Bi-anisotropy of optical metamagnetics studied with spectroscopic ellipsometry

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Abstract: Sub-wavelength gratings of paired Ag strips are measured and analyzed using spectroscopic ellipsometry, and show significant angular dependence of the electric and magnetic resonance properties, along with evidence of bi-anisotropy.

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Metamaterials can be considered in general as a bi-anisotropic material where the wave vector is related to not only permittivity and permeability but also to magneto-electric coupling coefficients. The constitutive relations for Maxwell's equations become more sophisticated in this case. They take the form [1]

$$\overline{D} = \overline{\overline{\varepsilon}} \cdot \overline{E} + \overline{\overline{\xi}} \cdot \overline{H}, \qquad \overline{B} = \overline{\overline{\zeta}} \cdot \overline{E} + \overline{\overline{\mu}} \cdot \overline{H},$$

where $\overline{D}$ depends on both $\overline{E}$ and $\overline{H}$, and so does $\overline{B}$ via the corresponding tensors. For the nonzero nondiagonal elements, $\xi_{xy} = -\xi_{yx} = \zeta_{xy} = -\zeta_{yx} = \frac{i}{c}\xi_0$, the bi-anisotropy parameter results in different effective impedances for light directed along the $+z$ and $-z$ directions $Z_{\pm} = \mu_y \Big/ \sqrt{n \pm \xi_0^2}\,; n = \sqrt{\varepsilon_x \mu_y - \xi_0^2}$. Some examples of bi-anisotropic metamaterials have been discussed earlier [2-4] mainly for metamaterials based on split ring resonators.

We study bi-anisotropic properties of metamagnetics based on subwavelength gratings consisting of pairs Ag strips [5]. All the demonstrated metamagnetics in the visible range so far were studied for a normal incidence of light. However the further development of metamaterials for imaging devices requires the accurate prediction and optimal design of material properties for arbitrary angles of light incidence [6]. We use a spectroscopic ellipsometry approach, which potentially enables the retrieval of all principal components of the optical tensors and brings an understanding of new effects and functionality associated with the oblique incidence of light at the interfaces of metamagnetics and negative index materials with usual optical materials.

Spectroscopic ellipsometry enables the measurement of angular and polarization dependences of the magnetic material. Metamaterial prototypes based on sub-wavelength gratings were fabricated by e-beam lithography similar to our previous experimental samples with a negative permeability in the visible range [5]. The negative permeability structure is a periodic array of pairs of silver strips 35x100nm separated by an alumina spacer of 40 nm in thickness. First, the geometry of the periodic thin silver strips is defined by use of an electron beam writer on a glass substrate initially coated with a 15-nm film of indium-tin-oxide (ITO). Then, electron beam evaporation is used to produce a stack of lamellar films. The period is about 250nm and the die size is about 500x500 µm. The transmission, reflection, and absorption spectra were measured and also modeled using finite-element method multiphysics (FEM) through commercially available Comsol Multiphysics software. Due to the semi-infinite nature of the strips, a 2D model was used. The transmission ellipsometry spectra at different angles (Fig.1) show that the resonance properties of the paired strips disappear for spectra at 40 and 60 degrees incidence, but is still present for 20 degrees. This is

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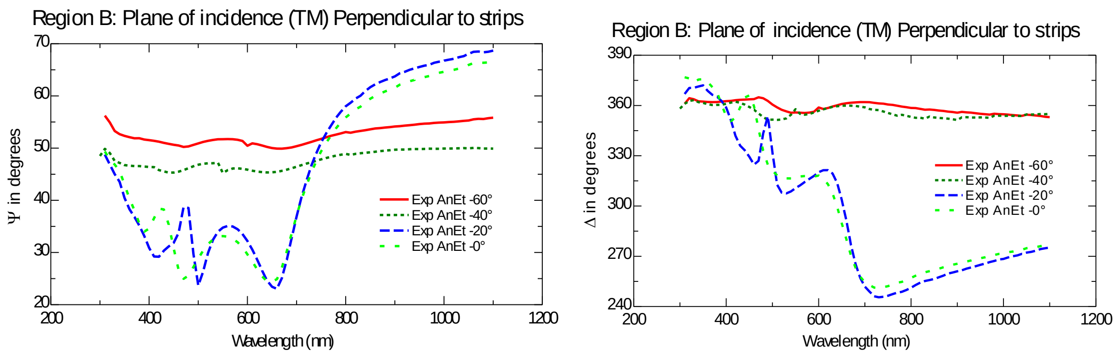

