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Coupling characteristics of the high-polarization dual-core photonic crystal fiber with mixing air holes*

CAO Ye (曹晔), CUI Dan-ning (崔丹宁), and TONG Zheng-rong (童峥嵘)**
Key Laboratory of Film Electronics and Communication Devices, Tianjin University of Technology, Tianjin 300384, China

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A high-polarization dual-core photonic crystal fiber (PCF) with mixing air holes is designed. The full-vector finite element method and coupled-mode theory are used to investigate the birefringence, coupling length, dispersion characteristics, normalized power and extinction ratio of this fiber. Numerical investigations demonstrate that by changing the structural parameters of the fiber, the birefringence is up to 1.48×10^{-2} at 1.55 μm, the coupling lengths are 79 μm and 94 μm for x-polarized and y-polarized modes, the fiber has two zero dispersion points, and the dispersion is very flat at the ultra-wide waveband scope from 0.7 μm to 1.7 μm.
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The dual-core photonic crystal fibers (PCFs) are composed by introducing two defect states in periodic arrangement of air holes, and have been widely studied for their good optical coupling characteristics. K. Saitoh et al[1] designed wavelength division multiplexer and demultiplexer based on coupling effect of dual-core PCF. N. J. Florou et al[2] studied high birefringence dual-core PCF beam splitter, and realized the polarization-independent beam splitter. Lou et al[3] designed and optimized the broadband dual-core PCF coupler. Jiang et al[4] numerically researched comb-filter based on two-core fiber coupler.

Birefringence and coupling length are two important physical parameters in dual-core PCF. Issa et al[5] drawed an elliptical-hole PCF with high ellipticity based on air hole deformation. Mejia et al[6] fabricated a highly birefringent elliptical-hole PCF by compressing a hexagonal structure. In this paper, we propose a new kind of dual-core PCF by introducing a row of gradient elliptical air holes parallel to the x axis. The full-vector finite element method and coupled-mode theory are employed to study the birefringence, coupling length, disperseon characteristics, normalized power and extinction ratio of this PCF. The results show that the designed dual-core PCF can realize the high birefringence, shorter coupling length and good dispersion characteristics at the same time, and the fiber can be produced for micro-coupler and polarization splitter with high extinction ratio.

Fig.1 shows the cross section of the proposed dual-core PCF. Removing two elliptical holes around center ellipse A_0 (long axis a_0=0.35 μm, short axis b_0=0.14 μm) to form double cores, the elliptical air holes on both sides of the fiber core are symmetrical. In order to facilitate discussion, we only give parameters about one side of elliptical air holes. The long axes of elliptic air holes A_1, A_2, A_3, A_4 are a_1=0.3 μm, a_2=0.4 μm, a_3=0.5 μm and a_4=0.6 μm, respectively, and the short axes are b_1=0.15 μm, b_2=0.2 μm, b_3=0.25 μm and b_4=0.3 μm, respectively. The diameter d of circular air holes is 1.0 μm, and the pitch Λ is 1.2 μm. From Fig.2, we can see that the mode fields of light waves are strictly restricted in two cores by air holes, and the energy is coupled between the two cores.

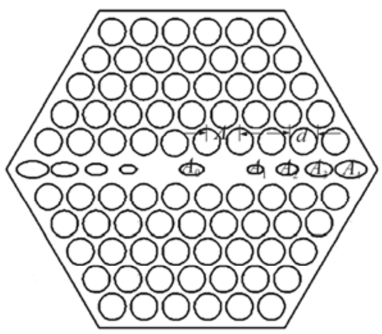

Fig.1 Cross section of the designed dual-core photonic crystal fiber

We numerically calculate the designed dual-core PCF through software COMSOL multiphysics which is based on finite element method. Setting the incident wavelength, the corresponding material parameters and per-

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** E-mail: cuidanning@163.com

fectly matched layer (PML) boundary condition, we can get the mode field distribution and the corresponding effective index, and the changing rules of the physical quantity with the structure parameters and the wavelength can be obtained through Matlab.

