A Dual Hollow-core Negative Curvature Fiber Polarization Beam Splitter Covering the O+E+S+C+L Communication Band

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Abstract: In this paper, a dual hollow-core negative curvature fiber is proposed for the polarization beam splitter. The effects of the structure parameters of the dual hollow-core negative curvature fiber on the coupling length and coupling length ratio of the x-polarized and y-polarized core modes and the higher-order mode extinction ratio are analyzed by the finite element method. Moreover, the normalized output powers of the x-polarized and y-polarized modes in the cores A and B and the corresponding extinction ratio are also investigated by the mode coupling theory. The simulation results show that the dual hollow-core negative curvature fiber polarization beam splitter with the length of 6.45 cm can achieve a broad bandwidth of 400 nm (1.23-1.63 μm), covering the O+E+S+C+L communication band. Besides, the higher-order mode extinction ratio is greater than 100 in the considered wavelength range, which means that it has good single-mode characteristics. It is believed that the proposed dual hollow-core negative curvature fiber polarization beam splitter will have significant application in the optical communication system.

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1. Introduction

As an important passive optoelectronic device, the optical fiber polarization beam splitter (PBS), which can split a beam of light into two beams of orthogonal linearly polarized beams, has a wide range of applications in the optical communication system and other fields [1-6]. For the optical fiber PBS, its length is relatively long due to the small birefringence, along with the narrow bandwidth. Photonic crystal fibers (PCFs) have broken through the bottleneck of the traditional optical fibers by relying on the geometric structure-induced unique optical properties, providing new opportunities for the design of the PBS [7-11].

In 2016, Wang et al. proposed a square lattice PCF PBS with the two elliptic air holes, where the PBS length was 93.3 μm and the bandwidth was about 70 nm [12]. In 2018, Wang et al. designed a liquid-filled dual-core PCF PBS, whose length was only 78 μm and extinction ratio could reach 87 dB at wavelength 1.55 μm [13]. In 2019, Rahman et al. demonstrated a gold-filled PCF PBS based on the surface plasmon resonance (SPR) effect, where the PBS length was only 57 μm and the bandwidth was up to 530 nm, covering all the
communication bands [14]. The previous reported works are based on the solid-core PCFs. For the solid-core PCFs, the absorption loss of the substrate material has the adverse effect on the PBS performance. In addition, in order to improve the birefringence of the solid-core PCFs, the elliptical holes, liquid filling, and gold filling are usually used, which make the fabrication process complex and increase the costs.

The hollow-core negative curvature fibers (HC-NCFs) can make the light energy propagated in the air core due to the anti-resonant structure [15-18], which makes it have the low propagation loss [19], low dispersion [20], and low nonlinearity [21]. In recent years, the HC-NCFs are widely used in the fiber sensing [22], high power pulse transmission [23], supercontinuum generation [24] and other fields [25-28]. The application of the HC-NCFs in the PBS has also been reported. In 2019, Zhao et al. proposed a dual hollow-core NCF (DHC-NCF) PBS with two elliptical tubes, where it had the length of 6.75 cm and the bandwidth of 310 nm (1.41 to 1.72 μm) [29]. In 2021, Jia et al. reported a DHC-NCF PBS with the length of 4.42 cm and the bandwidth of 460 nm (1.4 to 1.86 μm) [30]. In 2021, Jia et al. designed a single-mode PBS based on the DHC-NCF with two elliptical tubes nested with the circular tubes, where the PBS length was 8.15 cm and the bandwidth was 370 nm (1.28 to 1.65 μm) [31]. In 2022, Shaha et al. demonstrated a short-length DHC-NCF with two elliptical tubes splitting the two cores, where the bandwidth covered the wavelength range from 1.285 to 1.625 μm [32]. In the previous works, the reported DHC-NCF PBSs cannot cover the shorter wavelength range, such as the O and E bands. In addition, the fabrications of them are difficult due to the introduction of the elliptical tubes.

