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Phase interrogation birefringent-refraction sensor for refractive index variation measurements

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ABSTRACT

A birefringent-refraction (BR) sensor for measuring refractive indices of liquid solutions based on phase interrogation in a heterodyne interferometer is proposed. We theoretically investigate a comprehensive performance comparison between a surface plasmon resonance (SPR) sensor and the proposed BR sensor in terms of sensitivity and the dynamic range in refractive index measurements. In comparison with a typical SPR sensor, the simulations and experiments show that BR sensors can achieve the same order of sensitivity but with a flexible incident angle and a wide RI range.

1. Introduction

Refractive index (RI) measurements of liquids are important for a variety of applications in industry including the chemical and food processing industry [1–4]. Usually, the RIs of liquid solutions are dependent on the concentrations when mixed with other contents [5]. Moreover, RI monitoring can provide real-time performance analysis for lubricant oil and hydrogen fuel cells [6,7]. In optical metrology, the polarization state of a probe light is changed as well as the RI of the tested liquid by using an optical sensor. Various sensors for obtaining these RI measurements have been developed, such as surface plasmon resonance (SPR) [8–10], total internal reflection (TIR) [11,12], refraction beam displacement [13], and focal point shift [14]. Especially, SPR and TIR sensors have been widely demonstrated in optical bulk or waveguide sensors. In recent years, various fiber-based RI monitoring sensors have been successfully demonstrated by utilizing the SPR, interferometric, and grating coupling principles [15–18].

In an SPR sensor, the amplitude and phase of the reflection *p*-wave (electric-field parallel to the incident plane) are abruptly changed at a resonance angle. Otherwise, the reflection *s*-wave (electric-field perpendicular to the incident plane) is slightly changed. By measuring the RI-dependent reflectance of the probe light, angle or wavelength interrogations are proposed [10,19]. The dip curves are shifted due to the resonance conditions changed by the RI variations. The resolution is dependent on the full width at half maximum (FWHM) of the dip signals. Therefore, multi-layer waveguide structures have been proposed to improve the resolutions [19]. In the phase-interrogation approach, a common-path polarization interferometer and a splitting-path Mach-Zehnder interferometer have demonstrated higher sensitivity due to a step-like measured signal [20,21]. Moreover, the precise control of the incident angle and physical parameters of a metallic film (thickness and complex RI) are essential for attaining high sensitivity measurements [8,9]. To overcome the process's imperfections of gold film, the adjustable probing wavelengths are also critical for maintaining high sensitivity measurement [19,22]. Typically, the phase-interrogation SPR achieves high sensitivity values of 10^4–10^5 after optimizations on the fabrication process of metallic films and experimental setup. However, the dynamic range of RI variations is limited due to the intrinsically nonlinear phase curves. To extend the dynamic range, phase-interrogation combined with the angle-interrogation [8] was conducted to overcome such issues. However, these improvements need more signal process procedures and make the measurement system complex.

In the TIR sensors, the probe light is irradiated onto the interface between the prism and liquid. The critical angle is moved dependent on the RI changes of the liquid tested. The angle can be decided by measuring the corresponding pixel with an abrupt intensity change on the CCD camera [23]. Near the critical angle, a tiny RI change can cause an obvious reflectance change [24]. To remain in good linear operation, the dynamic angle range is limited for high sensitivity. When the incident angle is over the critical angle, the two orthogonally polarized lights will have phase delay modula-

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tion depending on the tested liquid's RI. In the phase-interrogation TIR [12], the incident angle is relaxed, and the impact of intensity noise is reduced in comparison with the intensity-interrogation measurements. In contrast to the SPR transducers, the phase curves of the TIR one are smoother, and the sensitivity is lower but with a wider dynamic range.

A birefringent material has been widely applied for fabrication of wave plates, polarization splitters, and tunable phase retarders [25]. To make a wavelength converter through nonlinear optics, high intensity resistant birefringent crystals, such as MgO-doped lithium niobate (MgO:LN) and potassium titanyl phosphate (KTP), are adopted to generate some useful light sources [26,27]. Therein MgO:LN is a uniaxial birefringent crystal with two different refractive indices.

In this study, we present a new birefringent-refraction (BR) sensor and a common-path heterodyne interferometer for measurements of RI variation. The BR sensor was fabricated by using a MgO:LN plate immersed in the tested liquids. The optical phase delay between two orthogonal polarizations (*p*- and *s*-wave) of the probe light is mainly dependent on the incident angle and the RI variations of the liquid solutions. At a constant incident angle, RI variations can be obtained by measuring the phase signals. Furthermore, the comparison between the SPR and the BR sensors, based on the scheme of phase-interrogation, is theoretically studied. The simulations indicate that the BR sensor has the advantages of a wide dynamic range and flexible incident angle with a really simple structure. To evaluate the capability of the proposed BR sensor, different weight percentages of glucose solutions were prepared to explore the relationship between the phase changes and the RI variation.

2. Sensing principles and simulations

Both structures of SPR and BR sensors are shown in Fig. 1. The typical SPR sensor in Kretschmann configuration consists of a prism, metallic film, and the tested liquid. To make reliable metallic film, a thinner adhesion titanium-film is deposited between the metallic film and the prism. In this simulation, only the single gold film (Au) is adopted to discuss the phase sensitivity and dynamic range in the RI variation measurements.

