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Tunable birefringent characteristic of the photonic crystal fibers filled selectively by magnetic fluid

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A novel birefringent photonic crystal fiber (BPCF) which is symmetrically filled with magnetic fluid (MF) into the transverse air-holes was presented firstly. The magnetically induced tuning properties of the BPCF filled MF were simulated and analyzed by the full-vector finite element method with a perfectly matched layer. The mode field distributions, polarization properties and the confinement loss of the BPCF filled MF were figured out and simulated. The results show that the properties of the BPCF filled MF can be tuned by adjusting the magnetic field and the duty ratio d/Λ. The phase birefringence B decreases with the increase of magnetic field H under the condition of the same duty ratio d/Λ. The B increases with the increase of duty ratio d/Λ under the condition of the same magnetic field H. When the wavelength λ=1550nm, the duty ratio d/Λ=0.9, the phase birefringence B decreases from 0.005575 to 0.004472 with the H changing from 20Oe to 300Oe. The birefringence effect is ten times higher than the general fiber and there is a fairly good linearity.

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Keywords: Birefringent Characteristic, Photonic crystal fibers, Magnetic fluid

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1. Introduction

The first photonic crystal fiber (PCF) was made by Knight in 1996 [1], and from then on, the theory and experimental research of the PCF have been widely reported. In recent years, the birefringent fiber based on the PCF has become a new hotspot. High-birefringent fiber is widely used in polarization optics devices, high-speed optical communication systems, supercontinuum generation and optical sensing field [2]. The mode birefringence of ordinary birefringent fiber (such as elliptic and Panda type birefringent fiber) is about 5×10^{-5} [3], which can't to meet the growing demand. Therefore, there is a necessity to explore new high-performance birefringent fiber. The size and shape of cladding air holes of PCF can be set flexibly in the production process, which offers the possibility to obtain high performance birefringent fiber. At present, the birefringence can be obtained by changing the transverse structure of PCF, for example, the oval air holes, the asymmetric center holes, the irregular air holes or the unsymmetrical distribution of the air holes [4-5].

The magnetic fluid (MF) is a novel functional material in optical field, which has the magnetism and the fluidity. It is widely used to measure magnetic field [6]. X Bai et al. proposed that MF-coated single mode fiber structure is inserted in the fiber ring laser cavity, which acts as a bandpass filter and the magnetic field sensing component simultaneously [7]. Zhao Yong et al. proposed various methods of magnetic field measurement based on magnetic fluid. The MF-filled high-birefringence photonic crystal fiber, the MF-filled photonic crystal cavity and MF-coated photonic crystal fiber taper were used as magnetic field sensing elements [8-11].

In this paper, we present a novel BPCF which is filled with the MF into the transverse air-holes symmetrically. The refractive index of MF is sensitive to external magnetic field, so the properties of the BPCF can be tuned by external magnetic field. We have simulated and analyzed the tunable properties of the BPCF by the full-vector finite element method when external magnetic field is applied. In addition, we have thoroughly investigated the relationships among the effective refractive index, normalized birefringence parameter B and polarization beat length L_B on magnetic field.

2. Theoretical model

The characteristics of the birefringent PCF are theoretically analyzed using full-vector finite-element method (FEM). The formulation of the FEM is based on the Maxwell equation. It reads [12]

$$\nabla\left[\frac{1}{\varepsilon_r}\nabla\times h(r)\right]=k_0^2\mu_r h(r) \tag{1}$$

Where ε_r, μ_r respectively are the dielectric constant and the magnetic permeability of medium. $h(r) = He^{-\gamma z}$ is magnetic field. $k_0 = 2\pi/\lambda$ is the wave number in the vacuum. λ is the wavelength. H is the field distribution on the transverse plane. γ is the complex propagation constant which has relation with the attenuation constant α and the effective index n_{eff}.

