Temperature-independent strain sensor based on a core-offset multi-mode fiber interferometer

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ABSTRACT

A novel temperature-independent multi-mode fiber (MMF) lateral strain sensor based on a core-offset interferometer is presented and demonstrated experimentally. Slightly misaligning a splice between an MMF and a single-mode fiber (SMF), high extinction ratio of the interferometer based on SMF-MMF-SMF structure can be obtained. When the lateral strain is applied to a short section of the MMF, the extinction ratio of the interferometer will decrease accordingly while the interference phase remains almost constant. Temperature variation only leads to shift in the transmission power spectrum of the interferometer and does not affect the extinction ratio. Experimental results show that there is a good quadratic relationship between the lateral strain and the extinction ratio. The proposed strain sensor has the advantages of temperature-independency, high extinction ratio sensitivity, good repeatability, low cost, and simplicity in structure.

Keywords: fiber sensor, interferometer, multimode fiber, strain

1. INTRODUCTION

Fiber-optic strain sensors offer unique advantages, such as immunity to electromagnetic interferences, high sensitivity, high resolution, durability against harsh environments, and fast response. Thus, different types of optical fiber sensors based on fiber Bragg grating (FBG) [1-4], Fabry-Perot (F-P) cavity [5], high-birefringence fiber [6-8], and multimode fiber (MMF) [9-11] have been widely presented and applied in different areas for strain measurements. However, the temperature-strain cross effect has mainly limited the practical applications of the fiber-optic sensors. Several methods have been presented to overcome the temperature-strain cross effect for the FBG strain sensors such as connecting another temperature reference sensing element [2-3], or adopting the specially designed beam to produce the chirped FBG [4]. However, all the above methods have the drawbacks of complex structure and high cost. Moreover, the FBG is fragile and has to be encapsulated carefully. Although the F-P cavity-based strain sensor [5] has high resolution to the longitudinal strain, the temperature-strain cross effect also limits its development. Moreover, the inherent drawbacks of fabricating this type sensor including coating, aligning, and encapsulating the F-P cavity, lead to high cost and limit its' practical applications. Most of the high-birefringence fiber strain sensor does not consider temperature-strain cross effect [6]; they also have to be connected another temperature reference sensing element [7] for temperature and strain discrimination. Although a temperature independent high-birefringence fiber strain [8] is presented, but it has to adopt a special photonic crystal high-birefringence fiber, which leads to high cost. Compared to the above fiber sensors, the MMF strain sensors [9-11] based on inter-modal interference have attracted much interest for their advantages of low cost and simple structure. However, most of the reported MMF strain sensors did not consider the temperature influence [9-10]. An approach [11] by connecting FBG as a temperature reference sensing element has been presented to discriminate temperature and strain, but the connected FBG leads to a complex sensing structure and high cost.

In this paper, we proposed a novel temperature-independent MMF lateral strain sensor based on a core-offset interferometer. The used MMF is based on a small core diameter dispersion fiber (DCF). High extinction ratio can be obtained by slightly misaligning a splice between an MMF and a single-mode fiber (SMF) for an SMF-MMF-SMF interferometer. With a lateral force applied to a short section of the fiber, the extinction ratio will decrease accordingly while the interference phase remains almost constant. Moreover, the induced lateral strains by the lateral force have good

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quadratic relationships with the extinction ratio, and the lateral strain resolution reaches 6.37με.The ambient temperature variations only lead to the shift of the interference spectrum and almost do not affect the extinction ratio. The proposed strain sensor has the advantages of temperature-independency, high extinction ratio sensitivity, good repeatability, low cost, and simple structure.

2. OPERATION PRINCIPLE

Figure 1 shows the schematic diagram of the experimental setup. The interferometer is an SMF-MMF-SMF structure and acts as a Mach-Zehnder interferometer (MZI) based on inter-modal interference. The used MMF with core/cladding diameter of 1.9μm/115.7μm was originally designed for dispersion compensation applications, with a large dispersion parameter of −270 ps/nm/km at 1550 nm and a cutoff wavelength of 1663 nm. It is claimed as an MMF because of the fact of the cutoff wavelength at 1663 nm, which makes it naturally a multi-mode fiber at the wavelengths shorter than 1663 nm. Our operating wavelength range is at C band.

