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Research paper

Fiber-optic surface plasmon resonance sensor based on spectral phase shift interferometric measurements

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ABSTRACT

We demonstrate for the first time a fiber-optic surface plasmon resonance sensor employing the interrogation method based on spectral interferometric measurements of the phase shift between fiber polarization modes. The sensor was fabricated on a specially designed birefringent D-shape fiber made of silica glass, which exhibits modal birefringence of the order of 10^{-5} and allows for direct deposition of a metal layer in the vicinity of the core. The sensor characteristics measured using the spectral interferometry method were compared with the reference results obtained using the conventional spectral transmission method. The two measuring techniques show similar sensitivity of 2700 nm/RIU for the refractive index of external medium equal to 1.386, however, the detection accuracy of the interferometric method is up to 3 times better.

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1. Introduction

The phenomenon of surface plasmon resonance (SPR) is widely used in fiber-optic sensors to detect chemical and biological analytes [1–3] because the resonance position is very sensitive to changes in refractive index of a medium surrounding the fiber. In standard bulk sensing heads employing prism coupling in Kretschmann configuration, the angular, wavelength, intensity, and phase interrogation methods can be used [4,5]. For fiber-optic SPR sensors, the spectral transmission method, first proposed by Jorgenson et al. [6], is by far the most commonly employed. This technique is based on the detection of spectral loss near the SPR resonance, which is induced by coupling of the guided core mode to surface plasmon. The phase interrogation method has not yet been widely explored in the context of the fiber-optic SPR sensors. In 2005 Chiu and coworkers reported a series of experiments involving the SPR induced phase shift measurements using the optical heterodyne technique [7–9]. For this purpose, a single mode side-polished fiber covered with a gold layer was applied. It was shown in [7] that by interferometric measurements of the phase shift, an accuracy and resolution of the SPR sensors can be improved. In [8,9] numerical studies were reported aiming at the improvement of the measurement sensitivity of the phase shift method. As the resonance condition is dependent on the refractive index of both the surrounding medium and the fiber core, the SPR based strain sensor using a common-path heterodyne interferometer for phase shift measurements was also proposed in [10]. A theoretical analysis of the phase behavior of an integrated optical surface plasmon resonance sensor based on Mach-Zhender interferometer (MZI) was presented in [11]. It is demonstrated that in such a device unwanted refractive index changes common in both branches of the MZI, arising for example due to temperature variations, can be suppressed [12].

In the most recent papers [13–16], numerical simulations analyzing the performance of the SPR fiber-optic sensor employing the phase interrogation method are presented. In particular it was shown in [16] that polarization cross-talk can be suppressed by using a microstructured fiber with high birefringence and consequently the stability of SPR sensor can be improved.

One of the challenges during the manufacture of the SPR fiber-optic sensor is making the sensing part with an exposed core. Usually for this purpose, the side-polishing, chemical etching or tapering methods are used [1–3]. The side-polishing method was also employed to make the SPR sensor on a birefringent fiber [17]. However, in such a case a special procedure is required for precise alignment of the fiber polarization axis with respect to the polished surface. To avoid laborious sensor fabrication, silica [18,19] and polymer [20] microstructured optical fibers with the core exposed

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along the whole fiber length were proposed. Recently, the SPR sensor based on a birefringent single mode D-shape polymer optical fiber was reported in [21]. The proposed fiber design allowed for direct metal deposition on the flat cladding surface located in the direct proximity of the core.

In this paper we demonstrate for the first time a fiber-optic surface plasmon resonance sensor based on a D-shape silica fiber. To determine the resonance wavelength, we employed the spectral phase shift interrogation method recently proposed by Hlubina et al. for interrogation of a prism SPR sensor [22,23]. A special fiber construction with the core located close to the flat surface of the cladding allowed for direct metal deposition without any extra pre-processing. The results obtained using the spectral interferometry method were verified against the spectral transmission method. The sensitivities of the SPR sensor obtained for both detection methods are practically the same, however, the detection accuracy of the interferometric method is better up to 3 times compared to the spectral transmission method.

2. Principle of the phase shift method

The working principle and advantages of the phase shift method over the spectral transmission method can be illustrated already for simple Kretschmann configuration of the SPR sensor shown in Fig. 1, with a glass prism covered by a gold layer of thickness q. For such structure, the amplitude reflection coefficient is given by the following analytical expression [24]:

$$r_{pmd} = \frac{r_{pm} + r_{md}\exp\left(2ik_y^m q\right)}{1 + r_{pm}r_{md}\exp\left(2ik_y^m q\right)}. \quad (1)$$

where r_{ij} indicate the reflection coefficients at respective boundaries (i,j stand for p, m, d). For TM polarization the coefficients r_{ij} can be expressed as follows [24]:

$$r_{ij} = \frac{\varepsilon_j k_y^i - \varepsilon_i k_y^j}{\varepsilon_j k_y^i + \varepsilon_i k_y^j}, \quad (2)$$

