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Abstract. The magneto-optical properties of surface-plasmon polaritonic crystals on ferromagnetic substrates have been studied. The resonant optical transmission of such magneto-plasmonic nanostructures can be efficiently controlled with the applied static magnetic field. The effect is explained by the influence of magneto-optical effects on surface-plasmon polariton waves supported by the metal/magnetic–dielectric interface and, in particular, on the plasmonic bandgap formation.

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Contents

1. Introduction

Surface plasmon polaritons (SPPs), electromagnetic excitations coupled to free-electron motion near a metal surface, are attracting increasing attention due to their potential in numerous applications for achieving and controlling light propagation in subwavelength geometries. These include strongly confined waveguiding, enhanced transmission of single and arrayed apertures and apertureless nanostructured metal films as well as other nanoplasmonic devices [1, 2]. The control of SPP modes on structured surfaces can be achieved via the modification of the nanostructure geometry. Of particular interest is the ability to actively influence plasmonic modes of the structure with external control signals such as electric and magnetic fields or all-optically with light [2]–[6]. Among these approaches, controlling SPPs with external magnetic field has always occupied an important place due to possible applications in magnetic and magneto-optical data storage as well as for the development of microscale optical isolators based on nonreciprocal photonic effects.

The theory of the in-plane modification of the SPP behaviour on smooth metal films by an applied magnetic field has recently been developed and some experiments have been carried out [4, 7]. Magnetic fields have been proposed as a means to control the enhanced transmission of SPP crystals [8, 9], but the required field strength is too high for the effect to be observed in good metals; it may, however, be achieved in doped semiconductors supporting plasmonic excitations in the THz spectral range [10]. It was predicted that the effect of magnetic fields on SPP modes can be enhanced via coupling to the neighbouring ferromagnetic medium [7]. It was also demonstrated that the magneto-optical effects in magnetic medium can be enhanced via the resonant coupling to plasmonic modes [11, 12] similarly to the resonant coupling in magneto-photonic crystals [13]. The magneto-optical effects due to cylindrical surface plasmons supported by arrays of plasmonic nanorods have also been investigated [14].

In this paper, we experimentally study the dependence of the optical transmission of magneto-plasmonic crystals under the application of an external static magnetic field. We show that the magneto-optical effects on the SPP field components induced by the magnetization of a dielectric layer affect the optical properties of the SPP crystals through both a net modulation of the transmitted intensity and a shift of the SPP-band edges.

2. Samples and experiment

Magneto-optically active plasmonic crystals were fabricated in a thin Au film (50 nm thickness) deposited onto a $3.5 \, \mu$m thick single crystalline iron garnet (IG) film of composition
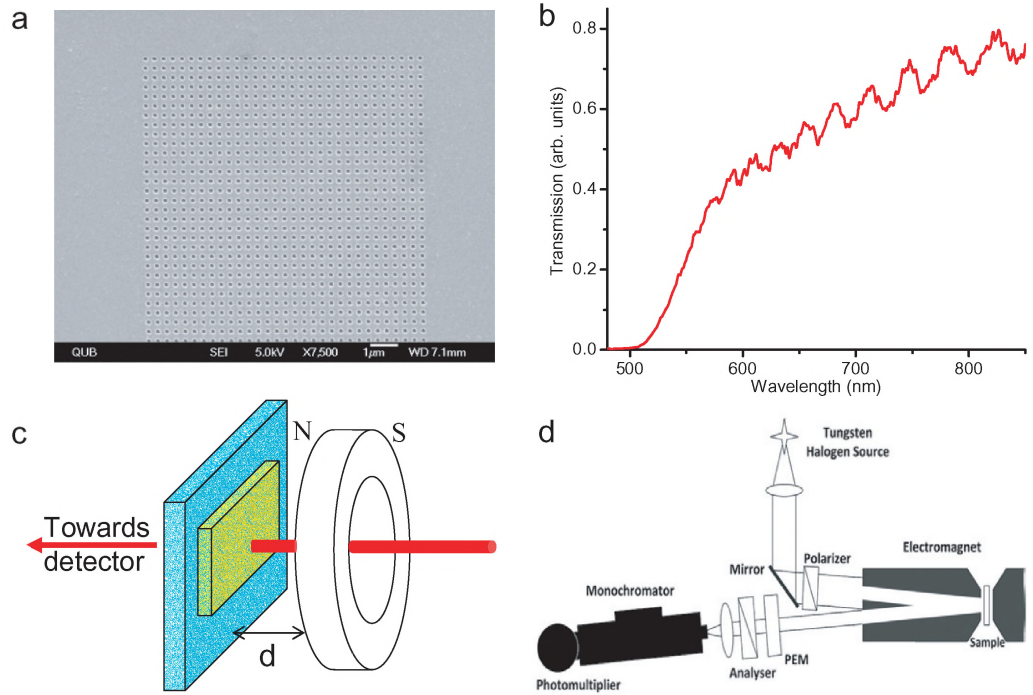
Figure 1. (a) SEM image of the plasmonic crystal on the magnetic substrate. (b) Transmission spectrum of the IG film on the GGG substrate. (c) Schematic of the magnetic-field-controlled transmission measurements. (d) Schematic of the magneto-optical electrometric spectroscopy.

