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RESEARCH ARTICLE

Polarization beam splitter based on photonic crystal fibers

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Abstract Polarization beam splitters (PBSs) are a special kind of coupler. They can split incoming light from a single fiber into two orthogonally polarized beams. They are usually used in coherent optical communication systems, optical sense systems and optical measurement systems. In this paper, two kinds of mechanisms of the PBSs based on photonic crystal fibers (PCFs) are discussed. The full-vector finite element method (FEM) was employed to analyze propagating properties, while the full-vector beam propagation method (BPM) was applied to analyze preferences of the splitters. The results show that it is possible to achieve a compact PBS with high extinction ratio.

Keywords fiber and waveguide optics, polarization beam splitters (PBSs), finite element method (FEM), photonic crystal fibers (PCFs)

1 Introduction

Polarization beam splitters (PBSs) are essential components in integrated photonics and have many applications. Light is divided into two orthogonal modes by PBSs and is emitted in different paths. Various types of PBSs have been reported in the literature. Tol et al. designed PBSs based on an asymmetric Y-branched semiconductor waveguide [1–3]. Miliou et al. reported a glass waveguide PBS based on stress-induced birefringence in an ion-exchange waveguide [4]. Thyagarajan et al. proposed PBSs based on resonant tunneling in three-core couplers [5]. These PBSs can be easily fabricated and are cost-effective, but long coupling length is required.

Recently, photonic crystal fibers (PCFs) have attracted great research interest [6–11]. PCFs consist of microscopic holes running parallel to the fiber axis and down the entire length of the fiber. These new fibers were first proposed by Knight et al. According to the light-guided mechanism, PCFs can be divided into two different types. The first is index-guiding PCFs, where light is guided by total internal reflection (TIR). The second is photonic band-gap fibers, where light is guided by the photonic band gap effect exhibited by a perfect periodic structure in the cladding region. PBSs based on PCFs have also attracted much attention. Zhang et al. reported PBSs based on highly birefringent dual-core PCFs [12]. The coupling length is 1.7 mm and the extinction ratio is −11 dB at wavelength λ = 1550 nm. Saitoh et al. proposed three-core PBSs based on resonant tunneling [13]. The coupling length is 1.9 mm and the extinction ratio is −36 dB at wavelength λ = 1550 nm. Rosa et al. reported PBSs based on square-lattice PCFs [14]. The coupling length is 20 mm and the extinction ratio is −23 dB at two wavelengths λ = 800 nm and λ = 3020 nm.

PBSs based on PCFs are mainly divided into two types. One is high-birefringence PBSs. High birefringence is induced in two-core PCFs by breaking their circle-symmetrical structure. The coupling length of the high-birefringence PBSs is short and the extinction ratio is relatively low. The other type is resonant tunneling PBSs. Resonant tunneling phenomenon is induced in three-core PCFs. The PCF is designed such that one polarization mode between the outer cores strongly interacts through the resonant tunnel, while the interaction for the other polarization mode is much weaker. The coupling length of this type of PBS is longer and the extinction ratio is relatively high.

In the paper, two different PBSs have been analyzed theoretically. The optimized cross-sections of two types of PBSs have been proposed. The indices of the two orthogonal modes have been calculated with a full-vector finite element method. The performance is discussed with a full-vector beam propagation method.

2 High-birefringence PBSs

There are four nearly degenerate supermodes in normal dual-core optical fibers. According to the parity of the mode field with respect to the geometric symmetry axis

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between two cores, they are the x-polarized even mode $E_{xe}(x, y)$, y-polarized even mode $E_{ye}(x, y)$, x-polarized odd mode $E_{xo}(x, y)$ and y-polarized odd mode $E_{yo}(x, y)$. The propagation constants are β_{xe}, β_{ye}, β_{xo} and β_{yo}, respectively. The coupling length of x-polarized mode L_c^x is the distance along the fiber in which there is a total transfer of x-polarized mode power from one core to the other. The coupling length of y-polarized mode L_c^y is the same.

$$L_c^x = \frac{\pi}{\beta_{xe} - \beta_{xo}}, \tag{1}$$

$$L_c^y = \frac{\pi}{\beta_{ye} - \beta_{yo}}. \tag{2}$$

If the dual-core optical fibers are induced high birefringence, the four supermodes no longer degenerate and need to resolve four equations. In this case, L_c^x is different from L_c^y. If the parameters of an optical fiber are chosen to satisfy the condition $L_c^y = 2mL_c^x$ (m = 1, 2, 3,...), the supermodes for different polarizations will yield different cores. Therefore, two orthogonal modes are split.

