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Magneto-optical Kerr effect enhancement at the Wood's anomaly in magnetoplasmonic crystals

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ABSTRACT

Magneto-optical Kerr effect enhancement in longitudinal and transversal configurations is systematically studied in one- and two-dimensional magnetoplasmonic crystals based on the nanostructured nickel films. Spectral dependences of magneto-optical effects demonstrate resonant features with the Fano-type lineshape in the spectral vicinity of the Wood's anomaly associated with excitation of surface magnetoplasmons in Voigt and Faraday configurations, respectively.

1. Introduction

Miniaturization of photonic devices stimulates the search for the ways of enhancement of magneto-optical phenomena which are intensively used in the wide number of applications. Such enhancement was experimentally observed in different types of magnetophotonic crystals which are periodically structured magnetic dielectrics with period comparable with wavelength of the optical range. Magnetophotonic crystals have been in the focus of attention within the latest few years due to unique abilities of light propagation control they provide utilizing nonreciprocity of magneto-optical effects [1]. In such structures significant Faraday angles and magneto-optical Kerr effect (MOKE) values were achieved [2–8]. Another approach deals with enhancement of magneto-optical response of periodically structured magnetic metallic materials, where propagating surface plasmon-polaritons (SPPs) can be excited due to the phase-matching between wavevectors of incident light and SPP and the vector of reciprocal lattice [9–12]. By analogy with magnetophotonic crystals, such materials can be called as magnetoplasmonic crystals controlling SPP generation and propagation by periodicity parameters. Resonant excitation of SPPs manifests itself in the specular reflection as the Wood's anomaly indicating the appearance of additional channel of light energy flux along the surface.

In this paper, both longitudinal and transversal configurations of MOKE are used for studying the spectral dependence of magneto-optical response enhancement at the Wood's anomaly of one- and two-dimensional (1D and 2D) magnetoplasmonic crystals based on the nanostructured nickel films. Nonsymmetrical Fano-type spectral profiles of Kerr rotation and relative changes in reflectivity are observed in longitudinal and transversal magnetic field applications, respectively. Such lineshape is associated with Faraday and Voigt configurations of magnetoplasmon excitation at the surface of magnetoplasmonic crystal.

2. Experimental

Samples of 1D magnetoplasmonic crystals were fabricated by thermal evaporation of a 100-nm-thick nickel film onto a polymer subwavelength diffraction grating made by nanoimprint lithography. The period is 320 nm and modulation depth is 50 nm. A 2D magnetoplasmonic crystal consists of a 2D array of nickel nanodisks arranged into hexagonal lattice and placed on 500-μm-thick nickel foil. The nanodisk height is 50 nm and diameter is 250 nm; the distance between centers of the neighboring disks is 465 nm. The microscopic images of the samples are shown in Fig. 1 exhibiting good periodicity in the 1D magnetoplasmonic crystal (Fig. 1a) and high-quality hexagonal lattice of the nanodisks in the 2D magnetoplasmonic crystal (Fig. 1b). The images were obtained by using atomic force and scanning electron microscopes, respectively.

3. Experimental results

Fig. 2 shows experimental spectra of reflectance and transversal MOKE (TMOKE) for the 1D magnetoplasmonic crystal measured at

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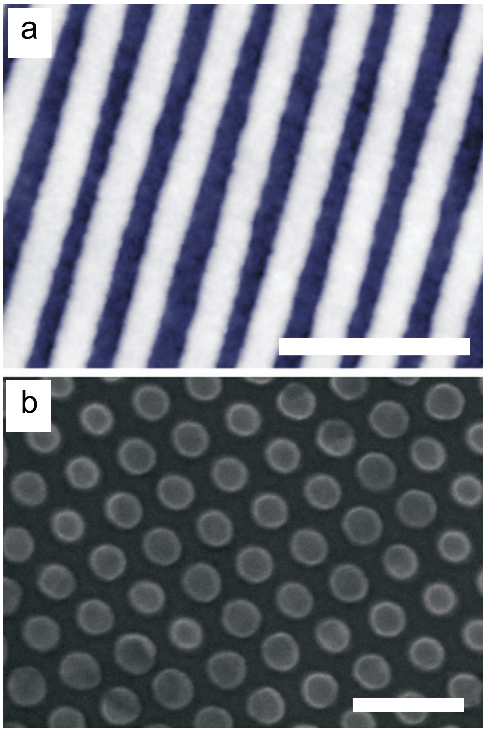

Fig. 1. (a) Atomic force microscopy image of a 1D magnetoplasmonic crystal. (b) Scanning electron microscopy image of a 2D magnetoplasmonic crystal. Scale bars at both images are equal to 1 μm.

