Wavelength-selective characteristics of high birefringence photonic crystal fiber with Au nanowires selectively filled in the cladding air holes*

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Filter characteristics of a designed gold-filled high birefringence photonic crystal fiber are investigated based on the finite element method. The wavelength filter resonances in the high birefringence photonic crystal fiber occur at different points for different polarized directions, and the resonance strength in the x-polarized case is much weaker than that in the y-polarized case. The much more obvious splitting filter characteristics and different resonance strength imply the study and application values in splitting and single polarization fiber devices. The simulation results show that increasing the number of the gold wires only enhances the resonance strength when there is no surface plasmon supermode formed. With the diameters of the gold wires increasing, the response wavelength moves to a longer wavelength, and the strength becomes stronger. When the diameter is increased to 1.4 μm, the response wavelength in the x-polarized case can be tuned to 1.318 μm, which is the communication wavelength. The strongest resonance occurs at 1.2375 μm in the y-polarized case, and the peaking loss can reach 435.83 dB/cm.

Keywords: photonic crystal fiber, birefringence, surface plasmon

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1. Introduction

The surface plasmon effects have attracted much attention.[1−3] Surface plasmon resonances (SPRs) can form at the frequencies with which the oscillating fields are able to fit around nano-scale metallic objects without discontinuities in phase. SPRs have potential applications in many fields, such as optical sensing, optical filtering, sub-wavelength near-field optical imaging, and plasma nonlinear optics.[4−6]

Various new technologies have been applied to integrate metal nanowires into optical fibers. Tyagi *et al.* reported that the molten Ge can be filled into individual hollow channels in silica-air photonic crystal fiber (PCF) at high pressure by using a selective hole closure technique, and the diameter of the Ge wire can be as small as 600 nm.[7] More recently, Tyagi *et al.* filled a micron-scale gold wire into a millimeter-scale fused silica cane, and successfully produced a high-quality gold wire with a diameter down to 260 nm. The direct stack-and-draw technique made it straightforward to incorporate a conventional step-index core adjacent to the gold wire in the cane.[8] Lee *et al.* have successfully filled selectively gold wires of 120 nm in diameter into the hollow channels of silica PCF by using a novel splicing-based pressure-assisted melt-filling technique.[9]

The high birefringence PCF (HB-PCF) has been widely investigated theoretically and experimentally in recent years.[10−12] For the metal filled PCF, most researches are dedicated to optical characterizations of the metal wires, little attention has been paid to the wavelength selective features. In a latest paper, Nagasaki *et al.* numerically investigated the polarization properties of a gold-wire filled PCF. The theoretical analysis indicated potential applications of the metal filled PCF in the field of optical filter.[13] However, Nagasaki *et al.* only described the polarization properties of the gold filled PCF with a simple hexagon structure. And the detail filter properties of the metal filled PCF were not studied.

In this paper, we numerically simulate the wave-

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length selective characteristics of a gold filled HB-PCF by using the finite element method (FEM). The fundamental characteristics of the fiber are studied. Moreover, the influences of the size of the metal wires on the resonance wavelength and the response strength are investigated. Our results show that the metal filled HB-PCF can be used in splitting and single polarization fiber devices.

2. PCF structure and the fundamental theory

The schematic diagram of the designed four-ring triangular array HB-PCF is shown in Fig. 1. Two large air holes each with a diameter of $d_1 = 2.2$ μm are introduced near the core region of the PCF along the x-axis direction. The air holes in the outer layers each have a diameter of $d_2 = 1$ μm. In order to increase the modal birefringence of the fiber, the air holes plotted in gray each have a larger diameter of $d_3 = 1.2$ μm. The two holes in black will be selectively filled with gold nanowires with diameters of d_4 and d_5 respectively. And the pitch of the holes is $\Lambda = 2$ μm.

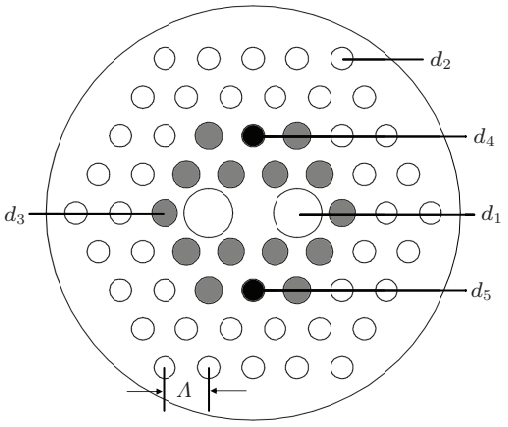


Fig. 1. Schematic diagram of the PCF.

