Journal of Magnetism and Magnetic Materials 383 (2015) 110–113

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Transverse magneto-optical Kerr effect in 2D gold–garnet nanogratings

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ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form
17 November 2014
Accepted 20 November 2014
Available online 23 December 2014

Keywords:
Magnetoplasmonics
Magnetoplasmonic crystals
Magnetophotonic crystals
Magneto-optical Kerr effect

ABSTRACT

Planar magnetoplasmonic nanogratings composed of a two-dimensional square array of gold nanoparticles embedded into thin magnetic garnet films are proposed for enhancement of the transverse magneto-optical Kerr effect due to excitation of a quasi-waveguiding mode with light concentrated mostly inside the magnetic film. A proper optimisation of the size and periodicity of plasmonic nanoparticles as well as the thickness of magnetic dielectrics allows spectral tuning of the waveguiding mode leading to the sharp asymmetric resonance in the magneto-optical response in the desired spectral region.

1. Introduction

Recently, magnetoplasmonics became a rapidly developed branch of magneto-optics targeted at realisations of various approaches of the magneto-optical effects enhancement involving plasmon excitations [1]. One of the efficient schemes for plasmon-induced control of magneto-optical effects is magnetoplasmonic crystals utilising the resonances of propagating surface plasmon–polaritons (SPP's) excited in nanostructured magnetic metal films [2–4] or in hybrid metal–dielectric nanostructures containing noble metals and magnetic dielectrics [5–7]. Subwavelength spatial localisation of SPP's at metal surfaces and metal–dielectric interfaces allows observation of reliable values of magneto-optical effects with relatively small vertical size of magnetoplasmonic crystals. Another approach deals with local or localised surface plasmons excited in noble metal nanoparticles embedded into host magnetic materials [8–12]. As a result, a significant progress in magneto-optical enhancement was achieved in configurations of Faraday [7,9,10], transverse [6,13] and longitudinal [14] Kerr effects.

One of the main advantages of magnetoplasmonic structures is the possibility to realise miniature submicron-sized magneto-optical devices due to the subwavelength spatial localisation of surface and local plasmons. However, optical losses arising from imaginary part of metal dielectric constant limit their figure-of-merit. One of the ways to overcome this limitation can be magnetoplasmonic structures with resonant optical fields localised mostly in a magnetic dielectric rather than in metallic inclusions.

In this paper, we demonstrate a realisation of a two-dimensional (2D) magnetoplasmonic grating consisted of a periodic 2D gold nanoparticle array embedded into a thin magnetic garnet film supporting excitation of a quasi-guided mode in the desired spectral range. A strong asymmetric resonance is observed in transverse magneto-optical Kerr effect (TMOKE) spectrum. Large Q-factor of the resonance is attributed to the localisation of optical fields in the magnetic garnet film.

2. Experimental

The sample is a square array of 110-nm gold nanoparticles with a period of 600 nm on a fused silica substrate covered by a 100-nm-thick Bi-substituted yttrium–iron garnet (Bi:YIG) film (Fig. 1).

It is designed to support local plasmon oscillations in gold nanoparticles, coupled plasmon modes [9] and quasi-guided modes with optical field localisation between the rows of the particles in the magnetic material. The fabrication procedure is similar to that reported in Refs. [10,15]. The square array of gold nanodisks on a fused silica substrate was fabricated by electron-beam lithography from a DC-sputtered gold film. The array was annealed at 1000 °C for 10 min to melt the disks and to obtain the spherical droplets. The Bi:YIG film was formed on the top of the grating by RF-magnetron sputtering and subsequent annealing of the sample. Fig. 1 shows an atomic-force microscopy (AFM) image

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http://dx.doi.org/10.1016/j.jmmm.2014.12.062
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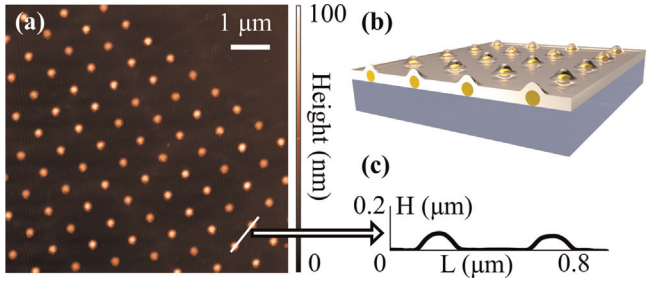

