Broadband single-polarization optical fiber based on surface plasmon resonance

Yingjie Zhang, Fengjun Tian,\* Zhenlan Su, Ruolan Bai, Li Li, Xinghua Yang, and Jianzhong Zhang

Key Lab of In-Fiber Integrated Optics of Ministry of Education, and School of Physics and Optoelectronic Engineering, Harbin Engineering University, Harbin 150001, China

\*Corresponding author: fenjuntian@hrbeu.edu.cn

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We present a new scheme of broadband single-polarization optical fiber with high extinction ratio based on surface plasmon resonance (SPR). The double-hole optical fiber with a Ge-doped core is modified by integrating the stacks of conductive and dielectric layers to support SPR. The strong couplings between the guided modes and surface plasmon mode can bring about serious polarization loss of TM mode, while support the efficient transmission of TE polarization in broadband. The achievable extinction ratio can be more than 25 dB covering a wide telecom band of 1.17~1.42 μm in short fiber lengths = 2.5 mm. Meanwhile, the insertion loss of the fiber is less than 0.25dB. The modified SPR fiber shows promising application in high quality fiber-integrated polarizers. © 2019 Optical Society of America

1. INTRODUCTION

The polarization changes of fiber guided mode have serious effect on the performance of fiber sensors [1-2]. In order to suppress the polarization effects, the popular solutions are to employ polarization-maintaining fibers, single-polarization fibers and polarizers into sensor systems. As a key component, all-fiber polarizers have been designed in various schemes involving metal or graphene-coated polarizers [3-6], tunable fiber polarizers [7-8] and fiber-grating polarizers [9-10]. Fiber polarizers maintain efficient transmission of single polarization mode, while deplete other polarization modes via certain mode-coupling mechanisms. Particularly, broadband polarizers covering the telecom bands are widely desirable in practice. However, it is basically difficult to achieve broadband operation in traditional fiber polarizers. Recently, some solutions were presented to overcome the limitation of working bandwidth to push broadband single polarization fibers. Typically, graphene-covered fiber polarizer was proposed to improve the bandwidth coverage from 1.56μm to 1.63μm. The extinction ratios were about 25dB to 36dB in a fiber length of 2.5 mm [11]. Fiber grating polarizers were also suggested to increase the working band in single polarization operation, but at the cost of larger sizes than metal-coated fiber polarizers [12]. For the tunable polarizers, some tunable parameters such as temperature or voltage have to be tuned in order to operate in broadband [7-8]. In contrast, double hole fibers (DHFs) can be much attractive in the applications of single polarization fibers and optical sensing due to compact scale, flexible and reliability [13-15].

In the paper, a new scheme of broadband single-polarization optical fiber near 1.31 μm with high extinction ratio is proposed by integrating surface plasmon resonance (SPR) regime. The double-hole fiber with a Ge-doped core can be modified by integrating the stacks of conductive and dielectric layers to support SPR. The strong couplings between the guided modes and surface plasmon mode can bring about serious polarization loss of TM mode, while support the efficient transmission of TE polarization in broadband [16]. Moreover, characteristics of the proposed fiber are studied numerically in detail. High extinction ratio can be achievable more than 25 dB covering a wide telecom band of 1.17~1.42 μm in short fiber lengths = 2.5 mm. The proposed fiber provides an effective bandwidth over 250nm and reduces the dependence of tunable polarizers on temperature or voltage. Furthermore, the effect of the geometric parameters of the structure on the polarization are discussed in detail by using the full vector finite element method (FEM).

**2. STRUCTURE AND PARAMETERS**

The cross section of the proposed fiber structure is shown in Fig.1. It consists of a Ge-doped core, two air holes and two gold-dielectric stacking layers. The gold-dielectric stacking layers are located respectively in the inner sides of the two air holes to support SPR. The diameters of the core, two air holes, and the pure silica cladding are defined as *d*1 = 8 μm, *d*2 = 30 μm, and *d*3 = 125 μm, respectively. The two air holes are arranged asymmetrically in the both sides of the fiber core. The distances between the air holes and the core are respectively described by *h*1 and *h*2. The gold-dielectric stacking layers are located on the inner sides of the two air holes, and is composed of a nanogold layer and a dielectric layer. The thickness of nanogold layer is defined as *h*Au, the thicknesses of dielectric layers are different, which expressed as *h*d1 and *h*d2, respectively. The refractive index of dielectric layer is described by *n*d = 1.438.



