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RESEARCH ARTICLE

Single polarization photonic crystal fiber filter based on surface plasmon resonance

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Abstract In this paper, we propose a photonic crystal fiber (PCF) polarization filter based on surface plasmon resonance (SPR) characteristics. Gold nanowire is used as the active plasmonic material. Light into silica core becomes coupled to gold nanowire stimulating SPR. It splits light into two orthogonal (x-polarization and y-polarization) polarization in the second order of surface plasmon polarization. Numerical investigations of the proposed PCF filter is finite element method (FEM). By tuning the diameter of gold nanowire and shifting their position, the performance of the proposed PCF filter is inspected rigorously. Filtering of any polarization can be obtained by properly placing the metal wires. The maximum confinement loss of x-polarization is 692.25 dB/cm and y-polarization is 1.13 dB/cm offers at resonance position 1.42 μm. Such a confinement loss difference between two orthogonal polarizations makes PCF a talented candidate to filter devices. Consequently, the recommended PCF structure is useful for polarization device.

Keywords photonic crystal fiber (PCF), surface plasmon resonance (SPR), perfectly match layer, polarization filter

1 Introduction

Photonic crystal fiber (PCF) is also known as micro-structure lattice in which silica is a background material [1,2]. First PCF was expanded from the fiber drawing tower in Knight et al. [3] and it has been concerned to the field of optical communication. Tunable dispersion, high nonlinearity, flexible design and high birefringence are matchless characteristics compared to the conventional optical fiber. It has been broadly used in many fields such as chemistry, medicine and biology for its convenient characteristics [4]. When light is propagates in a PCF through metal layer, the free electrons in the metal will take up the power of the light. The light signal in silica core couples with surface plasmon polaritons (SPPs). When their phases are same, surface plasmon resonance (SPR) happens [5]. The amalgamation of PCF and plasmonics is a promising research field in the area of light science. Remarkably, the polarization filter has been a major element of communication system. PCF filters are applied widely in sensing applications as a polarizer and fiber tools [6–16]. In 1993, Jorgenson and Yee [12] invented a PCF which encouraged SPP modes. Nagasaki et al. [13] accomplished a large polarization extinction ratio (ER) by proposing a polarization filter by carefully filling metal wires in the cladding region of PCF. Zi et al. [14] proposed a PCF polarization filter in which communication wavelengths was 1310 and 1550 nm by applying two gold coated air holes [10]. Zhang et al. have initially revealed that selective metal coating in the PCF is practicable [11]. Zhang et al. expressed an optical fiber which takes up polarizer by choosing coating metal on the surface of air hole [17]. Li and Zhao have established the operating wavelengths of optical polarizer and can be modulated by adjusting the air hole size [18]. So geometrical parameters of the PCF have been carefully optimized to create the loss of one polarization mode which is much larger than another polarized mode [19]. In this paper, we got maximum loss in x-polarization is 692.25 dB/cm and minimum loss in y-polarization is 1.13 dB/cm at the resonance position 1.42 μm.

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2 Design and numerical method

The cross segment view of the designed PCF is shown in Fig. 1. The asymmetric PCF is modified by varying the air holes arrangement. The gold coated air holes for the PCF filter can divide the resonance point of x-polarization and y-polarization. The thickness of gold layer can also influence the resonance strength and resonance wavelength. The resonance strength becomes weak as the coating layer is thicker. The birefringence of the proposed PCF is high and light can be divided into two orthogonal polarized modes. The proposed PCF constructed of three sizes circular shape air hole. The diameter of most common air holes is denoted by d_2, the diameter of most large air hole near the PCF core is denoted by d_1. The diameter of gold coated air holes which are placed in the horizontal direction is denoted by d and the thickness of gold layer is denoted by d_g. The distance between two nearby air holes is denoted by Λ.

