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# A polarization filter of gold-filled photonic crystal fiber with regular triangular and rectangular lattices

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ABSTRACT

A modified structure of photonic crystal fiber (PCF) with gold-filled air holes is presented in this paper. It consists of two kinds of air holes, one part is arrayed in a regular triangular lattice and the other part is arrayed in a rectangular lattice with different hole pitches in *x*-pol and *y*-pol, respectively, which can enhance the birefringence of the PCF and the 1st order surface plasmon polariton (SPP) mode can also be separated by a large distance. The polarization filter is based on the phenomenon of surface plasmon resonance (SPR). Numerical simulations with a full vectorial finite element method demonstrate that the resonance peaks occur at different wavelengths in two orthogonal polarization states. It is possible to obtain a resonance strength as high as 407 dB/cm at the communication wavelength of 1550 nm in *y*-polarized direction while the loss is very low in *x*-polarized direction. This makes it a promising candidate for polarization filter devices.

## 1. Introduction

With the development of photonic devices manufacturing process and theory, photonic crystal fibers have now been widely used in fiber communication system with its unique optical properties, such as no cut-off single-mode transmission, controllable dispersion, flexible non-linearity and highbirefringence [1–3]. Many photonic devices can be designed by PCF, like the PCF polarization beam splitters, PCF sensors, PCF WDM, etc. To fill fillers into the PCFs has aroused extensive attention and has been the focus of attention for many years. Various of materials have been filled into the fibers such as the liquid crystal, ethanol, metal of silver and gold and achieved many novel properties [4–6]. Recently, more and more researchers are steering their research objectives to the nanowire filling or metal coating into the optical fibers. Many novel natures have being discovered, such as the surface plasmon resonance (SPR) in the PCFs when we fill the nanowire into the air holes of the PCF. The SPR now has attracted much attention. It can occur at the frequencies where the core mode and the surface plasmon polariton (SPP) can coupled each other when the phase matching condition is met [7]. As we all know, the SPP can form on the surface of the metal when we coat or fill the nanowire into the optic fibers.

Jorgenson and Yee proposed the idea of making the PCF as a carrier to stimulate the SPP modes, and developed a PCF of surface plasmon resonance sensor in 1993 [8]. Recent years, a large variety of optical methods have been investigated [9,10]. Nagasaki et al. had selectively filled metal wires into different positions of the cladding air holes of the PCF in 2011 and obtained large polarization extinction ration [11]. In the same year, Lee et al. also reported a splicing-based pressure-assisted melt-filling technique for creating metallic nanowires in hollow channels in microstructured silica fibers [12].

In this paper, we proposed a polarizing filter of PCF with two kinds of air holes and the air holes are selectively filled with metal of gold. And its property parameters, especially confinement loss is computed and analyzed by using the finite element method (FEM). The result shows that the resonance peak at a certain wavelength can be altered by the diameters of the gold wires and air holes near the core. And the confinement loss at the wavelength of 1550 nm which lines in the communication band can nearly reach to 407 dB/cm and the resonance strength in *y*-polarized direction is much stronger than that in *x*-polarized direction.

## 2. Principle of operation

Fig. 1 shows the schematic cross-section of the proposed structure of PCF. The PCF consists of five layers of air holes in

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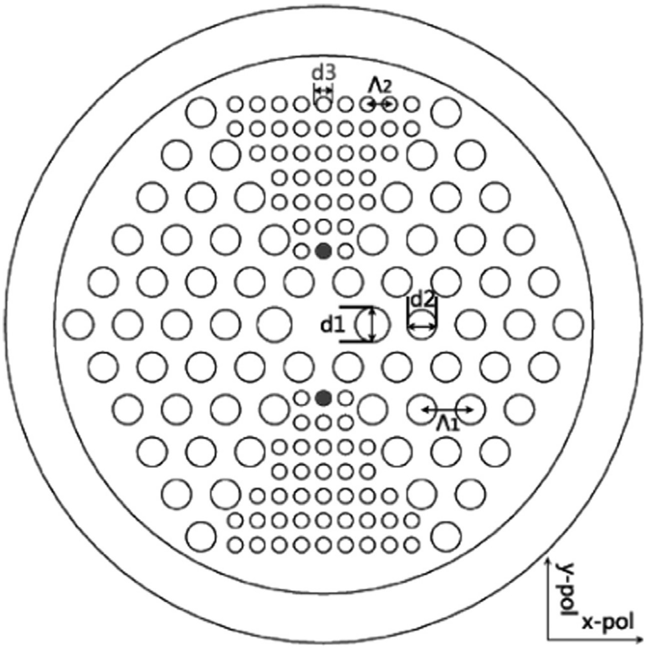

**Fig. 1.** Cross-section of the photonic fiber.

**Table 1**
Values of the optimized parameters.

| $\varepsilon_\infty$ | $\Delta\varepsilon$ | $\omega_D/2\pi$ | $\gamma_D/2\pi$ | $\Omega_L/2\pi$ | $\Gamma_L/2\pi$ |
|---|---|---|---|---|---|
| 5.9673 | 1.09 | 2113.6 | 15.92 | 650.07 | 104.86 |

the hexagonal structure in the $x$-polarized direction and seven layers of air holes in the $y$-polarized direction. The diameter of the two biggest air holes near the core in the $x$-polarized direction is $d_1 = 1.4$ μm. The diameter of the bigger air holes is $d_2 = 1.2$ μm with the pitch of $\Lambda_1 = 2$ μm between two adjacent air holes. Moreover, the diameter of the smaller air holes in the $y$-polarized direction is $d_3 = 0.6$ μm. The pitch between two adjacent small air holes is $\Lambda_2 = 0.9$ μm and 1.0 μm in $x$-polarized and $y$-polarized directions, respectively. The gray sections of the holes of $d_3$ are filled with metal of Au, on whose surface SPP mode can be formed.

