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Dual-channel surface plasmon resonance refractive index sensor based on modified hetero-core structure fiber

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A B S T R A C T

We propose and demonstrate a novel dual-channel SPR refractive index sensor based on hetero-core structure fiber. For the traditional hetero-core structure fiber SPR sensor, the resonance wavelength range is unchangeable. We solve this issue by polishing the traditional hetero-core structure fiber as circular truncated cone shape. By this method, we can adjust the resonance wavelength range flexible by changing fiber polishing angle. With increasing of fiber polishing angle, the resonance wavelength range will red-shift. When fiber polishing angle is 14°, and refractive index range is from 1.333 to 1.385, the resonance wavelength range is from 754 nm to 965 nm, which is away from that of the traditional hetero-core structure fiber SPR sensor (600 nm to 700 nm). Therefore, we realize dual-channel sensing by wavelength division multiplexing technology. The sensitivity of two channels are 1980.77 nm/RIU and 4057.69 nm/RIU respectively. In addition, the resonance wavelength and sensitivity of the sensor have a well consistency no matter which working way we adopt. The proposed dual-channel SPR sensor has important applications for multiple analytes detection.

1. Introduction

Surface plasmon resonance (SPR) is a widely used surface analysis method to detect changes in refractive index (RI) or thickness of an adsorbing layer with high sensitivities [1–3]. Compared with prism-based SPR sensors, fiber-based SPR sensors are fundamentally simpler in construction, lower in price, smaller in testing sample volume, and being much more amenable for remote sensing applications. For applications with realistic complex samples, recent years have witnessed intensive research efforts toward multi-channel SPR sensors. On the one hand, the multi-channel SPR sensor can detect multiple analytes simultaneously. On the other hand, the additional channel can be used to compensate for the background refractive index interference and reference the temperature change for improving detection accuracy.

Unlike the prism-based SPR sensor, which is easy for integrating multiple parallel sensing channels [4–6], the fiber-based SPR sensor has difficulty fabricating multiple parallel sensing channels in such a small size in the fiber core (~μm). Though there are some successful cases by using special multicore fiber [7,8], those sensors is very complex and weak. Therefore, the current multi-channel fiber SPR sensors work in the manner of wavelength modulation. In other words, the multi-channel fiber SPR sensors are fabricated by cascading two or more sub-channel sensing probes. The resonance wavelength ranges of the sub-channel sensing probes are required to be separated significantly, enabling simultaneous detection of the samples in different resonance wavelength range through wavelength division multiplexing (WDM) technology. Thus, it is very important for a multi-channel SPR sensor to adjust the resonance wavelength range of each sub-channel and enable the resonance wavelength range of each sub-channel sensing probe to be separated and distinguishable after it is cascaded.

There are five ways to adjust the resonance wavelength range of the fiber-based SPR sensor. The first way is coating different metal films such as gold film and silver film on the different position of optical fiber [9]. However, many metal films are easily oxidized and ineffective. The second way is adding a polymer modulation layer on the metal film surface [10,11]. This method is difficult to fabricate and will reduce sensitivity caused by the loss of the polymer absorption. The third way is changing the thickness of metal film [12,13]. In fact, there is always a most suitable thickness for whatever structures of fiber SPR sensors, and changing the thickness of metal film will deteriorate SPR dip. The fourth

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way is changing the refractive index of the resonance substrate [11,14]. However, for the fiber-based SPR sensor, the resonance substrate is fiber core, whose refractive index range is very narrow. The last and the most effective way is adjusting incident angle of light beam [15–17]. In this way, the fiber is usually polished as a taper, different polishing angle will generate different resonance wavelength range. But these sensors are usually based on special fiber which is hard to get.

The hetero-core structure fiber is very suitable for fabricating SPR sensor and has been many applications [12,18–20]. However, this structure has only one sensing channel. Multi-channel SPR sensor based on this structure has not been reported yet. Focusing on this issue, in this paper, we present a dual-channel SPR sensor based on modified hetero-core structure fiber, which is cascading by a traditional hetero-core structure fiber and a polished hetero-core structure fiber. The latter is polished as circular truncated cone shape. With increasing of fiber polishing angle, the resonance wavelength range will red-shift. When fiber polishing angle is 14°, and refractive index range is from 1.333 to 1.385, the resonance wavelength range is from 754 to 965 nm, which is away from that of the traditional hetero-core structure fiber SPR sensor (600–700 nm). Therefore, we realize dual-channel sensing by wavelength division multiplexing technology. In addition, the resonance wavelength and sensitivity of the sensor have a well consistency no matter which working way we adopt.

2. Principle of method

Fig. 1(a) shows the sketch diagram of the traditional hetero-core structure SPR probe [18]. The structure is consisted of a multi-mode fiber (MMF) as signal transmission line and a segment of about 10 mm length of single-mode fiber (SMF) as sensing interface. Since the core diameter of SMF is much smaller than that of MMF, most of the light wave coming from light source (LS) would leak into the cladding of SMF and occur total internal reflection on the surface of SMF. The surface of SMF is coated by a layer of gold film for exciting surface plasmon wave. Then, the reflective light wave which brings with sensing information would re-couple into the right MMF and collected by optical spectrum analyzer (OSA). Thought this structure is very easy to achieve, it can only detect one analyte.