Figure 1 shows the cross-section of the proposed high-birefringence PBSs based on PCFs. It is induced high birefringence by elliptical air cores and rectangular lattice. We choose the length of minor axes a = 0.2 μm, the length of major axes b = 0.8 μm, the short side of rectangular lattice w = 0.8 μm, and the long side of rectangular lattice Λ = 4 μm. Numerical results show that the coupling lengths are 0.534 and 1.054 mm for the x- and y-polarized mode, respectively. If the length of the PCF is 1.054 mm, the x-polarized mode can be obtained in core A and the y-polarized mode can be derived in core B.

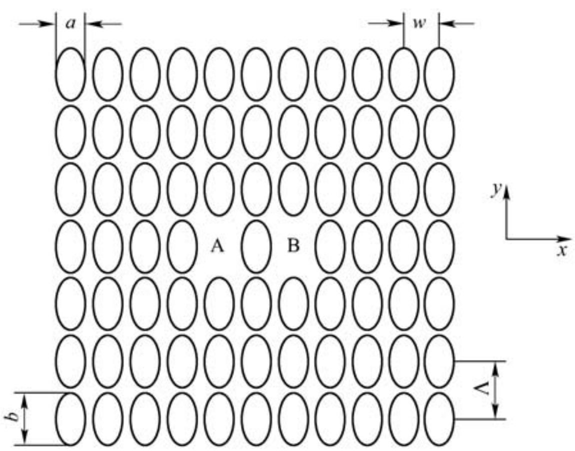

Fig. 1 Cross-section of PBS based on highly birefringent PCF

Figure 2 shows the normalized power distribution along the x-axis at the end of the PBSs. The length of the splitter is 1.054 mm. The incident wavelength is λ = 1550 nm. If the input field is x-polarized, the power is almost at the end of the splitter in core A. If the input field is y-polarized, the power is almost in core B.

Moreover, a high extinction ratio can be obtained for the PBSs. The extinction ratio is defined as [13]

$$E_R = 10\lg\frac{P_{y\text{-polarized}}}{P_{x\text{-polarized}}}, \tag{3}$$

where $P_{y\text{-polarized}}$ is the output power for y-polarized mode and $P_{x\text{-polarized}}$ is the output power for x-polarized mode.

Numerical results with beam propagation method (BPM) indicate that the extinction ratio is about −16.9 dB at λ = 1550 nm.

3 Resonant tunneling PBSs

Figure 3 shows the cross-section of the proposed resonant tunneling PBSs. The centers of all air holes are arrayed in a regular triangular lattice with pitch Λ = 2 μm. It consists of two identical cores A and C with high birefringence separated by another birefringent core B. The large air holes with diameter d_2 = 1.8 μm are placed above and below cores A and C. The diameter of small air holes is d_1 = 1 μm. To induce high birefringence in core B, it includes an elliptical air hole with ellipticity $\eta = a/b$, where a and b are the lengths of minor and major axes, respectively.

