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RESEARCH ARTICLE

Temperature measurement based on photonic crystal modal interferometer

Jian LIU, Hao ZHANG (✉), Bo LIU

Key Laboratory of Opto-Electronic Information and Technology, Ministry of Education, Institute of Modern Optics, Nankai University,
Tianjin 300071, China

Abstract Based on the interferences between core modes and cladding modes in photonic crystal fiber (PCF), a novel temperature sensor is presented and experimentally demonstrated. The peak wavelength of the interference spectrum linearly increased with an increase in temperature. A measurement sensitivity of 10.38 pm/°C was experimentally achieved for temperatures ranging from 30°C to 100°C. Experimental results also indicate that the curvature and transverse load do not have a distinguishable influence on the transmission spectrum of the proposed fiber sensor, which ensures its applicability for practical applications.

Keywords optical fiber sensor, temperature, photonic crystal fiber (PCF), measurement

1 Introduction

The interference, fiber Bragg grating (FBG) [1,2], long-period fiber grating (LPG), and tilted fiber Bragg grating (TFBG) based fiber sensors have attracted considerable research interest due to their high sensitivity and wide applications in the measurement of numerous physical parameters. Traditional interferometer sensors are rather large with complex configurations, making their sensor performances easily influenced by the surrounding environment. LPG and TFBG sensors utilize the mode coupling between core modes and cladding modes. A variety of fiber sensors have been developed based on LPGs and TFBGs. In 2010, Mosquera et al. reported an optical fiber refractometer based on a Fabry-Pérot interferometer constructed by two FBGs and an intracavity long-period grating to confine the light in the resonator interaction with the surrounding medium [3]. However, this equipment requires two exactly matching FBGs, and the sensor performances are influenced by other physical parameters such as curvature and temperature to some degree. In the same year, Han et al. demonstrated a self-compensated optical fiber refractometer based on a cladding-mode Bragg grating [4]. However, LPG and FBG are employed in this scheme, making the system structure more complicated, and complex grating techniques are also required.

Temperature measurement is one of the important applications for industry and fire forecasts. Many kinds of fiber-based temperature sensors have been reported, including LPG sensors [5], TFPG sensors [6], etc. However, conventional LPG sensors are too long for practical sensing applications and are extremely sensitive to many other parameters like curvature, pressure, and so on. Besides the complex technique required for the grating fabrication, the peak reflectivity of LPG and TFPG degenerates with time, which leads to sensor instability. Interference has also been employed to construct temperature sensors [7,8], which have high sensitivity, but they are usually too complicated and unavailable for distribution and multi-points measurement applications. In recent years, micro-structured fibers (MOFs) have become the subject of numerous studies. In this paper, based on the in-fiber modal interference, a very simple sensor configuration consisting of only a segment of photonic crystal fiber (PCF) is proposed for temperature measurement.

PCF is one type of MOF that consists of many voids periodically and is typically arranged in a hexagonal lattice [9]. This structure allows the possible existence of higher order cladding and guided modes, making it attractive for various investigations. In this paper, the interference between higher order cladding modes and the core guided mode is used for temperature measurement. It is demonstrated that the transmission spectral characteristics of the proposed sensor is insensitive to curvature and transverse pressure, showing the possibility of resolving the cross sensitivity issue.

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E-mail: haozhang@nankai.edu.cn

2 Experimental setup and operation principle

Figure 1 shows the experimental setup. In our experiment, a segment of 10 mm PCF is spliced with a communication single mode fiber (SMF), whose cross section is shown in Fig. 2(a). The voids of PCF around the splicing region are collapsed to excite mode coupling between the core modes and cladding modes. Via an optical circulator (OC), light from a broad band light source (BBS) is guided to the proposed sensor in a temperature controller chamber. After the interference, signal modulated with the temperature information propagates through the port 2 and 3 of the OC. An optical spectrum analyzer (OSA) with a resolution of 0.01 nm is employed for wavelength interrogation. The sensor is fabricated by manually splicing a segment of SMF with PCF. The air holes at the splicing part are collapsed and the other fiber end is cut smooth to ensure effective reflection.

