A novel polarization splitter based on octagonal dual-core photonic crystal fiber*

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(Received 14 March 2016)

A novel polarization splitter based on octagonal dual-core photonic crystal fiber (O-D-PCF) is proposed. The impacts of several fiber parameters on the coupling characteristics of the polarization splitter are investigated by full-vectorial finite element method (FV-FEM) in detail. Through optimizing the fiber configuration, a 4.267-mm-long polarization splitter with a bandwidth of 37 nm is achieved, and its extinction ratio (*ER*) is as high as 81.2 dB at the wavelength of 1.55 μm. Compared with the hexagonal dual-core photonic crystal fiber (H-D-PCF) based polarization splitter, both *ER* and bandwidth of the O-D-PCF based one are effectively improved.
Document code: A **Article ID:** 1673-1905(2016)04-0257-4
DOI 10.1007/s11801-016-6057-7

In recent years, a great number of polarization splitters based on photonic crystal fiber (PCF) have been reported. In order to achieve high extinction ratio (*ER*), three-core and elliptical-hole configurations were introduced[1-5]. Liu et al[6] demonstrated that the polarization splitter based on tellurite glass dual-core PCF possesses shorter length, and designed a 0.36 mm-long splitter at the cost of a narrow bandwidth. Meanwhile, the broadband characteristics of polarization splitters were also studied. Square-lattice dual-core PCFs are proved to be a competitive candidate for broadband polarization splitters[2,5,7]. Li et al[8] designed a novel polarization splitter with bandwidth of 190 nm, and it is a kind of dual-core hybrid PCF in which one-line air holes are replaced by high refractive index material. Similarly, Lu et al[3] presented an ultra-broadband polarization splitter based on a three-core PCF with two fluorine-doped cores, which has a bandwidth of 400 nm.

However, previously reported dual-core PCF-based polarization splitters were focused on good *ER*, short length and broad bandwidth, but few of them were fabricated successfully. Different sizes of air holes may cause deformation and collapse, especially, employing other refractive index material. Air holes with square-lattice arrangement usually lead to high confinement loss. Therefore, designing the splitters with a simple air-hole pattern and homogenous material is the key to practical applications. In this paper, an octagonal dual-core PCF (O-D-PCF) polarization splitter with greatly simplified structure is demonstrated, which has only one elliptical hole and a single host material. The proposed splitter provides *ER* of 81.2 dB at 1.55 μm. Moreover, the novel splitter can achieve an ultra-low confinement loss of 0.002 dB/m at 1.55 μm for ring number of 5. The proposed O-D-PCF may be useful for coherent optical communication systems and optical-fiber sensing systems.

The cross section of the proposed O-D-PCF is illustrated in Fig.1. Herein, air holes arrange in an octagonal array with lattice constant Λ_1, and the spacing between air holes on the same ring is $0.765\Lambda_1$, proportionately. The diameter of the circular air holes (d) is 1 μm. The elliptical air hole E in the center has major-axis R_x and minor-axis $d/2$. The pitch between E and the circular air hole M in the second ring is Λ_2. Core A and core B are formed by E, M, and the circular air holes around them. The refractive index of background can be obtained from the Sellmeier formula[9].

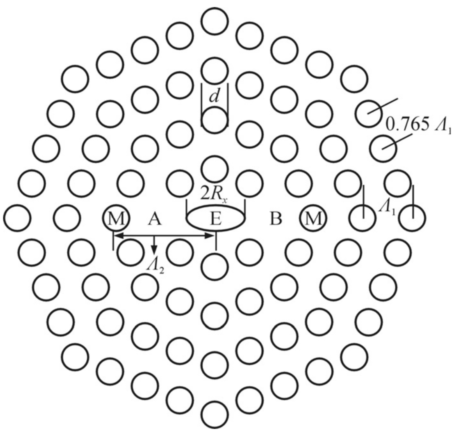

Fig.1 Cross section view of the proposed O-D-PCF

* This work has been supported by the National Natural Science Foundation of China (No.61405096).
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According to the theory of the mode coupling, the mode field of O-D-PCF consists of super-modes for *x* and *y* polarization, which are odd mode in *x* polarization, even mode in *x* polarization, odd mode in *y* polarization and even mode in *y* polarization. Modes with the same polarization produce mode coupling when they propagate along the fiber axis. The coupling length L_c can be derived as

