Coupling characteristics of high birefringence dual-core As_2S_3 rectangular lattice photonic crystal fiber*

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(Received 17 April 2011; revised manuscript received 21 August 2011)

A type of As_2S_3 chalcogenide glass mid-infrared dual-core photonic crystal fiber has been proposed. The dual-core photonic crystal fiber (PCF) consists of two asymmetric cores. The high polarization property and the coupling characteristics have been studied by using the finite element method and mode coupling theory. Numerical results show that the birefringence at wavelength $\lambda = 10$ μm is up to 0.01386 and the coupling length can reach wavelength $\lambda = 5$ μm, 261 μm and 271.44 μm for x-polarized mode and y-polarized mode, respectively. It demonstrates that a 6.786-mm-long fiber can exhibit an extinction ratio of better than −10 dB and a bandwidth of 180 nm.

Keywords: photonic crystal fiber, birefringence, coupling length, mid-infrared

PACS: 42.81.–i, 42.81.Gs, 42.82.Et **DOI:** 10.1088/1674-1056/21/3/034217

1. Introduction

In recent years, research on photonic crystal fiber (PCF) has been a hot area of research. Compared with a conventional optical fiber, PCF has many unique properties: high birefringence,[1−3] a maximum effective mode field area,[4−6] tunable dispersion,[7−9] high non-linearity,[10,11] and so on.

Dual-core fiber have been commonly used as couplers, multiplexers, splitters, sensors and all-optical switching. Varshney *et al.* studied the impact of elliptical deformations for optimizing the performance of dual-core fluorine-doped PCF couplers[12]. Argyros *et al.* fabricated and analysed a kind of twin-hollow-core optical fiber.[13] Liu and Chiang analysed the propagation of ultrashort pulses in a nonlinear two-core PCF by solving a pair of coupled-mode equations which include all the significant linear and nonlinear terms.[14] Salgueiro and Santos studied the different families of vortex modes in a PCF with two close defects forming a dual-core coupler.[15] Therefore, the dual-core PCF may be applied widely.

At present, the mid-infrared PCF has aroused great research interest. Chalcogenide glass is highly transparent in the mid-infrared range and offers a light transmission range of 3–10 μm. In addition, chalcogenide glass has a high linear and nonlinear refractive index.[16] Ung and Skorobogatiy introduced chalcogenide microporous fibers for linear and nonlinear applications in the mid-infrared range.[17] Tsay *et al.* analysed the mid-infrared characterization of solution-processed As_2S_3 chalcogenide glass waveguides.[18] Lepine *et al.* demonstrated the use of photoinduced fluidity in low-loss chalcogenide fibers for producing tapers with fine control of the diameter and geometry.[19] Therefore, As_2S_3 chalcogenide glass as a substrate material is expected to be applied to design PCF with high nonlinear and better transmission characteristics in the mid-infrared range.

In this paper, a novel kind of an As_2S_3 chalcogenide glass square lattice dual-core PCF with simple and asymmetric core structure is proposed. A finite element method[20] combined with an optical waveguide mode theory is employed to simulate the modal properties and to study the coupling properties.

2. Principle of operation

The new PCF structure is illustrated in Fig. 1. All air holes are circular and anchored in a square lattice. The lattice pitches $\Lambda_x = 6$ μm in x-axis and

*Project supported by the National Natural Science Foundation of China (Grant No. 10874145), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20091333110010), the Natural Science Foundation of Hebei Province, China (Grant No. F2009000481), and the China Postdoctoral Science Foundation (Grant Nos. 20080440014 and 200902046).

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$\Lambda_y = 5.4$ μm in y-axis direction. The host material is As_2S_3 chalcogenide glass with $n_{As_2S_3} = 2.44$. The dual-cores A and B in the PCF are formed by replacing three air-holes with As_2S_3 chalcogenide glass. We employ the finite element method to calculate the effective refractive indices of the horizontally polarized (x-polarized) mode and the vertically polarized (y-polarized) mode.

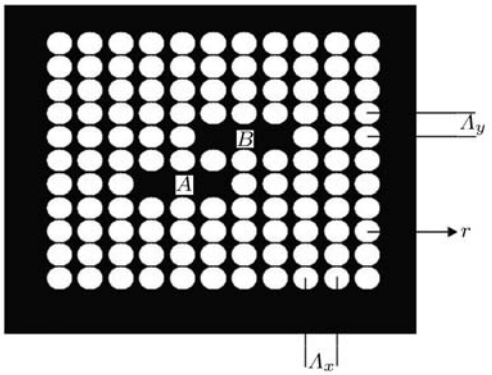


Fig. 1. The PCF structure.