and correspondingly for the TE polarization:

$$r_{ij} = \frac{k_y^i - k_y^j}{k_y^i + k_y^j} \quad (3)$$

In the above equations $\varepsilon_i, \varepsilon_j$ represent electric permittivities of adjacent media and k_y^i, k_y^j are normal components of the wave vectors. Finally, the reflectivity can be calculated versus the wavelength for both polarizations

$$R = |r_{pmd}|^2 \quad (4)$$

as well as the phase shift at the reflection ϕ is given by the relation $\exp(i\phi) = r_{pmd}/|r_{pmd}|$. In Fig. 1 we present the spectral dependence of the reflectivity R and the phase shift φ calculated for TE and TM polarizations for two different values of n_d. In the calculations we have assumed the material and geometrical parameters similar to those in the birefringent fiber used to fabricate the sensor, i.e. the prism made of silica glass, a 40 nm thick layer of gold (Drude-Lorentz model of permittivity [23]) and the angle of incidence $\theta = 83^\circ$, which corresponds to the fiber aperture angle of 0.12. As shown in Fig. 1, the effect of surface plasmon resonance is visible in the $R(\lambda)$ and $\varphi(\lambda)$ characteristics only for TM-polarized light. For the $R_{TM}(\lambda)$ curve, we observe a symmetric drop near the resonance wavelength λ_{SPR} determined by the minimum reflectivity. The reflectivity dip visible for single reflection gives rise to the resonant transmission loss when light propagates in the fiber covered with a metal layer and experiences multiple reflections.

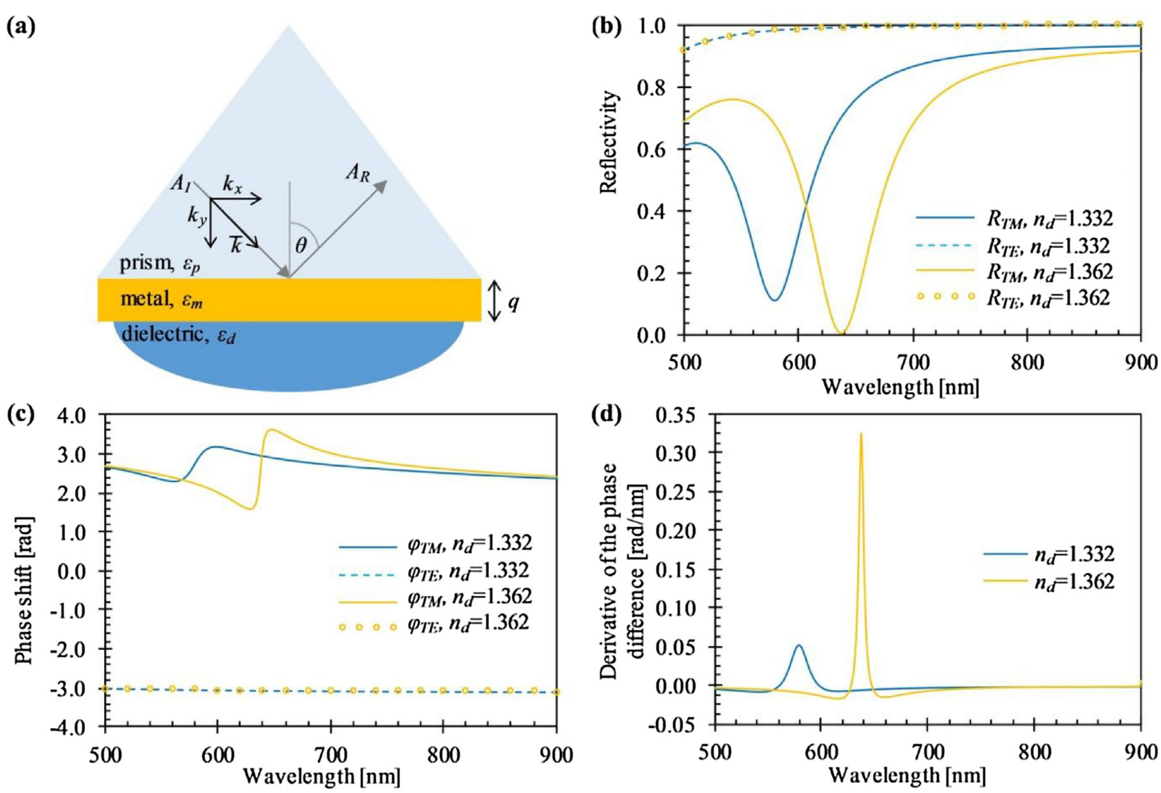

Fig. 1. Kretschmann configuration of the SPR sensor: prism made of silica glass and covered with a gold layer of thickness q = 40 nm, angle of incidence $\theta = 83^\circ$ (a). Reflectivity (b) and phase shift (c) as a function of wavelength calculated for both polarizations. Derivative versus wavelegth of the phase shift difference between TM and TE polarized waves (d).

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