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A Polarization Filter Based on a Novel Photonic Crystal Fiber with a Gold-Coated Air Hole by Using Surface Plasmon Resonance

Wan Zhang[1] · Shuqin Lou[1] · Xin Wang[1]

Abstract A novel design of a polarization filter based on photonic crystal fiber (PCF) is proposed in this paper. With the introduction of a gold-coated air hole, the resonance strength is much stronger in y-polarized direction than in x-polarized direction at some particular wavelengths, which is due to the metal surface plasmon effects. At the wavelength of 1.31 μm, the loss of y-polarized mode is 2138.34 dB/cm while the loss is very low in x polarization. Furthermore, the loss peak can be flexibly adjusted from the wavelength of 1.26 to 1.56 μm by changing the thickness of a gold layer, and the loss in y polarization can be kept above 1200 dB/cm. The significant loss in y polarization makes this PCF a good candidate for developing a polarization filter with high performance.

Keywords Photonic crystal fiber · Surface plasmon · Polarization filter

Introduction

As one kind of optical integrated devices, polarization filters have attracted intensive attention due to their important application in the field of optical fiber communication and optical information processing. Photonic crystal fibers (PCFs) with porous structures provide a novel way for the development of polarization splitters [1–3]; the air hole can be filled with different materials to achieve new features, such as liquid [4], liquid crystal [5], semiconductor [6], and metal [7]. In metal-filled or -coated PCFs, surface plasmon resonance (SPR) is formed at the surface of the metal when the surface plasmon polarization (SPP) modes have the same propagation constant with the core mode at certain wavelength. The energy in the core can be strongly coupled to SPP modes on the surface of metal so that the core mode will suffer high loss. When a strong coupling occurs between the SPP modes and only one polarization of the core mode, there will result in a great loss difference between the two polarizations of the core mode. This feature can be used for developing the polarization filter.

In 2007, Zhang et al. firstly proposed a polarization filter based on PCF, which was realized by selectively coating a metal silver film in air holes of PCF by using a high-pressure chemical deposition method (chemical vapor deposition, CVD) [8]. In 2011, Lee et al. completed a melt-filling gold technology based on a mosaic- and pressure-assisted method. The gold wire whose diameter is only 120 nm can be filled in the porous fiber. The implement of the technology has greatly promoted the study of metal-filled PCF [9]. In 2013, Xue et al. proposed a polarization filter based on PCF with SPR. A sharp loss peak was obtained in y polarization, and the highest loss is 508 dB/cm at the wavelength of 1.31 μm [10]. In 2014, An et al. proposed a modified structure of PCF with gold-filled air holes. The loss which is 407 dB/cm at the communication wavelength of 1.55 μm in y polarized direction is obtained [11]. In 2015, Jiang et al. reported a PCF with a gold-coated layer in one air hole. With different coating thicknesses, the loss in y polarization can reach 536.25 and 412.91 dB/cm at the communication wavelength of 1.55 and 1.31 μm, respectively [12]. For the filter, the higher the loss of a fundamental mode in y polarization is, the easier it is to achieve polarization filtering.

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Fig. 1 Cross-sectional schematic of the proposed PCF (a) and local enlarged plot (b)
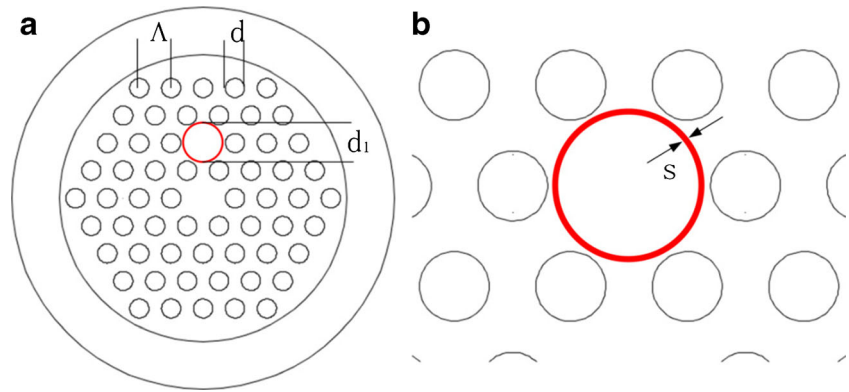
To enhance the loss in *y* polarization, we propose a novel polarization filter based on PCF with one big gold-coated air hole. The proposed PCF was investigated by COMSOL Multiphysics software with finite element method (FEM). A 3-μm-thick circular perfectly matched layer (PML) is set out of the pure silica fiber. The numbers of degrees of freedom are 191925. Numerical simulation results indicate that at the wavelength of 1.31 μm, the highest loss in *y* polarization is improved to 2138.34 dB/cm. In addition, after changing the thickness of a gold layer, the loss peak can be flexibly adjusted from the wavelength of 1.26 to 1.56 μm. The loss of *y*-polarized mode is above 1200 dB/cm and *x*-polarized mode is under 10 dB/cm. Such a great loss difference makes the fiber conductive to the development of a polarization filter, and it will be significive for other fiber plasmonic studies. The manufacture of the metal-coated optical fiber has been realized in experiments [8]. It can be implemented by using a high-pressure chemical vapor deposition (CVD) technique.

