Optik 149 (2017) 162–168

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Polarization filter based on plasmonic photonic crystal fiber with asymmetry around Au-coated and liquid-filled air holes

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ARTICLE INFO

Article history:
Received 6 August 2017
Received in revised form
11 September 2017
Accepted 12 September 2017

Keywords:
Photonic crystal fibers
Birefringence
Polarization filter

ABSTRACT

A novel photonic crystal fiber polarization filter with Au-coated and liquid-filled air holes is designed in this paper. The coupling theory is introduced to explain the complete coupling and incomplete coupling. We can adjust the resonance point to the communication band by optimizing the parameters of the fiber structure. Numerical simulation results demonstrate that the resonance strength can reach 434 dB cm^{-1} at the communication wavelength of 1.31 μm in x-polarized direction. By filling liquid analyte can help adjust the resonance peak to the proper place. Furthermore, when the fiber length of *L* equals to 0.1 cm, the crosstalk peak value can reach 353.74 dB at the wavelength of 1.31 μm, and the bandwidth of the crosstalk better than 20 dB can reach 80 nm when the length of the fiber *L* is 400 μm. These characteristics make it a promising candidate for designing new types of polarization filter devices.

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1. Introduction

With the development of optical communication technology, optical fibers have been the indispensable equipment in the long distance communication. Compared to the traditional fiber, photonic crystal fibers (PCFs) [1–4] have many excellent feathers such as flexible non-linearity [5], low loss [6], controllable birefringence [7], big mode area [8] and no cut-off single-mode transmission [9]. The refractive index distribution of PCFs depends on the size and shape of air holes in the cladding. Adjusting the size, shape and arrangement of the air holes in the fiber cladding can generate a variety of asymmetrical structures [10]. Recently, all sorts of materials are filled into PCFs, such as polymer [11], metal [12], liquid [13], liquid crystal [14], oil [15] or gases [16] and aroused extensive attention [17,18]. Now, a growing number of researchers are focusing their research target on filling metal wire or metal coating into the PCFs. Many novel characteristics have been discovered, for instance, the surface plasmon resonance (SPR) appears on the surface of the metal when the metal nanowire is filled into the PCF air holes. In recent years, the studies about polarization performance of PCFs have been explored. In 2012, Du et al. proposed the polarization-filter characteristics with metal wires [19]. In 2013, Xue et al. reported a polarization filter based on PCF with SPR [20]. In 2014, An et al. reported a modified structure of PCF with gold-filled air holes [21]. In 2015, Jiang et al. reported a PCF with a gold-coated layer in one air hole [22]. In 2016, Wang et al. proposed single-polarization single-mode

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http://dx.doi.org/10.1016/j.ijleo.2017.09.047
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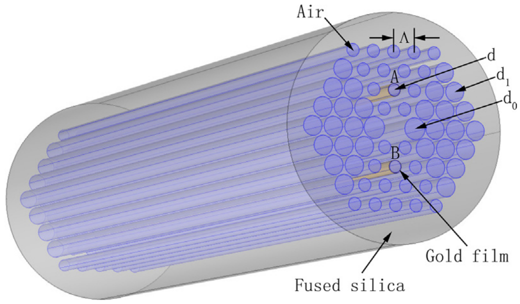

Fig. 1. Three dimensional schematic of the PCF with hexagonal lattice.

photonic crystal fiber filter [23]. In 2017, Feng et al. proposed a polarization filter with symmetry around gold-coated holes [24]. However, these PCFs do not have an outstanding performance as polarization filter.

In this paper, we design a polarization filter of PCF with asymmetry around Au-coated and liquid-filled air holes. The performances of the PCF polarization filter are investigated by using the finite element method (FEM). Numerous simulation results demonstrate that the resonance peaks at a certain wavelength can be altered by changing the thickness of metal film, the refractive index of the liquid-filled and the diameter of air holes near the core. By adjusting the structure parameters of PCFs, the confinement loss in x-polarized direction can reach 434 dB cm^{-1} at the communication wavelength of 1.31 μm when the thickness of the metal film is 40 nm, and the resonance strength in x-polarized direction is much stronger than that in y-polarized direction. The resonance peaks can be adjusted to the correct position by adding liquid. It is extremely beneficial for the design of the polarization filter.

2. Structure and theoretical model

A three-dimensional schematic of the presented polarization filter based on Au-coated air holes is shown in Fig. 1. The PCF consists of four layers of air holes in the x- and y-polarized direction, and the air holes are arranged in hexagonal lattice. The diameter of the two biggest air holes near the core in the horizontal direction is d_0, which is helpful for producing the birefringence. The diameter of the bigger air holes is $d_1 = 1.8$ μm. In addition, the diameter of the smallest air holes in vertical direction is $d = 1.2$ μm, which will produce dissymmetric factors. The black sections of the air holes A and B are coated with metal Au. The pitch between two adjacent air holes is $\Lambda = 2.0$ μm.

The background of material is fused silica whose material dispersion can be calculated according to the Sellmeier equation [25]. The material dispersion of gold can be obtained by the Drude–Lorentz model [26], so the mode confinement loss can be defined as:

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

Where the units of the confinement loss and the light wavelength are dB cm^{-1} and μm, respectively. λ is the operating wavelength, and the $\mathrm{Im}(n_{\mathrm{eff}})$ represents the imaginary part of the effective refractive index of the core. In order to cut down the energy loss, a scattering boundary condition and a perfectly matched layer are used in the simulating calculation.

3. Simulation results and analysis

3.1. Dispersion relation

Fig. 2 shows the core-guided mode loss spectrum and the dispersion relations between core mode and surface plasmon polariton (SPP) modes. The curve of the core mode intersects with the curve of the second- and third-order SPP mode, The effective refractive index of the core mode in x-polarized direction has a abrupt change at the wavelength of 1.31 μm, and the resonance peak is more stronger than that of y-polarization at this point. Then, a complete coupling happens at this phase-matching point. We also can find that the resonance wavelengths of x- and y-polarized mode are totally different, which has rarely been seen before. The main reason is that the small air holes and two big air holes near the core break the hexagonal symmetrical structure, so the difference in the effective refractive indexes of the core mode between the x- and y-polarization generate. Hence, the environment around the Au-coated film is dissymmetric, and the process is called introducing asymmetric factors, which has already been confirmed by our team. In addition, we find that an incomplete coupling happens between core mode and the third-order SPP mode in x-polarized direction when the wavelength is 0.89 μm, and it is much weaker than the complete coupling between the core-guided mode and the second-order SPP mode.

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