Dual-core photonic crystal fiber polarization splitter based on lead silicate glass*

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A dual-core photonic crystal fiber (PCF) polarization splitter based on lead silicate glass is proposed. The characteristics of the polarization splitter are analyzed using full-vector finite element method. Compared with the silica glass PCF polarization splitter with the same structure, it is shown that the new material polarizer can realize splitting with less coupling loss and higher extinction ratio. When the wavelength is 1 550 nm and the PCF length in the beam splitter is 688 μm, the coupling loss is only 0.001 9 dB, and the extinction ratio for the input core is −64.1 dB.

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Photonic crystal fiber (PCF)[1-4] is a kind of novel microstructure fiber, which has unique characteristics, including high birefringence, high non-linearity, large mode area (LMA) and tunable dispersion. PCF is widely used in the fields of optical communications and sensing systems. The polarization beam splitter[5-11] is often implemented by a dual-core fiber in optical fiber communications for separating a beam of light into two beams with orthogonal polarization directions. Traditional dual-core fiber polarization beam splitters have the disadvantages of tedious fabrication process, long polarization coupling length, low extinction ratio, etc., whereas the emergence of PCF provides a promising solution.

Recently, dual-core PCF polarization beam splitter based on quartz substrate material is the main focus. However, with the rapid development of material science and PCF fabrication technology, non-silica-based PCF attracts much attention. Non-silica-based materials have the characteristics of high non-linear refractive index, large transmission bandwidth and much lower softening temperature (several hundred degrees of centigrade) compared with quartz (above 2 000 degrees of centigrade). In 2013, Cui[8] designed a polarization splitter based on ZnTe tellurite-based glass, and an extinction ratio of more than −20 dB with bandwidth of 34 nm was obtained. In 2014, Sheng[9] reported a compact polarization splitter based on the dual-elliptical-core PCF with similar extinction ratio and bandwidth. Rui[10] demonstrated a highly birefringent PCF polarization splitter based on soft glass, and a crosstalk of less than −20 dB with bandwidth of 100 nm was obtained. In 2015, Sun[11] studied the polarization-dependent coupling characteristics of metal-wire filled dual-core PCF, and the extinction ratio of less than −20 dB was obtained over a bandwidth of 250 nm.

In this paper, a novel dual-core PCF polarization beam splitter based on lead silicate glass is proposed, and its performance is analyzed and optimized using full-vector finite element method. The simulation shows that it can achieve shorter coupling length, lower coupling loss and higher extinction ratio in comparison with those in Refs.[7]–[11]. We also compare the characterstics of the PCF polarization splitter based on lead silicate glass with that based on silica glass.

Fig.1 is the sectional view of the dual-core PCF polarization beam splitter, in which the air holes are arranged in hexagonal lattice and the two fiber cores are formed by removing four round air holes. An air hole with the diameter of d_1, is located between two fiber cores. Two elliptical air holes are adopted in every fiber core to improve the asymmetry and the birefringence. The diameter of cladding air holes is d. Moreover, the ellipticity of elliptical air holes is $\eta=a/b$, where a and b are the short-axis length and the long-axis length of elliptical air holes, respectively. The refractive index of the lead silicate glass is well described by the Sellmeier equation[3] as

$$n(\lambda)=\sqrt{1+\frac{B_1\lambda^2}{\lambda^2-C_1}+\frac{B_2\lambda^2}{\lambda^2-C_2}+\frac{B_3\lambda^2}{\lambda^2-C_3}}\ , \qquad (1)$$

where B_1=1.816 513 71, B_2=0.428 893 641, B_3=1.071 862 78, C_1=0.014 370 419 8, C_2=0.059 280 117 2 and C_3=121.419 942.

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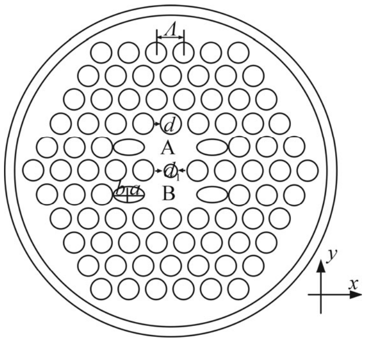


Fig.1 Cross section of the dual-core PCF polarization splitter

The transmission length for optical power to be completely transferred from one fiber core to another core is defined as the coupling length[4], which can be expressed as

$$L_x = \frac{\pi}{\beta_{xe} - \beta_{xo}} = \frac{\lambda}{2\left|n_{xe} - n_{xo}\right|},$$

(for x-polarization), (2)

$$L_y = \frac{\pi}{\beta_{ye} - \beta_{yo}} = \frac{\lambda}{2\left|n_{ye} - n_{yo}\right|},$$

(for y-polarization), (3)

where λ is the wavelength, β_{xe} and β_{ye} are the propagation constants of x-polarization and y-polarization for even modes, respectively, n_{xe} and n_{ye} are the corresponding effective refractive indices, and β_{xo}, β_{yo}, n_{xo} and n_{yo} are their odd mode counterparts. The effective refractive indices of odd modes and even modes can be calculated by using finite element method, and then the corresponding coupling length can be obtained by using Eqs.(2) and (3).

