Improved high birefringence photonic crystal fibres with dispersion flattened and single mode operation*

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A kind of improved high birefringence photonic crystal fibre (PCF) is proposed in this paper. The characteristics of birefringence, dispersion and leakage loss are studied by the multipole method. Numerical results show that the improved PCF possesses the properties of a flat dispersion and single mode operation. Moreover, with the operating wavelength $\lambda = 1.55$ μm, the modal birefringence increases greatly in comparison with that of the original PCF, and the leakage loss is about 10^4 times smaller than that of the original PCF because the modification gives rise to the strong confinement of guided modes. It is expected that the improved PCF can be used as high birefringence and dispersion flattened fibres.

Keywords: photonic crystal fibres, birefringence, nonlinear optics

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1. Introduction

Optical fibres with silica-air microstructures, called photonic crystal fibre (PCF),[1,2] have attracted a considerable amount of attention in recent years,[3−7] because of their unique properties that are not realized in conventional optical fibres. The PCF possesses numerous unusual properties such as high nonlinearities,[8,9] high birefringence and polarization-maintaining,[10−12] large effective mode area,[13,14] singular dispersion characteristics,[15,16] surface-enhanced Raman effect,[17] and so forth.[18−23] High-performance-polarization-maintaining fibres have an extremely wide range of applications in high-speed optical communication systems, polarization-maintaining of photonic devices, couplers, polarization-maintaining of fibre gyroscope, fibre optic ring and so on. The PCF with a flat dispersion profile, which is essential for wavelength division multiplexing (WDM) systems[24] and supercontinuum (SC) generations,[25] has attracted lots of interests. Many designs have been proposed to achieve broadband flattened dispersion in PCF.[26−28]

In this paper, we propose a kind of improved high birefringence PCF, using the multipole method to study optical properties. Numerical results show that the improved PCF has three crucial properties such as high birefringence, flat dispersion and single mode operation. Furthermore, the leakage loss is about 10^4 times smaller than that of the original PCF.

2. Theory and modeling

Multipole method is a simulation method which is based on the principle of electromagnetic scattering properties for PCF. The method was first proposed by White *et al.*[29] and Kuhlmey *et al.*[30] for the simulation of PCF. The multipole method expresses the electric field components and the magnetic field components in cylindrical coordinate system each as a Bessel function, using boundary conditions to solve the Helmholtz equation. It is suitable for analysing the PCF with circular holes. Another advantage of multipole method is that the output propagation constant is a function of input angular frequency and it can take into account the material dispersion.

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The multipole method can expand the mode field into the form of Bessel function, in the interior of section l air hole, the longitudinal electric field in polar coordinates can be expanded into

$$E_z = \sum_{m=-\infty}^{\infty} a_m^{(l)} \mathrm{J}_m\left(k_\perp^i r_l\right) \exp(\mathrm{i}\, m\phi_l) \exp(\mathrm{i}\, \beta z). \quad (1)$$

In the adjacent medium of the section l air hole, the longitudinal electric field can be expressed as

$$E_z = \sum_{m=-\infty}^{\infty} \left[b_m^{(l)} \mathrm{J}_m\left(k_\perp^e r_l\right) + c_m^{(l)} \mathrm{H}_m^1\left(k_\perp^e r_l\right)\right] \times \exp(\mathrm{i}\, m\phi_l) \exp(\mathrm{i}\, \beta z), \quad (2)$$

where $k_\perp^i = (k_0^2 n_i^2 - \beta^2)^{1/2}$, $k_\perp^e = (k_0^2 n_e^2 - \beta^2)^{1/2}$, the refractive index of air n_i= 1, n_e is the refractive index of silica, $k_0 = 2\pi/\lambda$ is the wave number of free space, and β is the modal propagation constant. Magnetic field component H_z may be expressed as the expression similar to the above expression. We can obtain the expressions of $a_m^{(l)}$, $b_m^{(l)}$ and $c_m^{(l)}$ by the electromagnetic field boundary conditions and further obtain the modal effective refractive index n_{eff} through $\beta = n_{\mathrm{eff}} k_0$.