The operation of this PBS can be explained in terms of the supermodes of the three-core directional coupler [13]. If core A, core B and core C are single-moded individually, the coupler can support three supermodes: two symmetric and one anti-symmetric mode. Figure 4 shows the field profiles E_y of the three supermodes. The two field profiles in Figs. 4(a) and 4(b) are symmetric and the one in Fig. 4(c) is anti-symmetric. The effective refractive indices are $n_{\text{eff},1}$, $n_{\text{eff},2}$, $n_{\text{eff},3}$, respectively. If $n_{\text{eff},1}$, $n_{\text{eff},2}$, $n_{\text{eff},3}$, satisfy the condition

$$n_{\text{eff},1} - n_{\text{eff},3} = n_{\text{eff},3} - n_{\text{eff},2}, \tag{4}$$

namely

$$2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2} = 0, \tag{5}$$

the total power will transfer periodically between core A and core C. This phenomenon is resonance. The period is coupling length

$$L_c = \frac{\lambda}{2(n_{\text{eff},1} - n_{\text{eff},3})}. \tag{6}$$

The closer $n_{\text{eff},1}$, $n_{\text{eff},2}$, $n_{\text{eff},3}$ are to the resonance condition, the stronger the power between core A and core C will interact.

In the proposed PBS, the circle-symmetric structure is broken. The effective refractive index of the x-polarized mode is larger than that of the y-polarized mode in cores A and C. In core B, the effective refractive index of the x-polarized mode is smaller than that of the y-polarized mode. Thus, it is possible to choose parameters as

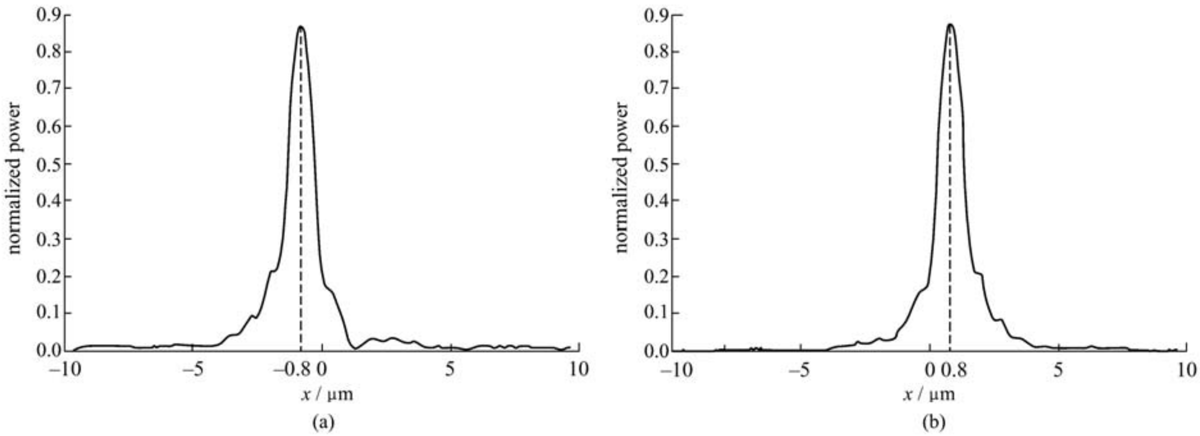

Fig. 2 Normalized power intensity for x- and y-polarized lights after a propagation of 1.054 mm. (a) x-polarization lights; (b) y-polarization lights