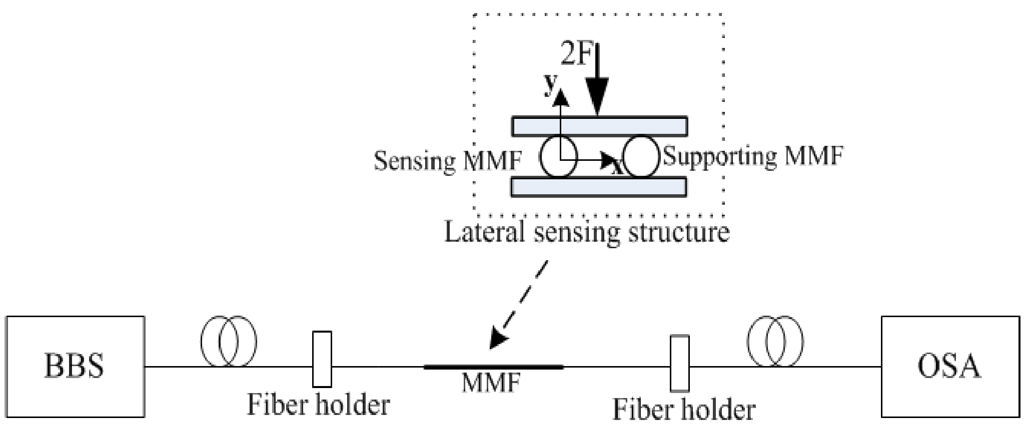

Fig.1 Schematic diagram of the experimental setup

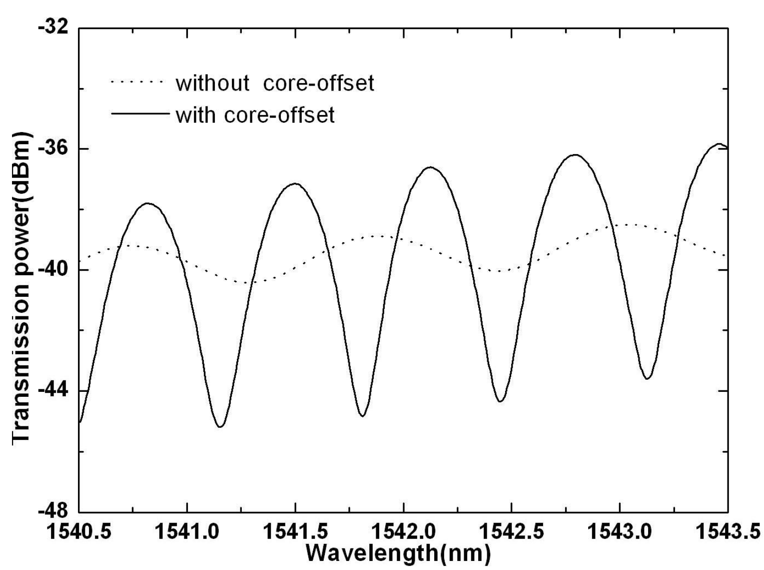

Fig. 2 Extinction ratios of the interferometer with and without core-offset

The MMF interferometer without core-offset generally has a lower extinction ratio. In order to obtain a high extinction ratio, we slightly core-offset the splice between the MMF and SMF. Figure 2 shows the extinction ratio of the interferometer for the cases with and without core-offset. Without core-offset, the extinction ratio is less than 2 dB whereas with core-offset, the extinction ratio is considerably increased to about 8 dB. The interference spectrum is mainly produced by two dominant modes, which indicates that other modes carry little powers comparing to the powers carried by the two dominant modes. In order to investigate the type of the interference modes, several core-offset MMF interferometers were fabricated with the cladding layer of the MMF being stripped. By putting the interferometers into the index match liquid, we found that there was no change on the transmission spectra, which confirmed that the interference modes are core modes. The measured interference shown in Fig. 2 can be approximately expressed as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[\frac{2\pi\Delta n L}{\lambda}], \tag{1}$$