Polarization maintaining fiber has a strong polarization maintaining capacity with linearly polarized light. The high mode birefringence in the light-propagation can enhance the polarization maintaining characteristic of the fiber. The mode birefringence can be expressed as

$$B_{\mathrm{m}} = |\ \mathrm{Re}(n_{\mathrm{eff}}^{y}) - \mathrm{Re}(n_{\mathrm{eff}}^{x})\ |, \tag{1}$$

where n_{eff}^{x} and n_{eff}^{y} are the effective refractive indices of in x-polarized and y-polarized modes, respectively, Re denotes the real part. Confinement loss is one of the most important parameters in the fiber transmission. The confinement loss can be expressed as[21]

$$L_{\mathrm{loss}} = \frac{20}{\ln 10}\frac{2\pi}{\lambda}\mathrm{Im}(n_{\mathrm{eff}}) \times 10^{6}. \tag{2}$$

In dual-core PCF, the total model can be considered to be a superposition of four modes, including the odd modes $E_{\mathrm{odd}}^{x,y}$ and the even modes $E_{\mathrm{even}}^{x,y}$. Their effective refractive indices are $n_{\mathrm{odd}}^{x,y}$ and $n_{\mathrm{even}}^{x,y}$, for x-polarized mode or y-polarized mode, respectively. The coupling length can be explicitly derived by using the following relation:

$$L^{x,y}(\lambda) = \frac{\lambda}{2(n_{\mathrm{even}}^{x,y} - n_{\mathrm{odd}}^{x,y})}, \tag{3}$$

where λ is the wavelength of light.

3. Simulation results

In this paper, the birefringence results from the asymmetry of the innermost air hole. Figure 2 shows the variation of birefringence as a function of the wavelength for different air hole radius. The birefringence increases with the wavelength for the case considered here. This is because the birefringence is caused by the asymmetric fiber core for x-direction and y-direction. When light propagates in the fiber, it is affected by the asymmetry of the innermost air hole. It is found that the birefringence of dual-core PCF with air-hole radius $r = 2.3$ μm is 0.01386 at wavelength $\lambda = 10$ μm.

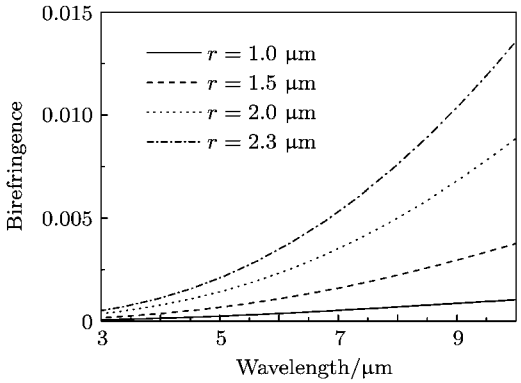


Fig. 2. The variation of birefringence as a function of the wavelength for different air hole radii.

Figure 3 shows the variation of the confinement loss as a function of the wavelength for the air hole radius $r = 2.3$ μm. The confinement loss increases with the increase of wavelength. It is found that the confinement loss is less than 1×10^{-10} for the wavelength λ from 2 to 7 μm. Dianov *et al.* theoretically calculated the material loss, and the loss below 1 dB/km has been achieved in a fairly wide wavelength range between 2.1 and 5.6 μm.[22] Thus, we choose to study the coupling properties at the wavelength $\lambda = 5$ μm.

Figures 4(a) and 4(b) show the variation of coupling length as a function of the wavelength for different air hole radius. As the wavelength increases, the mode field expands and the coupling between the dual-core becomes easier. Therefore, the coupling length decreases with the increase of wavelength. From Fig. 4 we can know the coupling length value by varying the air hole radius r from 1.0 to 2.3 μm. When the lattice pitches $\Lambda_x = 6$ μm and $\Lambda_y = 5.4$ μm, the coupling length decreases with the increase of air hole radius r. This is because with the increase of air hole radius, the core is compressed in the vertical direction, which results in the mode field expanding laterally, and finally makes the light-propagation coupling easy from one core to another. It is found that the coupling lengths of dual-core PCF, with the lattice pitches $\Lambda_x = 6$ μm, $\Lambda_y = 5.4$ μm, and air-hole radius $r = 2.3$ μm, are 261 μm and 271.44 μm for x-polarized mode and y-polarized mode, respectively, at wavelength $\lambda = 5$ μm.

