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A polarization filter at 1550 nm based on photonic crystal fiber with symmetry around gold-coated holes

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A polarization photonic crystal fiber based on surface plasmon resonance is proposed in this paper. The photonic crystal fiber with gold coated holes is studied through using the finite element method. The impacts of structural parameters on the resonance characteristics are discussed. Numerical simulations show that the resonance wavelength can be modulated by changing the parameters of the air holes and thickness of gold layer. At the resonance wavelength 1550 nm, the loss is 3.8045 dB/m in x-polarization and the loss is 28464 dB/m in y-polarization by adjusting the size of the gold-coated holes and the place of air holes. Results show that the loss of y-polarized mode is much larger than the loss of x-polarized mode. The y-polarized mode is suppressed, and only x-polarized mode can be guided at the resonance wavelength of y-polarized mode. The results indicate that the mode polarized in one direction can be filtered out selectively by adjusting the diameter of air holes, and the filtering effect in a communication band is achieved.

Keywords: photonic crystal fiber, polarization filter, finite element method, surface plasmon resonance.

1. Introduction

With the development of photonic devices theory and manufacturing process, photonic crystal fibers (PCFs) [1–6] as excellent optical and photonic devices have been widely used in fiber communication systems, with their particular optical properties, such as high birefringence, low loss, flexible nonlinearity, and big mode area. Many photonic devices can be designed by PCF, like the PCF sensors, PCF polarization beam splitters, PCF WDM, laser [7], amplifiers [8], *etc*. Meanwhile, PCF has a lot of advantages as an optical waveguide carrier. Many studies on PCF filled with metal wires or coated with metal layers have been reported [9–15]. Surface plasmon polariton (SPP) can appear on the surface of metal with the incident light coupled to the metal layer [10]. When core-guided light and SPPs phases match, they resonate and the loss of a core mode will increase quickly. At the resonance frequency where the surface plasmon resonance (SPR) is the strongest, the loss is maximum. Surface plasmon resonance is a kind of physical phenomena, when light is incident at a critical angle on the medium interface of two different refractive indexes and the light can cause the resonance of metal-free electrons. Because the free electrons can absorb light energy, the reflected light in certain angle greatly abates.

With the research on PCFs, different materials have been used to fill in or coat in the fibers such as liquid crystals [16], ethanol, polymers [17], and many novel properties have been achieved. The resonance wavelength can be modulated by adjusting the size and position of holes, or permittivity of the metal layer in the fiber. In 1993, JORGENSON and YEE creatively proposed the idea of using the PCF as a carrier to enhance the SPP modes, and manufactured PCF of a surface plasmon resonance sensor based on their method [9]. In 2008, LEE *et al*. proposed the polarization-maintaining PCFs where the coupling to surface plasmon modes on selectively introduced gold nanowires took place. The finite element simulations were consistent with the experimental results [11]. In 2011, NAGASAKI *et al*. selectively filled different positions of the linear porosity of the PCF coating with the metal line, and obtained a greater polarization extinction ratio [18]. In the same year, LEE *et al*. also reported a splicing-based pressure-assisted melt-filling technique for forming metallic nanowires in hollow channels in microstructured silica fibers [19]. In 2013, researchers studied the characters of a liquid-filled and gold-coated PCF polarization filter based on SPR [12]. In 2015, the effects of structural parameters on the resonance characteristics were studied [13].

In this paper, we analyze the polarization in PCFs with a gold-coated hole and propose a new structure. The PCF whose air holes are arranged in a hexagonal lattice with four kinds of holes (and the holes are selectively coated with gold) is simulated by finite element method (FEM). The core modes couple to the SPP modes when the phase-matching conditions are satisfied. By making the PCF with high birefringence, the resonance wavelengths of x- and y-polarized mode can be divided. In order to apply this polarization filter in communication system, we adjust different parameters. The loss of y-polarized mode becomes larger than the loss of x-polarized mode at 1550 nm. Finally, we achieve a polarization filter by optimizing the parameters of structure and have better performance in finite element simulations. Furthermore, compared with [12, 14, 20, 21], the PCF we proposed has a simple structure and good practicability for fiber filter production. At variance with other researches on the polarizing filter of the PCF, the core of our design was not highly birefringent but the symmetry around the gold-coated holes was significant. By changing the structure parameters, it is possible to obtain the extremely low transmitted light loss while ensuring the filter performance. The structure can be applied to a system with extremely high signal quality requirements.

