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Phase sensitivity of fundamental mode to external atmospheric pressure for hollow-core photonic bandgap fiber

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ABSTRACT

Hollow-core photonic bandgap fibers (HC-PBFs) are suitable for spaceborne fiber optical gyroscopes owing to their excellent environmental adaptability. However, hundreds of small holes full of air at one atmosphere of pressure can make the HC-PBF sensitive to external atmospheric pressure. In this study, we investigated the phase sensitivity of the fundamental mode to external atmospheric pressure for the HC-PBF, and the experimental result indicates that the phase sensitivity is approximately 1.6×10^{-5} ppm/Pa, which is mostly contributed by the change in the pressure-induced length. Through the choice of coating, the phase sensitivity to external atmospheric pressure can be reduced by about a factor of five compared to current HC-PBFs, and the excellent temperature performance can be maintained at the same time.

1. Introduction

The fiber-optic gyroscope (FOG) is a kind of angular velocity sensor developed about 30 years ago. Although FOGs have reached a precision of about $10^{-5\circ}$/h [1], in extreme environments, their performance deteriorates because conventional fiber is highly sensitive to temperature, electromagnetic fields, and irradiation. The advent of the hollow-core photonic bandgap fiber (HC-PBF) radically addressed this issue because the light now propagates in air, which is much more stable than conventional silica. The hollow-core photonic bandgap fiber-optic gyroscope (HC-PBFOG), which was first proposed by a group at Stanford University [2–4], has a greatly reduced sensitivity to temperature transients (~6.5) and the Faraday effect (> 20) as compared to conventional FOGs [4]. Moreover, its sensitivity to irradiation can be theoretically reduced by a factor of ten [5,6]. Therefore, HC-PBFOGs have great potential applications in space where harsh environments exist; in fact, the solid-core photonic crystal FOG has already been applied in space [7]. Low atmospheric pressure is a special issue for the HC-PBF when applied in space. There exist many small holes full of air at one atmosphere (~101.325 kPa) of pressure within the HC-PBF. These air holes expand in space when the external atmospheric pressure becomes lower than one atmosphere, thus deforming the microstructure cladding and affecting the optical performance. As a result, the phase of the fundamental mode may change and cause nonreciprocal phase error in HC-PBFOGs under the effect similar as popular Shupe effect [8].

Cao et al. studied the phase sensitivity of the fundamental mode to pressure applied internally only to the core of a HC-PBF and determined it as 1.044×10^{-2} rad/(Pa·m) [9]. Pang et al. investigated the phase sensitivity of the fundamental mode of the HC-PBF to strain and acoustic pressure [10]. Oliveira et al. studied the attenuation and birefringence within the nonconventional air-guiding transmission windows of the HC-PBF when internal and external pressure are applied to the fiber, based on which a simple pressure sensor was developed [11,12]. In contrast, the phase sensitivity of the fundamental mode to temperature has been studied by Refs. [13,14]. However, the phase sensitivity to external atmospheric pressure has never been investigated. In this work, we demonstrated the influence of atmospheric pressure on the phase of the fundamental mode. The results will be significant for the study of HC-PBFs and HC-PBFOGs.

2. Simulation results

At present, the seven-cell HC-PBF has been proven capable for use in a FOG [2,15], so we primarily analyze the influence of external atmospheric pressure on this kind of HC-PBF, as illustrated in Fig. 1(a) and (b). The inner cladding diameter, outer cladding diameter, and coating diameter were measured to be about 81, 129, and 247 μm, respectively. The core diameter and inner cladding pitch were approximately 10 and 3.5 μm, respectively. When the external atmospheric pressure changes, it causes a transverse expansion of the cladding structure and change in axial size, as illustrated in Fig. 2(a) and (b), which shows the situation when a vacuum exists outside the HC-PBF. The refractive index of the air within the holes also changes owing to the variation in volume of

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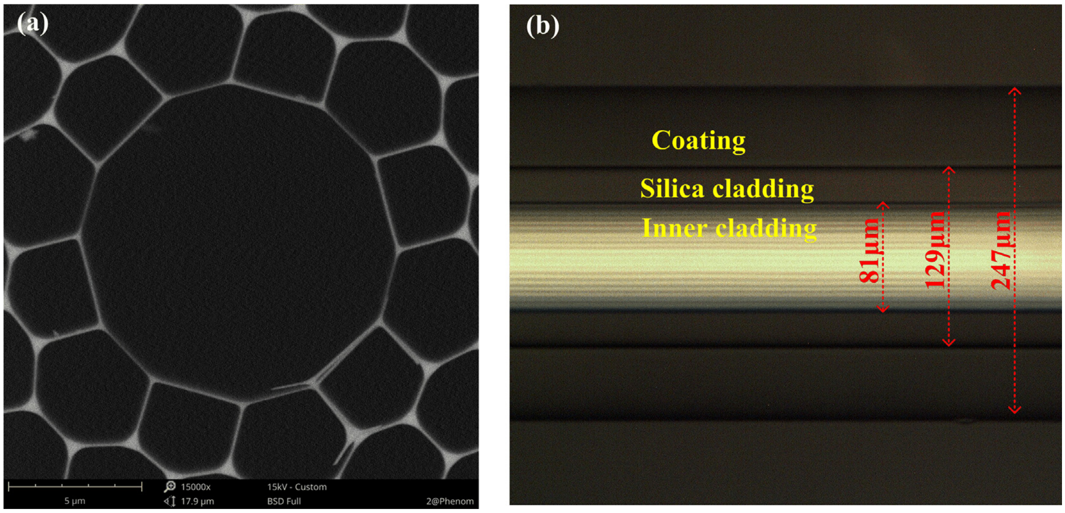

Fig. 1. (a) Cross-section of the HC-PBF. (b) Diameter of coating, silica cladding, and inner cladding.