The background material is pure silica, and the Sellmeier equation is used for calculating the chromatic dispersion of the silica, thus the material dispersion of the fiber has been taking into account.[14]

Generally, the attenuation of fiber caused by the leakage loss can be greatly reduced by adding additional rings of air holes around the core. For the metal filled PCF, researches have shown that when there are more than three ring layers surrounding the guiding core, the material loss will dominate in the total loss.[15] The material loss of the metal filled PCF is introduced by considering the imaginary part of the permittivity of the metal. A more accurate Drude–Lorentz model has been used to describe the dielectric constant of the metal. We select the bulk gold for calculation, and the dispersion of gold can be expressed as[16]

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_{\rm D}^2}{\omega(\omega + {\rm j}\gamma_{\rm D})} - \frac{\Delta\varepsilon \cdot \Omega_{\rm L}^2}{(\omega^2 - \Omega_{\rm L}^2) + {\rm j}\Gamma_{\rm L}\omega}, \quad (1)$$

where $\varepsilon_\infty = 5.9673$ is the permittivity of the gold, $\triangle\varepsilon = 1.09$ is the weighting factor, $\omega_{\rm D}$ and $\gamma_{\rm D}$ are the plasma frequency and the damping frequency, respectively, $\omega_{\rm D}/2\pi = 2113.6$ THz, $\gamma_{\rm D}/2\pi = 15.92$ THz, $\Omega_{\rm L}$ and $\Gamma_{\rm L}$ are the frequency and the spectral width of the Lorentz oscillator, $\Omega_{\rm L}/2\pi = 650.07$ THz, $\Gamma_{\rm L}/2\pi = 104.86$ THz.

In this paper, the FEM is used for numerical simulating the designed HB-PCF. The fundamental parameters, such as mode-propagation constant, propagation losses, and the effective mode area of the fiber, are available.

The fiber loss can be expressed as

$$L = 8.686 \times \frac{2\pi}{\lambda}{\rm Im}(n_{\rm eff}) \times 10^4, \quad (2)$$

where the units of the leakage loss and the wavelength are dB/cm and micrometer, respectively.

When the phases of the core modes and the surface plasmon polaritons (SPPs) match, the guided light in the core of the PCF will strongly couple to the surface plasmon of the metal nanowires, and the fiber loss increases rapidly. Therefore, the attenuation of fiber is caused by both material loss and leakage loss at the resonance wavelengths.

3. Results and discussion

3.1. Novel wavelength selective characteristics of HB-PCF

Firstly, we study the case with a gold wire filled in the upper black hole (d_4) of the designed HB-PCF. The wavelength-selective characteristics of the gold filled HB-PCF in two polarized directions are shown in Fig. 2. We find that the wavelength filter resonances occur at different points for the two orthogonal directions. For the second surface plasmon mode resonances, the wavelength filter points are 1.1625 μm and 1.125 μm respectively. This much more obvious splitting filter characteristic in the metal filled HB-PCF indicates the potential research and application values in fiber based splitting and filter studies.

Moreover, influenced by the fiber birefringence and the gold filling position, the resonance strength in the x polarized direction is much weaker than that in the y polarized direction. This is very useful for investigating the single polarizion filter fiber based devices.

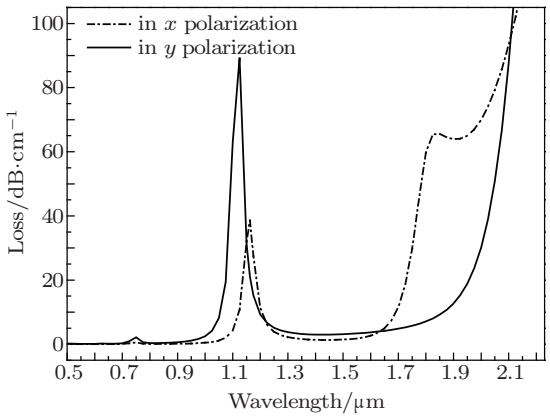


Fig. 2. Wavelength-selective characteristics of the gold filled HB-PCF in two polarized directions.

