Design and analysis of a photonic crystal fiber with four-hole unit

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ARTICLE INFO

ABSTRACT

A novel photonic crystal fiber (PCF) based on a four-hole unit is proposed in order to meet the requirements of high birefringence, negative dispersion and confinement loss in fiber-optic communication. The proposed design has been simulated based on the full vector finite element method (FVFEM) and anisotropic perfectly matched layers (APML). Analysis results show that the proposed PCF can achieve a high birefringence to the order of 10^{-2} at the wavelength of 1.55 μm, a large negative dispersion over a wide wavelength range and confinement losses lower than 10^{-9} dB/m simultaneously, which has important applications in polarization-maintaining (PM) fibers, single-polarization single-mode (SPSM) fibers, dispersion compensation fibers and so on.

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1. Introduction

Photonic crystal fibers (PCFs), are usually formed by a central solid defect region surrounded by multiple air holes with the same diameter arrayed in a regular triangular lattice, have become a new hotspot due to its unique properties, such as high birefringence, endlessly single-mode operation, shifted dispersion, and large mode area, which cannot be realized in standard optical fibers [1–7].

Among features of PCFs, birefringence and dispersion compensating are most important properties. Investigations show that high birefringence and dispersion compensating play an important role in fiber-optic sensing system and optical communication networks, which can further improve the performance of signal. For example, high birefringence PCFs can be widely used in polarization-maintaining fibers, single-polarization single-mode (SPSM) fibers, and so on [8,9], and dispersion compensation fiber can effectively compensate the positive dispersion of conventional single mode fiber and suppress the system perturbation caused by a series of nonlinear effects. There are many papers have been reported to investigate high birefringence PCFs with different structures, such as elliptical air holes, rhombic-hole and so on [10–14]. Recently, Chen et al. investigate high birefringence PCFs based on a double-hole unit, and numerical results shown the proposed double-hole PCF can achieve birefringence properties even up to the order of 10^{-2} and less confinement loss than the elliptical-hole PCF [15].

In this paper, we proposed a novel PCF with four-hole unit that will avoid the fabrication challenge inherent in elliptical hole PCFs by only use circular air-holes in the cross section. Although the proposed PCF based on four-hole unit also may not be simple to fabricate, the current progress in PCF nanophotonics technology has demonstrated that fabrication of complex PCF structures is not a great challenge. Analyses show that birefringence even up to the order of 10^{-2} at 1.55 μm, confinement losses lower than 10^{-9} dB/m simultaneously. In addition, negative dispersion also has been obtained over a wide wavelength range, which has important applications in designing dispersion compensation fibers.

2. Numerical method

The numerical method used in this paper is the full vectorial finite element method (FVFEM) with anisotropic perfectly matched layers (APML), which is specially designed for the analysis of general dielectric waveguide geometries and has been justified to be more flexible and reliable than other known techniques [16]. Using this method, the PCF cross-section, with finite number of air holes is divided into homogeneous subspaces where Maxwell's equations are solved by accounting for the adjacent subspaces [17]. The wave equation, which is deduced from the Maxwell's equations, can be written as following:

$$\nabla \times (\varepsilon_r^{-1} \nabla \times \vec{H}) - k_0^2 \mu_r \vec{H} = 0 \tag{1}$$

where $\vec{H}$ is the magnetic field vector μ_r and ε_r are the relative permeability and permittivity of the material which used in the PCF, $k_0 = 2\pi/\lambda$ is the wave number in the vacuum, λ is wavelength of light. Using the FVFEM, the solution for Maxwell is converted to the solution for eigenvalue problem. And the eigenvalue is the

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effective index n_{eff}, then the effective index will be obtained. With the effective index, the birefringence is given by

$$B = |n_{\text{eff}}^x - n_{\text{eff}}^y| \qquad (2)$$

where n_{eff}^x and n_{eff}^y are the refractive indices of the x- and y-polarized fundamental modes of the PCF respectively. The chromatic dispersion D of the PCF has been obtained from the n_{eff} values versus the wavelength using [18,19]

$$D(\lambda) = -\frac{\lambda}{c} \cdot \frac{\partial^2 |Re(n_{\text{eff}})|}{\partial \lambda^2} \qquad (3)$$

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

$$D(\lambda) \approx D_w(\lambda) + \Gamma(\lambda)D_m(\lambda) \qquad (4)$$

where Γ is the confinement factor in silica. To most index-guiding PCFs, Γ is set to 1 [20]. Material dispersion refers to the wavelength dependence of the refractive index of material caused by the interaction between the optical mode and ions, molecules or electrons in material. Wavelength dispersion depends among others on the core diameter and on the refractive index contrast between the core and the cladding of the PCF. They are calculated as follows:

$$D_m = -\left(\frac{\lambda}{c}\right)\frac{\partial^2 n_M}{\partial \lambda^2} \qquad (5)$$

$$D_w = -\left(\frac{\lambda}{c}\right)\frac{\partial^2 [Re(n_{\text{eff}})|n_{M(\lambda)=\text{const}}]}{\partial \lambda^2} \qquad (6)$$

where n_M is dependent on λ in dispersive media, it can be computed by Sellmeier formula. In our simulations Eq. (4) is used to calculate the chromatic dispersion.