The polarization beam splitter and the polarization-irrelevant optical fiber coupler can be fabricated by using the difference of the coupling lengths corresponding to the two polarization directions in a dual-core PCF with high birefringence. The optical fiber length should satisfy $L=mL_x=nL_y$, and if the parities of m and n are opposite, the polarization beam splitter can be made. When the optical power $p_{\text{in}}^{x,y}$ is launched into core A, the output powers from the two cores are[8]

$$p_{\text{A,out}}^{x,y} = p_{\text{A,in}}^{x,y} \cos^2\left(\frac{\pi}{2}\frac{z}{L_{x,y}}\right), \tag{4}$$

$$p_{\text{B,out}}^{x,y} = p_{\text{A,in}}^{x,y} \sin^2\left(\frac{\pi}{2}\frac{z}{L_{x,y}}\right), \tag{5}$$

where the superscripts of x and y denote x and y polarizations, respectively.

Normally, the performance of the polarization splitter can be evaluated by the extinction ratio of ER_{A}, which is defined as

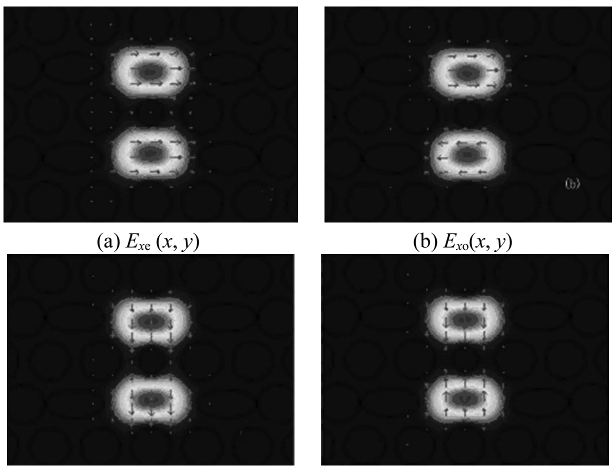
$$ER_{\text{A}} = 10\lg\left(\frac{P_{\text{A}}^{y}}{P_{\text{A}}^{x}}\right). \tag{6}$$

Ideally, when light is launched into core A, the x-polarization light is obtained from the output of core A, and the y-polarization light is obtained from the output of core B. The coupling loss of polarization beam splitter is defined as the ratio of output power and input power:

$$loss = -10\lg\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right). \tag{7}$$

The simulations for the silica glass PCF and lead silicate glass PCF with the same structure are performed. The diameter of cladding air holes d_1 is 1.1 μm, d is 0.7 μm, Λ is 1.4 μm, and the ellipticity η is 0.5. The refractive index of the lead silicate glass is given by Eq.(1), and it is 1.444 for the silica glass.

In the dual-core PCF, the overall core-mode field distributions in x and y polarizations are considered to be the superposition of even and odd modes, respectively. The composite even and odd modes are E_{xe} and E_{xo} for x polarization, E_{ye} and E_{yo} for y polarization, respectively. The field distributions of the dual-core lead silicate glass PCF for the four composite core modes are shown in Fig.2.

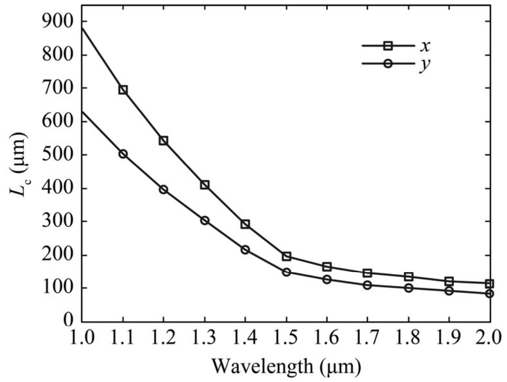


(a) $E_{xe}(x, y)$ (b) $E_{xo}(x, y)$

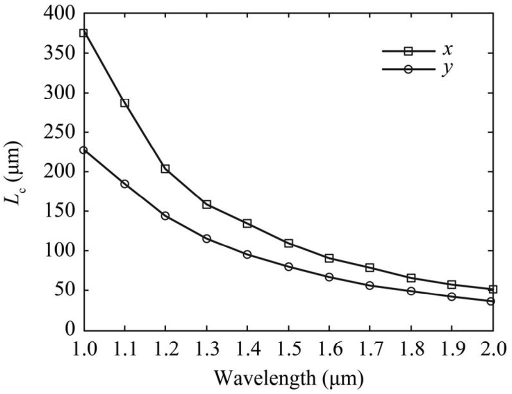
(c) $E_{ye}(x, y)$ (d) $E_{yo}(x, y)$

Fig.2 Four composite core-mode field distributions of the dual-core lead silicate glass PCF structure

