Equilateral pentagon polarization maintaining photonic crystal fibre with low nonlinearity*

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A new pentagon polarization maintaining photonic crystal fibre with low nonlinearity is introduced. The full vector finite element method was used to investigate the distribution and the effective area of modal field, the nonlinear properties, the effective indices of two orthogonal polarization modes and the birefringence of the new PM-PCF effectively. It is found that the birefringence of the new polarization maintaining photonic crystal fibre can easily achieve the order of 10^{-4}, and it can obtain higher birefringence, larger effectively mode-field area and lower nonlinearity than traditional hexagonal polarization maintaining photonic crystal fibre with the same hole pitch, same hole diameter, and same ring number. It is important for sensing and communication applications, especially has potential application for fibre optical gyroscope.

Keywords: photonic crystal fibres, fibre optical gyroscope, birefringence, nonlinearity

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1. Introduction

Photonic crystal fibres (PCFs), also known as 'holey fibres', are micro-structured fibres,[1] where arrays of holes run along the waveguide length of the fibres.[2] The PCFs have attracted significant attention recently because of their unusual properties,[3] which are strongly dependent on their geometrical parameters[4] and their flexible structures. We can provide a wide degree of freedom for PCFs by changing the geometric characteristics of the cross section of fibres. The PCFs can be made birefringent by having different air hole diameters along the two orthogonal axes[3,5] or by asymmetric core design.[6,7] In addition, the core of the optical power density can be reduced by enlarging the transmission mode area of optical fibre, thus the nonlinear effects of fibre can be reduced effectively.[8] In other words, PCFs can be made low nonlinearity by having effectively large mode-field area. The arrangement and size of air holes of PCFs have a great control freedom, thus we can design various characteristics of PCFs according to different demand.[9] The design of the micro-structure of the PCFs has become a hot research field recently.[10,11] The development and application of PCFs have provided new fibres for fibre optical gyroscopes (FOG). Compared with normal optical fibre, PCFs have characteristics of low bending loss, lower sensitivity of temperature, stress and flexibility design degree. The development of PCFs and applications provides a broad prospect of research for the FOG. The PCFs used in FOG is much more superior to the traditional optical fibre in decreasing FOG noise, size and thermal sensitivity and increasing the precision and stability.

In this paper, a new pentagon polarization maintaining photonic crystal fibre (PM-PCF) with low nonlinearity is proposed, which shows birefringence when the size of several holes near the core is enlarged. The distribution and the effective area of the modal field, the nonlinear properties, the effective indices of two orthogonal polarization modes and the birefringence of the new PCF are analysed by using a full-vector finite element method (FEM). Our analyses show that the birefringence of the new PM-PCF can easily achieve the order of 10^{-4} and it can obtain the effectively large modal field area and low nonlinearity, which has potential application for FOG.

2. Basic theory

At present, the modal solution approach based on the FEM is more flexible than most approaches as it matches well to the complex structure of PCFs.[6]

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Considering the Maxwell's equation for a lossless optical guide, we obtain a two-dimensional wave equation for the FEM analysis as

$$\nabla \times ([p]\nabla \times \boldsymbol{\Psi}) - k_0^2[q]\boldsymbol{\Psi} = 0, \tag{1}$$

if $\boldsymbol{\Psi} = \boldsymbol{E}$, $[p] = [\mu_r]^{-1}$ and $[q] = [\varepsilon_r]$, on the other hand, if $\boldsymbol{\Psi} = \boldsymbol{H}$, then $[p] = [\mu_r]$ and $[q] = [\varepsilon_r]^{-1}$. In Eq. (1), $\boldsymbol{H}$ is the full-vectorial magnetic field, $\boldsymbol{E}$ is the full-vectorial electric field, ε and μ are the permittivity and permeability, respectively of the waveguide, k_0 is the free space wave-number.

The computing function F to Eq. (1) can be expressed as:

$$F = \iint_{\Omega} (\boldsymbol{\nabla} \times \boldsymbol{\Psi})^* \{[p]\boldsymbol{\nabla} \times \boldsymbol{\Psi}\} \mathrm{d}\Omega - k_0^2 \iint_{\Omega} \boldsymbol{\Psi}^* \cdot \boldsymbol{\Psi} \mathrm{d}\Omega, \tag{2}$$

here Ω is the whole solution domain.