where I_1 and I_2 are the power distributed in the two interference modes, respectively, with $I_2 < I_1$; Δn is the mode index difference of the two modes, and λ is the wavelength of light in vacuum. The free spectral range (*FSR*) of the interfering spectrum can be given by Eq. (1) as

$$FSR = \frac{\lambda^2}{\Delta n L}. \tag{2}$$

It is clear that the *FSR* of the interfering spectrum is inversely proportional to both the mode index difference Δn and the length of the MMF *L*. The extinction ratio ER of the interferometer can be given by

$$ER = 10\log\left(\frac{1+\sqrt{I_2/I_1}}{1-\sqrt{I_2/I_1}}\right)^2. \tag{3}$$

Obviously, the extinction ratio is determined by the power ratio of I_2/I_1, and the two modes with equal power will lead to a maximum *ER*. By manually offsetting the cores of the MMF and the SMF, one could control the power ratio, which in turn impacts the extinction ratio.

The lateral force applied to the MMF will lead to the deformation of the MMF, which must lead to the power losses of all the modes. The higher-order mode will experience more power loss than the lower-order mode, which will give rise to the reduction of the power ratio. The bigger the force, the larger the deformation and the more the power ratio change, which results in more decrease of the extinction ratio.

With the lateral force just applied to a short section of the MMF, the elongation produced is far less than the length of the short section and it is almost negligible comparing to the whole length of the MMF. Hence the longitudinal strain induced by the lateral force is negligible.

The lateral strains can be indirectly applied by the lateral force. When a transversal force is applied to the MMF, the *x* and *y* components of the induced strain can be expressed as [12]

$$\left\{\varepsilon_x, \varepsilon_y\right\} = \left\{\frac{(1+3\gamma+2\gamma^2)}{\pi Ebl}F, \frac{(2\gamma^2 - \gamma - 3)}{\pi Ebl}F\right\}, \tag{4}$$

where *F* is the force acting on the fiber of length l, and γ, b, E are the Poisson's coefficient, outer radius and Young's Modulus of the fiber, respectively. E and γ are about 6.5×10^4 N/mm^2 and 0.17, respectively. Both the *x* and *y* components of the strains are proportional to the transversal force.

When the ambient temperature is varied, the mode index difference Δn and the MMF length L will change accordingly and the interference spectrum will have a wavelength shift of $\Delta\lambda$. The temperature response of the interferometer can be given by

$$\frac{\Delta\lambda}{\lambda} \approx (\alpha + \xi)\Delta T, \tag{5}$$

where $\Delta\lambda/\lambda$ is the relative wavelength shift caused by temperature change ΔT, $\alpha = \frac{dL}{LdT}$ is the thermal expansion coefficient of the MMF material, and $\xi = \frac{1}{\Delta n}\frac{d(\Delta n)}{dT}$ is the thermo-optic coefficient induced by the two interference modes in the MMF material. It can be seen that the wavelength shift induced by the temperature change is only determined by the characteristics of the MMF material.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Rotation or twist of the MMF shown in Fig. 1 can induce coupling between the dominant interference modes and other higher-order modes and will lead to the variation of the interference spectrum. In order to avoid any variation induced by rotation or twist, the MMF is supported by two fiber holders placed on an optical table; the sensing MMF and a supporting MMF (identical to the sensing MMF) are fixed between two aluminum flakes with smooth surfaces that apply the indirect lateral strains to the MMF. The width of the aluminum flake is about 1 cm. The whole length of the MMF is about 22cm. The transmission spectrum of the sensor is measured by an optical spectrum analyzer (OSA). Fig. 3 shows the transmission spectral responses to different lateral forces. It can be seen that the measured extinction ratio (between the two arrow marks) decreases with the increase of the lateral force and the interference spectrum almost does not shift, which agree with our theoretical predication. Fig. 4 shows the relationships between the lateral strain (x and y components of the lateral strains, ε_x and ε_y) and extinction ratio. There are good quadratic relationships between the extinction ratio and the lateral strains. Experimental results show that the lateral strain resolution reaches 6.37 με.