PCF Design and Theory

Figure 1 illustrates the cross section of the proposed PCF. It can be seen that the PCF has triangular lattice air hole arrangement in the cladding. The core of PCF is formed by omitting one air hole in the center. A large air hole is introduced above

the core. The air holes in the cladding have a diameter of $d = 1.2$ μm. The pitch of two adjacent air holes is $\Lambda = 2$ μm. The diameter of the large air hole is expressed as d_1. The thickness of the gold layer is expressed as s.

The background material of the proposed PCF is pure silica. The refractive index of pure silica is represented by the Sellmeier formula [13].

Because of the lack of central air hole of PCF, the lattice defect appears. Thus, the conduction wave in the fiber is limited in the core. However, after the introduction of the gold layer, the core conduction mode and the metal SPP modes have the same propagation constant at some certain wavelengths. The energy in the core is coupled strongly to the SPP modes on the surface of metal at these particular wavelengths. This will result in high loss for the core mode. The refractive index of the SPP mode is described by a wire helix approximation model [14, 15] and expressed as follows:

$$n_m = \sqrt{\frac{\varepsilon \varepsilon_m}{\varepsilon + \varepsilon_m} - \left(\frac{(m-1)\lambda}{d\pi}\right)^2}$$

where ε is the vacuum permittivity, ε_m is the permittivity of gold, d is the thickness of the gold, m is the order of the SPP modes, and λ is the wavelength of incident light.

The gold is chosen to coat inside of the large air hole. The permittivity of gold is described by a

Fig. 2 The distribution of the fundamental mode field in *x* (a) and *y* (b) polarization
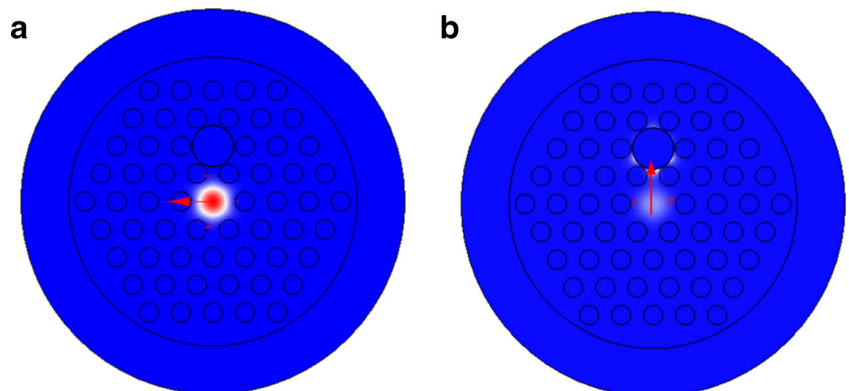
Fig. 3 The relationship between the loss and the effective refractive index of the core mode and SPP modes
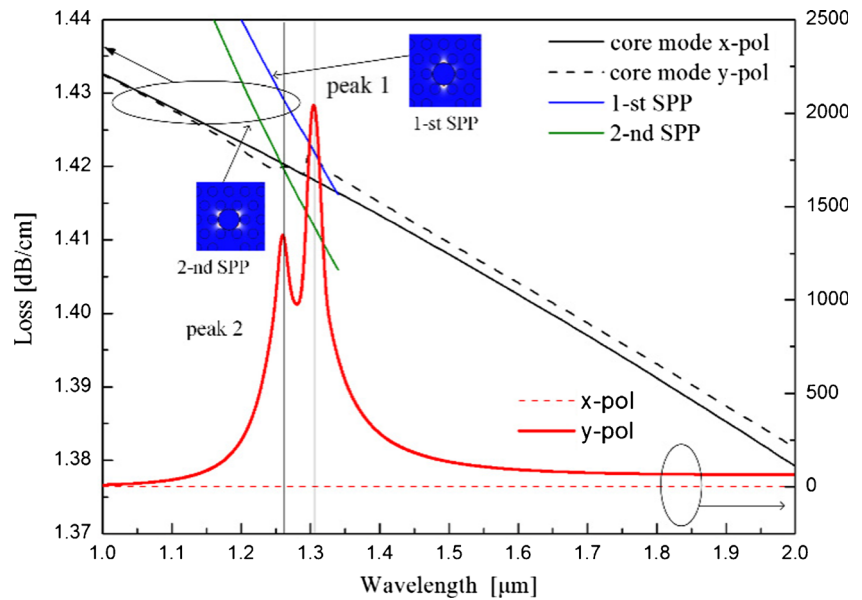
Drude–Lorentz model [16] and can be expressed as follows:

