Journal of Applied Physics

Transversal magneto-optical Kerr effect in two-dimensional nickel magnetoplasmonic crystals

A. V. Chetvertukhin, A. A. Grunin, T. V. Dolgova, M. Inoue, and A. A. Fedyanin

Citation: J. Appl. Phys. **113**, 17A942 (2013); doi: 10.1063/1.4801639
View online: http://dx.doi.org/10.1063/1.4801639
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v113/i17
Published by the American Institute of Physics.

JOURNAL OF APPLIED PHYSICS 113, 17A942 (2013)

Transversal magneto-optical Kerr effect in two-dimensional nickel magnetoplasmonic crystals

A. V. Chetvertukhin,[1] A. A. Grunin,[1] T. V. Dolgova,[1] M. Inoue,[2] and A. A. Fedyanin[1,a)]
[1]*Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[2]*Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan*

(Presented 17 January 2013; received 5 November 2012; accepted 4 March 2013; published online 12 April 2013)

Resonant transversal magneto-optical Kerr effect (TKE) is experimentally studied in 2D nickel magnetoplasmonic crystal. Gradual transition between collinear and bi-directional types of surface plasmon-polariton phase matching and its influence on TKE resonances are observed by measuring and analyzing dependence of reflectance and TKE spectra on the azimuthal angle. © *2013 AIP Publishing LLC* [http://dx.doi.org/10.1063/1.4801639]

I. INTRODUCTION

Magnetoplasmonic effects such as resonant enhancement of magneto-optical response in systems supporting either local/localized or propagating surface plasmons are intensively studied last years in various nanostructured metallic materials.[1–6] Besides, magnetoplasmonic crystals[7] are prospective media for time-domain femtosecond-scale magneto-optics similar to that in magnetophotonic crystals[8] because the mean lifetime of resonantly excited surface plasmon-polaritons (SPPs) varies from tens to hundreds of femtoseconds.[9,10] Experimental studies of magneto-optical effects in the systems supporting propagating plasmons are mainly focused on one-dimensional plasmonic gratings. Excitation of SPP requires phase matching conditions' fulfillment, which gives rise to Wood's anomalies in reflectance spectrum and asymmetric Fano-shaped resonances in magneto-optical response.[3] On the other hand, one-dimensional systems provide a single reciprocal lattice vector. It means that excitation of multidirectional SPP with non-collinear reciprocal vectors is impossible. Two-dimensional (2D) planar systems possessing more reciprocal vectors give an additional flexibility for controlling the SPP excitation and, as a consequence, magneto-optical response via the azimuthal angle, i.e., via mutual orientation of plane of incidence and reciprocal lattice of magnetoplasmonic crystal. Simultaneous bi-directional non-collinear SPP generation is geometrically allowed in a 2D plasmonic grating at a nonzero angle of incidence. In this paper, the resonant surface-plasmon-enhanced magneto-optical transversal Kerr effect (TKE) is studied in a hexagonal two-dimensional planar magnetoplasmonic crystal fabricated from 2D-nanostructured nickel film.

II. THEORY

Plasmonic crystals, which are metallic diffraction gratings with wavelength-scale period, support SPP propagation and provide its excitation by a beam diffracted along the surface.[11] Momentum conservation law is represented in the form of the following vector equation:

$$\mathbf{k}_{spp}(\omega) = \mathbf{k}(\omega) + \mathbf{G}, \tag{1}$$

where $\mathbf{k}$ is tangential projection of the incident light wavevector, $\mathbf{G}$ is the vector of reciprocal lattice, and $\mathbf{k}_{spp}$ is the SPP wavevector

$$|\mathbf{k}_{spp}| = |\mathbf{k}|\sqrt{\frac{\varepsilon_{\mathrm{Ni}}}{\varepsilon_{\mathrm{Ni}}+1}}. \tag{2}$$