$$L_c^{x,y}=\frac{\lambda}{2(n_{\mathrm{even}}^{x,y}-n_{\mathrm{odd}}^{x,y})}, \tag{1}$$

where λ is the operation wavelength, and $n_{\mathrm{even}}^{x,y}$ and $n_{\mathrm{odd}}^{x,y}$ are the effective indices of the even modes and odd modes for *x* polarization and *y* polarization, respectively. L_c^x and L_c^y usually are different because of the introduction of the birefringence. If the total physical length is $L=mL_c^x=nL_c^y$ (*m* and *n* are integers with opposite parity), the incident light with two orthogonal polarization directions will totally exit at different ports. We will define the ratio $\delta=L_c^y/L_c^x$ as the coupling length ratio. Further, the ratio can be described as follows:

$$\delta=\frac{n_{\mathrm{even}}^{x}-n_{\mathrm{odd}}^{x}}{n_{\mathrm{even}}^{y}-n_{\mathrm{odd}}^{y}}. \tag{2}$$

In order to obtain a short length and excellent performance polarization splitter, the optimal δ value is 2 (m=2, n=1, $L_c^y>L_c^x$). Assuming that the input port is core A, $P_{\mathrm{out},x}^{\mathrm{A}}$ and $P_{\mathrm{out},y}^{\mathrm{A}}$ are the output powers of *x* and *y* polarization directions in core A, and given by[10]

$$P_{\mathrm{out},x}^{\mathrm{A}}=P_{\mathrm{in}}\cos^2\left(\frac{\pi L}{2L_c^x}\right), \tag{3}$$

$$P_{\mathrm{out},y}^{\mathrm{A}}=P_{\mathrm{in}}\cos^2\left(\frac{\pi L}{2L_c^y}\right), \tag{4}$$

where P_{in} is the power of the incident light, and L_c^x and L_c^y can be acquired from Eq.(1).

The coupling length ratio δ, which affects both bandwidth and *ER*, is proved to be 2 as the best choice for the splitter. With respect to the O-D-PCF, three physical parameters (R_x, Λ_1 and Λ_2) have significant influence on the δ value. In this research, these geometrical parameters of O-D-PCF are continuously optimized by the finite element method (FEM).

Firstly, the effect of R_x on the coupling properties is discussed. Fig.2(a) shows the R_x variation of the coupling length and the δ value with Λ_1=2 μm, Λ_2=4 μm at λ= 1.55 μm. The coupling length L_c and δ value can be achieved from Eq.(1) and Eq.(2), respectively. It can be seen in Fig.2(a) that L_c^x, L_c^y and δ increase with R_x. The mode coupling is weakened as R_x increases, and L_c^y is always larger than L_c^x. When R_x is 1.1 μm, the δ value approaches 2. This enables the possibility of achieving a high performance splitter by use of the O-D-PCF.

Then, for the sake of optimizing δ value further, Λ_1 is varied. When parameters of R_x=1.1 μm and Λ_2=4.0 μm are fixed, the influence of Λ_1 on the coupling characteristics is investigated. The results indicate that L_c^y mainly decreases with Λ_1, while L_c^x remains almost flat in Fig.2(b). The δ value reaches 1.944 4, while Λ_1 is around 2.0.

