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Propagation properties of an index guiding high birefringence fibre*

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Based on a full-vector model, a theoretical study on a kind of high birefringence photonic crystal fibre is presented. Due to introducing air holes of two different sizes into the cladding, twofold rotational symmetry was obtained. We demonstrate the possibility of achieving high birefringence that is at least one order of magnitude higher than that of conventional polarization-maintaining fibres. The dependences of modal birefringence, modal field and differential group delay on the structure parameter of the fibres are discussed in detail. The numerical results are in very good agreement with the experimental results in the literature.

Keywords: photonic crystal fibre, birefringence, beat length, polarization mode dispersion
PACC: 4281, 4281D, 4281F

1. Introduction

Conventional single-mode optical fibres support two orthogonal polarization modes. As these polarization modes are degenerate, fields in these fibres are easily converted from one polarization mode to the other if there is a slight disturbance or perturbation. It is difficult to maintain the polarization state of the guided mode along their length. For sophisticated systems like coherent communication systems, sensory systems based on interferometric principles, or systems utilizing polarization-dependent components, these changes lead to signal fading and noise. High birefringence fibres, into which strong birefringence is deliberately introduced during the fibre fabrication, are much more resistant to such phenomena.[1,2] The required birefringence can be achieved by using non-circular core or cladding, or using the birefringent material to form the fibre.[3] Current modal birefringence is up to 5×10^{-4} for polarization maintaining fibre (PMF) such as bow-tie or panda fibres.

Since the first working example of so-called 'endless single-mode photonic crystal fibre' was reported,[4] intensive research has been generated by the development of photonic crystal fibres (PCFs). PCFs exhibit many unusual properties such as an endlessly single mode,[5] highly tunable dispersion,[6,7] and highly controllable mode effective areas for linear and nonlinear applications,[8,9] and so on. The index-guiding PCFs are characterized by a series of holes running throughout the length of the fibre arranged in a micro-scale structure around a high index core. There is a new possibility to create high birefringence in the index-guiding PCF because its index contrast is higher than that of conventional fibres and the stack-and-draw process allows the formation of the required asymmetric microstructure. So far, various highly birefringent index-guiding PCFs have been presented. Ortigosa-Blanch *et al*[10] reported a birefringent index-guiding PCF with a modal birefringence of 3.7×10^{-3} at a wavelength of 1.54μm. Saitoh and Koshiba[11] reported a polarization-maintaining (PM) index-guiding PCF with a modal birefringence of 1.4×10^{-3}. These high birefringence PCFs (HB PCFs) have potential for a number of applications such as high bit rate communication system, PM fibres loops for gyroscopes and so on.

Based on our previous work,[12,13] the propagation properties of a kind of HB PCF with two different air holes in its cladding were investigated in detail. We

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have shown a number of important quantities such as modal field, modal birefringence, polarization mode dispersion. Compared with the elliptical core PCF, this HB PCF exhibits a kind of more efficient structure to achieve the high birefringence. Furthermore, we focus on the dependence of the properties of HB PCFs on its structure parameter.

2. The full vector model

The cross-section of a HB PCF is depicted in Fig.1. It is a silica PCF that has an array of air holes running along its length. The air holes are arranged in a triangular lattice and the core is formed by the absence of one air hole in the centre of the fibre. Two different air holes are arranged in the cladding, all of them are spaced by the same pitch Λ; and small holes are arranged along the x axis. The refractive index of the silica region is 1.45. The sizes of big holes and small holes are characterized by the diameter d and d_s, respectively.

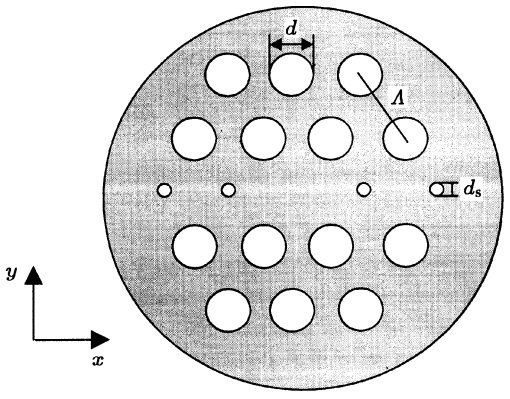


Fig.1. Cross-section of the high birefringence PCF.