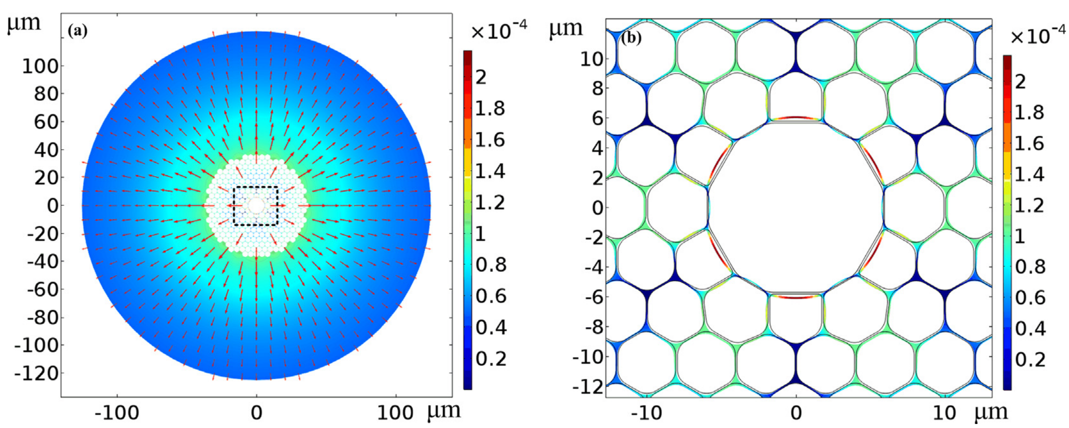

Fig. 2. Simulation results of the effect of external atmospheric pressure on the HC-PBF structure. (a) Comparison between structures at 0 Pa and one atmosphere, where the red arrows represent the displacement direction and amplitude. (b) Enlarged image of the area within the rectangle in (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the holes. As a result, the accumulated phase of the fundamental mode changes, which can be given by

$$\Phi = \frac{2\pi n_{eff} L}{\lambda} \tag{1}$$

where n_{eff} is the effective index of fundamental mode, L the length of HC-PBF, and λ the wavelength of the transmitted light. According to the definition in [13], the expression for the phase sensitivity to pressure can be defined as

$$S = \frac{1}{\Phi}\frac{d\Phi}{dP} = \frac{1}{n_{eff}}\frac{dn_{eff}}{dP} + \frac{1}{L}\frac{dL}{dP} - \frac{1}{\lambda}\frac{d\lambda}{dP} = S_n + S_L - S_\lambda \tag{2}$$

where P is the external atmospheric pressure. The relative change in the effective index, HC-PBF length, and wavelength caused by the pressure change per Pascal are expressed as S_n, S_L, and S_λ, respectively.

Based on the established model, we simulated S_n, S_L, and S_λ for the fundamental mode when the atmospheric pressure increases from 0 Pa to one atmosphere with an interval of 10.1 kPa. As illustrated in Fig. 3(a), the effective refractive index linearly decreases with a slope of about -1.66×10^{-12}/Pa as the external atmospheric pressure (P_0) increases, which corresponds to an S_n of approximately -1.67×10^{-6} ppm/Pa. Fig. 3(b) reveals that the fiber length linearly increases with a slope of 3.76×10^{-11} m/Pa as P_0 increases for the 1-m HC-PBF, which reveals that $S_L \sim 3.76 \times 10^{-5}$ ppm/Pa. Fig. 3(c) indicates that the wavelength linearly decreases with a slope of -1.42×10^{-13} μm/Pa as P_0 increases, which corresponds to an S_λ of about -9.16×10^{-8} ppm/Pa. Therefore, the total phase sensitivity to external atmospheric pressure is determined as about 3.6×10^{-5} ppm/Pa based on Eq. (2), as shown in Fig. 3(d). Clearly, S_L contributes most to the total phase sensitivity to external atmospheric pressure, which is about 22 times larger than S_n and about 400 times larger than S_λ. This can be explained by the fact that the HC-PBF coating has a much smaller Young's modulus compared to silica and is easily deformed and displaced.

3. Experimental results

A Mach–Zehnder interferometer was established for the investigation of the phase sensitivity of the fundamental mode to external atmospheric pressure, as illustrated in Fig. 4 [9]. In the signal arm, the approximately 30-m-long HC-PBF is connected to the pigtails of the couplers with fusion splicing and placed within a sealed vacuum chamber. The air pressure inside the vacuum chamber is controlled by a turbomolecular pump and can vary between 1×10^{-4} Pa and 101.325 kPa. An air pressure gauge is applied for the real-time monitoring of the air pressure within the vacuum chamber. Moreover, the temperature clearly changes as the air pressure varies within such a sealed chamber, so a thermometer is used for the real-time measurement of temperature. In the reference arm, all the pigtail fibers and couplers are kept inside a thermal insulation box to reduce the