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Fabrication and characterization of a refractive index Sensor based on SPR in an etched plastic optical fiber

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Abstract

The paper presents a refractive index sensor based on surface plasmon resonance (SPR) in etched plastic optical fibers (POF). The etching approach adopted here ensures the geometrical circular symmetry of the optical fiber. The influence of design parameters namely, residual fiber thickness and sensing length on the sensitivity of the proposed sensor was investigated. A lower value of residual fiber thickness and shorter sensing length result in greater sensitivity of the sensor. The proposed sensor provides numerous advantages such as simplicity in design, low cost of fabrication, higher mechanical strength, and ease of handling compared to other SPR structures.

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1. Introduction

Surface plasmon resonance (SPR) has attracted much attention for the past two decades due to its high sensitivity, label-free, non-destructive and real-time detection. Optical sensors based on SPR technique are capable of detecting small changes in the refractive index (RI) of the medium surrounding the sensor’s surface. The physical principles behind this phenomenon have been described elsewhere [1, 2].

Fiber-optic based SPR sensor structures have been in the limelight recently to enhance the performance of the sensor. Structures such as side-polished, etched and tapered fibers are some of the physical structures developed to achieve this [3-9]. A typical SPR fiber-optic sensor is normally made from silica fibers either single-mode fibers (SMF) or multi-mode fibers (MMF), but these fibers are still considered cost-prohibitive for cost-sensitive applications. So for low-cost applications, plastic optical fiber (POF) offers a good alternative. Apart from that, POFs are attractive due to their easy manipulation, great numerical aperture, large diameter, and excellent flexibility. Therefore, SPR sensors based on POFs have a number of advantages compared to those made from standard silica optical fibers including simplicity of design, low cost of fabrication and flexibility [10-12]. Most of the reported SPR sensors based on POF are made by side-polishing the polymer cladding which damages the circular symmetry of the optical fiber with consequent polarization dependent losses [13]. The circular asymmetry also reduces field interaction strength as it limits field interaction cross-section. In addition, the process of side-polishing is mechanically complex and the resulting side-polished fibers are difficult to splice resulting in additional losses [14-15]. In this paper we report the fabrication and characterization of an RI sensor based on SPR technique in etched POFs. The implemented cladding reduction technique preserves the circular symmetry of the POF. The etched part is then coated with a thin layer of gold. The resonance wavelengths are determined by placing sensing solutions of different RIs around the probe. The sensor is based on wavelength interrogation method. We studied the influence of residual fiber thickness and sensing length on the performance of the SPR sensor.

2. Experiments

2.1. Fabrication of probe

The fiber optic SPR probe was fabricated on a plastic optical fiber with a PMMA core diameter of 920 – 1040 μm and fluorinated polymer cladding diameter of 940 - 1060 μm. The RI of the core is 1.49 and the numerical aperture is 0.50. About 10 to 20 mm length of the outer jacket was removed by a specialized stripper and the polymer cladding was removed using chemical etching by dipping the stripped part in a concentrated acetone solution (purchased from Merck) for some time. The etched POF was then quickly re-wiped with acetone and rinsed with de-ionized water to remove any residuals. The etching method applied in our experiment ensures the cylindrical geometry of the optical fiber as shown in Fig. 1. The figure shows a cylindrical cross section of the etched fiber maintained at around 975 μm (image taken via scanning electron microscope). Typical total length of fiber used was 20 to 30 cm. Both ends of the fiber were polished with polishing papers to enhance the coupling of light in the fiber. Cleaned unclad portion of the fiber was coated with a thin film of around 50-55 nm thickness of gold (Au) using sputter coater (Emitech K575X). The sensing probes were affixed horizontally inside the sputter chamber and rotated to produce symmetric coating. The thickness of the depositing film on the unclad fiber can be determined by controlling the sputter current, pressure of evaporation, and sputtering time.

2.2. Experimental Set-up

The experimental set-up for the characterization of the sensor is shown in Fig. 2. The setup consists of a white light source (Ocean Optics HL-2000, Tungsten Halogen Source) illuminating the optical fiber system, fiber optic connectors, the proposed SPR sensor affixed in a u-groove platform, and a spectrometer (Ocean Optics USB4000-VIS-NIR). A series of aqueous NaCl (sodium chloride) solutions were papered to be used as sensing solutions. The RI of these solutions ranges from 1.33 to 1.37 was determined using ATAGO pocket refractometer at room temperature, 25 °C. The deployed white light source exhibits a wavelength emission ranges from 360 nm to 2000
nm. The spectrometer was connected to a computer installed with the SpectraSuite software to calculate and plot the transmitted SPR spectra in a wavelength range from 350 nm to 1100 nm.

