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Asymmetric elliptical-hole dual-core photonic crystal fiber with enhanced pressure sensitivity

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ABSTRACT

We propose an asymmetric elliptical-hole dual-core photonic crystal fiber (AE-DC-PCF) for hydrostatic pressure sensing. The transmission spectra of the AE-DC-PCF under hydrostatic pressure and the relationship between pressure sensitivity and the minor axis ratio at different elliptical ratios have been calculated. Our results show that the AE-DC-PCF has higher pressure sensitivity than that of conventional dual-core photonic crystal (DC-PCF) fiber which has the circular-hole. Based on a 10 cm fiber, the pressure sensitivity of the AE-DC-PCF as high as 50.6 pm/MPa were achieved at 1.55 μm, which is higher than the pressure sensitivity obtained from conventional DC-PCF (32.2 pm/MPa).

1. Introduction

Optical fiber sensors have attracted much research interest in both academia and industry [1–4] in recent years, due to their many well known advantages compact size, light weight, corrosion resistance, electromagnetic immunity, multiplexing capability.

There are numerous reports on applications of optical fiber sensors, including monitoring of different physical, chemical, biological and environmental parameters, such as, strain, pressure, position, displacement, temperature, refractive index, pH, relative humidity, and water salinity. In particular, pressure sensor using optical fiber have also attracted a lot of research interest, different designs of PCFs to fulfill specific pressure application have been early reported, such as pressure sensor based on the side-hole fiber [5,6], and polarization-maintaining fibers (PMFs) [7,8].

On the other hand, because of unique characteristics, photonic crystal fibers (PCFs) have gained great research interest for sensing applications [9–11]. One of the most attractive characteristics of these PCF-based sensors is their low temperature dependence when they are used as pressure sensors [12]. Various pressure sensors using PCF have been reported in the past [13,14], and PCF-based pressure sensors with a Sagnac interferometer configuration has also been investigated [15]. In this case, the pressure sensors are not compact because of the complicated structures is to be introduced.

In 2011, Daru Chen et al. proposed a pressure sensor using dual-core photonic crystal fibers (DC-PCFs) with 3.47 pm/MPa sensitivity [16]. One of the potential advantages of this pressure sensor is compactness. It was demonstrated in [7,17–19] that the sensitivity to pressure can be enhanced by inducing mechanical asymmetry in the cross section of the fiber.

To destroy the symmetry of the structure, one method has been proposed is to replace circular air holes with elliptical ones in the cladding of the PCF [20]. In 2007, the complex unit cell cladding structure PCF, which is composed of two different sizes of elliptical air holes, is proposed by Yuh-Sien Sun et al. [21]. However, these PCFs have only one core in the cross section and they are used as high birefringence fibers.

In order to obtain DC-PCFs-based hydrostatic pressure sensor with higher sensitivity, we propose a new design of DC-PCFs. The proposed DC-PCF is formed by a triangular-lattice of different sizes elliptical air holes, and two fiber cores by missing two larger elliptical air holes in the center of this structure. The hydrostatic pressure sensing characteristics and its dependence on the geometrical parameters of proposed DC-PCF are investigated numerically.

2. Structure, principle and simulation method

The cross section of two types of DC-PCFs is shown in Fig. 1. All of two DC-PCFs have triangular lattice air holes and with a pitch $\Lambda = 2.00\ \mu m$. Their outside diameters are 125 μm, and the refractive index of the air is 1. The first structure A(fiber A) is formed by circular air holes with a diameter $d = 1.4\ \mu m$, and this DC-PCF is studied in [16]. The second structure B(fiber B) is the DC-PCF that

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we proposed in this paper. It is formed by two different sizes of elliptical air holes, and the two cores in PCF are formed by removing two large elliptical air holes in the center of the PCF and replacing them with the pure silica. In our paper, we also call the fiber B as asymmetric elliptical-hole dual-core photonic crystal fiber (AE-DC-PCF).

The refractive index of the background silica material is 1.444 at the wavelength of 1.55 μm. Such a DC-PCF is characterized by the ellipticity ratio $\eta = r_i/r_j$, where r_i and r_j are the half lengths of the minor and major axes of the elliptical holes, respectively. The η is the ellipticity ratio of the large elliptical holes while $i = 1, j = 2$, and it is the smaller elliptical ones while $i = 3, j = 4$. For comparison, the triangular lattice pitch of our proposed structure is the same as the first structure A.

In the cross-section of DC-PCF, there are two fiber cores induce two adjacent independent waveguides, and the optical power transfer occurs between two cores. According to the theory of mode coupling, there are two supermodels (even and odd mode) for each polarization. The electric field distributions and vectors for the x-polarized odd mode and the even mode of the proposed DC-PCFs are shown in Fig. 2(a) and (b), respectively.