The reflection coefficients of the *p* and *s* waves can be expressed as [28]:

$$r_q = \frac{r_{gm}^q + r_{ml}^q \cdot \exp(j2k_m d)}{1 + r_{gm}^q \cdot r_{ml}^q \cdot \exp(j2k_m d)} = |r_q| \exp(j\phi_q), \qquad (1)$$

$$k_m = \frac{2\pi}{\lambda} \cdot n_g \cdot \cos\theta_i, \qquad (2)$$

$$\phi_{SPR} = \phi_p - \phi_s. \qquad (3)$$

where q (=p or s) represents the p or s wave; k_m is the wave vector perpendicular to the boundary in the gold film; λ and θ_i are the wavelength and incident angle, respectively; the subscripts g, m and l represent the prism, gold film, and liquid, respectively; and d is the thickness of the gold film. r_{gm} represents the Fresnel reflection coefficient at the interface between the prism and the gold film. r_{ml} represents the Fresnel reflection coefficient at the interface between the metal and the liquid. The RIs of the prism, metal, and liquid are represented by n_g, n_m, and n_l, respectively. The reflection coefficients r_p and r_s are both complex numbers, and ϕ_p and ϕ_s indicate the optical phase delay of the p and s waves due to the reflection at the boundary's surface. The amplitudes of the reflected p and s waves are represented by $|r_p|$ and $|r_s|$, respectively. The phase difference between them, $\phi_{SPR} = \phi_p - \phi_s$, is strongly dependent on n_l and θ_i. The BK7 prism with a refractive index of 1.515, Refractive Index Unit (RIU) and gold film with a permittivity of 12 + i1.26 were used for the simulations [29].

A schematic of the proposed BR sensor is depicted in Fig. 1(b). It is designed by inserting a 1 mm thick MgO:LN plate with a square area (10 mm × 10 mm) in a cubic glass cell. The phase difference between the two orthogonal p and s waves of the probe light is represented by:

$$\phi_{BR} = \frac{2\pi}{\lambda} \cdot t \cdot \left(\sqrt{n_e^2 - n_l^2 \cdot \sin^2\theta_i} - \sqrt{n_o^2 - n_l^2 \cdot \sin^2\theta_i} \right), \qquad (4)$$

where t is the thickness of the MgO:LN plate. The refractive indices of extraordinary and ordinary are represented by n_e and n_o (n_e = 2.203 and n_o = 2.286 at 632.8 nm) in the MgO:LN [30]. The s-wave is parallel to the n_e-axis of the MgO:LN plate.

Fig. 2 illustrates the simulations of an SPR sensor for studying the phase variation versus the incident angle (53.5–54.5°) under different gold thicknesses and RIs of solutions. Fig. 2(a)–(c) shows the phase response for gold thicknesses of 40 nm, 45 nm, and 47 nm, respectively. According to the typical phase-interrogation SPR scheme employed with a single probing wavelength, the amount of sensitivity incident angle for matching an SPR condition is dependent on the gold's thickness and the RI of the liquids. As shown in Fig. 2(c), the slope (phase vs. angle) becomes steeper when the thickness and RI approach resonance behavior. The phase curves toward a large incident angle as RI increases. Therefore, the phase is changed as well as the RI variation when the optimized incident angle is decided. By choosing the prompt incident angle, the RI variation can be further extracted based on the phase measurements.

Fig. 3 gives the simulation results of the phase change versus the refractive index for the three gold thicknesses and different incident angles ranging from 53.8 to 54.3°. The angle increases at a rate of 0.05°. When the gold thickness of 40 nm is far away from the resonance condition, as shown in Fig. 3(a), the phase curves have

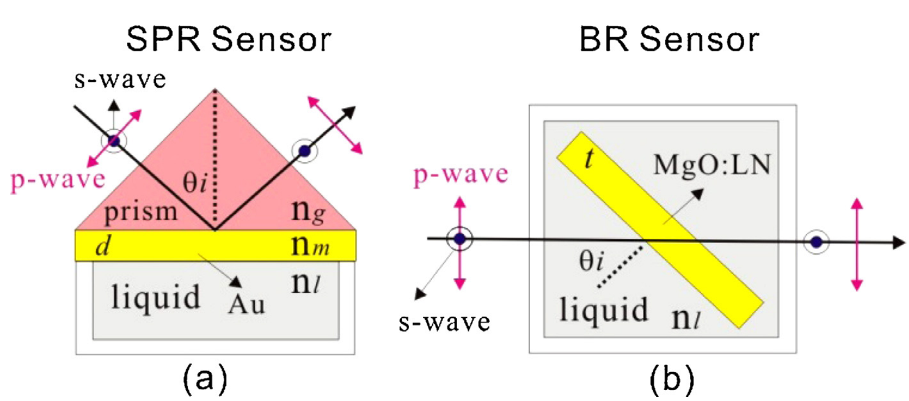

Fig. 1. Device structures for refractive index variation measurement: (a) SPR and (b) BR sensors.