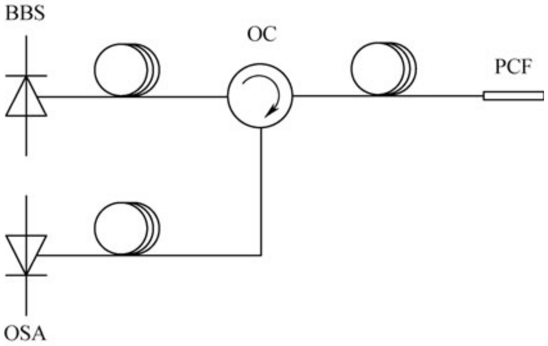

Fig. 1 Schematic diagram of experiment setup

The above sensor is put in a temperature controller chamber for a temperature range of 30°C to 100°C. The cross section of the PCF used in this experiment is shown in Fig. 2(a) with a pitch to diameter ratio of 5.8/3.5.

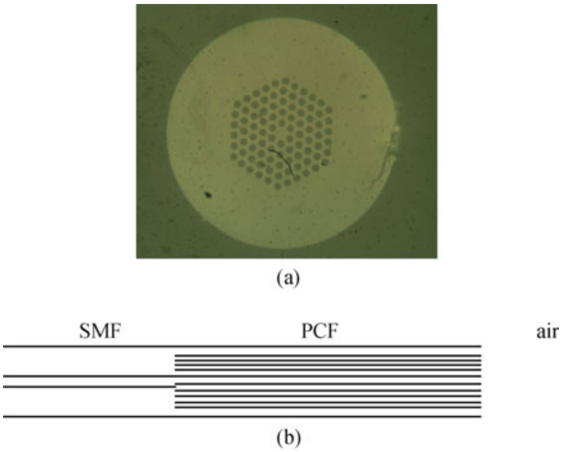

Fig. 2 (a) Cross section of PCF; (b) splicing region between SMF and PCF

The curvature sensitivity of this sensor is also investigated by inserting PCF into a capillary (its inner diameter is 250 μm and the outer diameter is ~400 μm). Both the capillary and fiber are clamped with two holders, one of which is mounted on a translation stage. As the stage moves, the curvature of PCF could be adjusted. The curvature (C) of PCF in terms of the experimental instrument geometry could be written as

$$C = \frac{2d}{d^2 + S^2},$$

where d is the displacement at the center of the capillary, and S is half of the distance between the two fiber holders, as shown in Fig. 3(a).

In order to investigate the transverse load characteristics, the proposed sensor is sandwiched between two planes with a segment of coat-stripped SMF in parallel, and the transverse load is applied from the top plane.

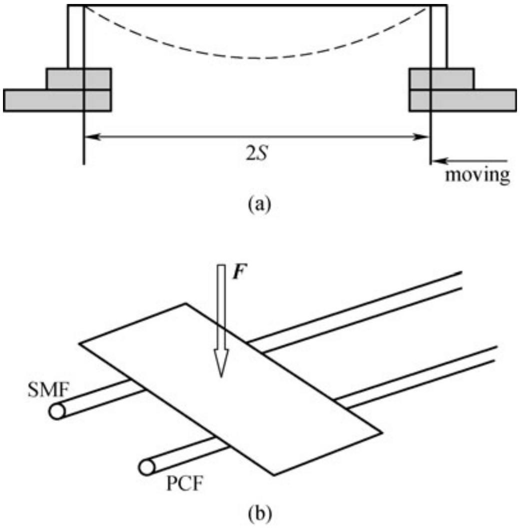

Fig. 3 (a) Geometry of curvature test instrument; (b) illustration of transverse loading test instrument

