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Polarization splitting filter characteristics of Au-filled high-birefringence photonic crystal fiber

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Abstract Polarization splitting wavelength-selective characteristics of Au-filled high-birefringence photonic crystal fiber (HB-PCF) based on the finite element method is investigated. Numerical results show that the polarization splitting effect can be observed in metal-filled HB-PCF. The resonances points and strength in two polarizations can be adjusted by changing the fiber birefringence, the pitch between the adjacent air holes and the size of the metal wires. Finally, two kinds of Au-filled HB-PCFs with completely polarization splitting and filtering characteristics in communication wavelength are designed. Results show that this polarization splitting effect in metal-filled HB-PCF is very useful for further studies in polarization-dependent wavelength-selective applications and other fiber-based plasmonic devices.

Keywords Birefringence · Photonic crystal fiber · Surface plasmons · Filters

1 Introduction

High-birefringence photonic crystal fiber (HB-PCF) has attracted great interest in many fields from theory to applications, such as the polarization relevant nonlinear application, the polarization transmitting in terahertz and the transverse load sensing technology [1–4]. Here, we present the polarization splitting effect based on HB-PCF selectively filling with metal wires in the cladding air holes.

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Surface plasmon resonance (SPR), formed at the interface of the metal and dielectric, has been widely used in optical sensing, sub-wavelength near-field optical imaging and many plasmonic applications [5–8]. In the metal-filled photonic crystal fiber (PCF), when the fiber modes and the surface plasmon polariton (SPP) modes are matching, the energy in the core will strongly couple to the SPP modes around the metal wires, which implies potential applications in fiber-based photonic devices. In recent years, different techniques have been used for making the metal-filled fiber. PCFs filling with metal nanowires has been successfully fabricated. By using a selective hole closure technique, Tyagi et al. filled the molten Ge into individual hollow channels of silica–air PCF [9]. More recently, Tyagi et al. successfully produced a high-quality gold wire with small diameter down to 260 nm by a straight stack-and-draw technique [10]. Lee et al. [11] reported the fabrication of 120 nm in diameter gold wires selectively filled into the hollow channels of silica PCF by using a novel splicing-based pressure-assisted melt-filling technique.

Studies about the polarization-dependent properties of metal-filled or -coated PCFs have been reported. The SPP mode coupling characteristics have been theoretically and experimentally investigated by Lee et al. [12], but the polarization-dependent losses are insufficient. Zhang et al. [13] demonstrated an in-fiber absorptive polarizer based on the selective metal coating technique for a specific PCF. Nagasaki et al. [14] have theoretically investigated the polarization properties of the PCF filled with metal wires, and strong polarization-dependent coupling characteristics in PCFs with closely-aligned metal wires were observed. Large polarization extinction ratio in a large wavelength range can be obtained by filling several gold wires aligned in the cladding of the PCFs. However, Nagasaki et al. only described PCF with hexagon structure, and the difference of the peak wavelength was caused by resonance of SPP super modes. In the hexagonal fiber, resonances of the two orthogonal polarized directions can be hardly separated.

In this paper, we investigate the polarization splitting phenomenon in the metal-filled HB-PCF by using the finite element method (FEM). The relation between the fiber birefringence and the SPP resonance has been discussed in detail. Results show that the resonances points and strength in two polarizations can be adjusted by changing the fiber birefringence, the pitch between the adjacent air holes and the size of the metal wires. Complete polarization splitting filter effects can be realized by adjusting the structure parameters of fiber and the metal wires appropriately. Two kinds of Au-filled HB-PCFs with complete polarization splitting and good filtering characteristics in communication wavelength have been designed. This kind of polarization splitting effect may find potential applications in developing polarization-dependent wavelength-selective filter, and it will be useful for other fiber plasmonic studies.

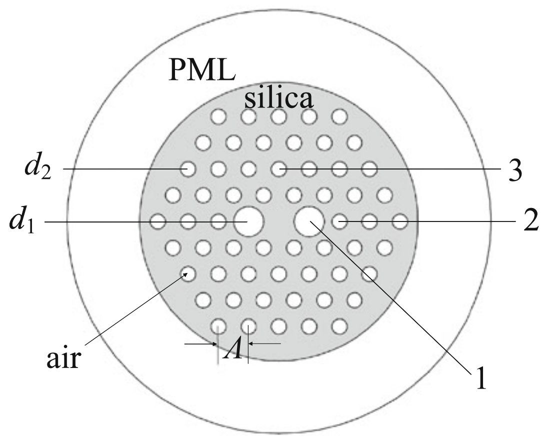

Fig. 1 Schematic diagram of the birefringence PCF. Diameters of the two big air holes and the other small air holes are d_1 = 2.0 μm and d_2 = 1.0 μm. The pitch between the adjacent air holes is Λ = 2.0 μm. Air holes 1, 2 and 3 are the positions that have to be filled with gold wires

2 Basic characteristics of the polarization splitting effect in metal-filled HB-PCF

In this paper, we consider a basic panda high-birefringence fiber with a gold wire filling in the cladding air holes. The schematic of the fiber structure is shown in Fig. 1. The

