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Investigation of high birefringence and chromatic dispersion management in photonic crystal fibre with square air holes

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ABSTRACT

In this article, a solid core photonic crystal fibre (PCF) with square air holes is proposed and numerically analysed. The confinement loss, the chromatic dispersion and the birefringence are calculated for both triangular and square lattices by using a full vector finite difference time domain (FV-FDTD) method and the perfectly matched layers (PML) boundary conditions. Two main applications are then investigated: high birefringence and chromatic dispersion management. For the first one, simulation results indicate that high birefringence of 2.5×10^{-3} is achieved at the wavelength 1.55 μm with a very low bending loss of 1.8×10^{-3} dB/km for bent radius of 2 mm. In the second application, ultra-flattened chromatic dispersion over a wide band of wavelengths from 1 μm to 1.8 μm can be obtained with both positive and negative regimes.

1. Introduction

Photonic crystal fibres [1], also known as microstructured fibres or holey fibres are single material fibres with a morphological micrometer sized and periodic structure of air holes running along the longitudinal axis with a defect region in the centre. Since their apparition for the first time in 1995 [2], PCFs have attracted a huge interest among the scientific community due to their several and unique optical properties. In fact, the high flexibility of the lattice design makes it possible the conception of PCFs with single mode behaviour over a wide range of wavelengths [3], high birefringence [4–9], tailorable chromatic dispersion [10–14], high nonlinearity [15,16] and so on. Due to these properties, many potential applications can be achieved, such as: dispersion compensator fibres [17–19], polarization maintaining fibres [20–22], highly nonlinear fibres [23–25], supercontinuum generation [26], fibre based lasers [27–29], sensors [30–32], terahertz applications [33–35] etc.

In PCFs, the light can be trapped into the core and guided according to two mechanisms: the modified total internal reflection (M-TIR) and the photonic band gap effect. The first one is similar to conventional optical fibres in which the index of the core is higher than the effective index of the cladding which is formed by an array of air holes [2]. These index guiding PCFs (IG-PCFs) have broad transmission window from below 500 nm to beyond 1800 nm. In the second mechanism, light is confined to a low index core (e.g., air) thanks to the band effect of the cladding which acts as a mirror [36]. Comparatively to IG-PCFs, photonic bandgaps PCFs (PBG-PCFs) have relatively narrower transmission bands [37].

Commonly, PCFs cladding is formed by a periodic structure of air holes with a circular or elliptical shape. In recent published works, the optical properties of PCFs with polygonal air holes have been studied. For instance, in [38], the authors have investigated the propagation properties of photonic crystal fibre with rhombic air holes. They found that it was possible to design photonic crystal fibre with very low loss at $\lambda = 1.55$ μm. Furthermore, the chromatic dispersion can be easily adjusted by only manipulating the internal angle of the rhombic air holes. The birefringence was also studied for this structure [39]. Comparatively to elliptical hole PCFs, the authors have found that rhombic holes PCFs exhibit more birefringence, up to 3.47×10^{-3} when they have the same air-filling fraction. Besides, the proposed PCFs structures can be developed by using a solgel preform fabrication method [40].

The guidance of light in a kagome structured hollow core PCF has been reported with the aim of understanding and also control the positions of high loss spectral features [41]. Besides, the authors

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have used a rigorous method such as the finite element method (FEM) to obtain accurate calculations of losses in kagome PCFs.

Moreover, in [42] the authors have presented modal solutions of planar photonic crystal waveguide with square and rectangular air holes. They have shown that the birefringence can be obtained when employing rectangular air holes. However, the chromatic dispersion was the same for both cases.

In [43], the authors have presented a comparative study of the single mode behaviour and the numerical aperture of a solid core PCF with circular and square air holes arranged in square lattice. They showed that the two structures become multimode when increasing the air filling fraction in the cladding region. Furthermore, the numerical aperture for the square air holes is larger than the one of circular air holes, for a wide range of wavelengths. Also in [44], the same authors have presented a theoretical study of large solid core square lattice PCF with square air holes. The core of the PCF that they have proposed was formed by omitting nine air holes. In comparison with PCF with circular air holes, their proposed structure has the same chromatic dispersion behaviour with the same zero dispersion point. Furthermore, they have shown that square air holes PCF presents a confinement loss ($\approx 10^{-6} - 10^{-7}$ dB/km) lower than circular air holes PCF.

Furthermore, a structural study of a photonic crystal fibre has been presented in the aim of achieving the single mode operation over a wide band of wavelengths [45]. PCFs with circular and square air holes arranged in triangular and rectangular lattice have been considered. In their comparative study, the authors have found that the rectangular pattern of circular air holes was in a better agreement with the single mode condition when the material background was silica.