The background material of the PCF is fused silica, whose refractive index is computed by the Sellmeier equation [20],

$$n^2(\omega) = 1 + \sum_{j=1}^{3} \frac{B_j \omega_j}{\omega_j^2}, \tag{1}$$

where B_j represents the jth resonance strength, and ω_j represents the resonance frequency. The Sellmeier constant are B_1= 0.6961663, B_2= 0.4079426, B_3= 0.8974794, λ_1= 0.0684043, λ_2= 0.1162414, λ_3= 9.896161 and where λ_j= $2\pi c/\omega_j$. To achieve optimum calculation, the dispersion of gold is also calculated and the dielectric constant of gold is considered by using Drude–Lorentz model [21],

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

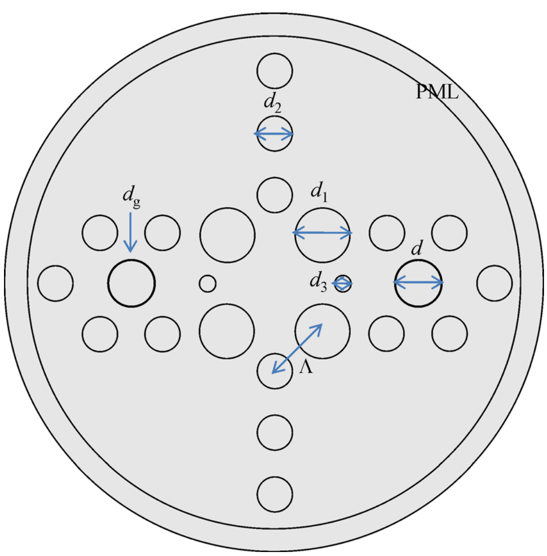


Fig. 1 Model of the proposed PCF coated with gold

where the high frequency dielectric constant is ε_∞ = 5.9673; weighted coefficient is $\Delta\varepsilon$ = 1.09; optical angular frequency is ω; plasmon frequency is ω_D, damping frequency is γ_D; $\omega_D/2\pi$ = 2113.6 THz; $\gamma_D/2\pi$ = 15.92 THz; the oscillator strength is ω_L, the frequency spectrum width is Γ_L and $\Omega_L/2\pi$ = 650.07 THz, and $\Gamma_L/2\pi$ = 104.86 THz respectively.

3 Numerical simulation and discussion

All investigation is done through COMSOL Multiphysics® version 4.2. Finite element method (FEM) is used to compute the numerical characteristics of the PCF. In this proposed PCF, we used gold as the active plasmonic material. Core mode will couple with the SPP mode when their transmission constants are same. The electric field distribution of the PCF in Fig. 2(a) shows the coupling mode of third order SPP and core mode, Fig. 2(b) represents x-polarization of SPP mode, Fig. 2(c) illustrates x-polarization of core mode, Fig. 2(d) shows y-polarization of core mode.

To attain better coupling phenomenon between SPP mode and core mode, couple mode theory is considered. The couple mode theory equations are expresses as follows (Eqs. (3) and (4)) and it is followed by the standard article [22],

$$\frac{dE_1}{dz} = i\beta_1 E_1 + ikE_2, \tag{3}$$

$$\frac{dE_2}{dz} = i\beta_2 E_2 + ikE_1. \tag{4}$$

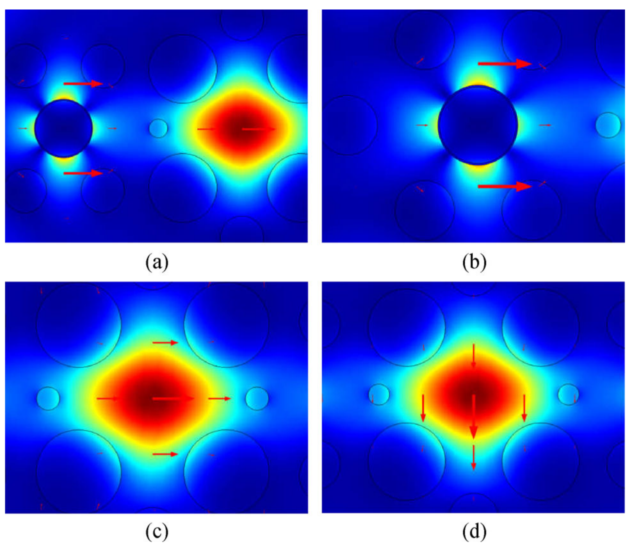


Fig. 2 Dispersion of electric field. (a) Coupled mode between the core mode and second order SPP mode; (b) x-polarization of SPP mode; (c) x-polarization of core mode; (d) y-polarization of core mode at resonance position 1.42

Here, β_1 and β_2 are the propagation constants of core mode and SPP mode, E_1 is electric field mode of core mode, E_2 is the electric field mode of SPP mode, z and k are the coupling propagation and strength length respectively. β is the propagation constant of the coupling mode. E_1 and E_2 can be described as $E_1 = A\exp(\mathrm{i}\beta z)$ and $E_2 = B\exp(\mathrm{i}\beta z)$.