Figure 1 shows the structures and fundamental mode field distributions of the original and improved PCF, where the hole-pitch $\Lambda = 1.4$ μm and the air hole diameter $d = 0.45$ μm. Original PCF is a kind of birefringence PCF. The purpose of this paper is to improve the original PCF so as to obtain a more optimized property. The improved approach is that with keeping the air hole spacing and the hole diameter of the original PCF unchanged, an extra air hole is inserted between the two certain adjacent air holes. The PCF obtained using this method is called improved PCF.

The mode field distribution corresponds to the fundamental mode when the incident light at the operating wavelength $\lambda = 1.55$ μm propagates in the PCF. In order to optimize the birefringence, dispersion and leakage loss of original PCF, the structure of the improved PCF is proposed in Fig. 1(b). The structure of the original PCF in which three neighbouring air holes are removed from the core is shown in Fig. 1(a). On the one hand, the improved PCF makes the distance between air holes shorter and optimizes the dispersion properties. On the other hand, compared with the original PCF, the index contrast between core and cladding of the improved PCF turns higher, thereby achieving the higher birefringence. In addition, it can be seen clearly that the mode confinement of the improved PCF is stronger than that of the original PCF, which can give rise to higher birefringence and lower leakage loss.

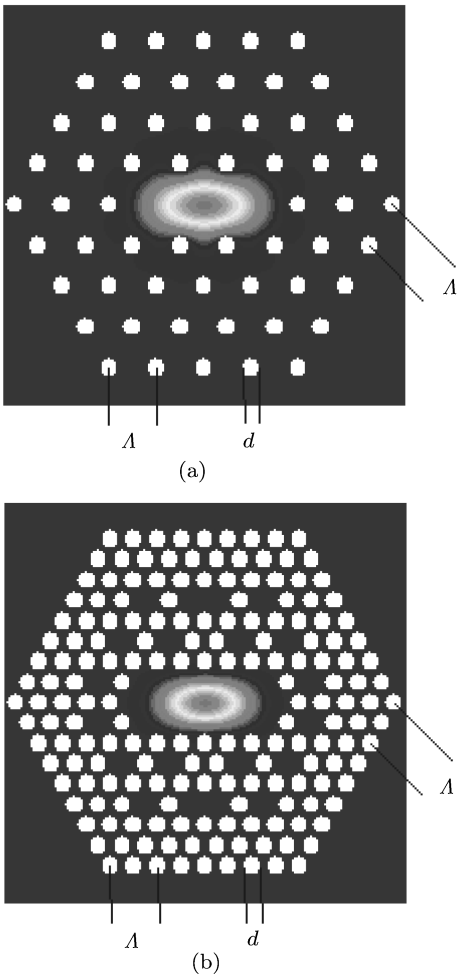


Fig. 1. Cross-sectional structures and fundamental mode field distributions of (a) original PCF and (b) improved PCF.

3. Optical properties of improved PCF

The modal birefringence, chromatic dispersion and leakage loss can be determined according to the following formulations:

$$B = \left|\mathrm{Re}(n_{\mathrm{eff}}^y) - \mathrm{Re}(n_{\mathrm{eff}}^x)\right|, \quad (3)$$

$$D = -\frac{\lambda}{c}\frac{\partial^2 \left|\mathrm{Re}(n_{\mathrm{eff}})\right|}{\partial \lambda^2}, \quad (4)$$

$$L = \frac{20}{\ln 10}\frac{2\pi}{\lambda}\mathrm{Im}\left(n_{\mathrm{eff}}\right) \times 10^6, \quad (5)$$

where n_{eff}^x and n_{eff}^y are the effective refractive indices of fundamental mode in x and y polarization modes, respectively, Re denotes the real part, λ and c are the wavelength and the velocity of light in a vacuum, respectively, Im denotes the imaginary part.

Figure 2 shows the modal birefringences, dispersions and leakage losses of the original and improved PCF, where $\Lambda = 1.4$ μm and $d = 0.45$ μm. By modifying the original PCF, the modal birefringence achieves a greater increase than that of original PCF and the dispersion curve presents a flat dispersion property in the band of wavelength division multiplexing (WDM) of optical communications (from 1.260 μm to 1.675 μm). In order to demonstrate the enhancement of mode confinement in the improved PCF, the leakage losses of the original and the improved PCF are calculated separately. From Fig. 2(c) the leakage loss of the improved PCF is significantly reduced from 2.32×10^3 dB/m to 0.194 dB/m at 1.55 μm compared with that of the original PCF.