To model the propagation properties, especially modal birefringence and polarization mode dispersion of the fibre as shown in Fig.1, the scalar approximation becomes inadequate. Thus a full vector model has been employed to accurately predict sensitive properties.

Assuming the PCF to be lossless and uniform in the propagation (z) direction, we focus on the transverse mode field distribution $e_x(x,y)$ and $e_y(x,y)$, which satisfy a pair of coupled wave equations:[14]

$$\begin{aligned}&\left(\nabla_t^2-\beta^2+k^2n^2\right)e_x\\&=-\frac{\partial}{\partial x}\left(e_x\frac{\partial\ln n^2}{\partial x}+e_y\frac{\partial\ln n^2}{\partial y}\right),\\&\left(\nabla_t^2-\beta^2+k^2n^2\right)e_y\\&=-\frac{\partial}{\partial y}\left(e_x\frac{\partial\ln n^2}{\partial x}+e_y\frac{\partial\ln n^2}{\partial y}\right),\end{aligned}\tag{1}$$

where $k=2\pi/\lambda$ is the wave number, $n=n(x,y)$ is the transverse refractive index profile, and β is the propagation constant of the corresponding mode.

To solve the wave equation above, we employ a superlattice to describe the transverse refractive index profile. The PCF is considered as a super cell $(D\times D)$. By introducing the period boundary condition, the superlattice is constructed with a number of cells as shown in Fig.2. This makes a finite structure extend periodically into infinity. Because the modal fields of the guiding mode in the PCF have the characteristics of localization, the localized Hermite–Gaussian functions are used as basis function to decompose the electric field. Thus the vector wave equation is related to the following eigenvalue systems:

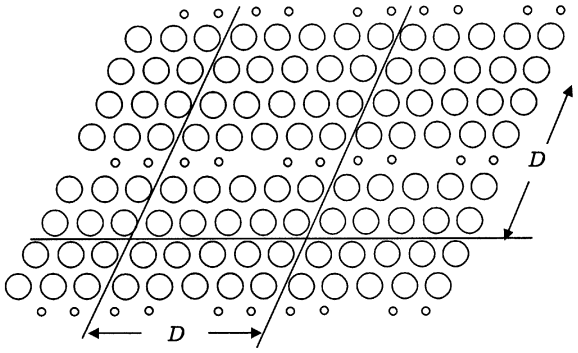


Fig.2. Configuration of the superlattice structure.

$$L\begin{bmatrix}e_x\\e_y\end{bmatrix}\equiv\begin{bmatrix}I^{(1)}_{\rm abcd}+k^2I^{(2)}_{\rm abcd}+I^{(3)x}_{\rm abcd} & I^{(4)x}_{\rm abcd}\\ I^{(4)y}_{\rm abcd} & I^{(1)}_{\rm abcd}+k^2I^{(2)}_{\rm abcd}+I^{(3)y}_{\rm abcd}\end{bmatrix}\begin{bmatrix}e_x\\e_y\end{bmatrix}=\beta^2\begin{bmatrix}e_x\\e_y\end{bmatrix},\tag{2}$$

where $I^{(1)}$,$I^{(2)}$, $I^{(3)}$ and $I^{(4)}$ are overlap integrals of the modal functions, which are defined in our previous work.[12,13] It is a significant advantage that all these integrals can be performed analytically, and the numerical precision and efficiency can be improved greatly, especially when a great number of terms are needed in the expansions.

By solving Eq.(2) at a particular wavelength λ, the modes and the corresponding β of the PCF at λ can be calculated. The transverse modal electric field can be obtained by substituting the eigenvector into the decomposed equation.[12]

3. Modal field

The HB PCF (Fig.1) has a pitch (centre to centre distance between the holes) of Λ=1.96μm, the relative hole diameter d/Λ=0.6 for big holes and d_s/Λ=0.2 for small holes. Using the full vector model developed in the previous section, we obtain the transverse field distribution of two polarized fundamental modes. Because a regular array of two different hole sizes is disposed around a pure silica core, the PCF has a twofold rotational symmetry. Generally, conventional PCFs with a triangle circular hole array have sixfold rational symmetry and the two orthogonal polarized states of the fundamental mode are degenerate. When the polarization degeneracy is removed in twofold symmetry fibres, the polarization modes become nondegenerate and appear as strongly linear polarization, as demonstrated in Fig.3.