2. Structure and principle of filter

The schematic cross-section of the proposed PCF is shown in Fig. 1. The background material of the fiber is pure silica, whose dispersion relationship is calculated by the Sellmeier equation [22]. The refractive index of air is 1. The PCF has three kinds of air holes and they are arranged in a hexagonal lattice. Their diameters are $d_1 = 1.4$ μm,

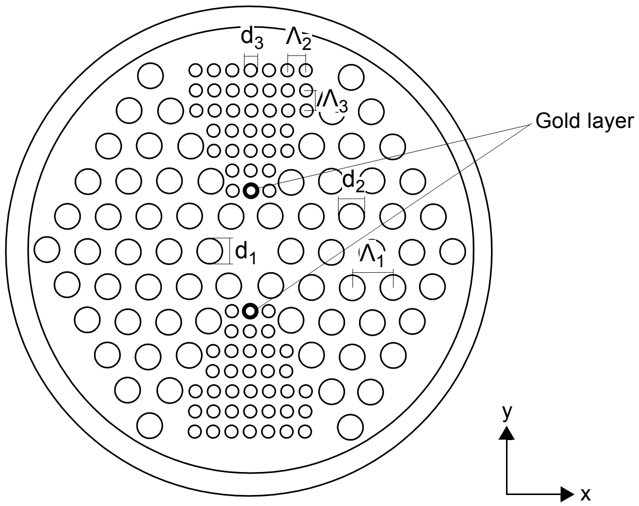


Fig. 1. Cross-section of the photonic fiber.

$d_2 = 1.2$ μm, and $d_3 = 0.6$ μm. Considering enhance high-birefringence, the asymmetry of cladding is proposed: the hexagonal pitch in the x direction is $\Lambda_1 = 2$ μm, $\Lambda_2 = 0.9$ μm and the hexagonal pitch in the y direction is $\Lambda_3 = 1$ μm. In the y direction, two air holes are coated with metal of gold with the thickness of 40 nm, on which the SPP mode can form. In order to consider the material dispersion, the Sellmeier equation and the Drude –Lorentz model [19] for metal is used

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\varepsilon\,\Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L\omega} \tag{1}$$

where ε_∞ is the permittivity of the metal, $\Delta\varepsilon$ can be interpreted as a weighting factor and ω is the angular frequency of guided light, γ_D and ω_D are the damping and plasma frequency, respectively, Ω_L and Γ_L represent the frequency and the spectral width of the Lorentz oscillator, respectively. We use the parameters presented in the Table as we select the bulk gold for calculation [23].

The mode loss L can be expressed as

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

where λ represents the wavelength of light and the $\mathrm{Im}(n_{\mathrm{eff}})$ represents the imaginary part of the effective refractive index of the fundamental mode.

T a b l e. Values of the optimized parameters.

ε_∞	$\Delta\varepsilon$	$\gamma_D/2\pi$	$\omega_D/2\pi$	$\Omega_L/2\pi$	$\Gamma_L/2\pi$
5.9613	1.09	15.92 THz	2113.6 THz	650.07 THz	104.96 THz

3. Simulation result and analysis

Polarization photonic crystal fiber (PCF) with gold coated holes based on surface plasmon resonance (SPR) is proposed. A finite element method is employed in the simulation. In order to absorb the wave vector completely, a perfectly matched layer and a scattering boundary condition are used. The solving domain is decomposed into many elements by meshing.

Figure 2 shows the electric field distributions of x-polarization, y-polarization, y-polarization coupled, and y-polarization SPP mode.

