Wood’s anomaly for plasmonic biosensor based on 1D magnetooptical nanostructure

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Abstract. We demonstrate spectra of slabs of plasmonic 1D nanostructures and show their ability to detect a specific binding of low-density lipoproteins. Optical spectra of the slabs exhibiting a spectrally sharp resonant peak have been analyzed numerically to demonstrate responses of biosensors under study. We show that the sensitivity to biomolecular binding can be considerably increased by utilizing magnetooptical materials as constituent element of plasmonic 1D nanostructures.

1. Introduction

For detecting and monitoring diseases at early stages and in development, when investigating concentrations of biomarkers in the interval from negligible to reference values, highly sensitive, reliable diagnostic approaches are necessary [1,2]. Optical biosensing techniques—using surface plasmon resonance (SPR) [3-5]—are up to date the most commonly used in healthcare and science. The way to increase the sensitivity is utilization of the magnetic layer in the plasmonic structure to measure a magnetooptical (MO) response instead of the transmittance one [6].

In the present work, we demonstrate 500-µm-sized slabs of plasmonic 1D nanostructures with and without magnetic layers for detecting low density lipoproteins (LDL). We experimentally and theoretically study their optical spectra, elucidate main dependencies between structural parameters of optical resonances, give an explanation on resonant light coupling. For the nanostructures having optimal designs, we measured and numerically analyzed optical and MO responses in the transmission geometries when modeling biomolecular binding for LDL with a low concentration.

2. Fabrication, calculation model and experiment

The fabricated 1D pattern had periods of D = 600, 625, 650 and 675 nm, a height and a width of the hydrogen silsesquioxane(HSQ) ridge were set parameters for all samples d_HSQ = 80 nm and h_HSQ = 65 nm correspondingly.
Magnetoplasmonic 1D nanostructure (sample B) had the following parameters: period D=500 nm, height and width of the bismuth-substituted yttrium iron garnet(Bi:YIG) ridge were d_h=60 nm and h_h=100 nm, correspondingly, Bi:YIG film’s thickness d_{Bi:YIG} = 135 nm. The transmission spectra were measured for polarized light by a spectrometer (Ntegra Spectra, NT-MDT) in the wavelength range of 700–950 nm. The measurements were carried out for the Ez-polarized light (see Fig. 1).

For COMSOL Multiphysics models of sample A and B were set up for one unit cell of the 1D grating, with the Floquet boundary conditions along the x axis describing the periodicity and being infinite along the z axis [Fig. 1]. Experimental differential spectra illustrating biomolecular binding were modeled for water conditions by changing the refractive index (n) and extinction coefficient (k) of a covering approx. 20-nm-thick biolayer (the size of LDL molecules), which was 10-nm-lifted from the slab surface (the size of fuctionalizing CS/ApolB biolayer).

3. Discussion
The main optical features (the Wood anomaly) in zero-order transmission spectra of the series of the samples follow the period of the 1D grating as shown in Fig. 2 (a). The asymmetrical Fano contour has a maximum of \( \lambda_R \) discussed in Ref. [7] that was red-shifted from a wavelength of \( \lambda_R = n_{PBS}D \) (the Rayleigh anomaly) and a minimum at \( \lambda_{SPR} = n_{eff}D \), where \( n_{PBS} \) and \( n_{eff} \) are the refractive index of PBS and effective refractive index for the SPR wave, and D is the period of the 1D grating. The spectra show a similar tendency—a slight decrease of the intensity of the Fano peak. These spectra were calculated numerically. The calculated spectra were in a good agreement with the experimental ones; see solid lines and stars for samples A having D = 650 nm and dashed line for sample B having D = 500 nm. Plots (b) in Figs. 2 illustrate responses \( \Delta T \) for optimized slabs. For considered samples A and B, the maximum of \( \Delta T \) =0.01 (sample A) and \( \Delta T \) = 0.005 (sample B) was obtained. The optical response of sample A was twice as much as response of sample B.

We have found that, by introducing Bi:YIG layer, the sensitivity can be significantly enhanced when measuring the MO response in the vicinity of the Fano peak. Indeed, a change in the angle of Faraday rotation \( \Delta \theta =3^\circ \) was demonstrated for sample B with optimized parameters. The mechanism of enhanced polarization rotation is discussed in detail in Ref. [8]. Suppression of the incident E, wave and decoupling the born via magneto-optical activity E, wave having a phase shift is a distinctive feature for the plasmon-enhanced MO response in the nanostructures under present study.

It is worth noting that the demonstrated experimental and calculated optical response allows us to make the next conclusions: (i) there are optimization parameters for a certain design of the grating; they are connected with each other and, correspondingly, influence the Q-factor of the Fano peak defining the sensitivity of the sensor and (ii) a significant increase in sensitivity can be achieved by introducing a magnetic component.

4. Conclusion
Optical spectra of various submillimeter-sized lithography-made 1D gratings have been studied and competitive levels of sensitivity to target biomolecules have been experimentally demonstrated. Our numerical studies demonstrated that the sensitivity can be increased when measuring magneto-optical response of plasmonic 1D nanostructures fabricated from a noble metal and a magnetooptical material.

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Fig. 1. A sketch of the unit cells of experimental sample A and the model of sample B.
Fig. 2. (a) Deferential transmission spectra for sample A (D = 650 nm) when detecting LDL with a concentration of 0.5 ng/µl (circles). Solid line shows fits of experiment (sample A) by modeling a 20-nm thick layer of binding molecules in water, changing optical constants of the layer. Dashed line shows magnetoplasmonic structure (sample B) by modeling a 20-nm thick layer of binding molecules in water, changing optical constants of the layer. (b) Calculated (solid line) and measured (stars) spectra for sample A.

Fig. 3 Magnetooptical response of sample B with an optimized structure (D = 500 nm and h_R = 100 nm). (a) Faraday rotation spectra illustrating biomolecular binding for LDL; (b) a differential Faraday rotation spectrum.