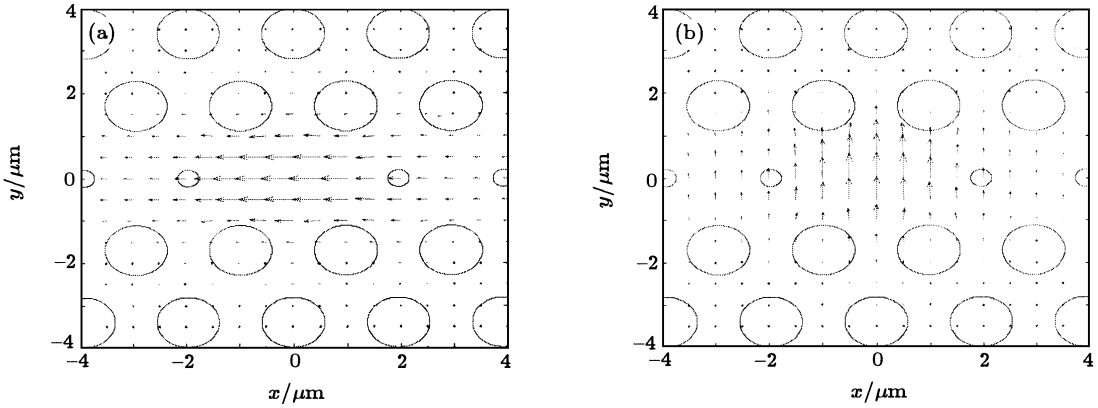


Fig.3. Fundamental mode field for a PCF with Λ=1.96μm, d/Λ=0.6 and d_s/Λ=0.2 at the wavelength 1550nm. (a) x-polarized fundamental mode field vector; (b) y-polarized fundamental mode field vector.

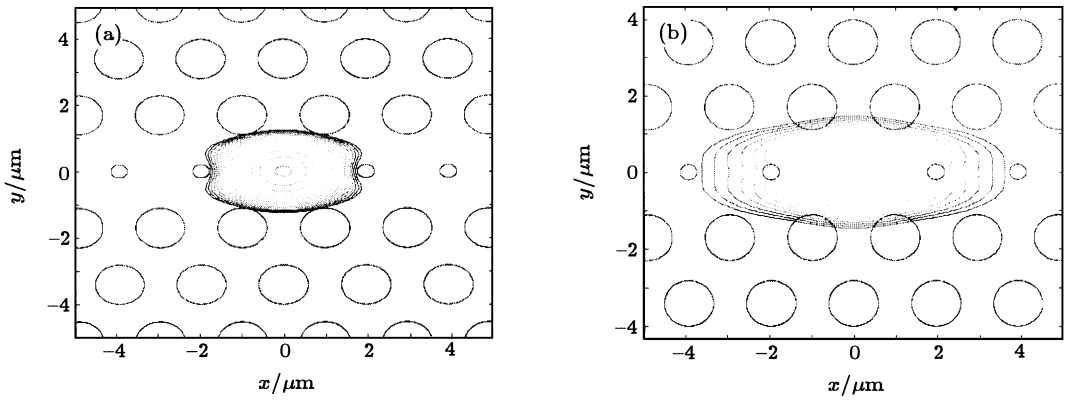


Fig.4. Contour map of x-polarized fundamental mode field intensity for a HB PCF with Λ=1.96μm, d/Λ=0.6 and d_s/Λ=0.2 at wavelength (a) λ=500nm and (b) λ=2000nm. The contour is at 2dB interval.