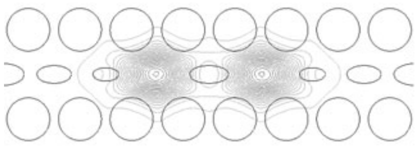


Fig.2 Transverse field profile of light coupling in two-core PCF

The mode birefringence B can be given by[7-9]

$$B = \left|\mathrm{Re}(n_{\mathrm{eff}}^{y}) - \mathrm{Re}(n_{\mathrm{eff}}^{x})\right| , \tag{1}$$

where n_{eff}^{x} and n_{eff}^{y} are the effective indices in the x-polarized and y-polarized directions, respectively. In addition, the effective refractive index of the real component can also be used for the calculation of dispersion. Generally speaking, the total dispersion of PCF including waveguide dispersion and material dispersion can be expressed as[10]

$$D(\lambda) = D_{\mathrm{W}}(\lambda) + D_{\mathrm{M}}(\lambda) , \tag{2}$$

where material dispersion $D_{\mathrm{M}}(\lambda)$ is

$$D_{\mathrm{M}}(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 n(\lambda)}{\partial \lambda^2} , \tag{3}$$

and waveguide dispersion is

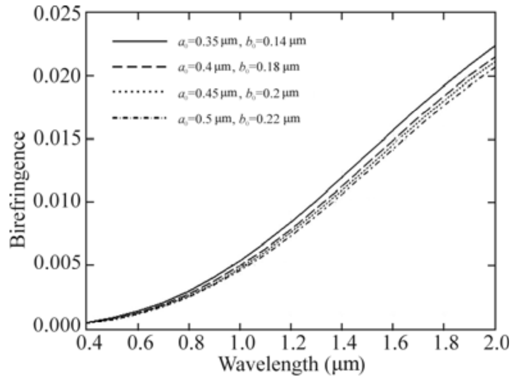
$$D_{\mathrm{W}}(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 \left|\mathrm{Re}(n_{\mathrm{eff}})\right|}{\partial \lambda^2} . \tag{4}$$

Transverse coupling phenomenon occurs between two optical waveguides which are close and parallel to each other, and this phenomenon can use the transverse coupling theory to describe. There are four polarized components of the fundamental mode in dual-core fiber, which are the odd mode E_{xo} and even mode E_{xe} of x-polarized direction, the odd mode E_{yo} and even mode E_{ye} of y-polarized direction. According to the waveguide mode coupling theory, the coupling length can be calculated as[11]

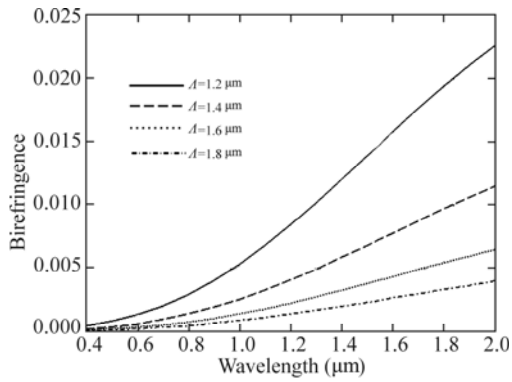
$$L_{\mathrm{C}} = \frac{\pi}{\beta_{\mathrm{s}} - \beta_{\alpha}} , \tag{5}$$

where β_{s} and β_{α} are the propagation constants of odd mode and even mode. For each transmission mode of optical fiber, effective index is $n_{\mathrm{eff}} = \beta / k_0$, k_0 is free space wave number, and $k_0 = 2\pi/\lambda$. Using the effective refractive indices of even mode and odd mode, we can obtain the coupling length.