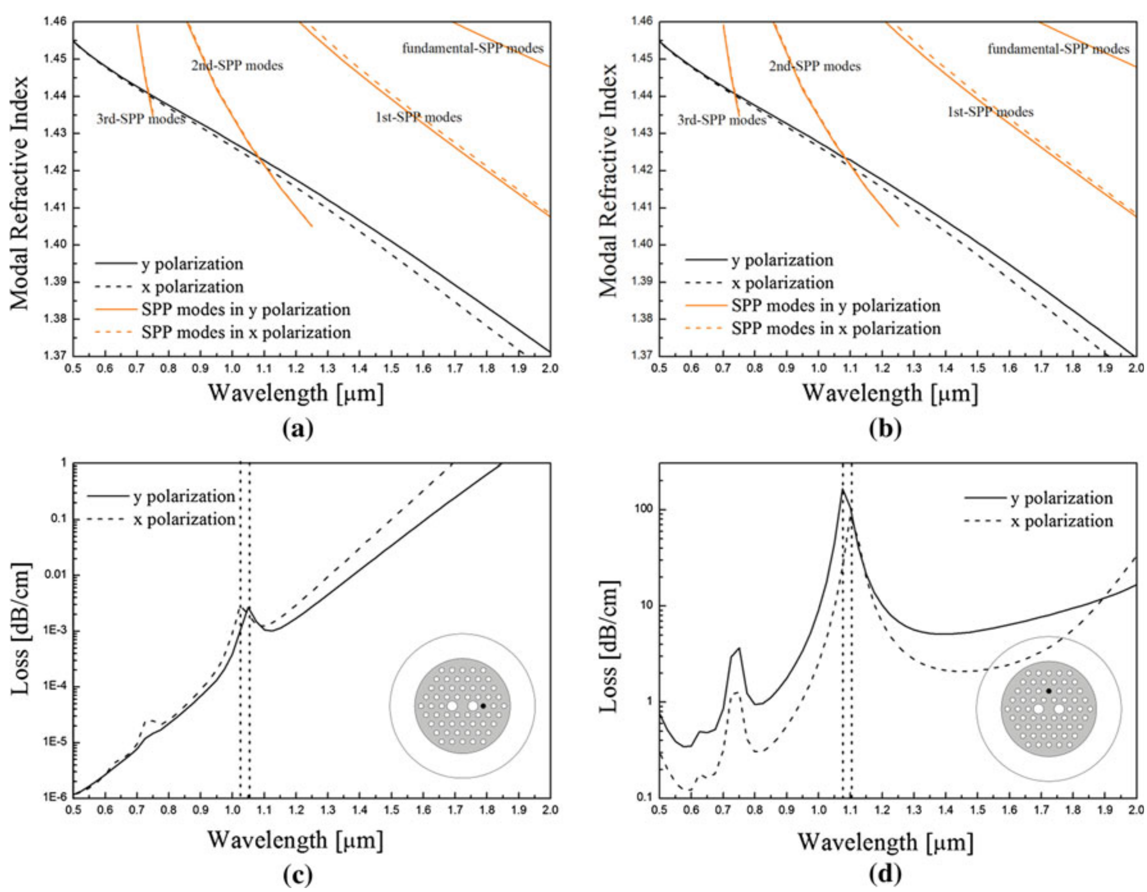

Fig. 2 Wavelength dependence of modal refractive indices and losses for Au-filled PCFs in *y* polarization (*solid*) and *x* polarization (*dash*). **a**, **c** Filled air hole 2. **b**, **d** Filled air hole 3. The *orange curves* represent the SPP modes around the metal wires. Sub-graphs in the *lower right corner* of **c** and **d** show the cross section of the Au-filled fibers

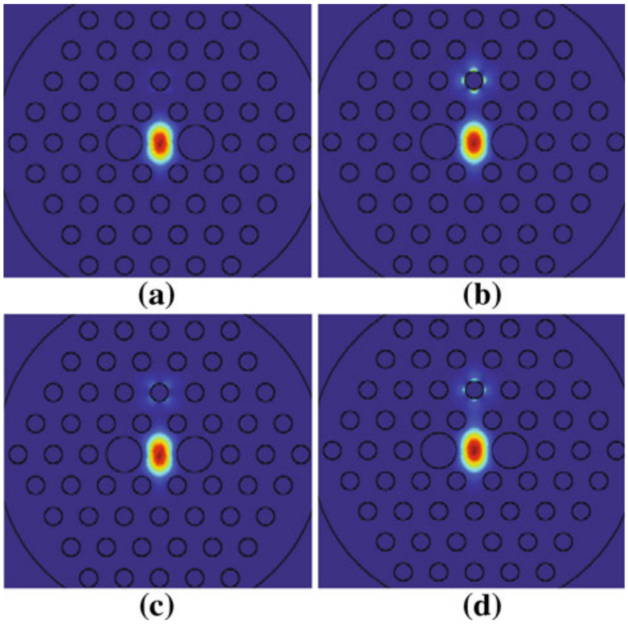

Fig. 3 Mode field distributions of the HB-PCF by filling with a gold wire in air hole 3 at the resonance wavelength of 1.075 μm in **a** *x* polarization and **b** *y* polarization, and 1.100 μm in **c** *x* polarization and **d** *y* polarization

diameters of the two big air holes and the other small air holes are $d_1 = 2.0$ μm and $d_2 = 1.0$ μm. The pitch between the adjacent air holes is $\Lambda = 2.0$ μm.

Considering the polarization effect of the fiber shown in Fig. 1, the metal wire can be filled into three basic positions near the fiber core. Horizontally, we can fill the metal wires in positions 1 and 2, and vertically, we can fill the metal wires in position 3. But in order to ensure the high birefringence of the fiber, we only consider the filling positions 2 and 3. The FEM modal solver is used for the numerical simulations. A perfectly matched layer (PML) is added to the external domain. The PML can absorb well the radiation energy for a wide range of incident angles without producing reflections. Here, the PML absorbs radiation energy in cylindrical coordinate directions from the longitudinal axis of the fiber. Furthermore, a scattering boundary condition outside the PML region is used to reduce the reflections.

The material dispersions of silica and metal are included by using Sellmeier equation and Drude–Lorentz model [15, 16]. In order to investigate the polarization filter properties of the Au-filled HB-PCFs, modal transmission parameters of two orthogonal polarization directions are calculated. Modal refractive indices and losses vary with wavelength for PCFs filled with a gold wire in air hole 2 and 3 as shown in Fig. 2. It can be seen from the figure that the Au-filled HB-PCFs have different resonance points in different polarization states. The splitting effect is more obvious when the fiber modes couple with the second SPP modes. This phenomenon is caused by the modal birefringence of the fibers. From Fig. 2a, b, as the HB-PCFs have unequal modal refractive indices in two polarization states, the core modes of the fibers match with the SPP modes of the gold wires at different wavelength points in different polarization directions. Therefore, there are different peaking loss wavelengths in *x* polarization and *y* polarization, which are displayed in Fig. 2c, d.

