Effective polarization splitters based on dual-core photonic crystal fibers with elliptical holes

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We investigate the coupling characteristics in dual-core photonic crystal fibers (PCFs) with elliptical air holes and their applications in the construction of polarization splitters by use of a full-vector beam propagation method. The numerical simulation results indicate the possibility of realizing a polarization splitter with an extinction ratio better than −20 dB at 1.55 μm and a total length of only 1.651 mm. It is also revealed that the total length of the polarization splitters can be further reduced by properly doping the core regions of the PCFs.

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In the last decade, much attention has been paid to photonic crystal fibers (PCFs) because of their unique properties that are not available in conventional optical fibers[1,2]. The cross section of a PCF usually consists of a periodic arrangement of air holes. In addition, a defect is generally introduced into the PCFs, acting as a core for guiding light. In PCFs, the mechanism for the guiding of light can be classified into two types. One is based on the index-guiding effect and another relies on the photonic bandgap (PBG) effect. The index-guiding in PCFs is quite similar to the total internal reflection in conventional optical fibers and light is trapped in the high-index defect[3,4]. As for PCFs utilizing the PBG effect, the refractive index of the core is allowed to be lower than that of the cladding[5,6].

Coupling devices based on dual-core fibers are highly desirable in optical communication systems. However, it is rather difficult to realize such devices by using conventional optical fibers[7]. Recently, realization of power directional couplers by use of dual-core PCFs has been reported by different research groups[8−12]. Apparently, PCFs offer an alternative way and more flexibility for the realization coupling devices. For example, Zhang *et al.* suggested a design principle for realizing of compact polarization splitter based on dual-core PCFs with large birefringence[13,14]. In addition, polarization splitters based on three-core PCFs have been proposed by Saitoh *et al.*[15]. However, the modification of the birefringence in these structures was realized by deliberately increasing or decreasing the size of some air holes near the core region, adding more difficulties in manufacture. It is also worth noting that PCFs with squeezed hexagonal lattice and rectangular lattice have been investigated, respectively[16,17]. However, the splitting length in these PCFs is too long to realize compact devices for integrated circuits.

We investigate the coupling characteristics of dual-core PCFs with uniformly elliptical air holes by use of a full-vector beam propagation method (BPM). Based on this, we propose a new polarization splitter in which the large birefringence is achieved by controlling the ellipticity of the air holes. By optimizing the structural parameters of the dual-core PCF, we can build a polarization splitter of only 1.651-mm long and with an extinction ratio better than −20 dB at 1.55 μm. Moreover, it is revealed that the total length of the polarization splitter can be further reduced by properly doping the core regions of the PCFs.

So far, various methods and techniques have been developed to study the propagation of light in PCFs[19,20]. Here, we employ the full-vector BPM to evaluate the coupling characteristics of PCFs with elliptical air holes. The validity and accuracy of the method have been demonstrated previously in Ref. [11].

The cross section of the dual-core PCF with elliptical air holes is schematically shown in Fig. 1(a). The three parameters used to describe the structure of the PCFs are the pitch (Λ) and the major (d_a) and minor (d_b) axes of the elliptical air holes. Here, we investigate the case in which the ellipticity η, which is defined as d_a/d_b, is larger than or equal to one (i.e., $\eta \geq 1$). The two core regions of the PCF, marked by A and B in Fig. 1(a), are formed by the removal of two air holes. In order to improve the physical properties of the dual-core PCF, one of the possible modifications is shown in Fig. 1(b), we can selectively dope the two core regions of the PCF. In Fig. 2, we present the dependence of the coupling length L for the x- and y-polarized light at 1.55 μm on the ellipticity of the air holes. The coupling length L is derived from the propagation constants of the even (β_e) and odd (β_o) modes of the PCF by

$$L = \frac{\pi}{\beta_\mathrm{e} - \beta_\mathrm{o}}. \qquad (1)$$

In Fig. 2, we have simulated three PCFs in which Λ is fixed to be 2.0 μm and the values of d_b are taken to be 0.40, 0.50, and 0.60 μm, respectively. Obviously, L

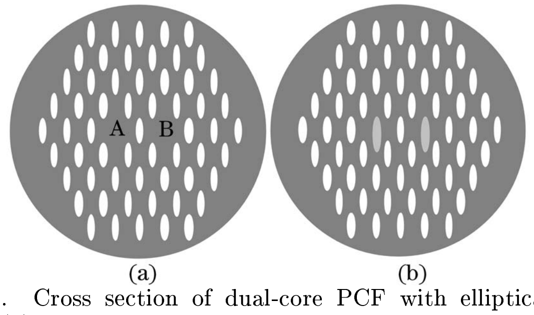

Fig. 1. Cross section of dual-core PCF with elliptical air holes (a) and modified dual-core PCF with doping in the two core regions (b). The French gray ellipses indicate the doped regions.

