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Resonant surface magnetoplasmons in two-dimensional magnetoplasmonic crystals excited in Faraday configuration

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The resonant excitation of surface magnetoplasmons in Faraday configuration is studied via spectroscopy of the longitudinal magneto-optical Kerr effect (LKE) in two-dimensional nickel-based magnetoplasmonic crystals. The fulfillment of phase matching conditions for surface plasmon-polaritons using both reciprocal vectors of the magnetoplasmonic crystal allows tuning of the LKE enhancement in the wide spectral range. © *2012 American Institute of Physics*. [doi:10.1063/1.3679574]

I. INTRODUCTION

The use of plasmonic and photonic resonances for the realization of magneto-optical effect enhancement in nanostructured materials has been studied in the past several years.[1,2] Both local[3] and propagating[4] surface plasmons were used to control the magneto-optical response of nanoparticles[3] and multilayer structures.[5] One of the up-to-date approaches for the observation of magnetoplasmonic effects is the use of magnetoplasmonic crystals, which are boundaries between magnetic and nonmagnetic media with subwavelength nanostructuring.[4] By analogy with their close counterpart, magnetophotonic crystals,[1,2,6–9] periodic nanostructuring of magnetoplasmonic crystals leads to modification of the light propagation in these materials. Recently, magneto-optical effect enhancement was realized in one-dimensional magnetoplasmonic crystals.[4] Two-dimensional periodicity provides the possibility of spectral tuning of the phase-matching conditions for surface plasmon-polaritons (SPPs) via the superposition of two reciprocal vectors of the structure. In this paper, the longitudinal magneto-optical Kerr effect (LKE) is studied in two-dimensional magnetoplasmonic crystals. Enhancement and resonance of the Kerr rotation are observed and are attributed to the resonant excitation of magnetoplasmonic modes in the Faraday configuration.

II. THEORY

The dispersion relation $\boldsymbol{k}_{spp}(\omega)$ for the surface plasmon-polariton propagating along the boundary between media with permittivities of ε_1 and ε_2 can be written as[10]

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

If one of the media is gyrotropic with a magnetization **M** directed along its surface (along the x axis), then the permittivity tensor $\hat{\varepsilon}$ will be written as follows:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & i\varepsilon Q \\ 0 & -i\varepsilon Q & \varepsilon \end{pmatrix}, \tag{2}$$

where Q is the normalized gyrotropy vector. Let us assume that SPP propagates along the x-axis with $\boldsymbol{k}_{spp} \| \boldsymbol{M}$. In the case of $Q \ll 1$, one can replace ε with[11]

$$\varepsilon(1 \pm Q) \tag{3}$$

for a gyrotropic medium in the concerned configuration. This is a Faraday configuration for magnetoplasmons.[12] In this configuration, superposition of the two coherent components of SPPs with different dispersion relations appears. The wavevectors of the components can be obtained by replacing ε_1 in Eq. (1) with $\varepsilon_1(1 \pm Q)$ as follows:

$$k^{\pm} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_2(\varepsilon_1 \pm \varepsilon_1 Q)}{\varepsilon_2 + (\varepsilon_1 \pm \varepsilon_1 Q)}} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}\sqrt{\frac{1 \pm Q}{1 \pm \varepsilon_1 Q/(\varepsilon_1+\varepsilon_2)}} = k_{spp}\sqrt{\frac{1 \pm Q}{1 \pm \varepsilon_1 Q/(\varepsilon_1+\varepsilon_2)}}. \tag{4}$$

In the case of $Q \ll 1$,

$$(1 \pm Q)^{1/2} \approx 1 \pm \frac{1}{2}Q, \tag{5}$$

$$\left(1 \pm \frac{\varepsilon_1 Q}{\varepsilon_1+\varepsilon_2}\right)^{-1/2} \approx 1 \mp \frac{1}{2}\frac{\varepsilon_1 Q}{\varepsilon_1+\varepsilon_2}. \tag{6}$$

Finally, by neglecting terms proportional to Q^2, one can obtain the dispersion relation of the two magnetoplasmonic components in the following form:[13]

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$$k^{\pm} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}\left(1\pm\frac{1}{2}\frac{\varepsilon_2 Q}{\varepsilon_1+\varepsilon_2}\right) = k_{spp}\left(1\pm\frac{1}{2}\frac{\varepsilon_2 Q}{\varepsilon_1+\varepsilon_2}\right). \tag{7}$$

The splitting of the dispersion relation of two magnetoplasmonic components can be treated as two separate dispersion laws for "left-" and "right-" conically polarized magnetoplasmons. The total effect of polarization rotation in the beam reflected from the surface can be treated as a Faraday effect for magnetoplasmons.