In this paper, a DHC-NCF PBS is proposed. Two silica tubes are introduced to separate the core region into the two symmetrical cores A and B. The coupling length (CL), coupling length ratio (CLR), and higher-order mode extinction ratio (HOMER) are analyzed. The normalized output powers of the x-polarized (x-pol) and y-polarized (y-pol) modes in the cores A and B and polarization extinction ratio (ER) are also investigated. The simulation results show that the proposed DHC-NCF PBS achieve a broad bandwidth of 400 nm, covering the O+E+S+C+L communication band, and has good single-mode characteristics.

2. The DHC-NCF PBS structure and theory

![Fig. 1. The cross-sectional structure of the designed DHC-NCF PBS.](image)

Fig. 1 shows the cross-sectional structure of the designed DHC-NCF PBS. From Fig. 1, the core region is composed of two silica tubes, and the diameter and thickness of the silica tubes are set as \(d_0\) and \(t_0\), respectively. The two cores A and B are separated by the two silica tubes. The cladding region of the DHC-NCF is composed of eight silica tubes, which are arranged
at different angles around the center point. The diameter of the two outer silica tubes in the horizontal direction (0° and 180°) is set as \( d_1 \), the diameter of the silica tubes in the vertical direction (90° and 270°) is set as \( d_3 \), and the diameter of the silica tubes at the four corners (55°, 125°, 235°, and 305°) is set as \( d_2 \). The ratio of the nested silica tube and outer tube diameter is \( k \), i.e., \( d_i = k^i d_1 \) (i = 1, 2). The thickness of all eight silica tubes in the cladding region is set as \( t \), and the diameter of the DHC-NCF is set as \( D \). The eight silica tubes of the outer cladding are connected to each other. Two silica tubes with the diameter \( d_0 \) are connected to the two ones with the diameter \( d_1 \). The width of the gap between the two silica tubes with the diameter \( d_0 \) can be calculated by \( D, d_1, \) and \( d_0 \). The initial structure parameters of the proposed DHC-NCF are set as following: \( d_1 = 20 \) \( \mu \)m, \( d_2 = 18.3 \) \( \mu \)m, \( d_3 = 9.8 \) \( \mu \)m, \( t = 0.5 \) \( \mu \)m, \( d_0 = 9 \) \( \mu \)m, \( t_0 = 0.5 \) \( \mu \)m, \( k = 0.5 \), and \( D = 60 \) \( \mu \)m. The propagation characteristic of the DHC-NCF can be calculated by the finite element method (FEM). The perfect match layer (PML) is added at the outside of the DHC-NCF, whose thickness and refractive index are chosen as 15 \( \mu \)m and \( n_{\text{silica}} + 0.03 \), respectively. Besides, the grid size of the silica is set as \( \lambda/5 \), and the grid sizes of the PML and air are set as \( \lambda/4 \).

The material dispersion of the silica can be obtained from the following Sellmeier equation [33]

\[
n_{\text{Silica}}(\lambda) = \sqrt{1 + \frac{A_1 \lambda^2}{\lambda^2 - B_1^2} + \frac{A_2 \lambda^2}{\lambda^2 - B_2^2} + \frac{A_3 \lambda^2}{\lambda^2 - B_3^2}},
\]

(1)

where \( A_1 = 0.6961663, A_2 = 0.4079426, A_3 = 0.897479, B_1 = 0.00684043, B_2 = 0.1162414, B_3 = 9.896161 \), and \( \lambda \) is the free space wavelength in micrometer.

The coupling lengths \( CL_X \) and \( CL_Y \) of the x-pol and y-pol core modes can be obtained by [34]

\[
CL_X = \frac{\lambda}{2(n_{\text{even}} - n_{\text{odd}})}
\]

(2)

\[
CL_Y = \frac{\lambda}{2(n_{\text{even}} - n_{\text{odd}})}
\]

(3)

where \( n_{\text{even}}, n_{\text{odd}}, n_{\text{even}}, \) and \( n_{\text{odd}} \) represent the effective indices of the x-pol even and odd modes and y-pol even and odd modes, respectively.