3.2. Wavelength selectivity in different filling states

3.2.1. Mode distributions

In this section, we will compare the coupling properties of the designed HB-PCF in different filling states. Figures 3(a), 3(b), and 3(c) illustrate the fundamental mode distributions of the unfilled, the one-wire (d_4) and the two-wire (d_4 and d_5) filled PCFs, respectively. The filling metal wires have the same diameters with the outer air holes, i.e., $d_4 = d_5 = d_3 = 1$ μm.

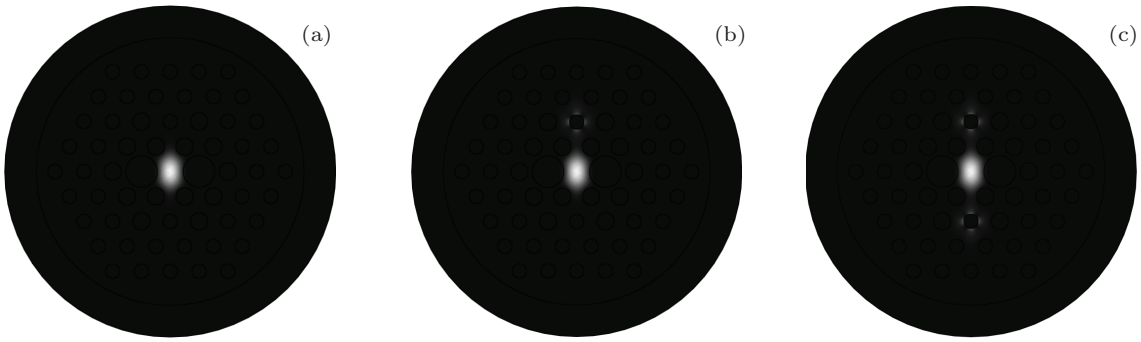


Fig. 3. Fundamental mode distributions of (a) the unfilled, (b) the one-wire and (c) the two-wire filled PCFs in the y polarized direction when the second SPP mode coupling occurs at the wavelength of 1.125 μm.

3.2.2. Dispersion relations

The x-polarized and the y-polarized dispersion curves of the fiber are displayed in Figs. 4(a) and 4(b), respectively. For clearly describing the coupling properties between the guided light and the SPPs, the metal SPPs of different orders are also shown in Fig. 4.

As can be seen from Fig. 4, in the transparent range of silica, the modal refractive indexes of the fundamental and the first-order SPP modes are higher than that of the core guided mode in fiber. Indeed, for the simple metal filled PCF without SPP supermode formed, it is difficult to realize the coupling of the fundamental and the first-order SPP modes with the guided modes in the core. The previous researches have shown that the fundamental and the first-order SPP modes formed on the metal generally have much higher modal refractive indexes than the core guided modes.[17]

3.2.3. Birefrigence

The strength of modal birefringence plays an important role in the polarization maintaining fibers. The variation of birefringence parameter B with the wavelength for the HB-PCF is shown in Fig. 5. Values of B are 0.00564, 0.00555, and 0.00547 at 1.55 μm for the PCFs filled with a single gold wire, two gold wires, and without the filling metal, respectively. As shown in Fig. 5, the modal refractive index is slightly influenced by the metal wires, so the curves are almost the same for different filling states.

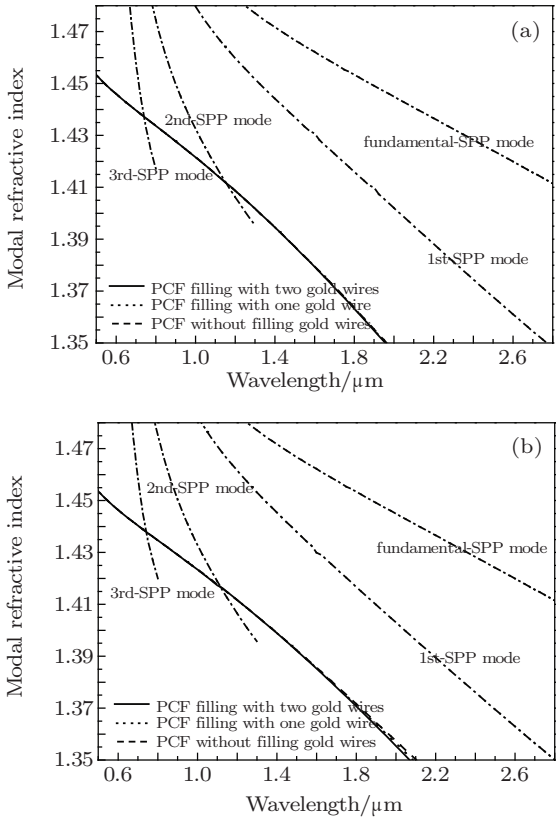


Fig. 4. Variations of model refractive index with wavelength for fibers in different filling states, panels (a) and (b) show the x-polarized and the y-polarized dispersion curves, respectively.

