# Temperature-Insensitive Interferometer Using a Highly Birefringent Photonic Crystal Fiber Loop Mirror

Chun-Liu Zhao, Xiufeng Yang, Chao Lu, Wei Jin, and M. S. Demokan

*Abstract*—**Utilizing the high birefringence and the low-temperature coefficient of birefringence of the highly birefringent photonic crystal fiber (HiBi-PCF), a temperature-insensitive interferometer made from a HiBi-PCF fiber loop mirror (FLM) is achieved. For the wavelength spacing of 0.43 nm, a wavelength spacing variation with temperature of only 0.05 pm/°C, and a transmission peak shift of 0.3 pm/°C is demonstrated. The stability of the FLM is improved dramatically when it uses a HiBi-PCF, as compared to FLMs using conventional HiBi fibers.**

*Index Terms*—**Fiber loop mirror (FLM), highly birefringent photonic crystal fiber (HiBi-PCF), interferometer.**

## I. Introduction

FIBER LOOP mirrors (FLMs) are interesting and very useful components for use in optical devices and systems. Many components based on FLM have been demonstrated for applications in wavelength-division-multiplexing filters and in sensors, among others [1]–[5]. In FLM, the two interfering waves counterpropagate through the same fiber and are exposed to the same environment. This makes it less sensitive to noise from the environment. In general, a conventional fiber loop mirror made of high-birefringent fiber (HiBi-FLM) has several advantages compared with a Mach–Zehnder interferometer, such as temperature insensitivity, high extinction ratio, and independence of input polarization [1], [2]. However, the optical path length shows temperature dependence caused by thermal refractive-index change and thermal expansion of the devices [6]. This can limit the practical use of the device.

The photonic crystal fiber (PCF) is a new class of optical fiber that emerged in recent years. Typically, these fibers incorporate a number of air holes that run along the length of the fiber and have a variety of different shapes, sizes, and distributions. Of the many unusual properties exhibited by a PCF, a particularly exciting feature is that the PCF can be made HiBi by arranging the core and the air-hole cladding geometry, thereby introducing asymmetry [7]–[9]. Their birefringence can be of the order of $10^{-3}$, which is about one order of magnitude larger than that of conventional HiBi fibers [7]. Unlike conventional polarization-maintaining fibers (PMFs) (bow-tie, elliptical core, or PANDA), which contain at least two different glasses each with a different thermal expansion coefficient, thereby causing the polarization of the propagation wave to vary with changing temperature, the PCF birefringence is highly insensitive to temperature because it is made of only one material (and air holes).

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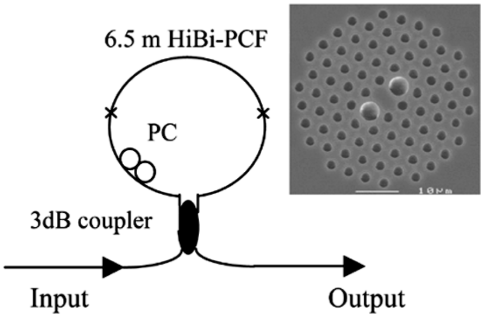


Fig. 1. Experimental setup of HiBi-FLM. Inset: Micrograph of the HiBi-PCF.

In this letter, a piece of HiBi-PCF is used as an FLM to make a temperature-insensitive interferometer. Utilizing the high birefringence and the low-temperature coefficient of birefringence, a temperature-insensitive HiBi-FLM with a simple configuration was demonstrated.

## II. Principle of Operation

The principle of operation of the HiBi-FLM has been described previously [1], [2]; therefore, we will summarize the essentials here. As shown in Fig. 1, the 3-dB coupler splits the input signal equally into two counterpropagating waves which subsequently recombine (at the coupler) after propagating around the loop. The interference of the counterpropagating waves will be constructive or destructive, depending on the birefringence of the cavity, and thus, the loop transmission response is wavelength dependent. The phase difference between the fast and slow beams that propagate in the HiBi fiber is given by

$$\delta = 2\pi \Delta n_g L/\lambda \tag{1}$$

where $\Delta n_g$, $L$, and $\lambda$ are, respectively, the group birefringence of the HiBi fiber, the length of the HiBi fiber, and the wavelength. When the variation of $\Delta n_g$ following the wavelength is small, there is $\Delta n_g \approx |n_x - n_y|$, where $n_x$ and $n_y$ are the effective refractive index for each polarization mode. Ignoring insertion loss of the 3-dB coupler and the attenuation of the HiBi fiber and the single-mode fiber (SMF) in the loop, the transmission spectrum of the fiber loop is approximately a periodic function of the wavelength, namely