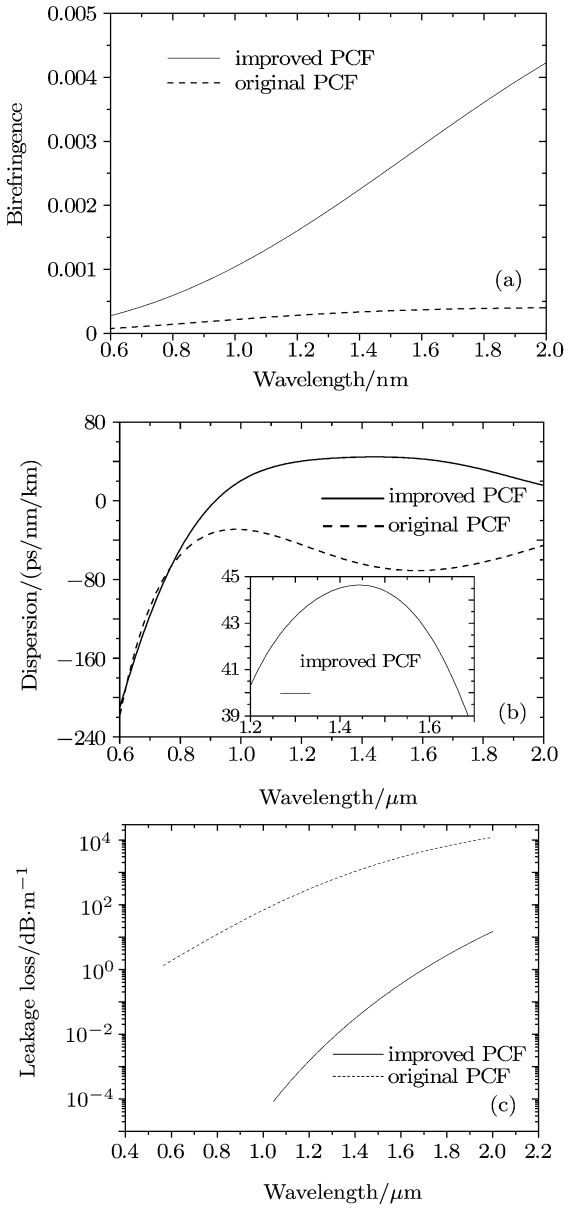


Fig. 2. (a) Birefringences, (b) dispersions and (c) leakage losses of the original and improved PCF.

It is comprehensible that the improved PCF shows properties of higher birefringence and flatter dispersion than those of the original PCF. For the improved PCF, the special structure leads to the light field restricted in the core areas, thereby enhancing the impaction of the clad air holes to light field. Therefore, the birefringence of improved PCF increases. The special structure of the improved PCF is required not only to control the high birefringence and obtain a flat dispersion, but also to increase the index contrast with maintaining the single mode operation. The advantage of the improved PCF is that it possesses all the three crucial properties of optical fibre such as high birefringence, flat dispersion and single mode operation.

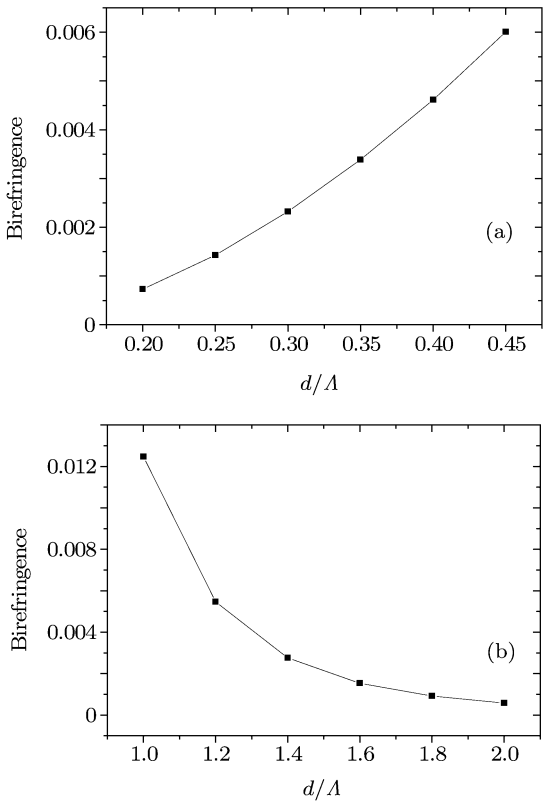


Fig. 3. Birefringences of (a) improved PCF by varying d/Λ from 0.2 to 0.45 when $\Lambda = 1.4$ μm and (b) varying Λ from 1.0 μm to 2.0 μm when $d = 0.45$ μm.