In order to achieve multiple analytes detection, we design the modified hetero-core structure for adding one sensing channel as shown in Fig. 1(b). The commercial SMF (SMF-28) whose core diameter is 8.2 μm and cladding diameter is 125 μm, and commercial MMF (GIF-105) whose core diameter is 105 μm and cladding diameter is 125 μm are employed to build the modified hetero-core structure fiber probe. We polish SMF and one of MMF as circular truncated cone shape with polishing angle of α and splice them. Then we coat gold film with thickness of 50 nm on the cladding surface of SMF to form sensing channel I, and coat another gold film with thickness of 50 nm on the polishing surface to form sensing channel II. When light wave is launched into lead-in MMF, it would transmit in cladding of SMF. Most of light wave would occur total internal reflection on the cladding surface and meanwhile excite SPR in channel I. Then, the light wave go on transmitting along with cladding and part of them would occur total internal reflection on the polishing surface and meanwhile excite SPR again in channel II. Finally, the light wave are collected by OSA via the lead-out MMF. In addition, the length of channel I is 10 mm, and the distance between channels I and II is 30 mm.

In channel I, the incident angle range θ_1 of light wave can be expressed as:

$$\arcsin\left(n_1/n_0\right) \le \theta_1 \le 90^\circ \tag{1}$$

where n_1 is the RI of analyte and n_0 is the cladding RI of the SMF (n_0 = 1.4658). There is no other variable except n_1 so that the resonance wavelength range of channel I is fixed. However, in channel II, the incident angle range θ_2 of light wave, which is related to the polishing angle α, can be expressed as:

$$\arcsin\left(n_1/n_0\right) - \alpha \le \theta_2 \le 90^\circ - \alpha. \tag{2}$$

Comparing Eqs. (1) and (2), we can find that θ_2 is smaller than θ_1. Considering that the SMF is short and straight, we can assume that the light wave path is almost parallel with the SMF, thus the incident angle range can be simplified. In other words, the incident angle $\theta_1 \approx 90^\circ$, and $\theta_2 \approx 90^\circ-\alpha$. Reviewing references [5,15–17], the resonance wavelength range red-shifts with decreasing of incident angle θ. Meanwhile, with increasing of polishing angle α, the incident angle is getting closer to the critical angle θ_c ($\theta_c = \arcsin(n_1/n_0)$), which can enhance the sensitivity [5,15]. Thus, we can take the resonance wavelength range of channel II away from that of channel I with a great difference. Sequentially, we can achieve dual-channel sensing by wavelength division multiplexing technology.

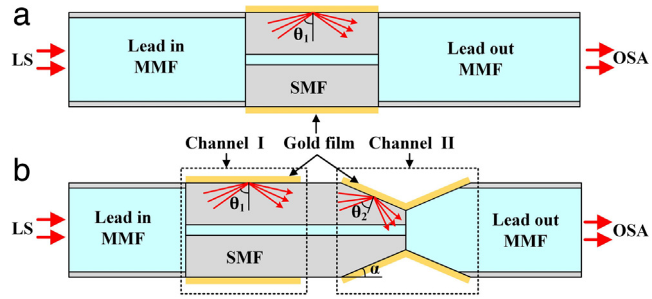

Fig. 1. (a) The sketch diagram of the traditional hetero-core structure SPR probe, which has only one sensing channel; (b) the sketch diagram of the modified hetero-core structure SPR probe, which have two sensing channels (channel I and channel II).

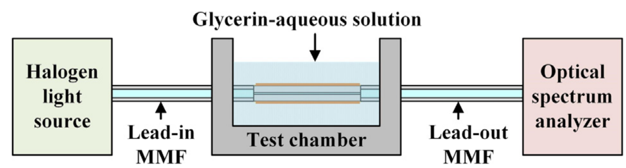

Fig. 2. The test sketch diagram of the traditional hetero-core structure fiber SPR probe.

3. Experiment process and results

3.1. Test of the traditional hetero-core structure SPR probe

Firstly, we test the resonance wavelength range of the traditional hetero-core structure SPR probe. We fabricate this fiber probe as follow 4 steps: (1) splicing a MMF (lead-in MMF) and a segment of SMF by using a fiber splicer; (2) cutting the SMF to 10 mm; (3) splicing another MMF (lead-out MMF) with the SMF; (4) coating gold film with thickness of 50 nm on the surface of SMF by using a plasma-sputtering apparatus (JS-1600, HTCY). To ensure the gold film surface is smooth and the thickness is even, we install a motor in the vacuum chamber of the plasma sputtering apparatus, which drives fiber spinning during gold film coating. The thickness of the gold film is measured by a three-dimensional morphology analyzer (New View 7200, Zygo).

We set up test system as shown in Fig. 2. The fiber sensing probe is placed into a small testing chamber. A halogen lamp (HL-2000, Ocean Optics), whose spectrum range is 360–2000 nm, is launched into the lead-in MMF and then transmitted in cladding of the SMF. The SPR is excited on the surface of cladding, and the transmitted light wave is sent to an optical spectrum analyzer (AQ6373, Yokogawa) by lead-out MMF. The spectrum detection range of OSA is 350–1200 nm. We inject the Glycerin-aqueous solution with difference refractive index into the