Enhancement of SPR-sensor Sensitivity in Magnetophotonic Plasmonic Heterostructures

D. O. Ignatyeva[1,2], **S. K. Sekatskii**[3], **A. N. Kalish**[1,2], **and V. I. Belotelov**[1,2]

[1]Faculty of Physics, Lomonosov Moscow State University, Moscow, Russi
[2]Russian Quantum Center, Moscow, Russia
[3]Ecole Polytechnique Federale de Lausanne, Institute of the Physics of Biological Systems
Lausanne, Switzerland

Abstract— We present a novel type of the surface plasmon resonance (SPR) sensor based on the magnetophotonic plasmonic heterostructure and show that utilization of specially designed 1D photonic crystals (PC) along with the magnetic layers (ML) significantly enhances the quality factor and magnitude of the optical and magnetooptical resonances and therefore allows for a several orders of magnitude increase of the SPR-sensor sensitivity.

1. INTRODUCTION

The surface plasmon resonance (SPR)-sensors are one of the most efficient optical sensors available nowadays. Their operation concept is based on the significant variation of the resonant conditions of the surface plasmon polariton (SPP) under the impact of the small variations of the surrounding medium [1, 2]. Such approach allows for a ultra-high sensor sensitivity to the refractive index variations and the selectivity of the sensor is achieved via the special coatings of the plasmonic layers (e.g., antibodies for antigen detection) that attracts the molecules or cells of the certain type. Therefore SPR-sensors are an efficient tool for a wide range of biological, medical and chemical applications among which are detection of chemical and biological compounds, investigation of biomolecular interactions, medical diagnostics pharmacological treatment, monitoring of environment and food control [2].

Lowering the detection threshold of the corresponding substances via the SPR-sensor sensitivity improvement is an important problem of further SPR-sensor development. One of the ways to increase the SPR-sensor sensitivity nearly by an order of magnitude is the utilization of the magnetic layers in the plasmonic structures and tracking of the magnetooptical (transversal magnetooptical Kerr effect (TMOKE), namely) resonance instead of the reflection one [3, 4]. TMOKE has sharper resonance and its magnitude is enhanced compared to the case of the isolated magnetic interface since the excitation of the surface waves leads to the increase of the effects associated with gyrotropic properties of the media [5–8].

The quality factor of the plasmonic or magnetoplasmonic resonance is determined by the damping of the SPP waves excited at the interface. For this reason the magnetic metals (e.g., cobalt, nickel or iron) that have high optical losses are usually used in a combination with the noble ones (such as gold) in the plasmonic structure [3, 4, 9]. If the sensor plasmonic structures are designed to support long-range propagating SPP modes [10–12] the sensitivity is enhanced due to the increase of the optical resonance quality factor. However, usually the refractive index of the analytes (gases or liquids) is smaller than the refractive index of the dielectric layers on which plasmonic structure is deposited on. This makes the structure asymmetric and prohibits the long-range propagating modes existence. At the same time, 1D photonic crystal (1D PC) can be designed to have almost any predetermined effective refractive index and therefore the structure 1D PC-metal-analyte can support long-range SPP modes [12]. It should be pointed out that besides the ultralong-range mode excitation PC is responsible for the enhancement of the MO effects [13].

We propose to use an original magnetophotonic plasmonic heterostructure for the significant enhancement of the SPR-sensor sensitivity. It contains the 1D photonic crystal (PC) for the support of the ultralong-range propagating modes tuned to have the same effective refractive index as analyte. The plasmonic layer contains the magnetic metal film that causes the magnetooptical effects and the layer of the noble metal that prevents the film oxidation.

2. MAGNETOPHOTONIC PLASMONIC HETEROSTRUCTURE FOR SENSING APPLICATIONS

An original magnetophotonic plasmonic heterostructure that is very sensitive to the environmental refractive index changes is proposed to be used in SPR-sensor. The structure is designed to have a resonance at the wavelength of $\lambda_{SPR} = 780\,\text{nm}$ and to perform sensing of the gas refractive indexes as analytes ($n_a \sim 1$). Let us discuss the basic compounds of the structure.

The laser radiation is transformed into the SPP wave via the glass prism made of BK-7 glass. At the operating wavelength it has the refractive index $n_{pr} = 1.513$ that correspond to the total internal reflection angle of $\theta_{TIR} = 41.39$ for the BK-7/air interface.