We can get β from Eqs. (3) and (4),

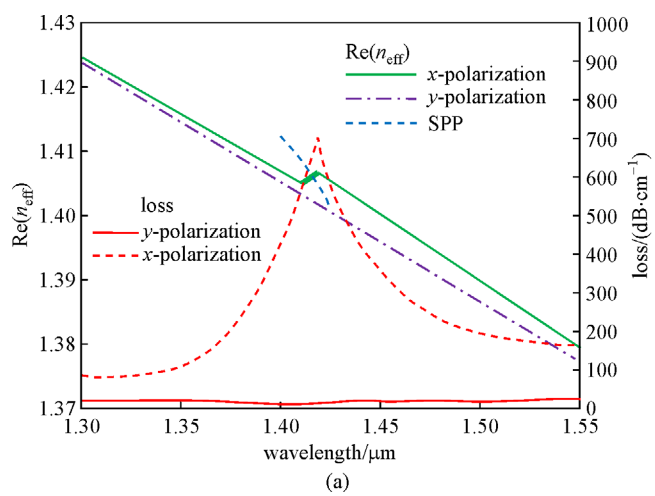
$$\beta_{\pm} = \beta_{\text{ave}} \pm \sqrt{\delta^2 + k^2}. \quad (5)$$

Here, $\delta = (\beta_1 - \beta_2)/2$, $\beta_{\text{ave}} = (\beta_1 + \beta_2)/2$. For the core mode and SPP mode, β_1 and β_2 are complex and δ can be written as $\delta = \delta_{\text{r}} + \mathrm{i}\delta_{\text{i}}$. The real part of transmission constants for SPP mode and core mode are same if the phase matching condition is fulfilled. For this, $\delta_{\text{r}} = 0$ and get $\delta^2 + k^2 = -\delta_{\text{i}}^2 + k$. When $\delta_{\text{i}} > k$, the real parts of β_+ and β_- are equal, the imaginary parts of β_+ and β_- are different, an incomplete coupling will occur. When $\delta_{\text{i}} < k$, the real parts of β_+ and β_- are different and imaginary parts are same then a complete coupling will occur.

The loss and refractive index dispersion graph are shown in Fig. 3(a) with the parameter $d = 0.9$ μm, $d_1 = 1.1$ μm, $d_2 = 0.7$ μm, $d_3 = 0.5$ μm, and $d_g = 20$ nm when coupling takes place between core mode and SPP mode at the resonance position 1.42 μm. It can be clearly observed that effective refractive index curve of SPP and core mode of x-polarization intersects at 1.42 μm. In addition, the peak loss is 692.25 dB/cm and 1.13 dB/cm for x-polarization and y-polarization respectively. As the gold layer is in x-direction and couple with core mode which progresses the peak loss of x-polarization. The peak loss of x-polarization is much higher than the peak loss of y-polarization which is comparable with Ref. [23]. This filtering phenomenon can also be described by refractive index graph. It can be seen that the refractive index graph of core mode of x-polarization has an instant change at resonance position 1.42 μm when coupling occurs between second order SPP mode and core mode. Figure 3(b) shows the loss relation of the SPP mode and the core mode of x-polarization. The SPP mode and core mode have same peak loss at the resonance position 1.42 μm when coupling happens. The loss of SPP mode gradually decreases and the loss of core mode(x-polarization) gradually increases. Finally, both (SPP and x-polarization) get the same value at resonance position. The loss of core mode of x-polarization achieves the maximum while the loss of SPP mode reaches the minimum. As a result a complete coupling happens and energy is transfer between second order SPP and core mode.