Figure 4 shows the modal field intensity pattern of x-polarized fundamental mode in the above PCF at the wavelengths λ=500nm and λ=2000nm superimposed on the transverse index profile. Comparing Figs.4(a) and 4(b), we can see that the electric field samples more than just the inner ring of holes at relatively short wavelengths. The modal field intensity pattern shows a mode that is well confined to the core region and elongated in the direction of the small air holes at relatively short wavelength. In that direction, the air-filling fraction is smaller so the fundamental mode sees a higher effective index in the cladding, while the apparent core size is also larger. At longer wavelengths, the field penetrates even further into the periodic cladding region and the magnitude of field extension along the direction of the small air holes is apparently larger than that along the direction of the large air holes. The fundamental mode fields appear

to have nearly elliptical shape. This accords with the experimental result in Ref.[10].

4. Polarization

4.1. Birefringence

Birefringence and beat length are important parameters for HB PCF. Birefringence of the fundamental mode is defined as the effective index difference between the x-polarized fundamental mode and the y-polarized fundamental mode, i.e. $B = \Delta n_{\rm eff} = |n^x_{\rm eff} - n^y_{\rm eff}|$. The corresponding beat length can be expressed as

$$L_{\rm B} = \frac{2\pi}{|\beta_x - \beta_y|} = \lambda/B. \qquad (3)$$

The variation in wavelength and structure parameters such as hole pitch and the relative hole diameter influence the birefringence of the HB PCF. Compared with the conventional triangular lattice PCF, the obvious characteristic of the HB PCF is the introduction of two different air holes into the cladding. The fibres become biaxial and the modal birefringence is improved sharply. Here we concentrate on the effect of the two different holes on modal birefringence.

The modal birefringence B of a fibre with a pitch Λ=1.96μm as a function of wavelength is shown in Fig.5. The magnitude of birefringence can reach 3.7×10^{-3} at wavelength λ=1540nm for a fibre with d/Λ=0.6 and $d_{\rm s}/\Lambda$=0.2, which is at least one order of magnitude higher than that of the conventional polarization maintaining fibre. This numerical result is in very good agreement with the experimental result in Ref.[10].

The modal birefringence of the HB PCF shows very different behaviour from the standard polarization fibres[15] in Fig.5. It must vanish in the scalar regime at short wavelengths. The birefringence increases monotonically with increasing wavelength. The long wavelength behaviour is caused by the fibre biaxial feature.

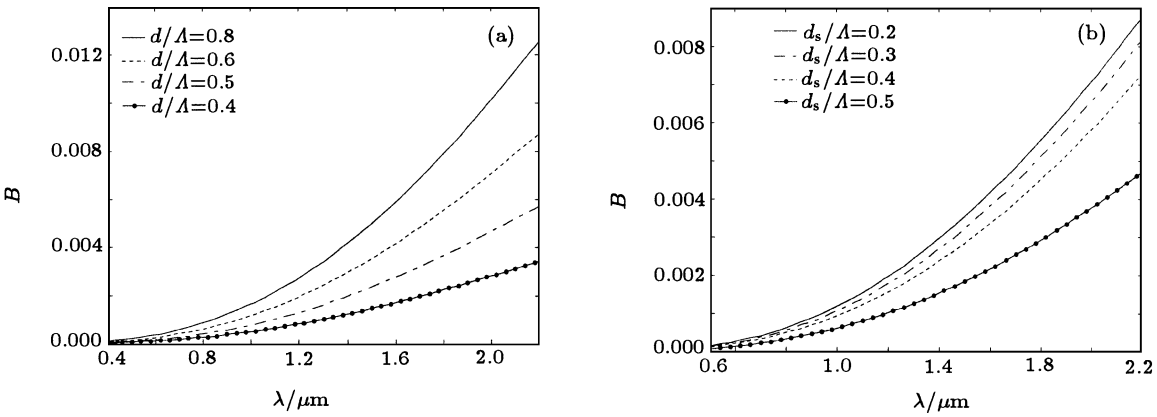


Fig.5. Birefringence as a function of wavelength for the HB PCFs with Λ=1.96μm and (a) $d_{\rm s}/\Lambda$=0.2 at different large hole diameter and (b) d/Λ=0.6 at different small hole diameter.

