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Regular Articles

Groove micro-structure optical fiber refractive index sensor with nanoscale gold film based on surface plasmon resonance

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ABSTRACT

A groove micro-structure optical fiber refractive index sensor with nanoscale gold film based on surface plasmon resonance (SPR) is proposed and analyzed by the finite element method (FEM). Numerical results show that the average sensitivity is 15,933 nm/refractive index unit (RIU) with the refractive index of analyte ranging from 1.40 to 1.43 and the maximum sensitivity is 28,600 nm/RIU and the resolution of the sensor is 3.50×10^{-8} RIU. The groove micro-structure optical fiber refractive index sensor do some changes on the D-shaped fiber sensor, compared with conventional D-shaped fiber sensor, it has a higher sensitivity and it is easier to produce than the traditional SPR sensor.

1. Introduction

Surface plasmon resonance (SPR) technology is a new technology developed in 1990s, it is widely used in the field of sensing. When the light is incident on the metal surface and its frequency matches the free electron frequency of the metal surface, SPR phenomenon occurs [1–3]. Micro-structure optical fiber have many excellent characteristics, such as low loss, large mode area, high birefringence [4–9]. And many devices have been designed and applied based on micro-structured optical fibers, including sensors, wavelength division multiplexer, polarization splitters, polarization filters lasers and so on [10–13]. In recent years, micro-structured optical fiber sensors based on SPR have attracted wide attention due to its high sensitive performance.

In order to realize the micro-structure optical fiber SPR sensor, the core-guided light needs to be leaked to the metal surface. There are several methods to achieve. The usual methods are making metal film on the inner surface of optical fiber air holes or fill metal wires, through these designs, optical fiber SPR sensor can be realized. However, because the coating thickness is uneven, the manufacture of these designs is very challenging. Therefore, the D-shaped micro-structure fiber sensor is proposed, and the D-shaped photonic crystal fiber SPR sensors have a large number of applications in the refractive index of analyte. In 2012, a D-shaped photonic fiber sensor based on SPR have been proposed by Tian et al. The sensitivity can reach a value of 7300 nm/RIU. A D-shaped sensor with the sensitivity of 7700 nm/RIU was presented by Gangwar et al. in 2016 [14,15].

In this paper, some changes are made on D-shaped SPR sensor. A groove micro-structure optical fiber refractive index sensor with nanoscale gold film based on surface plasmon resonance has been proposed. The average sensitivity is 15,933 nm/RIU with the refractive index of analyte range from 1.40 to 1.43 and the maximum sensitivity is 28,600 nm/RIU. The fabrication of grooved Micro-structure optical fiber can be prepared by AFM nano-machining technology [16].

1.1. Structure and theoretical modeling

The cross section of the groove micro-structure optical fiber sensor is shown in Fig. 1. As we can see, the micro-structure optical fiber consists of two layers of air holes. The diameters of big air holes are $d_1 = 2\,\mu m$ and the diameters of small air holes are $d_2 = 1.2\,\mu m$. The lattice pitch is $\Lambda = 3\,\mu m$. There is a groove in the upper part of the fiber. The width of the groove is $d_x = 3\,\mu m$. The distance from the center of the optical fiber to the groove is $h = 4\,\mu m$. A gold film covers the bottom of the groove, and the thickness of the gold film is $t = 35$ nm.

The finite element method (FEM) is used to analyze the characteristics of the micro-structure optical fiber SPP sensor by COMSOL Multiphysics software. A perfect matched layer and scattering boundary condition (SBC) are used to absorb energy. In the Fig. 1, the red region represents the PML layer, the analyte liquid is filled in the orange area, the background material is pure silicon, which is the gray part of the Fig. 1. Its chromatic dispersion can be calculated by the Sellmeier equation [17], which is defined as:

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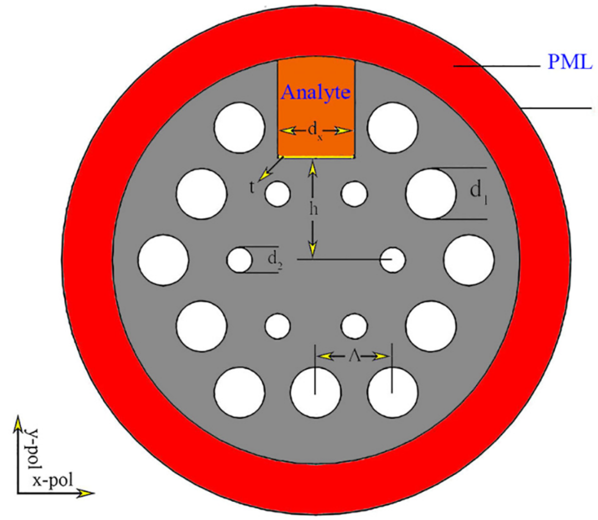


Fig. 1. The cross section of the groove micro-structure optical fiber sensor.

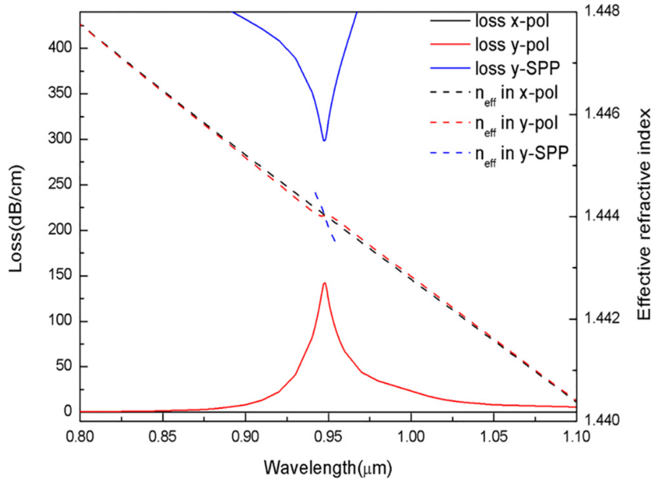


Fig. 2. The loss and effective refractive index of the proposed sensor with the analyte RI n = 1.42.

