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Highly birefringent photonic crystal fiber with a squeezed core and small modal area

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ABSTRACT

An index guiding photonic crystal fiber with a squeezed core is proposed and properties, including birefringence and effective modal area, are numerically analyzed using the multipole method. Numerical results show that high birefringence of 1.544×10^{-2} and a small modal area of 2.39 μm^2 are achieved at 1.55 μm simultaneously. Moreover, impacts of hole spacing and hole size on birefringence and effective modal area are also investigated in detail.

1. Introduction

Photonic crystal fibers (PCFs) [1,2], consisting of a periodical arrangement of air holes running along the fiber length and a defect region in the center, have been attracting considerable research interest over the past decade due to their unique and excellent properties which can hardly be realized in conventional optical fibers, such as a wide wavelength range of single-mode operation [3,4], controllable effective modal area [5–7], tailorable dispersion [8] and high birefringence [9,10]. In general, PCFs are divided into two categories based on their guiding mechanisms: index-guiding fibers [3,11], in which light is guided by the so-called total internal reflection; photonic bandgap fibers [12,13], in which light is guided by the photonic bandgap effect.

Of those important features of PCFs, high birefringence is of particular potentials in many applications, such as polarization maintaining fibers (PMFs) [14–16], single polarization transmission [17,18] and fiber-optic sensing. Usually, high birefringence is induced by destroying the symmetry of PCF structures, in other words, by introducing asymmetry into the cladding or the core region of PCFs. One of the methods is to employ elliptical holes in PCF structures and previously published results in Refs. [15,19] showed that high birefringence on the order of 10^{-3} at 1.55 μm could be achieved but elliptical air holes were introduced in the cladding or core region to induce a high asymmetry, which would increase the difficulty of fabrication process. Liou et al. [20] presented a structure with high birefringence of 1.74×10^{-3} at 1.55 μm but their design needs filling liquids into some air holes to realize the high birefringence, which could make the fabrication more complex.

A low effective modal area is a key parameter for nonlinear applications [21] and many papers have reported different PCF designs with low modal areas. Begum et al. [7] reported a low modal area of around 2.5 μm^2 at 1.55 μm but their structures contain eight rings of air holes of different sizes. In Ref. [22], Wang et al. proposed a PCF design with a small modal area of 6.48 μm^2 at 1.55 μm, but in their structure nine rings of air holes with two hole sizes and two hole spacings are utilized. Therefore, it's not easy or convenient to control the fabrication process of these structures mentioned above.

In this work, we propose a modified PCF structure with high birefringence and a small modal area in which only circular air holes are used and arranged in triangular lattice, which has a clear advantage in practical fabrication process compared with structures containing elliptical holes, many rings of holes or multiple structural parameters. By using multipole method, some properties, including effective refractive index, birefringence and effective modal area, are analyzed and meanwhile, high birefringence and a small modal area can be achieved simultaneously by altering the hole size and spacing.

2. Structure of the proposed PCF and theory

In order to induce high birefringence in the PCF, three central rows of air holes in the orthohexagonal structure are removed and the remaining rows are shifted vertically towards the center. Then

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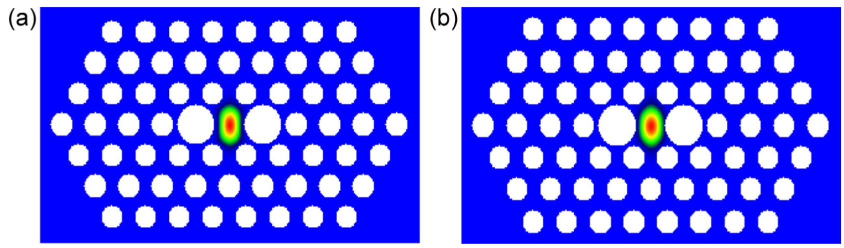

Fig. 1. Cross section of our proposed PCF and intensity distribution of fundamental modes. (a) x polarized, (b) y polarized.

two horizontal air holes nearby the center are enlarged to form the squeezed core. The cross section of our proposed PCF is illustrated in Fig. 1, which consists of circular air holes with two radiuses denoted by R and r, and Λ stands for the hole spacing. Here in Fig. 1, $r = 0.7$ μm, $R = 1.1$ μm and $\Lambda = 2$ μm.

As shown in Fig. 1, the blue parts denote the silica material, the white parts represent circular air holes, and the central colored parts show the intensities of modal fields which are well confined in the core region of the proposed PCF.