1D photonic crystal is used for the ultralong-range SPP mode excitation. We use a SiO_2/Ta_2O_5 layered structure ($n_{SiO_2} = 1.455$, $n_{Ta_2O_5} = 2.071$) which layer widths and number of layers are tuned to maximize the SPP propagation distance according to the impedance method described in [14]. Our analysis shows that the optimal layer widths are $l_{SiO_2} = 164\,\text{nm}$ and $l_{Ta_2O_5} = 119.4\,\text{nm}$, and the optimal number of layer pairs is 16. Such PC parameters correspond to the bandgap center at the operating wavelength near angle corresponding to the surface plasmon resonance:

$$n_{Ta_2O_5} l_{Ta_2O_5} \cos\left(\theta_{SPR}^{Ta_2O_5}\right) + n_{SiO_2} l_{SiO_2} \cos\left(\theta_{SPR}^{SiO_2}\right) = \frac{1}{2}\lambda_{SPR}, \tag{1}$$

where θ_{SPR}^{j} is the SPR incidence angle in the corresponding layer of the PC. The numerical simulations show that the quality factor of the SPR resonance is increased if the PC is accompanied by the defect layer of Ta_2O_5 deposited on the PC structure. Optimal width of the defect Ta_2O_5 layer is 108 nm.

The PC is coated with a cobalt film. On the one hand, this film provides the magnetooptical response of the structure. The saturation magnetic field for this film is as low as 7 mT so that very compact electromagnets can be used for remagnetizization of the structure. Application of a very moderate magnetic field of 10–15 mT causes the magnetooptical response of the structure with the gyration constant of about $g = -0.8 - 0.7i$. The magnetic field is applied in a transversal geometry in order to observe the transversal magnetooptical Kerr effect (TMOKE). On the other hand, Co has very high optical losses: the imaginary part of its permittivity is about 3 times larger than the real part $\varepsilon_{Co} = -9.2 + 33.0i$. In order to get the quality factor of the whole heterostructure as high as possible we use a thin Co film of 8 nm thickness in a combination with a gold film deposited on the top of the Co layer.

The imaginary part of the gold permittivity is rather small for this wavelength $\varepsilon_{Au} = -24.1+1.7i$ so the losses of the SPP wave excited in plasmonic structure are rather small. The width of Au layer is chosen 20 nm in order to protect Co layer from oxidation. At the same time, Au is a noble metal and has rather good environmental stability. The schematic representation of the considered magnetophotonic plasmonic heterostructure is shown in Fig. 1.

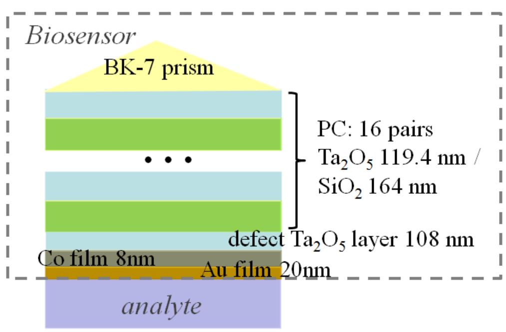

Figure 1: The magnetophotonic plasmonic heterostructure for the SPR-sensor.

The resonance associated with the SPP excitation in this structure is clearly seen in the absorption spectra for TM-polarized radiation (Fig. 2(a)). Due to the excitation of the ulralong-range propagating SPP waves the resonance is extremely narrow and has the spectral width of 4 nm and angular width of 0.08°. The minimal value of the reflection coefficient is 6%.

The magnetization of Co layer affects the SPP in a non-reciprocal way: the propagation constant acquires linear on gyration coefficient addition that has opposite sign for the opposite SPP propagation directions, or, which is the same, for the opposite direction of the magnetic field. This is the origin of the TMOKE δ which reveals in a difference between the structure reflection coefficients R_j for the two opposite magnetization directions:

$$\delta = 2\frac{R_{M+} - R_{M-}}{R_{M+} + R_{M-}}. \tag{2}$$

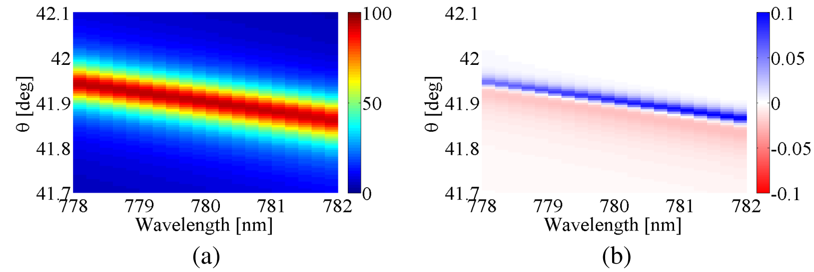

Figure 2: (a) The absorption and (b) TMOKE spectra of the magnetophotonic plasmonic heterostructure of the SPR-sensor.

The TMOKE spectra of the sensor structure is depicted in Fig. 2(b). It is clearly seen that TMOKE resonance is narrower than the reflection (absorption) one and have the spectral width 1.5 nm and angular width 0.03°. The excitation of the SPP wave rises its absolute value up to $\delta = 10\%$.