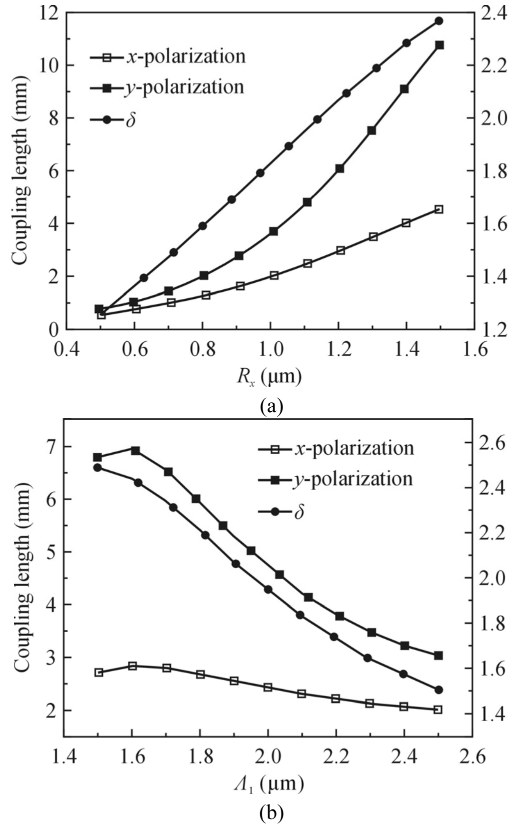


Fig.2 Coupling length and δ as a function of (a) R_x (Λ_1=2.0 μm, Λ_2=4.0 μm) and (b) Λ_1 (R_x=1.1 μm, Λ_2= 4.0 μm)

Further simulated results show that the distance between the air holes E and M (Λ_2) is a key parameter for the micro-adjustment of the splitter. As shown in Fig.3, the δ values are well confined around 2 (from 1.8 to 2.1). Meanwhile, both L_c^y and L_c^x are almost linearly correlated with Λ_2, under the condition that the parameters of R_x= 1.1 μm and Λ_1=2.0 μm are fixed. And the coupling strength is enhanced along with the decrease of Λ_2. We observe that the δ value is one step closer to 2 as Λ_2 is set to 3.9 μm in Fig.3.

Based on the above discussions, we find that when the optimal parameters of the O-D-PCF (R_x=1.1 μm, Λ_1= 2.0 μm, Λ_2=3.9 μm) are set, a high performance polarization splitter will be achieved. The coupling length and confinement loss are varied with the wavelength for *x* and *y* polarization in Fig.4(a). With increasing the wavelength, the coupling length decreases. The reason is that the constraint caused by the dual core for the incident light is weakened with the increase of the wavelength. Simulation results show that at λ=1.55 μm, $L_c^y = 4.267$ mm, $L_c^x = 2.137$ mm, δ=1.996 5, and the confinement loss is as low as 0.2 dB/m, which can be further reduced by adding the air hole rings in the cladding without affecting the coupling characteristics. Fig.4(b) shows the confinement losses of different polarizations versus wavelength for ring number of N_r=4 and 5. It can be concluded from Fig.4(b) that the confinement loss is reduced by two orders of magnitude. Fig.4(c) shows the fundamental electric field properties of odd modes and even modes for *x* and *y* polarization, and it is apparent that the fundamental modes are well confined in the cores.

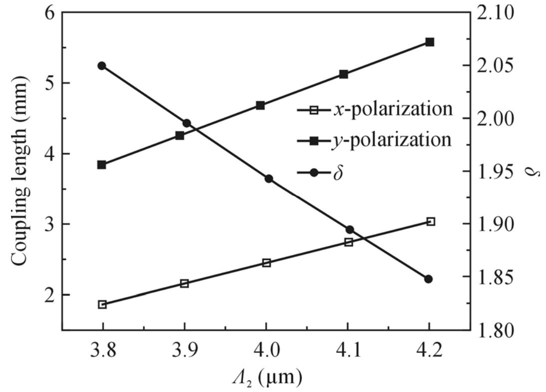
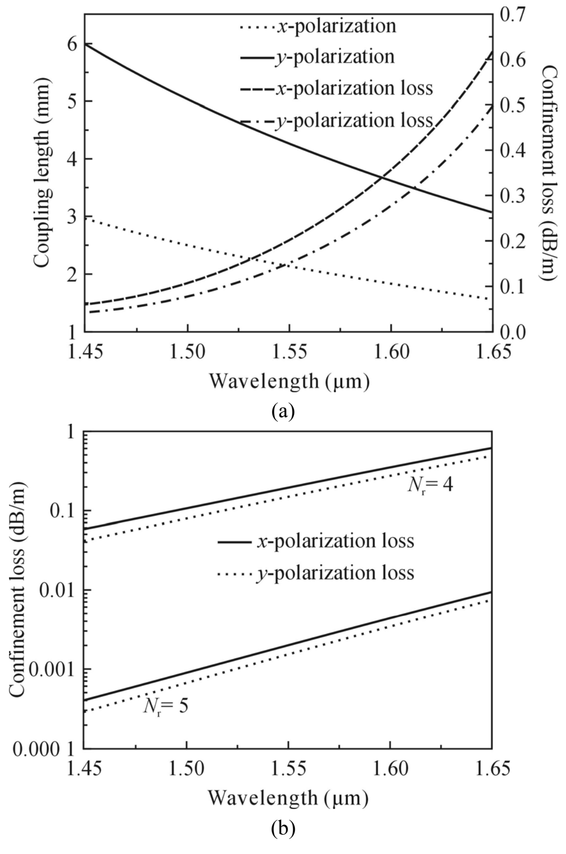