Figure 3 shows the dispersion relation of core and SPP modes, and the loss of core modes with different wavelengths when the thickness of gold layer is 40 nm. Figure 3**a** shows the effective refractive index dependence on wavelength for x- and y-polarized core modes. The dashed, solid, and dash-dotted lines in the dispersion diagram correspond to the fundamental x-polarized core mode, the fundamental y-polarized core mode, and the SPP modes with different order excited on the gold-coated layers covered on air holes, respectively. The parameters of the fiber are as follows: $d_1 = 1.4$ μm, $d_2 = 1.2$ μm, $d_3 = 0.6$ μm, $\Lambda_1 = 2$ μm, $\Lambda_2 = 0.9$ μm, $\Lambda_3 = 1$ μm, and the thickness of gold coating layer is 40 nm. The dispersion curves of x-polarized and SPP_1 intersect at 1335 nm, where the x-polarized 1st SPP strongest couples to x-polarized core mode. So the transfer of energy from x-polarized to SPP_1 is maximized; correspondingly, Fig. 3**b** shows the loss curve of x-polarized, where the peak appears at 1335 nm. The dispersion curves of y-polarized and SPP_2 intersect at 1550 nm, where the loss curve of y-polarized shows a peak, the resonance wavelength of y-polarized mode is 1550 nm, giving the best filtering effect. The simulation results show that the loss of y-polarized mode is larger than that of x-polarized mode in the entire range. It is due to the two air holes coated with gold which are arranged in the y direction; hence, SPP_2 more easily couples to core-mode than SPP_1. As we can see from Fig. 3**a**, the solid and dashed lines almost

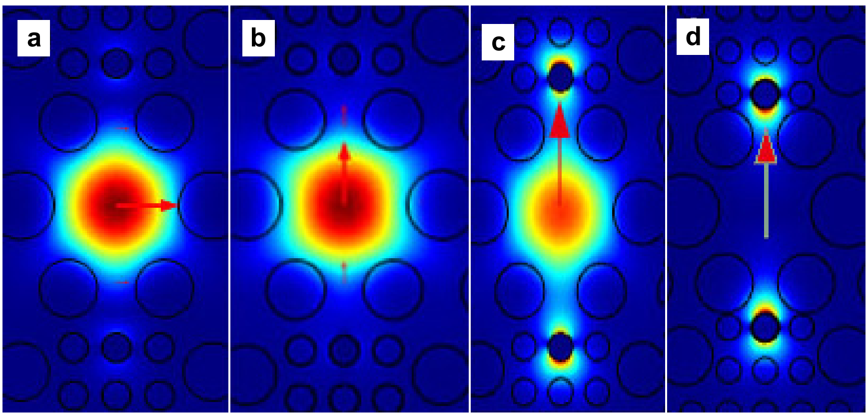
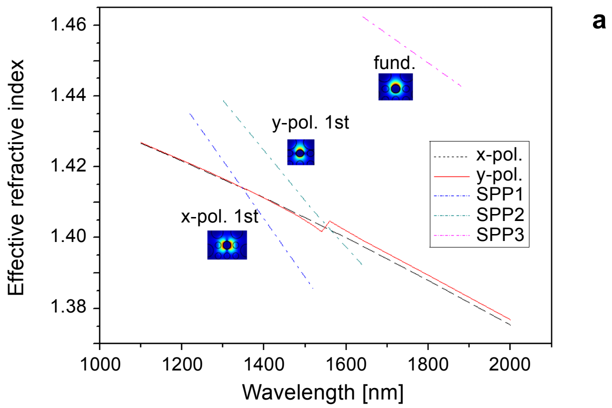
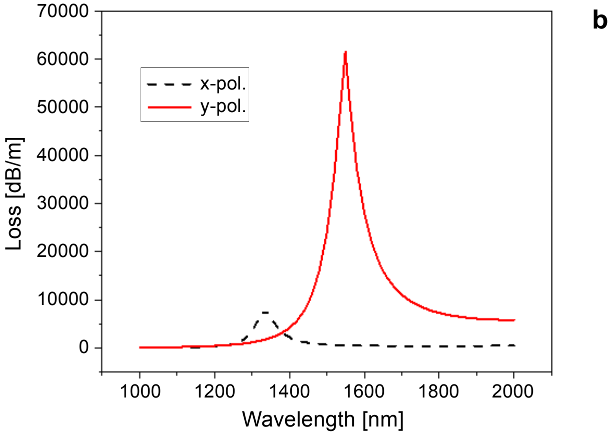