It is the interference between two same polarized modes that contributes to the inter-core coupling of power. For light traveling along a DC-PCF, the phase difference ($\Delta\varnothing$) of light between the cores at the point of the end of fiber can be described in effective index and fiber length

$$\Delta\varnothing = \frac{2\pi L \Delta n_{eo}^{i}}{\lambda}, \quad i = x, y, \tag{1}$$

where L is the length of the DC-PCF, $\Delta n_{eo} = n_e^i - n_o^i$ is the difference effective refractive indices between i-polarized even and odd modes, and λ is the operating wavelength of the light source. The transmission spectrum of the DC-PCF is given as [22]

$$I_{out} = 4I_o \cos^2\left(\frac{\pi L \Delta n_{eo}^{i}}{\lambda}\right), \quad i = x, y, \tag{2}$$

where I_o is the input intensity.

A hydrostatic pressure loading on the DC-PCF induces anisotropic stress distribution in the fiber cross section, and the consequence is a change of refractive index. The refractive index changes induced by the applied load are called photoelastic phenomena. Using the photoelastic relationship, the hydrostatic pressure induces principal effective refractive index change at any point (x, y, z) in the cross-section of the structure may be represented by the following equations [23]

$$\begin{aligned} n_x &= n_0 - C_1\sigma_x - C_2(\sigma_y + \sigma_z) \\ n_y &= n_0 - C_1\sigma_y - C_2(\sigma_x + \sigma_z) \end{aligned} \tag{3}$$

respectively for x- and y-polarization modes, where n_0 is the initial effective refractive index of undisturbed, C_1 and C_2 are stress-optic coefficients, σ_x, σ_y and σ_z are the pressure components induced stress at the point (x, y, z). For pure silica, stress-optic coefficients $C_1 = 6.5 \times 10^{-13} m^2/N$ and $C_2 = 4.2 \times 10^{-12} m^2/N$.

Due to the photoelastic effect, the change on the value of Δn_{eo} of two interfering modes induced by hydrostatic pressure will cause the shift of the transmission peak wavelength of the DC-PCF. The hydrostatic pressure sensitivity of the DC-PCF is defined as

$$\frac{d\lambda_p}{dP} = \frac{\lambda_p - \lambda_0}{P} \tag{4}$$

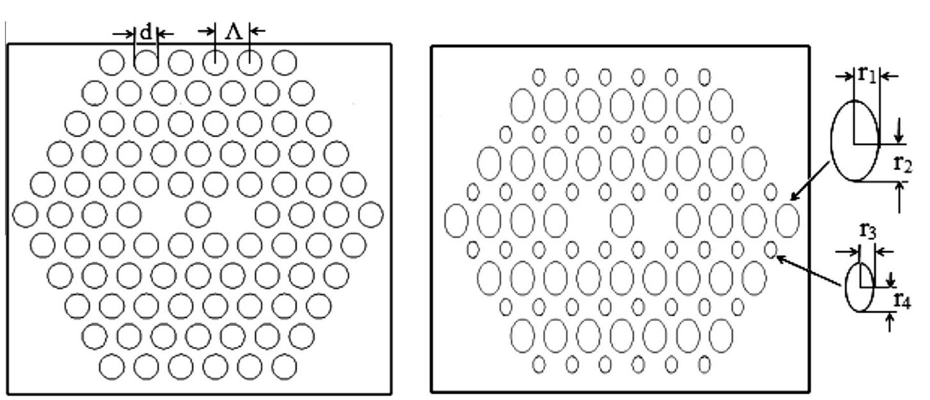
where λ_0 and λ_p are the transmission peak wavelength of the DC-PCP when it is free of pressure and is loaded of pressure, respectively, and P is the loaded hydrostatic pressure.

We firstly calculated the stress distribution in the fiber cross section using the material mechanical constants, Young's modulus $E = 73.1$ GPa and Poisson's ratio $\nu = 0.17$, for pure silica. In the second step, the effective refractive indexes of fundamental modes were calculated by using the pressure-induced refractive index Eq. (3) as the input data. Finally, the power and peak wavelength of the transmission spectra were obtained from Eq. (2).

3. Results and discussions

The influence of hydrostatic pressure on the effective index of DC-PCF is illustrated in Fig. 3, where the operating wavelength $\lambda = 1.55$ μm, and the structure parameters air hole of structure B fixed $r_1/r_2 = r_3/r_4 = 0.75$, $r_1 = 0.70$ μm, $r_1/r_3 = 3.0$. The solid line denote effective index of the even mode and the dashed line denote effective index of the odd mode for the x-polarized and the y-polarized, respectively. The results show that the effective index of DC-PCF increases with the increase of pressure.

In the simulation, two interfering modes of the DC-PCF which we investigate are y-polarized even and odd modes. Loading different hydrostatic pressure (varying in the range of [0,1] GPa) and the propagation distant of the light in DC-PCF is 10 cm, the normalized power intensity transmission spectra for y-polarized light are shown in Fig. 4(a) for the fiber A and in Fig. 4(b) for the fiber B when their parameters is with the same as in the Fig. 3. It can be clearly seen that the transmission peak wavelength has a blue-shift with the increasing the pressure applied, and the shift is more obvious in our proposed fiber B than that in fiber A. Fig. 5 shows the calculation results of comparing transmission the peak wavelength between the fiber A and our proposed fiber B. The data of peak wavelength and the pressure have a linear fitting. The



(a) (b)

Fig. 1. Cross section of DC-PCFs structure. (a) Fiber A(structure A) (b) fiber B(structure B).