Considering the application of the full-vector FEM, we should divide the fibre cross section into a number of curvilinear hybrid elements. In the FEM, the intricate cross section of the photonic crystal fibres can be accurately represented by using many triangles of different shapes and sizes.[3]

Then we can obtain the eigenvalue equation:

$$[K]\{\boldsymbol{\Psi}\}^T = k_0^2 n_{\mathrm{eff}}^2 [M]\{\boldsymbol{\Psi}\}, \tag{3}$$

where $[K]$ and $[M]$ are the finite element matrices, n_{eff} is the effective index. For each finite element, $[K]$ and $[M]$ can be expressed as[7]

$$[K] = -\int_{\Omega} A \frac{\partial\{N\}^{\mathrm{T}}}{\partial x}\frac{\partial\{N\}}{\partial x}\mathrm{d}x\mathrm{d}y - \int_{\Omega} B \frac{\partial\{N\}^{\mathrm{T}}}{\partial x}\frac{\partial\{N\}}{\partial x}\mathrm{d}x\mathrm{d}y + \int_{\Omega} C k_0^2 \{N\}^{\mathrm{T}}\{N\}\mathrm{d}x\mathrm{d}y, \tag{4}$$

$$[M] = \int_{\Omega} D k_0^2 \{N\}^{\mathrm{T}}\{N\}\mathrm{d}x\mathrm{d}y, \tag{5}$$

where $\{N\}$ is a row matrix standing for a complete set of base functions and $\{\}^{\mathrm{T}}$ represents a transposed matrix.

We can obtain the propagation characteristics of three-dimensional optical waveguide by solving Eq. (3).

3. Physical model

In order to obtain a large modal area, we can design fibres with small air-holes and large hole-to-hole distances. Furthermore, PM-PCF could be realized by changing the geometric characteristics of the cross section.[12] The fabrication of PM-PCF can use two different air hole diameters along two orthogonal axis near the core region, which provides effective index difference between two orthogonal polarization modes.[13] To date, most structures of PCF are hexagonal, named as the hexagonal PCF (H-PCF), in this fibre the air holes are arranged in the equilateral triangular lattice with six holes in the first ring surrounding the cores. The arrangement or amount of air holes has great impact on the fabrication of PCF. The PCF with less air holes or bigger hole dimension can be more easily fabricated. In this paper, based on the structure of Q-PCF which was proposed in our recent work,[14] we proposed a new PM-PCF with low nonlinearity. The low nonlinearity and large modal area were obtained by wiping off the first ring of Q-PCF and changing the size of the air holes, here we named it equilateral pentagon PCF, which is shown in Fig. 1(a). The birefringence was obtained by enlarging three air holes in the first ring of the equilateral pentagon PCF, here we named it equilateral pentagon PM-PCF. The structure of the equilateral pentagon PM-PCF is shown in Fig. 1(b), in which the smaller air hole diameter $d_1 = 2.5$ μm, larger air hole diameter $d_2 = 5$ μm, and the hole pitch $\Lambda = 5$ μm.

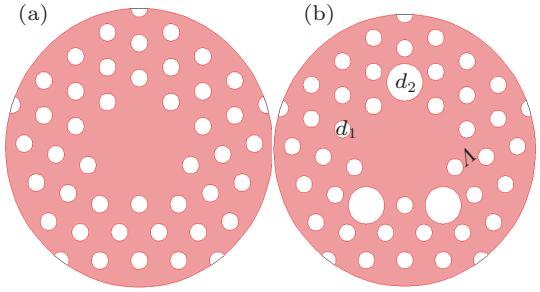


Fig. 1. (colour online) Structures of (a) equilateral pentagon PCF and (b) equilateral pentagon PM-PCF.

4. Results and discussion

4.1. The distribution and the effective area of modal field

When the hole pitch $\Lambda = 5$ μm, the hole diameter $d_1 = 2.5$ μm and $d_2 = 5$ μm, we obtained modal field profiles of x-polarization mode and y-polarization

mode of the equilateral pentagon PM-PCF at 1550 nm respectively, which are shown in Fig. 2.