Fig. 2. The electric field distributions of x-polarization (**a**), y-polarization (**b**), y-polarization coupled (**c**), and y-polarization SPP mode (**d**).



a



b

Fig. 3. The dispersion relation of core and SPP modes, and the loss of core modes with different wavelengths when the thickness of gold layer is 40 nm. Wavelength dependence of effective indices and losses of the x- and y-polarized core modes in the PCFs (**a**). A gold wire coated into two sections; the solid and dashed lines are the loss of core guided modes in x and y direction, respectively (**b**).

coincide with each other, because the difference between the effective index of x-polarized and that of y-polarized core modes is quite small. So the birefringence is not high at all. We can also see that the effective refractive index of the fundamental SPP modes is much higher than that of the core-guided modes, thus, it is quite difficult for the SPP modes to couple to the core mode. In addition, the loss curves indicate that the resonance coupling strength between the y-polarized 1st SPP mode and the x- and y-polarization modes is much stronger than the x-polarized 1st SPP mode. So, we only consider the y-polarized 1st SPP modes and x- and y-polarization modes of the coupling in this paper.

Several studies show that surface plasmon waves are very sensitive to the air holes, so we adjust many kinds of air holes in turn. First, we adjust the diameter of the biggest air hole d_1 to 1.0, 1.2, 1.4 and 1.6 μm, in turn. Figure 4 shows that the resonance wave-

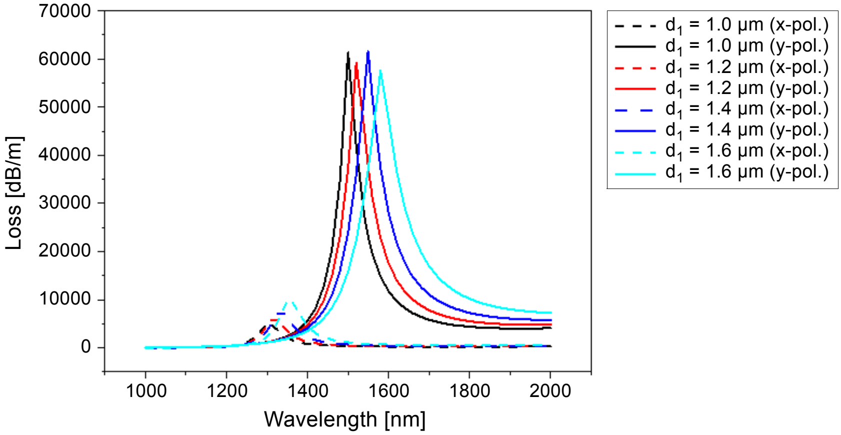


Fig. 4. Filter characteristics for different values the biggest air hole diameter d_1 in x and y direction. The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

lengths of x-polarized mode are 1305, 1320, 1335, and 1355 nm, and the resonance wavelengths of y-polarized mode are 1500, 1520, 1550, and 1580 nm, respectively. In Fig. 4, it is obvious that the resonance wavelengths of x-polarization mode and y-polarization mode shift towards the longer wavelength with the diameter of the biggest air holes increasing. Meanwhile, the amplitude of x-polarized peak increases with d_1 increasing. As shown in Fig. 4, the resonance wavelength is 1550 nm. Hence, we can get the best filtering effect in communication system when we are using d_1 = 1.4 µm. At 1550 nm, the loss of y-polarized mode is 61499 dB/m; in contrast, the loss of x-polarized mode is just 547.16 dB/m. The loss of y-polarized mode is much larger than the loss of x-polarized mode. It indicates that y-polarized mode is suppressed, and only x-polarized mode can be guided at the resonance wavelength of y-polarized mode.

