A Kind of Double-Cladding Photonic Crystal Fiber with High Birefringence and Two Zero-Dispersion Wavelengths *

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A kind of double-cladding photonic crystal fiber (DC-PCF) with high birefringence and two zero-dispersion wavelengths is proposed. It is found that the birefringence of DC-PCF with inner cladding air holes pitch 1.0 μm and diameter 0.8 μm is 1.001×10^{-2} *in the optical communication band at wavelength 1.55 μm by the multipole method. It is demonstrated that two zero dispersion wavelengths can be achieved in the optical communication band between 0.8 μm and 1.7 μm, and the first zero-dispersion wavelength is in the working wave band of the Ti:sapphire oscillator, which contributes to the frequency conversion of the Ti:sapphire femtosecond laser. PCF with two zero-dispersion wavelengths can make strong power supercontinuum spectral in the near infrared band.*

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Photonic crystal fibers (PCFs) have attracted significant interest in the past few years duo to their unique characteristics.[1] In traditional symmetrical PCFs, the fundamental mode is composed of two degeneracy orthogonal polarized modes. Because the effective indices of the two modes are very close, the optical field easily couples from one mode to another. To increase the effective index difference and to reduce the polarization coupling of the two modes, the fiber structure must be changed. This kind of fiber is called the birefringent PCF.[2]

In recent years, polarization maintaining fiber of good quality can be beneficial in polarization maintaining devices, high-speed optical communication systems, supercontinuum generation and optical transducer applications.[3] With the rapid development of high-speed optical communication, higher quality polarization maintaining fibers are required. Otherwise, the birefringence of traditional polarization maintaining fibers can only be achieved up to 5×10^{-5},[4] which can not contend with the requirement of our rapid development. The polarization maintaining fiber of birefringence 3.7×10^{-3} was obtained by Blanch *et al.*[6] through setting abnormity air holes in 2000. In 2003, the birefringence of PCFs made by Birks *et al.*[7] can be achieved up to 2.58×10^{-3}. In recent years, many studies[2,5,8–12] reported high birefringence, but the birefringence can be achieved up to the level of 10^{-3} at optical communication band wavelength 1.55 μm generally.

Recently published papers such as Kudlinski *et al.*[13] and Cumberland *et al.*[14] have shown that PCFs with two zero-dispersion wavelengths (ZDW) demonstrate stronger power spectral densities than a single ZDW PCF. Therefore, PCFs with two ZDW can be beneficial in supercontinuum applications.

The design of birefringent PCF was obtained by changing the structure of the nearest air holes from the fiber core, mostly. A kind of double cladding and high birefringent PCFs is proposed in this Letter. The outer air holes form an equilateral triangle structure, while the inner air holes form a right-angle triangle structure, the PCF has second-order rotation symmetry. In Fig. 1, the double-cladding PCF structure is shown. The diameter of outer air holes, outer air hole pitch, inner air hole diameter, the most inner air hole diameter and inner air hole pitch are denoted by d_1, Λ_1, d_2, d_3 and Λ_2, respectively. The fiber core length and width correspond to b and a. Moreover, the figures give the mode field distribution of HE^x_{11} and HE^y_{11} at 1.55 μm wavelength where outer air hole diameter $d_1 = 1.0$ μm, pitch $\Lambda_1 = 1.5$ μm and inner air hole diameter $d_2 = d_3 = 0.8$ μm, pitch $\Lambda_2 = 1.0$ μm.

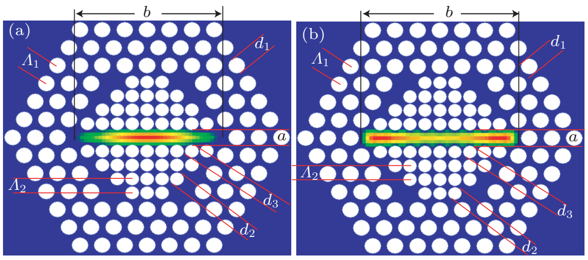

Fig. 1. Two cladding PCF structures and mode field distribution of (a) HE^x_{11} and (b) HE^y_{11}.

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Table 1. ZDW points of HE_{11}^x and HE_{11}^y modes.