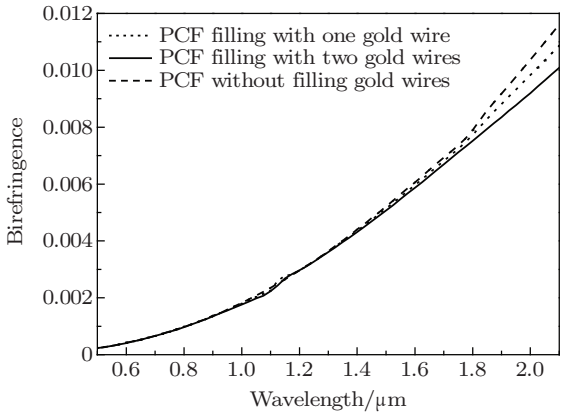


Fig. 5. Wavelength dependence of birefringence parameter B for the HB-PCF.

Numberical results show that the effective indexes for these three kinds of PCFs are almost coinciding. This indicates that selectively filling metal nanowires in the cladding of PCF can produce very weak effect on the mode refractive indexes. It only influences the energy distributions of PCF when the SPRs occur. Mathematically, selectively filling with metal nanowires in the cladding air holes of PCF has little effect on the real parts of mode effective indexes, but can greatly affect imaginary parts of mode effective indexes, which play a critical role on the transmission losses of fiber.

3.2.4. Losses

Losses of the x-polarized and the y-polarized core modes of the PCFs with different filling states are illustrated in Fig. 6. For the metal filled PCF, when the phases of the core modes and the SPP modes match, the fiber core mode couples to the surface of the metal, and the fiber attenuation shows a peak. The resonance wavelength is exactly corresponding to the cross point of the effective indexes of the core and the SPPs shown in Fig. 4. The strongest resonance appears when the second SPP mode and the guided mode in the core cross, and it becomes very weak for more than third order SPP resonance. The peaking value of the transmission loss indicates that the metal filled PCF can be used as a band-rejection filter.

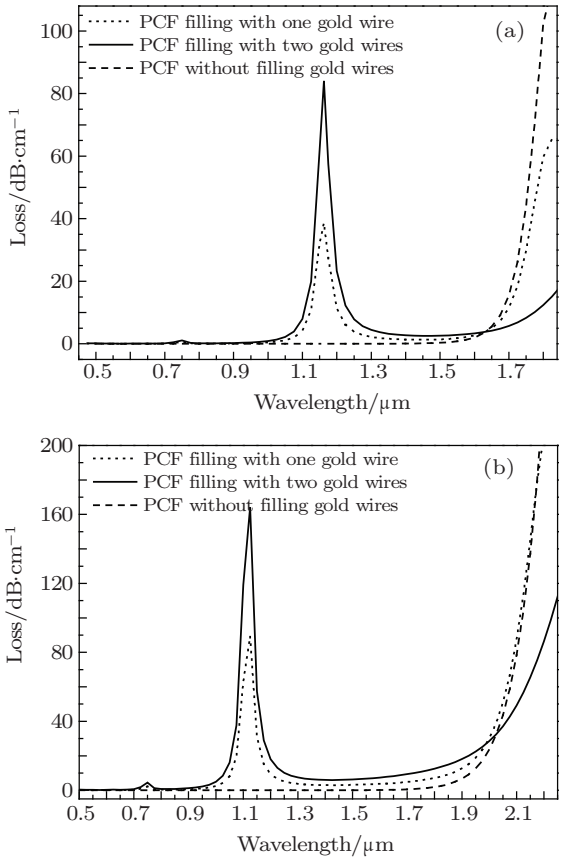


Fig. 6. Losses of (a) x-polarized and (b) y-polarized core modes in PCFs with different filling states.