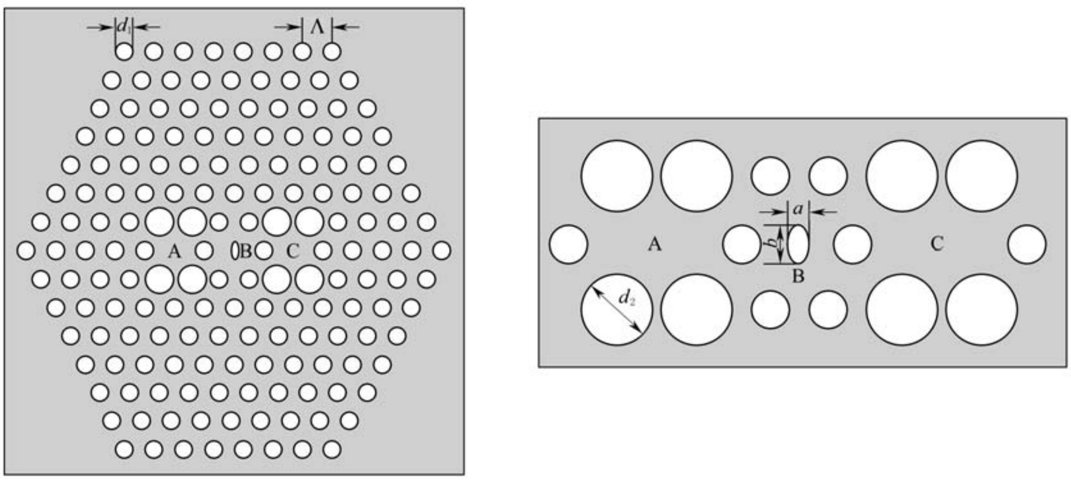

Fig. 3 Cross-section of PBSs based on resonant tunneling PCF

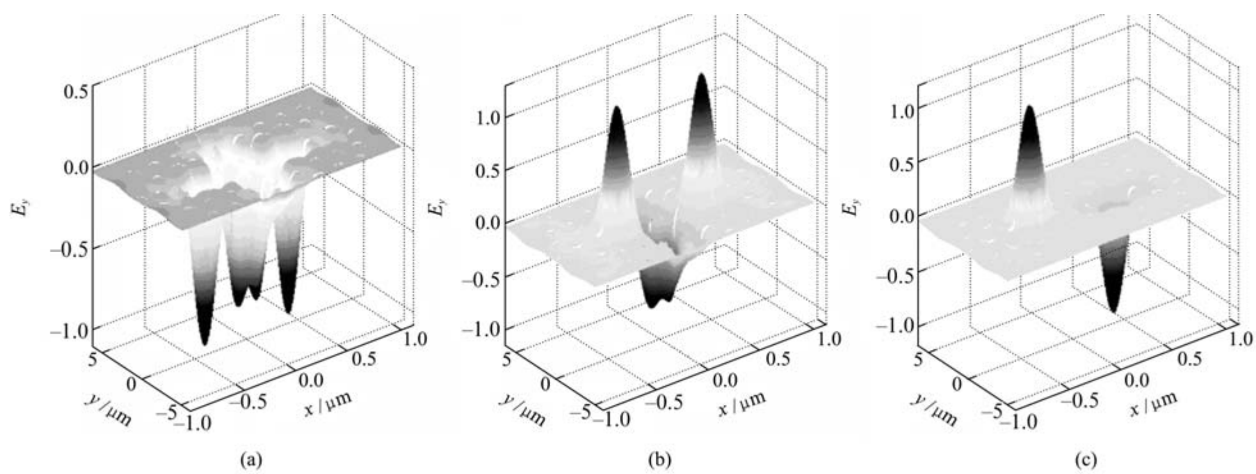

Fig. 4 Schematic diagram of three supermodes in a three-core PCF. (a) Mode 1 (even); (b) mode 2 (even); (c) mode 3 (odd)

$$(n_{\text{eff},1}-n_{\text{eff},3})_{y\text{-polarized}} \approx (n_{\text{eff},3}-n_{\text{eff},2})_{y\text{-polarized}}, \quad (7)$$

$$(n_{\text{eff},1}-n_{\text{eff},3})_{x\text{-polarized}} \ll (n_{\text{eff},3}-n_{\text{eff},2})_{x\text{-polarized}}. \quad (8)$$

The y-polarized mode is close to the resonance condition and the x-polarized mode is far from the resonance condition. Almost all power of the y-polarized mode will transfer periodically between core A and core C, while almost none of the power of the x-polarized mode will transfer. If the length of the PCF is

$$L = \frac{\lambda}{2(n_{\text{eff},1}-n_{\text{eff},3})_{\text{y-polarized}}}, \quad (9)$$

the power of the y-polarized mode will almost be put out in core C and the power of the x-polarized mode will be confined in core A. Thus, the orthogonal polarization states are split.

In the proposed configuration, we maintain the ellipticity η = 1/2. Figure 5 shows the value of n, $n = 2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2}$, for y-polarized mode as a function of the length of minor axes. At the point a = 0.302 μm, the value of n is nearly zero.