The coupling length ratio (CLR) can be obtained by [35]

\[
CLR = \frac{CL_Y}{CL_X},
\]

(4)

where the CLR should be approximately equal to 2 or 1/2 to make the PBS length shorter.

The HOMER can be used to describe the single-mode characteristics of an optical fiber, and it is defined as the ratio of the confinement loss of the higher-order modes (such as \( LP_{11} \)) and the confinement loss of the fundamental mode (\( LP_{01} \)) [36]

\[
\text{HOMER} = \frac{\text{Confinement loss of } LP_{11}}{\text{Confinement loss of } LP_{01}}.
\]

(5)

When the light is incident into the core A, the normalized output powers of the x-pol and y-pol modes in the cores A and B can be described by [37]

\[
P_{\text{out, A}}^{x,y} = P_{\text{in}} \cos^2 \left( \frac{\pi}{2} \frac{L_p}{CL_{X,Y}} \right),
\]

(6)

\[
P_{\text{out, B}}^{x,y} = P_{\text{in}} \sin^2 \left( \frac{\pi}{2} \frac{L_p}{CL_{X,Y}} \right).
\]

(7)

The \( ER \), which is an important parameter to evaluate the performance of the PBS, can be
described for the core A by [38]

\[ ER = 10 \log_{10} \frac{P_{\text{out},A}^X}{P_{\text{out},A}^Y}. \] (8)

The polarization beam splitting is possible when the \( ER \) is below -20 dB. Therefore, the wavelength range below -20 dB is considered as the bandwidth of the PBS. Because the two cores A and B of the DHC-NCF have the same structure, we only need to consider the variations of \( P_{\text{out}} \) along the \( x \)-pol and \( y \)-pol directions and the \( ER \) in the core A or B when the light is injected into one of the two cores.

3. Simulation results and discussion

According to the mode coupling theory [39], the proposed DHC-NCF could generate the four super modes, which are called as the \( x \)-pol even mode, \( x \)-pol odd mode, \( y \)-pol even mode, and \( y \)-pol odd mode, respectively. Because of the different propagation constants of the even and odd modes, the \( x \)-pol and \( y \)-pol lights will be transferred periodically between the two cores. In order to ensure that the two beams of orthogonally polarized light are well separated within a short coupling length, the birefringence properties of the DHC-NCF need to be enhanced. Therefore, we reduce the size of the vertical tubes, increase the size of the tubes on both sides of the core region, and introduce the nested tubes in the horizontal tubes. At the same time, the introduction of the nested tubes can also reduce the loss of the fundamental mode and increase the HOMER.

The effective refractive indices of the considered four super modes are shown in Fig. 2(a), where the inset shows the zoom-in view within the wavelength range from 1.48 to 1.58 \( \mu \)m. From Fig. 2(a) and the inset, the effective refractive indices of the \( x \)-pol even and odd modes are larger than those of the \( y \)-pol even and odd modes, and the effective refractive indices of the \( x \)-pol and \( y \)-pol even modes are larger than those of the \( x \)-pol and \( y \)-pol odd modes. In the considered wavelength range of 1.48 to 1.58 \( \mu \)m, the \( x \)-pol even mode has the highest effective refractive index, and the \( y \)-pol odd mode has the lowest effective refractive index. The effective refractive index difference between the \( y \)-pol even and odd modes is larger than that of the \( x \)-pol even and odd modes, which makes the \( CL_y \) of the \( y \)-pol core modes smaller than the \( CL_x \) of the \( x \)-pol core modes. Fig. 2(b) shows the mode field distributions of the four super modes and two lowest loss higher-order modes (\( LP_{11} \) modes) calculated at wavelength 1.55 \( \mu \)m. It can be seen from Fig. 2(b) that the super mode field energies are well confined in the two cores. And some of the energy of the \( LP_{11} \) modes is coupled into the silica tubes, which will enhance the HOMER and make the DHC-NCF achieve the better single-mode characteristics.