Fig.3 Coupling length and δ as a function of Λ_2 with R_x=1.1 μm, Λ_1=2.0 μm at λ=1.55 μm



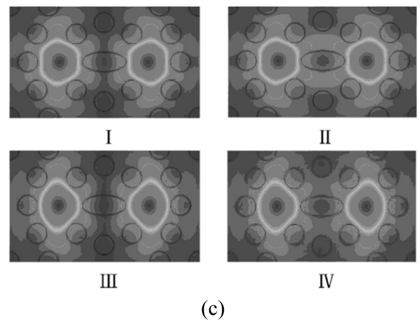


Fig.4 (a) Coupling length and confinement loss as a function of wavelength for optimal design parameters; (b) Confinement loss as a function of wavelength for N_r=4 and N_r=5; (c) Mode fields at 1.55 μm of (I) odd mode in *x* polarization, (II) even mode in *x* polarization, (III) odd mode in *y* polarization, and (IV) even mode in *y* polarization

The coupling lengths L_c^x and L_c^y of the O-D-PCF are different owing to the birefringence caused by the structure of the dual-core and the elliptical central hole, so the normalized powers for *x* and *y* polarization obtained from Eq.(3) and Eq.(4) are different. Supposing that the input port is core A at the wavelength of 1.55 μm, the variations of the normalized transmission power with propagation distance for different polarization are shown in Fig.5(a). It can be seen from Fig.5(a) that the output power for *x* polarization reaches the maximum while the power for *y* polarization is close to zero at propagation distance of 4.267 mm. These results show that the incident light can be split into two orthogonal polarization states when the length of O-D-PCF is *L*= 4.267 mm.

The *ER* is considered to be the standard for measuring the performance of a polarization splitter. Commonly, two perpendicular polarization states of light are deemed to be separated as the *ER* is more than 20 dB. Assuming that the incident light enters core A, the *ER* of output port A is defined as

$$ER = 10\log_{10}\frac{P_{\mathrm{out},x}^{\mathrm{A}}}{P_{\mathrm{out},y}^{\mathrm{A}}}, \qquad (5)$$

where $P_{\mathrm{out},x}^{\mathrm{A}}$ and $P_{\mathrm{out},y}^{\mathrm{A}}$ can be obtained from Eq.(3) and Eq.(4). Fig.5(b) shows the *ER* as a function of the wavelength with the device length of 4.267 mm. A polarization splitter with high *ER* of 81.2 dB at 1.55 μm is obtained from Fig.4(b). In addition, the bandwidth of the splitter is 37 nm from 1 531 nm to 1 638 nm.

The principle of the splitter is that the difference in effective indices of the *x* polarized and *y* polarized modes could be increased by enhancing the birefringence. As for dual-core PCF, low birefringence already exists[11]. The dual-core PCFs with different birefringence possess different coupling properties. Hence, the comparison of polarization splitters based on different kinds of PCFs is essential.