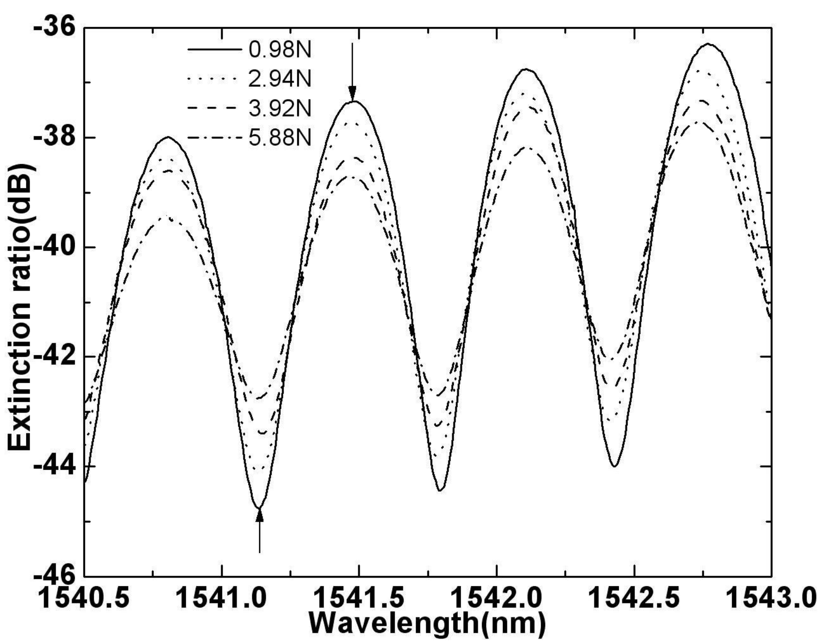

Fig.3 Transmission spectral responses to different lateral forces

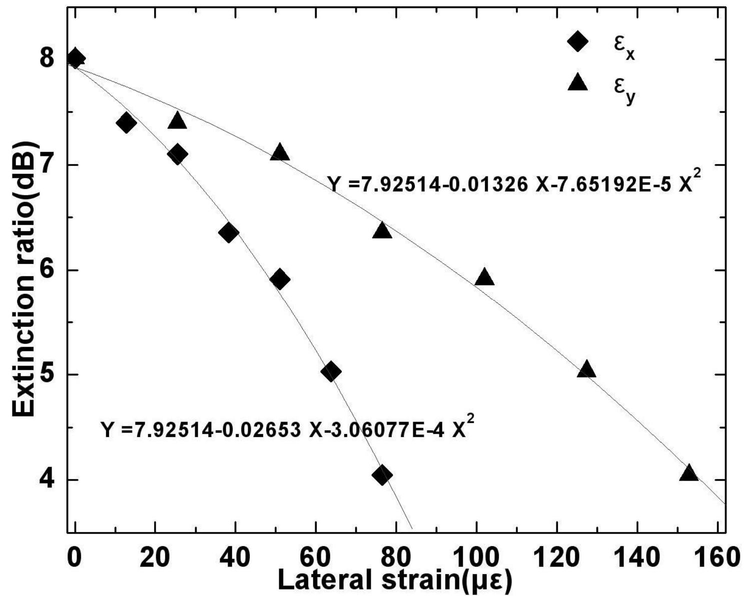

Fig.4 Relationships between the lateral strain and extinction ratio

Increase of ambient temperature produces a red shift in the interference spectrum, as shown in Fig. 5. It can be seen that the extinction ratio is not affected by the temperature variations. Fig. 6 shows the measured extinction ratio responses to temperature at different lateral forces. It can be seen that the extinction ratio at a fixed lateral force keeps almost a constant. Experimental results show that the fluctuation of the extinction ratio for different temperatures is less than 0.05dB. It should be noted that the extinction ratio responses to temperature will change irregularly when the temperature is over 60°C, which is the limit determined by the thermal property of the MMF and aluminum flake materials. The operational temperature range can be extended by encapsulating the sensing head into temperature compensation materials with negative temperature coefficient. The range of the strains in the measurement can be increased by encapsulating the MMF in materials with high Young's modulus for practical applications.