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{a_i\lambda^2}{\lambda^2 - b_i^2} \tag{1}$$

where λ is the wavelength of incident light, whose unit is micrometer. And $a_1 = 0.6961663$, $a_2 = 0.4079426$, $a_3 = 0.8974794$, $b_1 = 0.0684043$ μm, $b_2 = 0.1162414$ μm, $b_3 = 9.896161$ μm. Eq. (1) is valid for the wavelength lying between 0.37 μm and 2.2 μm.

Table 1
Changes of the loss peak and resonance wavelength with different analyte RIs.

RI	1.40	1.41	1.42	1.43
Wavelength (nm)	756	833	948	1234
Loss (dB/cm)	33.22	57.56	142.34	87.72

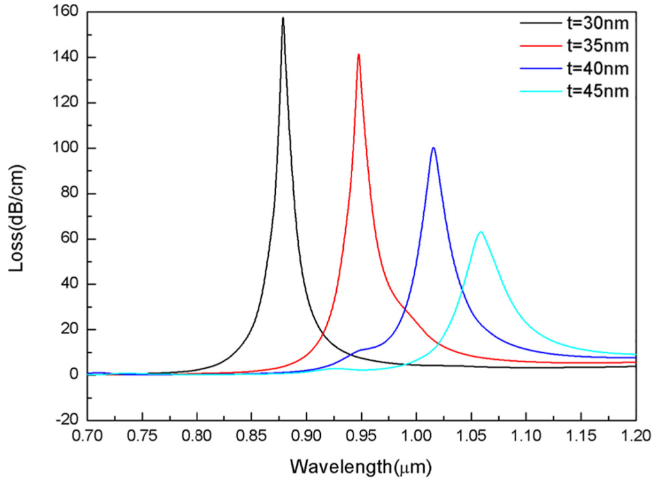


Fig. 4. The loss spectrum changes with different thickness of gold film when the RI of the analyte is n = 1.42.

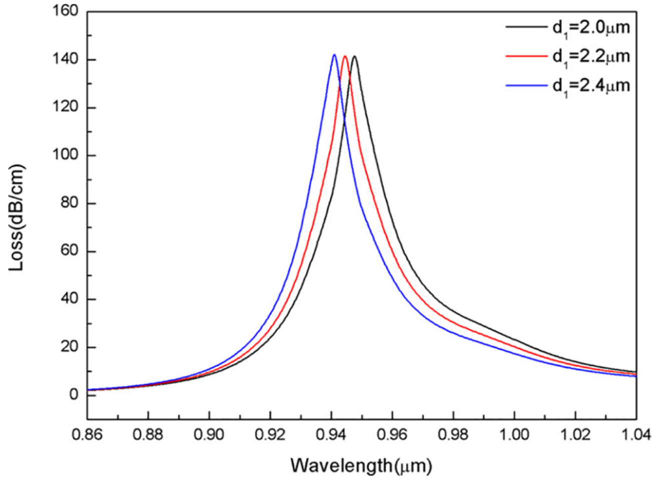
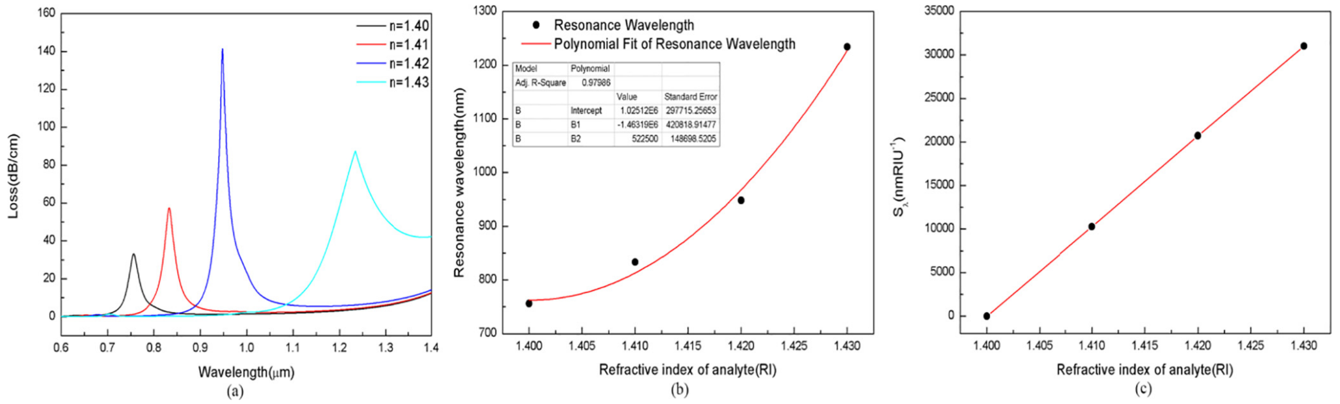


Fig. 5. The loss spectrum changes with the large holes diameters d_1 = 2.0 μm, 2.4 μm and 2.6 μm when the RI of analyte n = 1.42.



(a) (b) (c)

Fig. 3. (a) The changes of the loss peak and (b) the numerical fitting curve of the resonance wavelength and (c) the sensitivity curve with different analyte RIs.