



Magnetophotonic properties of inverse magnetic metal opals

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ABSTRACT

Nickel inverse opals were fabricated by templating a colloidal crystal. Perfect fcc ordering was confirmed by scanning electron microscopy. Several kinds of magneto-optical effects were studied: linear longitudinal and transversal Kerr effects, nonlinear longitudinal Kerr effect (magnetization-induced second harmonic generation), which were all consistent with the photonic band structure studied by reflectivity spectroscopy.

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1. Introduction

Metallic photonic crystals (PhCs) have recently attracted considerable attention due to their potential new properties in comparison with dielectric and semiconductor PhCs. Metallic PhCs possess unique optical absorption and reflectivity [1], which may be used for filters (including terahertz filters), thermally stimulated emission [1–3] and nanoplasmonic devices [4]. Using magnetic metals they could join the ranks of magnetophotonic crystals which at present involve, mostly one- [5–7] or two-dimensional [8,9] magnetic garnet PhCs (Bi:YIG, terbium gallium garnet, terbium aluminum garnet). Three-dimensional magnetophotonic crystals are mainly fabricated using artificial opals by infiltrating voids with magnetically active materials such as magnetite [10], magnetic garnets [11,12] or magnetic liquids [13]. Magneto-optical effects, both linear and nonlinear were studied extensively in one- and two-dimensional photonic crystals of different materials as well as garnet-based three-dimensional photonic crystals, both experimentally [5–12] and theoretically [14,15]. For magnetic metal inverse opals, so far only the magnetization was measured using non-optical techniques [16], which only confirmed the presence of magnetic properties, but did not give any information concerning their “magnetophotonic behavior”, i.e. the presence of the spectral dependence of magneto-optical properties which reflect the presence of photonic

bandgap similar to the ordinary reflectivity (transmission) spectra.

In this paper, we show the results of magneto-optical characterization of electrodeposited nickel inverse opals. Linear and nonlinear optical Kerr spectra show clear magnetophotonic properties in the spectral ranges in the vicinity of photonic singularities of their reflectivity spectra.

2. Experiment

Metal inverse opals were fabricated by templating a colloidal crystal [17]. The colloidal crystal films made of polystyrene microspheres with a diameter of about 550 nm were grown onto a conductive thin gold layer evaporated on a glass substrate. Nickel was electrodeposited from a Watts bath under potentiostatic mode and the polystyrene was dissolved subsequently. Top and side view of the fabricated nickel opal is shown in Fig. 1. According to the scanning electron microscopy (SEM) data, the nickel PhC possesses an ordered porous structure with uniform spherical pores and the periodicity was about $d = 550$ nm.

Reflectivity spectra at different angles of incidence were measured by a Variable Angle Spectroscopic Ellipsometer (VASE, J.A. Woollam Co., Inc.) in the range 350–1100 nm (1.13–3.54 eV) for both p- and s-polarizations at 45° incidence (for p- and s-polarization electric field vector of the electromagnetic wave lies in- or perpendicular to the plane of incidence, respectively). Generally, the reflectivity of a nickel PhC is lower than that of the

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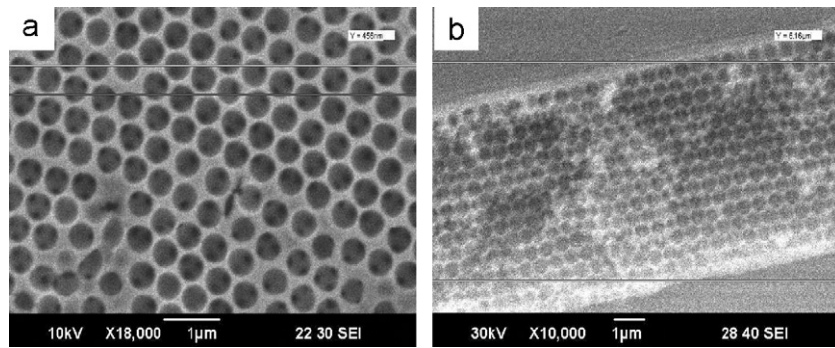


Fig. 1. SEM images of Ni photonic crystal: top view (a) and cross-sectional view (b).

nickel film and possesses oscillations with almost zero values at the reflectivity minima (thin lines in Figs. 2 and 3(a)).

Two types of linear Kerr effect were studied: longitudinal (LKE) and transversal (TKE) Kerr effect. The magnetization-induced second harmonic generation (MSHG) was measured only in the longitudinal geometry. LKE and MSHG were measured at 1 kOe, the TKE at 3.5 kOe.

The LKE and MSHG experiments were performed with a femtosecond Ti:Sap laser MaiTai (NewPort-Spectra Physics) with a “red” tuning range 710–990 nm, pulse width of about 100 fs, repetition rate of 82 MHz, and an average power of 100 mW focused onto a spot of about 50 μm at 45° incidence. The use of a doubling BBO crystal provided the “blue” spectral range 355–495 nm for LKE with an average power of 30 mW. For LKE and MSHG the incident waves were s- and p-polarized, respectively. The SHG wave was either p- or s-polarized. Much higher contrast in MSHG was observed for s-polarized SHG. TKE was measured using a Xenon lamp source with p-polarized light.