The various hole sizes also strongly influence the modal birefringence. The numerical results of the modal birefringence for the PCFs with various hole size are also presented in Fig.5. As expected, the modal birefringence increases with the increase in the ratio of the size of the big hole to the pitch [see Fig.5(a)] and the decrease in the ratio of the size of small hole to the pitch [see Fig.5(b)]. With increasing size of big holes or decreasing size of small holes, the corresponding modal birefringence will increase rapidly. However, increasing birefringence through reducing the size of the small holes may be impractical because the light confinement property of the fibre is affected when the hole size becomes small. In our simulation, we found that a large portion of light fields extends beyond the first small holes for a small value of $d_{\rm s}/\Lambda$ although a relative high birefringence can be obtained.

4.2. Polarization mode dispersion

The introduction of air holes with two different sizes into the cladding causes the degeneracy of two orthonormal polarization fundamental modes to be removed. The nondegeneracy of two polarized fundamental modes verified by the computed values of effective indices can lead to different group velocities. For pulsed propagation in high birefringence systems, intrinsic birefringence is much higher than the random birefringence caused by the variation in stress and core geometry. Therefore, polarization mode dis-

persion (PMD) is defined as the group time delay difference of two polarized fundamental modes through a metre of fibre, which can be expressed as

$$\tau = \frac{\mathrm{d}(\beta_x - \beta_y)}{\mathrm{d}\omega} = \frac{1}{c}\left[B(\lambda) - \lambda\frac{\mathrm{d}B(\lambda)}{\mathrm{d}\lambda}\right], \qquad (4)$$

where c is light velocity.

The PMD of fibres with a pitch Λ=1.96μm as a function of wavelength is shown in Fig.6. The values of PMD are negative and increase in the negative direction with increase of the wavelength. This behaviour is due to the strong dependence of birefringence on wavelength, which results in the dispersion terms $\lambda \mathrm{d}B(\lambda)/\mathrm{d}\lambda$ that play an important role in PMD. The PMD increases obviously with the increase in the size of big holes or the decrease in the size of small holes. This means that the magnitude of walkoff becomes large enough to reduce the coupling efficiency of two polarization fundamental modes rapidly due to phase matching condition being lost. Light can propagate through this fibre with a certain polarization state. In addition, high birefringence and large PMD offer a possibility to realize polarization-maintaining fibres with high performance.

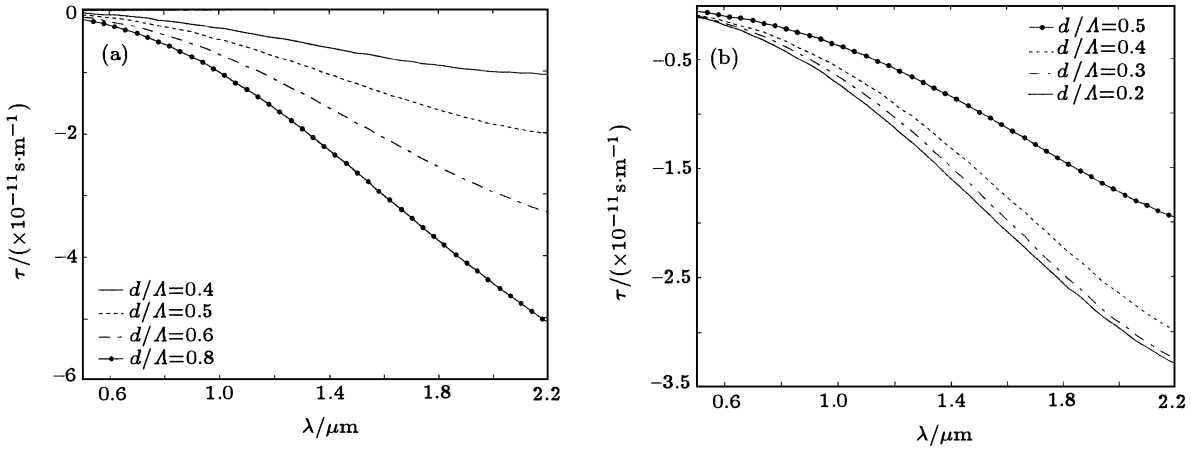


Fig.6. Polarization mode dispersion as a function of wavelength for PCFs with Λ=1.96μm and (a) d_s/Λ=0.2 at different large holes and (b) d/Λ=0.6 at different small holes.