$d_2 = d_3$ (μm)	HE_{11}^x mode		HE_{11}^y mode	
	The first ZDW (μm)	The second ZDW (μm)	The first ZDW (μm)	The second ZDW (μm)
0.6	0.957	1.382	0.894	1.32
0.7	0.892	1.528	0.827	1.463
0.8	0.866	1.65	0.787	1.524

In this study, the effective mode index $n_{\rm eff}$ of the PCF is obtained by employing the multipole method.[15,16] Then the dispersion D can be obtained by

$$D = -\frac{\lambda}{c}\frac{d^2{\rm Re}(n_{\rm eff})}{d\lambda^2}, \quad (1)$$

where c is the velocity of light in vacuum, Re means the real part. The material dispersion of the silica is taken into account via the Sellmeier equation. The confinement loss could be calculated by $\alpha = 8.686k_0{\rm Im}(n_{\rm eff})$ db/m, where Im means the imaginary part.[17]

If effective refractive indices $n_{\rm eff}^x$ and $n_{\rm eff}^y$ express the two linear polarization modes respectively, the birefringence B can be written as

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

When inner air hole diameter $d_2 = d_3 = 0.6$ μm, $d_2 = d_3 = 0.7$ μm and $d_2 = d_3 = 0.8$ μm, the changes of birefringence along with wavelength are shown in Fig. 2, in which we keep d_1, Λ_1 and Λ_2 unchanged. It is found that the birefringence with inner air hole diameter $d_2 = d_3 = 0.8$ μm is 1.001×10^{-2} in optical communication band 1.55 μm wavelength. The birefringence 1.001×10^{-2} is two orders of magnitude higher than that of the traditional polarization maintaining fiber, and higher than the birefringence reported by Refs. [2,8,10–12].

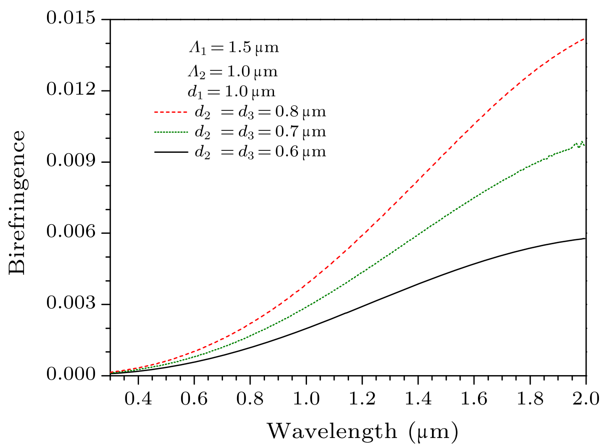

Fig. 2. Variation of birefringence as a function of the wavelength for different inner air hole diameters.

Group velocity dispersion is one of the most important parameters of optical fibers, and dispersion management for optical fibers is a great issue in almost all fiber based applications.[18] Figure 3 shows that the dispersion changes in HE_{11}^x and HE_{11}^y modes along with wavelength when keeping d_1, Λ_1 and Λ_2 unchanged, where the inner air hole diameter $d_2 = d_3 = 0.6$ μm, $d_2 = d_3 = 0.7$ μm, $d_2 = d_3 = 0.8$ μm respectively. As can be seen from Figs. 3(a) and 3(b), two zero dispersion wavelengths are achieved by the proposed PCF for inner air hole diameter $d_2 = d_3 = 0.6$ μm, $d_2 = d_3 = 0.7$ μm and $d_2 = d_3 = 0.8$ μm.

As shown in Table 1, the first ZDW is in the working wave band of the Ti:sapphire oscillator (700–980 nm) for the HE_{11}^x and HE_{11}^y modes, which contributes to frequency conversion of Ti:sapphire femtosecond laser. Moreover, two points of zero dispersion wavelengths are in optical communication band between 0.8 μm and 1.7 μm, which is not reported in Refs. [2,5,8-12]. The PCF that has two ZDW has been used previously for high power supercontinuum generation applications.[13,14,19] Also, Cumberland *et al.*[14] have shown that two ZDW PCFs can be used to control the long wavelength edge of the continuum when needed for specific applications.

