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# Ultra-broad band single-polarization single-mode photonic crystal fiber based on the zero-order surface plasmon polariton mode

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ABSTRACT

An ultra-broad band single-polarization single-mode photonic crystal fiber (SPSM-PCF) is investigated based on zero order surface plasmon polariton mode by using the full vector finite element method (FEM). Highly wavelength-dependent transmission is obtained because of the band gap-liked effect of the bonding zero-order surface plasmon polariton mode stimulated over the interface of gold/liquid. With a filled RI of 1.52, the polarization extinction is higher than 30 dB/cm among a large bandwidth of 360 nm in the second communication window. The proposed SPSM-PCF also presents a large tolerance of the size deviation of gold-coated layer.



## 1. Introduction

Photonic crystal fiber (PCF) based plasmonic devices, with vast design possibilities, large index contrast and compactness in size, have recently attracted considerable attention in design of sensor [1–3], polarization narrowband filter [4], wavelength splitter [5,6] and coupler [7]. Shuai et al. reported the multi-core PCF based plasmonic liquid refractive index (RI) sensor, and achieved high linearity with large RI detection range from 1.33 to 1.53 [1]. Xue et al. investigated the polarization filter characters of gold coated and liquid filled birefringent PCF, and the function of a narrow band polarizationfilter was achieved at 1310 nm band [4]. Chen et al. reported a single-polarization PCF wavelength splitter based on hybrid SPP, and realized single polarization in the1310 nm and 1550 nm bandswith high extinction ratio [6]. Zhang et al. theoretically analyzed the coupling property of a dual-core PCF filled with a metal wire in the center air hole. The analysis shows that the structure enhances the coupling efficiency by a more than one-order-of-magnitude reduction in coupling length [7]. Moreover, plasmonic PCFs have a potential use in realizing single-polarization single-mode (SPSM) fibers which guide only one polarization mode of the fundamental mode in the fiber core. With ability to eliminate polarization coupling and polarization mode dispersion, the SPSM fiberis particularly desirable for use as in-line fiber-type polarizer, fiber-optic gyroscopes, superluminescent sources and guiding media in fiber-optic sensors [8,9].

The key point of designing SPSM fibers is to attenuate one polarization while keep the orthogonal polarization propagating with low loss. In general, there are two approaches to achieve SPSM. First is to modifying the effective refractive index (RI) of one polarized core mode to be higher than the fundamental space-filling (FSM) mode. This can be achieved by increasing the birefringence of core [10,11] and FSM mode [12,13], introducing anisotropic RI distribution of the FSM mode [14], and infiltrating liquid [15]. The second approach utilizes the principle of resonant coupling. With proper design, the effective refractive index of one polarization can be matched to that of the leaky defect mode in cladding. Thus energy of the matched polarization is transferred to the defect mode. The leaky defect modes can be formed by reducing the diameter of certain air holes [16] and selectively filling air holes with liquid [17] or metal [18,19]. It should be noted that the polarization performances of these SPSM fibers need to be improved: First, the electric field distribution of the effective mode field in the highly birefringent PCF based SPSM fiber is the non-Gaussian field profiles [20]. Therefore such highly birefringent fibers will unavoidably increase the insertion loss when they are connected to standard optical fibers. Second, the length of the SPSM-PCF is several or tens of centimeters due to the required interaction length for complete transfer of the propagating electromagnetic wave from fiber core to leaky mode. Thus, such designs may not fulfill the high compactness requirement for miniaturized complex communication devices. Third, the largest SPSM bandwidth only covers half of the second communication window so that the SPSM fiber cannot accommodate more applications. Therefore, our work aims at breaking these three

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limitations by using a different operation principle with the plasmonic effect.

In this paper, a new SPSM fiber with a near-Gaussian mode field distribution is achieved through integration of two gold-coated layers filled with liquid. The polarization-selective function is realized by the band gap-liked property of the bonding zero-order SPP mode. The attenuation difference between the two orthogonally polarized modes is larger than 30 dB/cm, which indicates the SPSM fiber has a high polarization extinction value. Additionally the SPSM fiber can operate over a broad wavelength range of 358 nm, nearly covering the second communication window from O band to U band. The proposed SPSM fiber has a wide error-tolerance of the gold-coated structure and the RI of the filled liquid. According to the linear relationship between the resonance of the bonding zero-order SPP mode and RI of the filled liquid, it is also a good candidate for liquid RI sensor with high sensitivity. The results are demonstrated by a full-vector finite-element method (FEM) with perfectly matched layers.

## 2. The polarization-selective property of the bonding zero-order SPP mode

In this section, the operating principle of the proposed SPSM-PCF will be explored. The proposed SPSM-PCF is mainly based on the band gap-liked effect of the bonding zero-order SPP mode stimulated over the interface of gold/liquid ($spp_0$-inner mode). To the best of our knowledge, the selective polarization matching mechanism between the fundamental core mode and the bonding $spp_0$-inner mode has not yet been reported.