We also investigate the effects of geometric parameters air-filling fraction d/Λ and Λ on the birefringence and dispersion for the improved PCF, where operating wavelength $\lambda = 1.55$ μm. Figure 3(a) shows the birefringence value by varying d/Λ from 0.2 to 0.45 when $\Lambda = 1.4$ μm. The birefringence increases with the increase of d/Λ. Figure 3(b) shows the birefringence value by varying Λ from 1.0 μm to 2.0 μm when $d = 0.45$ μm. The birefringence decreases with the increase of Λ. Therefore, in order to obtain higher

birefringence, we should increase d/Λ or decrease Λ with keeping d/Λ unchanged. Figure 4(a) shows the dispersion of the improved PCF by varying d/Λ from 0.2 to 0.45 when $\Lambda = 1.4$ μm. The dispersion value increases with the increase of d/Λ for a certain wavelength and it presents a flat dispersion property in the band of the WDM of optical communications. Figure 4(b) shows the dispersion of the improved PCF by varying Λ from 1.0 μm to 2.0 μm when $d = 0.45$ μm. The dispersion value increases with the increase of Λ before $\lambda = 1.66$ μm and decreases with the increase of Λ after $\Lambda = 1.66$ μm. Moreover, with the increase of d/Λ, the wavelength of the zero-dispersion wavelength (ZDW) shifts toward the short wave band.

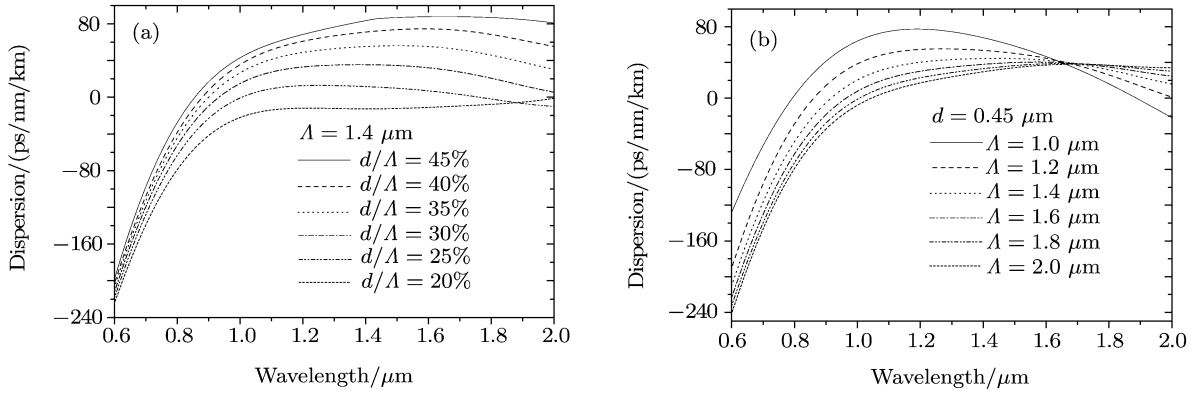


Fig. 4. Dispersions of (a) improved PCF by varying d/Λ from 0.2 to 0.45 when $\Lambda = 1.4$ μm and (b) by varying Λ from 1.0 μm to 2.0 μm when $d = 0.45$ μm.

4. Conclusion

A kind of improved high birefringence PCF with dispersion flattened and single mode operation has been proposed in this paper. For the improved PCF, it is found that with $\Lambda = 1.4$ μm and $d = 0.45$ μm, the dispersion curve presents a flat dispersion property in the band of the WDM of optical communications. Besides, the modal birefringence increases greatly and the leakage loss is about 10^4 times smaller than that of original PCF. The special structure of the improved PCF is required not only to control the high birefringence and obtain a flat dispersion, but also to increase the index contrast with maintaining the single mode operation. Therefore, the properties of high birefringence, flat dispersion and single mode operation are combined in the improved PCF perfectly.

