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Highly birefringent photonic crystal fibers with flattened dispersion and low effective mode area☆

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ABSTRACT

A highly birefringent index-guiding photonic crystal fibers with flattened dispersion and low effective area is proposed by introducing elliptical air holes in the cladding and small holes both in the core area and in the cladding. With the plane wave expansion (PWE) method, the birefringent, dispersion and effective area of the fundamental modes in such photonic crystal fibers are analyzed in detail. The simulation result shows that high birefringence with a magnitude of the order of 10^{-3}, flattened chromatic dispersion from 1100 nm to 1800 nm and low effective area (which mean high nonlinearity) are obtained. Furthermore, the influences on the birefringence and dispersion by geometrical parameters have also been discussed and a modest number of design parameters are given.

1. Introduction

Because of the excellent propagation properties, photonic crystal fibers (PCFs) have attracted considerable attention since their first fabrication in 1996 [1]. Many research groups all over the world are making constant effort to establish the superiority of PCFs over conventional fibers because of its novel optical characteristics. It has been reported that PCF can realize endlessly single-mode guiding [2], controllable nonlinearity [3], flexible chromatic dispersion over a wide wavelength range [4], large effective area [5,6] and highly birefringence [7,8]. Generally, PCFs can be classified into two different types by their light-guiding mechanism. They are index-guiding photonic crystal fibers in which light is guided by total internal reflection, and photonic bandgap fibers in which light is guided by the effect of bandgap [2,9].

Birefringence is usually an undesirable property of fiber optics, but highly birefringent fibers (HBFs) are usually required. High birefringence fibers have been widely used for polarization control in fiber-optic sensors, precision optical instruments, and optical communication systems [10,11]. In PCFs it can be simply realized, since the refractive index contrast between the core and the cladding is higher than the refractive index contrast of conventional fibers. To our knowledge, the key point in realizing the birefringence is to destroy the symmetry of the fiber structure and increase the effective index difference between the two orthogonal polarization modes [12]. Highly birefringence can be obtained by altering the air hole sizes near the core area [8,12,13], or by distorting the shape of the air holes (elliptical air holes) [14,15]. Introducing noncircular defect core [16] or including a central elliptical air hole [17] can also achieve highly birefringence.

Besides highly birefringence, PCFs also possess dispersion properties significantly different from those of conventional fibers because the novel cladding structure consist of an array of micrometer-sized air holes allows for flexible tailoring of the dispersion curves. Control of chromatic dispersion in PCFs is very important problem for realistic application of optical fiber communications [18], dispersion compensation [19], nonlinear optics [20], and flatten continuum spectrum generation [21]. To achieve appropriate chromatic dispersion, the parameters in the PCF need to be well designed. Up till now, several index-guiding PCFs with remarkable dispersion have been reported in [21–23].

For a number of applications it is essential to design PCFs that exhibit simultaneously high birefringence, low effective are and flattened chromatic dispersion at a wide wavelength band. To our knowledge, there are no PCFs that simultaneously exhibit such properties. In Ref. [12], highly birefringent PCFs with low confinement loss and ultraflattened chromatic dispersion at wide wavelength band were presented; in Ref. [24], flattened dispersion PCFs with low effective mode area were presented. But in many published papers, only one of the above properties is demonstrated. Therefore, in this paper, a highly birefringent PCFs with flattened dispersion and low effective mode area is proposed by introducing two small air holes in the core area, and distorting the shape of the air holes in the first ring and the medium array to elliptical ones.

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Then, we optimize our design by altering two arrays of air holes in the cladding.

2. Theoretical method

To analyze modal birefringence, chromatic dispersion and effective area of our proposed highly birefringent PCF (HB-PCF), a full-vector plane wave expansion (PWE) method which is highly suitable for the analysis of periodic structure with anisotropic perfectly matched boundary layers (PML) is applied. The PWE method is based on the electromagnetic field using Bloch's theorem. The modal fields and their propagation constants could be found easily by solving a matrix eigenvalue problem corresponding to the wave equation [22,25]. By using PML as boundary condition, propagation characteristics of dispersion can be accurately evaluated [26].

2.1. Birefringence

HB-PCFs are widely used for polarization control. Birefringence is defined as a difference between effective refractive indices of two fundamental polarization modes (HE_{11}^{x} and HE_{11}^{y})[8], which is calculated using:

$$B = |n_x - n_y| \tag{1}$$

where n_x and n_y are the effective refractive indices of each fundamental mode.