Figure 4 represents the confinement loss and refractive index dispersion of the proposed PCF with different thickness of gold layer $d_g = 15$ nm, $d_g = 20$ nm and $d_g = 25$ nm dependent on wavelength. Figure 4(a) shows that the peak loss of x-polarization is 633.35, 692.25 and 596.13 dB/cm at resonance position 1.41, 1.42 and 1.44 μm, respectively but the peak loss of y-polarization is 1.67, 1.13 and 1.78 dB/cm. As with the change of d_g, the refractive index and peak loss is also changed. We consider $d_g = 20$ nm because the peak loss difference between x-polarization (692.25 dB/cm) and y-polarization (1.13 dB/cm) is maximum. So we obtain highest confinement loss is 692.25 dB/cm for x-polarization and lowest confinement loss is 1.13 dB/cm for y-polarization which is comparable with Ref. [24]. Figure 4(b) shows that the refractive index curve of y-polarization has no change but in x-polarization is a sudden alternation at the resonance position 1.41, 1.42, and 1.43 μm for coupling happens between core mode and SPP mode.

Figure 5 shows the loss and dispersion of the refractive index with different thickness of $d_1 = 1.0$ μm, $d_1 = 0.9$ μm, $d_1 = 0.8$ μm with the function of wavelength. Figure 5(a) shows that the peak loss of x-polarization are 582.34, 692.25 and 600.09 dB/cm at resonance position 1.4, 1.42, 1.43 respectively but the loss in y-polarization is 1.83,



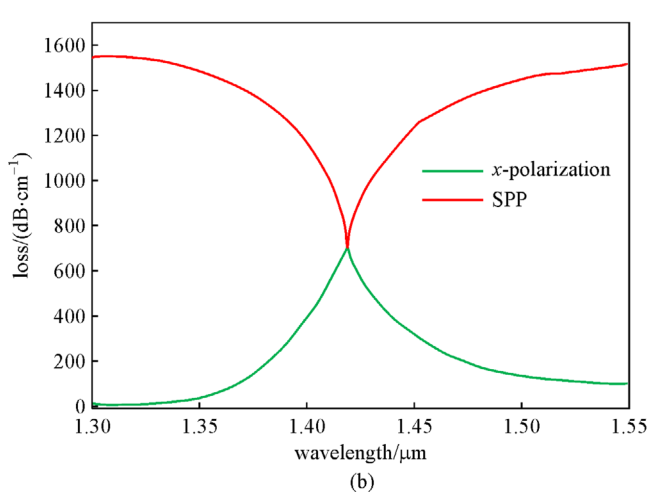


Fig. 3 (a) Loss and dispersion of the designed PCF with the parameter $d = 0.9$ μm, $d_1 = 1.1$ μm, $d_2 = 0.7$ μm, $d_3 = 0.5$ μm, and $d_g = 20$ nm at the wavelength of 1.42 μm. (b) Loss curve when coupling occurs between core mode and SPP mode with the parameter $d = 1.1$ μm, $d_1 = 0.9$ μm, $d_2 = 0.7$ μm, $d_3 = 0.5$ μm, and $d_g = 20$ nm at the wavelength of 1.42 μm

1.13, 1.54 dB/cm. We got maximum loss in x-polarization is 692.25 dB/cm and minimum loss in y-polarization is 1.13 dB/cm at the resonance position 1.42 μm which is comparable with Ref. [25]. The loss intensity of x-polarized core mode suddenly increases because coupling happened at 1.42 μm when d_1= 0.9 μm. Figure 5(b) shows the effective refractive index of x-polarization has a sudden change at resonance position 1.4, 1.42 and 1.43 μm but in y-polarization is almost same.

Figure 6 shows the refractive index dispersion and loss with different diameter of d_3= 0.5 μm and d_3= 0.0 (absent) with the variation of wavelength. Figure 6(a) shows the peak loss of x-polarization is 692.25 and 872.13 dB/cm at resonance position 1.42 and 1.44 μm but loss in y-polarization is 1.13, 1.93 dB/cm. We cannot take the confinement loss of x-polarization is 872.13 dB/cm because coupling wavelength is 1.42 μm. Figure 6(b) shows the effective refractive index of y-polarization is almost same but in x-polarization has a sudden change at resonance position 1.42 and 1.44 μm.

From Fig. 7, we regain that the crosstalk peaks enlarge repeatedly by the increase of fiber length. Here we just talk about the result at the resonance position. The value of crosstalk is 1393, 1790 and 1984 dB at the resonance position 1.42 when the fiber length is 0.5, 1.0 and 1.5 mm respectively.