![Fig. 2. (a) Effective refractive indices of the \( x \)-pol and \( y \)-pol even and odd modes, and (b) the mode field distributions of the \( x \)-pol and \( y \)-pol even and odd modes and \( LP_{11} \) modes calculated at wavelength 1.55 \( \mu \)m.](image)
Based on the initial structure parameters of the proposed DHC-NCF PBS, the calculated $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR in the wavelength range from 1.30 to 1.70 μm are shown in Fig. 3. Because the two cores and coupling channels are distributed along the $y$-pol direction, the $CL_X$ of the $x$-pol core mode is larger than the $CL_Y$ of the $y$-pol core mode, as seen from Fig. 3. This makes the $y$-pol core modes easier to couple from one core to the other one than the $x$-pol core modes. The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes simultaneously increase first and then decrease with the increasing wavelength, reaching a maximum at wavelength 1.48 μm. Thus, the coupling length ratio remains relatively stable around 0.7. In order to obtain the CLR of ~ 0.5, the structure parameters of the proposed DHC-NCF PBS need to be optimized. In the following simulation, the working wavelength is set at 1.55 μm.

![Fig. 3. The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR of the DHC-NCF PBS.](image)

![Fig. 4. (a) The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR, and (b) the confinement losses of the modes LP$_{01}$ and LP$_{11}$ and HOMER when $D$ increases from 40 to 80 μm.](image)

Figs. 4(a) and 4(b) show the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR and the confinement losses of the modes LP$_{01}$ and LP$_{11}$ and HOMER, respectively, when $D$ increases from 40 to 80 μm. From Fig. 4(a), the $CL_X$ and $CL_Y$ increase significantly with the increase of $D$ from 40 to 80 μm. Moreover, as $D$ increases, the effective refractive indices of the considered four super modes increase. The effective refractive index differences between the $x$-pol and $y$-pol odd and even modes will decrease significantly, so the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol odd and even modes will increase. Since the $CL_X$ and $CL_Y$ increase proportionally, the change of the CLR is very small. From Fig. 4(b), as $D$ increases, the confinement losses of the higher-order and fundamental modes decrease, and the
corresponding HOMER changes with a certain degree of fluctuation. By the comprehensive consideration of the decreased confinement loss and the increased coupling length of the DHC-NCF PBS, the value of $D$ should be chosen appropriately.

Fig. 5(a) shows the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and $CLR$ when $t$ increases from 0.44 to 0.64 $\mu$m. According to the resonant condition $\lambda = 2t(n_2 - n_1)^{1/2} / m (m = 1, 2, \ldots)$, the increase of $t$ will result in a red-shift of the resonant wavelength. From Fig. 5(a), as $t$ increases from 0.44 to 0.64 $\mu$m, the $CL_X$ of the $x$-pol core mode increases from 3.2 to 4.7 cm, while the $CL_Y$ of the $y$-pol core mode increases from 2.4 to 2.8 cm. As a result, the $CLR$ decreases from 0.75 to 0.55. Fig. 5(b) shows the relationships between the confinement losses of the modes $LP_{01}$ and $LP_{11}$, HOMER and $t$. From Fig. 5(b), the confinement losses of the modes $LP_{01}$ and $LP_{11}$ both decrease first and then increase as $t$ increases. When $t$ is equal to 0.56, the confinement loss of the mode $LP_{01}$ has the lowest value, and the HOMER is larger than 100. Besides, when $t$ is chosen as 0.56 $\mu$m, the resonant wavelength is located at 1.16 $\mu$m ($m = 1$). According to the principle of the anti-resonant reflection, the confinement loss of the mode $LP_{01}$ at the resonant wavelength is higher, and thus the working bandwidth of the DHC-NCF PBS should be avoided near the resonant wavelength.

Fig. 5. (a) The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and $CLR$, and (b) the confinement losses of the $LP_{01}$ and $LP_{11}$ and HOMER when $t$ increases from 0.44 to 0.64 $\mu$m.