On comparing Fig. 2c, d, we can see that the filter resonance strength is much weaker in c than in d. The splitting effect can also be observed by filling a metal wire in air hole 2. But restricted by the big inner air holes, the fiber modes are little affected by the filling metal wire. For the PCF filling air hole 3, the fiber modes have easier coupling with the SPP modes around the metal wire when the phases match. Therefore, the gold-filled fiber shown in Fig. 2d is more significant in fiber-based filter and sensor applications.

Figure 3 illustrates the fundamental mode field distributions of the fiber shown in Fig. 2d at resonance wavelengths of 1.075 and 1.100 μm. At 1.075 μm, the fiber core mode in *y* polarization matches with the second SPP mode around the metal wire. The core mode of the fiber intensely couples to the metal wire. Because of the high birefringence in the fiber, the coupling is quite weak in *x* polarization at this wavelength. The strong resonance point in *x* polarization occurs at 1.100 μm. At this wavelength, the fiber core mode in *x* polarization matches with the second SPP mode. The core mode of the fiber also couples with the metal wire. However, the resonance in *y* polarization can still be observed, as shown in Fig. 3d. This is because the splitting is not strong enough to completely separate the resonances in *x* and *y* polarizations and, influenced by birefringence of the fiber, the coupling strength is much stronger for *y* polarization than for *x* polarization at the same wavelength point.

3 Basic characteristics of the polarization splitting effect in metal-filled HB-PCF

In the previous section, the SPP polarization splitting resonances are observed in the Au-filled HB-PCFs, but the splitting effect is not strong enough to completely separate the two polarization resonances. In this section, we will investigate the factors that affect the spectral polarization splitting coupling in the HB-PCFs. Our analysis will be based on the HB-PCF shown in Fig. 1 filling a mental wire in air hole 3.

3.1 The strength of fiber birefringence

Based on prior analysis, the polarization splitting SPP resonances in Au-filled HB-PCFs are caused by the

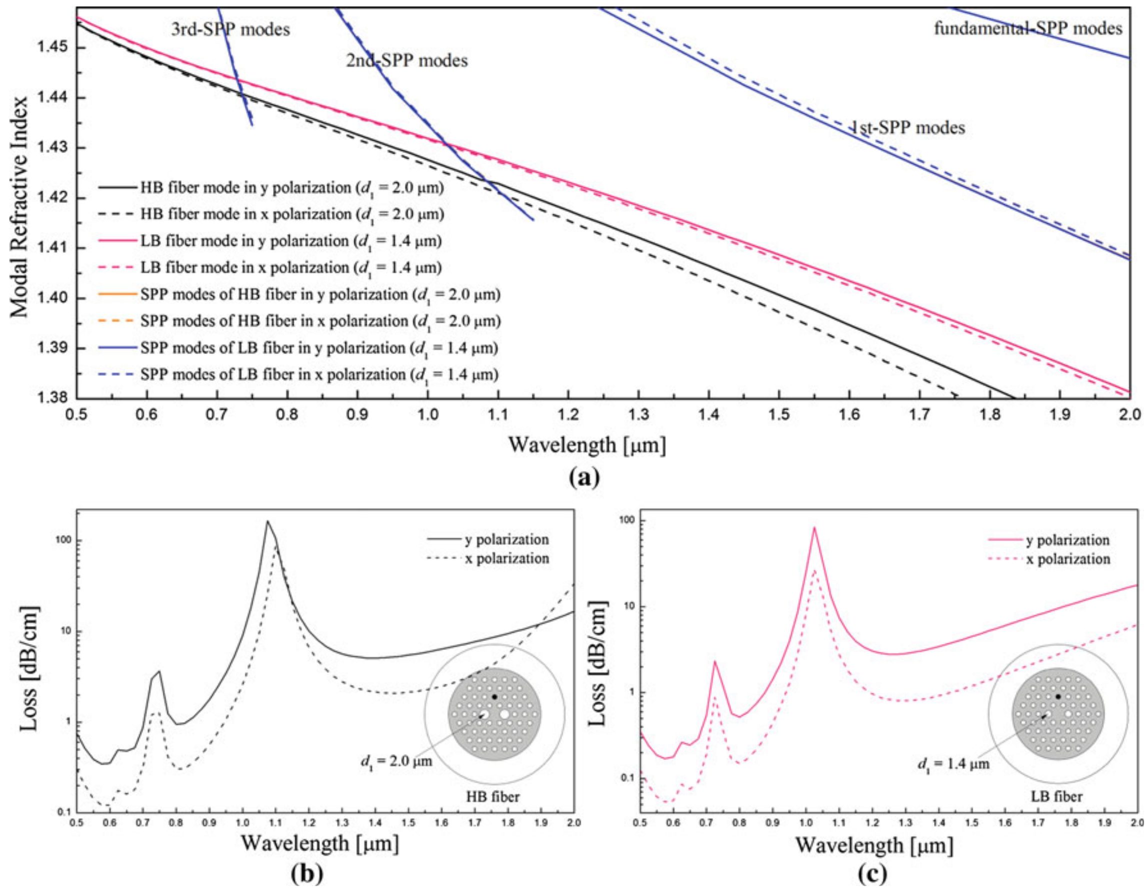

Fig. 4 Wavelength dependence of **a** modal refractive indices and **b**, **c** losses for PCFs with higher birefringence (HB fiber, represented by the *black curves*) and lower birefringence (LB fiber, represented by the *pink curves*) in *y* polarization (*solid*) and *x* polarization (*dash*). SPP modes of the HB and LB fibers around the metal wires are represented in **a** with *orange* and *blue lines*; it shows *blue* because the SPP modes of the two fibers are almost coinciding. The sub-graphs in the *lower right corner* of **b** and **c** show the cross section of the HB and LB fibers. The diameters of the two big air holes in the HB fiber and LB fiber are d_1 = 2.0 μm and d_2 = 1.4 μm