3. SENSITIVITY OF THE SPR-SENSOR BASED ON THE MAGNETOPHOTONIC PLASMONIC HETEROSTRUCTURE

The sensitivity of the sensor S can be determined as a derivative of the experimentally measured value A with respect to the refractive index of the sensor environment (analyte):

$$S = \frac{\partial A}{\partial n_a}. \tag{3}$$

The threshold variation of the refractive index that can be measured with the sensor equals to

$$\Delta n_{\min} = A_{\min}/S, \tag{4}$$

where $A_{\min}$ is the minimal detectable variation of the A value. There are two basic schemes of the refractive index variation measurement with the SPR-sensor of conventional or magnetooptical type.

The first scheme is to use a convergent light beam of the monochromatic laser radiation focused on a metal surface and an array detector (CCD matrix, for example). The angular components of the beam that corresponds to the near-SPR angle θ_{SPR} are significantly absorbed while the others are reflected so that the variation of the θ_{SPR} due to the environmental changes are seen as the shift of position of the minimal reflection intensity. Using the same scheme the shift of the TMOKE resonance position can be tracked. Notice that although the shift of the TMOKE is determined by the shift of the SPP resonance and thus has absolutely the same value it is usually much easier to measure the θ_{SPR} by magnetooptical measurement. The first reason for this is that the TMOKE resonance, as it is shown above, is much narrower than the SPR. Secondly, δ changes its sign near the SPR so that the shift of the point $\delta = 0$ can be measured more precisely than the shift of the minima of the reflection spectra. The sensing process is illustrated in Fig. 3(a).

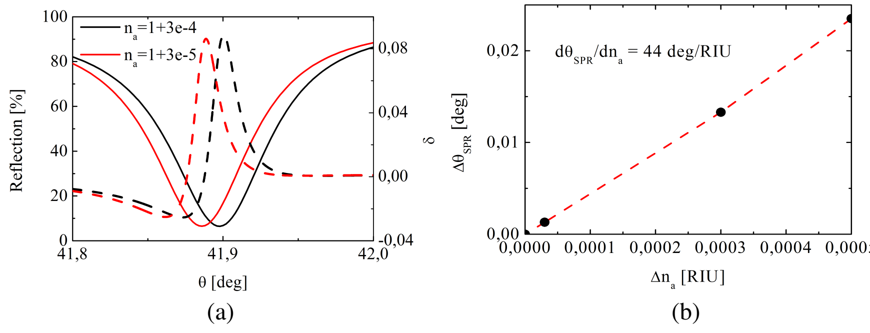

Figure 3: (a) Reflection and TMOKE spectra for two different analyte refractive indices. (b) The linear shift of θ_{SPR} for different refractive indices of analytes.

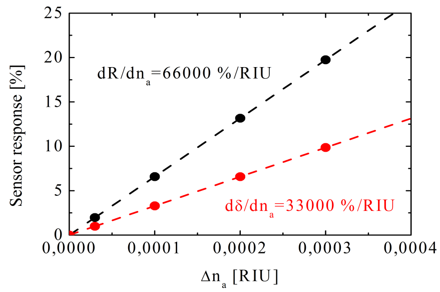

Figure 4: The variation of the structure reflectivity and TMOKE for different analyte refractive indices and the fixed measurement angle.

The numerical estimations predict the sensitivity $S = 44°/\text{RIU}$ (per refractive index unit). Taking the typical resolution of of θ_{SPR} measurement as $5 \cdot 10^{-6}$ (see, for example, [3, 12]) we obtain the threshold $\Delta n_{\min} = 10^{-7}$.

Analogous measurements can be performed with a polychromatic light source (¡halogen¿ lamp, for example) and spectrometer. Instead of the θ_{SPR} shift the wavelength corresponding to the SPR λ_{SPR} changes under the environmental variations. The numerical estimations predict the sensitivity of the proposed sensor $S = 1800\,\text{nm/RIU}$. Using a tunable laser with one can achieve 0.01 nm accuracy in spectral resolution and $\Delta n_{\min} = 5 \cdot 10^{-6}$.

The second scheme implies the usage of the collimated monochromatic light beam and the measurement with the photodetector of the reflection or TMOKE variation for the fixed operating angle and wavelength corresponding to the SPR of the reference analyte.

The sensitivity of the SPR-sensor in such scheme depends not only on the shift of the SPR position but also on the value of the measured value (reflectivity or TMOKE) gradient. The enhancement of the magnetooptical effects results in the increase of the sensitivity of the magnetooptical SPR-sensor compared to the conventional one since the TMOKE effect cam be measured with the higher precision. Fig. 4 illustrates the sensing process.

4. CONCLUSION

A novel type of the surface plasmon resonance (SPR) sensor based on the magnetophotonic plasmonic heterostructure was presented. The feature of this sensor is the simultaneous utilization of the magnetic layers in order to get the magnetooptical response and the specially designed 1D photonic crystals (PC) that significantly enhances the quality factor and magnitude of the optical and magnetooptical resonances. The resulting sensor is shown to have the ultra-high sensitivity compared to the conventional sensors.

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