Figure 5 is about the impact of different diameters d_2 (in Fig. 1) on the loss. The diameters of d_2 changed from 0.9 to 1.5 µm, while the diameters of other air holes remain unchanged in the cladding. It is obvious that the resonance wavelengths of x- and y-polarization mode have no shift with the d_2 changed from 0.9 to 1.4 µm. The amplitude of x-polarized peak decreases by a large amount but the amplitude of y-polarized peak has a little change. However, when d_2 = 1.5 µm, the loss peak experiences a large decrease in x- and y-polarized due to the symmetry of the structure which changed when d_1 = 1.4 µm and d_2 = 1.5 µm (d_1 is smaller than d_2). In conclusion, at 1550 nm, the loss of x-polarized and y-polarized mode decreases with d_2 increasing. As we can see from Fig. 5, we should choose d_2 = 1.4 µm.

Figure 6 shows the impact of different structures of PCF, with the interval Λ_3 of the air holes in small holes, on the loss. From Fig. 6, we can see that the x- and y-polarized peaks experience a shift towards the longer wavelength. At the same time, the amplitude of x- and y-polarized peaks also increases, but the increase in the y-polarized di-

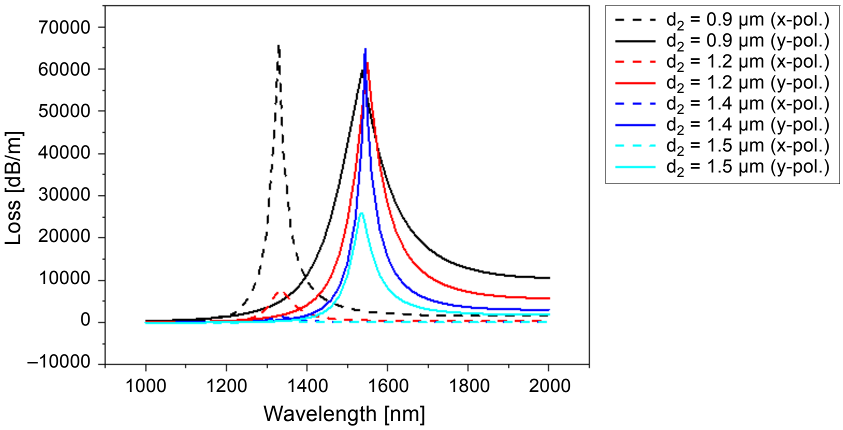


Fig. 5. Filter characteristics of different big air hole diameter d_2 in x and y direction. The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

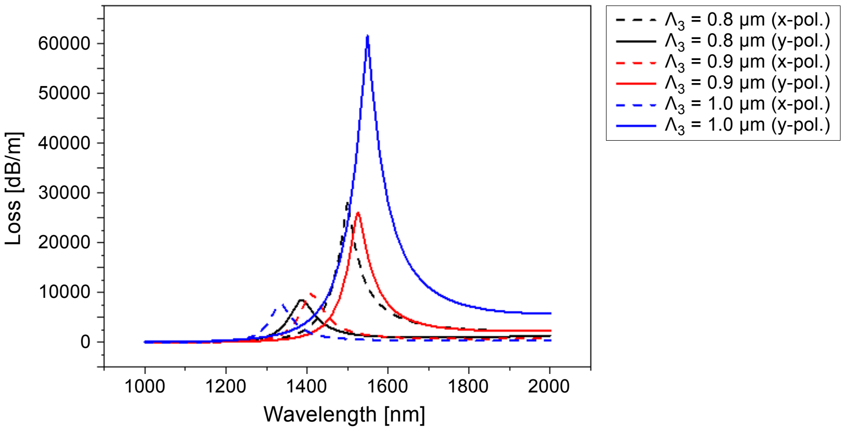


Fig. 6. Filter characteristics for different interval in y direction of small air holes. The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

rection is much larger than the x-polarized direction. It is worth noting that when Λ_3 = 1.0 μm, resonance wavelength of y-polarized mode is 1550 nm. Hence, if we intend to decrease the loss of x-polarized by adjusting Λ_3, we should find a parameter which makes the y-polarized peak experience a shift towards the shorter wavelength.

