Double-cladding rectangular-lattice birefringence photonic crystal fiber with elliptical air holes

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Received: 2 September 2014 / Accepted: 4 March 2015 / Published online: 15 March 2015
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Abstract We proposed a novel design of photonic crystal fiber with the characteristics of high birefringence and zero dispersion. The structure of the photonic crystal fiber is composed of the rectangular lattice with double-cladding and there is an elliptical air hole in the core of the photonic crystal fiber which has the same size with the holes of inner ring. Simulation results show that the elliptical air hole in the core can enhance the performance of mode birefringence and control the properties of chromatic dispersion at the same time. We obtain the high birefringence $B = 2.1 \times 10^{-3}$ and $B = 2.9 \times 10^{-3}$ at the wavelength of 1.31 and 1.55 μm respectively and the zero dispersion point at the wavelength of 1.31 μm . The proposed photonic crystal fiber with high birefringence and zero dispersion will be important in the applications of polarization maintaining transmission systems.

Keywords Photonic crystal fiber · Birefringence · Zero dispersion

1 Introduction

Photonic crystal fibers (PCFs) present a wavelength-scale periodic microstructure running along their length. It has been intensively studied due to their unique properties which could be difficult to realize in conventional optical fibers because of the flexibility for the cross section design (Russell 2007; Birks and Knight 2001; Knight 2003; Russell 2003; Philip 2009). Taking into consideration the propagation mechanism behind light guidance in PCFs, there are basically two types of PCFs: index-guiding PCFs which is based on

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modified total internal reflection and photonic bandgap PCFs which is based on the effect (Hansen et al. 2001; Saitoh and Koshiba 2002; Knight et al. 1998).

During the past decades, the theory of PCFs has developed in a variety of directions. It has a number of novel features such as low optical losses, high optical nonlinearity, ultra-negative dispersion and polarization effects compared with conventional optical fibers. Especially, the research of birefringence characteristics of PCFs has attracted more and more attention (Ortigosa-Blanch et al. 2000). In previous studies, a lot of methods to improve birefringence have been proposed, such as increasing the radius of some air holes in the cladding and using the intrinsic anisotropy of the elliptical air holes etc. (Steel and Osgood 2001). Hao et al. proposed a highly birefringent index-guiding photonic crystal fiber with low confinement loss by enlarging the central row of air holes in the structure in 2013. Simulation results indicate that high birefringence of 1.65×10^{-3} can be reached at the wavelength of 1.55 μm , and a low confinement loss on the order of 10^{-6} dB/km can be achieved at the same wavelength (Hao et al. 2013). However, they adopted a conventional hexagonal lattice structure which is not novel and the birefringence is not higher than the one that we obtain at the wavelength of 1.55 μm and the confinement loss is lower an order of magnitude compared with the one which we achieved. In the same year, an air holes rectangular arrange of photonic crystal fiber has been proposed by Xu et al. (2013) which has the different diameters of air holes in x-directional and y-directional. In their paper, the birefringence is in order of 2.1×10^{-3} at the wavelength of 1.55 μm which is not higher than ours. Chen et al. also proposed a kind of rectangular lattice photonic crystal fiber with the circular air holes whose width and length ratio of the fiber are different. They have achieved a high birefringence in order of 1.0×10^{-3} at the wavelength of 1.55 μm which is also lower than ours (Chen and Yu 2006). Comparing with the structures mentioned above, the structure that we proposed is novel which has double-cladding and square-lattice with elliptical air holes. More importantly, an elliptical air hole is added in the core to improve birefringence. As a result, a high birefringence is achieved which is in order of 2.9×10^{-3} at the wavelength of 1.55 μm and the zero dispersion appears at the wavelength of 1.31 μm where the birefringence is 2.1×10^{-3} .

In this paper, a modified rectangular lattice PCF is proposed which has double-cladding with the elliptical air holes and an elliptical air hole is in the core which has the same size with the air holes of inner ring. The properties of birefringence and chromatic dispersion is investigated by numerical simulation. This is novel idea that adding an air hole in the core in a double-cladding rectangular lattice PCF with elliptical air holes. We study the proposed fiber with the full vector finite element method (FV-FEM) (Koshiba 2002; Koshiba and Saitoh 2003) with perfectly matched layers (PMLs) (Koshiba and Tsuji 2000). This fiber will play a very important role in the fields of polarization maintaining transmission system and zero dispersion devices.

