Ultra-short and broadband polarization splitter based on PCF and metal surface plasmons resonance

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Abstract

An ultra-short and broadband polarization splitter based on PCF and metal surface plasmons resonance is proposed by designing a new structure and filling gold wire into certain air holes. The introducing of gold wire aims to couple with the basic modes. Then high birefringence is obtained to improve the splitter's performances including length, bandwidth and maximal extinction ratio. The numerical results demonstrate that the splitter can be the shortest length of 100 μm (to our knowledge) and the broad bandwidth is 470 nm simultaneously. And when the splitter's length is set as 104 μm, the widest bandwidth reaches the maximum 575 nm (to our knowledge) which covers almost all the E, S, C, L, and U communication band. In addition, the structure is relatively simple, so it is easy to fabricate using available methods. These properties will help designing splitter in the optical communication and sensing system.

1 Introduction

Polarization splitter has strong function of splitting one light that possesses two polarization states into two orthogonal states, which makes it widely be used in optical communication system as an important fiber component. Unlike the conventional fiber-based polarization splitters, photonic crystal fiber (PCF) (Knight and Russell 2002) based polarization splitters can be easier to avoid the disadvantages including narrow bandwidth and long splitter length, which was existing in the paper proposed in Peng et al. (1990) and other papers. Nowadays the optical communication systems are developing in the direction of large capacity and integration, which means, for the polarization splitter, its length should be shorter and the bandwidth should be wider. Then the appearance of PCF helps broadening the bandwidth and shorting the splitter length to meet the needs of optical communication and sensor systems.

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In recent decades, the PCF has attracted a great quantity of attention in optical field, which is not only because of its unique features and advantages, such as endless single mode transmission (Birks et al. 1997), low loss (Suzuki et al. 2001), high birefringence (Lu et al. 2011), large mode area (Knight et al. 1998), adjustable dispersion (Reeves et al. 2002), highly nonlinear (Li et al. 2014), and so on, but also because the structure of PCF can be adjusted as you want and the air holes in the PCF can be filled with kinds of materials including some solid, liquid and gas. These properties could help creating ultrashort and ultra-broadband polarization splitter. In the beginning, the researchers changed the structure of PCF to improve the properties of splitter. There are different air hole types: circular and ellipse (Hameed and Obayya 2009); different arrangement ways: square lattice (Rosa et al. 2006), triangular lattice (Li et al. 2011), and hexagonal lattice (Florous et al. 2005); and even different number of fiber cores: dual cores, and three cores (Saitoh et al. 2004). Then people found that after coating or filling some special materials into certain air holes of the PCF or replacing the pure silica cladding with other materials, the properties can be further improved in some way. So, the properties study of material coating or filled PCF emerged. For example; in Hameed and Obayya (2009) have proposed a polarization splitter based on soft glass and nematic liquid crystal (NLC) PCF in which the NLC was filled into the soft glass background, and in Podpliak and Horak (2017). designed a dual-core optical fiber with integrated electrodes and filled with liquid crystals; in 2010, Li et al. studied a novel polarization splitter based on dual-core hybrid PCF, and some air holes of the structure were filled with high refractive index material (Florous et al. 2005); in Sun et al. (2013) proposed a polarization splitting based on dual core PCF with metal wire (silver wire); Liu et al. (2015) has studied a PCF polarization splitter based on ZnTe glass.

Till now the main trend became utilizing a combination of kinds of ways to realize shorter length and wider bandwidth on the polarization splitter. Jiang et al. (2014) also proposed a polarization splitter based on dual-core PCF, the splitter had an ultra-short length of 119.1 μm and a bandwidth of 249 nm. Xu et al. (2015) reported a short polarization splitter based on dual-core PCF, the splitter had a length of 0.401 mm and a bandwidth of 140 nm. Zhao and Lou (2016) proposed an ultra-broadband polarization splitter based on three-core PCF. The splitter was 52.8-mm-long, but it had a wide bandwidth of 320 nm. Liu et al. (2016) have studied a polarization splitter based on dual-core soft glass PCF with micron-scale gold wire, the bandwidth of the splitter was 226 nm. In addition, Rajeswari et al. (2017) proposed a polarization splitter with dual-core PCF, and the study results show the bandwidth of x- and y-polarization modes are 100 nm and 55 nm respectively, and having a length of 2 mm. An asymmetric dual-core PCF wavelength-selective polarization splitter was designed by Younis et al. (2018), after analyzing and studying, the splitter has a device length of 5.678 mm and a bandwidth of 3 nm. Chao et al. (2018) reported a dual-core PCF that is used for polarization splitter, which has a short length of 103 μm and a bandwidth of 177 nm.