Figure 7 depicts the impact of different interval Λ_2 of d_3 (in Fig. 1) in the x direction changing from 0.8 to 1 μm on the loss, while the other parameters remain unchanged. The x- and y-polarized peaks experience a shift towards the longer wavelength. Although the loss peak of the PCF in y-polarized direction is decreased, it changed from 129.6 to 4929.5 dB/m in x-polarized direction. It is worth noting that the loss of x- and

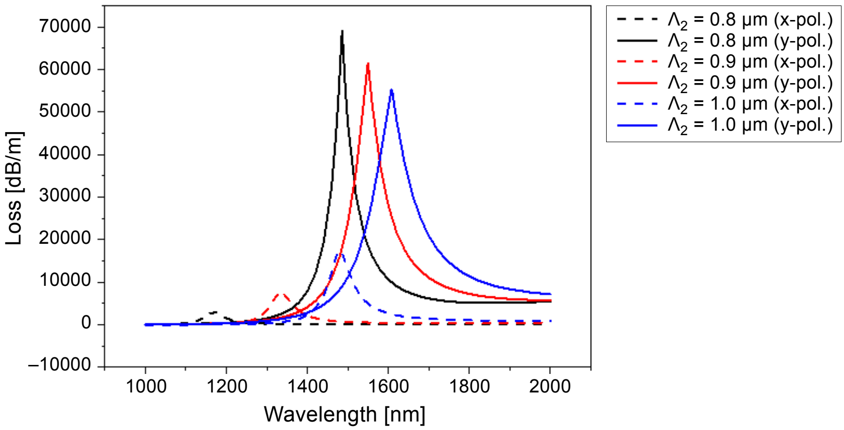


Fig. 7. Filter characteristics for different interval of the air holes in small holes. The dashed and solid lines are the loss of core guided modes in *x*- and *y*-polarized directions, respectively.

y-polarized is at 1550 nm wavelength, the interval Λ_2 of d_3 in x direction is chosen $\Lambda_2 = 0.9$ μm where the loss of *y*-polarized mode is 61499 dB/m. In contrast, the loss of *x*-polarized mode is just 547.16 dB/m. The loss of *y*-polarized mode is much larger than the loss of *x*-polarized mode. It indicates that *y*-polarized mode is restrained. Although it will cause *y*-polarized peak experience a shift towards the shorter wavelength by decreasing Λ_2, we can decrease the loss of *x*-polarized at the same time. Therefore, the filtering performance can be enhanced when we choose Λ_2 to be 0.85 μm in size.

Figure 8 shows the impact of different structures of PCF with interval Λ_1 of the air holes in small holes on the loss. From Fig. 8, we can see that both *x*- and *y*-polarized peaks experience a shift towards the longer wavelength. The amplitude of *y*-polarized

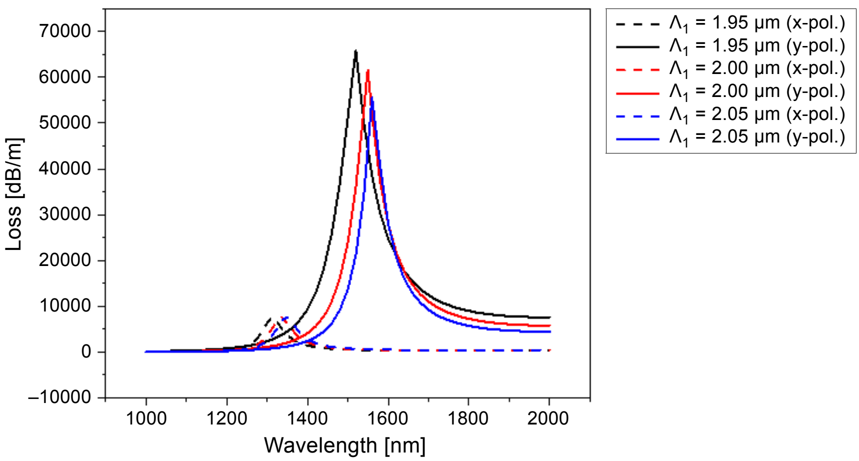


Fig. 8. Filter characteristics for different interval of the air holes in big holes. The dashed and solid lines are the loss of core guided modes in *x*- and *y*-polarized directions, respectively.