$Lu_{2.4}Bi_{0.6}Fe_{4.8}Ga_{0.2}O_{12}$. The latter was grown by isothermal liquid phase epitaxy on a (100)-oriented gadolinium gallium garnet (GGG) substrate. The substrate and IG film are transparent in the near-infrared and visible spectral region up to approximately 2.3 eV corresponding to a free-space wavelength of 540 nm. Arrays of holes (125 nm diameter, 400 nm period) were fabricated in the Au film using focused ion beam milling (figure 1(a)). In the absence of the external magnetic field, the IG film exhibits an in-plane magnetic anisotropy ($4\pi M_s \approx 2$ kG). The optical properties of the IG in the visible spectral range are dispersive [15], but assuming an average refractive index $n \approx 2.34$ is a reasonable approximation. The magneto-optical response of an IG film in the polar (p) configuration, when the external magnetic field is normal to the interface, longitudinal (l) or transversal (t) configurations when the magnetic field is in the plane of the interface and in the direction of SPP propagation or perpendicular to it, respectively, is described by the permittivity tensor [16]

$$\varepsilon = \begin{pmatrix} \varepsilon_0 & i\varepsilon_p & i\varepsilon_t \\ -i\varepsilon_p & \varepsilon_0 & i\varepsilon_l \\ -i\varepsilon_t & -i\varepsilon_l & \varepsilon_0 \end{pmatrix}, \tag{1}$$

where only one pair off-diagonal elements ε_i is nonzero for any given p-, l- or t-configuration. For an absorbing medium, the tensor components are complex. To the first order in the magnetization, the diagonal components ε_0 do not depend on magnetization **M**. The off-diagonal components $\varepsilon_{p,t,l}$ vary linearly with **M** and give rise to magneto-optical effects, such as Faraday or Kerr rotation resulting in the ellipticity of the transmitted or reflected, initially

linearly polarized light. The variation of the off-diagonal components of the permittivity tensor of the IG are typically of the order of $\Delta\varepsilon \sim 10^{-3}$ [15].

The magnetic-field-controlled optical transmission was investigated at normal incidence (figure 1(c)). For the spectroscopic measurements, collimated white light from a tungsten–halogen lamp was sent through a polarizer and illuminated the plasmonic crystal. After passing through the sample and an analyser, the light was collected using a high-magnification objective and coupled to the spectrometer equipped with a liquid nitrogen cooled CCD via a multimode optical fibre. The magnetic field strength around the plasmonic crystals was controlled by changing the distance between a permanent magnet and the sample. The magnet was made up of a neodymium–iron–boron alloy. Its annular geometry allowed for a homogeneous magnetization of the IG film and produces an axial field with a maximum magnitude of about 80 mT.

Magneto-optical Kerr-effect (MOKE) spectroscopic ellipsometry (the measurements of rotation and ellipticity of the reflected light) was performed in reflection at near normal incidence (figure 1(d)). The spectroscopic Kerr polarimeter operates in the wavelength range 400–860 nm. For the magneto-optical measurements, the sample was magnetized in a 8 kOe field produced between the poles of an electromagnet. Linearly polarized light is incident on the sample at an angle of approximately 3° through holes in the front pole piece. On reflection, the light is analysed by a 50 kHz photoelastic modulator and the signal is detected by a photomultiplier coupled to a lock-in amplifier at the frequency of the modulator. The signal is composed of two components related to the magneto-optical response of the sample: the 50 kHz fundamental component is proportional to the Kerr ellipticity and the 100 kHz second-harmonic component is proportional to the Kerr rotation [17].