The dispersion law splitting can be probed by analyzing the longitudinal magneto-optical Kerr effect spectrum. If a surface is magnetized along the plane of incidence, LKE presents itself as a rotation of the polarization of the reflected beam. A flat nickel surface demonstrates a smooth and slowly changing wavelength dependence for the LKE spectrum, whereas a magnetoplasmon has a narrow wavelength range to excite. One can observe a LKE spectrum in the presence of magnetoplasmons near frequencies of its excitation in order to study the enhancement of the polarization rotation caused by the "magnetoplasmonic Faraday effect."

When a plasmon propagates along a periodically modulated surface, its dispersion law is distorted, leading to the appearance of a plasmonic bandgap. Plasmons with a frequency lying within the plasmonic bandgap cannot propagate along a surface with any wavevector, whereas at the bandgap edges effects caused by a strongly nonlinear dispersion law can be observed.

III. EXPERIMENTAL

The experimental sample of a 2D magnetoplasmonic crystal was a hexagonally packed array of nickel disks with a height of approximately 50 nm and a diameter of 250 nm, fabricated on top of bulk nickel. The distance between the nearest disks is 465 nm. A SEM image of the sample is shown in Fig. 1.

The sample has three directions of periodicity. The periodic structure of the sample can be described by a hypothetical lattice with crosspoints placed on the centers of the disks. The reciprocal lattice of the sample has six reciprocal vectors, shown by solid blue arrows (labeled "G"), the directions

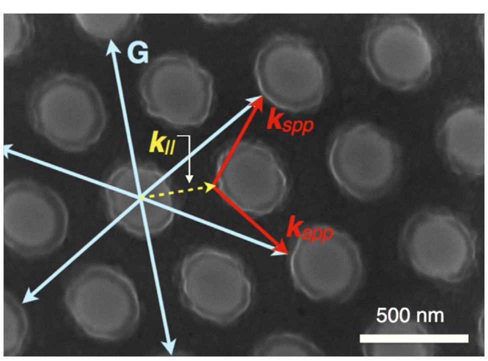

FIG. 1. (Color online) SEM image of the experimental sample of 2D magnetoplasmonic crystal. The diameter of the disks is 250 nm, the distance between the nearest disks is 465 nm, and the height is 50 nm. Six arrows (one of them is labeled as "**G**") stand for reciprocal vectors of 2D magnetoplasmonic crystal; the dashed arrow is for $\boldsymbol{k}_{||}$, and two vectors labeled "$\boldsymbol{k}_{spp}$" are for "$\boldsymbol{k}_{spp}$".

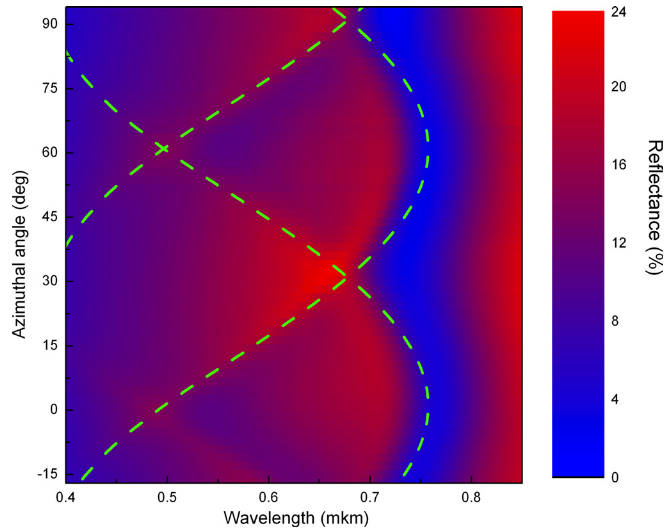

FIG. 2. (Color online) Experimental reflection spectra of the 2D magnetoplasmonic crystal sample. Reflectance is denoted by the colorscale. The angle of incidence $\theta = 45°$. The calculated spectral positions of the spectral resonance caused by SPP excitation are shown by dashed curves. The blue vertical band toward the right of the figure, moving with the azimuthal angle, represents a dip that is attributed to the SPP excitation. The periodicity of the graph is caused by the rotational symmetry of the sample.