In short, since modal birefringence and PMD are related to the ratio of the size of two different air holes, we can design polarization maintaining fibres with high performance by choosing a suitable ratio of the sizes of the two different air holes. These have potential in a number of applications such as high-bit rate communication systems, polarization-maintaining (PM) pigtailing of photonic devices, and PM fibre loops for gyroscope.

5. Dispersion

The total dispersion coefficient D_t is proportional to the second-order derivative of the modal effective index (or the propagation constant) with respect to λ.

Considerable attention has been devoted to the ability of PCFs to generate novel group velocity dispersion profiles. In Fig.7, it is shown that high birefringence PCF can extend some of these ideas. We show dispersion profiles of the fundamental modes for three fibres which are the conventional PCF and HB PCFs with Λ=1.46μm, d/Λ=0.78, d_s/Λ=0.37 and with Λ=1.96μm, d/Λ=0.6, d_s/Λ=0.2.

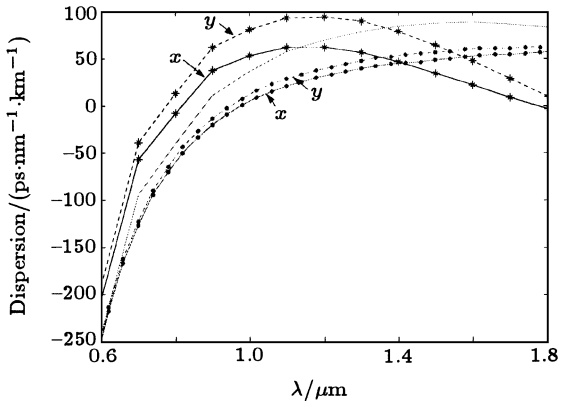


Fig.7. Dispersion of the conventional hexagonal PCF and x- and y-polarized mode of high birefringence PCF. The star line corresponds to HB PCF with Λ=1.46μm, d/Λ=0.78 and d_s/Λ=0.37, the point line is for Λ=1.96μm, d/Λ=0.6 and d_s/Λ=0.2, and the solid line is for the conventional hexagonal PCF with Λ=1.96μm, d/Λ=0.6.

Since the polarization degeneracy of the fundamental mode in HB PCF is removed, the dispersion curves of x-polarized mode and y-polarized mode sep-

arate from each other. The y-polarized mode is located above the x-polarized mode.

Dispersion in HB PCF strongly depends on the structure parameters of fibres such as the pitch and the relative hole diameter. Compared with the conventional PCF, dispersion profiles of HB PCFs change little at short wavelengths. This phenomenon is attributed to the light confinement at short wavelengths so that the modal field can be restrained in the core. However, there are some quite obvious changes at long wavelength. These changes are due to the influence of different air holes in the cladding, because more and more modal field penetrates further into the cladding with the increase in wavelength. More importantly, we can obtain zero dispersion at wavelengths 780 and 815nm for HB PCF with Λ=1.46μm, d/Λ=0.78, d_s/Λ=0.37. This causes zero dispersion to be shifted to the near visible region. There is clearly scope for considerable design exploration.

6. Discussion

Based on the superlattice method, the full vector model is an effective predictive tool allowing us to calculate the modal properties in a much fuller range of holey fibres than the scalar techniques allows. It is an efficient and accurate alternative to the existing technique. This method has been used for analysing the triangular PCF.[12,13] The results accord with the results of other numerical methods[5,16,17] and experiment.[4,5]

In order to demonstrate the efficiency of this kind of structure, we also simulate another kind of HB PCF whose core is formed by three missing holes [Fig.8(a)]; this kind of PCF with the approximate elliptical core can also offer the possibility to obtain high birefringence. Birefringence and PMD for two PCFs as functions of the wavelength are shown in Fig.9. Birefringence increases with the increase in wavelength for both PCFs. On the other hand, the PMD of both PCFs is negative and increases towards the negative direction with the increase in wavelength. However, the magnitudes of birefringence and PMD of the former is much higher than those of the latter at the same wavelength. The numerical results demonstrate that