For the same polarization, figure 6 also shows that the peaking losses of the PCFs with different filling states appear at the same wavelength, but the resonance strength is much stronger for the two gold wires

filled PCF. For the PCF filled with two gold wires, when the SPRs occur in a particular wavelength, the SPP modes form on the surface of the metal. Since the two gold wires along the y-axis direction on the second ring of the PCF are far from each other, the SPPs of them can hardly couple, which is also clearly displayed in Figs. 3(b) and 3(c). Therefore, when there is no SPP supermode formed, two gold wires filing in the PCF only enhance the intensity of the SPRs, but not change the resonance points. These results demonstrate convincingly that the strength of the SPRs can be adjusted by selectively filling and appropriately increasing the number of gold wires in the cladding.

Comparing Fig. 6(a) with Fig. 6(b), we can see clearly that because of the introduced high birefringence in the fiber, the response strength of the y-polarized core mode is much stronger than that of the x-polarized core mode for the PCF in the same filling state. And the response wavelength of the x-polarized core mode is longer than that of the y-polarized core mode.

3.3. Tunable filter characteristics of PCFs filled with gold wires of different diameters

In this section, we change the diameters of the metal wires filled in the designed PCF. Wavelength resonances of PCFs filled with two gold wires in different diameters in x and y polarizations are shown in Fig. 7, and the diameters of the gold wires are varied from 0.6 μm to 1.4 μm.

It can be seen from Fig. 7 that with the diameters of the gold wires increasing, the response strength becomes stronger. The peaking value of the leakage loss for the diameter of 1.4 μm is much larger than that for 0.6 μm. Moreover, the response wavelength will move to the longer wavelength with the diameters of the gold wires increasing. Therefore, adjusting the size of the gold wires filled in the fiber appropriately, we can tune the optical filters.

It should be noted that when the diameter increases to 1.4 μm, the response wavelength in the x-polarized case can be tuned to 1.318 μm, which indicates applications as optical filters in the communication wavelength.

The strongest resonance appeares at 1.2375 μm for the y-polarized case with a metal wire diameter of 1.4 μm. The peaking loss of the PCF can reach 435.83 dB/cm, which is much higher than that of the filters based on dual core fibers.[18,19] And the full width at half maximum (FWHM) is 46.4 nm.

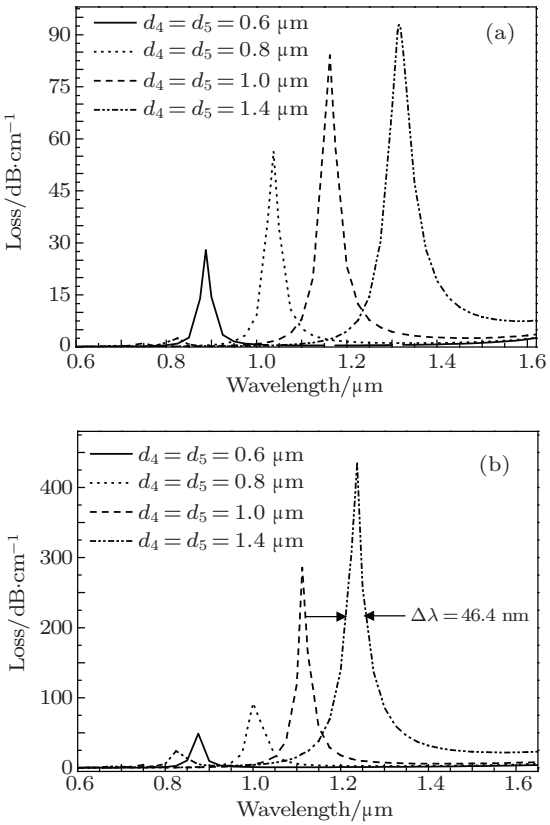


Fig. 7. Filter characteristics of PCFs filled with gold wires of different diameters in (a) the x-polarized and (b) the y-polarized directions.

3.4. Further explanation of the filter characteristics influenced by the size of gold wires

To further explain the filter characteristics influenced by the size of gold wires, we compare the PCFs filled with gold wires of 0.6 μm and 1.4 μm in diameter in Fig. 8. The diameters of the two filling gold wires are $d_4 = d_5 = 0.6$ μm, $d_4 = d_5 = 1.4$ μm, and $d_4 = 1.4$ μm, $d_5 = 0.6$ μm, respectively. Consistent with the previous conclusions, the resonance strength in the PCF filled with two big gold wires is much stronger than that in the PCF filled with two small gold wires. And the resonance wavelength will move to a longer wavelength with the increasing of the gold wire diameters. The resonance wavelength of the second-order SPP mode coupling in the PCF filled with two small metal wires is much closer to the point of weak third-order SPP mode coupling in the PCF filled with two large metal wires. Therefore, by designing the sizes of the metal wires appropriately and adjusting the resonance wavelength of one order SPP

coupling for different metal wires to the same point, the filter property can be improved greatly.