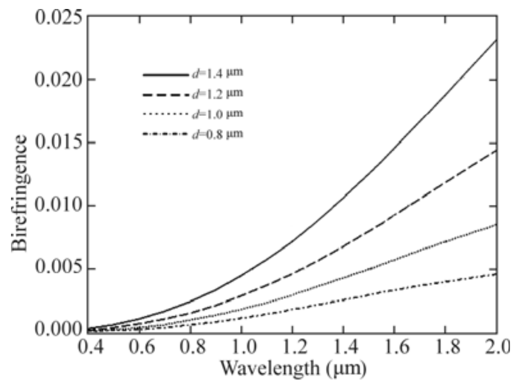
Fig.3 gives the dual-core PCF's birefringence with changing the fiber's structure parameters and wavelength. From Fig.3(a), with the structure parameters of a_0=0.35 μm and b_0=0.14 μm, the birefringence can reach 1.48× 10^{-2} at the wavelength λ=1.55 μm. This value is two orders of magnitude higher than that of traditional fiber, and higher than the reported values of 1.24×10^{-2}[11], 1.225×10^{-2}[12] and 1.09×10^{-2}[13]. In Fig.3(b), the birefringence decreases with increasing the pitch Λ, because when Λ increases, the two cores' areas increase at the same time, and the interaction between inner holes and mode fields abates. In Fig.3(c), with increasing the diameter d of the circular holes, the bounding ability of cladding strengthens, the influence of inner hole asymmetry on light fields increases, so the birefringence also increases. In Fig.3(d), when the areas of the elliptical holes on both sides of the cores increase, the asymmetries of two cores along x- and y-direction abate, so the birefringence decreases.



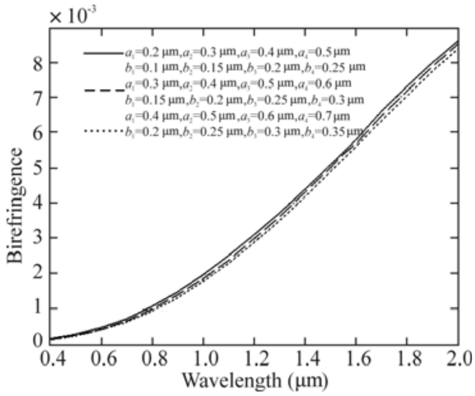
(a) Different center ellipses with Λ=1.2 μm and d=1.0 μm



(b) Different pitches of holes with a_0=0.35 μm, b_0=0.14 μm and d=1.0 μm



(c) Different diameters of circular hole with a_0=0.35 μm, b_0=0.14 μm and Λ=1.5 μm



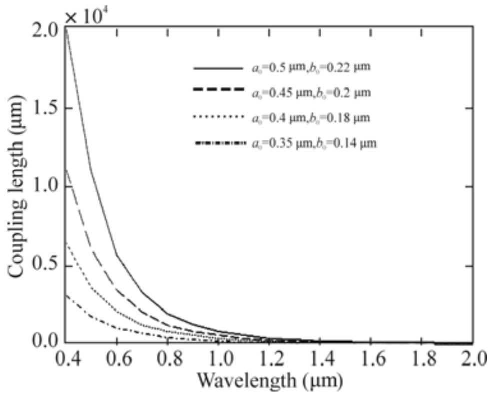
(d) Different ellipses on both sides of fiber core with a_0=0.35 μm, b_0=0.14 μm, Λ=1.5 μm and d=1.0 μm