Fig. 1. (a) Atomic-force microscopy (AFM) image of the sample surface. (b) Schematic of the two-dimensional gold–garnet nanograting sample. (c) AFM profile cross-section.

of the sample surface (a) and a schematic of the sample (b). Fig. 1 (c) shows a cross-section of the AFM image along a particle row. It is seen that the surface of the Bi:YIG film has 80-nm half-sphere bulbs over the particles. The image also shows a good periodicity of the grating. The vibrating sample magnetometer (VSM) measurements give the easy-magnetisation axis lying in plane of the sample with saturating magnetic field of 1 kOe.

The transmittance and TMOKE spectra were measured with polarised and collimated light of a halogen lamp and a monochromator with a spectral resolution of approximately 5 nm. The distinctive feature of the experiment is that the TMOKE signal is measured in transmission configuration. The TMOKE is defined as $\delta \equiv (T(+H) - T(-H))/T(0)$, where T is the sample transmittance. The effect is odd in magnetisation, thus the sign of δ changes with changing the angle of incidence θ to $-\theta$, or reversing magnetic field direction. The angle of incidence is tuned by an automated mechanical system with an accuracy better than 0.1°. The detected intensity is locked-in to the 131-Hz-modulated magnetic field H with a saturating amplitude of 1 kOe. The modulation frequency is far from the sample mechanical resonances.

3. Results and discussion

Fig. 2 (thick curves) shows a series of transmittance spectra for a set of angles of incidence θ.

The electric field polarisation is in the plane of incidence. The dip at 675 nm for the normal incidence is associated with the local plasmon excitation in the individual particles without any coupling. It is blue shifted down to 625 nm with the angle of incidence increase up to $\theta=20°$ due to the presence of the Bi:YIG film and a possible slight aspheric shape of the gold particles as well as anisotropic surroundings of the nanoparticles. The dip at 810 nm for normal incidence is a non-propagating coupled plasmonic mode [9] which is red-shifted with the angle of incidence. The peculiarities in the vicinity of 560 nm are related to a quasi-guided mode as it will be shown by numerical simulations below.

A TMOKE spectrum shown in Fig. 3 by dots was measured for $\theta=20°$ since the effect is forbidden for the degenerate case of $\theta=0°$.

The corresponding transmittance spectrum is shown by the solid curve. The spectrally wide TMOKE peculiarities at approximately 750 nm are related to the broad resonance of the local plasmons in the gold spheres. The TMOKE enhancement is also observed at 850 nm due to coupled-mode plasmonic oscillations. The enhancement of the Faraday rotation for the both resonances was reported elsewhere [9]. The most sharp and complex-shape features are observed in the TMOKE spectrum in the range from 525 to 575 nm. They are not so pronounced in the transmittance spectra, while changing the sign of the effect is observed in the TMOKE spectrum within approximately 20 nm spectral tuning.