Note that, to the best of our knowledge, high birefringence operation has not been investigated in PCFs with square air holes. Furthermore, the study of chromatic dispersion for the structure reported in [44] has not been achieved with the aim of showing its controllability.

In this paper, we investigate by using numerical simulations the high birefringence property and the chromatic dispersion management of an index guiding solid core PCF with square air holes arranged in triangular and square lattice. The confinement loss, the birefringence and the chromatic dispersion are calculated by using an efficient finite difference time domain method (FDTD) with perfectly matched layers (PMLs). High birefringence operation which is achieved by minimizing only two air holes is demonstrated and results are compared to a same PCF with circular air holes. Furthermore, the chromatic dispersion is shown to be tailorable in our proposed structure by simply doping the core with germanium.

2. Models and theoretical background

The cross-section of the proposed PCF is depicted in Fig. 1. The cladding is formed by an array of square air holes and the core

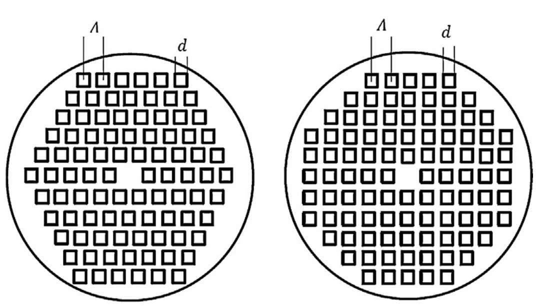

Fig. 1. Cross-section of square air holes photonic crystal fibre with triangular lattice (a) and square lattice (b).

is obtained by omitting one air hole in the centre. The air holes are arranged in a triangular lattice (Fig. 1(a)) and a square lattice (Fig. 1(b)). The material of the background is silica and its refractive index is given by the sellmeier equation [46]. The number of the air holes rings in the cladding region is chosen to be five and thus, the light remains well confined in the core.

In order to accurately simulate these structures, a full vector FDTD (FV-FDTD) method is used. From Maxwell's equations, the following vector wave equation can be derived:

$$\nabla \times \left([S]^{-1} \times \vec{E} \right) - k_0^2 n^2 [S] \vec{E} \qquad (1)$$

where, $k_0 = 2\pi/\lambda$ is the wave number in the vacuum, λ is the wavelength, $\vec{E}$ denotes the electric field, n is the refractive index, $[S]$ is the PML matrix and $[S]^{-1}$ is an inverse matrix of $[S]$. By applying the FV-FDTD method, the effective refractive index n_{eff} can be obtained from the eigenvalue Eq. (1). It satisfies the condition below:

$$n_{\text{FSM}} < n_{\text{eff}} < n_{\text{co}} \qquad (2)$$

Where, n_{co} is the core refractive index and n_{FSM} is the effective cladding refractive index corresponding to the fundamental space-filling mode.

2.1. Confinement loss

Theoretically, the light beam is totally confined into the PCF core due to the infinite periodic structure around the centre. Practically, only a few number of air holes rings form the cladding. Thereby, a fraction of the optical power leaks out of the structure. This kind of losses is called the confinement loss and its value can be calculated by using the formula [4]:

$$\alpha = 8.686 k_0 Im(n_{\text{eff}}) \qquad (3)$$

In decibel per meter, where n_{eff} is the imaginary part of the effective refractive index and k_0 is the free space wave number.

2.2. Chromatic dispersion

The control of chromatic dispersion in PCFs is a very important issue for practical applications in dispersion compensation of optical communication systems and nonlinear optics. The chromatic dispersion of a PCF is the sum of the material dispersion and the waveguide dispersion:

$$D = D_{\text{m}} + D_{\text{w}} \qquad (4)$$

The material dispersion, D_{m} is derived from the Sellmeier Eq. [46]:

$$n_{\text{silica}}^2(\lambda) = 1 + \sum_{k=1}^{3} \frac{b_k \lambda^2}{\lambda^2 - \lambda_k^2} \qquad (5)$$

where, $b_1 = 0.6961663$, $b_2 = 0.4079426$, $b_3 = 0.8974794$, $\lambda_1 = 0.0684043$ µm, $\lambda_2 = 0.1162414$ µm and $\lambda_3 = 9.896161$ µm.

The waveguide dispersion is given by [47]:

$$D_{\text{w}} = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2} \qquad (6)$$

where, λ and c are the wavelength and the speed of light, respectively.

Since waveguide dispersion can be anomalous and material dispersion normal, optimal dispersion design can be achieved by a suitable balance of the two components of the total dispersion. Hence, to design a PCF with zero or negative dispersion, the waveguide dispersion has to be reshaped by manipulating the opto-geometrical parameters of the PCF.