In this structure, we use pure silica as the background material. In order to consider the material dispersion, Sellmeier equation is used for dispersion of silica and Drude–Lorentz model [12] for metal defined as

$$[h]\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\varepsilon \cdot \Omega_L^2}{\left(\omega^2 - \Omega_L^2\right) - j\Gamma_L\omega}. \tag{1}$$

Here, $\varepsilon_\infty$ is the permittivity of the metal, $\Delta\varepsilon$ can be interpreted as a weighting factor, and is the angular frequency of guided light, $\omega_D$ and $\gamma_D$ are the plasma frequency and damping frequency, respectively. $\Omega_L$ and $\Gamma_L$ represent the frequency and the spectral width of the Lorentz oscillator, respectively. Because the metal here is gold, we just use the parameters presented in Table 1 as we select the bulk gold for calculation [13].

The mode loss can be defined as

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

where $\lambda$ is the wavelength of light and the $\mathrm{Im}(n_{eff})$ is the imaginary part of the effective refractive index.

In this paper, the perfectly matched layer and a scattering boundary are used. The guided light in the core of the PCF can strongly couple to the surface plasmon of the metallic nanowires when the phases of the core mode and the surface plasmon polaritons (SPPs) match. And the resonance peaks occur at different wavelengths in two orthogonal polarization states.

## 3. Simulation results and analysis

### 3.1. Dispersion relations

To investigate the polarization characteristics, here we calculate the dispersion relation of the SPP by using the following equation [14]:

$$n_m = \sqrt{\frac{\varepsilon\varepsilon_M}{\varepsilon + \varepsilon_M} - \left(\frac{(m-1)\lambda}{d\pi}\right)^2} \tag{3}$$

where $m$ is the SPR order, $\varepsilon$ and $\varepsilon_M$ are the dielectric constants of glass and metal, respectively, and $d$ is the diameter of the nanowires. By the above relationship, we can easily obtain each order of the SPP modes except zero-order mode. From Fig. 2, we can clearly find out the dispersion relation of SPP mode and core mode.

The couple properties are shown obviously in Fig. 2. The fundamental mode has much higher effective index than the core mode, and cannot couple to the core mode. But to our surprise, the

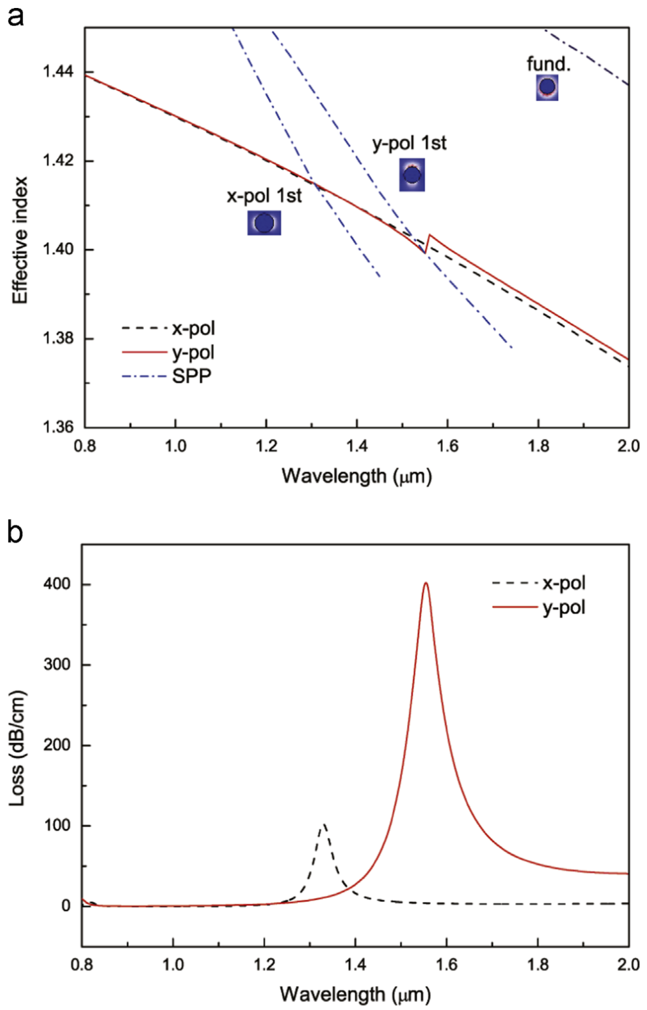

**Fig. 2.** Wavelength dependence of effective indices (a) and losses of the $x$-polarized and $y$-polarized core modes in the PCFs. (b) A gold wire is filled into the gray sections. The solid and dash lines are the loss of core guided modes in $y$-polarized and $x$-polarized direction, respectively.