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Surface plasmon induced polarization filter of the gold-coated photonic crystal fiber with a liquid core

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ABSTRACT

A new gold-coated photonic crystal fiber (PCF) which can achieve a specific wavelength filter has been proposed. The polarization filter characteristics of the PCF based on the finite element method are investigated. Numerical results show that moving the two gold-coated holes toward the central core in longitudinal direction and filling pure water in the central defected air-hole can effectively enhance polarization extinction ratio around the resonance wavelength. The resonance strength in *y*-polarized case is far stronger than that in *x*-polarized case, the peak loss of the PCF with different coating thickness in *y* polarization can reach 536.25 dB/cm and 412.91 dB/cm at the communication wavelength of 1.55 μm and 1.31 μm, respectively, while the losses are very low in *x* polarization. This is beneficial for the study and application in many polarization filter devices.

1. Introduction

Since their first experimental demonstration [1], photonic crystal fibers (PCFs), optical fibers with an array of air holes running along their length, have become a major topic of research due to their unique light guiding properties. Besides, many extraordinary optical properties of silica-air PCFs can be extended by infiltrating with liquid crystal [2], polymer [3], filling or coating metal [4,5] in the cladding holes and hollow core. In the metal-filled or -coated PCF, surface plasmon polaritons (SPPs) can form on the surface of metal [6], and the energy of the core-guided modes can be transferred to the SPP modes when the phases of them match. In recent years, metal-filled or -coated PCFs have been suggested for use as various tunable all-in-fiber devices. Kuhlmey et al. have provided a theoretical formalism for metal-coated PCFs and showed that their guidance can be combined with plasmonic resonances effects [7]. Zhang et al. have demonstrated selective silver coating of holes in PCFs, expected to be applicable as an in-fiber absorptive polarizer [8]. Hassani et al. have analyzed in detail design principles for two different PCF structures with metallic coating for sensor application [9]. Otherwise, the polarization-dependent properties of PCFs based on SPPs have already been reported by some people. Nagasaki et al. theoretically investigated the polarization properties of the PCF selectively filled with metal wires and showed strong polarization-dependent coupling characteristics in PCFs with closely-aligned metal wires [10]; however, there were multiple resonance peaks with not strong enough resonance strength. Du et al. designed two kinds of AU-filled high-birefringence PCF with polarization splitting and filtering characteristics [11], but two structures presented required holes of four different sizes and there were asymmetrical structures in the cladding. Xue et al. presented and numerically characterized the polarization filter characters of the gold-coated PCF [12]; however, to increase the loss in *y*-polarized direction, four holes (including the gold-coated holes) must be filled with liquid, and the loss is only more than twenty times stronger in *y* polarization than that in *x* polarization in the resonance peaks.

In this work, we numerically investigated the polarization filter characteristics based on SPPs within selectively coated PCF by the finite element method [13]. A defected circular air hole is introduced in the core of the PCF structure, which can lower the refractive index of the core modes to better match with that of the SPP modes. Numerical results demonstrate that the proposed PCF has good polarization filter characteristics at special wavelengths by changing the positions of the two gold-coated holes and filling pure water in a central air hole. At the communication wavelengths of 1.31 μm and 1.55 μm, the loss of unwanted polarization mode (*y*-polarized core mode) can reach 412.91 dB/cm and 536.25 dB/cm in two PCF structures respectively and the corresponding insertion loss(in *x* polarization) is only down to 2.02 dB/cm and 5.29 dB/cm. The loss is more than two hundred

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times stronger in y polarization than that in x polarization in the resonance peak of 1.31 μm. This fiber will play an important role in the fields of polarization dependent wavelength selective optical filtering and other fiber-based plasmonic devices.

2. Theoretical modeling

Fig. 1 shows a schematic illustration of the proposed PCF, which is composed of circular air-holes in the cladding arranged in a triangular array with lattice constant of $\Lambda = 2.2$ μm and diameters of $d = 1.4$ μm. The central core region is perturbed by including an extra air-hole with diameter of $d_c = 0.4$ μm, which depicted in gray is filled with pure water. The black sections of the two holes are coated with gold and the thickness of the gold layer is depicted as t. To perform a much simpler structure, the outside diameter of gold-coated holes is same as the other cladding holes diameters d. To properly estimate the fiber confinement loss, a perfectly matching layer (PML) [14] is also added to the outmost layer. Moreover, a scattering boundary condition outside the PML region is used to reduce the reflections.