From the data of these relative papers, we can know the record of the length and bandwidth is being refreshed all the time, but there is little part which can realize ultrashort and ultra-broadband polarization splitter simultaneously. So in this paper, a new structural polarization splitter based on metal surface plasmons resonance (SPR) is proposed. Under the combined effect of structure asymmetry and surface plasmon resonance, the splitter can operate over a very large bandwidth of 470 nm in which the extinction ratio (*ER*) value is lower than −20 dB, at the same time the splitter has the shortest length of 100 μm. Additionally, a splitter whose length is set as 104 μm will get a widest bandwidth of 575 nm. The proposed polarization splitter has a great significance to the application on high-speed ultra-broadband optical communication system to some extent.

2 The structure and the relative theory

Figure 1 shows the schematic cross section of the proposed dual-core polarization splitter. There are several geometry parameters in the structure, including Λ, d, d_1, d_m, d_x, d_y and L. Firstly, all the air holes, with a uniform diameter of d, are placed at a hole pitch Λ in a triangular lattice. And the cladding material except the air holes is pure silica whose refractive index can be calculated by the Sellmeier equation (Malitson 1965). Secondly we get a rectangular arrangement of two rows of holes, and the pitch between the two rows is L ($=\Lambda$) which is fixed in the optimal process. Then we replace the four air holes in the central of the structure with two symmetrical ellipses in horizontal direction whose long and short axis length are dx and d_y respectively. In addition, the diameter of the four big air holes is denoted by d_1. Finally, the above parameters setting makes core A and core B as the picture shows, and the gold wires are filled in the two holes with a diameter of d_m ($=d$).

The relative permittivity of gold could be obtained by the improved Drude–Lorentz model (Vial et al. 2005). The gold is stable in chemistry reaction and has strong corrosion resistance, which is why we choose gold wire as a filler.

In this paper, through introducing gold wire into the structure, the special modes aroused by surface plasmon resonance effect of gold will couple with the basic modes which could be regarded as the superimposition of even and odd modes. Therefore, the coupling effective (Saitoh et al. 2003) and the surface plasmon resonance effect become the basic theory of analyzing the performances and basic properties of the polarization splitter. The coupling length (*CL*), defined as the length of the fiber in which a complete transfer of power between core A and core B occurs, could be calculated by

$$L_i = \frac{\lambda}{2(n_i^{even} - n_i^{odd})}.$$ (1)

where the subscripts i expresses the x or y polarization, so L_i represents x- or y- coupling length; λ and n are the wavelength of incident light and the effective refractive index, respectively. Obviously, the function of polarization splitter is to separate the two polarized states, and when the coupling lengths satisfy the condition that $mL_x = nL_y = L_s$ (*m* and

Fig. 1 Cross section of the proposed dual-core polarization splitter
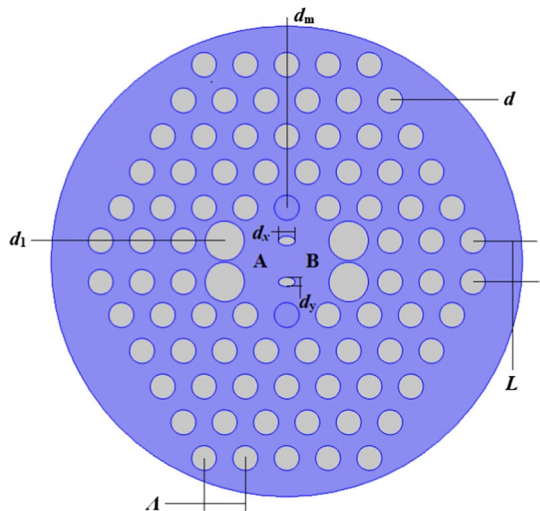
n are both positive integers, and L_s is the length of the splitter), the function is realized. In order to create a better splitter, an optical value 2 ($L_y > L_x$) or 1/2 ($L_x > L_y$) of the coupling length ratio ($CLR = L_y/L_x$) should be reached. With this key issue, there is possibility to obtain an ultrashort length and ultra-broadband splitter through the way adjusting geometrical parameters of the proposed structure. The transmission loss of the polarization splitter could be neglected because of the short length. When an incident light with a power Pin is inserted into core A, then the output power of x and y polarized light in core A can be calculated as