Dispersion relation for both components of dielectric constant of nickel, $\varepsilon'_{\mathrm{Ni}}$ and $\varepsilon''_{\mathrm{Ni}}$, should be taken into account: $\varepsilon_{\mathrm{Ni}} = \varepsilon_{\mathrm{Ni}}(\omega) = \varepsilon'_{\mathrm{Ni}}(\omega) + i\varepsilon''_{\mathrm{Ni}}(\omega)$. The values of real and imaginary parts of $\varepsilon_{\mathrm{Ni}}$ are comparable in the spectral region under consideration (visible and near infra-red). To fulfill collinear and bi-directional phase matching conditions, one can vary the azimuthal angle, that is, the angle between the plane of incidence and one of reciprocal vectors $\mathbf{G}$. The vector equation (1) thus contains azimuthal angle as a variable and there is a relationship between azimuthal rotation of the sample and the wavelength of incident light exciting SPP. Consequently, the wavelength of the SPP-induced dip in the reflectance spectra shifts with rotating the sample as shown in Fig. 2. The structure of the studied 2D magnetoplasmonic crystal has a 6-fold rotation symmetry (Fig. 1(a)). There are two special cases of mutual orientation of vectors $\mathbf{k}$, $\mathbf{G}$, and $\mathbf{k}_{spp}$. The first one is the collinear case as $\mathbf{k}$ is oriented along one of the $\mathbf{G}$-vectors and SPP is excited collinear to both of them as depicted in Fig. 1(b). The second one is a bi-directional case as $\mathbf{k}$ is the bisection of the angle between two $\mathbf{G}$ vectors. Thereby, two symmetrical surface plasmons are excited as seen in Fig. 1(c).

The TKE value is defined as $(R(H) - R(-H))/R(0)$, where H is the external magnetic field magnitude and R is the reflectance. Magnetic field is applied perpendicularly to the plane of incidence. Dispersion law of SPP is influenced by magnetization of sample[3,4] leading to resonant modification of TKE spectrum in the vicinity of the SPP excitation wavelength.

III. EXPERIMENTAL

Experimental sample is a hexagonal ordered array of Ni-disks fabricated by electron beam lithography on top of a

a)Electronic mail: fedyanin@nanolab.phys.msu.ru

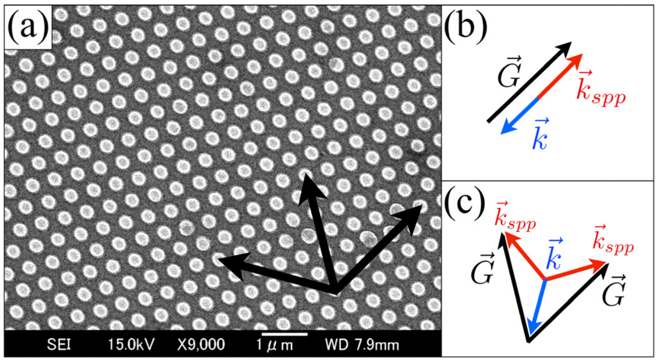

FIG. 1. (a) Scanning electron microscope image of the 2D magnetoplasmonic crystal sample. Black arrows show three of six reciprocal vectors **G** of the structure. (b) Collinear excitation of SPP. (c) Bi-directional excitation of SPP. **k** is the tangential projection of the incident light wavevector. Azimuthal angle is defined as the angle between **k** and **G**.

bulk nickel substrate. The period of the structure is approximately 420 nm in each of three main surface directions. The height of the disks is approximately 50 nm and diameter is approximately 290 nm. Three main vectors of the reciprocal lattice **G** are shown in Fig. 1(a).

The reflectance spectra for the *p*-polarized light are measured for various azimuthal angles at the fixed angle of incidence of 45°. A series of the spectra measured with the 2° step of the azimuthal angle are shown in Fig. 2. Central frequency of the resonant features is spectrally shifted with the azimuthal angle change. One can find a repeating pattern with the azimuthal angle period of 60°. The dashed curve in Fig. 2 is the phase matching condition calculated with both real and imaginary parts of $\varepsilon_{Ni}(\omega)$ taken into account. A typical shape of the resonance is shown in Fig. 3 (top panel) for the chosen azimuthal angle of 12° with the white solid curve (right-Y axis). Each U-shape path of the resonant features in Fig. 2 can be related to SPP excitation with one of the reciprocal lattice vectors **G** fulfilling the phase matching condition. Cross points of U-shape paths (azimuthal angle 30° in Fig. 2) can be treated as two different SPPs, which are simultaneously excited involving two different reciprocal vectors **G**. The simultaneous excitation of two different SPPs can be observed in 2D plasmonic crystals due to their geometrical properties. The reflectance maxima at the cross points can be attributed to plasmonic band gap formed by two projections of SPP k vectors.