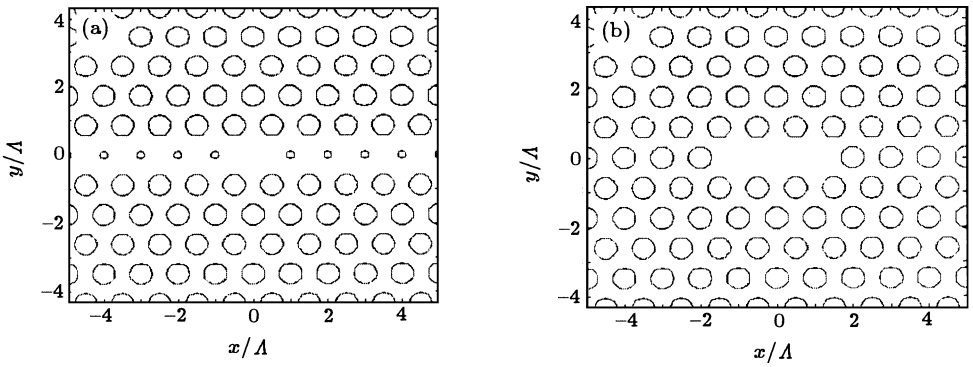


Fig.8. Cross sections of birefringence structure with (a) hexagonal core and the cladding containing holes of different diameters: Λ=1.96μm, d/Λ=0.6, d_s/Λ=0.2 and (b) an approximate elliptical core and uniform hole cladding: Λ=1.96μm, d/Λ=0.6.

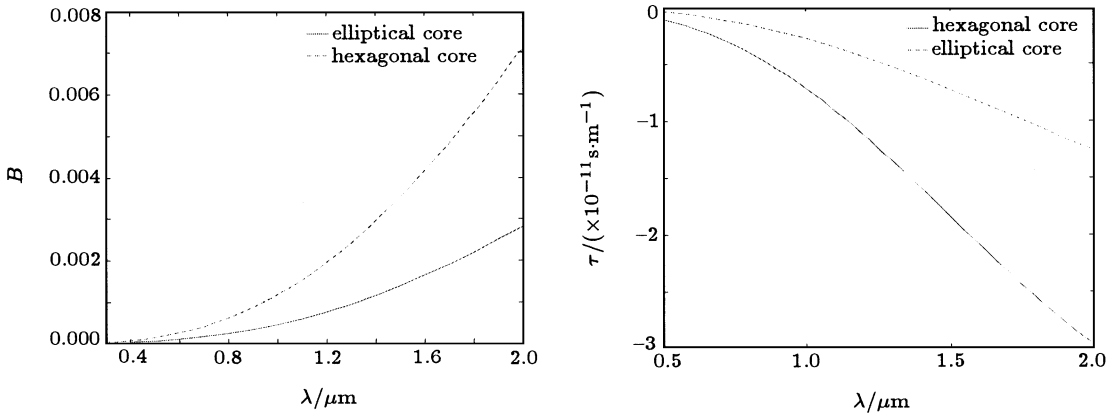


Fig.9. Dependence of modal birefringence (a) and polarization mode dispersion (b) upon wavelength for the structure with approximate elliptical core and hexagonal core.

the HB PCF with two different holes in the cladding is the more effective structure than that with an elliptical core. High birefringence and large walkoff can be obtained by choosing suitable parameters such as hole pitch, the relative hole diameter and so on. This can efficiently restrain the first-order PMD. We can design high performance polarization maintaining fibres that have been known for a long time.

7. Conclusion

We have demonstrated a full vector model based on the superlattice method that is an efficient method for modelling the modal properties of many PCFs. A kind of HB PCF with two different air holes in the cladding has been investigated in detail. The numerical results exhibit that the modal birefringence of this HB PCF is much higher than that of the conventional polarization maintaining fibres and may be further enhanced by increasing the size of big holes and decreasing the size of small holes. The structure of this HB PCF is more efficient in increasing modal birefringence than that of the other with elliptical core. The calculated modal field and birefringence is in very good agreement with experimental results reported previously in the literature. This PCF has a high degree of flexibility, and can be designed to suit a very wide range of applications.

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