SPPs can form at the metal-dielectric interface. In the proposed structure, two gold-coated layers with the same size filled with liquid are embedded into a hexagonal lattice background. There are two kinds of SPP mode in the gold-coated layer filled with liquid: One is the SPP stimulated at the gold/silica interface [4–7]. Once the basic structure parameters of PCF are designed, such as the hole-filling fraction and the outer diameter of the gold-coated hole, the effective propagation constant of this SPP is affected little by the RI change of the inner liquid. The other SPP at the gold/liquid interface can be stimulated if the RI value of the inner liquid varies around 1.45 [1–3]. The RI change of the inner liquid would change the phase matching condition with the fiber core mode. Thus the resonant wavelength varies with the RI value of the inner liquid. As two gold-coated layers are utilized in the structure, the degenerated SPP modes which possess similar modal refractive index will affect each other and finally form bonding SPP mode and anti-bonding SPP mode [21]. Because of the high modal RI value of the $spp_0$ mode, it is usually hard for the core mode to match the phase with the $spp_0$ mode. With a proper RI design of liquid infiltrating, the $spp_0$ mode locates at the gold/liquid interface can be matched to the core mode. Fortunately, this $spp_0$-inner mode contributes to the wide band SPSM operation. Therefore, we focus on the matching between a core mode and a bonding $spp_0$-inner mode.

To help fully understand the unique characteristics of a bonding $spp_0$-inner mode, we carries out FEM simulations of the electric field distribution of double aligned gold-coated layers filled with liquid arranged in a hexagonal air hole lattice background. In the simulation, we set 2 μm, 1.2 μm and 40 nm as lattice pitch, air hole diameter, and thickness of the gold-coated layer, respectively. The RI of the liquid filled into the gold-coated holes equals 1.52. 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. For accurate

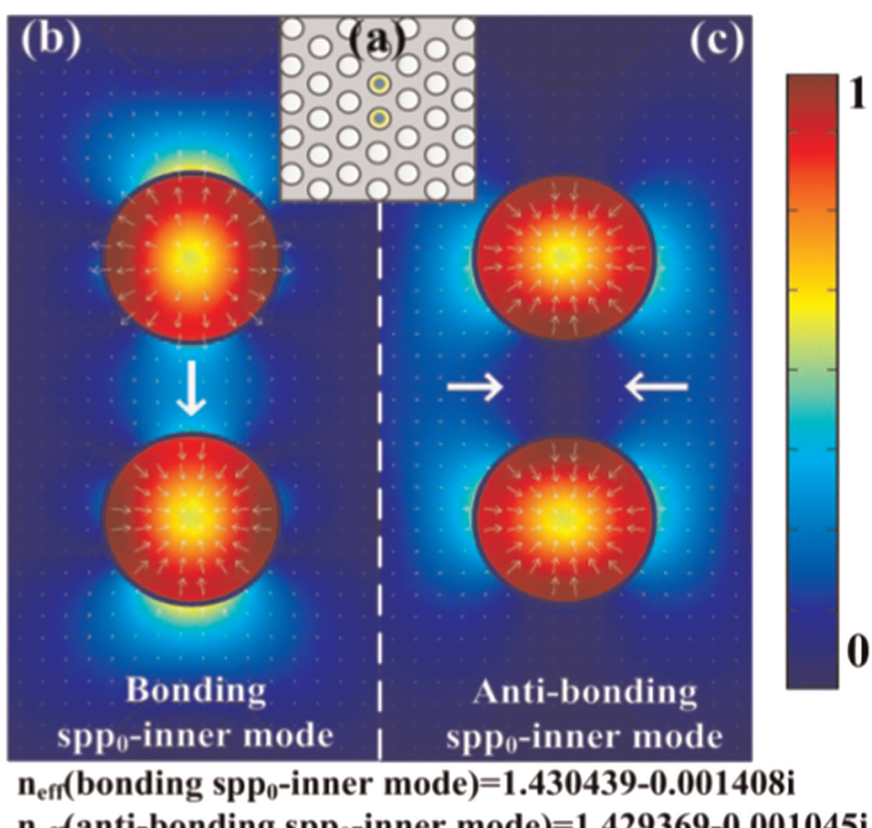


**Fig. 1.** The (a) cross section of the two adjacent gold-coated layers embedded in a finite hexagonal air hole lattice, and the electric field distribution of the (b) bonding $spp_0$-inner mode and (c) anti-bonding $spp_0$-inner mode at 1550 nm when $n_a = 1.52$. The arrows represent the directions of the local transverse electric fields.