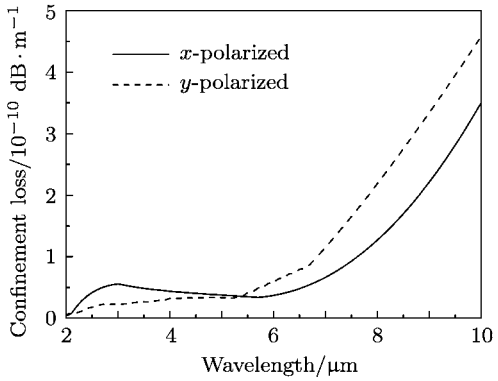


Fig. 3. the variation of the confinement loss as a function of the wavelength for the air hole radius $r = 2.3$ μm.

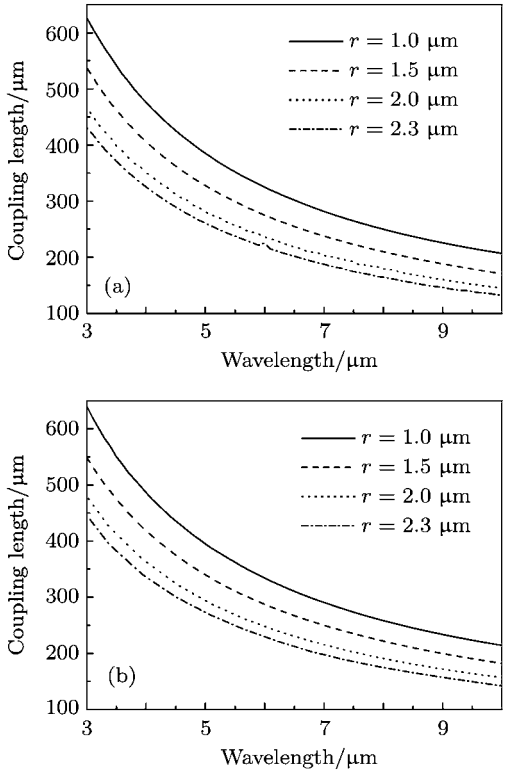


Fig. 4. The variation of coupling length as a function of the wavelength for different air hole radii: (a) x-polarized mode; (b) y-polarized mode.

4. Applications

In this work, we proposed a novel dual-core PCF, which has different coupling lengths in two polarized directions. Based on this characteristic, we can fabricate a polarization beam splitter and a polarization coupler. The length of the dual-core PCF $L = mL_x = nL_y$, where m and n are positive integers. For the polarization independent coupler, m and n should be either odd numbers or even numbers; while for the polarization beam splitter, the parity of m and n should be opposite.

Figure 5 shows the normalized transmission power with the variation of distance, where the lattice pitches $\Lambda_x = 6$ μm and $\Lambda_y = 5.4$ μm, air-hole radius $r = 2.3$ μm and wavelength $\lambda = 5$ μm, the coupling lengths are 261 μm and 271.44 μm for x-polarized mode and y-polarized mode, respectively. It is found that when $L = 26L_x = 25L_y = 6.786$ mm, two polarized lights are separated, which means that the PCF could be used as a polarization beam splitter. When $L = 52L_x = 50L_y = 13.572$ mm, the PCF could be used as a polarization independent coupler.

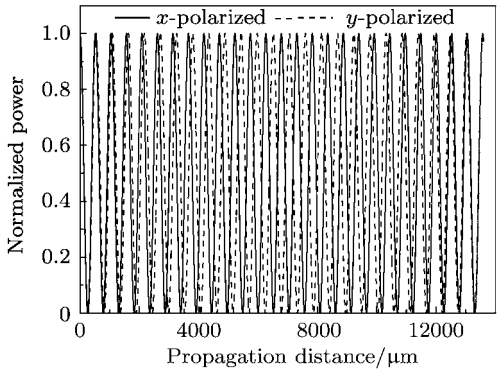


Fig. 5. The normalized transmission power versus propagation distance.