3 Experimental results and discussion

Figure 4 shows the reflection spectra of the sensor for $T = 30$°C, and $L = 10$ mm. It is apparent that there is a periodic pattern with equal wavelength interval in the interference spectrum. The initial peak value is about 0.6 dBm, and when we shorten the PCF length, a larger peak value could be acquired. The operation principle of the proposed sensor is as follows. Around the splicing region, light from the 2 port of OC is partly coupled to the higher cladding modes of the PCF due to the deformation introduced by the collapse of the voids, while the other portion of the light continuously propagates in the core mode. When the two portions come to the end of the PCF, they are partly reflected because of the refractive index difference. As they come back to the splicing region, the higher order cladding

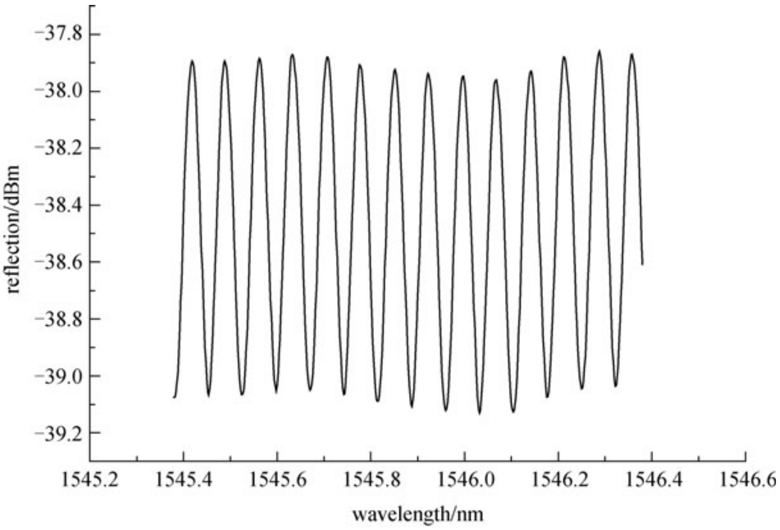

Fig. 4 Reflection spectra of proposed sensor for $L = 10$ mm and $T = 30$°C

mode light is recouped to the core mode owing to the collapse of the voids. Since the core and higher order cladding modes possess different refractive indices, the phase difference between these two portions of light is produced, and therefore interference would occur. In order to simplify the analysis, let us only consider the interference between the core mode and one certain cladding mode (the ith mode). The resonance wavelength satisfies

$$\left(n_{\mathrm{co}} - n_{\mathrm{cl},i}\right) 2L = m\lambda, \tag{1}$$

where n_{co}, $n_{\mathrm{cl},i}$ represent the refractive indices of the core mode and the ith cladding mode, respectively, L refers to the PCF length, and m is a positive integer. As temperature increases, the interference peak wavelength will shift due to the thermal effect on the effective mode refractive index and the linear expansion of the fiber.

The wavelength shift of one peak for temperature ranging from 30°C to 100°C was studied. From Fig. 5, it can be seen that the proposed sensor exhibits a quite high linearity. The temperature sensitivity turns to be 10.38 pm/°C and the coefficient of determination reaches 0.99943 by using linear regression fitting.

The influence of environmental perturbations on the reference pattern shift could be characterized by the following equation:

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\xi} = \frac{2L}{m}\left(\frac{\mathrm{d}n_{\mathrm{co}}^{\mathrm{eff}}}{\mathrm{d}\xi} - \frac{\mathrm{d}n_{\mathrm{cl},i}^{\mathrm{eff}}}{\mathrm{d}\xi}\right), \tag{2}$$

where ξ represents the environmental perturbation including curvature, transverse load, etc.

Figure 6 shows the curvature response of the peak wavelength for a curvature range of 0 to 25 m^{-1}, and Fig. 7 shows the transverse load response of the peak wavelength for a transverse load ranging from 0 to 0.2 kg. From the above experimental results, it can be seen that the resonance wavelength has no distinguishable shift for a curvature range of 0 to 25 m^{-1} or a transverse load ranging from 0 to 0.2 kg. This trend implies that the influence of curvature or transverse load on the effective index of the cladding mode and core mode is almost equal compared with the temperature. Therefore, it can be concluded that this sensor is insensitive to the curvature and transverse load, which makes it possible to avoid the cross sensitivity effect.