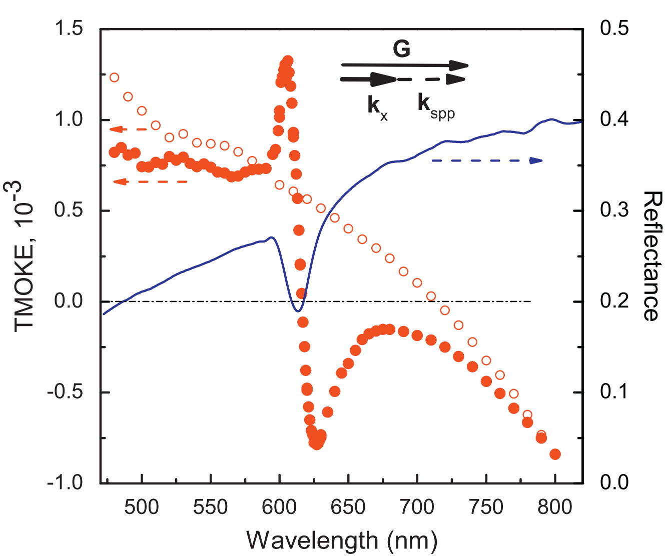

Fig. 2. TMOKE (filled circles) and reflectance (curve) spectra of 1D magnetoplasmonic crystal for reciprocal vector oriented within the plane of light incidence. Open circles: TMOKE spectrum of 1D magnetoplasmonic crystal with reciprocal vector perpendicular to the incident plane. Angle of incidence is 60°. Inset: schematic of the SPP phase-matching conditions.

angle of incidence of 60° for two azimuthal orientations of reciprocal vector **G** with respect to the incident plane. The TMOKE value is defined as $\delta=(R(\mathbf{M})-R(-\mathbf{M}))/R_0$, where $R(\mathbf{M})$, $R(-\mathbf{M})$ and R_0 are the reflectance with and without external magnetic field. The curve in Fig. 2 is a reflectance spectrum for p-polarized light measured in the specular direction as reciprocal vector **G** is oriented within the plane of incidence providing the phase-matching conditions for effective excitation of surface plasmons. A resonant dip associated with the Wood's anomaly is seen at 615 nm. The energy coupled to surface plasmons is adsorbed strongly by the nickel film yielding short

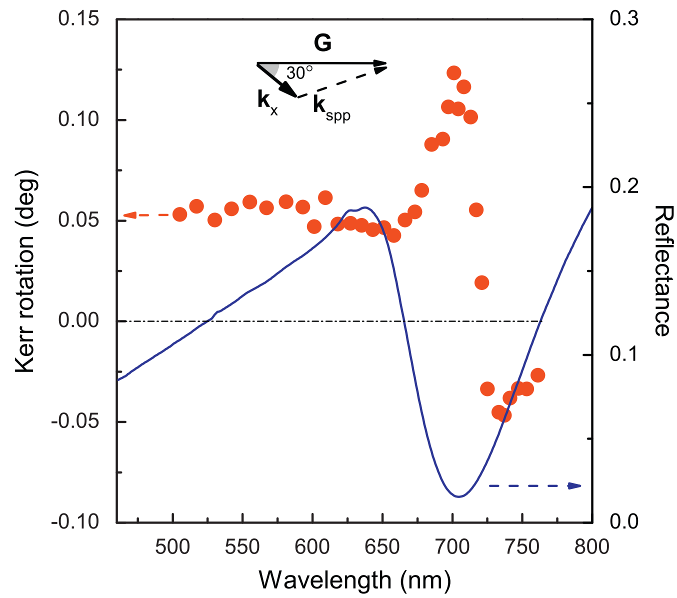

Fig. 3. Spectral dependences of Kerr rotation angle in longitudinal MOKE configuration (circles) and of reflectance (curve) measured in 2D magnetoplasmonic crystal. Angle of incidence is 45°. Inset: schematic of the SPP phase-matching condition.

plasmon lifetime, small phase shifts of the re-radiated light, and consequently symmetric line shape of the Wood's anomaly. The TMOKE spectrum shown in Fig. 2 demonstrates the bright resonant behavior in a narrow vicinity of the Wood's anomaly. The TMOKE resonance is strongly asymmetric and has the spectral lineshape typical for the Fano-type resonance. The specific feature of the TMOKE resonance is the change of the sign. The reference TMOKE spectrum shown by open circles is measured for the sample azimuthal orientation as reciprocal vector is perpendicular to the incident plane providing the spectral behavior similar to a plain nickel film. The spectrum decays monotonously with the wavelength as it was expected for a non-structured nickel surface. The schematic of the phase matching conditions fulfilled at the Wood's anomaly is sketched in the inset of Fig. 2, where k_x is projection of the light wave vector onto the sample surface and k_{spp} is the SPP wavevector.