$$P_{i-out} = P_{in} \cos^2\left(\frac{\pi L_p}{2 \cdot L_i}\right). \tag{2}$$

where L_p is the propagation distance, i represents the x or y polarization, and L_i could be given from (1). Further, the normalized powers (NP) are as follows:

$$NP_i = \frac{P_{i-out}}{P_{in}} = \cos^2\left(\frac{\pi L_p}{2 \cdot L_i}\right). \tag{3}$$

There is another important key parameter called extinction ratio (ER) that can be used to describe the performance of a polarization splitter. The ER is explained as the normalized power of one particular polarization over the other polarization in the same core at the output port. And when it comes to core A, the ER can be calculated by

$$ER = -10 \cdot \lg\left(\frac{P_{out}^{Ax}}{P_{out}^{Ay}}\right). \tag{4}$$

3 The numerical result and analysis

The properties of the structure are studied by the finite element method (FEM), using a simulation software called the COMSOL Multiphysics 5.2. In the process of the study, the Perfect Matched Layer mesh size (PML) and the scattering boundary condition are set to absorb radiant energy and reduce reflecting energy respectively. With regard to PML parameter settings, it is possible to set different PML parameters and then observe whether the simulation results have changed. Since the electric field at the edge of the photonic crystal region is weak, there is almost no difference in the position of the PML. The mesh size is set up as shown in the Fig. 2. In the mesh, the calculation area is divided into 16,924 triangular subdomains. When the mesh size is decreased, the loss will arrive a peak. And the existence of the peak means there is convergence in the results of the study.

Through numerically calculating the dispersion relation of four super-modes, the result could be known clearly from the Fig. 3a and b. Figure 3 represents the relation between wavelength and effective index when the structure is without gold and with gold, respectively. By contrasting (a) and (b) and analyzing the trend of the curves, we can find that, after filling the gold into the structure, all the super-modes change but in different ways. This is because there are coupling between certain super-modes and surface plasmon polaritons (SPPs) modes. Firstly, the effective index of the four super-modes all shows different degrees of reduction owing to the different intensity of reacting with SPP modes. Second, in the x-odd and y-even mode, the corresponding curves show a relatively significant change, but the change in the rest two modes is small. Finally, the result of the

Fig. 2 The mesh size setting of the proposed structure
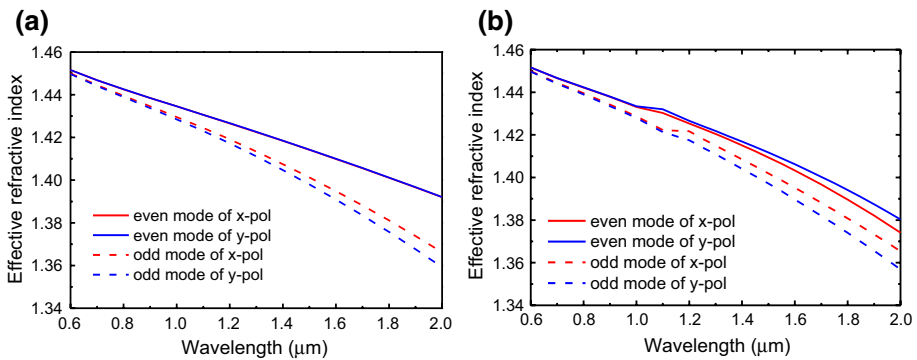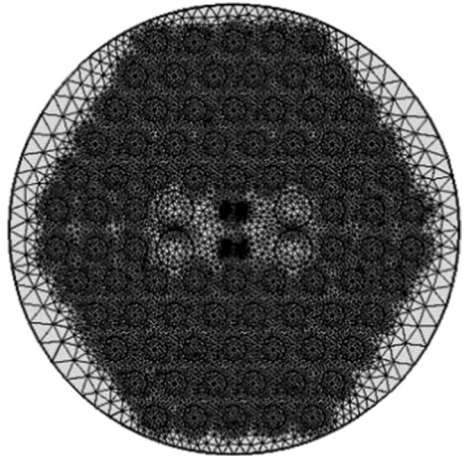

(a)

(b)

Fig. 3 Effective refractive index as a function of wavelength for the four super-modes of the PCF based polarization splitter **a** without gold filled and **b** with gold filled

coupling effect is that the difference between x-even and x-odd reduces and the difference between y-even and y-odd increases, which is helpful for creating a splitter.