3. Results and discussion

The transmission spectra of the magneto-plasmonic crystals under investigation are determined by the transmission of the IG film and the transmission of the nanostructured Au film related to plasmonic resonances. Due to the relatively high refractive index of the substrate compared to the air superstrate, SPP Bloch modes on Au/air and Au/IG interfaces are significantly spectrally separated at normal incidence. Additionally, as a result of the short period of the SPP crystal lattice, the low-order SPP resonances associated with the Au/air interface are situated in the spectral range where the substrate absorption is very significant and can be neglected in the following considerations. Based on the estimations of the SPP modes in the model of an almost empty lattice [18], the transmission resonances observed in the visible spectral range (figure 2(a)) can be assigned to the scattering of photons due to the (1,1) and (2,0) SPP Bloch modes on the Au/IG interface [3]. The application of the magnetic field leading to small variations of the off-diagonal elements of the permittivity tensor may influence the transmission spectra via modifications of the effective refractive index of SPP Bloch modes. The polarization effects due to the enhanced Faraday rotation in the plasmonic resonances [11] arise when the magnetization direction of the substrate changes upon application of magnetic field. This magnetic field effect can be easily observed in the cross-polarized configuration with the analyser probing the optical properties of the crystal along the (1,0) lattice vector, the incident field being polarized along the (0,1) lattice vector, and vice versa.

The effect of the applied magnetic field on the cross-polarized transmission spectrum is shown in figures 2(b)–(d) for different polarizations of the incident light. The changes in the
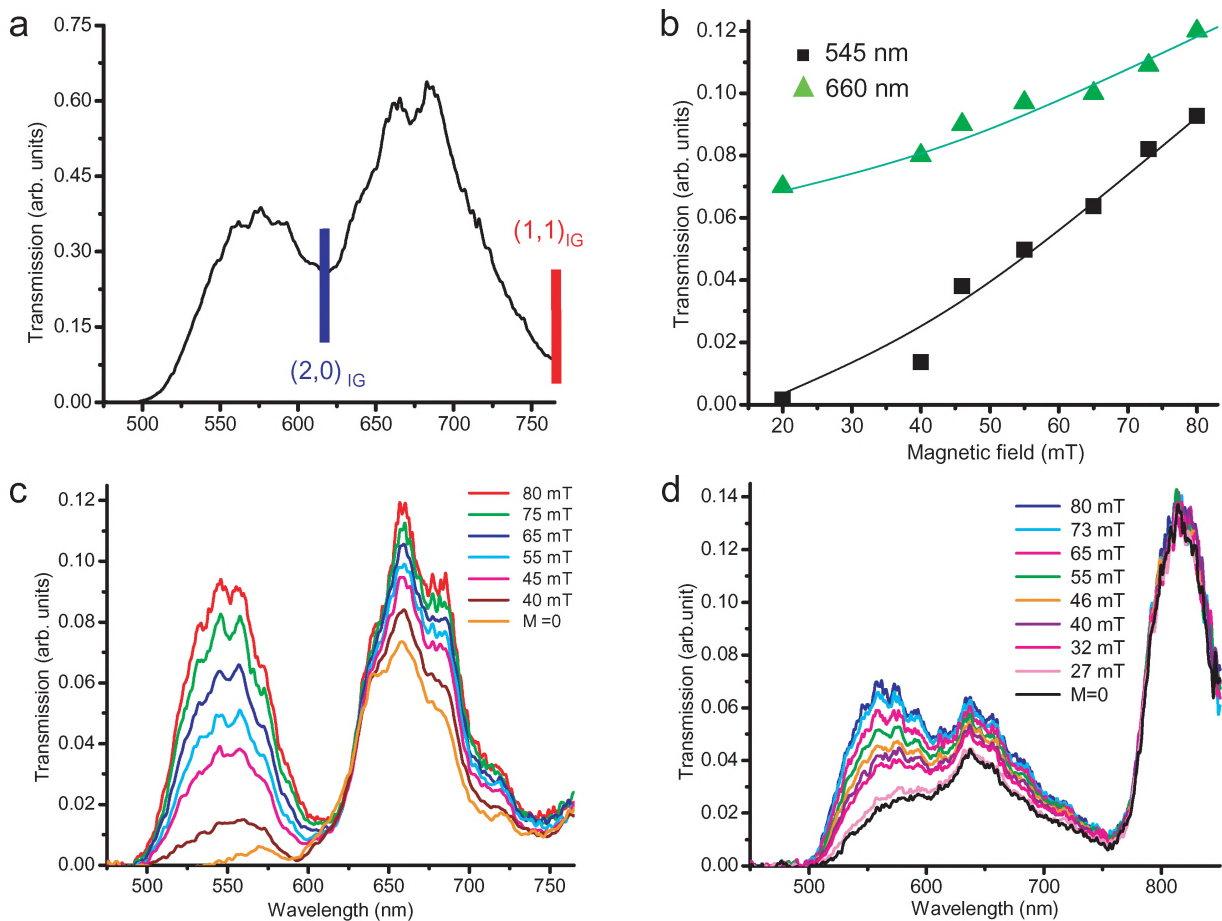
Figure 2. (a) Transmission spectrum of the magneto-plasmonic crystal. The spectrum is measured at normal incidence in the zero-order direction. The positions of the SPP Bloch modes estimated in the almost empty lattice model are shown. (b) The dependence of the cross-polarized transmission at the wavelength of 545 and 660 nm on the applied magnetic field. (c, d) Cross-polarized transmission spectra of the magneto-plasmonic crystal in the varying external magnetic field (0–80 mT) for the polarization of the incident light along the two axes of the crystal lattice: (c) for (1,0)- and (d) for (0,1)-directions.

