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Improvement of the sensitivity of the surface plasmon resonance sensors based on multi-layer modulation techniques

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ABSTRACT

In this study, a multi-layer modulation technique was used in an SPR optical fiber sensor to enhance the sensitivity of the SPR optical fiber sensor by adjusting the SPR resonant wavelength. The sputtering process deposited 20 nm of TiO_2, 11 nm of SiO_2 and 30 nm of gold film on the material surface to change the refractive index. Regardless of the different refractive index solutions (1.32 and 1.36), the sensitivities in wavelength interrogation of the SPR optical fiber with the single gold thin film and multi-layers modulation were 1.08×10^{-5} RIUs and 1.74×10^{-6} RIUs, respectively. The results showed the significant differences between the different refractive index solutions of 1.32 and 1.36 using the 850 nm light source to analyze the SPR optical fiber sensor in real-time. The sensitivities in intensity interrogation of the SPR optical fiber with the single gold thin film and multi-layers modulation were 1.08×10^{-3} RIUs and 1.73×10^{-4} RIUs, respectively, which indicated that the multi-layer modulation techniques could enhance the sensitivity of the SPR optical fiber sensor. The compact size of the multi-layer SPR fiber sensor had a wider detecting range of the refractive index and higher sensitivity, which had the potential for other applications in biological analysis with suitable wavelength.

1. Introduction

Over the past decade, surface plasmon resonance (SPR) has been used in a wide range of chemical and biological sensing applications. SPR is a charge density oscillation that may exist at the interface of two media with dielectric constants of opposite signs, for instance, a metal and a dielectric. The excitation of a surface plasmon wave leads to the appearance of a dip in the measured intensity of reflected light, which must be considered in determining the sensitivity of SPR sensing. The first use of SPR in prism coupling was proposed in 1968 by Kretschmann [1]. In the early years after the basic configuration of the SPR phenomenon by Kretschmann was presented, some attempts were made to develop an SPR sensor based on the optical interaction effect. Since then, surface plasmons have been studied intensively, and their major properties have been assessed [2]. The sensitivity of the SPR sensor is defined as the derivative of the monitored SPR parameter, which can detect the change in the refractive index. Several detection schemes have been demonstrated for SPR prism-based sensors; they include angular interrogation [3], wavelength interrogation [4], and intensity measurement [5].

Compared to the conventional prism-based SPR sensing devices, optical fiber SPR sensors have recently attracted considerable attention with the advantages of the smart structure, small sample volume, low cost and amenability towards remote sensing applications [6]. The optical fiber SPR sensors have proved their good performance (specifically, in terms of sensitivity) and their versatility and they are a very good option to be considered as basis for any kind of chemical and biological sensors [7].

Since Jorgenson and Yee proposed using optical fibers for SPR sensing in 1993, many types of optical fiber sensor have been proposed, including single-mode dip fibers, single-mode D-type fibers, and D-shaped fibers [8]. In recent years, studies of SPR

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sensing systems have focused on the attenuated total reflection geometry obtained by the use of prism-coupling optics. However, those systems of optical fiber sensors need bulky structures as well as complicated signal processing to improve their high sensitivity. Therefore, the side-polished multimode fiber sensor provides a simple structure and system for chemical and biological sensing with high sensitivity in wavelength interrogation [9], and it also shows a high detection limit for biomolecules [10,11]. Time-dependent measurements of SPR optical fiber sensors are important for applications in biosensors and in environmental monitoring, and the sensitivity of intensity measurements with the side-polished fiber sensor has been proved [12,13]. Based on the bimetallic structure to fiber optic absorption sensor, Gupta and Sharma [14] theoretically investigated the performance of the structure in terms of sensitivity of the sensor for a *p*-polarized light source using ray approximation. The results demonstrated that the sensitivity increased as the silver to gold thickness ratio increased. It had been found that the sensitivity was better for the lower off-resonance excitation frequency. Hosoki et al. [15] developed a novel fiber optic surface SPR hydrogen sensor based on hetero-core structured fiber optics with multi-layer films of gold (Au), tantalum pentaoxide (Ta_2O_5) and palladium (Pd) uniformly coated onto a cylindrical cladding surface. The experimental results showed that the sensor with a thin 3 nm Pd film rapidly responded within 15 s to Pd hydride with a sufficiently high sensitivity for detection.

However, most of the current SPR optical fiber sensors employ the 635 nm wavelength for excitation of surface plasmon resonance, which is not suitable for optical fiber communication wavelength (850 nm, 1310 nm and 1550 nm) [10], resulting in decrease of the sensitivity and stability of the SPR optical fiber sensor. In this study, we follow an admittance loci design method to present a novel multi-alternating metal layer film design for the fiber-optic SPR sensor [16,17].