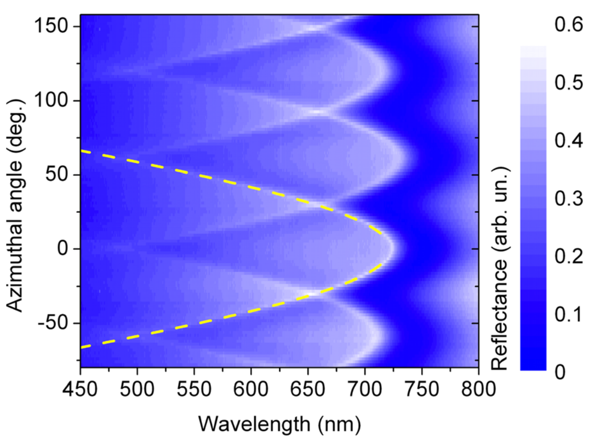

FIG. 2. Reflectance spectra of the 2D magnetoplasmonic crystal sample measured for the *p*-polarized incident light. Dashed curve shows the position of the SPP resonance calculated from the phase matching condition (1). Azimuthal angles of −30°, 30°, 90°, and 150° correspond to the bi-directional phase matching shown in Fig. 1(c); azimuthal angles of −60°, 0°, 60°, and 120° correspond to the collinear phase matching (Fig. 1(b)).

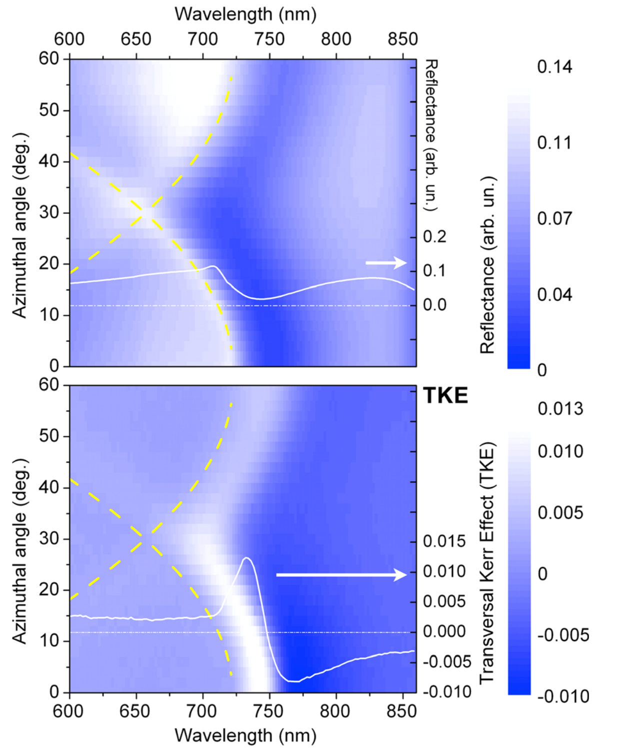

FIG. 3. Top panel: Reflectance spectra of 2D magnetoplasmonic crystal measured for *p*-polarization of the incident light. Solid white curve is the reflectance spectrum measured at the azimuthal angle of 12° (the right-Y axis). Bottom panel: TKE spectra measured under the same conditions. Dashed curves denote SPP dispersion laws calculated by using Eq. (1). Solid white curve is the TKE spectrum at azimuthal angle of 12° (the right-Y axis). Horizontal dotted-dashed lines in both panels depict zero level for the right-Y axes.

The TKE spectra were measured using a halogen incandescent light source and a detection system locked-in to 70 Hz-modulated magnetic field. Fig. 3 shows a set of reflectance and TKE spectra measured with varying the azimuthal angle with a 2° step. For each azimuthal angle, the TKE resonance has similar shape but shifted to the red as compared to the reflectance spectrum. Dashed curves show calculated positions of the SPP central wavelength obtained with taking real and imaginary parts of ε_{Ni} into account.