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

where ε_∞ is the permittivity in the high frequency, $\Delta\varepsilon$ can be interpreted as a weighting factor, ω is the angular frequency of guided light, ω_D and γ_D are the plasma frequency and damping frequency, and Ω_L and Γ_L represent the frequency and the spectral width of the Lorentz oscillator. The parameters of the gold are presented in reference [16].

The leakage loss of the fiber can be expressed as follows:

$$L = \frac{20}{\ln 10} k_0 \text{Im}(n_{\text{eff}})$$

Analysis of Filter Characteristic

Figure 2 shows the electric field distributions of a fundamental mode in x and y polarization respectively for the proposed PCF with $d_1 = 2.6$ μm and $s = 26$ nm at the wavelength of 1.31 μm. In Fig.2a, the energy of the fundamental mode in x

Fig. 4 The relationship of the losses between the core and SPP modes
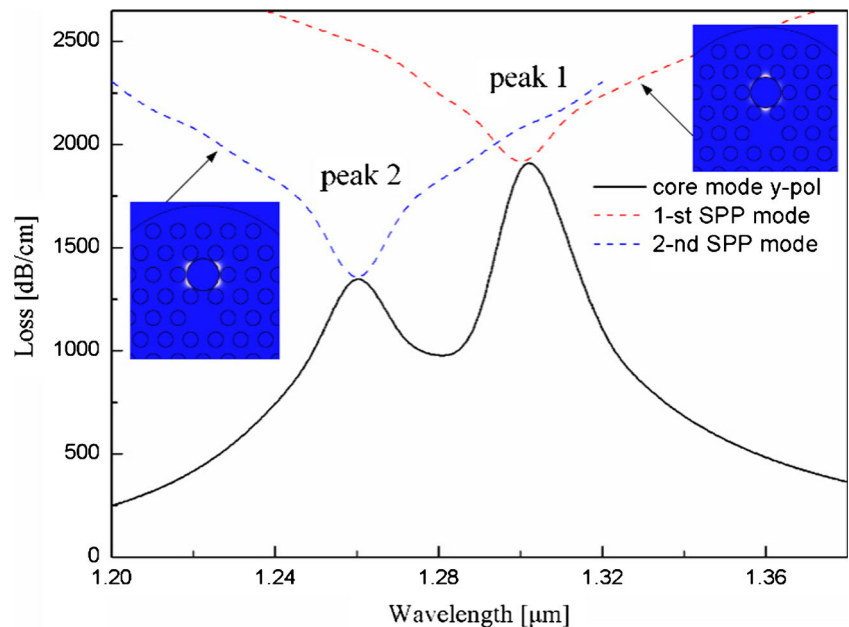
**Fig. 5** The contrast of losses in *y* polarization of the PCF with different thicknesses of the gold layer
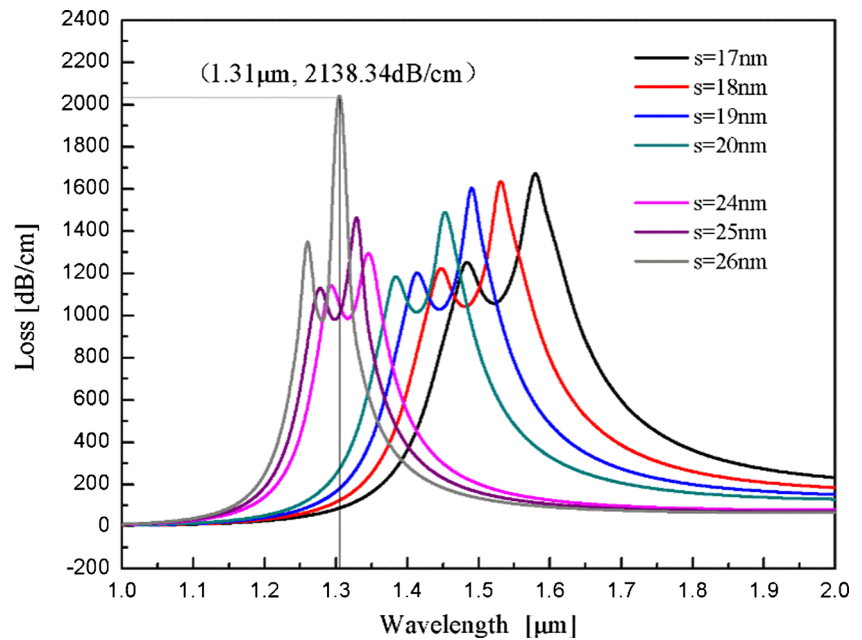
polarization is well confined in the core. While for the *y* polarization, it can be seen from Fig.2b that the energy is coupled to the gold layer, which means that *y* polarization suffers higher loss than *x* polarization.

Figure 3 shows the relationship of effective refractive index and loss between the core mode and first- and second-order SPP modes with the structure parameters $d = 1.2$ μm, $\Lambda = 2$ μm, $d_1 = 2.6$ μm, and $s = 26$ nm. The blue and green solid lines represent the effective refractive index of the first-order and second-order SPP mode, respectively. It is obvious that the corresponding

curve of effective refractive index in *y* polarization has a distinct change where the SPP effective refractive index curve and the core mode effective refractive index curve in *y* polarization intersect. It can be observed that there are two loss peaks appearing at the wavelength where the intersections are. As a result, the loss of the core mode in *y* polarization extends at these special wavelengths. The losses in peak 1 and peak 2 reach up to 2138.34 and 1520.61 dB/cm, respectively. Such a high loss of *y* polarization makes the fiber conductive to develop a polarization filter with high performance.