Fig. 6(a) shows the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and $CLR$ when $k$ increases from 0.48 to 0.68. From Fig. 6(a), as $k$ increases from 0.5 to 0.68, the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes decrease by a small margin simultaneously. As a result, the $CLR$ increases slightly. Fig. 6(b) shows the relationships between the confinement losses of the modes $LP_{01}$ and $LP_{11}$, HOMER and $k$. From Fig. 6(b), as $k$ increases from 0.48 to 0.68,
the confinement loss of the mode LP_{11} first increases and then decreases, while the confinement loss of the mode LP_{01} first decreases and then increases. When $k$ is equal to 0.56, the confinement loss of the mode LP_{11} achieves the maximum value, while the confinement loss of the mode LP_{01} is kept at a lower value. Therefore, the HOMER is larger than 200. As shown in Fig. 1, the nested tubes exist only inside the six silica tubes in the cladding region. Although the sizes of the nested tubes have less effect on the mode coupling between the two cores, they have significant effect on the confinement losses of the modes LP_{01} and LP_{11} and HOMER.

Fig. 7(a) shows the effects of $d_1$ on the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and the CLR at wavelength 1.55 μm. Since the eight silica tubes in the cladding region are closely spaced, the size of $d_2$ is dependent of the sizes of $d_1$ and $d_3$. The decrease of $d_2$ will lead to the increases of the two core regions, so the relative mode field also increases. When the coupling channel width remains unchanged, the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes will increase. From Fig. 7(a), as $d_1$ increases from 19.5 to 21.5 μm, the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes are growing in the same trend, and the CLR remains almost constant. Thus, the variation of $d_1$ has less effect on the CLR. Fig. 7(b) shows the relationships between the confinement losses of the modes LP_{01} and LP_{11}, HOMER and $d_1$. From Fig. 7(b), the confinement losses of the modes LP_{01} and LP_{11} change slightly as $d_1$ increases. The position of the silica tubes with the size of $d_1$ is relatively far away from the two cores, so the effect of $d_1$ on the confinement loss is smaller. When $d_1$ increases from 19.5 to 21.5 μm, the HOMER is larger than 200, and can be up to 360 when $d_1$ is chosen as 20.3 μm.

The effects of $d_3$ on the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and the CLR are shown in Fig. 8(a). From Fig. 8(a), as $d_3$ increases, the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes increase simultaneously, and the CLR remains nearly unchanged. When $d_3$ increases from 9.5 to 11.5 μm, the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes increase from 3.6 to 7.5 cm and from 2.5 to 5.3 cm, respectively. And the CLR slightly decreases from 0.73 to 0.71. The increase of $d_3$ leads to the decrease of $d_2$, which will increase the mode field area and the coupling length. The relationships between the confinement losses of the modes LP_{01} and LP_{11}, HOMER and $d_3$ are shown in Fig. 8(b). From Fig. 8(b), as $d_3$ increases, the confinement loss of the mode LP_{01} first decreases and then increases, and the confinement loss of the mode LP_{11} first increases and then decreases. When $d_3$ is equal to 10.5 μm, the confinement loss of the mode LP_{01} is close to 1 dB/m, while the confinement loss of the mode LP_{11} is higher than 1000 dB/m. Therefore, the HOMER increases first and then decreases as $d_3$ increases from 9.5 to 11.5 μm, and reaches the maximum value of 2500 for $d_3$ of 10.5 μm.
The two silica tubes in the middle and the gap between the two silica tubes form the coupling channel for the two cores. It can be known that $t_0$ and $d_0$ have significant effects on the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and the CLR. The effects of $t_0$ on the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and the CLR are shown in Fig. 9(a). From Fig. 9(a), the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes decrease and the CLR increases gradually as $t_0$ increases. When $t_0$ decreases from 0.48 to 0.58 μm, the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes decrease from 5.7 to 3 cm and from 4 to 2.3 cm, respectively. And the CLR increases from 0.7 to 0.76. Fig. 9(b) shows the relationships between the confinement losses of the modes $LP_{01}$ and $LP_{11}$, HOMER and $t_0$. From Fig. 9(b), as $t_0$ increases, the confinement loss of the mode $LP_{01}$ does not change significantly and remains around 1 dB/m, and the confinement loss of the mode $LP_{11}$ also changes little and remains above 1000 dB/m. And the HOMER is larger than 1500 in the $t_0$ range of 0.49 to 0.57 μm. It indicates that $t_0$ has little effect on the confinement loss of the core modes.