Magnetoplasmons propagate along a magnetized surface; their dispersion relation depends on the magnetization.[12,13] TKE resonances are spectrally shifted in comparison with that observed in the reflectance spectra. Light coupled to SPPs effectively interacts with magnetic medium and is re-emitted back. Interference between specularly reflected light and light re-emitted from magnetoplasmon results in a Fano-shape spectral resonance. One can see that the reflectance spectrum at an azimuthal angle of 12° (solid white curve in Fig. 3, top panel) has an asymmetrical Fano-type lineshape with the maximum at approximately 710 nm and the minimum at approximately 745 nm. The TKE spectrum shown in the bottom panel of Fig. 3 measured at 12° demonstrates more pronounced Fano-shape resonance at the same azimuthal angle (solid white curve) with changing the sign of the TKE. Spectral cross point of different TKE resonances is correlated with the cross point of resonances in the reflectance spectra; this can be treated as excitation of bi-directional surface magnetoplasmons in 2D magnetoplasmonic crystal.

IV. CONCLUSIONS

Excitation of surface magnetoplasmons propagating along a 2D nickel magnetoplasmonic crystal is probed by optical spectroscopy at various azimuthal angles. Enhancement of reflectance at the azimuthal angle near the bi-directional SPP excitation can be related to plasmonic bandgap formed by two projections of the SPP wavevectors. Resonant lineshape of the TKE spectrum associated with surface magnetoplasmon excitation is studied at two distinctive phase matching cases of collinear and bi-directional configurations. Correlations of frequency position and shift of Fano-type resonances of the TKE spectra with the reflectance spectra prove the relationship between TKE resonances and excitation of surface magnetoplasmons.

ACKNOWLEDGMENTS

This work was supported by Russian Ministry of Education and Science, Russian Foundation for Basic Research (12-02-12092, 12-02-33107, 13-02-92116) and Ministry of Education, Culture, Sport and Technology of Japan.

[1]A. B. Khanikaev, A. V. Baryshev, A. A. Fedyanin, A. B. Granovsky, and M. Inoue, Opt. Express **15**, 6612 (2007).
[2]G. Armelles, A. Cebollada, A. García-Martín, J. García-Martín, M. González, J. González-Díaz, E. Ferreiro-Vila, and J. Torrado, J. Opt. A, Pure Appl. Opt. **11**, 114023 (2009).
[3]A. A. Grunin, A. G. Zhdanov, A. A. Ezhov, E. A. Ganshina, and A. Fedyanin, Appl. Phys. Lett. **97**, 261908 (2010).
[4]C. Clavero, K. Yang, J. R. Skuza, and R. A. Lukaszew, Opt. Lett. **35**, 1557 (2010).
[5]A. A. Grunin, N. A. Sapoletova, K. S. Napolskii, A. A. Eliseev, and A. A. Fedyanin, J. Appl. Phys. **111**, 07A948 (2012).
[6]V. I. Belotelov, A. N. Kalish, A. K. Zvezdin, A. V. Gopal, and A. S. Vengurlekar, J. Opt. Soc. Am. B **29**, 294 (2012).
[7]A. V. Chetvertukhin, A. A. Grunin, A. V. Baryshev, T. V. Dolgova, H. Uchida, M. Inoue, and A. A. Fedyanin, J. Magn. Magn. Mater. **324**, 3516 (2012).
[8]A. V. Chetvertukhin, M. I. Sharipova, A. G. Zhdanov, T. B. Shapaeva, T. V. Dolgova, and A. A. Fedyanin, J. Appl. Phys. **111**, 07A944 (2012).
[9]D. S. Kim, S. C. Hohng, V. Malyarchuk, Y. C. Yoon, Y. H. Ahn, K. J. Yee, J. W. Park, J. Kim, Q. H. Park, and C. Lienau, Phys. Rev. Lett. **91**, 143901 (2003).
[10]A. S. Vengurlekar, A. V. Gopal, and T. Ishihara, Appl. Phys. Lett. **89**, 181927 (2006).
[11]H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer, 1988).
[12]A. G. Zhdanov, A. A. Fedyanin, A. V. Baryshev, A. B. Khanikaev, H. Uchida, and M. Inoue, Proc. SPIE **6728**, 67282V (2007).
[13]A. V. Chetvertukhin, A. V. Baryshev, H. Uchida, M. Inoue, and A. A. Fedyanin, J. Appl. Phys. **111**, 07A946 (2012).