Confinement loss is the light confinement ability within the core region. By suitable choice of pitch, number of rings, position and diameter of air-holes, it is possible to control both dispersion and confinement loss. The confinement loss L_c, with unit of dB/m, is subsequently obtained from the imaginary part of n_{eff} as follows [21,22]:

$$L_c = \frac{40\pi}{In(10)\lambda}Im(n_{\text{eff}}) = 8.686k_0 Im(n_{\text{eff}}) \quad [\text{dB/m}] \qquad (7)$$

where $Im(n_{\text{eff}})$ is the imaginary part of the refractive index, the complex refractive index of the fundamental modes can be solved from Maxwell's equations as an eigenvalue problem.

3. Design model

The cross section of the proposed four-hole unit PCF is illustrated in Fig. 1. The PCF core is formed by omitting a four-hole unit at the center of the PCF. The number of the air-hole layers is assumed to be 4. For the proposed four-hole PCF, four small air-holes form a basic unit, b and a are the lengths of two diagonal lines of a unit. The b is directed along the y-axis, while the a is parallel to the x-axis. Such the proposed PCF is characterized by the coefficients $\gamma = b/a$. Then four rings of arrays of the basic four-hole units are arranged as a conventional hexagonal-lattice structure with a unit-to-unit distance (Λ) in the cross section of the PCF, which ensures the stability and flexibility when fabricating the fiber preform. To simplify this theoretical analysis process, the refractive index of the dielectric material and the surrounding air is assumed to be 1.45 and 1, respectively. The birefringence of PCF is relative to the shape, size and spacing of the four-hole unit, and then we will show them in detail in following.
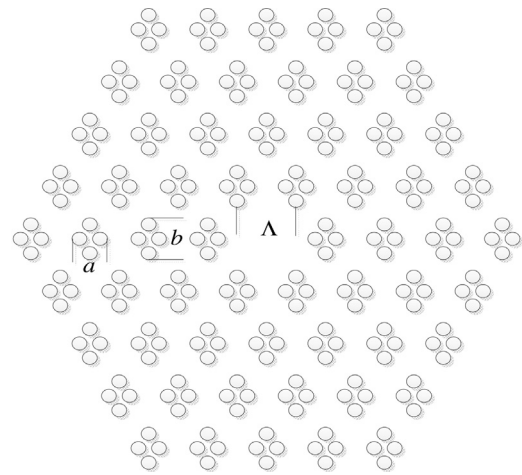

Fig. 1. Schematic cross-section of the proposed four-hole unit PCF.

4. Simulation results and discussion

First, we investigate the effect of the coefficient γ on the birefringence. Fig. 2 shows the birefringence curves as a function of wavelength with different coefficient $\gamma = 2, 3, 4, 5, 6$ at the condition of $\Lambda = 2.4\,\mu\text{m}$. From Fig. 2, we can see that all the birefringence curves increase monotonically with the increase of wavelength and vary inconspicuously in the long wavelength region. In addition, it is also observed that birefringence increasing with the γ increasing at the same wavelength. The reason for which is that a high γ value will make the PCF structure more asymmetric, result in the difference between the effective indices of y and x polarization modes increases, which is consistent with the published results in literature [14,23].

Then, we also study the influence of the unit-to-unit distance Λ on the birefringence for the proposed PCF, which is illustrated in Fig. 3. Fig. 3 illustrates the relationship between birefringence and wavelength with different Λ under the condition of $\gamma = 3$. It can be seen that birefringence increases with the decreasing of the Λ due to reduce Λ further increases the PCF structure asymmetric. It is clear that the birefringence increases from 3.3×10^{-2} to 4×10^{-2} at $\lambda = 1.55\,\mu\text{m}$, when the value of Λ from $2.4\,\mu\text{m}$ to $2.0\,\mu\text{m}$. So we can conclude that the proposed four-hole unit PCF can easily achieve high birefringence up to the order of 10^{-2} by carefully adjust the parameter γ and Λ. In addition, the birefringence of the proposed PCF is higher than the elliptical-hole PCF or rhombic-hole PCF of previous reports [10–14].

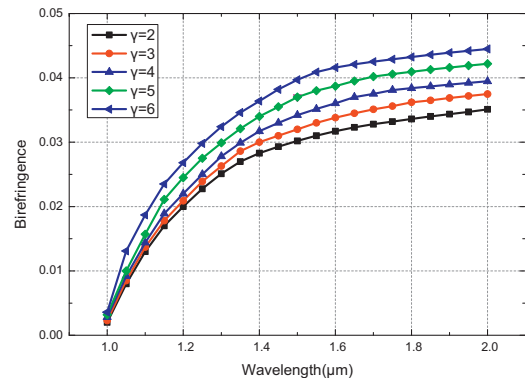**Fig. 2.** Birefringence as a function of wavelength with different γ at the condition of $\Lambda = 2.4\,\mu\text{m}$.