Fig.3 Birefringences with different fiber structure parameters and wavelengths

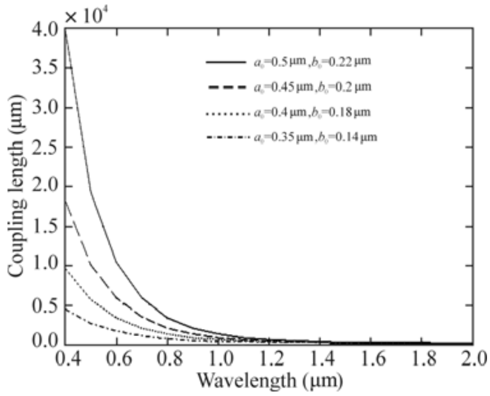
We can see the coupling length changing with the structure parameters and the wavelength in Fig.4. From Fig.4(a) and (b), we know the coupling length of x-direction is longer than that of y-direction, because in this paper we place the two cores parallel to x axis, and when the wavelength is certain, with decreasing the ellipse A_0, the coupling length decreases greatly. As the long axis a_0=0.35 μm and short axis b_0=0.14 μm, the coupling lengths of x- and y-polarization at the wavelength λ=1.55 μm are 79 μm and 94 μm, respectively. The values of coupling lengths are one order of magnitude smaller than those in Refs.[14,15] and less than those in Ref.[13]. But the ellipse A_0 can't infinitely decrease, because when A_0 is very small, the electric field energy of even mode directly infiltrates, and then the two cores are no longer independent. Here we only discuss the coupling characteristic of x-polarization direction, because the changing trends of coupling length in two polarization directions are the same.

When the wavelength is confirmed as shown in Fig.4(c), coupling length increases with increasing the pitch. When the pitch increases, the wavelength becomes shorter, the limitation of light fields in fiber is enhanced, the mode fields mainly focus on fiber's core area, so coupling is difficult, and thus the coupling length becomes longer. In Fig.4(d), the two cores are longitudinally compressed with the diameter of cladding circular holes increasing, leading to the mode fields laterally spreading, so the coupling becomes easy, and the coupling length decreases. In Fig.4(e), the coupling length is shorter when the elliptical holes on both sides of the cores increase. Because as the elliptical holes increase, the outward diffusion of the optical fields abates, the inward diffusion is enhanced, and then the coupling becomes easy.

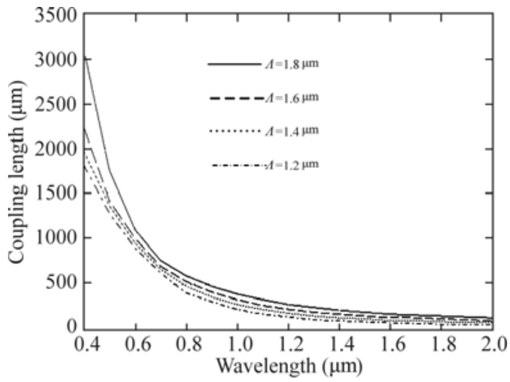
The coupling lengths in two polarization directions in this paper are different. Using this feature, the designed fiber can be fabricated as mini polarization splitter and coupler. As long as the length of the fiber satisfies $L=mL_x=nL_y$, where m and n are positive integers, if the parity is identical, the fiber can be made into polarization independent coupler; if not, it can be made into polarization splitter. Fig.5 shows the normalized transmission power with distance. From Fig.5, we can use the dual-core PCF as the polarization splitter at the wavelength of λ=1.55 μm and $L=6L_x=5L_y$=470 μm, the length of polarization splitter is one order of magnitude smaller than that reported in Refs.[13] and [15], and we can get a polarization independent coupler at the wavelength of λ=1.55 μm and $L=13L_x=11L_y$=1032 μm. Fig.6 shows the extinction ratio by varying wavelength as polarization splitter. We can see the bandwidth of 20 dB extinction ratio is almost 19.4 nm from 1.5403 μm to 1.5597 μm. At wavelength of λ=1.55 μm, the extinction ratio can reach 70.3 dB.