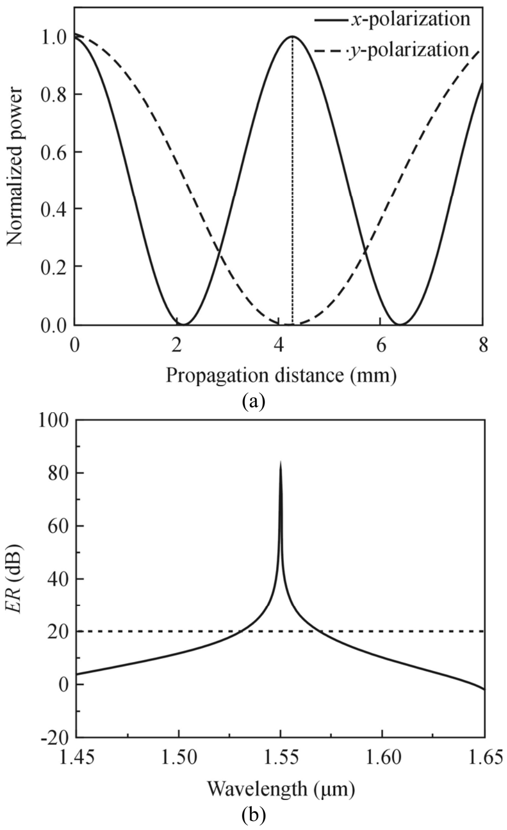
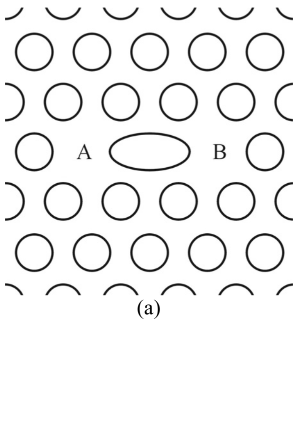


Fig.5 (a) Normalized power for *x* and *y* polarization versus propagation distance; (b) Wavelength dependence of *ER* at the optimal parameters

To verify the characteristics of the novel splitter with high *ER* and broad bandwidth, another reference simulation about the most common PCF (hexagonal dual-core photonic crystal fiber, H-D-PCF) with the same parameters is carried out. Fig.6 shows the cross sections of H-D-PCF and O-D-PCF. Polarization splitters based on the two types of PCFs embody splitting properties of the coupling length ratio (δ), fiber length (*FL*), *ER* and bandwidth for core A (ER_A, BW_A), *ER* and bandwidth for core B (ER_B, BW_B). These properties are listed in Tab.1 (λ=1.55 μm). By contrast, the δ value of the O-D-PCF is closer to 2 than the H-D-PCF. Therefore, the splitter based on the O-D-PCF can achieve higher *ER* and broader bandwidth for both core A and core B. In particular, the bandwidth of core B for H-D-PCF is zero, for its *ER* is under the standard (20 dB). In a word, the splitter based on O-D-PCF can achieve higher performance for both *ER* and bandwidth.



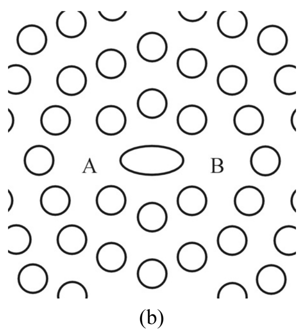


Fig.6 Cross section views of (a) H-D-PCF and (b) O-D-PCF

Tab.1 Comparison of coupling characteristics between the O-D-PCF and the H-D-PCF at 1.55 μm

Structure	δ	*FL* (mm)	ER_A (dB)	BW_A (nm)	ER_B (dB)	BW_B (nm)
H-D-PCF	1.915	3.710	68.926	24	17.518	0
O-D-PCF	1.997	4.267	81.243	37	45.022	19

In summary, a novel simple-structure high-performance polarization splitter based on the O-D-PCF is proposed. The numerical simulation results indicate that the high ER of the O-D-PCF is 81.2 dB at 1.55 μm, and its confinement loss is as low as 0.002 dB/m. In comparison with the hexagonal dual-core PCF, both *ER* and bandwidth are effectively improved. Due to the excellent splitting characteristics, the proposed O-D-PCF based polarization splitter will be a promising candidate for coherent optical communication systems.

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