Fig. 6 The contrast of losses in *y* polarization of the PCFs with different diameters of the large air hole when $s = 26$ nm
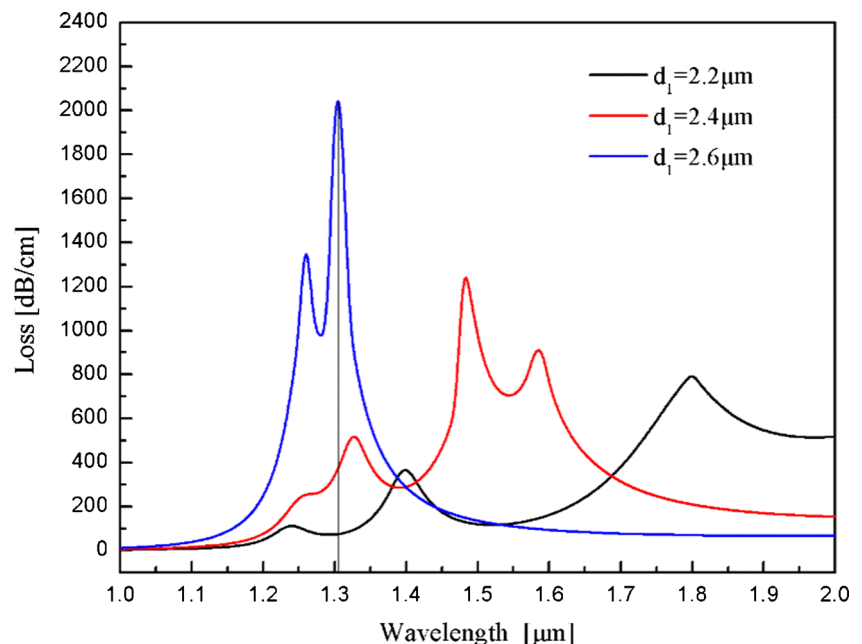
Fig. 7 The comparison of the losses between gold-plated PCF and not gold-plated PCF
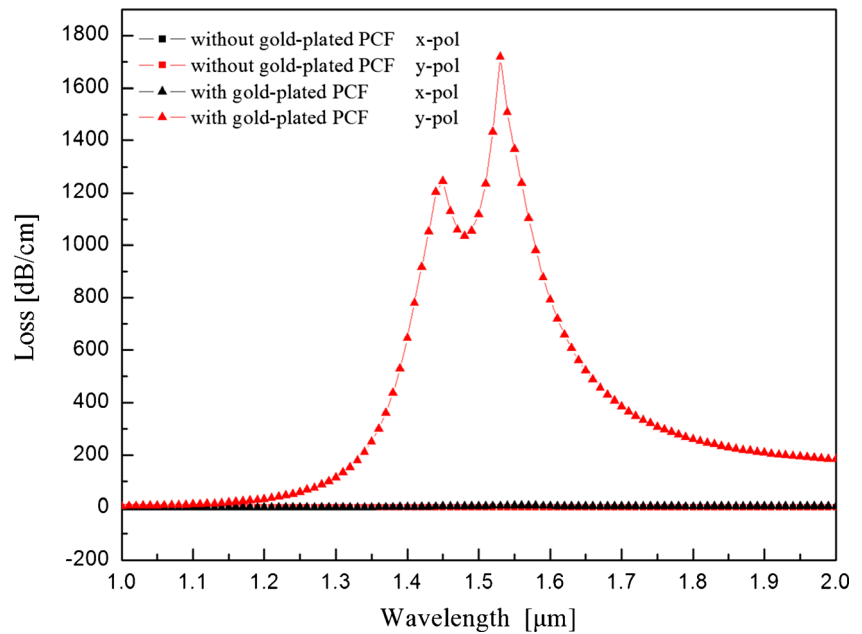

Figure 4 gives the explanation of the formation of loss peaks. The loss of the core and SPP modes was analyzed. It can be found that the loss of the core mode enlarges at the wavelength where the loss of the first-order and the second-order SPP modes reduces. The energy of the core mode transfers to the SPP modes. It is obvious that the formation of loss peak 1 is due to the coupling between the first-order SPP mode and the core-guided mode (around 1.31 μm) and the formation of loss peak 2 is due to the coupling between the second-order SPP mode and the core-guided mode (around 1.26 μm).

Figure 5 shows the loss in y polarization of the proposed PCF with different thicknesses of the gold layer. Because the loss in x polarization is very low, only the loss in y polarization will be analyzed in the next discussion. It can be found that the loss peaks in y polarization are shifted from the wavelength 1.26 to 1.6 μm when the thickness of the gold layer increases from 17 to 26 nm. The loss in y polarization is higher than 1200 dB/cm. When $s = 26$ nm, y polarization mode has an extremely high loss of 2138.34 dB/cm at the wavelength of 1.31 μm. Moreover, by adjusting the thickness of the gold layer, the position of the loss peak can be changed, which means the polarization filter can be implemented in different wavelength bands.

