Infrared Physics & Technology 67 (2014) 148–154

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Novel single-mode and polarization maintaining photonic crystal fiber

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HIGHLIGHTS

- We report a PCF with perfect single-mode condition and highly birefringence.
- Increase the birefringence by increasing the ellipticity η.
- Increase d/Λ, the range of mono-mode operation decreases.

ARTICLE INFO

Article history:
Received 6 May 2014
Available online 24 July 2014

Keywords:
Photonic crystal fiber
Birefringence
Single-mode
Optical devices

ABSTRACT

In this paper, we present and propose a novel structure for improved birefringence and single-mode propagation condition photonic crystal fiber (PCF) in a broad range of wavelength. The birefringence of the fundamental mode and single mode property in such a PCF is numerically estimated by employing full vector finite element method (FVFEM) and anisotropic perfectly matched layers (APML). The simulation results illustrate that we can achieve a high birefringence and perfect single-mode condition by employing silica-filled into one-line elliptical air holes parallel to x-axis and rotated by an angle. Obviously, the proposed PCF is quite useful for optical devices.

1. Introduction

Photonic crystal fibers (PCFs), also known as micro-structured fiber or holey fiber, are usually formed by a solid pure silica core region surrounded by a periodic arrangement of microscopic air-holes with the same diameter arrayed in a regular triangular lattice that offer feasibility of adjusting fiber properties in smart way [1]. Over the past few years, PCFs have attracted significant interest and considerable attention in various areas of optical communication due to their unique optical properties, such as high birefringence, nonlinearity, endlessly single-mode operation, shifted dispersion, and large mode area, which cannot be realized in standard optical fibers [2–8].

Among features of PCFs, birefringence and single-mode operation are most important properties. Investigations show that high birefringence and single-mode operation are important for many applications in fiber-optic sensing system, fiber laser, high-power transmission [9]. For example, high birefringence PCFs focus potential application in polarization-maintaining fiber and high bite rate transmission system. It is well known that birefringence in the polarization maintaining fibers (PMFs) can be realized in two major ways. One is to introduce asymmetric micro-structure in either the cladding or the core region to make the PCF structure more asymmetric than usual and the effective index more different for two orthogonal polarization states. The other is to apply asymmetrical stress to the core region by materials with larger thermal expansion coefficients. So far, various high birefringence PCFs on the order of 10^{-3} have been reported [10,11]. Habib et al. designed a new hybrid cladding for improved birefringence and highly nonlinear photonic crystal fibers (PCFs) in a broad range of wavelength bands. The result shows the highest modal birefringence at the excitation wavelength of $\lambda = 1.55$ μm can be achieved at a magnitude of 1.77×10^{-2} [12]. Recently, Hu et al. investigate high birefringence PCFs by introducing rhombic air-hole, the rhombic-hole PCF design by modulating the related parameters, a birefringence as high as 3.47×10^{-3} was obtained [13]. In addition, PCF also offer a novel way to realize single-mode operation [14]. Poli et al. investigated the single-mode regime of square-lattice circular-hole PCFs and illustrated that the single-mode operation region of square-lattice PCFs is wider than that of triangular ones, and that the normalized cut-off frequency V^* is lower than π [15]. In 2012, Lebbal et al. compared different kinds of structures of PCF, and the simulation results of PCF shows that the cubical cross sectional pattern of air holes in a silica fiber is in a better agreement with the single-mode condition [16].

In this paper, we propose a novel PCF by introducing silica-filled into one-line elliptical air holes parallel to x-axis and y axis,

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http://dx.doi.org/10.1016/j.infrared.2014.07.014
1350-4495/

respectively and rotated by an angle to two different directions, as shown in Fig. 1. Although the proposed PCF may not be easy to fabricate, the current progress in PCF nano-photonics technology has demonstrated that fabrication of complex PCF structure is not a great challenge [17–19]. Numerical results shows that designed PCF has improved birefringence and perfect single-mode character by selectively filling the PCF with appropriate material and modulating the shape of air holes to create asymmetric PCF structure. Another advantage of the proposed PCF is that it possesses modest number of design parameters.

2. Theoretical method

In this paper, a full vectorial finite element method (FVFEM) with anisotropic perfectly matched layers (APML) has been used to investigate the properties of the PCF (the software is the COMSOL Multi-physic). The FVFEM is a powerful and versatile tool to cope with any kind of structure geometry and provide full vector analysis of various photonic waveguide devices [20–23]. 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 [24]. 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' equation is converted to the solution for eigenvalue problem. And the eigenvalue is the effective index n_{eff}, then the effective index will be obtained. With the effective index, the birefringence is given by

$$B = \left| n_{eff}^x - n_{eff}^y \right| \tag{2}$$

where n_{eff}^x and n_{eff}^y are the refractive indices of the x-and y-polarized fundamental modes of the PCF respectively.

