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A compact, flexible fiber-optic Surface Plasmon Resonance sensor with changeable sensor chips

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ABSTRACT

We propose and demonstrate the concept of a novel compact, flexible fiber optic Surface Plasmon Resonance (SPR) sensor based on a double-pass Kretschmann-type configuration, where the SPR sensor chip can be replaced for various sensing applications. Simulation and experimental results demonstrate that the proposed fiber-optic SPR structure has a sensitivity to salt concentration of around 4.8 μW/ppt.

1. Introduction

Surface Plasmon Resonance (SPR) is a high-sensitivity optical sensing technique that is used for the real-time detection of small changes in the effective refractive index of metal-dielectric interfaces. SPR has been widely used for real-time monitoring of bio-molecular interactions and detecting chemical and biological analytes in liquid or gas media. This technique is based on the interaction between light and free electrons of the semitransparent noble metallic layer (or chip). At resonance conditions, the frequency of incident light matches the oscillation frequency of the metal's electrons, hence the intensity of the light reflected off the metal layer decreases significantly, and a surface plasmon wave is generated through photon energy transfer into the thin metallic layer. Silver and gold are the preferred metals for triggering SPR due to the fact that they are chemically stable while providing reasonable sensitivity to refractive index changes [1–5].

Fiber optic sensors have become attractive sensing candidates due to several unique features, such as immunity to electromagnetic interference, high sensitivity, and small foot print, which enables them to be integrated with a multiple-fiber sensing platform for the simultaneous detection of many compounds.

With the increasing demand for in-situ and real-time monitoring for environmental, industry process, gas, food, biomedicine, and health applications, the miniaturization of SPR sensors has recently attracted great attention. Several fiber optic techniques have been reported for the realization of compact SPR sensor devices [6–8]. These fiber optic SPR sensors involve complex fabrication processes such as chemical etching and evaporation of metallic materials along the fiber core. Usually the metallic sensing layer has a short life span that depends on the environment within which the sensor operates. In harsh environments, the performance of the fiber optic SPR sensor dramatically decreases when the quality of the metallic sensing layer degrades, necessitating the disposal of the whole sensor.

Additionally, sensors based on the use of planar waveguides have been reported [9–11]. This type of sensors are typically used for biosensing since they enable the detection of different types of analytes with high resolution. In particular, sensors based on the use of metal-clad waveguides (MCWGs) have (i) narrower full-width half maximum (FWHM) shape dips than their SPR sensor counterparts, making them attractive for analysing analytes [12], and (ii) longer lifetime, due to the use of a chemical barrier that protects the metal nano-layer [13].

In this paper, we propose and demonstrate a novel compact, flexible fiber optic sensor featuring simple fabrication with changeable SPR sensor chips. Experimental results show that the proposed fiber optic SPR sensor is able to detect changes in the refractive index of water samples of salinities with a sensitivity of 4.8 μW/ppt. To the best of our knowledge, the proposed fiber optic SPR sensor is the first compact sensor that offers SPR sensor chip replacement, and this opens the way for the development of multi-functional SPR sensor platforms.

2. Proposed fiber-optic SPR sensor structure

Fig. 1 shows the proposed fiber optic SPR sensor structure, which comprises a fiber optic polarisation maintaining collimator with the

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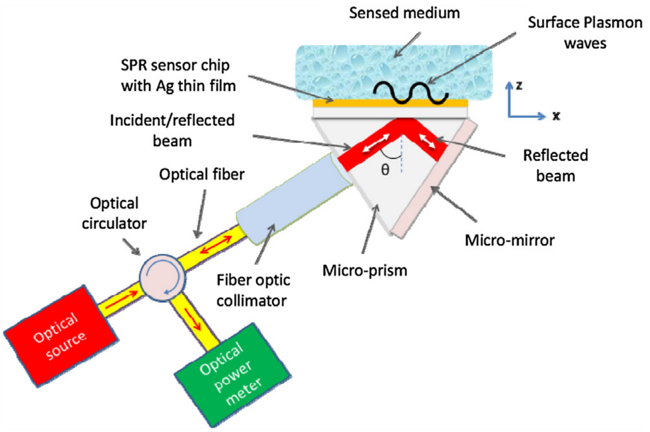

Fig. 1. Proposed double-pass Kretschmann-type fiber optic SPR sensor. Light beam emerging from the optical fiber interacts twice with the Ag nano-thin-film SPR sensing chip, before and after reflection by a high-reflection mirror.

following specifications of a 1.8 mm in diameter size C-type lens, a working distance of 10 cm, a beam diameter of ~0.4 mm and a working wavelength range of 1300–1900 nm. Also, micro-prism of cross section dimensions 5 mm × 5 mm × 4.46 mm and height 5 mm was made using BK7 glass. A high reflectivity 100 nm silver layer was deposited onto one of the micro-prism's sides using an e-beam evaporation system. Furthermore, a re-attachable silver nano-thin-film SPR sensing chip of thickness 55 nm was deposited onto a 5 mm × 5 mm × 0.5 mm BK7 glass substrate with the aid of an e-beam evaporation machine. A 1550 nm light source operating over the telecommunications C-band is launched into the input optical fiber port and routed to a fiber collimator through an optical circulator. This optical signal is then collimated by a collimating lens integrated onto the end of the optical fiber.