transmission are most pronounced in the 500–700 nm wavelength range where the magneto-optical effects in the IG film are strongest [15]. The applied magnetic field impacts the optical properties of the SPP crystal in two ways. Firstly, the magnitude of the cross-polarized resonant transmission is strongly modified with varying magnetic field. This modification is dispersive, with a stronger effect at higher optical frequencies. Secondly, the transmission spectra also reveal the changes in the SPP bandgap structure. In particular, the field-induced reorientation of magnetization shifts the band edges of both the (1,1) and the (2,0) bands to longer wavelengths as the magnitude of the magnetic field is increased. Here again, the effect is dispersive with a stronger shift observed for the (2,0) bands.

For the SPPs existing on the interface of a metal and a dielectric with permittivity given by the tensor in equation (1), the electric field components E_x (along the SPP-propagation

direction) and E_z (normal to the interface) are coupled via off-diagonal tensor components. Thus, pure transverse electric (TE) and transverse magnetic (TM) surface electromagnetic modes cannot be separated and plasmonic excitations are not purely TM waves in longitudinal and polar configurations [7, 19]. Significant changes of the effective refractive index of SPPs have been observed even for smooth metal films on a magneto-optically active substrate with nonreciprocal SPP propagation [7]. Even stronger effects should be expected near the SPP bandgap, since the bandgap formation will be affected by the nonreciprocic effects removing directional degeneracy of the (i, 0)/(−i, 0), (i, i)/(−i, −i), etc modes.

At the same time, for the polarization of the incident field normal to the previous one, the observed magnetic-field dependencies are slightly different (cf figures 2(c) and (d)). This can be explained by preferential orientation of the magnetic domains in the IG film leading to the situation where predominantly longitudinal or transverse configuration is realized for different polarizations of the incident light. Application of the external field results in the changes in all the off-diagonal elements of the permittivity tensor, thus its influence on different SPP Bloch modes along different directions will be different.