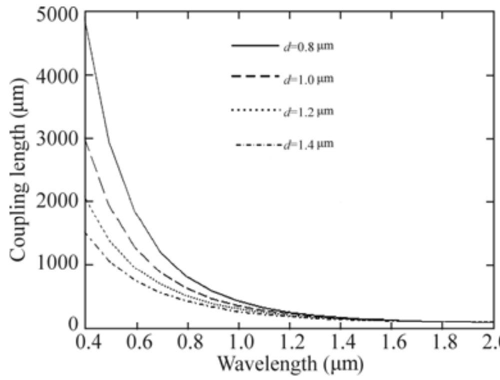
(a) x polarization direction with different center ellipses and Λ=1.2 μm, d=1.0 μm



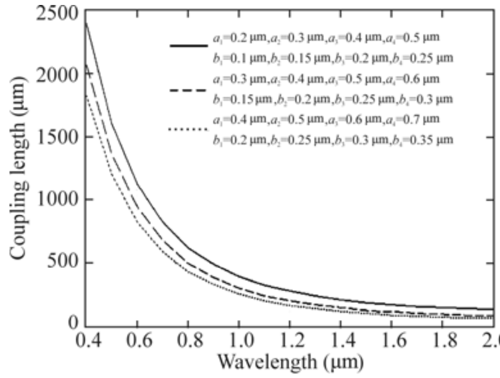
(b) y polarization direction with different center ellipses and Λ=1.2 μm, d=1.0 μm



(c) x polarization direction with different pitches of holes and a_0=0.35 μm, b_0=0.14 μm, d=1.0 μm



(d) x polarization direction with different diameters of holes and a_0=0.35 μm, b_0=0.14 μm, Λ=1.5 μm



(e) x polarization direction with different ellipses on both sides of fiber core and a_0=0.35 μm, b_0=0.14 μm, Λ=1.5 μm, d=1.0 μm

Fig.4 Coupling lengths with different fiber structure parameters and wavelengths

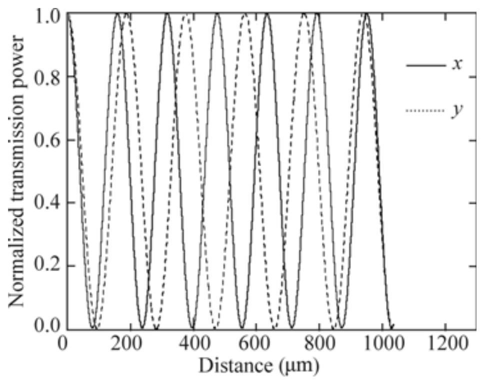


Fig.5 Normalized power with transmission distance

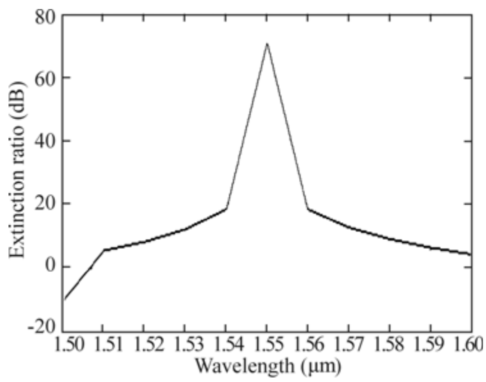
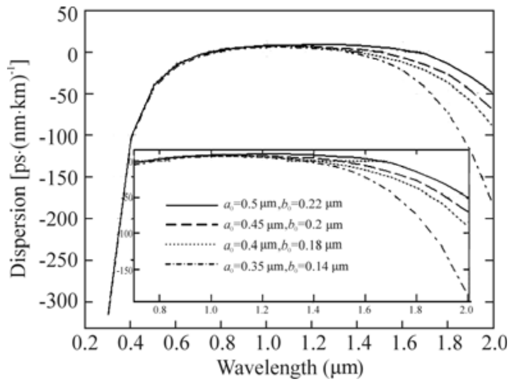
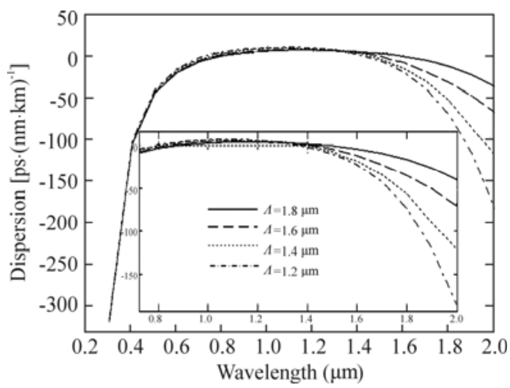