$$\gamma = \alpha + jk_0 n_{\mathrm{eff}} \tag{2}$$

By applying the variational finite element procedure, Eq. (1) yields the algebraic problem

$$\left([P] - \left(\frac{\gamma}{k_0}\right)[Q]\right)\{H\} = 0 \tag{3}$$

Where the eigenvector $\{H\}$ is the discretized magnetic field vector distribution of the mode. The efficient solutions of Eq.(3) are obtained using high-performance algebraic solvers when the matrices $[P]$ and $[Q]$ are sparse and symmetric. In order to enclose the computational domain without affecting the numerical solution, anisotropic Perfectly Matched Layers (PML) is placed before the outer boundary. This formulation is able to deal with anisotropic material both in terms of dielectric permittivity and magnetic permeability, allowing anisotropic PML to be directly implemented.

3. Simulations and analysis

Fig. 1 shows the structures of BPCF. The cross-sectional of PCF contains a pure silica core surrounded with four hexagons of air holes characterized by a diameter d and the hole to hole spacing Λ of 1.8μm and 2μm respectively. The air holes in the middle line were filled with MF. The refractive index of substrate n_{si} =1.4566.

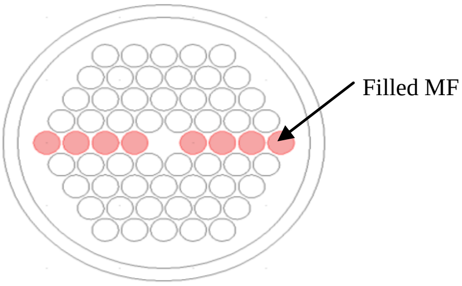
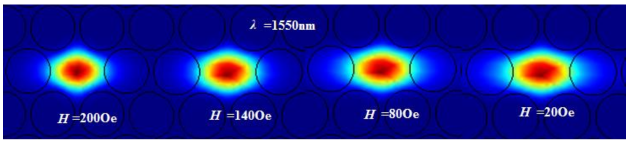


Fig. 1. The cross section of the birefringent PCF

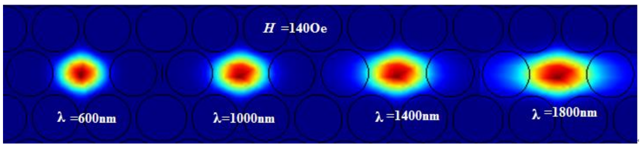
In order to make the guiding mechanism is governed by the modified TIR, the average index of the solid-core must be higher than that of the cladding with periodic air-holes. The water-based Fe_3O_4 MF with concentration of 1.2 g/ml was selected as filling material, and the filling length was 2cm. When H increased from 0Oe to 300 Oe, the corresponding refractive index of the MF n_{MF} decreased from 1.44714 to 1.43318.

3.1. Mode field distributions

When incident wavelength λ=1550nm and duty ratio d/Λ=0.9, the mode field distributions of the MF-filled BPCF on different magnetic field H (H=20Oe, 80Oe, 140Oe and 200Oe respectively) are shown in Fig. 2. It can be seen that the mode field distributions can be tuned with the applied magnetic field H and the wavelength λ. That is to say the birefringence of the MF-filled PCF are sensitive to external magnetic field and the wavelength. The birefringence of the PCF is lower with the increasing of H, but the birefringence of the PCF is higher with the increasing of λ. The reason is that the effective refractive index of cladding mode is increasing with the decreasing of H or the increasing of λ, which leads to the birefringence of the PCF higher.



(a) Under different magnetic field H when λ=1550nm



(b) Under different wavelength λ when H=140Oe

Fig. 2. The mode field distributions of the birefringent PCF filled MF with d/Λ = 0.9

3.2. Polarization properties

Polarization properties can be characterized by two important parameters, and they are phase birefringence B and polarization beat length L_{B}. These two parameters were defined as [13]

