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Refractive index sensor based on magnetoplasmonic crystals

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ABSTRACT

A magneto-optical surface plasmon resonance (MOSPR) sensor based on a magnetoplasmonic crystal trilayer structure is presented. The sensitivity of the MOSPR sensor is studied as a function of ferromagnetic layer thickness and at the different modes of operation. The enhancement of the sensitivity caused by using the MOSPR sensor in magneto-optical modulation regime in comparison with reflection regime is observed.

1. Introduction

In recent decades, the miniaturization of chemical and physical sensing devices and their integration into single microchips for multichannel sensing have become a dominant goal of sensor research and development. In addition, the enhancement of the sensitivity and label-free detection has always been a challenge for sensing devices. Following the first demonstration [1], surface plasmon resonance (SPR) sensing has become a leading technique for highly sensitive and label-free detection. SPR detection devices provide real-time measurements and, coupled with micro-scale dimensions, can be applied to biochemical, physical, medical and environment analyses.

Surface plasmon polaritons (SPPs) are collective plasma oscillation phenomena that exist at the boundary of a metal (ε_1) and dielectric (ε_2) media with different signs of dielectric conductivity constants and condition of $\varepsilon_1 < 0,\ |\varepsilon_1| > \varepsilon_2$. These oscillations excite electromagnetic waves with the wave vector

$$k_{spp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1(\omega)\varepsilon_2(\omega)}{\varepsilon_1(\omega) + \varepsilon_2(\omega)}}, \tag{1}$$

that propagate along the interface of both media; the maximum intensity is located at the metal-dielectric interface, and the waves decay exponentially into metal and dielectric. The excitation of SPPs decreases the intensity of external electromagnetic waves and can be observed as a sharp resonant dip in the reflection spectrum [2,3]. The parameters of this dip, including the position and width, strongly depend on the dielectric constants of both media and, as a consequence, on the refractive index. This dependence is commonly used for sensing purposes as a function of the refractive index of the external dielectric media.

The main performance characteristics of SPR sensors include sensitivity, accuracy, precision, repeatability and lowest detection limit. To improve these characteristics, many transducer schemes and sensing techniques have been applied. The classical SPR detector is based on the Kretschmann scheme, where the sensing layer is a thin gold film sputtered onto a glass prism. This scheme, low cost and high performance due to its simplicity, is one of the most employed. Depending on the application needs, different types of metals (Au, Ag or their combination), detection schemes (angular, spectra-angular, or phase) and modulation techniques have been used. As proven in [4], the modulation technique can enhance the performance of the sensing characteristics including sensitivity, lowest detection limit and signal-to-noise ratio (SNR); therefore, different modulation techniques have been developed (mechanical, phase, and polarization). Moreover, a new modulation technique based on magneto-optical (MO) and SPR interactions was developed very recently. This type of sensor was called a magneto-optical surface plasmon resonance (MOSPR) sensor [5,6]. It is well known that substantial enhancements of MO effects can be observed in structures that demonstrate simultaneous excitation of surface plasmon polaritons and MO effects [7–9]. Combinations of ferromagnetic materials with noble metals can be used to enhance both MO and SPP activities [8–10]. Gold and silver are the typically used metals for biosensing applications because of their satisfactory plasmonic properties. The MOSPR sensing capabilities of trilayer structures have been studied in Kretschmann scheme [5,6], and the theoretical calculations predicted an order of sensitivity magnitude enhancement.

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The objective of this work is the experimental demonstration of the possibility of using periodical magnetoplasmonic nanostructures, namely magnetoplasmonic crystals [8,11,12], for refractive index detection by using MO probes. This type of sensor represents a possible type of biosensing device. Such plasmonic crystal (PlC) biosensors based on SPR on metal grating provide good sensitivity, simple design and integration because they do not require the Kretschman scheme and can serve as a basis for the development of multichannel sensors and biochips. Another argument for PlC biosensors is that transparency of the sensing layer is not necessary to achieve stable operation. In this paper characteristics of the magnetoplasmonic crystal sensor are studied in comparison with the PlC sensor.

2. Magneto-optical surface plasmon resonance sensor

To describe the sensitivity of the MOSPR sensor on gratings, one must first consider the transversal magneto-optical Kerr effect (TMOKE) and SPR excitation conditions in periodical structures [11,13,14]. On periodical structure the phase-matching conditions of the incident electromagnetic wave vector (k_0) and the propagating SPP wave vector (k_{spp}) can be written as

$$-k_{spp} = k_0 \sin\theta + nG, \tag{2}$$

where G is the reciprocal lattice vector, n is the diffraction order, k_0 is the incident wave vector, and θ is the angle of incidence. In this letter, we consider the Voigt configuration of the MOSPR sensor when the external magnetic field is oriented along the boundary perpendicular to the SPP wave vector. Magnetization of the metallic media on air/metal boundary ($\varepsilon_2 = 1$) produces non-diagonal components in the ε_1 tensor, thereby changing Eq. (1) and the phase-matching conditions for SPP excitation [11,12]

$$k_{spp} + k_0 \sin\theta + k_0 \frac{-ig}{\sqrt{\varepsilon_1 - \varepsilon_1^2 + 1}} = -nG, \tag{3}$$

where ig is the gyration constant. Thus, the minimum in the reflection spectrum (related to SPP excitation) obtained from the magnetoplasmonic crystal shifts by the following value:

$$\Delta\lambda = \frac{-igd}{\sqrt{1 + \varepsilon_1(1 - \varepsilon_1^2)}}, \tag{4}$$

where d is the period of magnetoplasmonic crystal.