Fig. 8. (a) The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR, and (b) the confinement losses of the modes $LP_{01}$ and $LP_{11}$ and HOMER when $d_3$ increases from 9.5 to 11.5 μm.

Fig. 9. (a) The $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and CLR, and (b) the confinement losses of the modes $LP_{01}$ and $LP_{11}$ and HOMER when $t_0$ increases from 19.5 to 21.5 μm.

Fig. 10(a) shows the $CL_X$ and $CL_Y$ of the $x$-pol and $y$-pol core modes and the CLR when $d_0$ increases. From Fig. 10(a), as $d_0$ increases from 8.6 to 9.6 μm, the $CL_X$ of the $x$-pol core mode increases significantly from 3.7 to 6.4 cm. In contrast, the variation of the $CL_Y$ of the $y$-pol core mode is relatively gentle, the $CL_Y$ of the $y$-pol core mode has a bulge in the middle, changing within the range of 3.2 to 3.5 cm. And the CLR decreases from 0.85 to 0.53. The main reason is considered that the increase of $d_0$ makes the coupling channel in the $x$-pol direction narrower, so it is more difficult for the $x$-pol core mode to be coupled from one core.
to the other one, while the $y$-pol core mode is not significantly affected. Fig. 10(b) shows the relationships between the confinement losses of the modes $LP_{01}$ and $LP_{11}$, HOMER and $d_0$. From Fig. 10(b), as $d_0$ increases from 8.6 to 9.6 μm, the confinement loss of the mode $LP_{01}$ is above and below 1 dB/m, and the confinement loss of the mode $LP_{11}$ is always around 1000 dB/m. And the HOMER can be up to 500 in the $d_0$ range of 8.6 to 9.6 μm.

![Fig. 10.](image). (a) The $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and CLR, and (b) the confinement losses of the modes $LP_{01}$ and $LP_{11}$ and HOMER when $d_0$ increases from 8.6 to 9.6 μm.

![Fig. 11.](image). The $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and CLR in the wavelength range of 1.2 to 1.7 μm.

Based on the above results, the structure parameters of the DHC-NCF PBS have different effects. Thus, the optimized structure parameters are chosen as following: $t = 0.56 \mu m$, $k = 0.56$, $d_1 = 20.3 \mu m$, $d_2 = 18.1 \mu m$, $d_3 = 10.5 \mu m$, $d_0 = 9.6 \mu m$, $t_0 = 0.5 \mu m$, and $D = 60.6 \mu m$. At this time, the corresponding $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and the CLR in the wavelength of 1.20 to 1.70 μm are shown in Fig. 11. From Fig. 11, the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes change little in the wavelength range of 1.25 to 1.60 μm, and increase simultaneously in the wavelength range of 1.2 to 1.25 μm. In the wavelength range of 1.65 to 1.7 μm, the $CL_X$ of the x-pol core mode increases and then decreases, and the $CL_Y$ of the y-pol core mode decreases slightly. Therefore, the variation of the CLR remains flat in the wavelength range of 1.20 to 1.70 μm, and the CLR value changes within the range of 0.45 to 0.54. Because the $CL_X$ and $CL_Y$ of the x-pol and y-pol core modes and the CLR only occur to change slightly within a certain wavelength range, the DHC-NCF PBS could be expected to have a broad bandwidth.