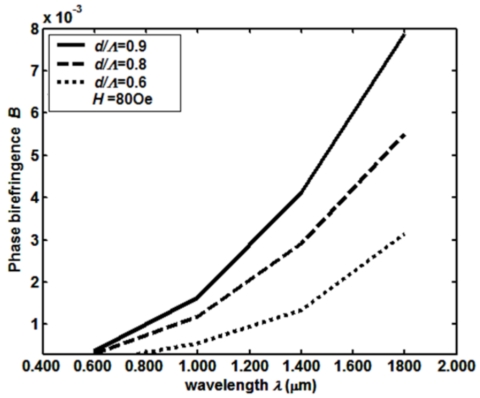
$$B = n_y - n_x = \frac{\lambda}{2\pi}\left(\beta_y - \beta_x\right) \tag{4}$$

$$L_B = \frac{\lambda}{n_x - n_y} \tag{5}$$

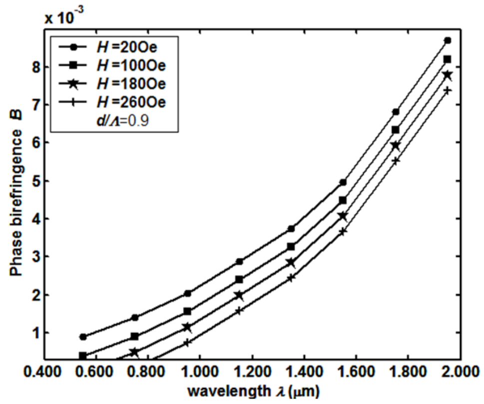
Where β_{x} and β_{y} are the two orthogonal polarization mode propagation constants, and n_{x} and n_{y} are the effective refractive indexes of orthogonal polarization mode.

The n_{x} and n_{y} can be calculated by full-vector finite-element method. The numerical analysis results show that the polarization characteristics of the BPCF filled MF are changing with applied magnetic fields and the d/Λ of the PCF. Fig. 3 (a) shows the phase birefringence B of the birefringent PCF filled MF with different d/Λ when the wavelengths between 400nm and 2000nm. Fig. 3 (b) shows the phase birefringence *B* of the BPCF filled MF when the wavelengths between 400nm and 2000nm on different *H*.

From the Fig. 3, we can see the followings. Firstly, the phase birefringence *B* increases linearly with the increasing of wavelength. The reason is that the optical field were converged in the center when the wavelength is shorter, and the air holes of cladding have little effect on optical field. With the wavelength increasing, more of the optical field were distributed in the cladding, and then the birefringence effect is obviously enhanced. Secondly, the phase birefringence *B* enhances with the increasing of duty ratio d/Λ, and the larger the duty ratio is, the faster the phase birefringence *B* changes with wavelengths. The phase birefringence *B* is independent of geometric parameters of PCF at short-wave, the reason is that mode field is confined to the core. But the phase birefringence *B* is dependent on geometric parameters of PCF at long-wave, the reason is that mode field penetrates into the cladding holes region. Finally, the phase birefringence *B* decreases with the increasing of magnetic field when λ is fixed, while the speed of decreasing becomes slower when the air-holes become smaller. Looking at the three phase birefringence *B* curves shown in Fig. 4, it is possible to notice the phase birefringence *B* with larger d/Λ is more sensitive to magnetic field. It was found that the *B* decreases from 0.005575 to 0.004472 when d/Λ=0.9, the *B* decreases from 0.003851 to 0.003291when d/Λ=0.8, the *B* decreases from 0.001866 to 0.001663 when d/Λ=0.6, while the magnetic field *H* always changes from 20Oe to 300Oe.