On the other hand, TMOKE in the Voigt configuration is measured by the relative change in the reflected light intensity $R(\mathbf{M})$ when the magnetization of medium $\mathbf{M}$ is switched and can be described by the following value:

$$\delta = (R(\mathbf{M}) - R(-\mathbf{M})/R(0) = \Delta R/R(0), \tag{5}$$

where $R(0)$ is the reflectance coefficient when the external magnetic field is not applied. Hence, when $\Delta\lambda/\lambda_0 \ll 1$, where λ_0 is the resonance wavelength, the value of TMOKE can be written as the derivation of the reflection spectrum with respect to wavelength:

$$\delta = \frac{\Delta R}{R(0)} = \frac{dR}{d\lambda}\frac{\Delta\lambda}{R(0)}. \tag{6}$$

Consequently, the value of TMOKE is proportional to the first derivative of the reflection spectrum with respect to wavelength. For sensing applications, we need to quantify and compare MO effects when the reflection index of the dielectric media (n_d) varies. The sensitivity of the MOSPR sensor to changes in the refractive index can be written as

$$\eta = \partial\delta/\partial n_d = \frac{\partial\delta}{\partial A}\frac{\partial A}{\partial n_d}, \tag{7}$$

where A is the wavelength (or another parameter e.g. incident angle). R could be used instead of η for the case of SPR sensor sensitivity. Substituting δ from (5) to (6) one can obtain that the sensitivity of the MOSPR sensor is proportional to the second derivative of the reflection spectrum $R(\lambda)$ with respect to wavelength:

$$\eta = \frac{\lambda}{n_d}\frac{\partial}{\partial\lambda}\left(\frac{dR}{d\lambda}\frac{\Delta\lambda}{R(0)}\right). \tag{8}$$

The sensitivity η has the dimension of inverse refractive index and is measured in RIU^1, where RIU is a refractive index unit [4,5].

3. Experiment

To evaluate the properties of the MOSPR sensor, the designed experimental setup (Fig. 1) is used. It consists of a halogen lamp that functions as a source of incident electromagnetic waves, a monochromator, a Glan Taylor prism to provide p-polarized light that is necessary for SPP excitation, a collimation system, an electromagnet and a detector.

To reduce optical noise, light reflected from the sample was collected by a fiber-optic device with a low numeric aperture. We used a photomultiplier tube operating in a spectral range of 400–860 nm to detect the collected signal, which was further registered by the lock-in amplifier at the frequency of the external magnetic field (118 Hz). For the sensing applications, a flow cell was constructed to enable control of the concentration of liquids in the mixture with high accuracy. The refractive index of the liquids for reference was also monitored by using a refractometer. As a sample for the MOSPR sensor transducer, we chose a trilayer magnetoplasmonic crystal based on a polymer substrate with a lattice period of 320 nm with Ag/Fe/SiO_2 layers sputtered onto the substrate. The other parameters of these magnetoplasmonic crystals are shown in [10]. The Ag/Fe layers were deposited to provide simultaneous SPP and MO activity. The SiO_2 coating was used to protect the sample from degradation in a liquid media and its effect on the optical properties is negligible. Three samples with different Fe layer thicknesses (5, 10, and 20 nm) were fabricated, thickness of an Ag layer was 100 nm.

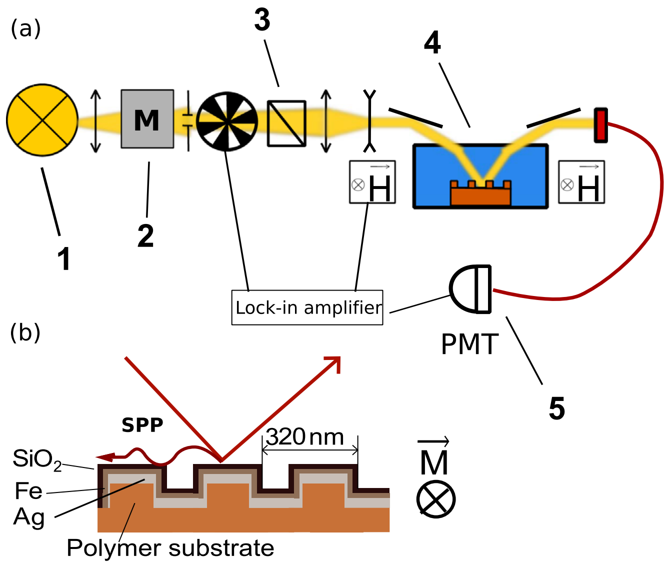

Fig. 1. (a) The scheme of the experimental setup for the magneto-optical surface plasmon resonance sensor: 1 – light source, 2 – monochromator, 3 – Glan-Taylor prism, 4 – flow cell with magnetoplasmonic crystal in an alternating magnetic field, and 5 – photomultiplier tube. (b) The scheme of the magnetoplasmonic trilayer structure and excitation of surface plasmon polaritons.