differences between the modal refraction indices in two orthogonal polarization directions. So if we change the strength of the fiber birefringence, the distance of the phase matching points of the SPP modes and the fiber core modes in two polarizations can be adjusted, resulting in enhanced or weakened polarization splitting effect. We adjust the size of the two big air holes to change the birefringence of the fiber. Calculation results are shown in Fig. 4; the diameters of the two big air holes are 2.0 and 1.4 μm, respectively, and other parameters of the fiber are the same as the fiber in Fig. 1. As expected, we can see from Fig. 4 that with increasing birefringence, the modal refractive indices have much larger difference in the two polarizations. However, since the metal wire is not changed and the fiber birefringence has little effect on metal SPP modes, polarization splitting effect becomes much more obvious in the higher birefringence PCF.

3.2 The pitch between the air holes in fiber

Polarization splitting effect will enhance as the birefringence strength increases according to Sect. 3.1. Nevertheless, the SPP modes vary with wavelength much more rapidly than that of fiber core modes, especially in the short wavelength region. The polarization splitting enhancement caused by increasing birefringence is not sufficient. If the SPP resonance points can be tuned to the longer wavelength, the splitting results will be much better. Figure 5 shows the wavelength-selective characteristics of the HB-PCF with different air filling fractions. The air fraction is tuned by adjusting the pitch of the adjacent air holes. Fibers with pitch of 2.0 and 2.1 μm are illustrated in Fig. 5, corresponding to the higher and lower air fractions, respectively. The SPP resonance of the fiber with lower air fraction will be turned to longer wavelength, in which region the SPP modes change slowly with wavelength.

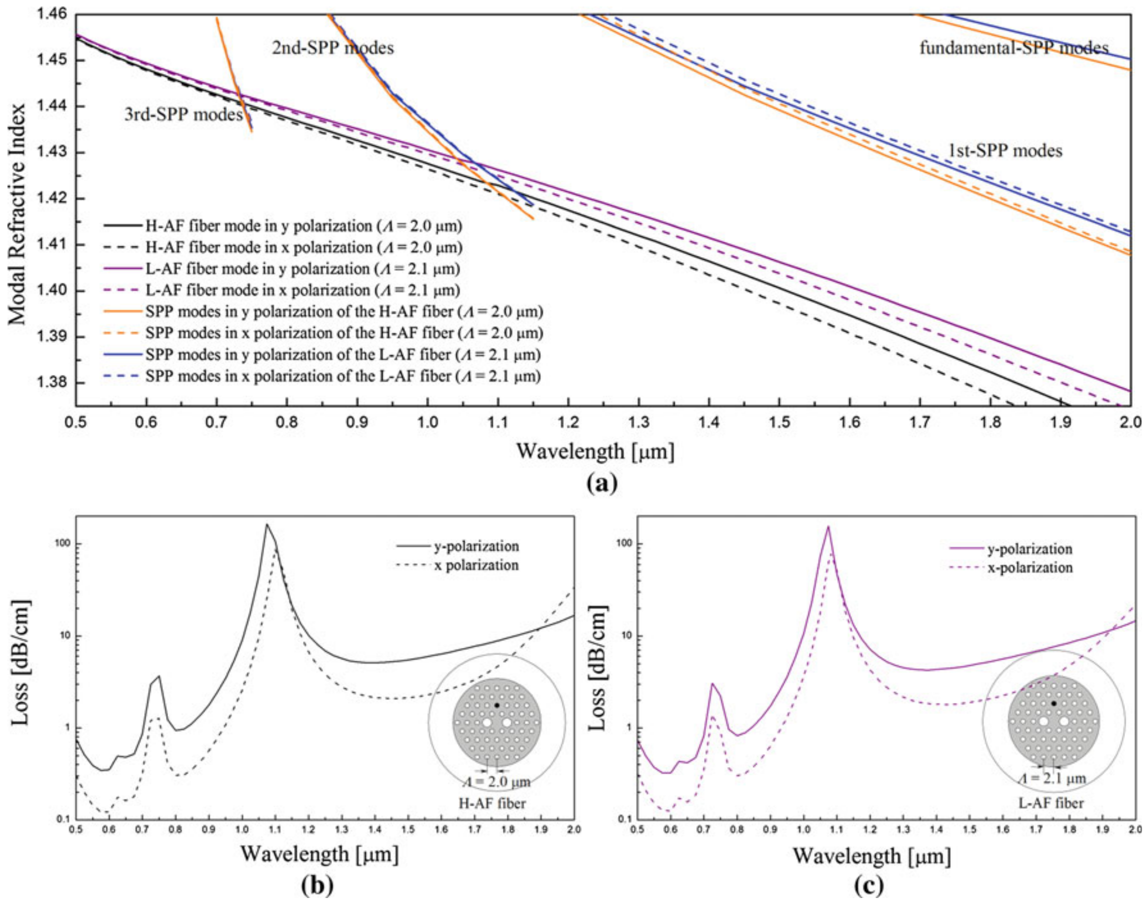

Fig. 5 Wavelength dependence of **a** modal refractive indices and **b**, **c** losses for PCFs with higher air fraction (H-AF fiber, represented by the *black curves*) and lower air fraction (L-AF fiber, represented by the *purple curves*) in *y* polarization (*solid*) and *x* polarization (*dash*). SPP modes of the H-AF and L-AF fibers around the metal wires are represented in **a** with *orange* and *blue lines*. The sub-graphs in the *lower right corner* of **b** and **c** show the cross section of the H-AF and L-AF fibers

Along with the changing of the air fraction in fiber, the core effective refractive will also be changed. However, the second and higher order SPP modes are almost unchanged. So for the same metal wire, we can adjust the resonance points by tuning the air fraction of the fiber.