$$T = [1 - \cos(\delta)]/2. \quad (2)$$

The maximum transmission wavelengths are the resonance wavelengths satisfying

$$2\pi \Delta n_g L/\lambda = (2k+1)\pi \quad (3)$$

where $k$ is any integer. The wavelength spacing between transmission peaks is given by

$$\Delta\lambda = \lambda^2/\Delta n_g L. \quad (4)$$

## III. Experiment and Results

Fig. 1 shows the experimental setup. The HiBi-FLM is formed with a 3-dB coupler, a 6.5-m length of HiBi-PCF, and a polarization controller (PC). The HiBi-PCF used in our experiment is fabricated by Blaze-Photonics Com., and the cross-sectional scanning electron micrograph is shown in the insertion of Fig. 1. Mode field diameters at the two orthogonal polarizations are 3.6 and 3.1 $\mu$m. The HiBi-PCF has a group birefringence $\Delta n_g$ of $8.65 \times 10^{-4}$ at 1550 nm (measured according to the method described in [8] and [9]), and a nominal beat length of 1.8 mm. Both ends of the HiBi-PCF are spliced to conventional SMF by using a $CO_2$ laser splicing system [10]. The PCF-SMF splicing loss is large (about 3.5 dB) because of mismatching of mode field and numerical apertures between the PCF and the SMF. The splicing loss will be reduced when a pretapering technology is used. The PCF-SMF splicing losses will increase the total insertion loss of the HiBi-PCF-FLM. The setting of the PC can affect the contrast of the transmission function. By adjusting the state of the PC, transmission bands with large extinction ratio can be obtained. The device characteristics are measured with a tunable laser source (Agilent 81689 A) which can be tuned from 1.5 to 1.6 $\mu$m and a power sensor (Agilent 81634 A).

Fig. 2 shows the transmission spectra of the HiBi-PCF-FLM at different temperatures. The temperature of the HiBi-PCF-FLM is controlled by a temperature chamber during measurement. The transmission spectrum is approximately a periodic function of wavelength, as given by (2). The corresponding wavelength spacing between transmission peaks is about 0.43 nm, which is consistent with (4). The extinction ratio is nearly 26 dB and the total insertion loss of the HiBi-PCF-FLM is 10 dB.

Since the phase difference $\delta$ is given by (1), a change of the phase matching condition caused by the environment leads to a wavelength spacing variation and a resonance wavelength shift. As shown in Figs. 2 and 3, when the ambient temperature of the HiBi-PCF-FLM is increased, the transmission peaks shift a little to shorter wavelength. We choose the transmission peak at

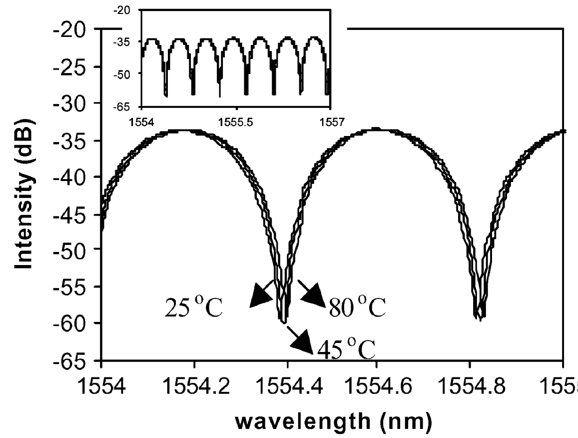


Fig. 2. Transmission spectra as a function of temperature for the HiBi-PCF-FLM. Inset: Transmission spectra in the range of 1554–1557 nm.

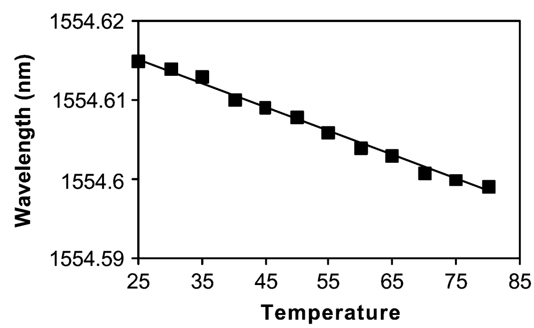


Fig. 3. Variation of the transmission peak wavelength at 1554.6 nm with temperature for the HiBi-PCF-FLM.