2 Principles and formulas

We used the full-vector finite element method (FEM) with the perfect matched layer (PML) boundary conditions to analyze the birefringence and dispersion of the proposed PCF. PCF is a special optical waveguide in which the light transmits by the theory of electromagnetic waves transmission. Maxwell equation is the starting for the numerical simulation. Through the mathematical calculations for time-harmonic Maxwell equations, We obtain the Helmholtz equation:

$$\begin{aligned}\nabla \times \nabla \times \vec{E}(\vec{r}) &= \frac{\omega^2}{c^2} \varepsilon(r) \vec{E}(\vec{r}) \\ \nabla \times \left[\frac{1}{\varepsilon(r)} \nabla \times \vec{H}(\vec{r}) \right] &= \frac{\omega^2}{c^2} \vec{H}(\vec{r})\end{aligned}\quad (2-1)$$

where E is electric field, H is magnetic field, ε is the waveguide dielectric function, ω is the angular frequency and c is the speed of light in vacuum. The Partial differential equations is transformed into the matrix equation by finite element method with the PML boundary conditions for Numerical Solution.

The degree of mode birefringence B of the PCF is defined by

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

where n_{eff}^x and n_{eff}^y are model effective index of the two orthogonal polarization states to the x and y axis, respectively.

The chromatic dispersion of the PCFs contain two parts which are the material dispersion D_m and the waveguide dispersion D_w . They are expressed as

$$\begin{aligned}D_m(\lambda) &= -\frac{\lambda}{c} \frac{d^2 n_m}{d\lambda^2} \\ D_w(\lambda) &= -\frac{\lambda}{c} \frac{d^2 \text{Re}(n_{\text{eff}})}{d\lambda^2}\end{aligned}\quad (2-3)$$

where n_m can be obtained by Sellmeier formula and n_{eff} is the mode effective index of PCFs. So the total dispersion of PCFs can be exhibited as

Fig. 1 Cross section of the double-cladding *square-lattice* PCF with elliptical air holes. The air holes have two different sizes. The inner and outer elliptical air holes's minor axis is $a_x = 0.125$ and $A_x = 0.5$ μm , respectively. Both of them have the same ellipticity $\eta = 0.5$ (The η is defined as the ratio of the minor axis and major axis of the ellipse). The pitch of tow adjacent air holes of the outer air holes cladding along the x - and y - direction is $\Lambda_x = 1.5$ and $\Lambda_y = 2.5$ μm , respectively. The pitch of tow adjacent air holes of the inner air holes cladding along the x - and y - direction is $B_x = 0.75$ and $B_y = 0.83$ μm , respectively. The elliptical air hole in the core has the same size with the inner air holes

$$D(\lambda) \approx D_w(\lambda) + D_m(\lambda) \quad (2-4)$$

The confinement loss of the fiber can be expressed as

$$L = 8.686 \times \frac{2\pi}{\lambda} \text{Im}(n_{\text{eff}}) \times 10^4 \quad (2-5)$$

where n_{eff} is the effective refractive index of the core, and the units of the confinement loss and the wavelength are dB/cm and micrometers, respectively.

In this paper, when the material of the fiber is settled, the material dispersion is considered, so the final outcome is the total dispersion.

3 Design, simulation results and discussion

Firstly, a rectangular latticed is used in the cladding of the PCF. Secondly, the elliptical air holes is adopted in the cladding. Then, an elliptical air hole is added in the core to affect the birefringence and the chromatic dispersion. The cross section of the proposed PCF is

Fig. 2 Electric field distribution of (a) (c) x- and (b) (d) y-polarized for the proposed PCF without air hole in the core and the one with it, respectively

shown legibly in Fig. 1. The pure silica was adopted as the background material whose chromatic dispersion was calculated by the Sellmeier equation, thus the material dispersion of the fiber was taken into account.

Figure 2 shows that the electric field distributions of the x- and y-polarized fundamental modes respectively for the proposed PCF and the one without the air hole in the core. It is obviously that the mode of the PCF without air hole in the core (Fig. 2a, b) is uniform and the one of the proposed PCF is manacled around the air hole in the core (Fig. 2c, d). A phenomenon is exhibited by comparing Fig. 2c, d that the x-polarized mode is more uniform than the y-polarized mode. Field distribution is directly related to the effective refractive index of the mode such that the x-polarized mode with more bounded around the hole as shown in Fig. 2a, c will result in a lower effective index. For the proposed PCF, high birefringence is induced by magnifying the polarization dependent disparity in the field distributions. As is shown in Fig. 3, it is clearly that the mode effective index of the PCF without air hole in the core is higher than the proposed PCF, because the existence of the air hole in the core impact the distribution of mode effective index. Furthermore, the mode effective index of y-polarization of the proposed PCF is higher than that of x-polarization.