3.3 The size of the metal wires

The SPP modes around the metal wires are relevant to the diameters of the wires according to [17] and [18]. As a result, when we change the diameters of the gold wires, the SPP modal refractive indices will be different. Figure 6 shows the polarization characteristics of the HB-PCF filling with gold wires with diameters of 1.0 and 1.6 μm, respectively. We can see from the figure that the size of the metal wires has little effect on the fiber core modes, but the SPPs change greatly with slight adjusting of the metal wire. Thus, the resonance wavelengths and the polarization splitting effects can be tuned by filling metal wires with different sizes. It will be very useful for adjusting the filter points to a specific wavelength.

4 Designs for polarization-dependent wavelength-selective fiber filters

According to the above analysis, the polarization splitting filter effect in Au-filled HB-PCF is relevant to such factors as the strength of fiber birefringence, fiber air fraction and the size of filling metal wire. We can infer that the polarization splitting effect can be enhanced by increasing the modal birefringence or decreasing the air proportion in the fiber approximately. In addition, the SPP modes can be tuned by adjusting the diameter of the metal wire, along which the SPP modes coupling points also change. Based on the above rules, two improved “panda” style gold-filled HB-PCFs with perfect splitting effect at communication wavelength are designed. It is promising for further studies

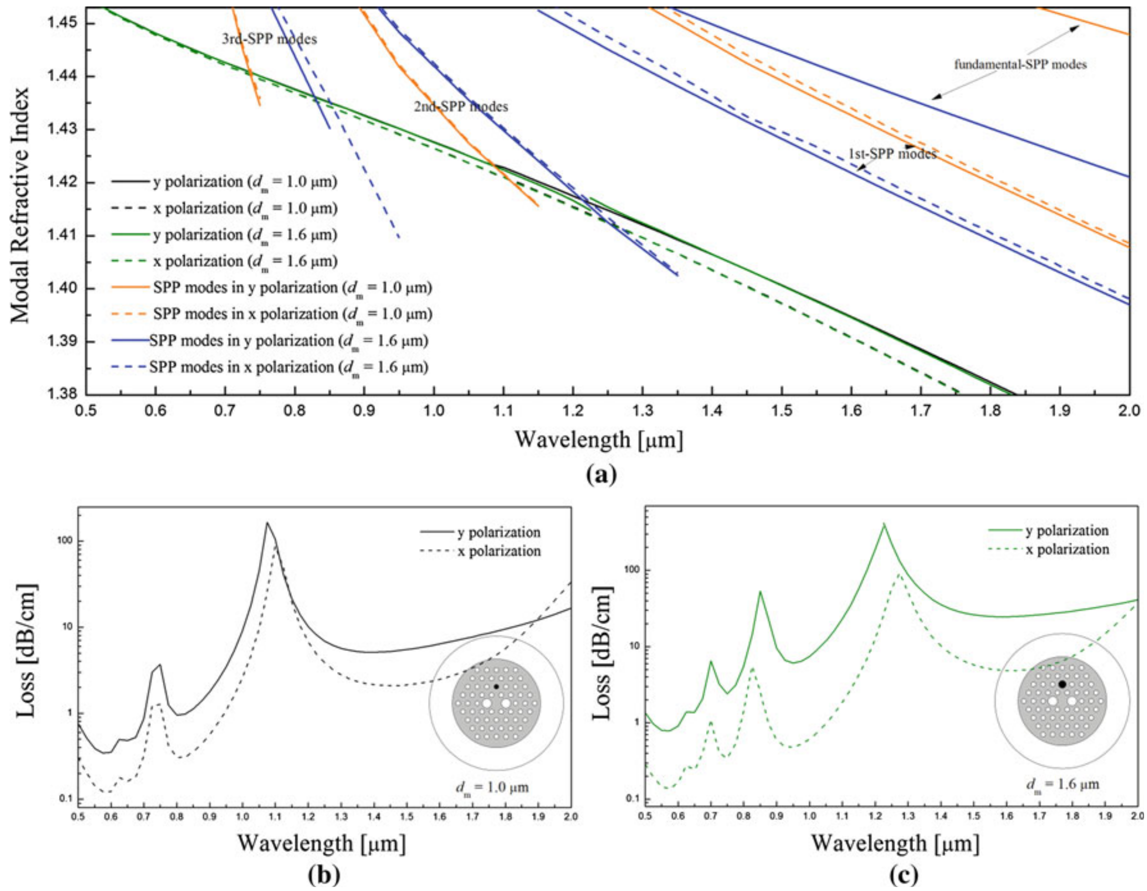

Fig. 6 Wavelength dependence of **a** modal refractive indices and **b**, **c** losses in *y* polarization (*solid*) and *x* polarization (*dash*) for PCFs filling with small (the *black curves*, $d_m = 1.0$ μm) and big (the *olive curves*, $d_m = 1.6$ μm) gold wires. SPP modes of the fibers around the metal wires are represented in **a** with *orange* and *blue lines*. The subgraphs in the *lower right corner* of **b** and **c** show the cross section of the fibers

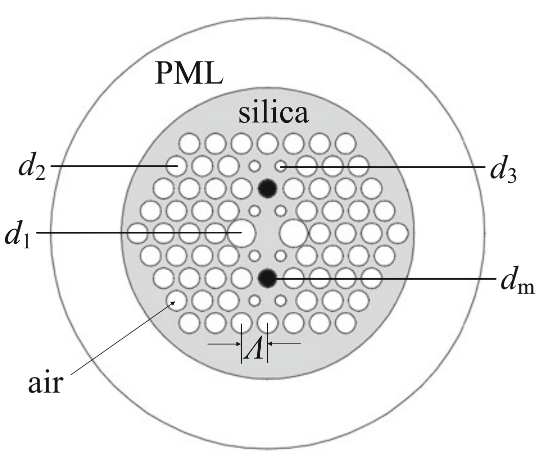

Fig. 7 Schematic diagram of the simple designed HB-PCF. Diameters of the two big air holes, the eight small air holes and the other air holes are $d_1 = 2.6$ μm , $d_3 = 1.0$ μm and $d_2 = 1.9$ μm. The pitch between the adjacent air holes is $\Lambda = 2.4$ μm. The diameters of the two filling gold wires are $d_m = 1.7$ μm

in polarization-dependent wavelength-selective fiber filter applications and other in-fiber plasmonic devices.