of which coincide with the directions of periodicity of a 2D magnetoplasmonic crystal. Reciprocal vectors can contribute to the fulfillment of phase-matching conditions for effective SPP excitation, which can be written as

$$\boldsymbol{k}_{spp} = L(\mathbf{G}) - \boldsymbol{k}_{||}, \tag{8}$$

where $\boldsymbol{k}_{||}$ is the projection of the wave vector of the incident light to the surface of the sample and $L(\mathbf{G})$ is a linear combination of **G**-vectors. Figure 2 shows the series of experimental reflectance spectra measured as a function of azimuthal angle and wavelength. The azimuthal angle ψ is defined as the angle between $\boldsymbol{k}_{||}$ and one of the reciprocal vectors. There are two particular phase-matching condition configurations in the case of a 2D hexagonal lattice for each of six equivalent reciprocal lattice vector directions. The first phase-matching condition appears if $\boldsymbol{k}_{||}$ is parallel to **G** and $\boldsymbol{k}_{spp}$ simultaneously. It involves a single vector **G** and corresponds to $\psi = 0°$, 60°. The second type of phase-matching is observed at $\psi = 30°$, 90°, as two non-collinear **G**-vectors are involved symmetrically. The spectral position of the dip in reflection spectra observed in the spectral interval between 700 and 750 nm is attributed to SPP excitation. The dip shifts with the azimuthal angle due to changes in the phase-matching conditions. The six-fold symmetry of the spectra over the azimuthal angle corresponds to hexagonal ordering of nickel disks on the nickel surface.

The experimental setup for magneto-optical measurements includes a filament lamp as a light source with a monochromator to separate and tune a wavelength. Behind the monochromator a polarizing Glan prism is placed. The sample is fixed at the two-axes rotation stage to control its azimuthal angle and angle of incidence. The saturating magnetic field of 3 kOe is applied along the direction of incidence. The second Glan prism analyzes the light polarization

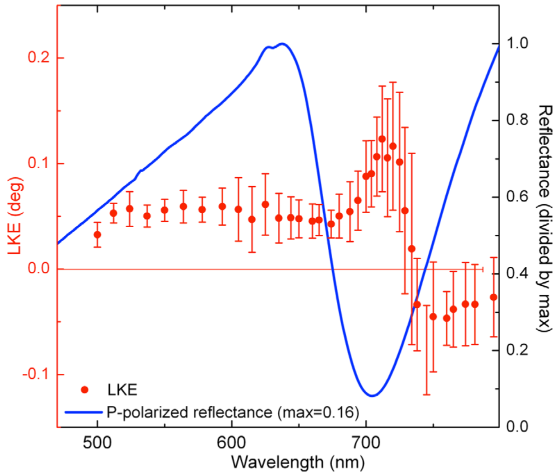

FIG. 3. (Color online) LKE spectrum for a sample of 2D magnetoplasmonic crystal (solid circles). Reflectance spectrum for p-polarization of the incident beam is also shown by the solid blue line. Reflectance spectrum is normalized over the maximal value in the spectral interval shown. The angle of incidence is 45°; the azimuthal angle is 30°.

state to extract the Kerr rotation angle. The magnetic field sign alternation allows one to extract a low Kerr signal from the background.

Figure 3 shows the LKE spectrum measured at $\theta = 45°$ and $\psi = 30°$ for a p-polarized incident beam. The reflectance spectrum of the p-polarized wave is represented in Fig. 3 by the solid blue curve. The spectral position of the LKE resonance correlates with the SPP-resonance position. This can be attributed to energy coupling from the incident beam to SPPs propagating in the gyrotropic medium and then being re-emitted from it. The sensitivity of SPPs to magnetic field yields LKE resonance in the vicinity of their excitation frequencies. It can be interpreted as magnetoplasmon excitation in a Faraday configuration with magnetization along the plane of incidence. The asymmetrical Fano-type line shape of the LKE resonance is in agreement with previously provided calculations.[13]

IV. CONCLUSION

A surface magnetoplasmon excitation in 2D magnetoplasmonic crystals is observed via measurement of the longitudinal magneto-optical Kerr rotation spectrum. The periodicity of magnetoplasmonic crystal allows one to excite surface plasmon-polaritons by fulfilling the phase-matching involving reciprocal vectors of 2D magnetoplasmonic crystal. The small difference in dispersion laws for left- and right-conical components of surface magnetoplasmons in the presence of magnetization leads to resonant changing of the longitudinal Kerr effect spectrum. The difference allows one to treat the polarization rotation phenomenon with magnetization directed along the propagation direction of the magnetoplasmons as a Faraday effect for magnetoplasmons. The asymmetrical shape of longitudinal Kerr effect resonance can be treated as a result of interference between reflected light and light re-emitted by magnetoplasmons.

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