Fig. 1. Cylindrical geometry of the etched POF

Fig. 2. Schematic diagram of the experimental setup

3. Results and Discussion

3.1. Background

An SPR spectrum is produced by taking the ratio between the transmission spectrum of the standard medium (such as air) and that of the sensing medium surrounding the sensing probe. The position of the minimum with respect to wavelength is called the resonance wavelength or the SPR wavelength ($\lambda_{res}$). An increase in the RI of the sensing medium results in a shift in the resonance wavelength towards the right side or red shift denoted as $\Delta \lambda_{res}$.

Sensitivity is one of the main performance parameters usually used to describe the performance of SPR sensors. The sensitivity has been defined as the change in resonance wavelength per unit change in the refractive index of the sensing medium and it’s given by:

$$S_{\lambda} = \frac{\Delta \lambda_{res}}{\Delta n_s}$$  \hspace{1cm} (1)

where $\Delta \lambda_{res}$ is the shift in resonance wavelength and $\Delta n_s$ is the change in RI of the surrounding medium. It can be seen from Eq. (1) that the sensitivity highly depends on the amount of shift in resonance wavelength in response to changes in the RI of sounding medium which is influenced by the sensor’s design parameters.

To study the response characteristics of the sensor, SPR spectra were obtained for the SPR probe immersed in measuring liquids with different refractive indices (RIs). As can be seen from Fig. 3(a), the minimum transmitted power in the spectrum at RI of 1.3353 is obtained at 591 nm. Furthermore, increasing the refractive index of the sensing medium shifts the spectral curve towards longer wavelengths. Therefore, we can use the proposed sensor to
detect the resonant wavelength to measure RI changes in aqueous solutions. It is found that as the refractive index of the sensing medium increases the resonance wavelength increases as shown in Fig. 3(b).

Fig. 3. (a) SPR spectra at residual thickness of 974 μm and sensing length of 20 mm with Au thickness of 55 nm for refractive indices varying from 1.3353 to 1.3653 in steps of 0.01 and (b) variations of the shift in resonance wavelength with the refractive index of the measuring solution.

3.2. Residual Thickness

The amount of residual thickness of the POF after etching, \( d \) is dependent on the length of the time of immersion in acetone and is monitored by measuring the fiber diameter with an optical microscope fitted with camera. A schematic diagram of the POF before and after etching highlighting the residual thickness parameter is shown in Fig. 4.

Fig. 4. Schematic diagram of the POF before and after etching.

To investigate the effect of residual thickness, \( d \) on the SPR resonance characteristics, we used a set of three sensors made of 10 mm etched POF with different values of \( d = 964, 974, \) and 994 μm respectively coated with 55 nm of gold. The RI of the sensing medium is changed from 1.3353 to 1.3453. The SPR spectra are shown in Fig. 5 (a-c). As can be seen from Fig. 5, the shift in resonance wavelength increases with the decrease of residual fiber thickness, whereas the resonance width and depth depend weakly on the parameter \( d \). The SPR sensitivity increased from 1424 nm/RIU to 1600 nm/RIU when changing the residual fiber thickness from 994 μm to 964 μm, see Fig. 6.
Fig. 5. (a-c) SPR transmitted spectra at different residual thicknesses, \( d \) with Au thickness of 55 nm; the RI of the ambient is changed from 1.3353 to 1.3453. The length of the sensing region was fixed at 10 mm.

Fig. 6. Influence of residual thickness of the POF on the sensitivity. Au thickness was fixed at 55 nm and the sensing length at 10 mm.

3.3. Sensing Length

Fig. 7. (a) Comparison of SPR transmitted spectra for two different sensing lengths (10 and 20 mm) when the RI of the surrounding medium was varied from 1.3353 to 1.3553. The diameter of the POF is 974 \( \mu \text{m} \) and the gold thickness is 55 nm; and (b) relationship between the sensitivity and refractive index of measuring solutions for the two configurations.
Fig. 7(a) Shows the SPR spectra obtained for sensors having two different sensing lengths, 10 mm and 20 mm coated with 55 nm of gold. The RI of the sensing medium is changed from 1.3353 to 1.3553 and the fiber diameter was 974 μm. It can be seen from the figure that the resonance depth is highly influenced by the sensing length. Increasing the sensing length results in deeper SPR curves but it also decreases the shift in resonance wavelength. This is due to the increase in the number of reflections taking place in the longer sensing region of the optical fiber. Fig. 7(b) depicts the influence of the sensing length on the sensitivity of the sensor.

4. Conclusions

We presented an analysis of an SPR refractive index sensor based on etched plastic optical fibers. We have shown that the etching technique implemented preserves the cylindrical geometry of the POF. We systematically investigated the impact of different design parameters on the performance of SPR optical fiber sensors based on POFs. A lower value of residual fiber thickness results in a greater sensitivity of the sensor. The sensing length greatly influences the depth of the resonance dips. Shorter sensing lengths improve the sensitivity at the expense of a drop in the resonance depth. We achieved sensitivity as high as 1600 nm/RIU through etching off the cladding along a length of 10 mm from the middle of a POF leaving a residual thickness of around 964 μm.

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References