Figure 6 shows the normalized transmission power value by varying wavelength λ from 4.0 to 6.0 μm, where the lattice pitches $\Lambda_x = 6$ μm and $\Lambda_y = 5.4$ μm, air-hole radius $r = 2.3$ μm and transmission length $L = 6.786$ mm. It is found that the normalized transmission powers of the x- and y-polarized modes for the proposed fibers change periodically with the variation of wavelength, which is same as a traditional

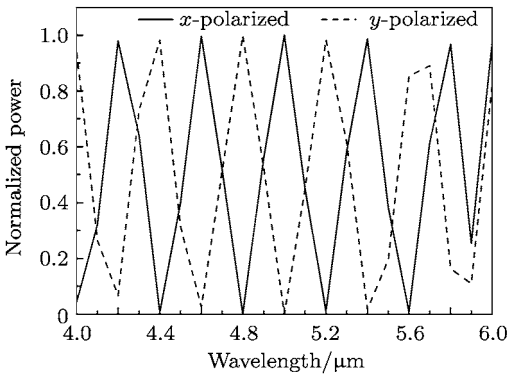


Fig. 6. The normalized transmission power versus wavelength.

directional coupler. Figure 7 shows the extinction ratio value by varying wavelength λ from 4.0 to 6.0 μm. The extinction ratio in the measured bandwidth is better than −10 dB, where the bandwidth is as much as 180 nm (from 4.9 to 5.08 μm), and the largest extinction ratio can reach −64.6 dB at wavelength $\lambda = 5$ μm.

We perform the numerical simulation by using the full-vector beam propagating method[23] to confirm our proposed fiber characters. In Fig. 8 we present the electric field distribution of the As_2S_3 chalcogenide glass mid-infrared dual-core PCF at propagation lengths of $z = 0$, $L/2$, L at wavelength $\lambda = 5$ μm for the two different polarization states. At $z = 0$, we see an input field in the B core, and then the power transfers from the B core to the A core very smoothly, and finally, at $z = 261$ μm x-polarized mode power transfers into the A core, and then at $z = 271.44$ μm y-polarized mode power transfers from the B core to the A core. Therefore, a long enough PCF can be used to fabricate micro-polarization beam splitters and couplers, which contributes to the development of photonic devices in integrated optics greatly.

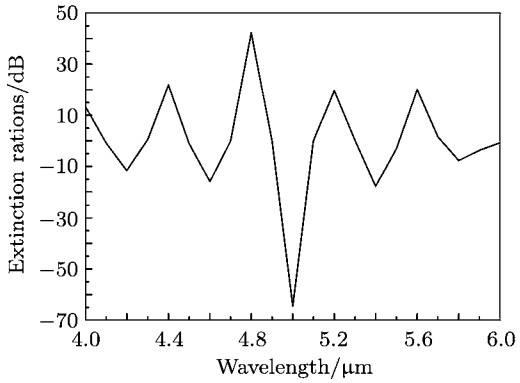


Fig. 7. The extinction ratios versus wavelength.

