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Surface plasmon resonance induced tunable ultra-wideband polarization filters based on gold film coated photonic crystal fibers

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ABSTRACT

Surface plasmon resonance induced tunable broadband polarization filters based on photonic crystal fibers (PCFs) were designed and investigated. The characteristics of the designed PCF were calculated by using the finite element method (FEM). The air holes in the PCFs which were arranged in hexagonal lattice were of the same size except one big air hole. The big air hole which was located on the right side of the fiber core was designed to be coated with gold film in the inner wall. Because of the arrangement of the big air hole, the surface plasmon resonance inspired on the surface of gold film was quite different for the two orthogonal polarized incident lights. As the edge of the big air hole approaching the adjacent air holes, the plasmon modes were influenced strongly by the adjacent air holes and as a results the cascaded resonances appeared. The index-matching liquid infilling in the big air hole was used to adjust the resonant wavelengths and strength. Numerical simulation results showed that the bandwidth of the polarization filter was 1200 nm covering the wavelengths from 1.0 μm to 2.2 μm with high extinction ratio (ER).

1. Introduction

Photonic crystals (PCs) are composite materials constituted by regular arrays of monomeric units, which is designed to confine, control and manipulate photons depending on the array spacing. The PCs have been found application in optical devices such as physical sensor and bio-sensor. The preparation of PCs for different uses have attracted a lot of attentions. Kondo [1] prepared ideally ordered TiO_2 hole arrays with high aspect ratios by anodizing pre-textured Ti. The fabricated TiO_2 was two dimensional photonic crystals, in all directions of light propagation in the lattice, formed a photonic band gap. Venditti [2] synthesized conjugated polymeric nanobeads for photonic band gap materials by a modified emulsion polymerization. They studied the effects of reaction conditions on their chemical and physical properties of the nanobeads and their ability to form an ordered arrays. The UV–vis spectra performed on conjugated polymeric nanobeads shew continuous absorption. The PCs combined with plasmonic materials are now considered as a basis for designing new photonic media for sensing, optoelectronics and nonlinear optics. Khokhar [3] demonstrated a simple process of incorporating nano-gold particles inside the interstices of polystyrene-based three-dimensional PCs. The optical reflection experiments were carried out on gold-infiltrated polystyrene PCs and the results shew the presence of surface plasmon resonance bands. Lu [4] fabricated a new photocatalyst by infiltrating Au nanoparticles into TiO_2 photonic crystals. They demonstrated that the light absorption by Au nanoparticles was amplified after they were infiltrated into TiO_2, due to the localized surface plasmon resonance of Au nanoparticles and the photonic effect of the TiO_2. Xavier [5] combined optical nanocavities and PCs with plasmonic nanoparticles making optoplasmonic sensors to detect at the nanoscale with extraordinary sensitivity, including single-molecule detection and even single-ion sensing.

The application of PCs in optical fiber technology is the most promising field. The main issues involved are about the periodic microstructures of high refractive index fibers. The periodically arranged pores run through the entire length of the fiber and light waves can be confined to propagate in the core region of a low index of refraction. The above mentioned fibers are photonic crystal fibers (PCFs), also known as microstructured optical fibers (MOFs). They have many new features which are distinct from traditional optical fibers such as endless single mode, controlled dispersion, highly nonlinearity, high birefringence, polarization effects, miniaturization and flexible design [6–11]. More and more researchers focused their research interest in PCFs. PCFs have been designed as a variety of fiber devices including high-power lasers

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[12], sensors [13], supercontinuum generators [14], amplifiers [15,16], polarization filters [17]and polarization splitters [18]. The air holes in the cladding of PCFs are flexible design in size, shape and arrangement. Furthermore, the air holes also can be filled with functional materials which provide more possibility for designing various innovative photonic devices [19]. Ma [20] fabricated a temperature sensor possessing high sensitivity based on solid-core PCF infiltrated with temperature sensitive liquids. Liu [21] reported a nanosecond-pulse erbium-doped fiber laser that was passively mode locked by filling few-layered graphene oxide solution into a hollow-core PCF.

Surface plasmon is the electron transport wave on the surface of metal and can be inspired through the interaction of input light and free electrons. The induced surface plasmon resonance (SPR) provides a new approach for developing highly sensitive photonic device [22]. Based on SPR effect, PCFs which were coated with metal film or infiltrated with metal wires shew extensive applications in filtering, nonlinear optics and sensing fields [23–25]. Because of the application prospect of SPR in fiber devices, many technologies such as suction, evaporation and deposition of metal nanoparticles into the PCF air holes were developed. Zhang [26] utilized the high-pressure chemical deposition method to achieve coating silver film on the inner wall of the pores of the PCF. The PCF was used as an in-fiber absorptive polarizer. Lee [27] employed the method of splicing and pressure to achieve the selective infilling of gold wires into PCF air holes. The diameters of gold wires were as small as 120 nm.