Fig. 1. Cross section of the proposed fiber structure(a), cross section of fiber sample(b)

For the proposed optical fiber, the wavelength dependence of the refractive index is given by the following Sellmeier relation [17].  **(1)**

where, *SA*1 = 0.6961663, *SA*2 = 0.4079426, *SA*3 = 0.8974794, *SL*1 = 0.0684043, *SL*2 = 0.1162414, *SL*3 = 9.896161, *GA*1 = 0.80686642, *GA*2 = 0.71815848, *GA*3 = 0.85416831, *GL*1 = 0.068972606, *GL*2 = 0.15396605, *GL*3 = 11.841931, *Χ* is the mole fraction of GeO2, and S*A*i, *GA*i, *SL*iare the Sellmeier coefficients for the SiO2 and GeO2 glasses. The GeO2 mole fraction of the core is defined as *X*core = 0.07, the refractive indices of the core and the cladding are *n*core = 1.4572 and *n*clad= 1.4486 at *λ* = 1.310 μm, respectively.

The material dispersion of nanogold layer is characterized by the Drude model, which can be expressed as  **(2)**

where, *λ*p and *λ*care the plasma wavelength and the collision wavelength of metal respectively. Where, *λ*p = 1.6826×10−7 m, *λ*c = 8.9342×10−6 m, for the nanogold [18].

The optical fiber with surface plasmon resonance can be fabricated. First, the two air holes realized by using an ultrasonic mill on the optical fiber preform. After that, the optical fiber preform is stretched by the fiber drawing tower to form the optical fiber. Similar double-hole fibers have been fabricated [19-20]. Chemical vapor deposition (CVD) and high-pressure microfluidic can respectively achieve the nanogold and dielectric layers coated on the inner sides of the two air holes [21].

The *xoz*-plane is defined as the plane of incidence. The characteristics of TE mode and TM mode and SPP modes are calculated by using frequency domain solver of COMSOL Multiphysics 5.2a software. The normal element type with the average element quality of 0.83 provides accurate simulation accuracy for the fiber. Perfectly matched layer (PML) is used as a boundary condition.

**3. RESULTS AND DISCUSSION**

Firstly, the mode characteristics are analyzed numerically. For the proposed fiber, the normalized parameter is expressed as

 **(3)**

where the normalized frequency of fiber is defined *V*, *λ* is operation wavelength, *n*core and *n*clad represent the refractive index of the core and cladding, respectively.



Fig. 2. Mode characteristics of the proposed fiber with various *h*1, *h*2 values at *λ* = 1.31 μm.

In order to demonstrate the dependence of mode number to air holes, the effects of *h*1 and *h*2 on mode characteristics are studied. As shown in Fig. 2, LP01 is the fundamental polarization mode and LP11 is the lowest high-order polarization mode. The non-zero cut-off frequency of the fundamental polarization mode and the lowest high-order polarization mode are represented by *V*FMC and *V*HMC respectively. *h*1 and *h*2 are from 1 μm to 2.5 μm, while other parameters are fixed. It is found that the *V*FMC of LP01 and the *V*HMC of LP11 decrease with increasing *h*1 and *h*2. When *h*1 and *h*2 increase gradually to infinity, the *V*FMC is close to zero, the *V*HMC approaches to 2.405, that is a common fiber.



Fig. 3. Electric field distribution of (a) TM mode and (b) TE mode at *λ*=1.21 μm, (c) TM mode and (d) TE mode at *λ*=1.31 μm.

For the proposed fiber, furthermore, SPR characteristics are studied in detail. The both gold-dielectric layers are located respectively in the inner sides of the two air holes to support SPR. Where *h*1, *h*2, *h*d1, *h*d2 and *h*Au are 1.3 μm, 1.5 μm, 1.1 μm, 1.7 μm and 50 nm, respectively, and other structure parameters are the same as in Fig. 1. In Fig. 3, there are TM mode and TE mode in the fiber core, meanwhile, the SPP modes appear in the gold-dielectric stacking layers. As shown in Fig. 3(a), it can be found that at *λ* = 1.21 μm the most energy of the TM mode is coupled into the left SPP mode. Comparing Fig. 3(a) with Fig. 3(b), the electric field intensity of TE mode is stronger than TM mode, because the most energy of TM mode is most coupled into the SPP mode and removed, while the TE mode is hardly coupled into the SPP mode and retained. Meanwhile, as shown in Fig. 3(c) and (d), at *λ* = 1.31 μm the most energy of the TM mode is coupled into the right SPP mode, and the TE mode is retained.



