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Plasmon induced modification of the transverse magneto-optical response in Fe antidot arrays

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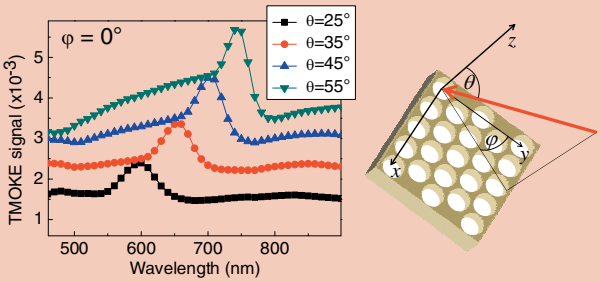
In this Letter we present the effects that the excitation of plasmon-like modes in periodically perforated Fe films have over the Transverse Magneto-Optical Kerr Effect (TMOKE). The excitation of the modes gives rise to clear signatures in the TMOKE spectra. We analyze the spectral position of the structures as a function of both the polar and azimuth angle.



Schematic representation of the system, and TMOKE signal for a Fe membrane along $\varphi = 0°$.

During the last decade an increasing interest has been devoted to the analysis of the effect that plasmon resonances have on the magneto-optical properties of patterned nanostructures. It has been mostly focusing on the excitation of the plasmon in a patterned noble metal in combination with a continuous magneto-optical material [1–4]. In the case of purely ferromagnetic metals, most of these studies consider the magnetic field applied perpendicular to the sample plane (polar configuration), where, in the spectral region of the plasmon resonances, an enhancement of the magnetic field induced changes of the polarization state of the reflected light has been observed both for columnar-type systems [5–7] and for membrane-like ones [8–12]. On the other hand, when a magnetic field is applied in the plane and perpendicular to the propagation direction of surface plasmon polaritons (SPP) (transverse configuration – TMOKE), a modification of the SPP wave vector has been observed in Au/Co/Au continuous films [13–15]. Also, the TMOKE response has been analyzed in corrugated (grating-like) ferromagnetic films [16].

In this Letter we study the TMOKE signal in perforated Fe nanostructures. This is done through the analysis of the magneto-optical (MO) response of ferromagnetic membranes in the transverse configuration. The TMOKE consists in an intensity change of the p-component of the reflected light upon application of the magnetic field,

$$\mathrm{TMOKE} = \frac{\Delta R}{\Sigma R} = \frac{R_{pp}(+H) - R_{pp}(-H)}{R_{pp}(+H) + R_{pp}(-H)}, \qquad (1)$$

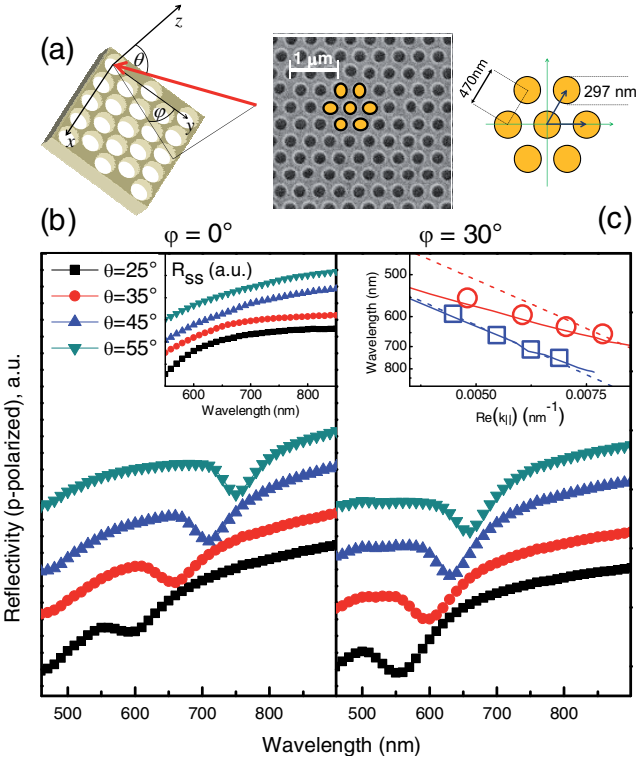


Figure 1 (online colour at: www.pss-rapid.com) (a) Schematic view of the system and angle definitions, real space representations and SEM micrograph of the analyzed membrane. (b) Reflectivity for p-polarized light for different incidence angles along the high symmetry line $\varphi = 0°$. The inset represents the reflectivity for s-polarized light at $\varphi = 0°$. (c) The same for $\varphi = 30°$. The inset represents the spectral location of the dips as a function of the in-plane wave vector: open symbols are for the experimental results (squares $\varphi = 0°$ and circles $\varphi = 30°$), thick lines are the theoretical results and dashed lines are the folded SPP-BW dispersion curves. The reflectivity curves have been shifted for clarity.