The coupling effect is shown by the coupling length, i.e., the smaller the coupling length, the stronger the coupling effect. The relation between wavelength and coupling length for x and y polarized light can be obtained from Eqs.(2) and (3). The coupling lengths versus wavelength for lead silicate glass and silica glass PCFs are shown in Fig.3. At the wavelength of 1.55 μm, the coupling lengths of lead silicate glass dual-core PCF are 174.23 μm and 137.52 μm for x-polarization and y-polarization directions, respectively. The corresponding coupling lengths of silica glass dual-core PCF are 103.52 μm and 80.73 μm for x-polarization and y-polarization directions, respectively. The coupling length difference between x and y polarized light for the lead silicate glass PCF is larger than that for the silica glass PCF.



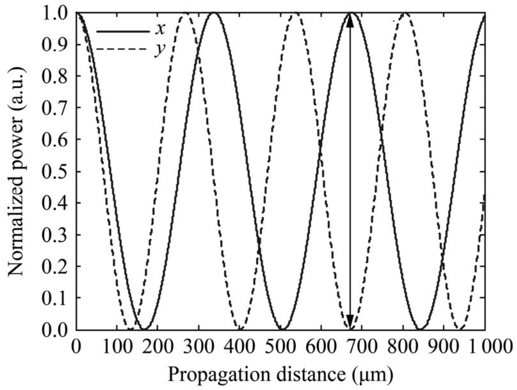
(a)



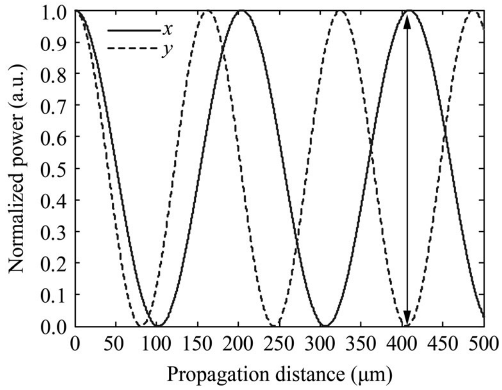
(b)

Fig.3 Coupling length versus wavelength for (a) lead silicate glass PCF and (b) silica glass PCF

Normalized transmission power versus propagation distance in core A of the dual-core PCFs based on lead silicate glass and silica glass at wavelength of 1.55 μm is shown in Fig.4. From Fig.4(a), we can see that in the lead silicate glass PCF, if the fundamental mode power is launched into the core A, and L=4L_x=5L_y=668 μm, the power of y-polarized light is completely coupled to the core B, whereas the power of x-polarized light is totally confined to the core A. From Fig.4(b), we can see that for silica glass PCF polarization splitter, when L=4L_x=5L_y=404 μm, the separation of the two polarized light beams is realized.



(a)



(a)

Fig.4 Normalized transmission power versus propagation distance for (a) lead silicate glass PCF and (b) silica glass PCF

The coupling losses for the two kinds of dual-core PCFs are calculated and compared in Fig.5. The lead silicate glass PCF with a length of 688 μm and the silica PCF with a length of 404 μm both correspond to the polarization splitter. Assuming that the light power is launched into the core A, the total output power is calculated by the sum of x-polarized light power in the core A and y-polarized light power in the core B. From Fig.5, we can see that the coupling loss of the lead silicate glass PCF splitter can achieve 0.001 9 dB at λ=1.55 μm, whereas it is 0.013 dB for the silica glass PCF splitter. This indicates that the proposed lead silicate glass PCF splitter has less coupling loss.

