Multi-hole Optical Fiber Surface Plasmon Resonance Sensor

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Abstract A microstructured-fiber containing six large air holes is proposed to construct the surface plasmon resonance (SPR) sensor. The finite element method is used to analyze characteristics of the surface plasmon resonance sensor. The effects of the thickness of metal films, pitch between air holes, diameter of air hole, and refractive index of liquid on the resonance wavelength are elucidated. The results show that the resonance wavelength is sensitive to the thickness of metal film and refractive index of liquid, while the resonance wavelength doesn’t change basically when the pitch between air holes and diameter of air holes vary. The proposed surface plasmon resonance sensor exhibits high sensitivity up to 10^-4.

1. Introduction
Surface plasmon resonance (SPR) biosensor was driven by modern physics and biology. Optical fiber SPR biosensors are undoubtedly required for the future development of miniaturized and compact SPR sensor systems. Fiber SPR sensors have some advantages over the conventional bulk SPR sensors, such as small size, light weight, remote sensing, multiplexing possibilities, and high capacity matched with the optical fiber communication system. As a result, optical fiber SPR sensors have generated considerable interests in the field of SPR sensors [1-4]. Optical fibers led to improve analysis method and signal measurement in long distance real-time multichannel. The detection and identification of biological analytes and biophysical analysis of biomolecular interactions are obtained by measuring resonant wavelength shift or change of light intensity from the output at a fixed wavelength or half-width of the power spectrum. Recently, wide applications of microstructured fiber in optical sensor and communication have been rapidly propelled by its mature fabrication process [5-7]. In 2006, Sazio [8] proposed a solution to fabricate homogeneous metallic films on inner surface of air holes in microstructured fibers using high-pressure microfluidic chemical deposition technique, which made it possible to design SPR sensor in air-hole microstructured fiber. Subsequently, many theoretical and experimental results were reported in the literatures [9-12]. M. Hautakorpi proposed a SPR sensor configuration based on coating the holes of a three-hole microstructured optical fiber, and added a low refractive index dielectric layer around the fiber core to confine most light within the fiber core, and obtained 10^-4/RIU sensitivity for aqueous analytes [11]. A. Hassani proposed a photonic crystal fiber (PCF) SPR sensor, in which phase matching between a surface plasmon mode and a core mode can be enforced by introducing air-filled microstructure into the fiber core.

Simple multi-hole optical fibers were proposed to construct SPR sensors in the present paper. The effects of fiber parameters on the properties of SPR sensor were analyzed using the finite element method.
2. Sensor structure
It is well-known that only at higher frequencies plasmon refractive index becomes high enough as to match that of a waveguide core mode and consequently simple structured microstructured fibers can also be applied to be SPR sensor. Similar to optical fiber structure in Ref. [13], we designed one type of multi-hole fiber-based SPR sensor, illustrated in figure 1. The solid silica core was surrounded by six large air holes, where the diameter of air holes is \( d \), the distance between two adjacent air holes is \( \Lambda \) and the thickness of gold films covered on inner surfaces of air holes is \( d_m \). Next, we consider the performance of multi-hole optical fiber SPR sensor, launching the measured liquid with the refractive index \( n \) into air holes.

![Figure 1](image1)

**Figure 1** Structure of multi-hole fiber-based SPR sensor.

3. Numerical results and analysis
Considerable numerical methods have been adopted to conduct theoretical research of optical fiber and optical components. The finite element method is pretty powerful to research arbitrarily shaped optical fiber. Therefore, the properties of multi-hole optical fiber SPR sensors were calculated with the finite element method. Sellmeier equation described the dispersion of silica \(^{[14]}\) and the relative permittivity of gold was found in Ref. 15.