peaks decreases, however, there is no significant change in the peak of x-polarized mode. Therefore, in order to achieve a higher loss in y-polarized mode at 1550 nm, we choose Λ_1 to be 2 μm in size.

Now, we consider the effects of different diameters of holes coated with gold wire on the loss. Figure 9 illustrates the influence of variation of diameter on the loss, with the diameter of the d_3 changing from 0.5 to 0.8 μm. All the other parameters remain unchanged in all these simulations except the diameter that we need to study. The x-polarized peak experiences a shift towards the shorter wavelength and the amplitude of x-polarized peak decreases with d_3 increasing, as shown in Fig. 9. When the diameter of holes d_3 = 0.8 μm, at 1550 nm, the loss of y-polarized mode is 63200 dB/m; in con-

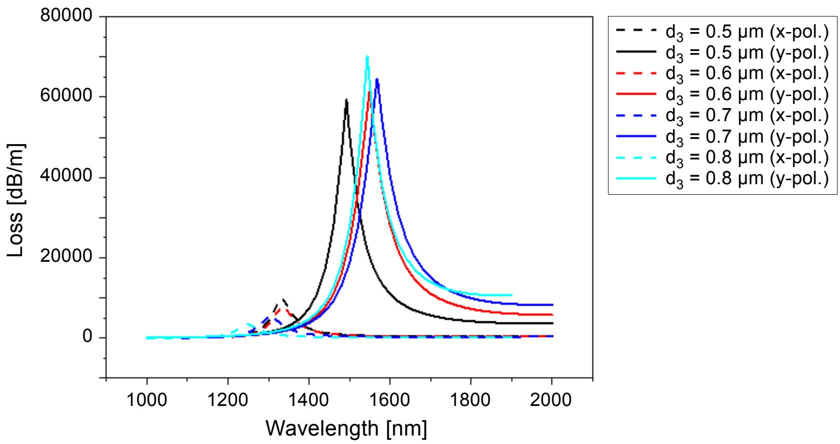


Fig. 9. Filter characteristics for PCFs coated with gold wires of different diameters. The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

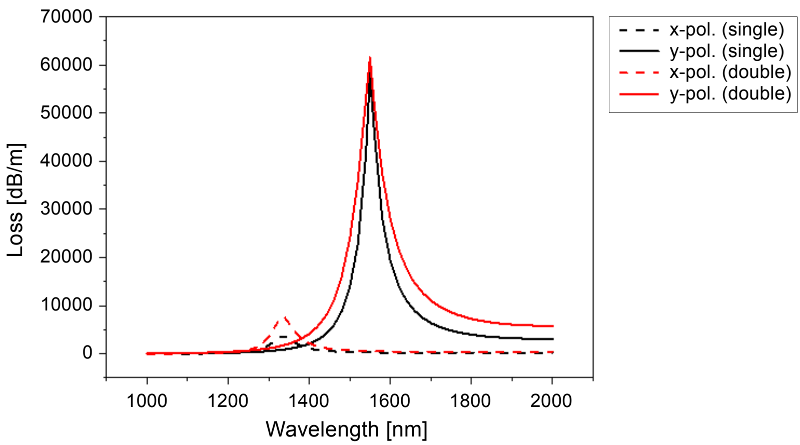


Fig. 10. Filter characteristics for PCFs coated with single and double gold wires. The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

trast, the loss of x-polarized mode is just 217.34 dB/m. The loss of y-polarized mode is much larger than the loss of x-polarized mode. It indicates that y-polarized mode is restrained, and only x-polarized mode can be guided at the resonance wavelength of y-polarized mode.

