Optics Communications 354 (2015) 240–245

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Spectral interferometry-based surface plasmon resonance sensor

P. Hlubina [a,b,*], M. Duliakova [a], M. Kadulova [a], D. Ciprian [a,b]

[a] Department of Physics, Technical University Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic
[b] Regional Materials Science and Technology Center, Technical University Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form
16 May 2015
Accepted 5 June 2015
Available online 9 June 2015

Keywords:
Surface plasmon resonance
Spectral interferometry
Wavelength interrogation
Sensitivity

ABSTRACT

A two-step spectral interferometric technique is used to measure a surface plasmon resonance (SPR) phase difference from the spectral interferograms recorded in the Kretschmann configuration. The technique employs a polarimetry setup with a white-light source and birefringent crystal and allows one to obtain a channeled spectrum. Two such spectra, one including reflection of *p*- and *s*-polarized waves from the SPR structure for air when the SPR phenomenon does not occur in the source spectral range, and the other one for an analyte when the SPR phenomenon occurs, are used to retrieve the wavelength-dependent SPR phase difference. The new method is applied for aqueous solutions of ethanol with different parameters, the concentration of ethanol in water in a range from 0 to 60 weight percent and the refractive index in a range from 1.333 to 1.362. The sensing scheme uses a wavelength interrogation method and the position of a sharp maximum in the spectral derivative of the SPR phase change is measured as a function of the analyte parameter in a range from 644 to 690 nm. In the same setup, the spectral dependence of the ratio between the reflectances of both polarization states is measured as a function of the analyte parameter. It is revealed that the detection accuracy of the interferometric measurements is more than three times higher than that of the polarimetric measurements.

1. Introduction

The concept of optical sensing of a large variety of physical/chemical processes at interfaces based on surface plasmon resonance (SPR) [1–3] has been proved to be very useful over the last several decades. In addition, the SPR sensing is very practical for numerous biology applications [4,5]. The SPR arises from the interaction of light with free electrons at a metal–dielectric interface [6]. Under certain conditions, the collective oscillations of free electrons, called surface plasmons (SPs), can be optically excited at that interface by the attenuated total reflection (ATR). The excited SPs are strongly localized across the interface and may be considered as electromagnetic surface waves that propagate along the interface. The waves are basically transverse magnetically polarized so that they can be resonantly excited only by a *p*-polarized incident light wave. The field of SPs decays exponentially in the direction perpendicular to the boundary, in the metal as well as in the dielectric. When a specific resonance condition is fulfilled, the incident light wave can be coupled to the SPs and the power carried by reflected light wave drops down.

The resonance condition is extremely sensitive to changes in the refractive index of the surrounding medium (analyte). Such changes may result in changes in the intensity [7], the phase [8], the resonant angle [9] or the resonant wavelength [10] of the reflected light wave. Most widely used SPR sensing systems [5] include configurations with a coupling prism, grating and optical waveguide. In the prism-based excitation of SPR, the most efficient way for generating SPs provides the Kretschmann configuration [1]. The base of a prism of high refractive index is coated with a thin metal film and the SPs are excited in the metal film by ATR mechanisms. The prism itself plays the role of a coupling element between the evanescent wave excited on its base and the SPs under the condition that the light beam incident angle exceeds its critical value. The evanescent wave passes through the thin metal film and the SPs are excited at film lower boundary where the metal is in contact with the analyte. SPR sensing can be performed in an angular or spectral domain (angular or wavelength interrogation). In the angular interrogation [11], a monochromatic beam is used and a sharp minimum (dip) is observed in the angular spectrum. Similarly, in the wavelength interrogation [11,12], a dip is observed in the reflection spectrum.

The detection limit of the phase-based SPR sensors is higher [13–15] than that of sensor implementations with intensity, angular or spectral interrogations. However, more complicated interferometric setups [16–24], compared to the intensity-based measurement schemes, need to be used to measure the phase response of the SPR sensor. The measurement methods are using a

* Corresponding author at: Department of Physics, Technical University Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic. Fax: +420 597 323 139.
E-mail address: petr.hlubina@vsb.cz (P. Hlubina).

http://dx.doi.org/10.1016/j.optcom.2015.06.011
0030-4018/

Mach–Zehnder interferometer [16,17], configurations with a photoelastic phase modulator [18] or electro-optic modulator [19], heterodyne interferometry [20,21], a rotating analyzer method [22], phase quadrature interferometry [23], and differential phase spectral interferometry [24].

The objective of the paper is to propose and verify a new phase measurement technique enabling to increase the detection accuracy of an SPR setup. A two-step spectral interferometric technique is used to measure an SPR phase difference from the spectral interferograms recorded in the Kretschmann configuration. The technique, which is a modification of the technique originally employed for measuring the ellipsometric phase of a thin-film structure [25], utilizes a polarimetry configuration with a birefringent crystal and allows one to obtain a channeled spectrum. In the first step, the phase difference between p- and s-polarized waves propagating in the setup is retrieved for air when the SPR phenomenon does not occur in the spectral range of a source. In the second step, the additional phase change the polarized waves undergo on reflection from the SPR structure is retrieved for an analyte when the SPR phenomenon occurs.