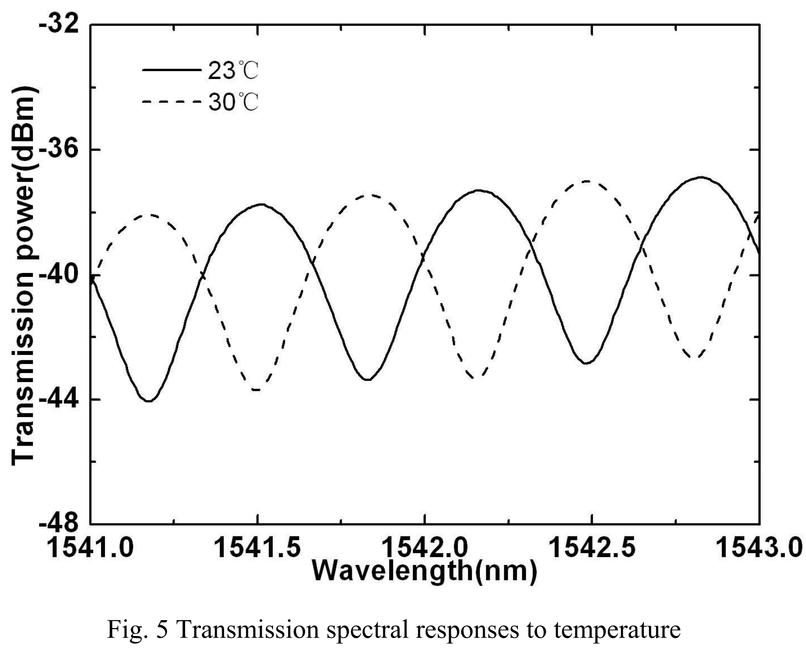

Fig. 5 Transmission spectral responses to temperature

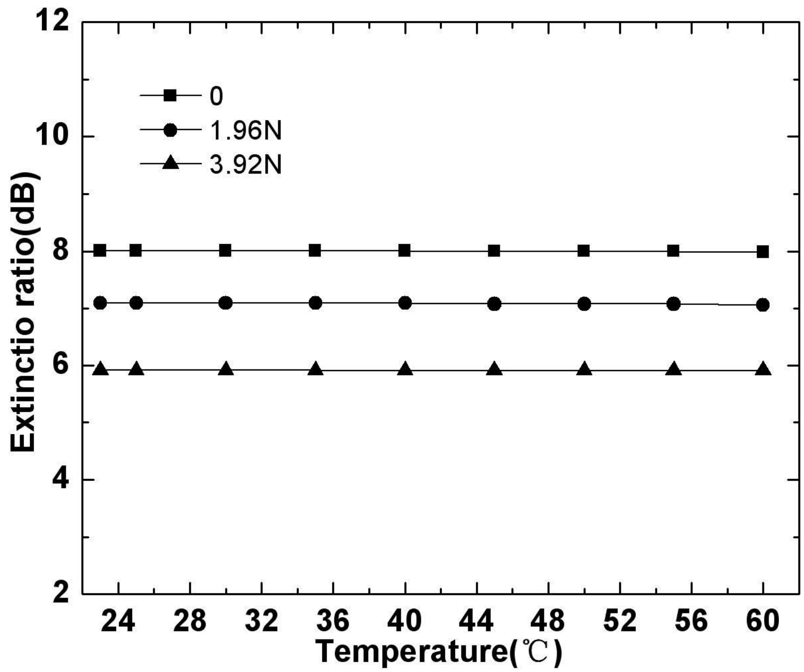

Fig. 6 Extinction ratio responses to temperature at different lateral forces

4. CONCLUSION

We proposed a novel lateral strain sensor based on a core-offset MMF interferometer. Experimental results show that there is a good quadratic relationship between the extinction ratio and the lateral strains. With the lateral force applied to a short section of the whole MMF, temperature variations almost do not affect the extinction ratio, which can be used for temperature independent strain measurement. The advantages of the sensor include temperature-independency, high extinction ratio sensitivity, good repeatability, low cost, and simple structure. It is expected to have practical application in fiber-optic strain sensors.

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