To gain a better understanding of the experimental observations, we performed full-vectorial finite element modelling (FEM) of the magnetic field effect on the optical properties of magneto-plasmonic crystals. The model crystal consists of circular holes of 150 nm diameter placed in a square array with a period of 400 nm in a 50 nm thick Au film. The crystal is supported by a 50 nm thick IG substrate whose optical response is described by the dielectric tensor as in equation (1). The superstrate is air. The chosen thickness of the IG film enables us to solely analyse the behaviour of the plasmonic crystal and minimize the magneto-optical effect that the substrate has on the polarization of the transmitted light. For technical reasons related to numerical simulations, we also assumed a dispersionless and lossless permittivity of the IG film with the average values in the visible spectral range of $\varepsilon_0 = 5.5$ and $\varepsilon_{t,p,1} = 0.02$ for the diagonal and off-diagonal elements, respectively [15]. In the simulations, a linearly polarized plane wave is normally incident on the crystal from the air side. The incident field is polarized along one of the crystal's principal axis ($\mathbf{E} \| x$) and the polarization of the light transmitted through the structure is analysed in the zero-order spectra as a function of the magnetization direction of the garnet substrate. Figures 3(a) and (b) present the spectra calculated for magnetization oriented either in ($\mathbf{M} \| y$) or out ($\mathbf{M} \| z$) of the plane of the IG film. The spectra presented in red are obtained for the transmitted light whose state of polarization is unaltered by passing through the magneto-plasmonic crystal, whereas the spectra in blue correspond to the transmitted light with a rotated polarization. The introduction of nonzero off-diagonal elements in the dielectric tensor leads to the rotation of the plane of polarization of the transmitted light as is observed in the cross-polarized spectra where maxima in the transmission are observed near the band edges of the crystal (figures 3(a) and (b)). This also demonstrates that the polarization rotation due to magneto-optical effects in the substrate are minimal in the calculated geometry where the sensitivity of the SPP Bloch modes dispersion to the dielectric tensor governs the transmission of the structure. A similar effect is observed for both in-plane and out-of-plane magnetization with a difference originating from the sensitivity of the hybrid modes, responsible for the appearance of the bandgaps, to the form of the dielectric tensor (equation (1)). Figure 3(c) represents the changes in the cross-polarized intensity of the transmitted light as the magnetization direction in the IG film flips from an in-plane to an out-of-plane direction. Experimentally, this represents the variation in the transmitted intensity measured as the external static magnetic field is turned on compared to the in-plane orientation of the magnetization in the substrate when the external
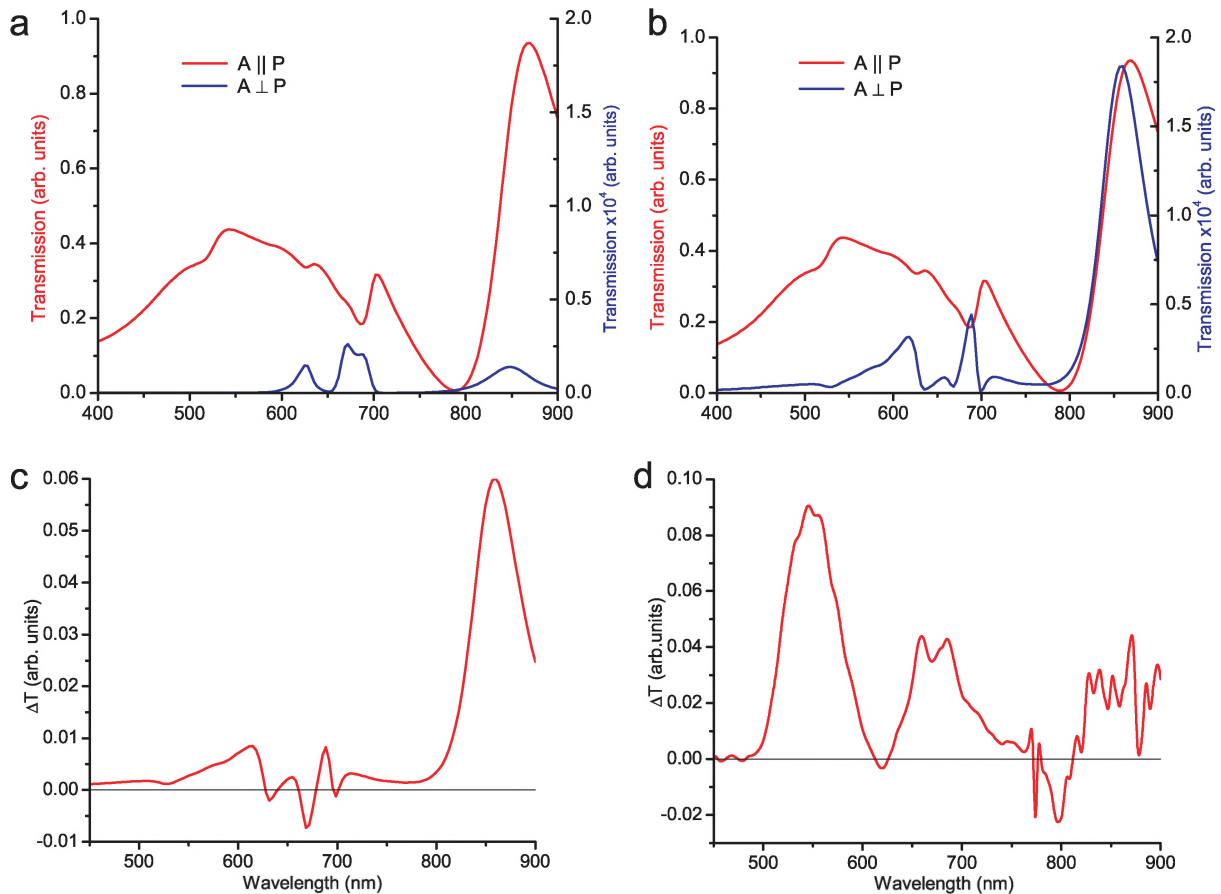
Figure 3. Finite element simulations of the optical properties of the magneto-plasmonic crystals (150 nm diameter circular holes placed in a square array with a period of 400 nm; Au film thickness is 50 nm; SPPC is supported by a 50 nm thick IG substrate). (a,b) The transmission spectra calculated for a magnetization oriented in ($\mathbf{M}\|y$) and out of ($\mathbf{M}\|z$) the plane of the substrate, respectively. The red and blue curves represent the spectra obtained with parallel and perpendicular orientation of the polarizer and analyser, respectively. The incident light is linearly polarized with $\mathbf{E}\|x$. (c) Simulated and (d) experimentally measured changes of the transmission spectra with the variation of the magnetization direction of the IG substrate.