Figure 4 shows the birefringence versus wavelength for the proposed PCF and the one without air hole in the core. The PCF without the air hole in the core has high birefringence which reach to 1.7×10^{-3} , while the one with it reach to 2.9×10^{-3} at the wavelength of $1.55 \mu\text{m}$. Obviously, the PCF with the air hole in the core has higher birefringence. As we know, birefringence is determined by mode effective index. The anisotropic elliptical air hole in the core effects the distribution of mode effective index at the x-pol and y-pol, which leads to the big difference.

The simulation results, the effect of an elliptical air hole in the core on the chromatic dispersion, are shown in Fig. 5. With the increase of the wavelength the dispersion value of the PCF with the air hole in the core increases. The zero dispersion is found at y-polarized direction at the wavelength of $1.31 \mu\text{m}$. However, that of the PCF without the air hole in the core is at the wavelength of $1.01 \mu\text{m}$. It is clearly that the air hole in the core of the PCF

Fig. 3 Mode effective index of x-pol and y-pol for the PCF with the air hole in the core or not

Fig. 4 Mode birefringence of the fundamental modes for the PCF with an air hole or not

Fig. 5 Chromatic dispersion of the fundamental modes for the proposed PCF

can control the position of the zero dispersion point. As is shown in Eq. (2-3), the waveguide dispersion D_w is associated with the second derivative of the refractive index. The mode of the light which propagates in the waveguide is determined by the structure of the waveguide and the refractive index is a characterization of the amount of light propagation modes. As a result, the changes of structure have a moderating effect on the dispersion.

To further investigate the impact of the design parameters of the proposed PCF, we analyze the relationship between the mode birefringence and the size of the air holes of the inner air ring while the ellipticity remains unchanging as Fig. 6 shown. The birefringence

Fig. 6 Influences of the structure parameters on the birefringence of the proposed PCF with different a_x

becomes larger as a_x increase, and it can up to 3.23×10^{-3} while $a_x = 0.15$ at the wavelength of $1.55 \mu\text{m}$. In other words, the larger elliptical air hole can give rise to the higher birefringence for the inner ring.

Next, the impact of the design parameters on the chromatic dispersion of the proposed fiber is investigated. The curve of dispersion is shown in the Fig. 7. Illustration in Fig. 7 under right shows that the zero dispersion wavelengths of the proposed PCF with different structure parameters. It is found that the zero dispersion moves to the short wavelength with the increase of size of inner ring's air holes. When the minor axis of elliptical air hole of the inner ring is $0.125 \mu\text{m}$, the zero dispersion of y-polarization is at the wavelength $1.31 \mu\text{m}$ which is in the communication band.

Fig. 7 Influences of the structure parameters on the dispersion of the proposed PCF with different a_x

As the proposed PCF has six rings air holes, the confinement loss is as low as 10^{-7} dB/km at the wavelength both of 1.31 and 1.55 μm . Moreover, the birefringence is also high enough in order to 2.1×10^{-3} at the wavelength of 1.31 μm , so it can be used as zero dispersion polarization maintaining photonic crystal fibers.

Finally, we briefly consider the possibility of fabrication for the proposed PCF. In the fabrication process, the elliptical holes may be susceptible to collapse and to change into circular one due to the surface tension. To overcome these problems, a new fabrication method of the new multi-step process of forming perform was suggested by Falkenstein (2004) and elliptical photonic crystal fiber (EPCF) were experimentally realized in Ref (Falkenstein et al. 2004). In addition, by introducing new methods for fabrication PCFs such as performs drilling, sol–gel casting, and tapering (Issa and van Eijkelenborg 2004; Domachuk et al. 2005; Guenneau et al. 2003), the possibility of drawing the proposed PCF is enhanced.

4 Conclusion

In this paper, we have proposed a birefringent photonic crystal fiber with elliptical air holes with rectangular-lattice and analyzed the effects of structure parameters on the mode birefringence and the chromatic dispersion. We found that the PCF with an air hole in the core has high birefringence and the zero dispersion in the communication band. By changing the size of the inner ring's air holes, we obtain a better optimization results that the birefringence reached to 2.1×10^{-3} and 2.9×10^{-3} at the wavelength of 1.31 and 1.55 μm respectively and the zero dispersion at the wavelength of 1.31 μm . The proposed PCF will be very useful to the applications of fiber optic systems with high birefringence and zero dispersion point in the communication band.

Acknowledgments The work is supported by the National Natural Science Foundation of China (Grant No. 61178026), and the Natural Science Foundation of Hebei Province, China (Grant No. E2012203035).

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