increases rapidly with increasing d_b for the same η. For both the x- and y-polarized light, it increases with increasing η when d_b is fixed. In all cases, the increase of L with η is more rapid for the y-polarized light. In Fig. 2, we also notice that the increase of L is not linear and a rapid increase appears when η is larger than 2.0, especially for the y-polarized light. In conventional waveguide couplers, it is known that the difference in coupling length for two orthogonal modes is generally governed by the different boundary conditions at the core-cladding interfaces. In the dual-core PCFs studied here, however, the physical mechanism for light coupling is different. In fact, it has been revealed that the polarization dependence of light coupling originates mainly from the different effects of the narrow silica bridges on the polarized light[14]. For example, d_a is 1.0 μm when d_b is 0.50 μm for $\eta = 2$. In this case, the distance between the edges of two adjacent elliptical air holes is about 1.0 μm in the y direction. Thus, the structural size of the silica bridges is comparable to light wavelength (1.55 μm)[14]. When $\eta = 4.0$, d_a is 2.0 μm for $d_a = 0.50$ μm. The two adjacent elliptical air holes in the y direction are very close and the structural size of the silica bridges becomes smaller. Therefore, the change of coupling length is more obvious for the y-polarized light when η is increased from 2.0 to 4.0. In contrast, the change in the structural size of the silica bridges is much smaller in the x direction as η is increased because d_b is maintained invariable. Therefore, it is easily understood why L is much sensitive to the increase of η for the y-polarized light than for the x-polarized one.

In practice, it is convenient to introduce form birefringence B, which is defined as

$$B = \frac{L_y - L_x}{L_y}, \tag{2}$$

for describing the birefringence of the dual-core fibers. Here, L_x and L_y represent the coupling lengths for the x- and y-polarized light, respectively. In our case, the dependence of the form birefringence B on the ellipticity

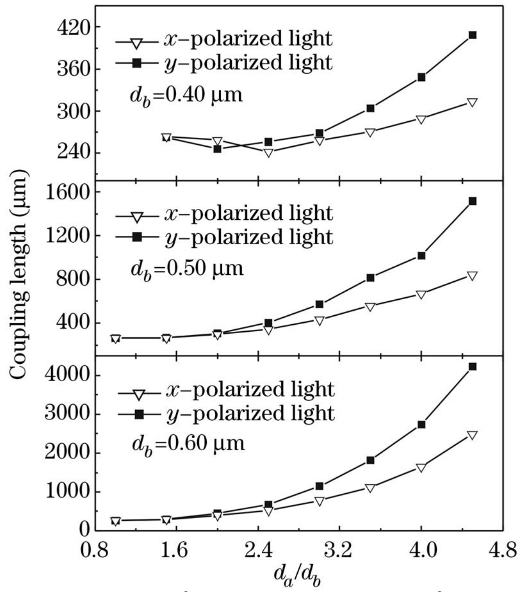

Fig. 2. Dependence of the coupling lengths for the x- and y-polarized lights on the ellipticity of the air holes.

η for the dual-core PCFs at 1.55 μm is shown in Fig. 3. It is observed that B increases with the increase of η. In addition, it is larger for bigger d_b. When $d_b = 0.50$ μm, B is close to zero for $\eta = 2.0$. When η becomes 4.0, B is markedly increased to 0.343. From Fig. 2, it is also obvious that the coupling lengths for the two polarized light are not so long ($\sim$1000 μm) in case of $d_b = 0.50$ μm. Therefore, it is expected that both high form birefringence and short coupling length could be achieved in the proposed dual-core PCFs. In the following, we will focus on the PCFs in which $d_b = 0.50$ μm. The above discussion implies that the modification of the form birefringence can be easily realized in the dual-core PCFs with uniform elliptical air holes without deliberately enlarging or decreasing the size of the air holes around the core region. In order to find out the conditions for the construction of polarization splitters possessing high extinction ratio and short splitting length, we have examined various structures with $\eta \sim 4.0$ by numerical simulations. It is found that effective polarization splitters can be achieved with structure parameters of $\Lambda = 2.0$ μm, $d_a = 1.90$ μm, and $d_b = 0.50$ μm.

We have performed numerical simulations by use of the full-vector BPM to characterize the proposed polarization splitters. Linearly polarized light with Gaussian intensity distribution is launched into core A. The wavelength of the incident light is chosen to be 1.55 μm. A strong polarization dependent coupling is observed in the normalized power transferring curves shown in Fig. 4(a). It is apparent that the x- and y-polarized lights have different coupling lengths which are estimated to be 541.3 and 829.4 μm, respectively. The two polarized modes are well separated from each other at a propagation length of $\sim$1.651 mm. Extinction ratios of −18.20 dB and −20.25 dB are achieved for the x- and y-polarized modes, respectively. The intensity distributions for the two modes at the output of the splitter are shown in Fig. 5. It can be seen that the most of the x-polarized light has been transferred to core B while the y-polarized light is remained in core A. Therefore, the dual-core PCF acts as a wonderful polarization splitter. In Fig. 6, we illustrate the normalized power in core A at the output of the splitter as a function of the incident wavelength. Obviously, there exists a 50-nm bandwidth (from 1.515 to 1.565 μm) in which the extinction ratios are better than −12.0 dB. More interesting, it is observed that the x- and y-polarized modes are also separated at $\sim$1.30 μm with

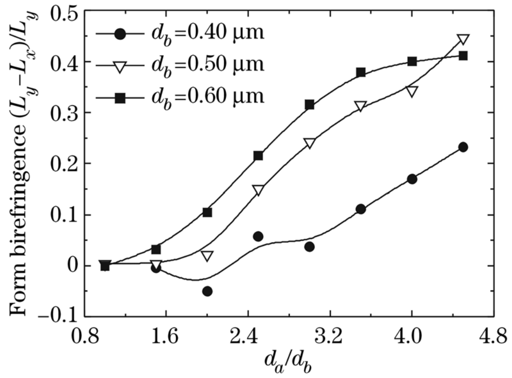

Fig. 3. Dependence of the form birefringence of the dual-core PCF on the ellipticity of the air holes.