2.2. Chromatic dispersion

Chromatic dispersion of the optical fibers is a major factor causing optical pulse broadening. This dispersion is caused by combined effects of material and wavelength dispersion [9]. The chromatic dispersion D of the PCF has been obtained from the n_{eff} values versus the wavelength using:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\ \mathrm{Re}[n_{eff}]}{d\lambda^2} \tag{2}$$

where c is the velocity of light in a vacuum and $\mathrm{Re}(n_{eff})$ is the real part of the n_{eff}. The total dispersion is calculated as the sum of the waveguide dispersion (or geometrical dispersion) and material dispersion in the first-order approximation:

$$D(\lambda) \approx D_g(\lambda) + \Gamma(\lambda)D_m(\lambda) \tag{3}$$

where Γ is the confinement factor in silica. To most index-guiding PCFs, Γ is set to 1 [27]. The material dispersion can be obtained directly from the three-term Sellmeier formula, while the waveguide dispersion can be calculated the same as in Eq. (2).

2.3. Effective mode area

The effective area A_{eff} of the PCFs is related to the effective area of core area, which is calculated using:

$$A_{eff} = \frac{\left(\iint |E|^2 dx\,dy\right)^2}{\iint |E|^4 dx\,dy} \tag{4}$$

where E is the electric field of the medium. A low effective area provides a high density of power needed for nonlinear effects to be significant.

3. Design model and simulation results

The schematic cross-section of the PCF structure that we proposed to achieve highly birefringence, chromatic dispersion and low effective area is shown as in Fig. 1(a). It is a four-ring PCF with

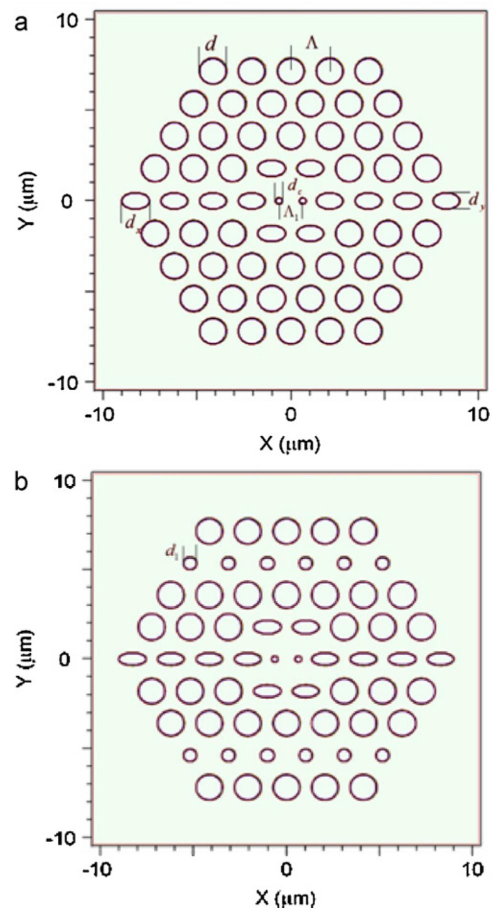

Fig. 1. (a) The schematic cross-section of the highly birefringence PCF we proposed. (b). The schematic cross-section of the highly birefringence PCF we proposed. The schematic cross-section of the highly birefringence PCF we optimized with ultra flattened dispersion.

elliptical air holes in the first ring and the medium array arranged in a silica background. Two small air holes are introduced into the core area for more highly birefringence. In our work, the refractive index of the air hole is $n_0 = 1$, and the refractive index of the silica background is $n = 1.45$. The air hole pitch is $\Lambda = 2.07\,\mu$m, but the pitch between the small air holes in the core area is $\Lambda_1 = (2/3)\Lambda$. The diameter of the air holes in the cladding and in the core area is d and d_c, where $d/\Lambda = 0.71$. d_x and d_y are the major and minor axes of the elliptical air holes, respectively. We set $d_x = d$ to confine the waveguide in the core area. The ellipticity $\eta = d_y/d_x$. d_c and η will be discussed in this part below to achieve highly birefringence.

We calculate the modal birefringence of only the fundamental modes. Fig. 2 shows the modal birefringence of the proposed PCFs in Fig. 1(a) as a function of wavelength with the ellipticity $\eta = 0.6$. Dotted, dashed and solid curves are corresponding to $d_c/d = 0.4$, 0.2 and 0.25, respectively. All three modal birefringence curves in Fig. 2 increase monotonically as wavelength increase. When $d_c/d = 0.25$, the maximum of the modal birefringence can be up to 1.97×10^{-3} for the operating wavelength 1550 nm. It can be found that for any corresponding wavelength the modal birefringence first increase with the increase of d_c/d, after it reach the maximum, then decrease. This could be explained by the fact that for too large or too small air hole in the core area, the symmetry of the core area becomes better, which makes the modal birefringence decrease. With our extra simulation work, it can be found that for the proposed PCFs when $\eta = 0.6$, $d_c/d = 0.25$ is the appropriate selection for highly birefringence.