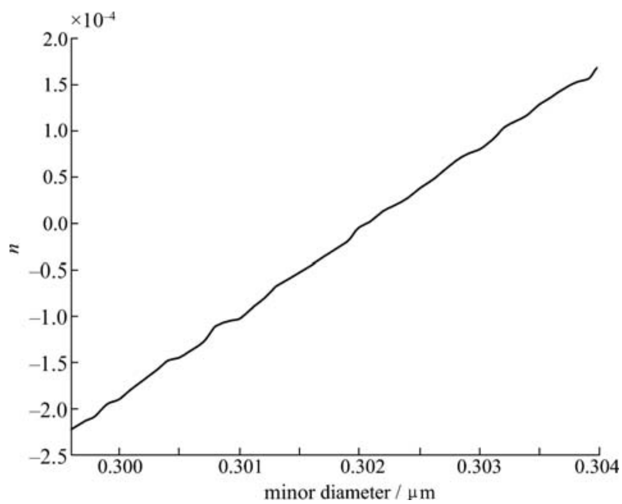

Fig. 5 Variation of the value of n for y-polarization light versus the minor axes of an elliptical-hole

Figure 6 shows the normalized power transfers in core A and core C along the PBSs. The length of the splitters is 1.039 mm, while the incident wavelength is 1550 nm. We can see that the power of the y-polarized mode is almost in core C at the end of the PBSs, while the power of the x-polarized mode is almost confined in core A. Numerical results with BPM indicate that the extinction ratio is −36.98 dB at λ = 1550 nm.

4 Conclusion

Two orthogonally polarized modes can be divided by a PBS. Such splitters are widely used in the field of coherent communication systems, optical fiber sensor systems and optical fiber measurement systems. High birefringence can be easily induced in PCFs because the index contrast is higher than that in conventional fibers and the cross-sections of PCFs can be designed flexibly. It is advantageous for designing PBSs. In this paper, two different types of PBSs have been proposed: high-birefringence PBSs and resonant tunneling PBSs. Numerical results show that it is possible to optimize a PCF to achieve a compact PBS with high extinction ratio.

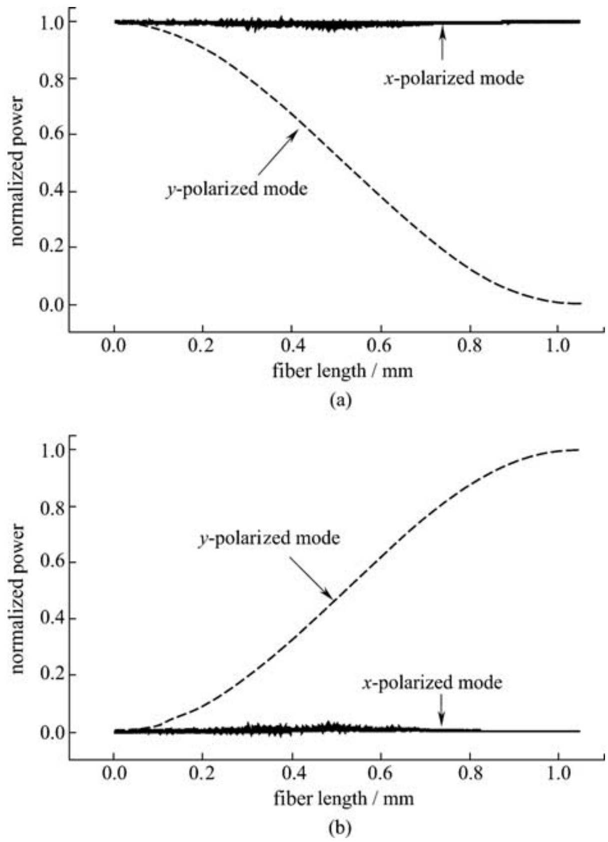

Fig. 6 Normalized power transfers versus the length of fiber. (a) In core A; (b) in core C

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