Figure 4a–c shows the electric field distribution when the coupling is happening and in the four pictures, the influence of y-even (c) suffering from the 2nd SPP is biggest, the next is the x-odd (b), and the effect of rest modes (a, d) is too small to be neglected.

In order to find an optimal structure parameters combination, keeping $L = 2$ μm and $d_m = 1.2$ μm fixed and adjusting the rest four parameters are implemented to satisfy the condition: a *CLR* of 2. The curves that represent how the numerical change of geometrical parameters affect the *CL* and *CLR* are showed in Figs. 5 and 6 when the wavelength is 1.55 μm.

As Fig. 5a shows, while keeping other parameters fixed and making Λ change from 1.8 to 2.2 μm, L_x and L_y increases and *CLR* decreases, which is because the increase of hole pitch leads to a decrease of birefringence of even and odd modes then the change makes the coupling length become larger. In the Fig. 5b, both the L_x and L_y increase slowly as the d changes from 1.0 to 1.4 μm, and the *CLR* decreases from the beginning but almost doesn't change in the back part. From the physics angle, the diameter of the cladding air
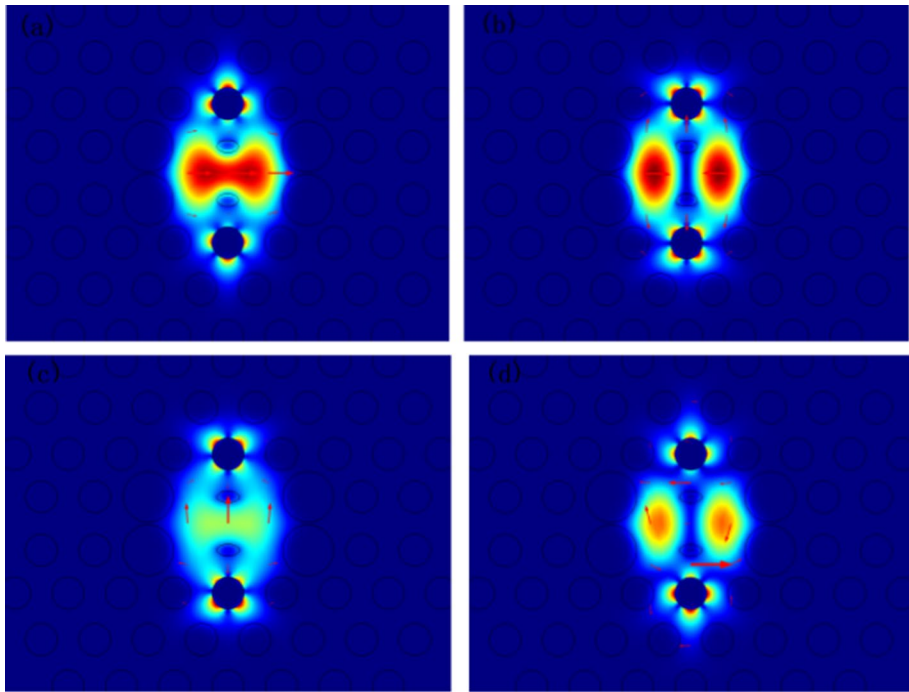
Fig. 4 Modal electric fields of the **a** odd mode of x-polarization **b** even mode of x-polarization **c** odd mode of y-polarization **d** even mode of y-polarization

holes increases, then the difference of core effective index and the cladding effective index increases, furthermore, results in the different effect on even and odd mode of x or y polarization. At last both the L_x and L_y increase as the d changes from 1.0 to 1.4 µm. And the change of d puts little effect on coupling length. And from Fig. 5c, L_x and L_y decrease as d_1 vary from 1.75 to 1.95 µm at a slight difference and the *CLR* also decreases as d_1 increases. As is explained before, the increasing of d_1 pulls up the effective index of the core field, which makes the birefringence down. After analyzing these curves and considering the fabricating tolerance, the parameters are decided to be $\Lambda = 2$ µm, $d = 1.2$ µm, $d_1 = 1.9$ µm, which can make the *CLR* approach the value 2 in a very small difference.