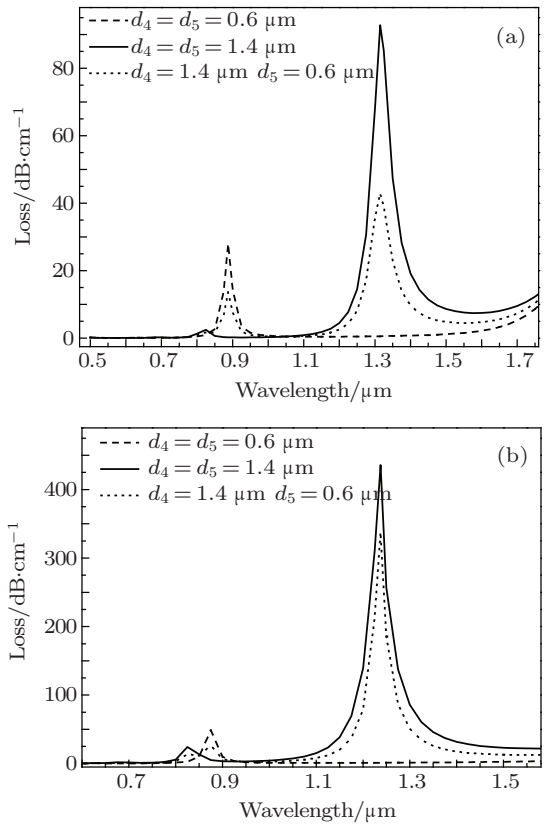


Fig. 8. Filter characteristics of PCFs filled with gold wires of different diameters in (a) the x-polarized and (b) the y-polarized directions.

For the resonance of the PCF filled with metal wires of $d_4 = 1.4$ μm, $d_5 = 0.6$ μm at longer wavelength, it is equivalent to the second SPP mode coupling of the PCF filled with only a single gold wire of 1.4 μm in diameter. It is just because of the very short response wavelength of the PCF with two small gold wires. We can see it clearly in Fig. 9. In the resonance wavelength of 1.225 μm for the y-polarized case, the two curves coincide almost completely.

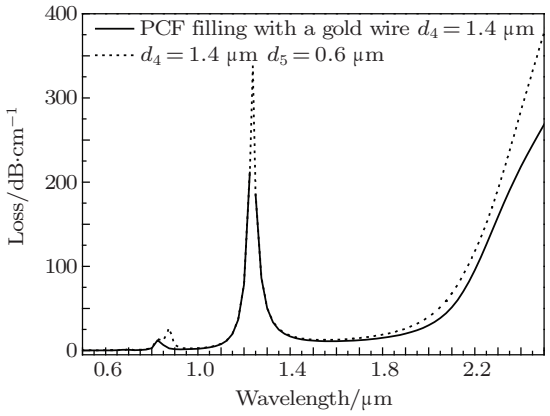


Fig. 9. Filter characteristics of PCFs.

4. Conclusions

Wavelength-selective characteristics of gold filled HB-PCFs have been investigated in this paper. The wavelngth resonances occur at different points, and the response strength is much stronger for the y-polarized case than that for the x-polarized case because of the introduced high birefringence in the fiber.

The results show that increasing the number of the gold wires only enhances the strength of the resonance when there is no SPP supermode formed. Moreover, when the diameter of the gold wires increases, the response strength becomes stronger, and the response wavelength moves to a longer wavelength.

The response wavelength is longer for the x-polarized case than that for the y-polarized case. When the diameter increases to 1.4 μm, the response wavelength in the x-polarized case can be tuned to 1.318 μm, which is the communication wavelength. And the strongest resonance strength occurs at 1.2375 μm in the y-polarized case. The peaking loss of the PCF can reach 435.83 dB/cm, and the FWHM is 46.4 nm. The researches also show that the filter property can be improved greatly by adjusting the response wavelength of one order SPP coupling for different metal wires to the same point.

It suggests that the metal filled HB-PCF can be used in splitting and single polarization fiber devices and tunable band rejection fiber filters by adjusting the sizes of the gold wires or changing the filling styles of the fiber.

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