In addition, the effects of diameter of the large air hole on the filter characteristics are discussed. It can be seen from

Fig. 8 The contrast of losses of the PCFs with gold wire filling and a gold-plated layer
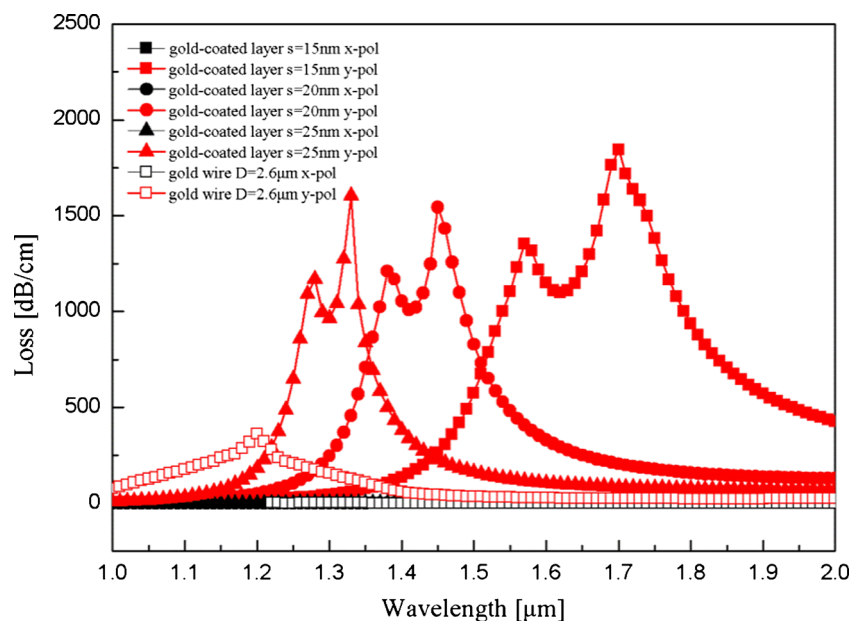
Table 1 The comparison of different filters based on PCF

The characteristics	The position of the loss peak (μm)	The value of the loss peak (dB/cm)	The way to achieve SPP
Ref. 9	1.31	508	gold-coated liquid-filled
Ref. 10	1.55, 1.31	536.25, 412.91	gold-coated a liquid core
Ref. 11	1.55	407	gold wire-filled
Ref. 17	1.31	720	gold-coated
Ref. 18	1.01	770.4	gold wire-filled
Polarization filter in this paper	1.54, 1.31	1717.98, 2138.34	gold-coated

Fig. 6 that the diameter of large air hole has an obvious effect on the position of the loss peak in y polarization. By adjusting the diameters of large air hole, the position of the loss peak also can be changed. This offers another efficient way to adjust the position of the loss peak.

## Comparison and Discussion

To verify the significance of gold-coated large air hole in improving the performance of the polarization filter, we compare our proposed PCF with the one without gold coat, with gold-filled wire, and some other reports in this section.

The Comparison of the Losses Between Gold-Coated and not Gold-Coated PCF

The comparison of losses of gold-coated and not gold-coated PCF is shown in Fig. 7. The structural parameters are $d = 1.2$ μm, $d_1 = 2.6$ μm, $\Lambda = 2$ μm, and $s = 18$ nm. It can be concluded that for the PCF without gold coat, the loss in x and y polarization is both under 10 dB/cm. However, for the

Fig. 9 The structure diagrams of the PCFs in the references in the table. **a** One gold nanowire selectively introduced into PCF. **b** Two gold-coated and four liquid-filled air holes in PCF. **c** Two gold nanowire-filled air holes in PCF with two kinds of air hole arrangement. **d** Two gold-coated air holes in PCF with square lattice. **e** One gold-filled air hole in PCF with a spiral arrangement