A side of the micro-prism is glued onto the collimating lens and another side is coated with (i) a light reflector and (ii) a silver nano-thin-film SPR sensing layer (deposited on a glass substrate to form an SPR chip). The collimated optical signal emerging from the fiber collimating lens strikes the SPR sensor chip at a total-internal-reflection (TIR) angle of θ (see Fig. 1). After reflection back off the Ag coated side, the beam strikes the SPR sensor chip again at the same TIR angle, θ, and eventually couples back through the collimating lens into the optical fiber, where a 3-port polarisation maintaining single-mode optical fiber circulator routes it to a Newport 1830-C optical power meter, employing a Newport 818-IR free-space photo-detector, for analysis.

When the sensing Ag layer is exposed to an aqueous solution, the light source launched into the micro-prism produces an evanescent field that excites a surface plasmon wave at the metal-prism interface, thus resulting in optical signal attenuation.

The coupling of the evanescent optical field into the generated surface plasmon wave strongly depends on the wavelength of the input optical signal, the water refractive index, the ambient temperature and the metallic layer properties (thickness, pattern, etc). The spectral reflectance of the SPR sensor is typically evaluated by an optical spectrum analyser (OSA) at the monitoring end.

Compared to other fiber-optic based SPR sensors, the proposed one has many advantages. First, it uses disposable sensing chips so that it can be used as a platform for remotely sensing and measuring various compounds using different sensing chips. Second, conventional fiber optic SPR sensors have a limited measurement range, while the proposed sensor has a wide and selectable measurement range that depends on the selected chip substrate material. By increasing the refractive index of the substrate a wider measurement range can be achieved. Third, the sensitivity of the proposed sensor depends on the refractive index of the selected substrate of the sensor chip as well as the wavelength of the light source, therefore, the sensitivity of the sensor can be much higher than that of a conventional fiber-optic sensor counterparts, whose sensitivities are limited by the properties of the optical fiber used. These unique properties of the proposed SPR sensor are especially crucial for various emerging sensing applications, such as toxic gas detection, food quality and safety analysis, medical diagnostics, and environmental monitoring.

3. Theoretical analysis

In a conventional Kretschmann-type SPR sensor configuration, the incident light interacts once with the surface plasmon wave at the interface of the metallic nano-thin-film layer and the sensed sample (this is referred to as "single pass configuration"). Since the thickness of the sensor chip substrate is far greater than the light wavelength, a three-layer Fresnel equation for the *p*-polarized light can be used for the reflected light intensity R [14]

$$R = \left|\frac{\mathrm{r_{pm}} + \mathrm{r_{ms}} e^{2i\mathrm{k_{mz}}\mathrm{d_m}}}{1 + \mathrm{r_{pm}}\mathrm{r_{ms}} e^{2i\mathrm{k_{mz}}\mathrm{d_m}}}\right|^2 \tag{1}$$

where $\mathrm{r_{pm}}$ and $\mathrm{r_{ms}}$ are the reflection coefficients for the substrate-metal layer interface and the metal layer-sensing sample interface, respectively. $\mathrm{r_{pm}}$ and $\mathrm{r_{ms}}$ are given by [14]

$$r_{pm} = \frac{\mathrm{k_{pz}}\varepsilon_\mathrm{m} - \mathrm{k_{mz}}\varepsilon_\mathrm{p}}{\mathrm{k_{pz}}\varepsilon_\mathrm{m} + \mathrm{k_{mz}}\varepsilon_\mathrm{p}} \tag{2}$$

$$r_{ms} = \frac{\mathrm{k_{mz}}\varepsilon_\mathrm{s} - \mathrm{k_{sz}}\varepsilon_\mathrm{m}}{\mathrm{k_{mz}}\varepsilon_\mathrm{s} + \mathrm{k_{sz}}\varepsilon_\mathrm{m}} \tag{3}$$

where

$$k_{jz} = \frac{\omega}{c}\sqrt{\varepsilon_j - \varepsilon_p(\sin\theta)^2} \tag{4}$$

ε_j is the dielectric constant of the medium j (p for prism, m for metal and s for sample media), $\mathrm{k_{jz}}$ is the wave vector perpendicular to the interface in medium j, $\mathrm{d_m}$is the thickness of the metal layer, ω is the angular frequency of the incident light, θ is the light incidence angle at the substrate-metal interface, and c is the speed of light.

Unlike the conventional Kretschmann configuration, the proposed fiber optic SPR sensor structure enables the optical beam to strike the metal-sample interface twice. Since the two reflections at the interface are identical, the light intensity coupled back to the fiber collimator $\mathfrak{R}$ can be expressed as,

$$\mathfrak{R} = R^2 \tag{5}$$

To compare the performances of the conventional single-pass configuration and the proposed SPR sensors, a numerical simulation was conducted. Fig. 2 shows the calculated SPR spectra for sample refractive indices of 1.33 and 1.3305, and different silver SPR thin film thicknesses of (a) 45 nm, (b) 50 nm and (c) 55 nm. In each case, the full width at half maximum (FWHM) bandwidth for the double-pass configuration is wider than that for the single-pass configuration. Compared to the single-pass configuration, the double-pass configuration exhibits a wider FWHM bandwidth, as evidenced from Figs. 2(a–c). It is important to note that for an SPR sensor based on wavelength interrogation, the double-pass configuration experiences a lower signal-to-noise ratio, thus less detection accuracy compared to the single-pass configuration, while sharing the same sensitivity (wavelength shift for a given index change). In addition, as shown in Fig. 2(c), for the double-pass configuration, a relatively thicker SPR chip metal layer results in a relatively narrower FWHM bandwidth.

On the other hand, if the intensity interrogation is used (i.e., the source wavelength is fixed), the double-pass configuration could exhibit better sensitivity than that of the single-pass configuration.