Fig. 4. The loss spectra of TM and TE modes, and the effective refractive index of TM mode and SPP mode.

The confinement loss of TM mode and TE mode, and the effective refractive index real part of the TM mode (Re(*n*eff)) and the SPP mode (Re(*n*spp)) are both shown in Fig. 4. It can be found that there are two intersections between the curve of Re(*n*spp) and the curve of Re(*n*eff), correspondingly there are two peaks in the curve of TM mode confinement loss in the range of wavelength from 1.00 μm to 1.50 μm. The two intersection points correspond respectively to the wavelengths called resonance wavelength. They are the first resonance wavelength *λ*1 = 1.21 μm and the second resonance wavelength *λ*2 = 1.31 μm respectively. Coupled mode theory can explain how the TM mode couples with the SPP mode, when the real parts of the propagation constants of TM mode and SPP mode matches, the energy of the TM mode is strongly coupled into the SPP mode [22].

At the first resonance wavelength, the most energy of TM mode is coupled into the left SPP1 mode, which is matched to the Fig. 3(a). Meanwhile the first resonance wavelength is aligned perfectly with TM mode loss peak. At the second resonance wavelength, the most energy of TM mode is coupled into the right SPP2 mode, which is matched to the Fig. 3(c). Finally, in the range between the two resonances wavelength, the TM modes are coupled simultaneously into the SPP modes on the both sides of core, and removed. Meanwhile, the confinement loss of TE Mode keeps very low, and is retained. The proposed single polarization optical fiber can operate in broadband.

The confinement loss of the core mode can be expressed as

 **(4)**

where *λ* represents the wavelength, Im(*n*eff) is the imaginary part of the effective refractive index, and the unit of *α* is dB/cm.





Fig. 5. Wavelength dependence of confinement loss on *h*1 and *h*2. (a) *h*1 = 1.3 μm, *h*2 = 1.5, 1.6, 1.8 and 2.0 μm, respectively. (b) *h*2 = 1.5 μm, *h*1 = 1.3, 1.5, 1.7 and 2.0 μm, respectively.

Furthermore, the effects of geometric parameters on single polarization properties are discussed. It is defined that the confinement loss of TM mode is more than 100 dB/cm and the confinement loss of TE mode is less than 1 dB/cm within an effective bandwidth. The confinement loss is controlled by *h*1 and *h*2. Fig. 5(a) shows wavelength dependence of confinement loss on *h*2. When *h*1 = 1.3 μm is fixed, the confinement loss and the bandwidth decrease with increasing *h*2 from 1.5 μm to 2.0 μm. At the first resonances wavelength, the confinement loss of TM mode decreases from 139.5 dB/cm to 111.1 dB/cm. At the second resonances wavelength, the confinement loss of TM mode decreases from 155.3 dB/cm to 86.8 dB/cm and the confinement loss of TE mode decreases from 0.95 dB/cm to 0.72 dB/cm.

Wavelength dependence of confinement loss on *h*1 is shown in Fig. 5(b), when fixing *h*2 = 1.5 μm, the confinement loss and the bandwidth decrease with increasing *h*1 from 1.3 μm to 2 μm. At the first resonances wavelength, the confinement loss decreases from 139.5 dB/cm to 71.3 dB/cm and the confinement loss of TE mode decreases from 0.96 dB/cm to 0.65 dB/cm. At the second resonances wavelength, the confinement loss decreases from 155.3 dB/cm to 127.6 dB/cm. Specially, it is found that the two resonances wavelengths are not shifted when changing *h*1 and *h*2, moreover, when *h*1 =1.3 μm and *h*2=1.5 μm, the proposed fiber maintain single polarization within a broadband as shown in Fig. 5(a) and (b).



Fig. 6. Spectra of the confinement loss with various thicknesses of gold films.

The resonance wavelength is determined by the gold-dielectric stacking layer, including nanogold film and dielectric layer. To ensure the robustness of the fiber, the thickness of the gold films needs to be more than 45 nm []. The wavelength dependence of confinement loss on thicknesses of the nanogold layers is characterized in Fig. 6. The both peak wavelengths move towards longer wavelengths and the loss peaks become wider when increasing thicknesses of nanogold film from 50 nm to 55 nm. The first resonances wavelength moves from 1.21 μm to 1.26 μm and the second resonances wavelength moves from 1.31 μm to 1.41 μm. The both of resonances wavelengths have red-shifted. The red-shift phenomenon is also reflected in the reference [12]. The confinement losses of TM mode at the two resonance wavelengths decrease from 139.5 dB/cm to 114.5 dB/cm and from 155.3 dB/cm to 150.2 dB/cm, respectively. As the thickness of the gold films increases, the confinement loss of TE mode increases more and more rapidly.