R(±H) being the reflectivity with the magnetic field (enough to saturate the sample) pointing to opposite directions.

The system under consideration will be Fe antidot arrays prepared on a Si(111) substrate using self-assembly nanosphere lithography with polystyrene (PS) spheres (diameter of 470 nm). After the formation of a hexagonal closed-packed monolayer of PS spheres, the diameter is shrunk by means of reactive ion etching. The control of the etching parameters enables us to control the diameter of the PS spheres, 297 nm. This structure is used as a mask for the evaporation of the ferromagnetic material (100 nm thick iron films) by means of molecular-beam epitaxy and a base pressure of 10^{-7} mbar. In order to obtain a smooth and continuous Fe film, a seed layer of 2 nm Ti was deposited prior to Fe evaporation. To prevent subsequent oxidation of the surface a capping layer of 2 nm gold was deposited on top. Afterwards, a chemical treatment dissolved the PS spheres to get the final perforated membrane. For a more detailed description of the process see Ref. [17].

In Fig. 1(a) we show a scanning electron micrograph of the structure, together with a pictorial view of the system, depicting the angles under consideration as well as the geometrical parameters, and the real lattice representation.

Also we present the reflectivity of p-polarized light for two different high symmetry crystallographic directions $\varphi = 0°$ (b) and $\varphi = 30°$ (c) as a function of the incident angle θ. As it can be seen the spectra show a marked dip whose spectral position depends on the incoming angle and crystallographic orientation. As seen in the inset of Fig. 1(b), this dip is absent when considering s-polarized light for $\varphi = 0°$. A similar result (not shown) is observed for $\varphi = 30°$.

The inset in Fig. 1(c) represents the spectral position of these dips as a function of the in-plane wave vector of the incident light (open symbols). The thick continuous lines are the calculated positions by using a scattering matrix technique [5] obtaining a very good quantitative agreement with the experimental results. In the same figure we depict the dispersion relation of the so called SPP-Bloch waves (SPP-BW), which are obtained from the folding of the Fe SPP dispersion curve according to the crystal orientation. As expected [18] the general trend is well captured but there are quantitative differences. All these facts indicate that the dips appear as a consequence of SPP-BW excitation.

In Fig. 2 we present the TMOKE signal for the same crystal orientations as in Fig. 1 and for the same incidence θ angles. In the inset we present the TMOKE for the continuous Fe film.

The signal for the continuous Fe film appears as a basically featureless signal in the spectral range under consideration. However, for the two high symmetry directions the TMOKE spectra of the membranes present a clear peak structure that evolves to larger wavelengths (low energies) as a function of the incidence angle in both cases. The evolution of the peak depends on the in-plane crystallographic

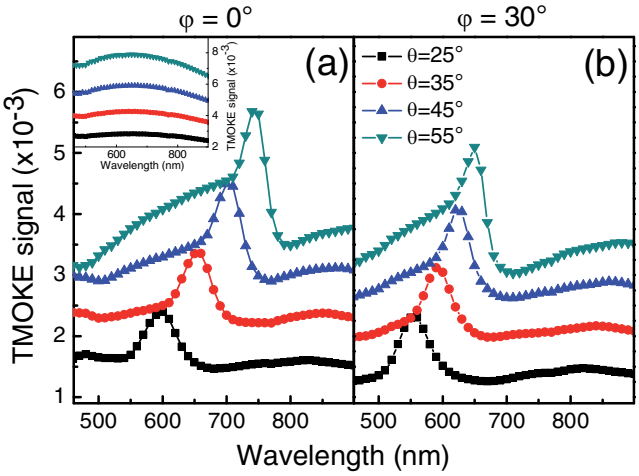


Figure 2 (online colour at: www.pss-rapid.com) TMOKE signal as a function of the wavelength and incidence angle θ for the two crystal orientations. The inset in (a) is the TMOKE corresponding to the continuous Fe film.

