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# Refractive index sensor based on SPR in symmetrically etched plastic optical fibers

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ABSTRACT

In this work, we fabricate and characterize a surface plasmon resonance sensor based on etched plastic optical fibers. The etching method used ensures the geometrical circular symmetry of the optical fiber. The sensor was tested by immersion in sensing solutions of different refractive indices and the transmittance is measured using a spectrometer system. The sensor performance in terms of sensitivity and detection accuracy can be controlled by adjusting the design parameters such as gold thickness, residual fiber thickness, and sensing length. We realized a sensitive, cost-effective, and robust sensor suitable for aqueous media sensing by reducing the overall fiber thickness up to 964 μm with a sensing length of 10 mm coated with a thin gold film of around 55 nm. The demonstrated sensor exhibits a sensitivity of 1600 nm/RIU and a full width at half maximum of around 154 nm.

## 1. Introduction

Over the past two decades, the deployment of optical fibers as surface plasmon resonance (SPR) devices has received a lot of attention due to numerous advantages brought by optical fibers such as the high level of miniaturization of SPR devices and sensing capability in inaccessible locations. Since then, a great effort has been made to boost the performance of the fiber optic SPR sensors [1–3]. Generally, for SPR sensors, an evanescent field is needed to generate surface plasmon waves (SPW) at the interface of a metal layer and the surrounding medium. A number of different structures of fiber optic SPR sensors have been proposed and developed for this purpose. Some examples of these structures include partially unclad [3], side-polished [4], and tapered optical fibers [2,5,6]. Photonic crystal fiber [7], D-shaped optical fiber [8], and fiber grating SPR sensors [9] have also been reported to enhance the reliability of fiber optic SPR sensors.

Although fiber-optic SPR sensors are typically made from all-silica fibers, these fibers nevertheless remain cost-prohibitive for cost-sensitive applications. Plastic-clad silica fibers (PCS) provide a lower cost option but they are stiff and difficult to handle due to their large silica core [10]. Therefore, plastic optical fibers (POF) offer an attractive alternative for low-cost applications. They also provide other advantages for SPR sensors applications including easy manipulation, large numerical aperture and diameter, and excellent flexibility [11,12]. However, the spectral width of the resonance spectrum in SPR sensors based on POF is broader than those using silica fibers due to the large number of guided modes. POF is also prone to damage by certain chemicals such as acidic and organic solvents which remains a key challenge in sensor fabrication and a major limitation to its applications.

Most of the reported SPR sensors based on POF are fabricated by side-polishing the polymer cladding. For example, Cennamo et al. [11,12] used a classic fabrication technique by side-polishing the cladding of a POF along half the circumference making a D-shaped structure. However, polishing the plastic fiber destroys the circular symmetry of the optical fiber and causes additional

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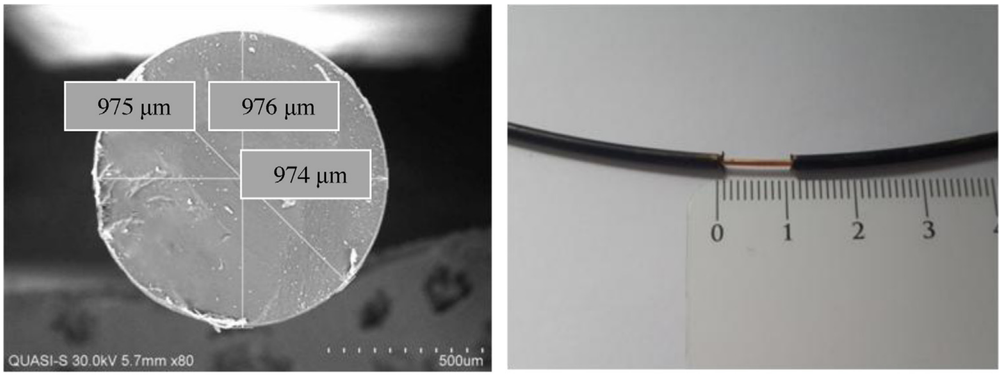

(a) (b)

**Fig. 1.** (a) Cylindrical cross section of the etched fiber. (b) Photo of the actual fabricated sensor.

polarization dependent losses [13]. The circular asymmetry in such structures also limits field interaction cross-section, which in turn, reduces field interaction strength. Additionally, the process of side-polishing is mechanically complex and the resulting side-polished fibers are difficult to splice leading to extra losses [14,15].