Fig. 1. Transmission ellipsometry spectra of the magnetic grating at 0, 20, 40, and 60 degrees of the incident beam (plane of incidence perpendicular to the strips, p-polarization).

the qualitatively expected result since the projection of the electric field onto the sample plane is reduced as the angle of incidence increases. Strong angular dependence has been observed also for the reflection ellipsometry spectra. A significant difference in the ellipsometry spectra for parameters Psi and Delta were observed between front and rear illumination of the sample caused by the bi-anisotropy of the magnetic grating (Fig.2).

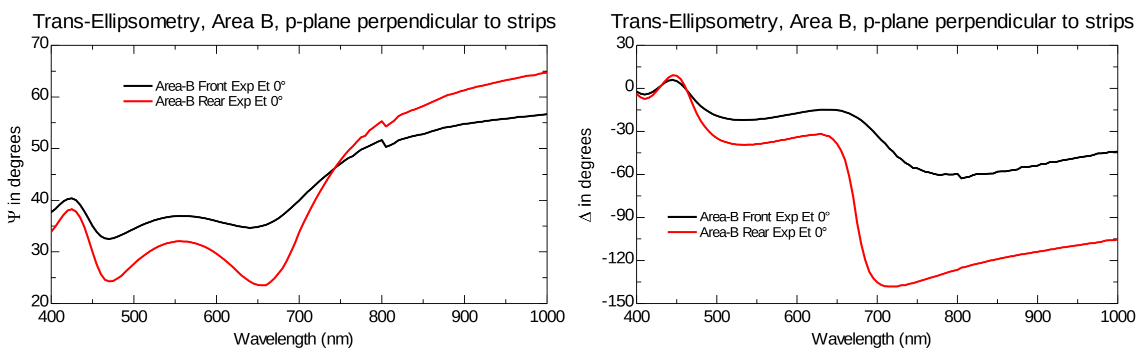

Fig. 2. Transmission ellipsometry spectra of the magnetic grating at the front and rear illumination and normal incidence of the beam (plane of incidence perpendicular to the strips, p-plane).

To summarize, a significant angular dependence of the metamagnetic resonance properties is observed with spectroscopic ellipsometry along with evidence of bi-anisotropy. All the experimental and simulated data, including generalized ellipsometry spectra and Mueller Matrix components and their analysis will be discussed in this talk.

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References:

[1] A. Serdyukov, I. Semchenko, S. Tretyakov, and A. Sihvola, "Electromegnetics of bi-anisotropic materials: theory and applications," Gordon and Breach Science Publishers 2001.
[2] N. Katsarakis, T. Koschny, M. Kafesaki, E. N. Economou, and C. M. Soukoulis, "Electric coupling to the magnetic resonance of split ring resonators," Appl. Phys. Lett. **84**, 2943 (2004).
[3] X. Chen, B.I. Wu, J. A. Kong, and T. M. Grzegorczyk, "Retrieval of the effective constitutive parameters of bianisotropic metamaterials," Phys. Rev. E **71**, 046610 (2005).
[4] Z. Li, K. Aydin, and E. Ozbay, "Determination of the effective constitutive parameters of bianisotropic metamaterials from reflection and transmission coefficients," Phys. Rev. E **79**, 026610 (2009).
[5] W. Cai, U. K. Chettiar, H.-K. Yuan, V. C. de Silva, A. V. Kildishev, V. P. Drachev, and V. M. Shalaev, "Metamagnetics with rainbow colors," Opt. Express **15**, 3333 (2007).
[6] C. Menzel, C. Rockstuhl, T Paul, T. Pertsch, and F. Lederer, "Retrieving effective parameters for metamaterials at oblique incidence," Phys. Rev. B **77**, 195328 (2008).