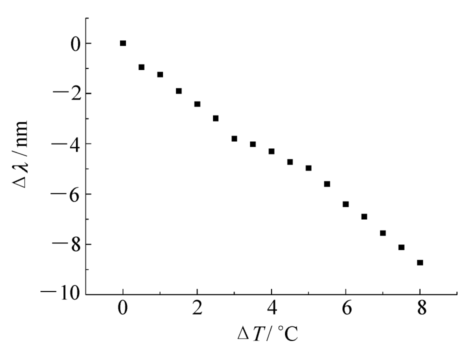


Fig. 11 Wavlength shift of flat-top comb filter based on Panda polarizaiton maintaining fibre loop mirror due to the change of temperature.

the proposed flat-top filter based on a high birefringence photonic crystal fiber loop mirror has a better temperature stability, which is only 4.36% of the temperature sensitivity of the former.

4 Conclusions

In this paper, a flat-top filter based on a high birefringence photonic crystal fibre loop mirror is proposed and realized. The improved temperature stability of this filter is also demonstrated by experiments. If developments can be made to improve the extinction ratio, smoothness and other parameters, this filter can be expected to be used in practical fibre-optical communication systems in the future.

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