On top of the discussion, we get the peak loss of x-polarization is 692.25 dB/cm and y-polarization is 1.13 dB/cm. The proposed PCF filter has advantages in terms of ease and fabrication is also simple. The fabrication of the proposed PCF can be attained by stack and draw method in fiber drawing tower with suitable temperature

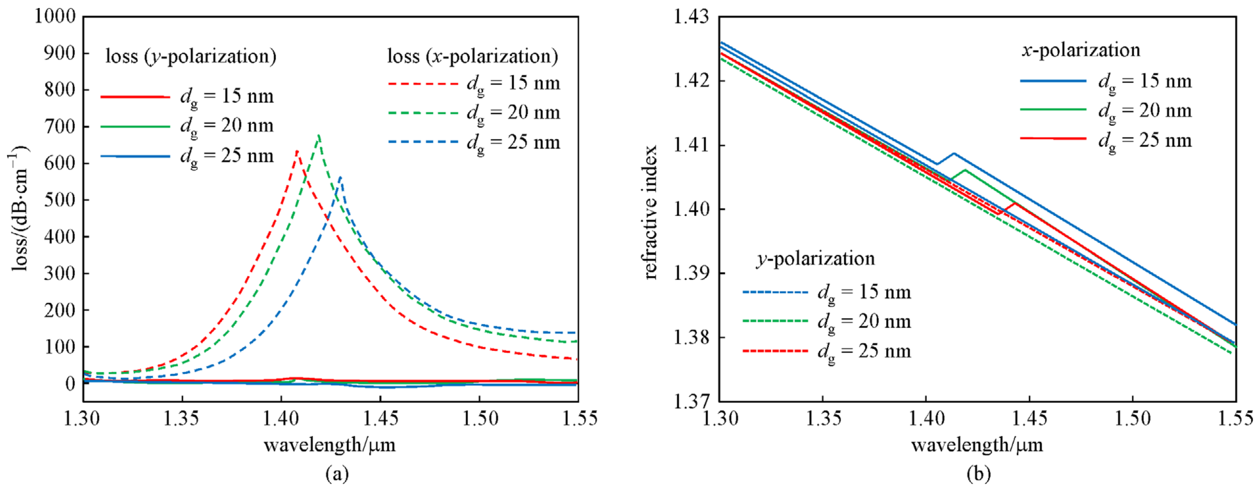


Fig. 4 (a) Loss of proposed PCF with the variation of wavelength and different thickness of gold layer d_g= 15, 20, 25 nm. (b) Refractive index dispersion as a function of wavelength with d_g= 15, 20, 25 nm