The effect situation that d_x and d_y put on *CL* and *CLR* is showed in Fig. 6a and b. In general, as d_x and d_y increase from 0.6 to 1 µm and 0.3 to 0.6 µm, respectively, both L_x and L_y increase and the increasing trend of L_x is faster than L_y both in d_x and d_y. In addition, the *CLR* also increases as d_x and d_y vary. In some way, the increasing of and can intensify the degree of structural asymmetry, which makes the structure gain bigger birefringence. These means through changing the value of dx and d_y, the birefringence could be controlled effectively. And this is because the two symmetrical ellipses in the proposed structure play an important role in the contribution of birefringence. Therefore, the value of d_x and d_y should be 0.8 µm and 0.45 µm whose *CLR* results are nearest to 2.

For the purpose of studying the property of the proposed structure in the situation of gold filled, a contrast between the curves of *CL* and *CLR* as functions of the wavelength is made as illustrated in Fig. 7a and b. On the one hand, from (a), we can find that the
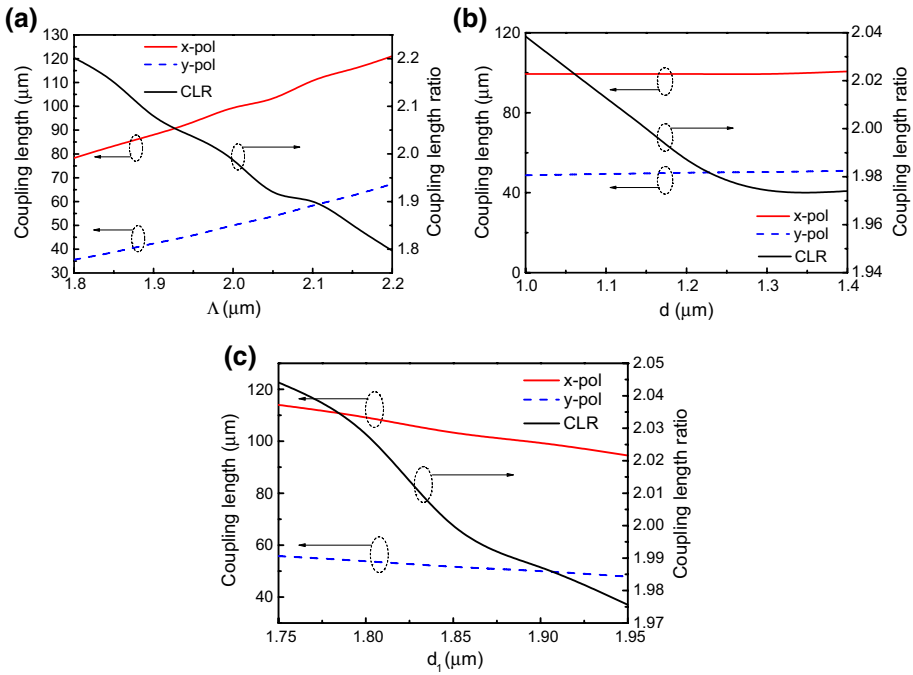
Fig. 5 Dependence of the coupling length (*CL*) for the x and y-polarization, and their ratio (*CLR*) upon **a** the hole pitch (Λ), **b** the diameter (*d*) of the air holes in the cladding and **c** the diameter (d_1) of the four air holes in the row arranged in square lattice
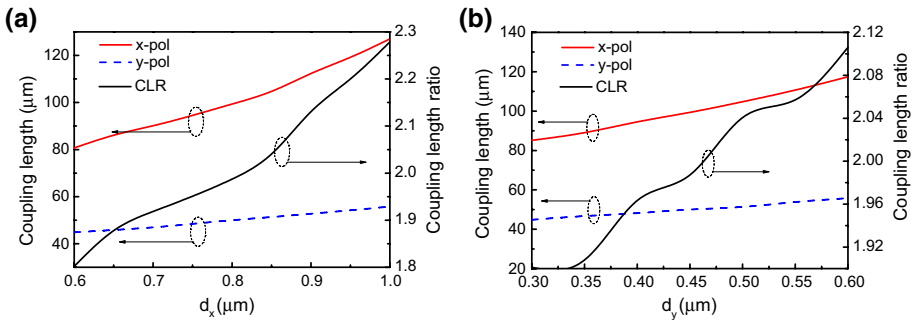