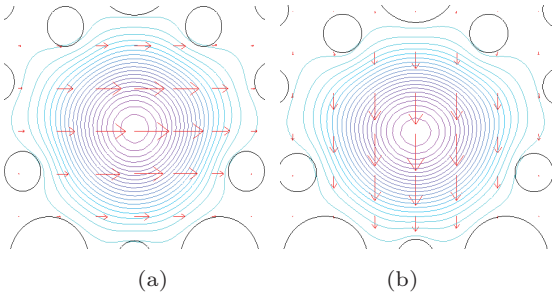


Fig. 2. (colour online) Modal field profiles of the equilateral pentagon PM-PCF at 1550 nm: (a) x-polarization mode; (b) y-polarization mode.

The field can penetrate the lattice near the center of the fibre, but it dies out after a few holes. It can be observed that the modal field of this fibre can be well restricted. The x-polarization mode possesses the characters of TE-mode, whose effective index is slightly higher than that of y-polarization mode. It also can be observed that x-polarization modal field expands larger than that of y polarization at the same wavelength.

Using finite element method, we can calculate the modal effective area $A_{\text{eff(PCF)}}$ by using the following equation:[15]

$$A_{\text{eff(PCF)}} = \frac{[\iint |E(x,y)|^2 \mathrm{d}x\mathrm{d}y]^2}{\iint |E(x,y)|^4 \mathrm{d}x\mathrm{d}y}. \tag{6}$$

When the hole pitch $\Lambda = 5$ μm, the hole diameter $d_1 = 2.5$ μm and $d_2 = 5$ μm, the effective mode-field area of the new PM-PCF and traditional H-PM-PCF curves corresponding to wavelength λ were shown in Fig. 3. It was found that effective mode-field area increases with the increase of wavelength and the value of the new PM-PCF is higher than that of H-PM-PCF at the same wavelength. At the wavelength of 1550 nm,

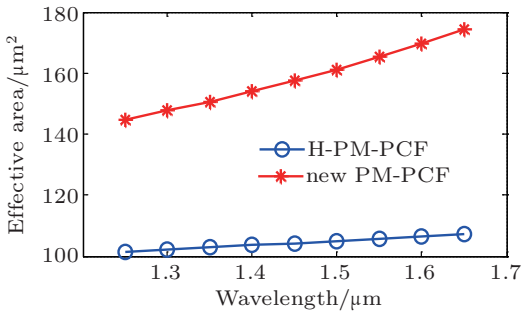


Fig. 3. (colour online) The effective mode-field area curves corresponding wavelength λ.

the effective mode-field area of the new PM-PCF can achieve 165.2402 μm^2.

4.2. The nonlinear properties

Using the finite element method, we can calculate the nonlinear coefficient γ_{PCF} of the PCF by using the following equation:[16]

$$\gamma_{\text{PCF}} = \frac{2\pi n_2}{\lambda A_{\text{eff(PCF)}}}, \tag{7}$$

where $n_2 = 3.0\times10^{-20}$ m^2·W^{-1} is the nonlinear index of silica, $A_{\text{eff(PCF)}}$ is the modal effective area, and λ is the operating wavelength.

Using formula (7) we can easily gain nonlinear properties of the new PM-PCF and traditional H-PM-PCF. When the hole pitch $\Lambda = 5$ μm, the hole diameter $d_1 = 2.5$ μm and $d_2 = 5$ μm, the nonlinear coefficient γ_{PCF} curves of these two fibres corresponding to wavelength λ were shown in Fig. 4.

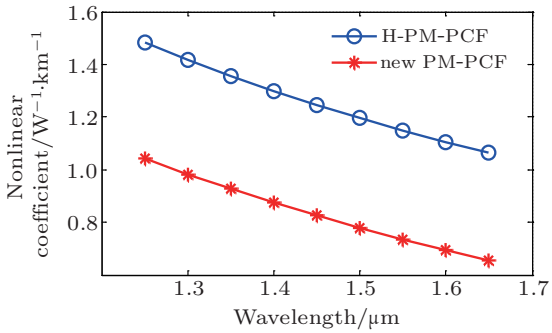


Fig. 4. (colour online) The nonlinearity curves corresponding to wavelength λ.

It could be found that nonlinearity decreases with the increase of wavelength and the nonlinear coefficient value of the new PM-PCF is lower than that of H-PM-PCF at the same wavelength. At the wavelength of 1550 nm, the nonlinearity of the new PCF can achieve about 0.736 W^{-1}·km^{-1}.