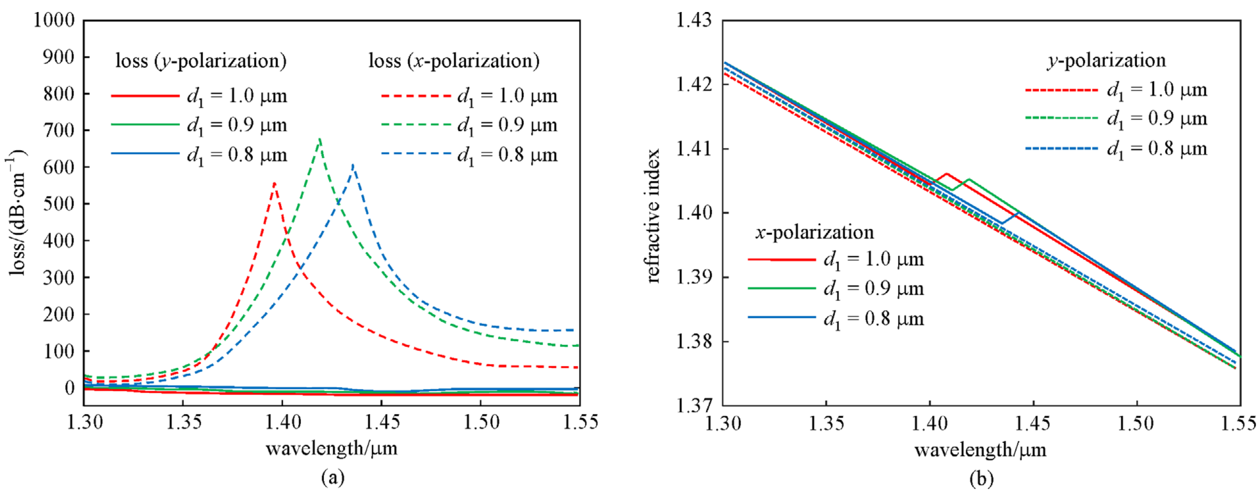


Fig. 5 (a) Loss of proposed PCF dependent on wavelength with different thickness of d_1= 1.0, 0.9, 0.8 μm and parameter d = 1.1 μm, d_2= 0.7 μm, d_3= 0.5 μm, and d_g= 20 nm. (b) Dispersion of refractive index with the variation of wavelength and different diameter of d_1= 1.0, 0.9 μm, 0.8 μm

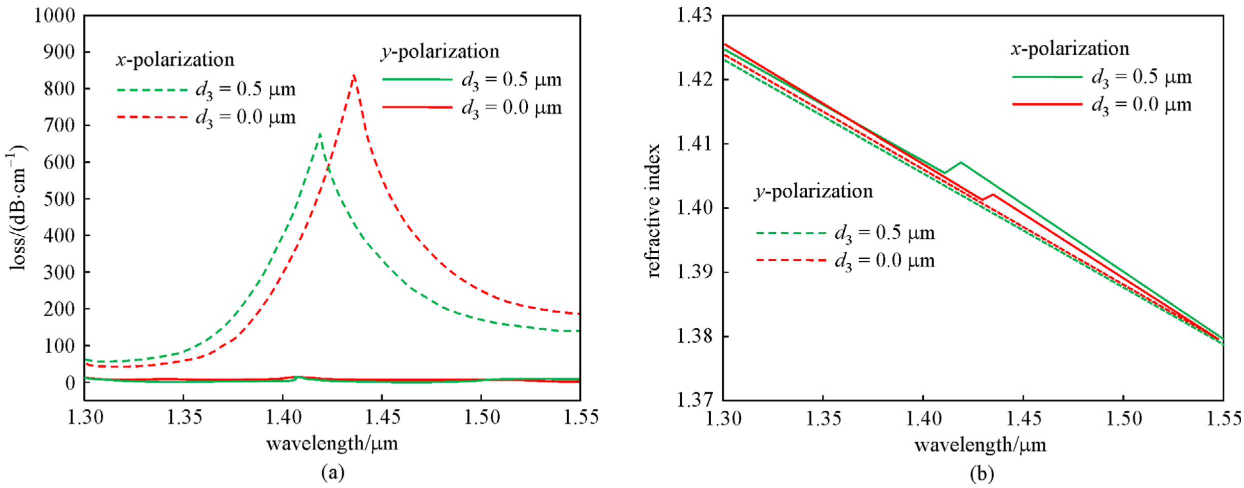


Fig. 6 (a) Optimization loss of the designed PCF with wavelength at d_3= 0.5, 0.0 µm (absent). (b) Dispersion with the variation of wavelength with d_3= 0.5, 0.0 µm (absent)

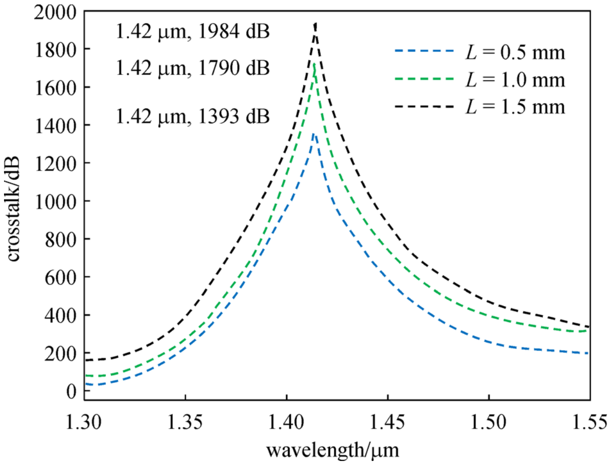
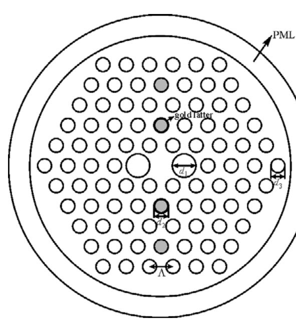