Figure 10 presents the impact of different structures of PCF with single and double gold wire on the loss. We can see clearly that the peak loss of the double gold wire is twice than the single gold wire in the x-polarized direction. It is obvious that the resonance wavelengths of x- and y-polarization mode have no shift. At 1550 nm, the loss of y-polarized mode is 58458 dB/m in single gold wire and 61499 dB/m in double gold wire, respectively. The loss of x-polarized mode is 275.88 dB/m in single gold wire and 547.16 dB/m in double gold wire, respectively. Using single gold-coated wire can really help decrease the loss in x-polarized mode and improve the performance of the polarization filters.

Several studies show that surface plasmon waves are very sensitive to the thickness of the metal layer. We adjust the thickness of the gold layer to 40, 45, and 50 nm in turn. In Fig. 11, it is obvious that the resonance wavelengths of x- and y-polarized modes a shift towards the shorter wavelength with the thickness of gold layer increasing. In order to modulate the resonance wavelength to 1550 nm, obtaining the best filtering effect at 1550 nm, we choose the thickness of the gold layer in 40 nm. When the thickness of the gold layer is 40 nm, the resonant wavelength of y-polarized mode happens to be 1550 nm. Meanwhile, the loss of y-polarized mode is 61499 dB/m; in contrast, the loss of x-polarized mode is just 547.16 dB/m. The loss of y-polarized mode is much larger than the loss of x-polarized mode. It indicates that y-polarized mode is restraining, and only x-polarized mode can be guided at the resonance wavelength of y-polarized mode.

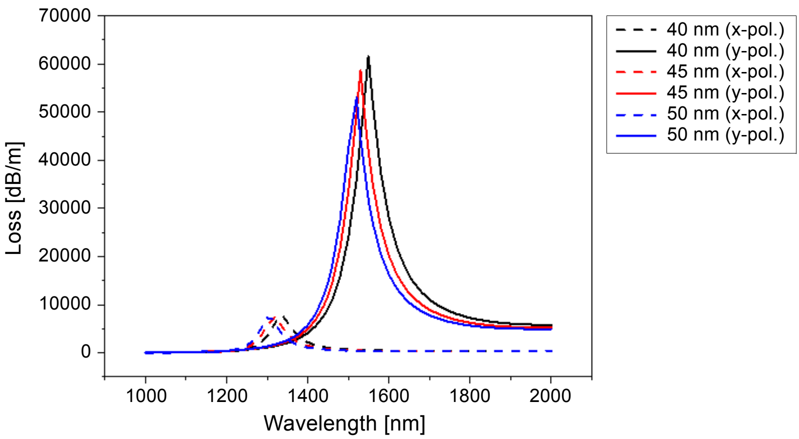


Fig. 11. Filter characteristics for different thicknesses of the gold layer (40, 45, and 45 nm) The dashed and solid lines are the loss of core guided modes in x- and y-polarized directions, respectively.

4. Conclusion

We proposed a new structure based on an asymmetric hexagonal structure of PCF with four kinds of holes and rectangular lattice arrayed air holes based on SPP. In order to use the filter in communication band and to have a good performance, we can choose the large air holes on structure $d_1 = d_2 = 1.4$ μm, air holes interval in x direction $\Lambda_1 = 2$ μm, $\Lambda_2 = 0.85$ μm and small air holes interval in y direction $\Lambda_3 = 1.016$ μm. Because of the limitation of wavelength, only the gold wire with diameter $d_3 = 0.8$ μm can be selected for coating. Meanwhile, we can improve the performance of the filter by using a single gold coated hole, and the thickness of gold layer is 40 nm. At the resonance wavelength 1550 nm, the loss of y-polarized mode is 28464 dB/m, and the loss of x-polarized mode is just 3.8045 dB/m, and the y-polarized mode is suppressed, and the two polarized modes can be divided very well. All these properties make the PCF a promising candidate for designing new types of polarization filters. The parameters can be further optimized for better results.

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