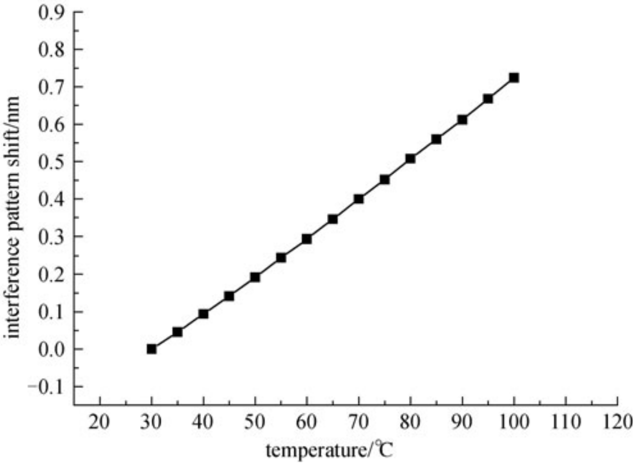

Fig. 5 Wavelength variation as function of temperature

4 Conclusion

In conclusion, a novel sensor with a simple structure designed for temperature measurement is presented and experimentally demonstrated. The sensor is constructed by splicing a segment of PCF with communication SMF,

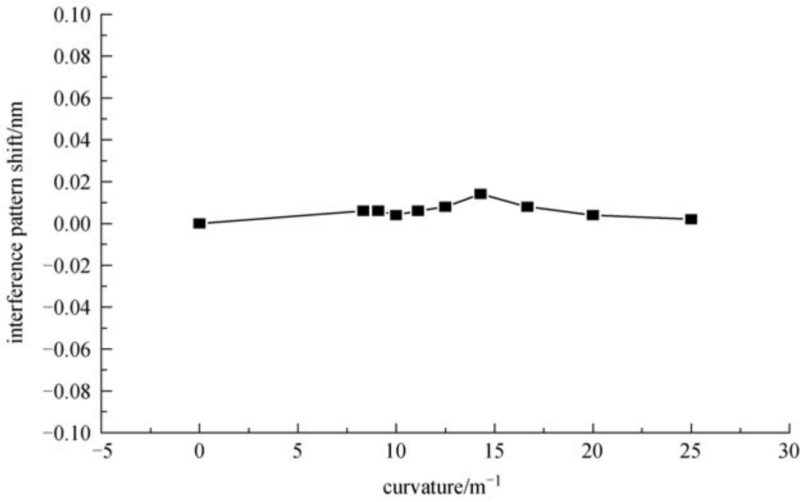

Fig. 6 Wavelength variation as function of curvature

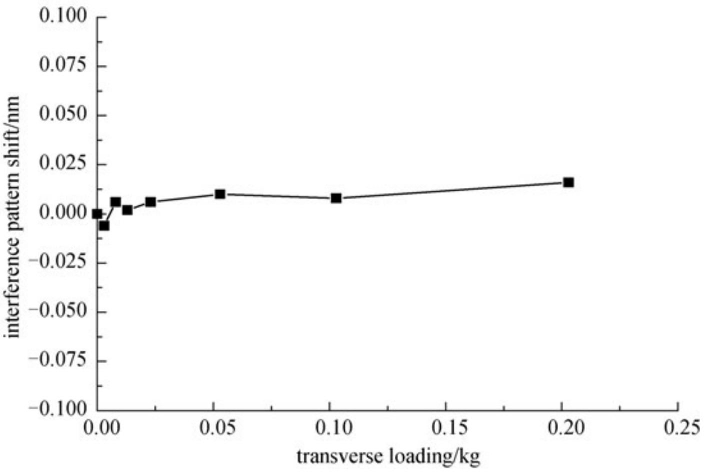

Fig. 7 Wavelength variation as function of transverse load

making use of interference between the core modes and cladding modes of the PCF. Experimental results indicate that the interference peak wavelength linearly increases with the increase in temperature and the sensor is insensitive to curvature or transverse load. A temperature sensitivity of 10.38 pm/°C was experimentally achieved.

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