In this paper, we report the fabrication and characterization of a refractive index (RI) sensor based on SPR in etched POF. Our fabricated sensor exhibits high sensitivity and detection accuracy, robustness, and low cost compared to other fiber-based SPR sensors which utilize complex fabrication and alignment techniques or costly optical fibers instead. We implement a cladding reduction approach using chemical etching with a precise control of the immersion time to control the fiber diameter while preserving the cylindrical geometry of the optical fiber. The etched area of the POF is then coated with a thin layer of gold (Au) using a sputter coater machine. The resonance wavelengths are determined by placing a series of aqueous solutions made with different refractive indices around the sensing probe. We experimentally investigate the influence of gold thickness, residual fiber thickness, and sensing length on the performance of the fabricated sensor in terms of its sensitivity and detection accuracy.

## 2. Experiments

The fiber optic SPR probe was fabricated on a POF with a poly(methyl methacrylate) (PMMA) core diameter of 920–1040 µm and 20-µm fluorinated polymer cladding. The RI of the core is 1.49 and the numerical aperture is 0.50. SPR phenomenon requires the interaction of the evanescent field of photons inside the fiber with the SPWs in the metal layer coating on the fiber. In order to achieve that, the buffer and cladding of the fiber must be removed along the sensing region. About 10–20 mm length of the outer jacket was removed by a specialized stripper and the polymer cladding was chemically etched by dipping the stripped part in a concentrated acetone solution purchased from Merck. The etched area was then rinsed with deionized water to remove any residuals. The etching method used in our experiment preserves the cylindrical symmetry of the optical fiber as shown in Fig. 1 (a). The figure shows a cylindrical cross section of the etched fiber maintained at around 975 µm (image taken by a scanning electron microscope). A photo of the actual fabricated sensor is depicted in Fig. 1 (b). 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. Microscopic images showing the residual thickness of the POF made at different dipping times are given in Fig. 2. Total length of fiber used was around 30 cm and both ends of the fiber were polished with polishing papers to enhance the coupling of light into the fiber. Cleaned unclad portion of the fiber was coated with a thin film of gold using a sputter coater. The sensing probes were affixed horizontally inside the sputter chamber and rotated to produce symmetric coatings. The thickness of the depositing film was determined by controlling the sputter current, pressure of evaporation, and sputtering time.

The experimental setup is shown in Fig. 3. The system consists of a white light source (Ocean Optics HL-2000, wavelength range: 360 nm to 2000 nm), fiber optic connectors, the proposed SPR sensor mounted in a u-groove platform, and a spectrometer (Ocean Optics USB4000-VIS-NIR). The spectrometer is connected to a computer installed with SpectraSuite software to calculate and plot the transmitted SPR spectra in a wavelength range from 350 to 1100 nm. The transmitted SPR spectrum is the sensor response in terms of its normalized transmission with respect to wavelength. The normalized transmission $T_\lambda$, as a percentage relative to a standard substance (e.g., air) at wavelength $\lambda$ can be estimated by SpectraSuite using the following equation [6]:

$$\%T_\lambda = \left((S_\lambda - D_\lambda)/(R_\lambda - D_\lambda)\right) \times 100\% \tag{1}$$

where $S_\lambda$ is the sample intensity at wavelength $\lambda$ when the sensing solution is present, $D_\lambda$ is the intensity of the dark spectrum (when no light passes through the fiber) and $R_\lambda$ is the reference intensity before adding any sample.

A series of aqueous solutions made from NaCl (sodium chloride) in water dissolved in dionized water was papered to be used as sensing solutions. The RI of these solutions was measured using an ATAGO pocket refractometer at room temperature (i.e., 25 °C) and found to be ranging between 1.33 and 1.37.

## 3. Performance parameters

The performance of SPR sensors is typically evaluated using two main parameters: sensitivity and detection accuracy which both should be kept as high as possible to realize higher performance. The sensitivity has been defined as the change in resonance wavelength per unit change in the refractive index of the sensing medium and it is given by [16]

$$S_{\lambda_n} = \Delta\lambda_{res}/\Delta n_s \tag{2}$$

where $\Delta\lambda_{res}$ is the shift in resonance wavelength and $\Delta n_s$ is the change in RI of the surrounding medium. According to Eq. (2), the sensitivity improves as the shift increases. Studies concerning the sensitivity of the SPR sensors aim to enhance the coupling between the evanescent field waves and SPW which depends on

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