Reflective Refractive Index Sensor Based on Surface Plasmon Resonance with MMF-SMF Structure

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Abstract. A reflective and high-sensitive refractive index sensor was proposed based on surface plasmon resonance (SPR) with multimode fiber-single mode fiber (MMF-SMF) structure coated with gold film. In order to verify the performance of the reflective sensor, we also made a transmitted SPR sensor based on the multimode fiber-single mode fiber- multimode fiber (MMF-SMF-MMF) structure as comparison. The experiment results showed that the sensitivity of the reflective sensor reached 2029.3 nm/RIU in the refractive index range of 1.3338-1.3804, which was higher than the sensitivity of the transmitted sensor with sensitivity of 1888.8 nm/RIU. Moreover, the reflective probe is robust, easily packaged and suitable for remote measurement.

Introduction

Measuring the refractive index of the liquids plays a significant role in the composition analysis and physicochemical properties of the liquids [1, 2]. For example, the concentration of glucose can be accurately obtained by measuring the refractive index of the glucose solution, which has great application in the biomedical field. Similarly, in the detection of ocean parameters, the salinity of seawater has a corresponding relationship with the refractive index. For the most part, the measurement of salinity is converted into the measurement of refractive index. Most of the traditional measurements always use the physical and chemical analysis methods and cannot be monitored online. Moreover, the equipment is complex and the measurement sensitivity is low.

Optic fiber sensing is a new type of technology which uses light as carrier and uses optic fibers as the dielectric to sense changes in the external environment [3]. By observing the change of a certain characteristic parameter of the light and the external variable, the corresponding relationship can be obtained and the measurement of the parameter is realized. Optic fiber sensing has quite a few advantages such as high sensitivity, anti-electromagnetic interference, small size, and easy arraying. Many scholars have conducted in-depth research on it, and it have been applied in various fields [4].

For refractive index measurement, a lot of technology including Mach-Zehnder interference [5], Fabry-Perot interference [6], Fiber Bragg Grating [7], and Surface Plasmon Resonance (SPR) [8] have been proposed. In comparison with other types of fiber optic refractive index sensors, the SPR sensors have the advantages of high sensitivity, rapid response, and strong stability. Recently, the performance of fiber optic SPR sensors has been greatly improved by using different structures, such as multimode fiber-single mode fiber-multimode fiber (MMF-SMF-MMF) [9], hollow-core photonic crystal fiber (PCF) [10] and MMF-PCF-MMF [11]. However, most of the current fiber optic SPR sensors utilizes the transmitted structure, which may limit its applications in some occasions that need remote measurement. Besides, the transmitted sensor probe is inconvenient to package.

In this paper, we propose a reflective fiber optic SPR sensor based on the MMF-SMF structure with gold film. Then we compare its performance with the general transmitted SPR sensor based on the MMF-SMF-MMF structure. Firstly, we analyze the mechanism of SPR and use the simple MMF-SMF-MMF structure to illustrate the principle adopted for fibers. Secondly, we fabricate the sensor probes and build an experimental system for the refractive index measurement. Through the performance measurement of the two sensors, we find that the sensitivity of transmitted and reflective
probes reached 1888.8 nm/RIU and 2029.3 nm/RIU respectively in the range of refractive index of 1.33-1.38. Besides, with the increasing of refractive index, the output resonant wavelength of the two sensors both show linear shift. Nevertheless, in comparison with the transmitted SPR sensor, the reflective SPR sensor has improved stability, sensitivity and mechanical strength, so that the sensor can be used in a variety of complex measurement conditions. Moreover, the sensor probe is easily packaged and can be mass-produced.

**Working Principle**

The fiber optic SPR sensor is based on the principle of surface plasmon resonance. Surface plasmon resonance (SPR) is a physical optical phenomenon which is generated by the interaction of incident light waves with free electrons on the surface of the metal conductor. Generally, it refers to the resonance generated by the coupling between p-polarized (or TM-polarized) light and a metal surface plasmon wave (SPW). It usually occurs at the interface between the metal and the dielectric. The SPR theoretical model for optic fiber is based on the three-layer dielectric structure of Krestchmann. When two electromagnetic waves travel in the same direction with the same wave vectors and frequencies, they will resonate. If the thickness of the metal layer is less than the effective depth of the evanescent wave, the evanescent wave which is generated by total reflection can exist at the metal-medium interface through the metal layer. Then the wave vector in the X direction of the evanescent wave can be expressed as:

\[
k_x = \frac{\omega}{c} \sqrt{\varepsilon_0 \sin \theta}
\]

where \(\varepsilon_0\) is the dielectric constant of the fiber cladding, \(\theta\) is the angle of the incidence light, and \(\omega\) is the frequency of the incident light, \(c\) is the speed of light. Assuming that the plane of the metal film is XY, then the surface plasmon wave vibration is in the Z direction. According to the boundary conditions corresponding to the radiation-free transient electromagnetic fields of SPR and Maxwell's equations, the wave vector of the surface plasmon wave at the metal-dielectric interface is:

\[
k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}
\]

where \(\varepsilon_1\) is the dielectric constant of the metal film, \(\varepsilon_2\) is the dielectric constant of the environmental medium on the metal film. Therefore, the excitation conditions for surface plasmon resonance can be explained by the fact that the real part of the surface plasmon wave vector and the evanescent wave vector has the same X-direction component. When \(k_x = \text{real} (k_{sp})\), surface plasmon resonance occurs.