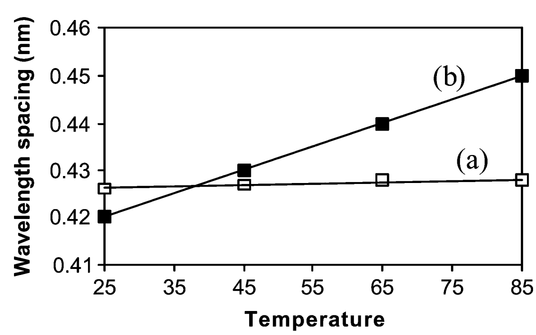


Fig. 4. Variation of the wavelength spacing with temperature. (a) HiBi-PCF-FLM. (b) PMF-FLM.

1554.6 nm as an example. The wavelength shift of the transmission peak with temperature is 0.3 pm/°C. Fig. 4(a), which is for the HiBi-PCF-FLM, shows the wavelength spacing change with temperature. The variation of wavelength spacing is very small: only 0.05 pm/°C.

In order to compare the new HiBi-PCF-FLM with the conventional FLM, we used a PANDA PMF as the HiBi fiber. The PANDA PMF is from Fujikura (SM-13P) with a measured birefringence of $\Delta n_g = 3.85 \times 10^{-4}$ at 1550 nm. The length of the PANDA PMF is about 14.8 m. The wavelength spacing of the PMF-FLM is about 0.42 nm at temperature 25 °C. The extinction ratio is about 25 dB. As shown in Fig. 5, the transmission peaks shift very significantly at different temperatures. Fig. 4(b) shows the temperature dependence of the wavelength spacing

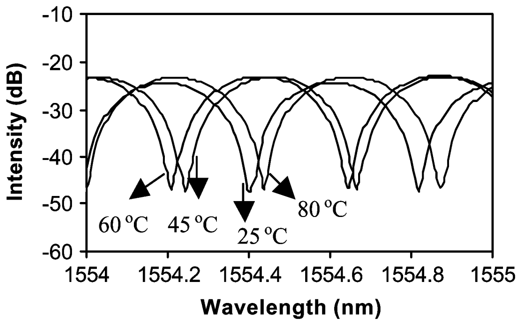


Fig. 5. Transmission spectra for the HiBi-PMF-FLM at different temperatures.

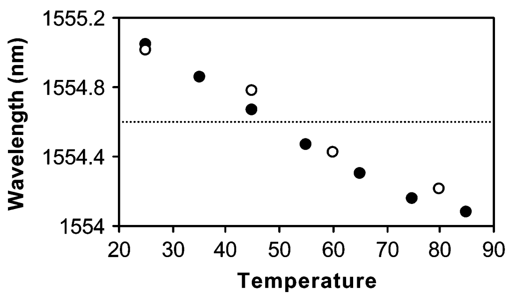


Fig. 6. Variation of the transmission peak wavelengths near 1554.6 nm with temperature for the HiBi-PMF-FLM. (•: Theoretical. ○: Experimental.)

for the conventional PMF-FLM. The variation of the wavelength spacing with temperature is about 0.5 pm/°C, which is nearly ten times of that for the HiBi-PCF-FLM. Furthermore, Fig. 6 shows the transmission peak shift as a function of temperature for the PMF-FLM. In theory, the wavelength shift of transmission peaks with temperature is nearly 16.6 pm/°C. In the experiment, however, the polarization of the propagation wave may vary with temperature, because different glasses of the PMF have different thermal expansion coefficient. This also effects the stability of the PMF-FLM. Such a large variation of the properties of the FLM made of conventional PMF with temperature makes it unsuitable for many applications in optical communication or sensor systems. However, by using HiBi-PCF, temperature-insensitivity of the FLM is improved by about 55 times.

## IV. Conclusion

The PCF is a new class of optical fiber. PCFs are virtually insensitive to ambient temperature, because these fibers are made from a single material, and incorporate a number of air holes that run along the length of the fiber. A temperature-insensitive HiBi-PCF-FLM has been demonstrated. In the case of a wavelength spacing of 0.43 nm between the transmission peaks, the variation of wavelength spacing with temperature is only 0.05 pm/°C, and the shift in the peak is 0.3 pm/°C. The temperature-insensitivity of the FLM was improved 55 times by using the HiBi-PCF, mainly because the temperature coefficient of birefringence in PCF is measured to be 30 times lower than that of conventional PMF, along with the effect of a higher birefringence in PCF as compared to conventional SMF.

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