a Ref. 9　　**b** Ref. 10　　**c** Ref. 11
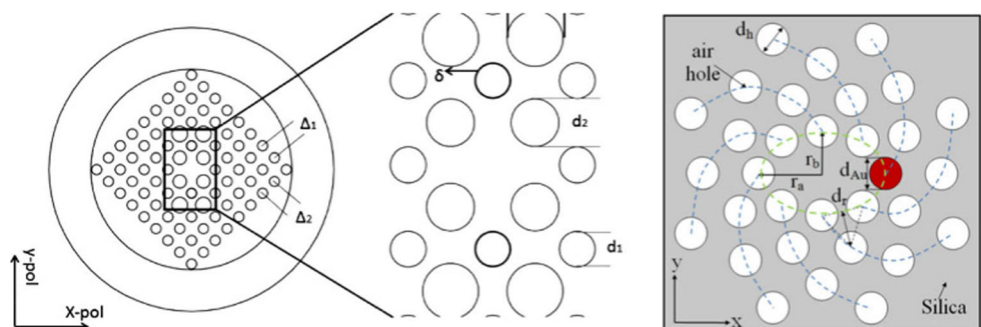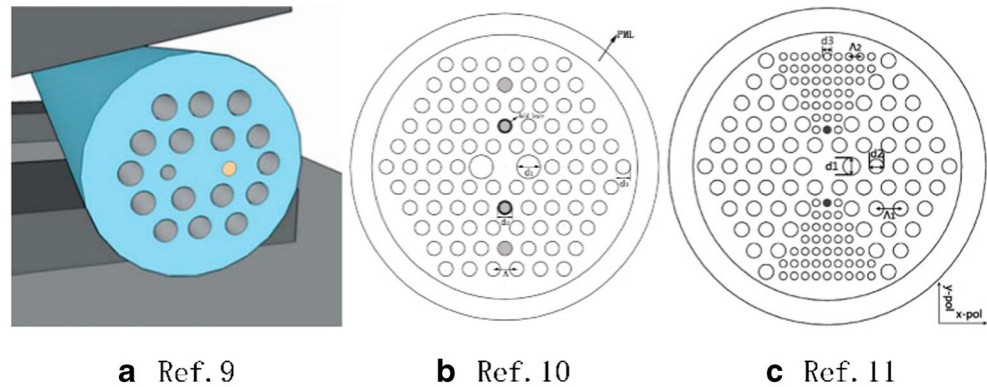
d Ref. 17　　**e** Ref. 18

PCF with gold coat, high loss peaks appear in y polarization. The reason is that the core mode in y polarization couples with SPP modes and the energy in the core strongly couples to the SPP modes. It is no doubt that coating gold on the inner walls of the air hole can help to achieve a plasmon resonance effect.

The Comparison of Losses of the PCFs with a Gold-Filled Wire and a Gold-Coated Layer

Figure 8 shows the comparison of losses of the PCFs with a gold-filled wire and a gold-coated layer. For the PCF with a gold-filled wire, the diameter of gold wire is $D = 2.6$ μm. For the PCF with a gold-coated layer, three different thicknesses of the gold layer ($s = 15, 20, 25$ nm) are discussed. From the Fig. 7, we can see that the loss in y polarization of the gold-filled PCF is 490 dB/cm which is lower than that of the PCF with a gold-coated layer. By contrast, for the PCF with a gold-coated layer, the losses in y polarization are in the range from 1600 to 1800 dB/cm when s changes from 15 to 25 nm. The loss in y polarization of the PCF with a gold-coated layer is three times higher than that of the PCF with a gold-filled wire. x polarization modes in two kinds of PCF both exhibit very low losses.

The Comparison of Different Filters Based on PCF

Table 1 summarizes the performances of some reported filters based on PCF. From Table 1, it can be seen that the polarization performance of our design has been significantly improved than those reported by others. Moreover, because of the high price of the gold, gold-coated PCF is more cost-effective than gold-filled one. Figure 9 shows the structure diagrams of the PCFs in the references in the table. Fig. 9a, b, c, d, e is the structure diagrams of the PCFs in Ref. 9, Ref. 10, Ref. 11, Ref. 17, and Ref. 18, respectively.

Conclusion

In this paper, a polarization filter based on gold-coated PCF is proposed. Taking advantage of the surface plasmon resonance, the introduction of the gold-coated large air hole leads to a high loss in y polarization of a fundamental mode. Numerical analyses imply that when the thickness of the gold layer is $s = 26$ nm, the loss is 2138.34 dB/cm in y polarization at the wavelength of 1.31 μm. Moreover, by adjusting the thickness of the gold layer and the diameters of large air hole, the position of the loss peak can be changed, which means the polarization filter can be implemented in different wavelength bands. While the thickness of the gold layer varies from 17 to 26 nm, the loss peak position can be adjusted from the wavelength of 1.25 to 1.56 μm. The loss in y polarization is higher than 1200 dB/cm. Compared with other reports, the loss in y polarization has been significantly improved in our design, and compared with the gold-filled design, our gold-coated design is more affordable.

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