4.1 A simple design of splitting filtering fiber

Firstly, a birefringence fiber with a relatively simple structure is given and the schematic diagram of the designed HB-PCF is shown in Fig. 7. In order to increase fiber birefringence and split the coupling points of SPP modes and fiber core modes into two polarizations, eight small air holes around the metal wires are introduced. The diameters of the eight small air holes, the two big air holes and the other air holes are $d_3 = 1.0$ μm, $d_1 = 1.6$ μm and $d_2 = 1.9$ μm. The pitch between the adjacent air holes is $\Lambda = 2.4$ μm. In order to increase the resonance strength, two gold wires are symmetrically filled in the fiber air holes. Because the two metal wires are far from each other and no super-SPP modes are formed, it only enhances the strength of the filter effect. The diameters of the two filling gold wires are $d_m = 1.7$ μm.

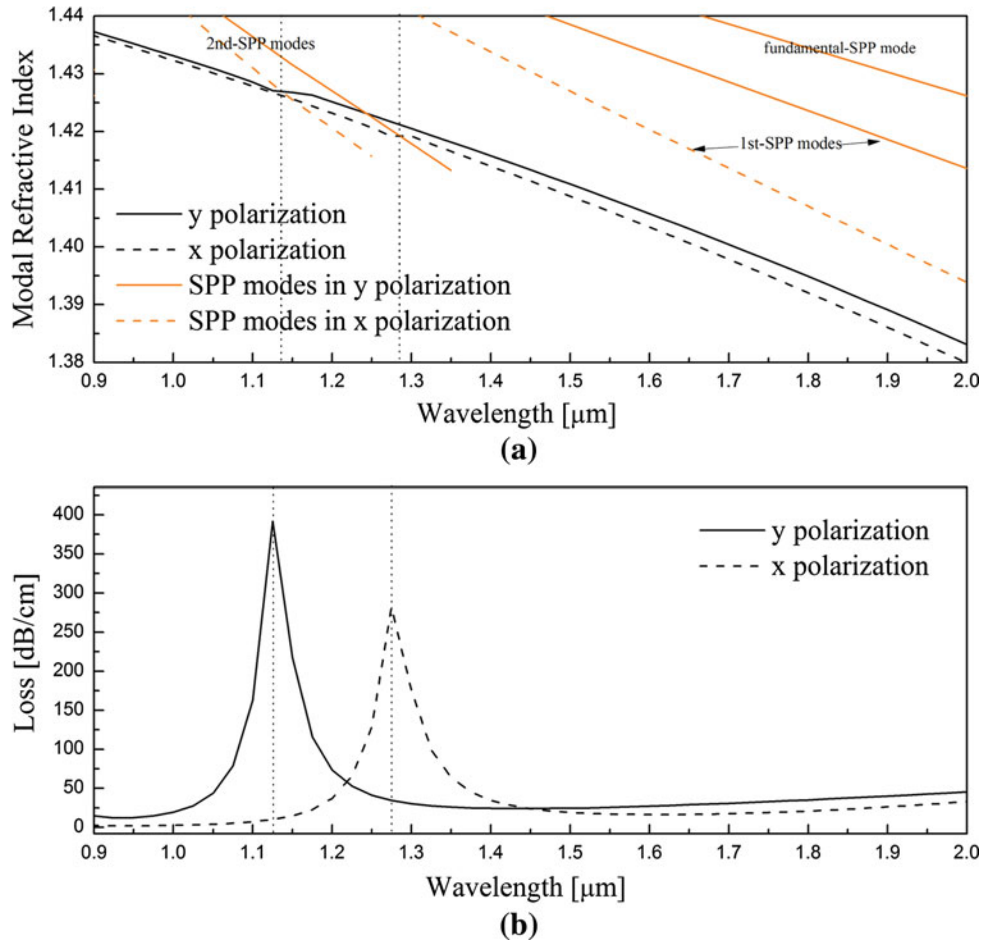

Fig. 8 Wavelength dependence of **a** modal refractive indices and **b** losses for the designed HB-PCF in *y* polarization (*solid*) and *x* polarization (*dash*). SPP modes of the fiber around the metal wires are represented in **a** with *orange lines*

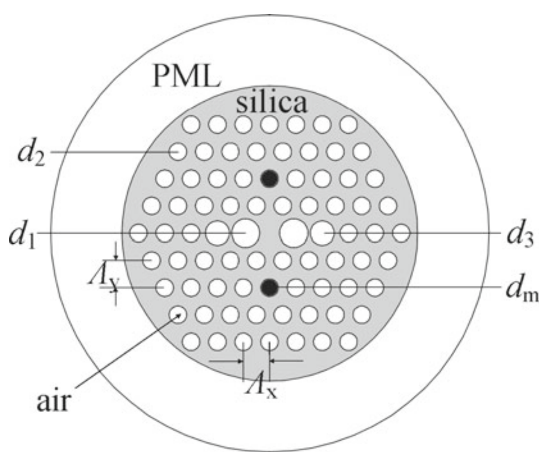

Fig. 9 Schematic diagram of the specially designed HB-PCF. The diameters of the two big air holes, the second big air holes and the other air holes are $d_1 = 2.6$ µm, $d_2 = 2.2$ µm and $d_3 = 1.6$ µm. The diameters of the two filling gold wires are $d_m = 1.6$ µm. The pitch between the adjacent air holes in the horizontal direction is $\Lambda_x = 2.4$ µm

The numerical results are illustrated in Fig. 8. The modal refractive indices and losses for the designed HB-PCF in two polarizations are calculated. The splitting filter resonances can be observed from the figure. The 2nd-SPP modes are coupled with fiber core modes at 1.125 and 1.275 µm for *y* polarization and *x* polarization, respectively. The resonance peaks are separated from each other, and polarization splitting filter effect can be realized by this fiber.