The effect of dielectric layers thicknesses on the confinement loss is characterized in Fig. 7. The thicknesses of dielectric layers on the both sided of the fiber core are described by *h*d1 and *h*d2, respectively. As shown in Fig. 7(a), at the first resonances wavelength the confinement loss increases with increasing *h*d1 from 0.8 μm to 1.1 μm and fixing *h*d2 = 1.7μm. The first resonances wavelength shifts from 1.10 μm to 1.21μm. Meanwhile, the second resonances wavelength does not shift and the confinement loss increases a little. When *h*d2 = 1.7 μm and *h*d1= 1.1 μm, the proposed fiber can operate in a broadband covering 1.17 ~ 1.42 μm. The effect of *h*d2 on the confinement loss is characterized in Fig. 7(b). With increasing *h*d2 from 1.4 μm to 1.7 μm and fixing *h*d1= 1.1 μm, the second resonances wavelength shifts toward 1.31 μm and the confinement loss increase. Meanwhile, the first resonances wavelength is not shifted and the confinement loss decreases. In order to obtain high confinement loss of TM mode and low confinement loss of TE mode at 1.31 μm, *h*d2 should be selected to be 1.7 μm.





Fig. 7. Spectra of confinement loss with various thicknesses of dielectric layer.

The wavelength dependence of confinement loss on the refractive index of dielectric layer is shown in Fig. 8. The both of resonances wavelengths move towards longer wavelengths and the both of confinement losses at the resonance wavelengths increase with increasing the refractive index of dielectric layer from 1.435 to 1.438. Furthermore, the distance between the two resonance wavelengths also increases with increasing the refractive index of dielectric layer.



Fig. 8. Spectra of the confinement loss with various refractive index *n*d of dielectric layer.

The ER and the insertion loss (IL) can represent the performance of single polarization fiber, the ER is defined as [23]

 **(5)**

The IL of the TE mode can be represented as [24]

 **(6)**

where *P*out (*x*) and *P*out (*y*) are the *x* component and *y* component of *P*out(*x*,*y*), respectively. *P*out(*x*,*y*) represents output power, which is defined as [23-24]

 **(7)**

where *P*in (*x*,*y*) represents input power, *P*in (*y*) is the y component of *P*in (*x*,*y*), the confinement loss is expressed as *α* (*x*,*y*), the length of single polarization fiber is *L*.





Fig. 9. Spectra of ER (a) and insertion loss of the TE mode (b) at a fiber length of L = 2.5 mm.

The IL of the TE mode and the ER of the fiber are shown in Fig. 9, when the length of the optical fiber is *L*=2.5 mm. In Fig. 9(a), the ER shows a fluctuating state covering a wide band of 1.0~1.5 μm, the ER achieves a maximum value 38.8 dB at *λ* = 1.31 μm. The optical fiber can operate in single-polarization from 1.17 μm to 1.42 μm, when defining the wavelength region whose ER exceeds 25dB is the effective bandwidth of the optical fiber. In Fig. 9(b), the trend of the insertion loss is similar to the ER. When the fiber operates in a broadband covering 1.17 ~ 1.42 μm, the IL of the TE mode does not exceed 0.25dB.

For the proposed fiber, the operating bandwidth is approximately twice than the fiber polarizer in the reference [11]. For the tunable polarizers, in order to operate in broadband some tunable parameters have to be controlled such as temperature or voltage [8]. Compared with the polarizers described above, the proposed broadband single-polarization optical fiber can extend the polarization bandwidth, maintain a high extinction ratio, reduce dependence on the tunable parameters.

**4. CONCLUSIONS**

In conclusion, a new scheme of broadband single-polarization optical fiber based on SPR has been proposed and studied numerically in detail. By integrating nanogold/dielectric layer in two air holes, the single-polarization, broadband, high extinction ratio can be obtained simultaneously. The geometric effects on the polarization properties have been studied numerically. The results show that the single-polarization at high extinction ratio can operate in a broadband covering 1.17 ~ 1.42 μm. The effective bandwidth is 250 nm. When the proposed fiber length is 2.5 mm, the ER exceeds 25 dB and the IL is less than 0.25 dB within the broadband. At *λ* = 1.31 μm, the ER can be achieved 38.8 dB. The modified SPR fiber has promising applications in high-quality fiber-integrated polarizers.

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