As shown in Fig. 1, for the simple MMF-SMF-MMF structure, part of the incident light couples into the metal layer due to the mismatch of core diameter when light enters into the SMF core from the MMF core. Then there will be a loss of energy in the output spectrum, and the output spectrum will have a resonant dip. With the refractive index increasing, the resonant wavelength will have a red shift. This is the principle of the SPR sensor for measuring the refractive index.

![Figure 1](image-url)  
(a) Fiber optic SPR schematic based on MMF-SMF-MMF structure. (b) Diagram of the resonant wavelength shift.
**Experiment Measurement**

The sensor probe is made of ordinary single mode fiber and multimode fiber. Firstly, the structure is fused by using the fusion splicer (Furukawa FITEL S178). For the transmitted sensor based on MMF-SMF-MMF structure, a 10 mm single mode optical fiber is fused with two multimode fibers. At the same time for the reflective sensor based on MMF-SMF structure, we weld one end of the single mode fiber to the multimode fiber and the length of the single mode fiber is 10 mm. Secondly, the gold film is plated in the single mode fiber section by an ion sputtering coating machine (SAINTINS JS-1600) to excite SPR. Finally, we examine the quality of fiber coating by scanning electron microscopy. The electron microscope image of the probes is shown in Fig. 2.

![SEM image of the sensor probe with 1500 times magnification.](image1.png)

![SEM image of the end face of reflective probe with 5000 times magnification.](image2.png)

*Figure 2. (a) SEM image of the sensor probe with 1500 times magnification. (b) SEM image of the end face of reflective probe with 5000 times magnification.*

The experimental system consists of a halogen light source (OSPEC LS-3000, wavelength range 360-1000nm), refractive index solution (1.33-1.38), Y-type bifurcated fiber (BIF600-VIS-NIR), ocean spectrometer (OCEAN OPTICS USB2000+) and a laptop. Light from the light source is transmitted through the optical fiber to the refractive index modulation area, then the modulated light is output to the spectrometer for analysis. Finally, the output spectrum is displayed on the computer. As shown in Fig. 3 the structure diagram of the transmitted sensor access system is on the left, and structure diagram of the reflective sensor is on the right.

![Structure diagram of the optical fiber SPR refractive index sensing system](image3.png)

*Figure 3. Structure diagram of the optical fiber SPR refractive index sensing system: inset (1) shows the transmitted SPR structure, while inset (2) shows the reflective SPR structure.*

Two types of the fiber optic SPR sensors based on different structure are connected to the sensing system for the refractive index measurement experiments. As shown in Fig. 4, with the refractive index increasing, the resonant wavelength of the transmitted fiber optic SPR sensor has a red shift.
Figure 4(a) shows that resonant wavelength shift of the t sensor is 76nm within the range of 1.3315-1.3706 RIU. Figure 4(b) exhibits good linear relationship (R-square=0.9974) between wavelength $\lambda$ (nm) and refractive index $n$ (RIU), which can be expressed as:

$$\lambda=1888.8n-1909.5$$

(3)

Figure 4. (a) Experimental spectrum and (b) refractive index sensitivity of fiber optic SPR sensor based on MMF-SMF-MMF structure.

The sensitivity of the sensor reaches 1888.8nm/RIU. Due to the measurement condition is relatively limited. We optimize the proposed transmitted structure by replacing the transmitted structure with a reflective structure to fabricate a fiber-optic SPR sensor based on MMF-SMF structure. The experimental measurement of the fabricated reflective sensor shows that the reflective SPR structure has a similar SPR spectrum with the previous transmitted SPR structure sensor. As it is shown in Fig. 5(a), in the refractive index range of 1.3338 to 1.3804RIU, with the refractive index increasing, the resonant wavelength also has a red shift of 96nm. Fig. 5 (b) also exhibits a good linear relationship (R-square = 0.9974) between wavelength $\lambda$ (nm) and refractive index $n$ (RIU), which can be expressed as:

$$\lambda=2029.3n-2081.8$$

(4)

Compared with the transmitted structure, the reflective structure not only has the same linearity, but also increases the transmitted sensor sensitivity. Moreover, the measurement environment of the reflective structure is simpler than the transmitted structure. This type of reflective probe greatly improves the practical application of transmitted probes. Moreover, the performance has also been improved extremely.

Figure 5. (a) Experimental spectrum and (b) refractive index sensitivity of fiber optic SPR sensor based on MMF-SMF structure.
Conclusion

In this paper, a reflective fiber optic SPR sensor based on MMF-SMF structure was proposed for measuring the refractive index of liquid. The structure was welded by a fusion splicer with ordinary single mode fiber and multimode fiber. The gold film was prepared by the ion sputtering coating machine. Then, we compared the performance of this reflective fiber optic SPR sensor with traditional transmitted fiber optic SPR sensor based on MMF-SMF-MMF structure. We found that the sensitivity of the reflective sensor reached 2029.3nm/RIU, which was higher than the sensitivity of the transmitted sensor 1888.8nm/RIU. The stability and strength of the sensor have also been improved. Moreover, the measures conditions of this type of reflective sensor are more widely and the sensor have widespread application in medical, environmental monitoring and other fields.

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References