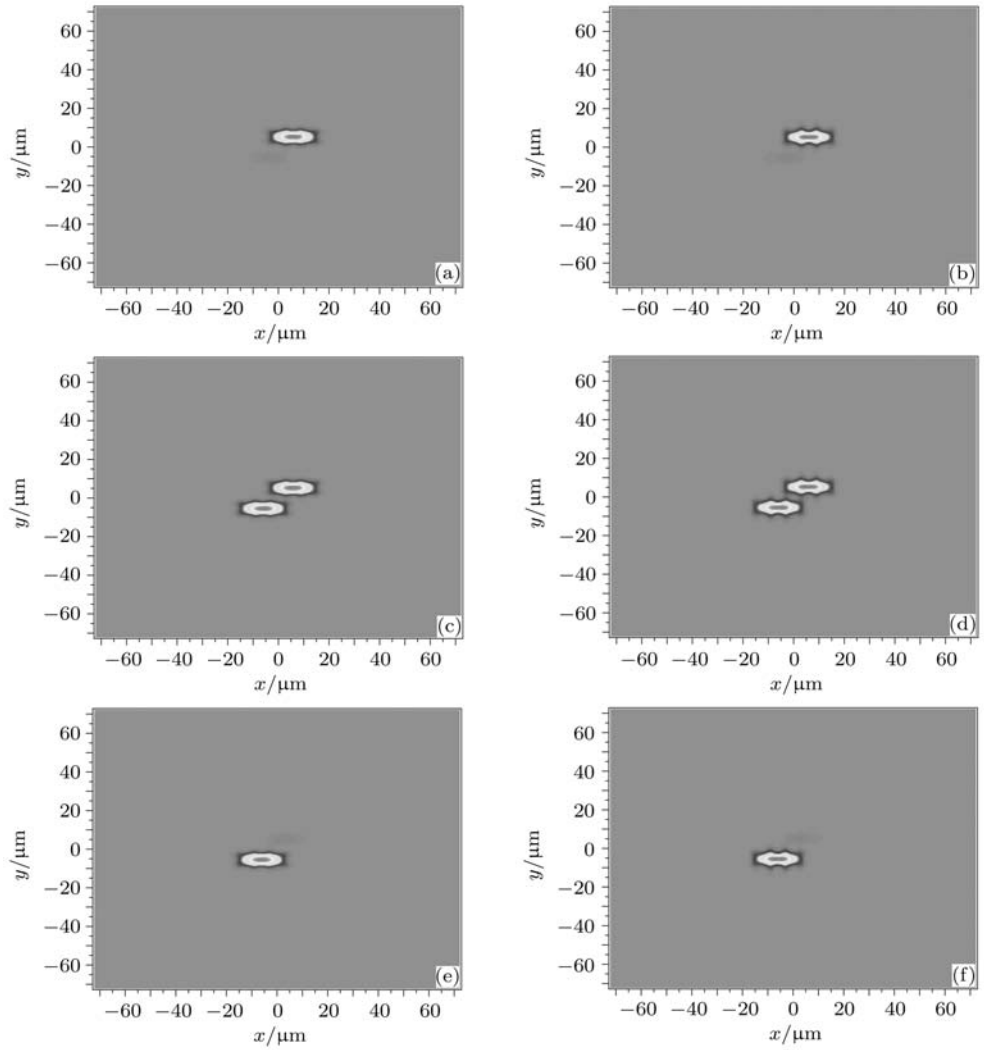


Fig. 8. Electric field distribution at wavelength 5 μm for (a) x-polarized (E_x) $z = 0$ μm, (b) y-polarized (E_y) $z = 0$ μm, (c) x-polarized (E_x) $z = 130.5$ μm, (d) y-polarized (E_y) $z = 135.72$ μm, (e) x-polarized (E_x) $z = 261$ μm, (f) y-polarized (E_y) $z = 271.44$ μm.

As_2S_3 chalcogenide glass has high linear and nonlinear refractive index, so it has been widely used to fabricate mid-infrared PCF. From a practical point of view, the most important thing affecting loss is impurity, especially the OH ion. To prepare high-purity As_2S_3 chalcogenide glass with less impurities, the glass needs to be heated, distilled and then condensed. Nowadays, the double-crucible method is widely ap-

plied in manufacturing chalcogenide glass PCF. This dual-core PCF we designed is arranged in a rectangle and is composed uniform air holes, which will help to reduce the negative impact of material stress in the manufacturing process. Meanwhile, the moderate air-filling fraction is selected to avoid the collapse of large air holes. Our research group is preparing As_2S_3 chalcogenide glass for experiment and test, and stands a good chance of fabricating an appropriate structure for PCF.

5. Conclusion

This paper presents an As_2S_3 chalcogenide glass mid-infrared dual-core PCF. The high polarization maintaining property and the coupling characteristics of this PCF is studied by using the finite element method and mode coupling theory. When the lattice pitches $\Lambda_x = 6$ μm and $\Lambda_y = 5.4$ μm and air hole radius $r = 2.3$ μm, the birefringence can reach 0.01386 at wavelength $\lambda = 10$ μm, and the coupling lengths are 261 and 271.44 μm for x-polarized mode and y-polarized mode at wavelength $\lambda = 5$ μm, respectively. When the fiber length is 6.786 mm, it can achieve the separation of two polarized lights, so we can use this PCF as a polarization beam splitter. When the fiber length is 13.572 mm, due to generating coupling of two beams of polarized light, it can be used as polarization independent coupler. At wavelength $\lambda = 5$ μm, the extinction ratio can reach -64.6 dB, and are better than -10 dB from 4.9 to 5.08 μm with a bandwidth of 180 nm. In conclusion, the coupling length and polarization maintaining are combined in the As_2S_3 chalcogenide glass mid-infrared dual-core PCF, which has a great application value for manufacturing mid-infrared band optical fiber couplers or polarization beam splitters.

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