(a)With different d/Λ when H=80Oe



(b) Under different magnetic field *H* when $d/\Lambda=0.9$

Fig. 3. The phase birefringence B of the birefringent PCF filled MF vs. wavelengths λ

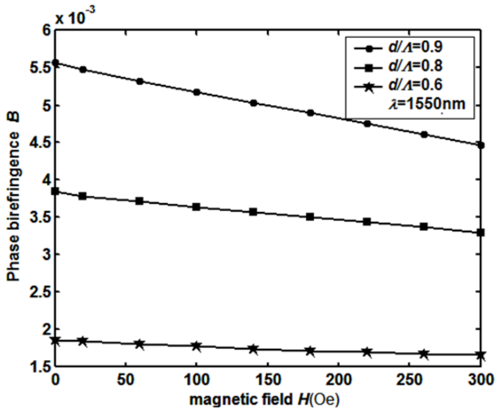
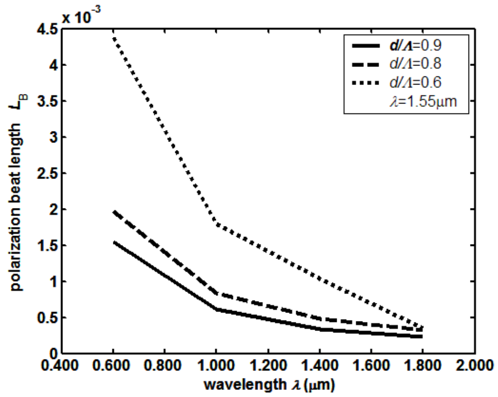
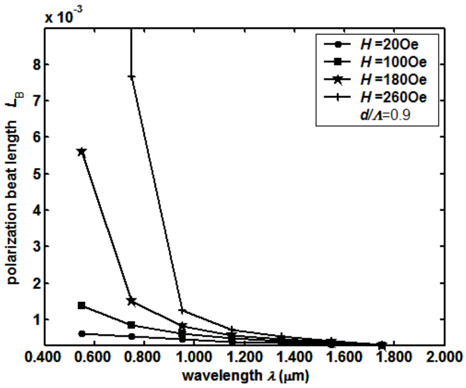


Fig. 4. The phase birefringence B of the PCF filled MF with different duty ratio vs. magnetic field

Fig. 5 shows that the changing of beat length L_B with the wavelength is opposite to the changing of the *B* with wavelength. Fig. 6 shows that the changing of beat length L_B with the magnetic field *H* is opposite to the changing of the *B* with *H*.



(a) With different d/Λ when H=80Oe



(b) Under different magnetic field *H* when $d/\Lambda=0.9$

Fig. 5. The beat length L_B of the PCF filled MF vs. wavelengths λ

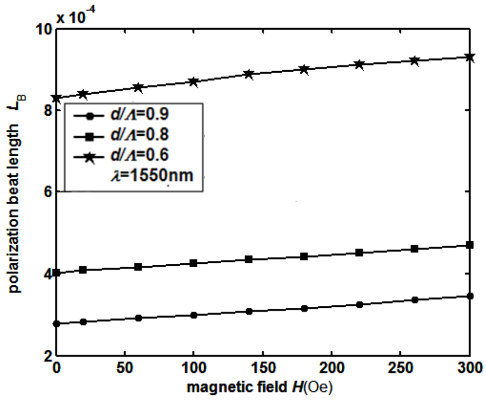


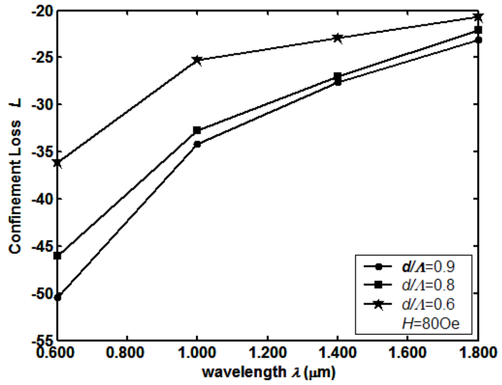
Fig. 6. The beat length L_B of the PCF filled MF with different duty ratio vs. magnetic field