References

[1] Russell J 2003 *Science* **299** 358
[2] Knight J C 2003 *Nature* **424** 847
[3] Lu J H, Meng Z M, Liu H Y, Feng T H, Dai Q F, Wu L J, Guo Q, Hu W and Lan S 2009 *Chin. Phys.* B **18** 4333
[4] Zhang M Y, Li S G, Yao Y Y, Fu B and Zhang L 2010 *Chin. Phys.* B **19** 047103
[5] Wang H L, Leng Y X and Xu Z Z 2009 *Chin. Phys.* B **18** 5375
[6] Fu B, Li S G, Yao Y Y, Zhang L, Zhang M Y and Liu S Y 2009 *Acta Phys. Sin.* **58** 7708 (in Chinese)
[7] Yuan J H, Sang X Z, Yu C X, Xin X J, Li S G, Zhou G Y and Hou L T 2010 *Chin. Phys.* B **19** 074218
[8] Chick B J, Chon J W M and Gu M 2008 *Opt. Express* **16** 20099
[9] Khan K R, Wu T X, Christodoulides D N and Stegeman G I 2008 *Opt. Express* **16** 9417
[10] Yue Y, Kai G Y, Wang Z, Sun T T, Jin L, Lu Y F, Zhang C S, Liu J G, Li Y, Liu Y G and Yuan S Z 2006 *IEEE Photon. Technol. Lett.* **18** 2638
[11] Zografopoulos D C, Kriezis E E and Tsiboukis T D 2006 *Opt. Express* **14** 914
[12] Chen X, Li M J, Koh J and Nolan D A 2008 *Opt. Express* **16** 12060
[13] Her T H 2008 *Opt. Express* **16** 7197
[14] Chen M Y 2007 *Opt. Express* **15** 12498
[15] Gérôme F, Auguste J L and Blondy J M 2005 *Opt. Lett.* **29** 2725
[16] Huttunen A and Torma P 2005 *Opt. Express* **13** 627
[17] Kocabas A, Ertas G, Senlik S S and Aydinli A 2008 *Opt. Express* **16** 12469
[18] Li S G, Li Y G, Zhang H G, Liu S Y, Zhou G Y, Han Y and Hou L T 2007 *Appl. Phys.* B **87** 71
[19] Kim S, Kee C S, Ko D K, Lee J and Oh K J 2006 *Korean Phys. Soc.* **49** 1434

[20] Chesini G, Cordeiro C M B, Matos de C J S, Fokine M, Carvalho I C S and Knight J C 2009 *Opt. Express* **17** 1660
[21] Kim S, Kee C S and Lee C G 2009 *Opt. Express* **17** 7952
[22] Li S G, Zhang W, Wei Z Y, Zhou G Y and Hou L T 2009 *Chin. Phys.* B **18** 1996
[23] Fang X H, Hu M L, Li Y F, Chai L and Wang Q Y 2009 *Acta Phys. Sin.* **58** 2495 (in Chinese)
[24] Oikawa Y, Hasegawa H, Suzuki K, Inoue Y, Hirooka T and Nakazawa M 2007 *IEEE Photon. Technol. Lett.* **19** 613
[25] Yamamoto T, Kubota H and Kawanishi S 2003 *Opt. Express* **11** 1537
[26] Saitoh K and Koshiba M 2003 *Opt. Express* **11** 843
[27] Saitoh K, Florous N and Koshiba M 2005 *Opt. Express* **13** 8365
[28] Varshney S K, Fujisawa T, Saitoh K and Koshiba M 2006 *Opt. Express* **14** 3528
[29] White T P, Kuhlmey B T, McPhedran R C, Maystre D, Renversez G, Sterke de C M and Botten L C 2002 *J. Opt. Soc. Am.* B **19** 2322
[30] Kuhlmey B T, White T P, Renversez G, Maystre D, Botten L C, Sterke de C M and McPhedran R C 2002 *J. Opt. Soc. Am.* B **19** 2331