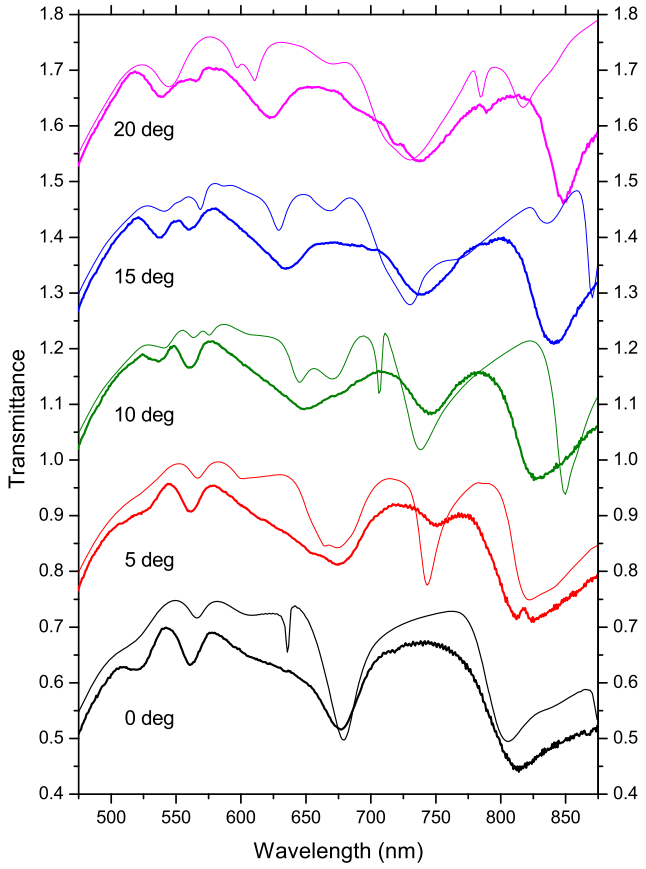

Fig. 2. Experimental (thick curves) and simulated (thin curves) transmittance spectra of the two-dimensional gold–garnet nanograting for a set of angles of incidence. For clear presentation each plot is shifted vertically by 0.25 units relatively to the previous one.

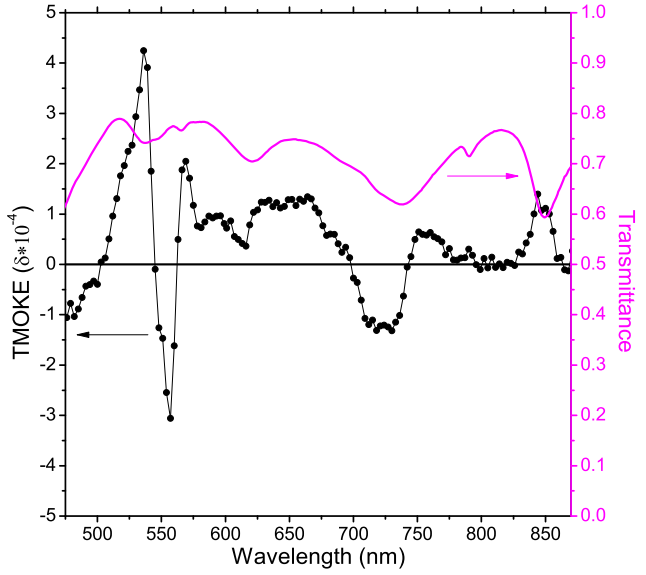

Fig. 3. The spectrum of the transverse magneto-optical Kerr effect of the two-dimensional gold–garnet nanograting for angle of incidence $\theta=20°$.

Transmittance spectrum extrema bring to TMOKE sign changes because the effect is proportional to the transmittance spectrum derivative due to small resonance shift under external magnetic field.