Along with the development of fiber communication, optical information processing and fiber sensing, there is an increasing demand for the extremely wide optical transmission bandwidth in optical communication networks. Wavelength Division Multiplexing (WDM) is a common method of adding capacity that transmits data over optical fibers at multi-carrier wavelengths. In a WDM system, optical filters are essential components. PCF based polarization filters meet the requirements of the compact and integrated WDM components and can achieve good polarization filtering effect at the operating wavelengths. Therefore, the PCF based polarization filter attracts the attention of more and more researchers. Xue [17] designed a narrow bandwidth liquid-filled PCF polarization filter based on SPR. The two air holes that were symmetrical with respect to the core in the Y-Polarized (Y-P) direction were plated with gold film which is used to introduce the resonance between the SPP modes and fiber core modes. The liquid filled in the gold-coated air holes was proved to increase the loss of core mode in Y-P direction around the resonance peak. The resonance strength was much stronger in Y-P direction than in X-Polarized (X-P) direction and it achieves 50.8 dB/mm for Y-P mode at the communication wavelength of 1311 nm, and the full width half maximum (FWHM) was 20 nm. Hameed [28] proposed a tunable SPR polarization filter based on PCF selectively filled with gold wires in the cladding holes. The central hole filled with a nematic liquid crystal acted as the fiber core. Energy transfer occurred between the fiber core and the air holes filled with metal wires when SPR occurred. The resonance wavelengths and strength can be tuned with temperature and external electric field. In our previous work, a tunable narrow bandwidth polarization filter [29] based on gold-coated PCF was realized. We coated gold film on the inner wall of the air hole just above the fiber core and filled nematic liquid into the two air holes on both sides of the gold-coated air hole. We obtained a dual channel filter at the communication wavelength of 1.31 μm and 1.55 μm for Y-P direction and X-P direction. Another single channel polarized filter at 1.55 μm was also achieved by adjusting the refractive index of the infilling liquid. Chen [30] designed an ultra-broadband polarization filter with the bandwidth as broad as 1 μm based on gold film coated D-shaped PCFs. The gold film was deposited on the polished plane of the D-shaped PCF generating multiple resonances between surface plasmon polaritons and photons. Thanks to the close proximity of the resonance points, the effect of broadband filtering was obtained. The resonant intensity in Y-P direction was much stronger than in X-P direction and the confinement loss of fundamental mode reached the highest value of 49.521 dB/mm at the wavelength of 1.56 μm. Liu [31] investigated the SPR induced broadband polarization filter with the bandwidth as broad as 430 nm based on a 3 mm long PCF. Around the core were arranged three types of air holes of different diameters. They plated the gold film on the inner wall of an air hole in the vertical direction to introduce the SPR. The resonant intensity in Y-P direction was also stronger than in X-P direction and the confinement loss of fundamental mode was 10.200 dB/mm in Y-P direction and 0.08 dB/mm in X-P direction at the wavelength of 1.55 μm.

In this paper, we proposed a tunable ultra broadband SPR polarization filter based on gold film coated and liquid filled PCFs. The air holes in the PCFs which were arranged in hexagonal lattice were of the same size except one big air hole. The inner wall of the big air hole was designed to be coated with gold film and then infiltrated with index-matching liquid. The adjustment of the center filter wavelength can be achieved by changing the refractive index of the filled liquid. The simulation results showed that the confinement loss of core fundamental modes were 163.877 dB/mm in X-P direction and 3.196 dB/mm in Y-P direction respectively at the communication wavelength 1.55 μm. The refractive index of the filled index-matching liquid is 1.38. As the fiber length is set as 1 mm, the ER can reach to −1396 dB at the resonant wavelengths of 1.55 μm, and meanwhile the bandwidth with ER better than −20 dB can reach to 1200 nm. Obviously, the ER is better and the bandwidth is broader than that reported in [30,31]. Moreover, the structure of our designed PCFs is simpler.

2. Design and principle of broadband polarization filter

The cross-section of the designed PCF polarization filter is depicted in Fig. 1. As shown in the structural sketch, the PCF structure is simple for all the air holes having the same diameters of d_2 except for one big air hole. The diameter of the big air hole is of d_1. Comparing with other PCF structures with several different-sized holes, this design is relatively easy to fabricate. One air hole is removed to form a transferring core. The big air hole which is located on the right side of the fiber core is selected to be coated with gold film and infiltrated with index-matching liquid. Then the big air hole acts as a defect core. As SPR between SPP modes and fiber core mode occurs, the light energy transferring in the fiber core couples to the surface of gold film. The air holes are arranged in equilateral triangle and the pitch between holes is expressed by Λ. The thickness of the gold film is addressed by t.

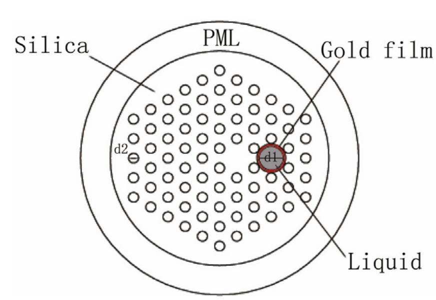

Fig. 1. Cross-section of the designed PCF polarization filter. The grey big air hole was designed to be coated with gold film and infiltrated with index-matching liquid.