In a conventional fiber, the number of bound modes is governed by the V parameter, which increases without limit as the wavelength decreases [25]. It is possible to define an effective V number for PCF that indicates reasonably whether or not a fiber is single-moded:

$$V_{eff} = 2\pi \frac{\Lambda}{\lambda} \sqrt{n_0^2 - n_{eff}^2} \tag{3}$$

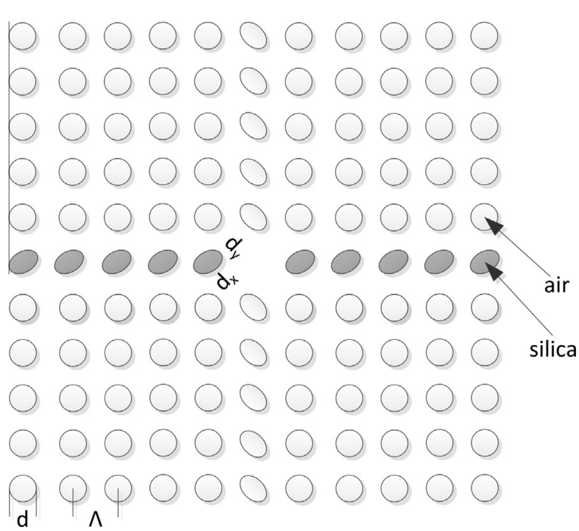

Fig. 1. Cross-section of the proposed photonic crystal fiber.

where Λ is the lattice period, n_0 is the silica index in the structure and n_{eff} is an "effective cladding index" in the infinite periodic cladding structure. Under these conditions, the cut-off condition of the second-order mode is given by $V_{eff} = 2.405$ [26]. So the parameter V_{eff} is greater than 2.405 when the wavelength is less than the cut-off wavelength $\lambda < \lambda_c$ and then the PCF is multi-modes. On the contrary, the PCF is mono-mode when a wavelength higher than the cut-off wavelength.

3. Geometry of the proposed PCF

Fig. 1 shows the transverse cross section of the proposed square PCF. It is a PCF with five layers of air-hole ring and the central air hole in the structure is omitted creating a high-index defect allowing for guidance of light by total internal reflection.

By filling the silica into one line elliptical air holes parallel to x-axis and rotated by an angle of $\theta = 45°$, meanwhile introducing one line elliptical air holes parallel to y-axis without any material and rotated by an angle of $\theta = 45°$ to other direction, so we can break the symmetry of the PCF structure dramatically in order to obtain high birefringence. Where d is the diameter of the circular air hole and Λ is the center-to-center spacing between the neighboring air holes. d_x and d_y are the major and minor axes of the elliptical air holes, respectively. The ellipticity $\eta = d_x/d_y$, and n_q is the refractive index of the filled liquid. So in our design, there are three degrees of freedom, liquid index n_q, the ellipticity η and rotated angle θ. There are some optimized structural parameters should be searched out in PCF design process and we will show them in detail in following.

4. Simulation results

4.1. Single mode operation

First, we study the influence of the refractive index of the guiding material on the V parameter. Fig. 2 depicts the dependence of the V parameter on wavelength at the condition of $d/\Lambda = 0.1$, $\eta = 5$ and $\theta = 45°$ for three different kinds of guiding material. Here, the three guiding material are CS_2, glass and silica. CS_2 is a liquid with a large refractive index 1.63, the refractive index of glass is 1.51 and the silica is 1.45. From this figure, we can see that all the V parameter curves decrease with increase of wavelength and increase with increasing the effective index of guiding material at a specific wavelength. In addition, it is clear to see that as the guiding material index decreases the cut-off wavelength decreases and PCF becomes mono-mode for a large wavelength range. The cut-off wavelength of silica, glass and CS_2 are 0.6122 μm, 0.6734 μm, 0.7858 μm. Thus, the wavelength range which guaranties the single mode character increase if the index difference between the guiding material and the air hole decreases.

Then, we also investigate the effect of air filling factor d/Λ on V parameter. Fig. 3 shows the V parameter as a function of wavelength for different values of air filling factor d/Λ ranging 0.1–0.5 when $\eta = 5$ and $\theta = 45°$. From the Fig. 3, we observe that the curves are similar with the curves of Fig. 2, the V parameter increase with increase of d/Λ at a certain wavelength. Based on the values of d/Λ, if we increase d/Λ, the range of mono-mode operation decreases and the fiber with d/Λ of 0.1 was single mode in the overall wavelength region(from 0.8 μm to 1.8 μm).

4.2. Birefringence

Next, we further investigate the influence of two-line elliptical air-hole paralled to x-axis and y axis, respectively on rotation-induced birefringence of PCFs. Fig. 4 shows birefringence as a function of wavelength ranging from 1.0 μm to 1.8 μm with