4.2 A good polarization splitting filter fiber at communication wavelength

In this section, a filter fiber with better splitting effect at communication wavelength is designed. The structure of the designed HB-PCF is shown in Fig. 9. The diameters of the two big air holes, the second big holes and the other air holes are $d_1 = 2.6$ µm, $d_2 = 2.2$ µm and $d_3 = 1.6$ µm, respectively. In order to increase the resonance strength, we also symmetrically fill two gold wires in the fiber air holes. The pitch between the adjacent air holes in the horizontal direction is $\Lambda_x = 2.4$ µm. For enhancing the splitting effect further, we take a special design for this fiber. Studies show that when we stretch the fiber in the vertical direction and make the two big air holes in the first ring a little nearer to the center, the birefringence and polarization relevant splitting effect will enhance. In this fiber, we make the pitch in the vertical direction Λ_y is 0.4 µm larger than that in the

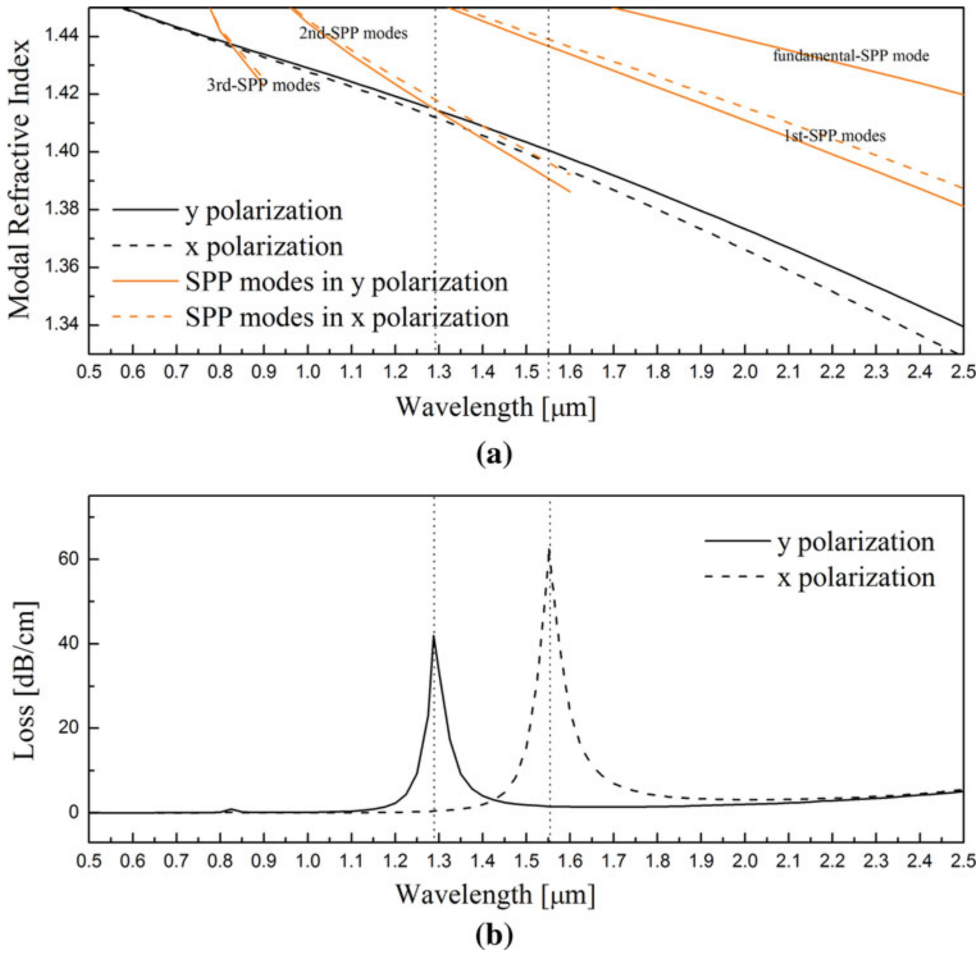

Fig. 10 Wavelength dependence of **a** modal refractive indices and **b** losses for the designed HB-PCF in *y* polarization (*solid*) and *x* polarization (*dash*). SPP modes of the fiber around the metal wires are represented in **a** with *orange lines*

ordinary fiber and make the two big air holes in the first ring 0.2 μm nearer to the center.

For this special design, much better results can be achieved, as shown in Figs. 10 and 11. The diameters of the two filling gold wires of the fiber illustrated in Fig. 10 are d_{m} = 1.6 μm, the same as that around air holes. The resonances of the two polarizations are separated completely. The 2nd-SPP modes coupling points are 1.550 and 1.295 μm in *x* polarization and *y* polarization, respectively. Mode field distributions of the designed HB-PCF at resonance wavelength 1.550 μm in the two polarizations are also shown in Fig. 11. At a resonance wavelength of 1.550 μm, we can see that the fiber modes are strongly coupled to the SPP modes around the metal in *x* polarization. But the fiber modes are limited in fiber core in *y* polarization. It indicates that this fiber will be very promising for applications in polarization splitting fiber-based filter at communication wavelength.