Fig. 6 Variation of coupling length (*CL*) for x-polarization and y-polarization and corresponding coupling length ratio (*CLR*) as a function of the **a** long axis length (d_x) and **b** short axis length (d_y) of the elliptical holes

curve of *CLR* is relatively flat in the first half and the *CLR* increases as the wavelength goes large in the second half. On the other hand, in the case of unfilled gold, L_x is smaller than the L_x that is under filled gold at a big difference, which makes the *CLR* too small to approach the required value of 2. Therefore, filling gold in special air holes of the proposed structure is of great significance for creating a polarization splitter with excellent properties.
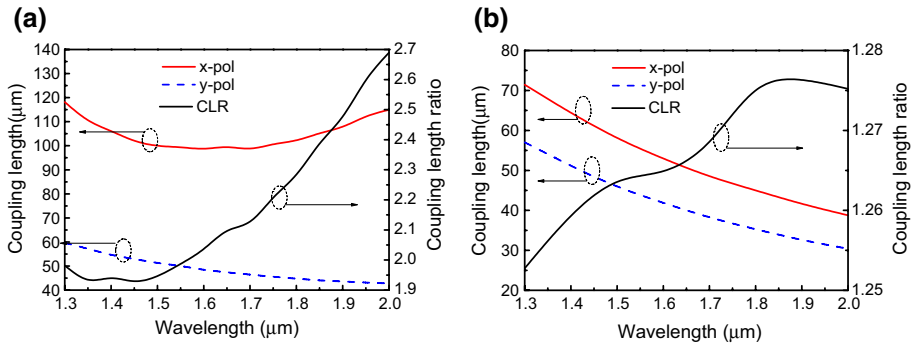
(a)

(b)

Fig. 7 Coupling length for x-polarization and y-polarization and corresponding coupling length ratio as a function of the wavelength for the proposed structure: **a** gold filled; **b** gold unfilled

Based on the above numerical analyzing and related discussion about the Figs. 2, 3, 4, 5 and 6, an optimized geometry parameters group is chosen to be $\Lambda = L = 2$ μm, $d = d_m = 1.2$ μm, $d_1 = 1.9$ μm, $d_x = 0.8$ μm, $d_y = 0.45$ μm, and when $\lambda = 1.55$ μm, $CLR = 1.9872$ which is very close to 2. Under the condition, it is necessary to research the NP as a function of propagation distance that is on behalf of the transmission state of input beam in the core A when the propagation length changes from 0 to 200 μm. As Fig. 8a shows, when the propagation length is 99.36 μm, the output NP of y-polarization is close to 1 and of x-polarization is close to 0, which means when the polarization splitter length is 99.36 μm, the two polarization states can be separated effectively with low loss. Next, in Fig. 8b, the extinction ratio (ER) spectra as a function of the wavelength is illustrated while the polarization splitter length is set as 99.36 μm, the smallest ER about -62 dB appears at $\lambda = 1.55$ μm. In addition, in that case, the bandwidth is 470 nm from 1390 to 1860 nm with the ER lower than -20 dB and the range covers almost all the communication band including E, S, C, L, and U.

Considering the optimal splitter length 99.36 μm is not integer and the fabricating tolerances of the PCF, the ER under different splitter lengths is studied to analyze the bandwidth
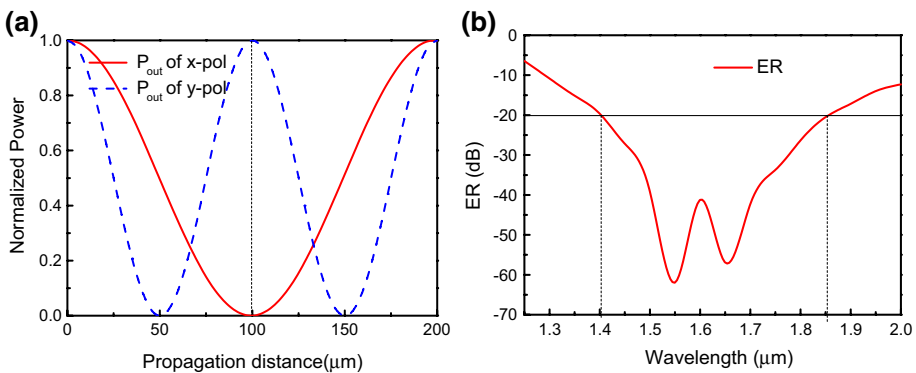
(a)