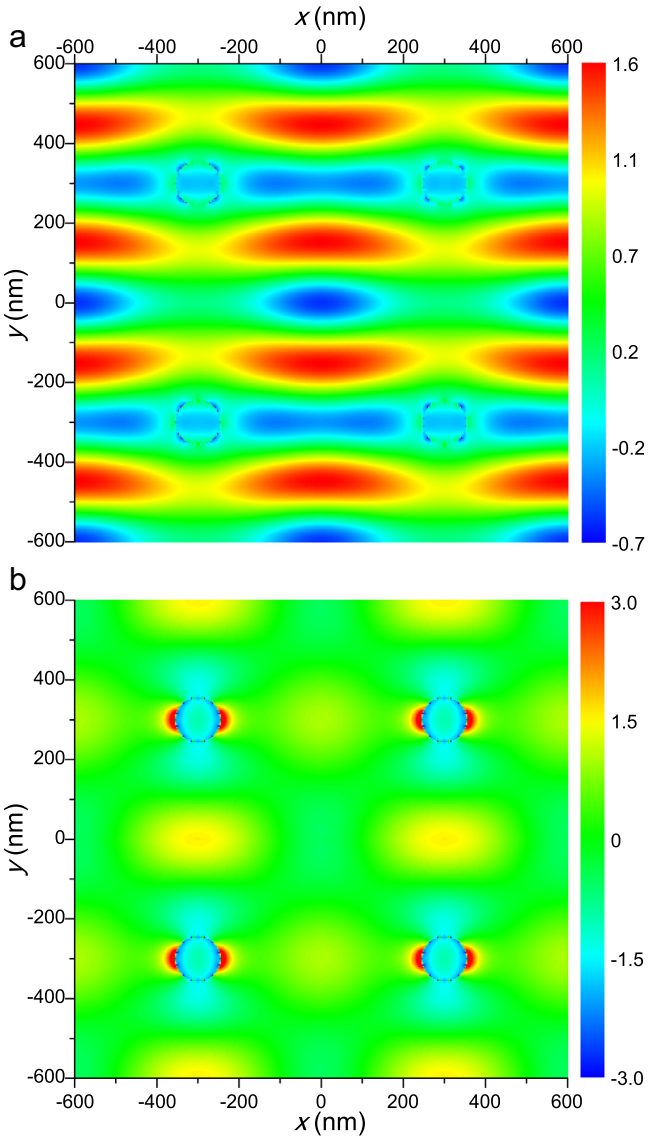

Fig. 4. The finite-difference time-domain simulation of local electromagnetic field distribution (real part of the field x-component) at the normal incidence of the x-polarised light in the plane of the gold particles centers for the light wavelength of 560 nm (quasi-guided mode resonance) (a) and 675 nm (local plasmon resonance) (b).

Within the studied spectral range, the gratings support quasi-guided modes propagating along the surface with the high local-field concentration in the magnetic material. Together with the high transmittance, the modes provide longer light-medium interaction yielding enhanced magneto-optical response. The effective waveguide is formed by the rows of gold nanoparticles in the lateral direction and restricted in the vertical direction within the few hundreds of nanometers by high dielectric contrast, unlike to the quasi-guided mode localised within several-micron-thick magnetic film reported in [16]. Fig. 4 shows the finite-difference time-domain simulation of local electromagnetic field distribution in the plane of the gold particles centre for the light wavelength of 560 nm (quasi-guided mode resonance) (a) and at 675 nm (local plasmon resonance) (b).

The gold particles are modelled as a spheres with a diameter of 110 nm on the fused quartz substrate immersed into a flat 95-nm-thick Bi-substituted yttrium–iron–garnet film. The semi-spherical 80-nm-high Bi:YIG bulbs over the particles observed with atomic-force microscopy are also included into the model. Optical dispersion and absorbance of both gold and garnet are taken into account. The data are obtained from an auxiliary optical experiment for a particular garnet film used in magneto-optical measurements. The thin curves in Fig. 2 are the transmittance spectra calculated with the above parameters. They reproduce all principal features of the experimental spectra verifying the relevance of the selected model geometry and parameters. The field distribution shown in Fig. 4(a) exhibits strong electric field concentration in magnetic spacers between the rows of gold particles. The concentration effect is spectrally narrow which is confirmed by the narrow experimental TMOKE resonance (Fig. 3). The absolute value of the maximal electric field in the film is not high, and the corresponding transmittance resonance at this spectral region is not so pronounced if compared to the local-plasmon resonance. The electric field distribution at the local-plasmon excitation resonance at 675 nm is given in Fig. 4(b) for comparison. The maximal amplitude of the local electromagnetic field is concentrated at the plasmonic particle surface showing dipole distribution. In the case, interaction of light with the magnetic medium is enhanced due to high local field concentration but the absorbance is also high which reduces the magneto-optical figure-of-merit value.

4. Conclusions

In conclusion, sharp asymmetric resonance of the transverse magneto-optical Kerr effect is observed in transmission through a planar magnetoplasmonic nanograting consisted of a 100-nm-thick magnetic garnet film covering an array of 110-nm-sized gold nanoparticles forming a two-dimensional square lattice with a period of 600 nm. The enhancement of magneto-optical response is attributed to excitation of a quasi-waveguiding mode formed by rows of plasmonic nanoparticles. A high figure-of-merit is achieved by the combination of light localisation into the magnetic layer and the proper design of the nanograting, which tunes the waveguiding mode to the edge of the garnet film optical absorption. The approach of thin planar magnetoplasmonic nanostructures operating at the near-normal incidence supporting laterally propagating modes is prospective for the miniature magneto-optical device design.

Acknowledgements

The authors gratefully acknowledge A.A. Ezhov and N.S. Perov for assistance in AFM and VSM measurements, respectively. The work was supported partly by Russian Foundation for Basic Research, Russian Science Foundation (#14-12-01144) (optical measurements), Russian Ministry of Education and Science (14.613.21.0029) (magneto-optical measurements), and Ministry of Education, Culture, Sport and Technology of Japan (sample fabrication).

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