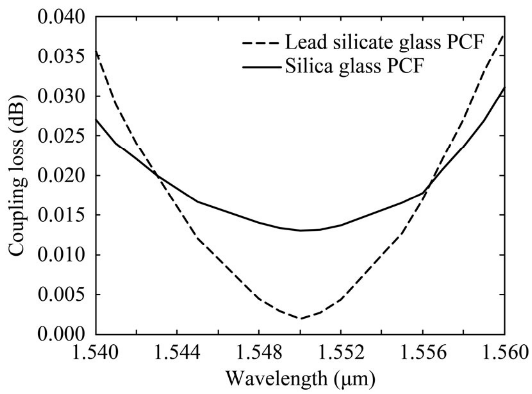
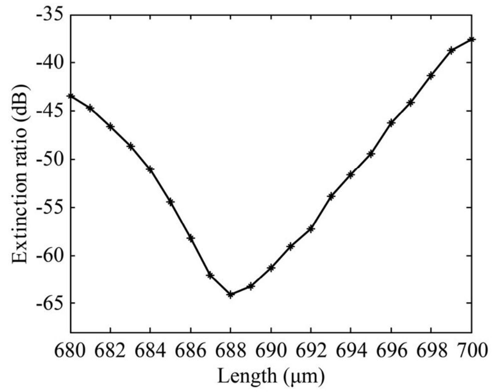


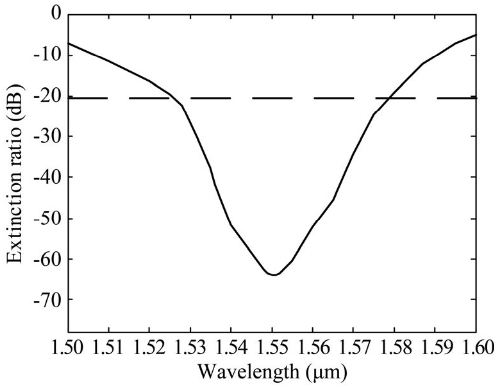
Fig.5 Coupling loss versus wavelength for two kinds of polarization beam splitters

Extinction ratio is an important index to measure the performance of the polarization beam splitter. The greater the extinction ratio, the more effective the separation of two polarized light beams. From Fig.6(a), we can see that for lead silicate glass PCF polarization splitter at λ=1.55 μm, as its length varies from 680 μm to 700 μm, the extinction ratio of the core A can reach −64.1 dB at the length of 688 μm. As shown in Fig.6(b), the splitter with length of 688 μm demonstrates a bandwidth (extinction ratio lower than −20 dB) of almost 51 nm from

1.527 μm to 1.578 μm. From Fig.7(a), we can see that for silica glass PCF polarization splitter at λ=1.55 μm, as its length varies from 396 μm to 415 μm, the extinction ratio of core A can reach −47.1 dB at the length of 404 μm. As shown in Fig.7(b), when the length of silica glass PCF is 404 μm, the bandwidth of −20 dB extinction ratio is almost 60 nm from 1.524 μm to 1.584 μm. Therefore, the lead silicate glass PCF polarization splitter can achieve higher extinction ratio and larger tolerance to the length deviation from the designed value.

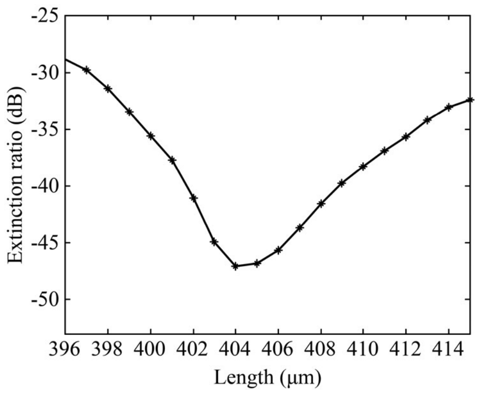


(a)

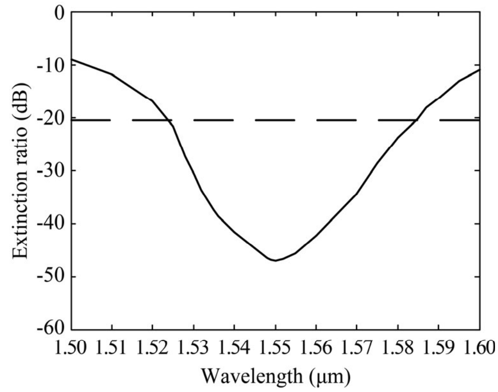


(b)

Fig.6 Extinction ratio variations with (a) length and (b) wavelength for lead silicate glass PCF polarization beam splitter



(a)



(b)

Fig.7 Extinction ratio variations with (a) length and (b) wavelength for silica glass PCF polarization beam splitter

A dual-core polarization beam splitter based on lead silicate glass PCF is proposed. The characteristics of the polarization splitter are analyzed using the full-vector finite element method and the coupled-mode theory. Then it is compared with the silica glass PCF polarization beam splitter with the same structure. It is shown that the lead silicate glass PCF polarization splitter has less coupling loss and higher extinction ratio. At the wavelength of 1.55 μm, when the PCF length is 688 μm, the coupling loss is only 0.001 9 dB, and the extinction ratio of core A is −64.1 dB. The bandwidth for the extinction ratio less than −20 dB is 51 nm.

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