Assuming that the input light at wavelength 1.55 μm being launched into the core A, the normalized output powers of the cores A and B as functions of the propagation distance are
shown in Fig. 12. From Fig. 12, when the propagation distance reaches 6.45 cm, the normalized output power of the $x$-pol light in the core A decreases to 0, but the normalized output power of the $y$-pol light in the core A is almost at its maximum. In the core B, the normalized output power of the $x$-pol light reaches a maximum, and the normalized output power of the $y$-pol light becomes 0 when the propagation distance is 6.45 cm. At this time, the $x$-pol light only exists in the core B, and the $y$-pol light only exists in the core A, which indicates that the $x$-pol and $y$-pol lights are well separated into the cores A and B.

![Fig. 12. The normalized output powers of the cores A and B as functions of the propagation distance.](image)

Fig. 13. The polarization $ER$ as a function of wavelength, the insert showing the mode field distribution of the $y$-pol odd mode calculated at wavelength 1.44 μm.

When the length of the DHC-NCF PBS is 6.45 cm, the polarization $ER$ as a function of wavelength is shown in Fig. 13. From Fig. 13, the polarization $ER$s of -53.4 dB and -58.8 dB are achieved at wavelengths 1.26 μm and 1.52 μm, respectively. In addition, there is a turning point at wavelength 1.44 μm, and the inset of Fig. 13 shows the mode field distribution of the $y$-pol odd mode at this turning point. From the inset, the two silica tubes in the middle are very close to each other, and the $y$-pol odd mode couples with the walls of the two silica tubes and a part of the energy leaks to the silica tube walls. And the polarization $ER$ is below -20 dB in the wavelength range of 1.23 to 1.63 μm. Therefore, the proposed DHC-NCF PBS has a bandwidth of ~ 400 nm with the $ER$ below -20 dB, covering the O+E+S+C+L communication band.

Fig. 14 shows the confinement losses of the modes $LP_{01}$ and $LP_{11}$ and HOMER as
functions of wavelength. From Fig. 14, the confinement loss of the mode LP\(_{01}\) always remains about 1 dB/m in the wavelength range of 1.35 to 1.62 \(\mu\)m, and the confinement loss of the mode LP\(_{11}\) is always higher than 1000 dB/m in the wavelength range of 1.20 to 1.70 \(\mu\)m. And the HOMER is larger than 100 in the wavelength of 1.23 to 1.7 \(\mu\)m, and reaches 1000 near wavelength 1.55 \(\mu\)m, which indicates that the proposed DHC-NCF PBS has good single-mode characteristics.

The proposed DHC-NCF PBS could be fabricated by the stack and draw technique [40]. First, the silica capillaries with different sizes are stacked according to the designed DHC-NCF structure, and then several short capillaries are inserted into the ends to support the long silica capillaries and the inner nested capillaries to avoid the position shift and stack collapse. Second, the preform is drawn into the desired DHC-NCF using the drawing tower at high temperature, and the air pressure inside the preform is controlled during the drawing to prevent the silica tubes from collapsing. Finally, the ends of the fabricated DHC-NCF are cut off, and only the desired middle portion is retained.

![Fig. 14](image.png)

Fig. 14. The confinement losses of the modes LP\(_{01}\) and LP\(_{11}\) and HOMER in the wavelength range of 1.2 to 1.7 \(\mu\)m.

4. Conclusion

In conclusion, a broad bandwidth DHC-NCF PBS is proposed. The effects of the structure parameters of the DHC-NCF PBS are analyzed to obtain the CLR of \(~0.5\). The simulation results show that the polarization ER of the proposed DHC-NCF PBS can reach -53.4 dB and -58.8 dB at wavelengths 1.26 \(\mu\)m and 1.52 \(\mu\)m, respectively, and the maximum value of the HOMER can reach 948 at wavelength 1.58 \(\mu\)m. In the wavelength range of 1.23 to 1.63 \(\mu\)m, the polarization ER is less than -20 dB, and the HOMER is higher than 100. It means that the designed DHC-NCF PBS has good single-mode characteristics and a broad bandwidth of \(~400\) nm, covering the O+E+S+C+L communication band. It is believed that the proposed DHC-NCF PBS has important application in the optical communication system.

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Disclosures
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