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Study on photonic crystal fiber filter with two large gold layer air-holes based on surface plasma resonance

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ABSTRACT

We design a crystal photonic fiber (PCF) polarization filter with asymmetric structure and two large air-holes coated with gold film. The influence of the thickness of metal layers and the diameter of large air-holes on the filtering characteristic is investigated using finite element method (FEM). In calculations, the sixth and the third order surface plasma modes (SPM) are presented. The resonance positions are well separated by the asymmetry of the structure in vertical direction. The loss of unwanted polarization is 829 and 1267 times than that of wanted polarization at 1.48 and 1.55 μm respectively. When the fiber length is 3 mm, the crosstalk is 1055 dB and 927 dB for 1.48 and 1.55 μm. The bandwidth with crosstalk better than 20 dB can reach to 1000 nm, covering almost all communication band. What's more, gold excitation of SPR and silver excitation of SPR are compared and studied.

1. Introduction

Photonic crystal fiber (PCF) is also called microstructure optical fiber or porous fiber. The holes are arranged periodically and their magnitude of size is similar to the light wavelength. The fiber core can be solid or hollow core. Compared with the traditional optical fiber, it has many advantages, such as flexible control, low loss, large mode area and so on [1], which have attracted many scholars' attention and research, such as dispersion compensation [2], polarization filtering [3,4], sensing characteristics [5,6] and other aspects. Because of its flexibility and controllability, PCF is widely used in the design of optical fiber devices. Some functional materials like metal [7–9], liquid [10], molecular gas [11], or semi-conductor [12] are filled in the core or cladding of PCF to achieve more demanded functions, especially the filling of metal.

The combination of PCF technology and surface plasma resonance (SPR) is a hot research topic in recent years. When the metal surface is exposed to light and meet certain conditions, a surface plasma element can be generated. Once the transmission constants of surface plasma and fiber core match, coupling phenomena will occur, which make the PCF device based SPR has better characteristics. Such as the PCF polarization filter, SPR can greatly improve the limited loss that improves the filtering characteristics. There is a lot of coverage on it:In 2016, Zi J [13] proposed a polarization filter with two large diameter gold coated air holes, when fiber length is 1 mm, extinction ratio can reach 396 dB at 1.31 μm. In 2016 Yogalakshmi [14] designed and analysed a photonic crystal fiber based polarization filter using surface plasmon resonance. The loss can reach 348.55 and 302 dB/cm for y-polarized and x-polarized light at 1.52 and 1.56 μm respectively for single gold wire.

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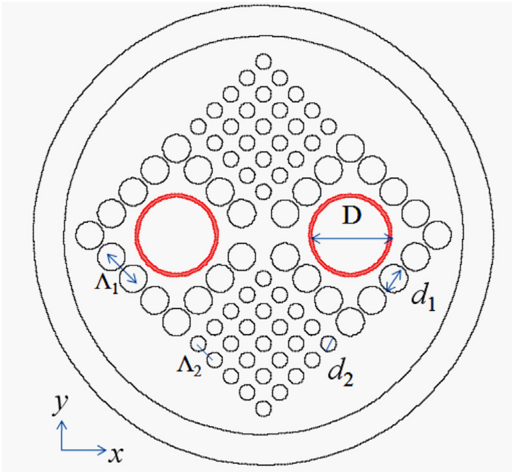

Fig. 1. The designed PCF filter model structure.

In 2016, An G [15] proposed high birefringence photonic crystal fiber polarized filter filled with metal wires which can selectively filter out the polarized light in one direction by adjusting the wire diameter. In 2016, Zhen H [16] obtained symmetrical high birefringence photonic crystal fiber filled with Au. The core mode loss in x-direction light could reach 473 dB/cm, however the core mode loss of y-direction light was almost not affected by the surface plasma polarized mode at the wavelength of 1.55 μm. In 2016, Liu [17] studied that the gold wires are selectively filled into the cladding air holes of PCF, the loss of x-polarized mode is 443.36 dB/cm at 1.31 μm, and the corresponding loss of y polarization mode is 2.24 dB/cm. G Wang [18] studied PCF polarized filtering with nanoscale gold film, the confinement loss in x direction can reach 857.80 dB/cm at the resonance wavelength. When the length of fiber is longer than 30 μm, the extinction ratio is better than 20 dB at the wavelength 1.31 μm.

In this paper, we design a single polarized PCF filter with two large air-holes. The loss in x-polarized direction is much larger than that in y-polarized direction. The loss in x-polarized direction is 405.50 dB/cm and 356.49 dB/cm at the communication wavelength 1.48 and 1.55 μm, but the corresponding loss in y-polarized direction is only 0.32 dB/cm and 0.43 dB/cm. The loss in x direction is 1267 and 829 times of y direction. When the fiber length is 3 mm, the crosstalk is 927 dB and 1055 dB respectively. The designed filter has perfect filtering performance better than Refs. [14], [17] and [22]. Operable bandwidth can reach to 1000 nm and is wider than Ref. [20].

2. Model structure and theoretical knowledge

Fig. 1 is the designed PCF filter model, which is a square rotation of 45°. There are two large air holes coated with gold layer. The rest small holes are divided into two kinds of different sizes. The asymmetric structure can make the resonant positions of two vertical directions are well separated even without high birefringence. This view has been presented by Zhang in Ref. [19]. The SPR effect can greatly improve the loss of x direction light and improve the filtering performance. In the model, the diameter of the big gold layer hole is D. The thickness of gold later is *t*. The smaller holes diameter is d_1 and holes spacing is Λ_1. The diameter of the smallest air holes is d_2, holes spacing is Λ_2. What's more, we employ full vector finite element method (FV-FEM) for simulating both core mode and SPP mode, which is a powerful software that is recognized as the most suitable for solving fiber complex cross section structures. To improve the calculation accuracy, the scattering boundary conditions and the perfect matching layer of several micrometers are set to absorb the energy radiated outward. The fiber material is silicon. Besides, the dispersion of silicon and metal are considered in simulation. The refractive index of silicon is calculated by Sellmeier equation.

The dielectric constant of gold is determined by Lorentz-Drude model [20]:

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega - i\gamma_D)} - \frac{\Delta\varepsilon \cdot \Omega_L^2}{(\omega^2 - \omega_L^2) - i\Gamma_L\omega} \tag{1}$$

In the formula, ε_∞ is the high frequency dielectric constant, $\Delta\varepsilon$ is the weighted coefficient, ω is the guiding optical angular frequency, ω_D is the plasma frequency and γ_D is damping frequency, Ω_L represents the oscillator strength of the Lorenz oscillator, and Γ_L is the frequency spectrum width of the Lorenz oscillator.

The mode loss is an important optical fiber indicator and can be calculated by the formula [21]:

$$Loss = \frac{20}{\ln(10)} \times \frac{2\pi}{\lambda} I_m(neff) \times 10^4 dB/cm \tag{2}$$

$I_m(neff)$ is the imaginary part of the effective refractive index.