Fig.6 Extinction ratio with wavelength

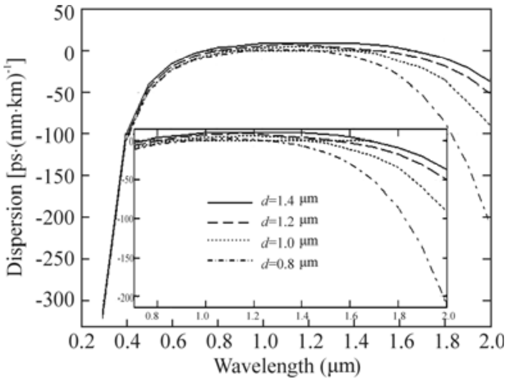
Fig.7 shows the change of odd mode dispersion value with the wavelength in x polarization direction with different structure parameters, and the trends of even and odd mode changes are roughly the same. For a certain wavelength, as shown in Fig.7(a), the dispersion value increases with the elliptical area increasing, and the curve of dispersion is gradually flat, when the long axis is a_0=0.5 μm and short axis is b_0=0.22 μm. And the distance between the two zero dispersion points gradually increases with increasing the ellipse's area. The anomalous dispersion appears between the two zero dispersion points, and if the ultrashort pulse is injected in the area of anomalous dispersion, soliton self-frequency shift and four-wave mixing effect are produced[11]. So through changing ellipse A_0, we can get good dispersion characteristics. In Fig.7(b), the dispersion value increases with hole's pitch decreasing. The dispersion curve is relatively flat, and the change trend of two zero dispersion points is consistent with that in Fig.7(a). In Fig.7(c), the dispersion first increases and then decreases, and the second zero dispersion point moves to long-wavelength direction with the increase of the circular hole's diameter. In Fig.7(d), the change trends of dispersion and the second zero dispersion point are the same with those in Fig.7(c) with increase of ellipse's area on the both sides of the two cores. From the above, we know that we can get favorable flat dispersion characteristics by using the appropriate parameters.



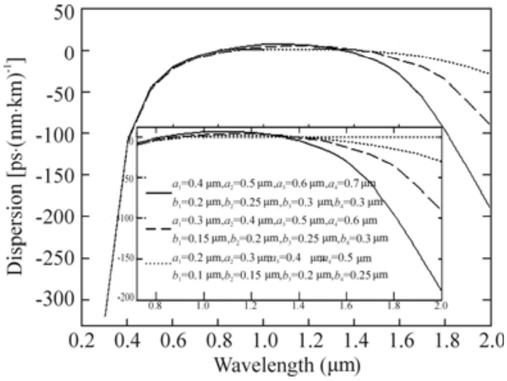
(a) Different center ellipses with Λ=1.2 μm and d=1.0 μm



(b) Different pitches of holes with a_0=0.35 μm, b_0=0.14 μm and d=1.0 μm



(c) Different diameters of circular hole with a_0=0.35 μm, b_0=0.14 μm and Λ=1.5 μm



(d) Different ellipses on both sides of fiber core with a_0=0.35 μm, b_0=0.14 μm, Λ=1.5 μm and d=1.0 μm

Fig.7 Dispersions with different fiber structure parameters and wavelengths

The full-vector finite element method and coupled-mode theory are employed to research the designed dual-core PCF in this paper. The birefringence, coupling length, normalized power, extinction ratio and dispersion properties of this fiber with wavelength and structure parameters are analyzed. By choosing appropriate fiber structure, the combination of high birefringence, short coupling length and ultra-smooth dispersion characteristics can be realized. The structure of fiber in this paper can be widely used in designing high polarization-maintaining and dispersion-flatted coupler, and has an important potential in the development of new type photonic device.

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