Furthermore, we change the size of the filling gold wires of the specially designed fiber. The splitting effect becomes much more obvious. Figure 12 shows the properties of this fiber filling with different sizes of gold wires. According to prior analysis, the SPP modes are affected by the metal wires, so the SPP resonance wavelengths and the splitting strength are adjusted by the size of the metal wires. Obviously, as the diameters of the metal wires increase, the spread of the SPP resonance wavelengths in two

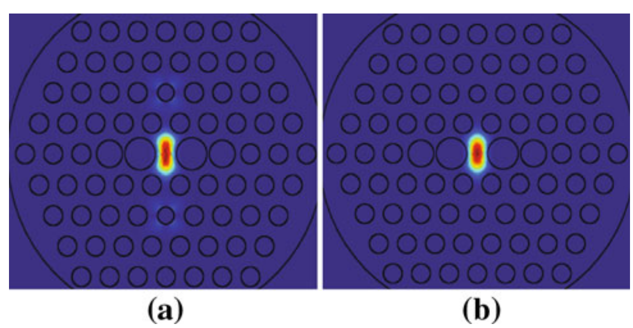

Fig. 11 Mode field distributions of the designed HB-PCF at resonance wavelength 1.550 μm in **a** *x* polarization and **b** *y* polarization

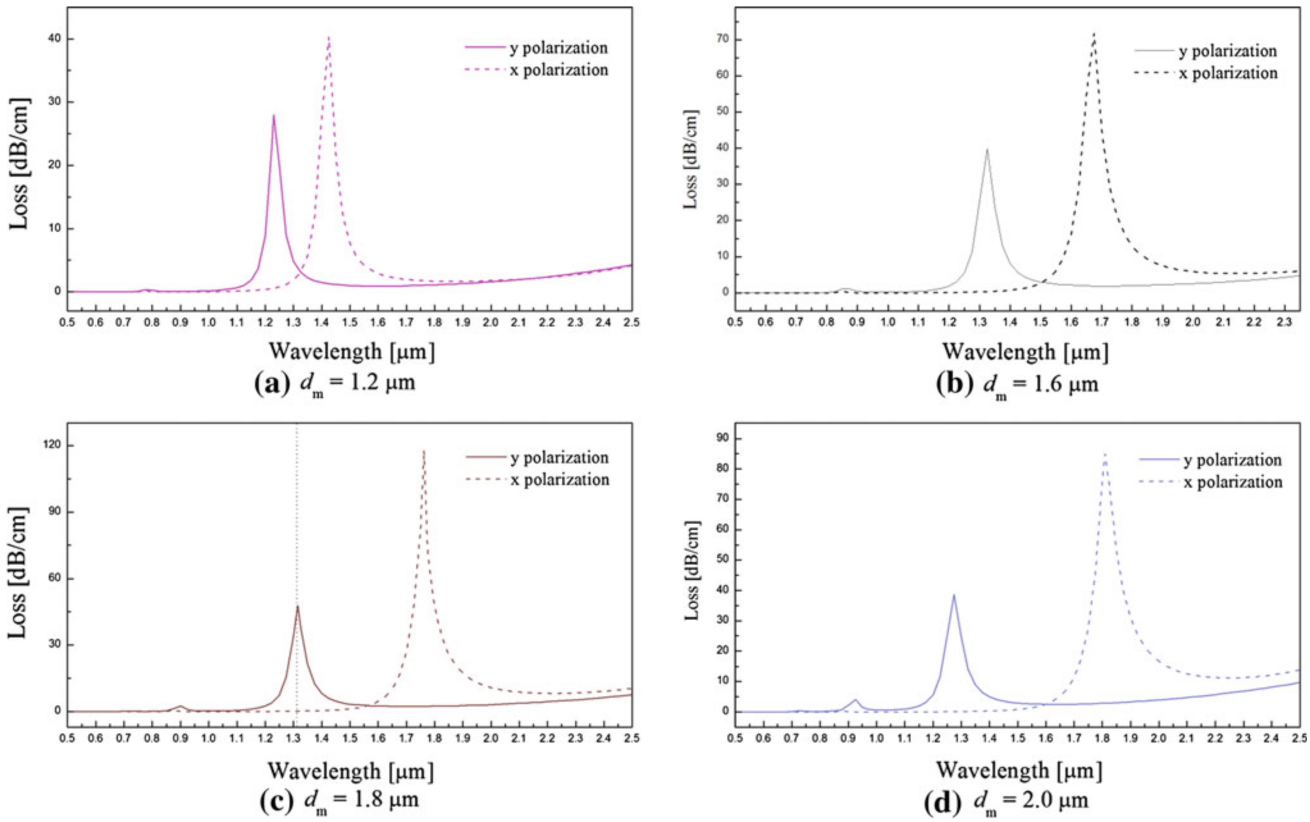

Fig. 12 Polarization-dependent wavelength-selective characteristics of the designed HB-PCF filled with gold wires of different diameters

polarizations gets larger. Much better polarization splitting effect can be realized by filling bigger metal wires. It should also be noted that the coupling point of *x* polarization is about 1.31 µm when the diameters of the metal wires are d_m = 1.6 µm. This is very useful for fiber-based applications at this wavelength.

5 Conclusions

In this paper, wavelength-selective characteristics of Au-filled HB-PCF are investigated. Compared with the symmetric hexagon fiber, polarization splitting resonance filter properties are observed in the metal-filled HB-PCF. The calculated results show that the polarization splitting effect is greatly influenced by the strength of the fiber birefringence, the air fraction of the fiber and the size of the metal wires. Finally, two kinds of Au-filled HB-PCFs have been designed. Complete polarization splitting and good filtering characteristics at communication wavelength are realized in these fibers. Results show that it will be very useful for further studies on polarization-dependent wavelength-selective applications and other fiber-based plasmonic devices.

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