In the previous research [19,20], the double-layer structure of SPR optical fiber sensor had been studied. As compared with the control group side-polished SPR fiber sensor with only one single sensing layer of Au was inefficient in enhancement of sensitivity as adjusted SPR wavelength shifts toward only a certain direction, the additional AZO layer was used to increase the sensitivity of the SPR based sensors for refractive index variation of a testing solution. However, the double-layer structure had shown that there was limitation in the enhancement of the sensitivity, even if they could adjust the resonance wavelength.

This study propose a multi-layer modulation technique in an SPR optical fiber sensor; 20 nm of TiO_2, 11 nm of SiO_2 and 30 nm of gold film were deposited on the material surface to change the refractive index for enhancement of the sensitivity. The SPR resonances in wavelength versus the refractive index from 1.32 to 1.36 were measured by a spectrometer, and the sensitivity of the fiber-optic SPR sensor to the rate of 1.32 and 1.36 was verified by an 850 nm light source system.

2. Materials and methods

2.1. The side-polished SPR optical fiber sensor

The SPR optical fiber sensor consists of a gold thin film and a side-polished structure, as shown in Fig. 1(a). The graded-index multimode optical fiber with a 62.5-μm core diameter and a 125-μm cladding diameter fabricated by Prime Optical Fiber Corporation (POFC) was side-polished to make the SPR optical fiber sensor. For high yield rate polishing processes, a silicon V-groove must be fabricated to hold bare fibers. Thus, we grew the oxides layer on a 4-inch silicon wafer and used photolithography to etch a SiO_2 channel with 25% HF. The V-groove channel was etched by 45.3% KOH, and the channel's length and width were 5 mm and 125 μm, respectively. The multimode optical fiber was mounted on a V-groove holder with a photoresist and monitored by optical microscopy. After the photoresist became hard, we polished these optical fibers which were embedded in the wafer using polishing diamond films with grain sizes of 6 μm, 1 μm and 0.1 μm. In order to increase the sensitivity of the SPR measurements, the length of the polished surface was set to 5 mm and the depth to 62.5 μm for the fundamental mode region. The dimensions of the polished

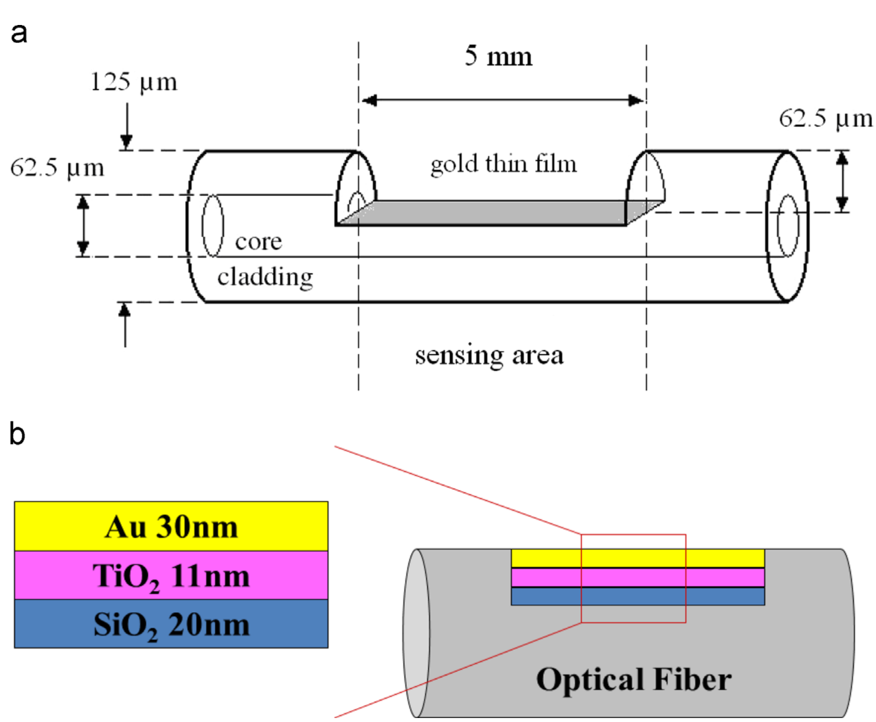

Fig. 1. (a) The schematic diagram of SPR fiber sensor with side-polished structure. (b) The schematic structure of the multi-layer SPR fiber sensor.