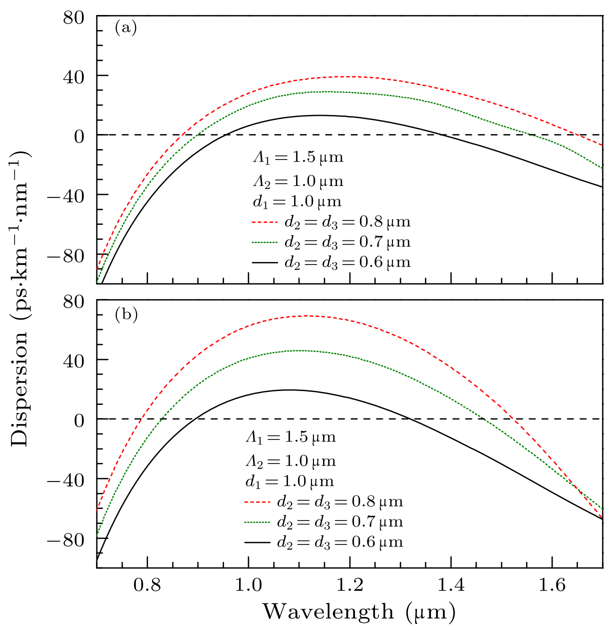

Fig. 3. Variation of the dispersion of (a) HE_{11}^x and (b) HE_{11}^y mode as a function of the wavelength for different inner air hole diameters.

In practice, the PCF whose air hole diameter is less than 1 μm was reported in 2004.[20] Considering the tolerance in the drawing process, the deviation of birefringence and dispersion along with wavelength is shown in Figs. 4 and 5, respectively, where 5% of the most inner air hole diameter d_3 is changed while other parameters unchanged. As can be seen in Figs. 4 and

5, the change of birefringence and dispersion is very small.

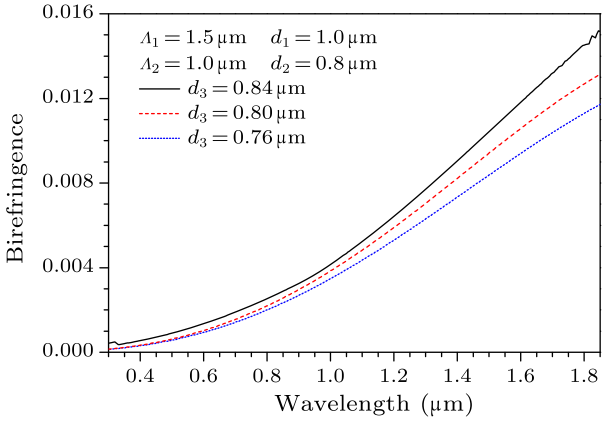

Fig. 4. Deviation of birefringence along with wavelength for the different most inner air hole diameters.

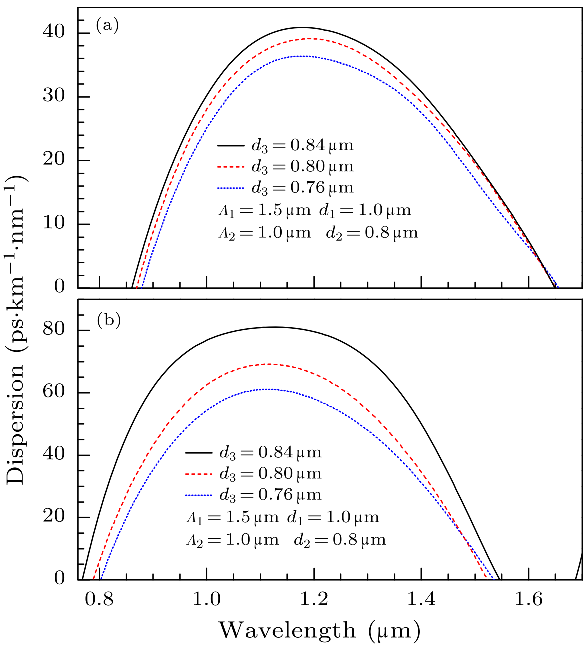

Fig. 5. Deviation of dispersion of (a) HE_{11}^{x} and (b) HE_{11}^{y} mode along with wavelength for the different most inner air hole diameters.