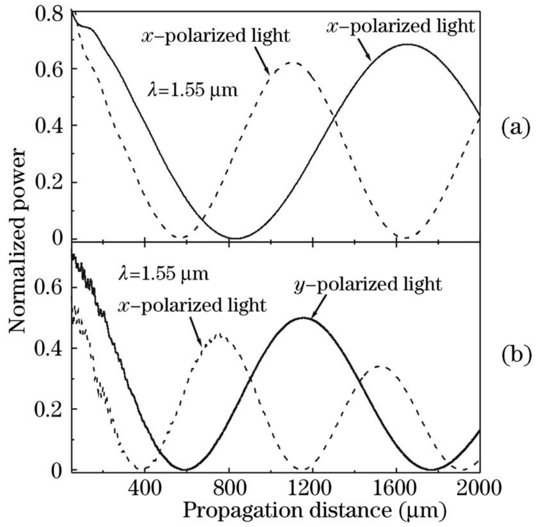

Fig. 4. Normalized power transfers for the x- and y-polarized lights versus the length of the dual-core PCF (a) and modified dual-core PCF with doping (b).

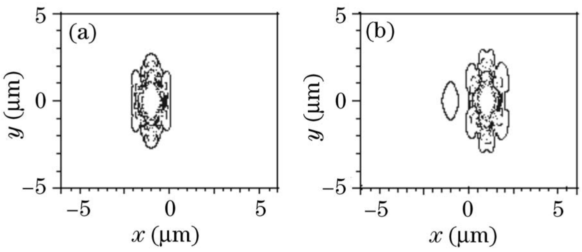

Fig. 5. Distributions of the field intensity after a propagation distance of 1.651 mm for the y-polarized (a) and x-polarized lights (b).

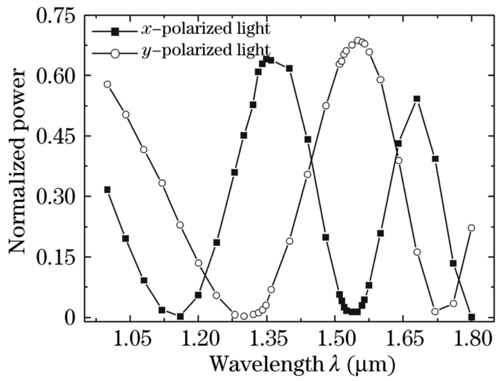

Fig. 6. Normalized power transfers for the x- and y-polarized lights versus the wavelength of the incident light.

an extinction ratio better than –12.0 dB.

Apparently, the characteristics of the polarization splitters can be further improved by either adjusting the shape of the central elliptical air hole or doping the two core regions. Here, we present some initial results on the latter modification. The structure of the PCFs with doped cores is schematically shown in Fig. 1(b). The French gray ellipses indicate the doped regions in the two cores. The absolute refractive-index difference between the pure and doped core regions is assumed to be Δ and axes of the elliptical doped regions are demoted as d_{ac} and d_{bc}, respectively. Here, we choose $\Delta = 0.03$ (down-doping) and $d_{ac}(d_{bc}) = 1.4d_a(d_b)$. The other parameters are remained unchanged ($\Lambda = 2.0$ μm, $d_a = 1.90$ μm, $d_b = 0.50$ μm). The normalized power transferring curves shown in Fig. 4(b) indicate a strong polarization dependent coupling. In addition to the high extinction ratios for the x- and y-polarized modes, we can see that the splitter length is reduced markedly from 1.651 to 1.15 mm. Thus, we think that the doping of the core regions may be an effective way to reduce the size of the polarization splitters. The issues concerning the effects of the shape and the doping level of the doped regions on the coupling length are also very attractive for device applications and are remained for exploration in future research works.

In summary, we have investigated the coupling characteristics of the x- and y-polarized light in dual-core PCFs with elliptical air holes and proposed effective polarization splitters based on these PCFs. Numerical simulation results based on a full-vector BPM have shown that the novel polarization splitter has a short length of about 1.651 mm and an extinction ratio better than -20 dB at $\lambda = 1.55$ μm. A bandwidth of 50 nm with an extinction ratio better than -12 dB is achieved at $\lambda = 1.55$ μm. Moreover, the total length of the polarization splitter can be further reduced by properly doping the core regions, making them attractive for applications in future integrated circuits. It is noticed that the fabricating technique for PCFs with elliptical air holes has been reported very recently[18].

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