3.3. Confinement loss

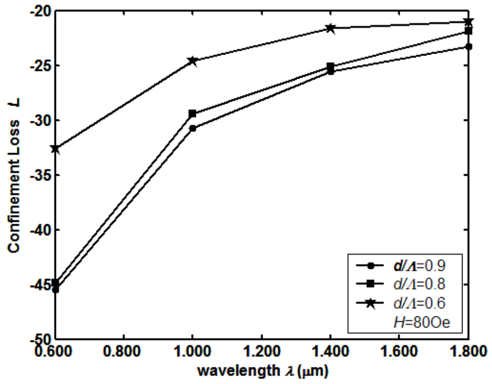
The confinement loss L defined as [14]

$$L = \lg 8.868\,\mathrm{Im}\left(\frac{2\pi}{\lambda} n_{\mathrm{eff}}\right) \tag{6}$$

Where Im represents imaginary part. Fig. 7 shows the confinement loss L of the birefringent PCF filled MF with different d/Λ when the wavelengths between 600nm and 1800nm.



(a) x-direction



(b) y-direction

Fig. 7. The confinement loss L of the birefringent PCF filled MF with different duty ratio vs. wavelengths λ

It can be seen that the confinement loss L increases with the increasing of wavelength, and the L of x direction is greater than that of y direction. The reason is that the air holes of x direction were filled with MF, which leads to the ability of limiting light enhancing. In addition, the L of the PCF with larger d/Λ is lower, which reveals that the limiting light ability of larger air holes is better than that of small air holes. Fig. 8 shows the confinement loss L of the BPCF filled MF with d/Λ=0.9 when the magnetic field changes from 20Oe to 300Oe. It can be seen that the confinement loss L decreases with the increasing of magnetic field. The reason is that the n_{MF} decreases with the increasing of magnetic field, and then the n_{eff} of cladding decreases. The larger the difference between n_{eff} and n_{co}, the stronger the ability of limiting light enhances. As a result, the confinement loss L is lower.

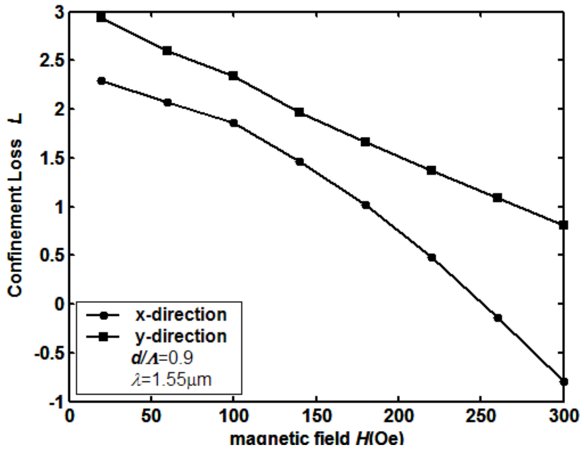


Fig. 8. The confinement loss L of the birefringent PCF filled MF vs. magnetic field

4. Conclusion

A novel BPCF which is symmetrically filled with MF into the transverse air-holes was presented firstly. The magnetically induced tuning properties of the BPCF filled MF were simulated and analyzed by the full-vector finite element method with a perfectly matched layer. Based on these theoretical, we established the simulation model of BPCF filled MF that contains a pure silica core surrounded with four hexagons of air holes. The diameter of air hole d is 1.8μm, 1.6μm, 1.2μm respectively and the hole to hole spacing Λ is 2μm. The mode field distributions, polarization properties and the confinement loss of the BPCF filled MF were figured out and simulated. The results show that the properties of the BPCF filled MF can be tuned by adjusting the magnetic field and d/Λ. The phase birefringence B decreases with the increasing of magnetic field H under the condition of the same duty ratio d/Λ and the B increases with the increasing of duty ratio d/Λ under the condition of the same magnetic field H. When the wavelength λ=1550nm, the duty ratio d/Λ=0.9, the phase birefringence B decreases from 0.005575 to 0.004472 when the H changes from 20Oe to 300Oe. The birefringence effect is ten times higher than the general fiber and there is a fairly good linearity, but its tunable sensitivity is not very high. In order to obtain better performance of the birefringent PCF filled MF, we need to further optimize the structure parameters of PCF, and to improve the sensitivity of the n_{MF} with the change of magnetic field H.

Acknowledgments

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