Firstly, let us consider how the SPR resonant peak depends on the thickness of gold film. Supposed that the refractive index of liquid is 1.33, the distance of two air holes is \( \Lambda = 5\mu m \) and the diameter of air holes is \( d = 4.3\mu m \), the loss spectrum of the fundamental mode in the fiber is shown in figure 2 for different thick gold films with 30nm, 40nm and 50nm. Several resonances occur in the whole wavelength range due to asymmetrical feature of gold films to the fiber core, which is in good agreement with the conclusion in Ref. [16]. The resonant peak in the visible range moves to long wavelength as the thickness of gold film increases while the resonant peak in the near-infrared range moves to short wavelength. It is also observed that relative large loss in the nonresonant near-infrared

![Figure 2](image2)

**Figure 2** Gold layer thickness dependence of loss spectra of the fundamental mode.
range can not been ignored. Though the resonance occurs in the near-infrared range, they can hardly be detected due to large loss in the nonresonant range. In the following parts, the properties of SPR in the visible range are mainly investigated. The loss spectrum of multi-hole fiber without gold films in figure 3 exhibits that losses in the whole visible range are low and light can mostly be confined into the fiber core. When the thickness of gold films is 50nm, the field distribution of resonant wavelength 0.59µm is described in figure 4. The field attenuates away from the interface between the liquid and gold film, however, the field is enhanced on one side of gold film close to the liquid owing to SPR.

![Image of loss spectrum](image)

**Figure 3** Loss spectra of the fundamental mode for the fiber without the gold film.

![Image of mode profile](image)

**Figure 4** Mode profile at 0.69µm wavelength (a) and |E| on the x-axis (b).

The responses of SPR to different measured liquid are also considered. Here, the thickness of gold film is 50nm, $\Lambda = 5\mu m$, $d = 4.3\mu m$. Loss spectra of the fundamental mode are shown in figure 5 when air holes are filled with different refractive index liquid samples. The resonant wavelength moves upwards and losses at the resonant peak increase and the half-width of the power spectrum is broadened resulting from the increasing refractive index. The increasing refractive index of measured liquids leads to small difference between fiber core and ambient medium, resulting in decreasing effective refractive index of fundamental modes. Thus, the resonant peak shifts to long wavelength. Therefore, the refractive index change of ambient medium can be measured by monitoring the power at a fixed wavelength or shift of resonant wavelength.
The air holes will exert effects on SPR and the calculated results are shown in figure 6. The thickness of gold film is 50nm, the refractive index of liquid is 1.33. The diameter of air holes and the distance between two air holes are analyzed separately. Large diameter of air holes widens the resonant peak and brings about increasing loss, but the resonant peaks do not change their position. The effect of the distance between two air holes on the resonant peak is similar to that of air hole diameter. When the distance increases, the resonant peak is also kept unmoved, however, the loss at the resonance decreases.

One of the most important parameters of SPR sensors is its sensitivity. When the power at a fixed wavelength is measured to evaluate the performance of sensors, the sensitivity parameter can be expressed as \[ S = \frac{\Delta \alpha / \Delta n}{\alpha_a} \] (1)

where \( \alpha_a \) denotes the loss of optical fiber at \( n = a \). For the sensor of length \( 1/\alpha_a \), Eq(1) is a good approximation when the refractive index of liquid in air holes changes slightly. At \( n = a = 1.33 \), the sensitivity curve is plotted in Figure 7. If one assumes that 1% change in the transmitted power can reliably be detected, \( 1.4 \times 10^4 \) change of refractive index (for \( S = 70 \)) could be detected with this sensor. The proposed multi-hole optical fiber SPR sensors can treat weak signal detection indicating that its sensitivity is comparable to that of conventional SPR sensors.
4. Conclusions
The SPR sensor was proposed on basis of multi-hole optical fiber containing six air holes. The finite element method was utilized to analyze effects of the geometrical and physical parameters on the resonance. The results reveal that the resonant wavelength is sensitive to the thickness of gold film and the refractive index of ambient medium while the peak wavelength of the resonance is insensitive to the diameter of air holes and distance between two air holes. As a result, the measurement of refractive index can be achieved based on monitoring the power in the resonant vicinity and the wavelength change of the resonant peak. The microstructured fiber SPR sensor proposed has high sensitivity up to $10^{-4}$.

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