4.3. The modal effective index

The variation of the effective indices of two orthogonal polarization modes, are shown in Fig. 5, by a solid line and a dashed line respectively. It can be shown that both effective index values reduce monotonically with the increase of the operating wavelength λ, effective index values of x-polarization modes are higher than that of y-polarization modes at the same wavelength.

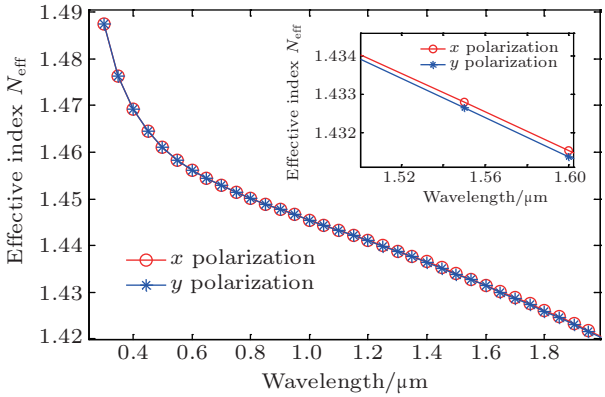


Fig. 5. (colour online) The variation of effective index with operating wavelength λ.

4.4. The birefringent characteristics

The PCFs are usually fabricated from a single material (fused silica). Therefore, the birefringence of the PCFs attributed mainly to geometric anisotropy.[16] The degree of modal birefringence B of the PCF is defined by the difference between the real parts of $n_{\rm eff}(x)$ and $n_{\rm eff}(y)$:[6,17,18]

$$B = n_{\rm eff}(x) - n_{\rm eff}(y), \tag{8}$$

where $n_{\rm eff}(x)$ and $n_{\rm eff}(y)$ are effective indices of x-polarization mode and y-polarization mode, respectively.

When the hole pitch $\Lambda = 5$ μm, the hole diameter $d_1 = 2.5$ μm and $d_2 = 5$ μm, the modal birefringence B as functions of the wavelength for the new PM-PCF and traditional H-PM-PCF was shown in Fig. 6. From Fig. 6 we can see that the modal birefringence B of the new PM-PCF is higher than that of traditional PM-PCF, and the value is up to 1.75×10^{-4} for the equilateral pentagon PM-PCF at the wavelength $\lambda = 1.55$ μm. Although it is not very high relative to many known microstructure fibres, the modal birefringence B is high enough for many applications,

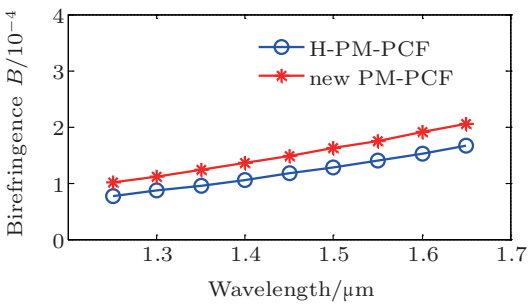


Fig. 6. (colour online) The variation of birefringence with operating wavelength λ.

e.g., FOG. In addition, it also can be concluded that the modal birefringence B of PCFs are mainly determined by the asymmetric microstructure near the core and could be obtained by increasing the asymmetric degree of the air-holes situated in the inner one or two rings.[17]

5. Conclusion

A novel pentagon PM-PCF with low nonlinearity was successfully modeled and analysed by using a full-vector FEM. The distribution and the effective area of modal field, the nonlinear properties, the effective indices of two orthogonal polarization modes and the birefringence of the new PCF were simulated and analysed. The new PM-PCF can obtain higher birefringence, larger effectively mode-field area, and lower nonlinearity than traditional H-PM-PCF with the same core diameter, same hole diameter and same ring number. From numerical results it was found that the birefringence of the new polarization maintaining photonic crystal fibre can easily achieve the order of 10^{-4} and the modal birefringence B is up to 1.75×10^{-4} at the wavelength $\lambda = 1.55$ μm, which is high enough for application of FOG. In addition, it can obtain the effectively large mode-field area and low nonlinearity. At the wavelength $\lambda = 1.55$ μm, the effective area of pentagon PM-PCF is up to 165.2402 μm^2 and the nonlinearity of pentagon PM-PCF is 0.736 W^{-1}·km^{-1}. This new PCF is important for sensing and communication applications, especially has potential application for FOG.

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