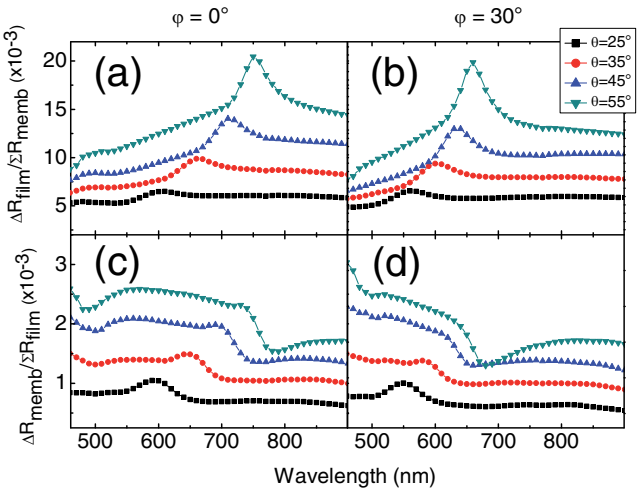


Figure 3 (online colour at: www.pss-rapid.com) Modified TMOKE signal for different incidence (polar) angles along the two high symmetry lines $\varphi = 0°$ and $\varphi = 30°$, respectively.

orientation, the evolution being faster for $\varphi = 0°$ than for $\varphi = 30°$.

The shape of the TMOKE signal (peak) seems to point towards an origin based on signal variation (i.e. field enhancement due to the excitation) rather than to an origin based on wave vector modulation.

As stated in Eq. (1) the TMOKE signal has two main contributions. One comes from the magnetic field induced variation of the reflectivity ΔR. The other comes from ΣR, which we call 'optical term' since its contribution would be roughly $\Sigma R = 2R(0) + O(H^2)$, where the quadratic term is usually very small. To analyze the effect of nanostructures we present in Fig. 3(a, b) a modified TMOKE where ΔR is extracted from the continuous film and ΣR is extracted from the perforated membranes, and in Fig. 3(c, d) the complementary where ΔR is extracted from the perforated membrane and ΣR from the film.

Comparing Fig. 3(a, b) with Fig. 2, it can be observed that the peak position and shape for all incident angles is well captured.

In Fig. 3(c, d) there are also some features at similar spectral locations but with much smaller intensity and very different shape. This indicates that the dominant contribution to the TMOKE is the 'optical' part due to the excitation of lattice SPP-BW. However, the features found in Fig. 3(c, d) could be an indication of plasmon wave vector modulation that deserves a further analysis. In fact it has been shown that if the TMOKE comes from the modification of the wave vector it would give rise to an s-like shape structure in the spectra [13, 14].

In summary, we have presented an analysis of the TMOKE response for periodically perforated Fe films. We have observed the excitation of SPP-BW, which give rise to clear signatures in the TMOKE. As expected for periodically structured media, the spectral position of the structures is a function of both the polar and azimuth angle. Our analysis points towards a predominant contribution of purely optical effects over wave vector modulation as the origin of the TMOKE features.

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References

[1] V. I. Belotelov, L. L. Doskolovich, and A. K. Zvezdin, Phys. Rev. Lett. **98**, 077401 (2007).
[2] V. I. Belotelov, D. A. Bykov, L. L. Doskolovich, A. N. Kalish, and A. K. Zvezdin, J. Opt. Soc. Am. B **26**, 1594 (2009).
[3] G. A. Wurtz et al., New J. Phys. **10**, 105012 (2008).
[4] G. Armelles et al., Opt. Express **16**, 16104 (2008).
[5] A. Garcia-Martin, G. Armelles, and S. Pereira, Phys. Rev. B **71**, 205116 (2005).
[6] J. B. Gonzalez-Diaz et al., Adv. Mater. **19**, 2643 (2007).
[7] S. Melle et al., Appl. Phys. Lett. **83**, 4547 (2003).
[8] M. Diwekar, V. Kamaev, J. Shi, and Z. V. Vardeny, Appl. Phys. Lett. **84**, 3112 (2004).
[9] Y. M. Strelniker and D. J. Bergman, Phys. Rev. B **77**, 205113 (2008).
[10] J. B. Gonzalez-Diaz et al., Appl. Phys. Lett. **94**, 263101 (2009).
[11] G. Ctistis et al., Nano Lett. **9**, 1 (2009).
[12] Th. Papaioannou et al., Phys. Rev. B **81**, 054424 (2010).
[13] C. Herman et al., Phys. Rev. B **64**, 235422 (2001).
[14] J. B. Gonzalez-Diaz et al., Phys. Rev. B **76**, 153402 (2007).
[15] V. V. Temnov et al., Nature Photonics **4**, 107 (2010).
[16] D. M. Newman et al., J. Phys.: Condens. Matter **20**, 345230 (2008).
[17] A. Kosiorek et al., Nano Lett. **4**, 1359 (2004).
[18] H. Gao, W. Zhou, and T. W. Odom, Adv. Funct. Mater. **19**, 1 (2009).