A number of numerical simulation methods [23] have been developed to analyze characteristics of PCFs, such as the plane wave expansion method, localized-function method, finite difference method, vector boundary-element method. The multipole method (MM) [24,25] is an effective and efficient method based on the principle of electromagnetic scattering, which was first proposed by White and Kuhlmey to simulate electromagnetic field distributions in PCFs. The method is suitable for analyzing PCFs with circular holes and possesses a high accuracy and is also able to deal with a variety of properties of optical fibers.

In this work, the relationship between the effective index and wavelength is calculated by this method. Some properties, such as birefringence and effective modal area, are also derived from the calculation results. Birefringence of a PCF is determined by the difference between the effective indices of two orthogonal polarized modes [26].

$$B = \left| Re\left(n_{\mathrm{eff}}^{x} - n_{\mathrm{eff}}^{y}\right) \right| \tag{1}$$

where B represents birefringence, Re stands for the real part of the effective index, n_{eff}^{x} and n_{eff}^{y} denote effective refractive indices of the x- and y-polarized fundamental modes, respectively.

The effective modal area of PCFs is related to the effective area of the core region, which is expressed by using the following formula [27]:

$$A_{\mathrm{eff}} = \frac{\left(\iint |E|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\iint |E|^4 \mathrm{d}x\mathrm{d}y} \tag{2}$$

where E is the electric field of fundamental modes in the structure.

3. Numerical results and discussion

Fig. 2 below shows the relationship between the effective index and wavelength from 1.3 to 1.7 μm with $R = 1.1$ μm and $\Lambda = 2$ μm. The difference between effective indexes of x- and y-polarized modes is obvious due to removing some air holes and enlarging those two holes, i.e. the asymmetric shape of the fiber core.

Fig. 3 illustrates the dependence of the birefringence on wavelength and it shows with the big hole's radius increasing, the birefringence is increased due to higher asymmetry of the squeezed core. When $r = 0.7$ μm, $R = 1.25$ μm, birefringence is 1.125×10^{-2} at 1.55 μm. In general, asymmetry can be enhanced by reducing the

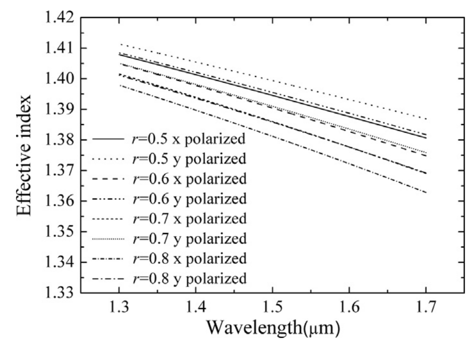

Fig. 2. Effective index versus wavelength, $R = 1.1$ μm and $\Lambda = 2$ μm.

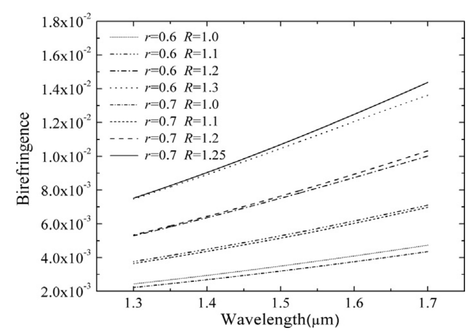

Fig. 3. Birefringence as a function of wavelength, $\Lambda = 2$ μm.

hole spacing and so the birefringence is shown below with smaller hole spacings.

According to Fig. 4, for the same structural parameters, birefringence with $\Lambda = 1.8$ μm is larger than that with $\Lambda = 2$ μm, and when $r = 0.65$ μm, $R = 1.1$ μm and $\Lambda = 1.8$ μm the birefringence is 1.178×10^{-2} at 1.55 μm. In order to analyze the impacts of hole spacing on birefringence, we alter the hole spacing and simulation results are shown below.

Fig. 5 clearly indicates that a smaller hole spacing results in higher birefringence which results from higher asymmetry.

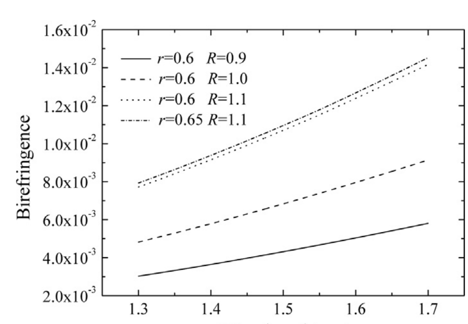

Fig. 4. Birefringence as a function of wavelength, $\Lambda = 1.8$ μm.