The background material is pure silica and its material dispersion is determined by the Sellmeier equation, in which optical constants are based on experimental results [15]. And the material dispersion of gold is characterized by a Drude–Lorentz model and its dielectric constants are based on empirical results [16]. The central air hole is filled with pure water and its material dispersion is calculated using the corresponding Sellmeier equations with parameters given in [17]. The dispersion of SPP modes was described by wire helix approximation model [18,19]. It is pointed out in [20] that higher order modes do not contribute to the core power transfer, hence, only the fundamental core-guided modes were discussed in this paper. A finite element method was used to find the complex propagation constants of the core-guided and the plasmonic modes. The effective refractive indices (n_{eff}) of various modes were obtained, and the modal loss can be expressed by the following equation [13]:

$$\alpha = 8.686 \times \frac{2\pi}{\lambda} \times \mathrm{Im}(n_{eff}) \times 10^4 \tag{1}$$

where λ is the wavelength of light and the $\mathrm{Im}(n_{eff})$ is the imaginary part of the mode effective refractive index. The units of the confinement loss and the wavelength are dB/cm and micrometer, respectively. The full width at half maximum (FWHM) of the loss curve corresponds to the bandwidth of the polarization filter, and polarization filters with smaller bandwidth are needed in many applications. When the phases of the core modes and the SPP modes match, the core-guided light can be strongly coupled to the SPP modes on the surface of the gold layer at some particular wavelengths where the fiber losses increase rapidly.

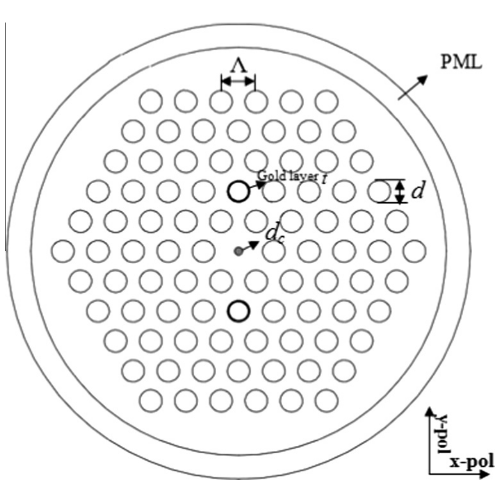

Fig. 1. Cross-section of the proposed PCF.

3. Simulation results and analysis

The FEM providing high accuracy and flexible triangular meshes was implemented to characterize the designed polarization filter. The PCF was divided into 34,568 triangular meshes. To illustrate the corresponding computational accuracy by FEM, we simulate theoretically one of PCFs with gold-coated holes in the literature [12], the simulation results are in good agreement with the results shown in this literature. Fig. 2(a) represents the losses of the x-polarized and y-polarized core modes in the PCF with a solid core and a defected air hole of $d_c = 0.4$ μm, and the other parameters are fixed as $\Lambda = 2.2$ μm, $d = 1.4$ μm, $t = 0.055$ μm. It is obvious from the figure the resonance strength of the PCF with a central air hole is much stronger than that of the PCF with a solid core. The central air hole is able to reduce the average refractive index of the fiber core, which offers an easier phase matching between the core mode and SPP mode. Moreover, introducing a central air hole in the fiber core region can effectively decrease the FWHMs of the peak losses of the PCF. The dispersion relation of SPP modes for various orders, the fiber core-guided modes, and the losses of the core modes in the PCF with a central air hole are shown in

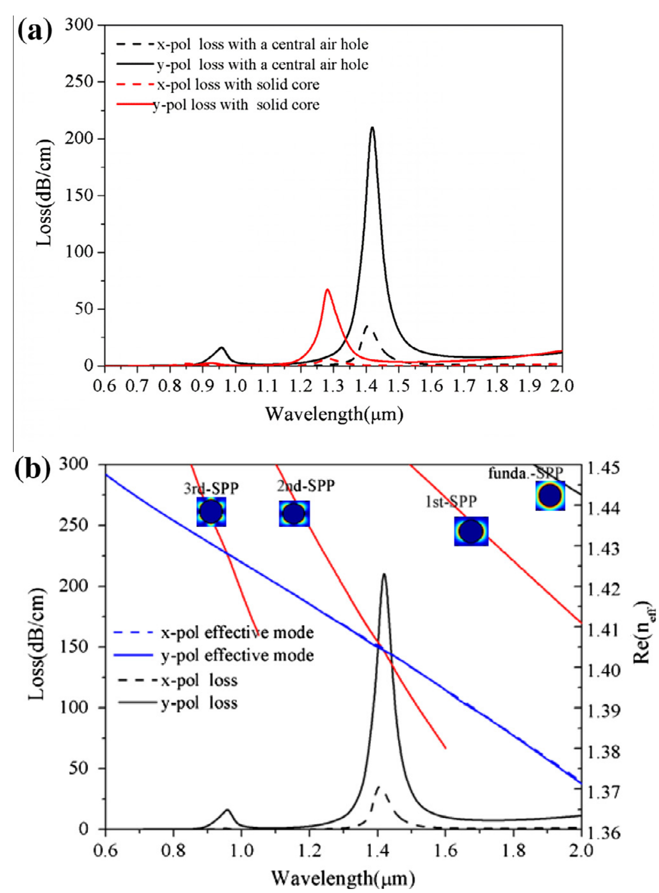

Fig. 2. Wavelength dependence of (a) losses of the core modes in the PCFs with a solid core and a central air hole; (b) dispersion relation of SPP modes for various orders and the core mode, and the loss spectra of the core modes in the PCF with a defected air hole. The red lines represent SPP modes of the specific mode orders and the insets show the magnitude of the longitudinal Pointing vector of the SPP modes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)