Fig. 3 shows the results of the longitudinal Kerr effect measurements in 2D magnetoplasmonic crystal at the angle of incidence of 45° for saturated magnetic field of 3 kOe. The sample is oriented exactly in between two reciprocal vectors of hexagonal lattice with **G** tilted at 30° with respect to the plane of incidence. The specular reflectance spectra for p-polarized light shows the Wood's anomaly at 700 nm. The Kerr rotation angle θ_K measured in longitudinal MOKE configuration is enhanced up to 0.15° at the resonance wavelength coinciding with the dip in the reflectance spectra and changes the sign upon spectral tuning across the Wood' anomaly.

4. Discussion

SPP excitation in nickel magnetoplasmonic crystals is proved experimentally by the strong difference in reflectivity spectra for s- and p-polarized incident light. For p-polarized light energy flux is redistributed among the (-1)-st diffraction order, specular reflected light (the 0-th order of diffraction) and the SPP wave. Excitation of SPPs needs some supplementary energy that is accompanied by weakening the intensity of specularly reflected light. This manifests itself as the Wood's anomaly in the reflectivity spectrum. For the s-polarized light weakening of the reflected beam is not observed due to SPP polarization selection rule. The full-width at half maximum (FWHM) of the Wood anomaly is approximately 30 nm that is several times wider than the FWHM value observed in plasmonic crystals fabricated from noble metals. The Wood's anomaly width is mostly defined by absorption damping of SPPs in nickel due to the large imaginary part of its permittivity being $\varepsilon'' \approx 13.6$ at $\lambda = 620$ nm while $\varepsilon' \approx -9.3$.

Enhancement of transversal MOKE can be phenomenologically interpreted as a result of the SPP dispersion curve shift upon the magnetization reversal at the surface of magnetoplasmonic crystal. Thus, the reflectivity minimum associated with the Wood's anomaly is also shifted in spectrum because of the change in the SPP phase-matching condition. Since the value of transversal MOKE is proportional to the reflectivity difference for opposite magnetization directions, the spectral dependence of transversal MOKE has an asymmetric resonant lineshape.

The observation of MOKE enhancement at the Wood's anomaly can be treated as a finger-print of the dc magnetic-field influence on the surface plasmon propagation since in the presence of external magnetic field SPPs have properties of magnetoplasmons [13]. In this way transversal MOKE relates to the Voigt configuration of magnetoplasmons, while longitudinal MOKE experiments represent the Faraday configuration. Surface magnetoplasmon modes in the Voigt configuration becomes asymmetric with respect to the magnetization direction and the dispersion spectrum reveals a magnetic-field-induced shift. Polarization of magnetoplasmon wave remains to be TM just as in the absence of magnetic field, while the wavevector of magnetoplasmonic mode, k_{spp}^{M}, depends on the value of the off-diagonal component of dielectric permittivity, g, in the following form [13,14]:

$$k_{spp}^{M} = k_{spp}\left(1 \pm \frac{g}{\xi}\right), \quad (1)$$

where

$$\xi = \sqrt{\varepsilon_0 \varepsilon_1}\left(1 - \frac{\varepsilon_0^2}{\varepsilon_1^2}\right), \quad (2)$$

and

$$k_{spp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_0 \varepsilon_1}{\varepsilon_0 + \varepsilon_1}} \quad (3)$$

is the SPP wavevector in the absence of magnetization, ε_0 is the dielectric permittivity of the space outside the magnetoplasmonic crystal and ε_1 is the diagonal component of the nickel dielectric permittivity. Thus, phase matching for SPP excitation in opposite magnetization directions are fulfilled for slightly different wavelengths that results in asymmetric spectral lineshape of the transversal MOKE enhancement.

Another situation is realized in the Faraday configuration of magnetoplasmonic modes excitation which is experimentally probed via longitudinal MOKE. In this case plasmonic wave contains a TE component as well and SPP can be represented as a coherent superposition of two components with right and left conical polarizations [15]. Within the approximation linear in g, dispersion relation for these components can be written as

$$k_{spp}^{R(L)} = k_{spp}\left(1 \pm \frac{1}{2}\frac{\varepsilon_0}{(\varepsilon_0 + \varepsilon_1)\varepsilon_1} g\right). \quad (4)$$

Total amplitude of SPP is determined by the sum of these components and the SPP polarization is determined by the phase shift between them. The phase difference controls the enhancement of Kerr rotation obtained in the specular direction. The asymmetric lineshape of the Kerr rotation spectra at the Wood's anomaly is attributed to slightly different phase-matching conditions for SPP modes with wavevectors k_{spp}^{R} and k_{spp}^{L}.

5. Conclusions

In conclusion, spectral behavior of transversal and longitudinal magneto-optical Kerr effects in one- and two-dimensional magnetoplasmonic crystals possesses resonant Fano-type enhancement in the angular-spectral vicinity of the Wood's anomaly, which is associated with the phase-matching with magnetoplasmon modes excited in Voigt and Faraday configurations, respectively.

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