Figures 6(a) and 6(b) shows the variation of confinement loss for the modes of HE_{11}^{x} and HE_{11}^{y} as a function of wavelength when keeping d_1, Λ_1 and Λ_2 unchanged, where the inner air hole diameter $d_2 = d_3 = 0.6$ μm, $d_2 = d_3 = 0.7$ μm, $d_2 = d_3 = 0.8$ μm respectively. At the operating wavelength 1.55 μm, the confinement loss of HE_{11}^{x} and HE_{11}^{y} is 0.046 dB/m and 0.303 dB/m for $d_2 = d_3 = 0.8$ μm, respectively.

Fiber core length $a = 11$ μm and width $b = 1.2$ μm. The effective area $A_{\rm eff}$ for the modes of HE_{11}^{x} and HE_{11}^{y} along with wavelength is shown in Figs. 7(a) and 7(b), respectively. This can be used as a reference in the coupling process.

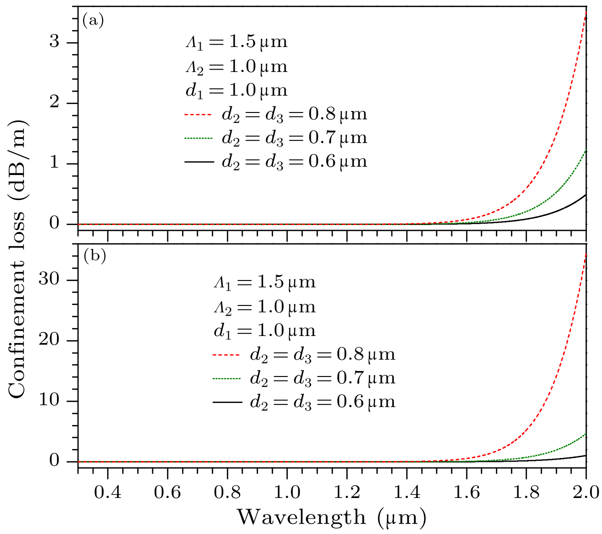

Fig. 6. Confinement loss of (a) HE_{11}^{x} and (b) HE_{11}^{y} mode as a function of the wavelength for different inner air hole diameters.

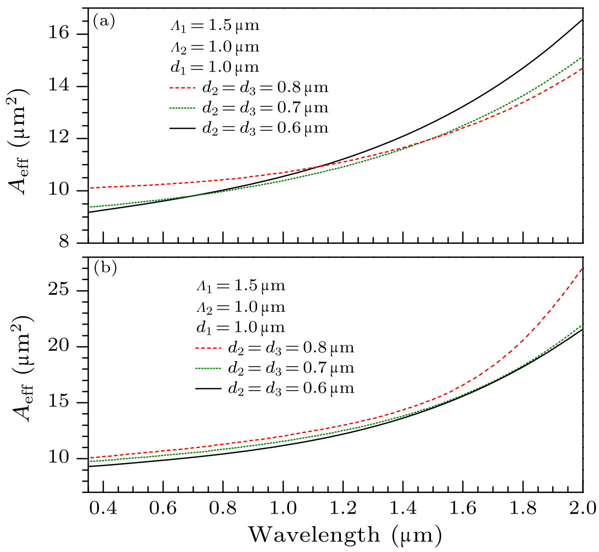

Fig. 7. Effective area $A_{\rm eff}$ for the modes of (a) HE_{11}^{x} and (b) HE_{11}^{y} along with wavelength for different inner air hole diameters.

In summary, we have presented a kind of double-cladding photonic crystal fiber (DC-PCFs) with high birefringence and two ZDWs. Birefringence can achieve 1.001×10^{-2} in optical communication band 1.55 μm wavelength, which can improve the quality of polarization maintaining fiber in a large extent. The first ZDW is in the working wave band of the Ti:sapphire oscillator, which contributes to frequency conversion of Ti:sapphire femtosecond laser. Furthermore, two points of the ZDW are in the optical communication band between 0.8 μm and 1.7 μm. The appearance of two ZDWs in the DC-PCF is beneficial for supercontinuum applications.

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