Fig. 7 Crosstalk of the proposed PCF when the fiber length of 0.5, 1.0, 1.5 mm with parameters d = 1.1 µm, d_1= 0.9 µm, d_2= 0.7 µm, d_3= 0.5 µm, and d_g= 20 nm

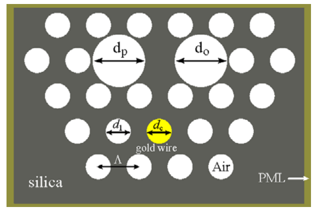
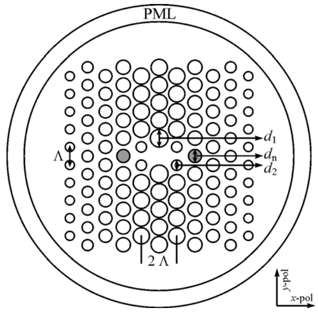
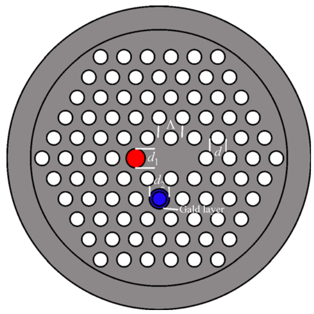
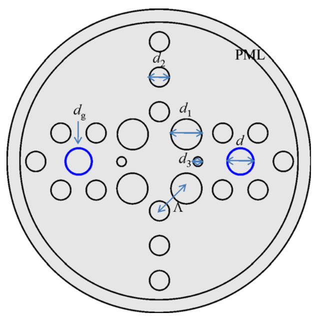
management. Using chemical vapor deposition technology with force supported or spray technology, the coating of gold film can be attained. Finally, in order to corroborate the methodical authenticity of our work, we contrast the results with the SPR based PCF filters previously stated in Table 1.

A PCF filter based on SPR is reported [26] where peak loss is 508 dB/cm in the y-polarized direction. Since the thickness of gold is 40 nm so it is fabrication is expensive. Reference [27] has proposed a PCF filter which peak loss is 292.8 dB/cm at the wavelengths of 1.55 µm in y-polarization and peak loss 4.6 dB/cm in x-polarization. The difference of losses between two orthogonal polarizations is too small. Another filter [28] is proposed where they used different sizes air holes which is very difficult to fabricate. A filter which used a single gold coated air hole [29] which cannot create strong coupling. In this paper, we proposed a simple asymmetric PCF filter which very easy to fabricate and the loss difference between two orthogonal polarizations is high shown in Table 1.

Table 1 Comparison with SPR based proposed PCF filter with previously published filters

PCF filter	bandwidth /nm	resonance wavelength	resonance strength (dB·cm^{-1})	extinction (L = 1 nm)/dB	structural diagram
Ref. [26]	20	1.31 µm (y-pol)	508.00		

(*Continued*)

PCF filter	bandwidth /nm	resonance wavelength	resonance strength (dB·cm^{-1})	extinction (L = 1 nm)/dB	structural diagram
Ref. [27]	88	1.31 µm (y-pol)	244.90	208	
Ref. [28]	60	1.31 µm (y-pol)	231.60	240	
Ref. [29]	750	1.48 µm (y-pol)	417.21	38	
our works	830	1.42 µm (x-pol)	692.25	253	

4 Conclusion

In summary, a gold coated PCF polarization filter is proposed. Second order of SPP mode is stimulated owing to gold layer. Finally second order of SPP mode and core mode of x-polarization produce coupling altogether. The peak loss of x-polarization is 692.25 dB/cm due to the gold coated air holes are in x-direction. Besides, peak loss of y-polarization is 1.13 dB/cm. The peak loss in x-polarization is higher while the peak loss in y-polarization is too small. In addition, the difference of peak loss between two orthogonal polarizations is a phenomenon of good filtering.

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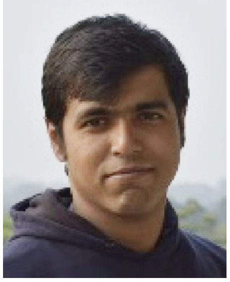

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