(b)

Fig. 8 **a** Normalized output power for x-polarization and y-polarization as a function of the propagation distance, **b** Extinction ratio (ER) spectra as a function of the wavelength for the optimal geometrical parameters

Fig. 9 Different extinction ratio (*ER*) spectra as a function of the wavelength for different polarization splitter length
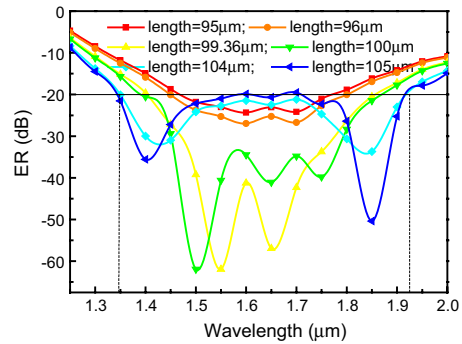

Table 1 The characteristic parameter comparison of splitter based on PCF

References	PCF length (μm)	Bandwidth (nm)	ER (dB)
Jiang et al. (2014)	119.1	249	118.7
Xu et al. (2015)	401	140	110.1
Zhao et al. (2016)	52,800	320	38
Liu et al. (2016)	8100	226	60
Rajeswari et al. (2017)	2000	100(x-) & 55(y-)	− 52.5(-x) & − 37.85(-y)
Younis et al. (2018)	5678	3	
Chao et al. (2018)	103	177	73(A) & 45(B)
Proposed by this paper (2018)	100	470	62
	104	575	

changes. From Fig. 9, the length, satisfying that the corresponding extinction ratio is under − 20 dB at a continuous wavelength range, is from 95 to 105 μm. At the same time, the graph also shows that when the splitter length is 104 μm, its bandwidth can reach the maximum about 575 nm from 1350 to 1925 nm. Thus, the polarization splitter length could be set flexibly according to the actual need.

Table 1 is the comparison of parameters of PCF polarization splitters and the splitter proposed in this, paper. From the data listed in the table blow, it is evident to know that the splitter we proposed has obvious advantages, possessing the ultra-short length and ultra-wide bandwidth simultaneously. As is known to all and mentioned in the beginning, splitter is a device which is widely applied in optical communication system, and it is the development of the system towards high speed and high integration that requires the splitters becoming shorter and wider. As a result of this, the PCF structure reported by the paper has significant meaning for the future study about the fiber optic field.

Compared with the conventional ruled circular air hole structure, the elliptical type air hole is added to the structure proposed in this paper, which undoubtedly increases the difficulty in fabricating the optical fiber. However, with the development of science and technology, the fiber drawing technology has also been upgraded and innovated, which has made more and more fiber structure design ideas possible and become a reality. Issa et al. (2004) fabricated the first microstructure optical fibers with uniformly oriented elliptical holes. It is found that a high degree of hole ellipticity can be achieved with a simple technique that relies on hole deformation during fiber draw. Beltrán-Mejía et al. (2010)

reported an experimental realization of a highly birefringence PCF with rotated elliptical air holes as a result of compressing a regular hexagonal structure. Tian et al. (2012) proposed a novel configuration of embedded multi-elliptical-cores fiber with a hollow air hole, and experimentally demonstrated the fabrication of the embedded multi-elliptical-cores hollow fiber (EECHF). Its preform was fabricated by using a modified technology, named "suspended core-in-tube technique". In summary, the drawing of the optical fiber structure containing the elliptical air holes in this paper is feasible.

4 Conclusion and perspectives

In summary, we proposed an ultra-short and broadband polarization splitter based on PCF and SPR. After adjusting the structure parameters through FEM, an optimal structural parameters combination is decided to be $\Lambda = L = 2$ µm, $d = d_m = 1.2$ µm, $d_1 = 1.9$ µm, $d_x = 0.8$ µm, and $d_y = 0.45$ µm. According to the numerical results, the coupling length ratio is 1.987179 at $\lambda = 1.55$ µm, the proposed splitter possesses a shortest length of 100 µm (to our knowledge) and a very wide bandwidth of 470 nm with the *ER* lower than -20 dB. And when we set the splitter length as 104 µm, the widest bandwidth of 575 nm (to our knowledge) can be achieved. The ultrashort and ultra-broadband polarization splitter can be widely used in high-speed optical communication system.

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