The new method is used to determine the wavelength-dependent SPR phase differences for aqueous solutions of ethanol with different parameters, the concentration of ethanol in water in a range from 0 to 60 weight percent and the refractive index in a range from 1.333 to 1.362. The sensing scheme uses a wavelength interrogation method and the position of a sharp maximum of the spectral derivative of the SPR phase change is measured as a function of the analyte parameter in a range from 644 to 690 nm. Moreover, in the same polarimetric configuration, the ratio between the reflectances of both polarization states is measured as a function of the analyte parameter. The dependencies of the resonance wavelength on both the concentration of ethanol in water and the refractive index of the analyte obtained are compared with those resulting from interferometric measurements and good agreement is confirmed. In addition, the detection accuracy of the interferometric measurements is more than three times higher than that of the polarimetric measurements.

2. Experimental methods

2.1. Interferometric method

Let us consider an experimental setup shown in Fig. 1. The setup can be used for measuring the wavelength dependence of the phase difference between p- and s-polarized components of an incident light beam subjected to the SPR phenomenon at the fixed angle of the incidence. The collimated beam from a white-light source passes through collimating lens CL and polarizer P oriented 45° with respect to the plane of incidence so that both p- and s-polarized components are generated. Next, the beam passes through birefringent crystal BC (thickness t) whose optical axis is perpendicular to the plane of incidence and the phase delays $\phi_{p,s}(\lambda)$ of the p- and s-polarized components are introduced. Finally, these retarded components undergo, owing to reflection from an SPR structure consisting of a high refractive index glass prism and a thin metallic layer, the amplitude and phase changes that are related to the complex reflection coefficients:

$$r_{p,s}(\lambda) = \sqrt{R_{p,s}(\lambda)}\exp[i\delta_{p,s}(\lambda)], \tag{1}$$

where $R_{p,s}(\lambda)$ and $\delta_{p,s}(\lambda)$ are the wavelength-dependent reflectances and phase changes on reflection for both polarizations, respectively. The two orthogonally polarized components are mixed with analyzer A and are launched by microscope objective MO into a read fiber of a spectrometer. The interference of the polarized components is resolved as a channeled spectrum in which the phase difference $\Delta(\lambda) = \delta_p(\lambda) - \delta_s(\lambda)$ between the p- and s-polarized components is inscribed.

To retrieve the SPR phase difference $\Delta_{\mathrm{SPR}}(\lambda)$ from the recorded channeled spectrum, the measurement procedure needs to consist of two steps. In the first step, the reference phase difference $\phi_{\mathrm{ref}}(\lambda) = \phi_p(\lambda) - \phi_s(\lambda)$ between the p- and s-polarized components is retrieved from the spectral interferogram obtained when the SPR structure is subjected to air. In this case the angle of incidence of a white light on the thin metallic layer is not satisfying the phase matching condition [1–3] in the source spectral range, and the SPR phenomenon does not occur. The reference phase difference $\phi_{\mathrm{ref}}(\lambda)$ includes the phase difference (retardance) $\phi_{\mathrm{BC}}(\lambda)$ introduced by the birefringent crystal and the reference phase difference $\Delta_{\mathrm{ref}}(\lambda)$ between the p- and s-polarized components. The spectrum recorded by a spectrometer of a Gaussian response function can be represented in the form [26]

$$I_{\mathrm{ref}}(\lambda) = I_{0\mathrm{ref}}(\lambda)\{1 + V(\lambda)\cos[\phi_{\mathrm{BC}}(\lambda) + \Delta_{\mathrm{ref}}(\lambda)]\}, \tag{2}$$

where $I_{0\mathrm{ref}}(\lambda)$ is the unmodulated spectrum and $V(\lambda)$ is a visibility term given by

$$V(\lambda) = \exp\left\{-\frac{\pi^2}{2}\left[\frac{G(\lambda)t\Delta\lambda_{\mathrm{R}}}{\lambda^2}\right]^2\right\}, \tag{3}$$

where $G(\lambda)$ is the group birefringence of the crystal and $\Delta\lambda_{\mathrm{R}}$ is the width of the spectrometer response function.

In the second step, the spectral interferogram is recorded for the analyte under study when the SPR phenomenon occurs. The spectrum recorded by the spectrometer is given by

$$I(\lambda) = I_0(\lambda)\{1 + V_{\mathrm{R}}(\lambda)V(\lambda)\cos[\phi_{\mathrm{BC}}(\lambda) + \Delta(\lambda)]\}, \tag{4}$$

where $I_0(\lambda)$ is the unmodulated spectrum and $V_{\mathrm{R}}(\lambda)$ is a visibility

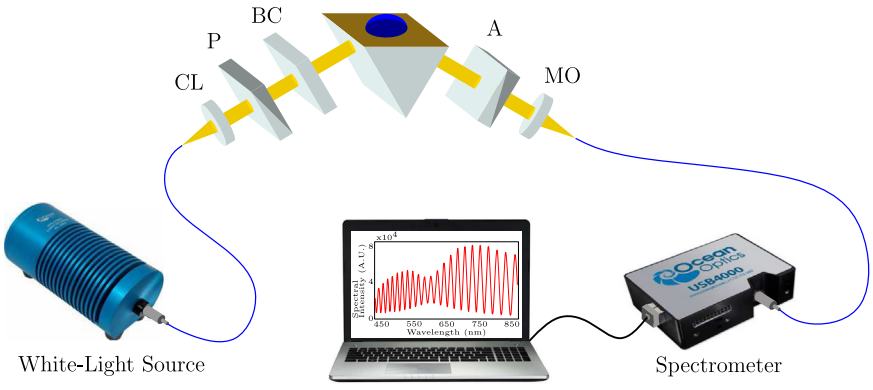

Fig. 1. Polarimetry setup with an SPR structure; collimating lens (CL), polarizer (P), birefringent crystal (BC), analyzer (A) and microscope objective (MO).