field is absent $\mathbf{M} = 0$. The associated experimental data obtained from figure 2(c) are plotted in figure 3(d). The plots show that the model calculations account for the general behaviour of the observed phenomenon. The differences in the spectra are due to the nondispersive values of the permittivity used in the calculations as well as the influence of the bulk magneto-optical effects in the IG substrate.

To characterize the magneto-plasmonic properties of the crystals, the ellipsometry of the reflected light from the SPP crystal on the magnetic substrate was performed (figure 4). In this configuration, the incident linearly polarized light interacts with the magnetic substrate primarily via SPP modes of the crystal. The magneto-optical spectra exhibit clear polarization effects with the resonance at around 570 nm where the magneto-optical rotation of 0.4 angular
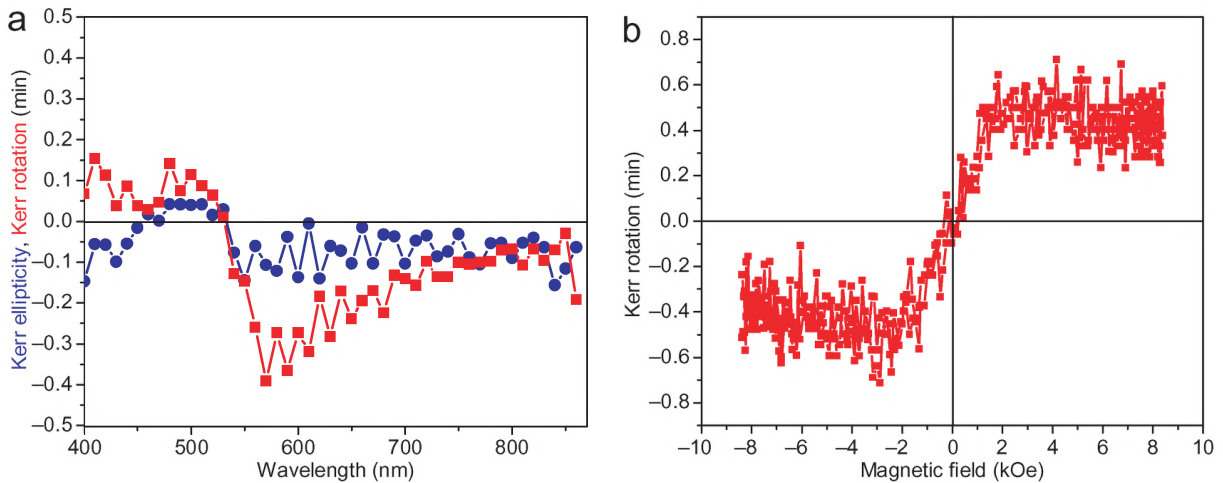
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Figure 4. (a) Spectra of the magneto-optical Kerr rotation (squares) and ellipticity (circles) measured in reflection from the magneto-plasmonic crystal at near normal incidence. (b) Polar Kerr-loops measured at the resonant wavelength of 570 nm where the maximum Kerr rotation and resonant transmission (figure 2) are observed.

minutes has been measured and significant ellipticity of the reflected light has been observed. The (polar) Kerr-loop taken at this wavelength confirms that the observed effect originates from the magnetization of the garnet film.

4. Conclusion

We have studied the magneto-optical properties of SPP crystals deposited onto a magneto-optically active substrate. It was shown that the optical transmission of such structures can be efficiently controlled via the application of a weak ($\lesssim$80 mT) external magnetic field with the achievable modulation contrast of up to 98% at certain resonant wavelengths. The effect is explained by the influence of magneto-optical effects on the SPP states on the metal/IG interface and, in particular, on the bandgap formation.

Acknowledgments

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