3. Results and discussion

An ideal metallic inverse opal system can be considered as a periodic array of spherical metal cavities [18]. In this case, the fields are mostly localized inside the cavities and the interaction between cavities is very weak. Therefore, the dispersion of the propagating EM modes is negligible and their frequencies almost coincide with the eigenfrequencies of a single ideal spherical cavity: $\omega_1 = \zeta_1 2\pi c/d$, where $\zeta_1 = 0.88$, $\zeta_2 = 1.23$ and $\zeta_3 = 1.42$ [18]. This gives $\lambda_1 = d/\zeta_1 = 625$ nm, $\lambda_2 = 447$ nm and $\lambda_3 = 387$ nm. For non-ideal metals and a filling factor less than unity, the eigenmodes are shifted to lower frequencies. Moreover, due to dispersion, for higher angle of incidence the eigenmodes are shifted from their values at normal incidence and split due to the lifting of degeneracy: in our experiments for p-polarization $\lambda_{11}^p = 900$ nm and $\lambda_{12}^p = 775$ nm (Fig. 2(a)), for s-polarization $\lambda_{11}^s = 860$ nm and $\lambda_{12}^s = 419$ nm (Fig. 2(b)).

Generally, for all kinds of photonic crystals, enhancements of nonlinear optical and magneto-optical effects are observed at the photonic bandgap edge [19]. In our measurements, we found that nonlinear optical effects and magneto-optical effects behave differently, particularly in the “red” spectral range.

For TKE, the difference between PhC and Nickel film appears at about 1000 nm and increases with the decrease in wavelength (Fig. 2(a)). TKE spectral dependence shows obvious magnetophotonic oscillatory behavior similar to the reflectivity spectral dependence: positions of minima in TKE spectra (or maxima by TKE absolute values) are quite close to the positions of maxima in reflectivity spectra.

For LKE, basically no spectral dependence was found in the “red” range in the vicinity of the strongest reflectivity minimum,

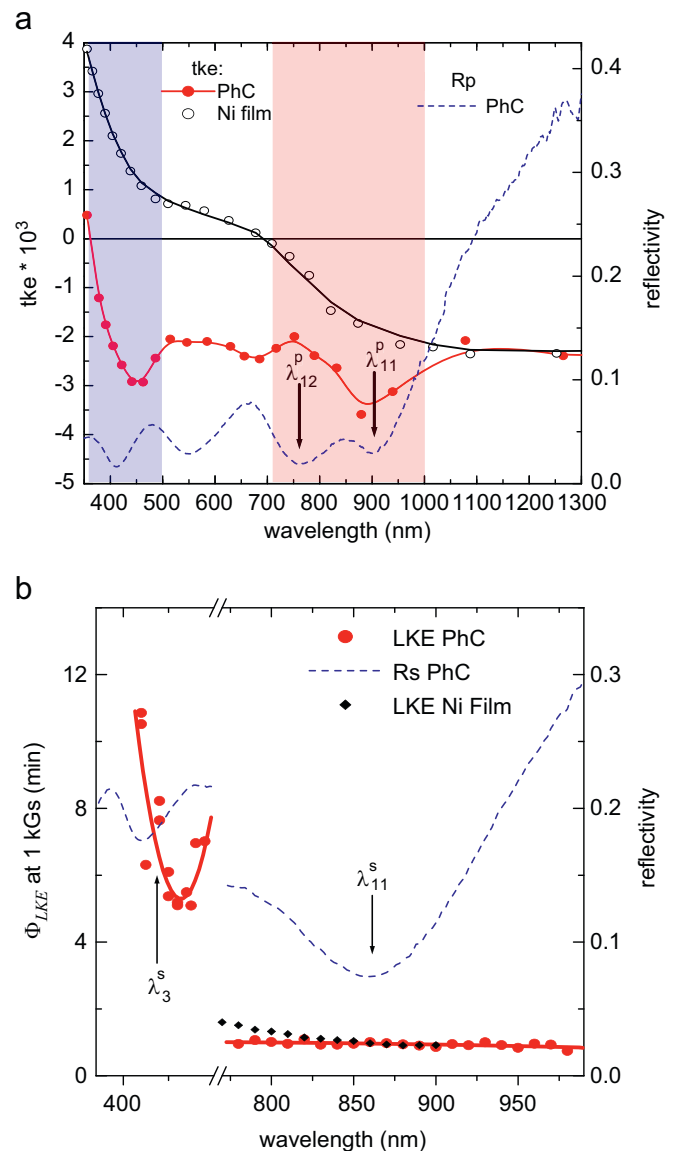


Fig. 2. (a) TKE amplitude (left scale) for PhC and nickel film and reflectivity (right scale) for PhC in p-polarization at the angle of incidence of 80°; (b) LKE rotation angle (left scale) and reflectivity (right scale) in s-polarization at the angle of incidence of 45°. Colored areas in (a) correspond to the “red” and “blue” ranges of (b).

see Fig. 2(b). The value of the Kerr rotation angle in this range is around 1 min, which is close to the value observed for a continuous nickel film [20]. According to Ref. [21] in a continuous

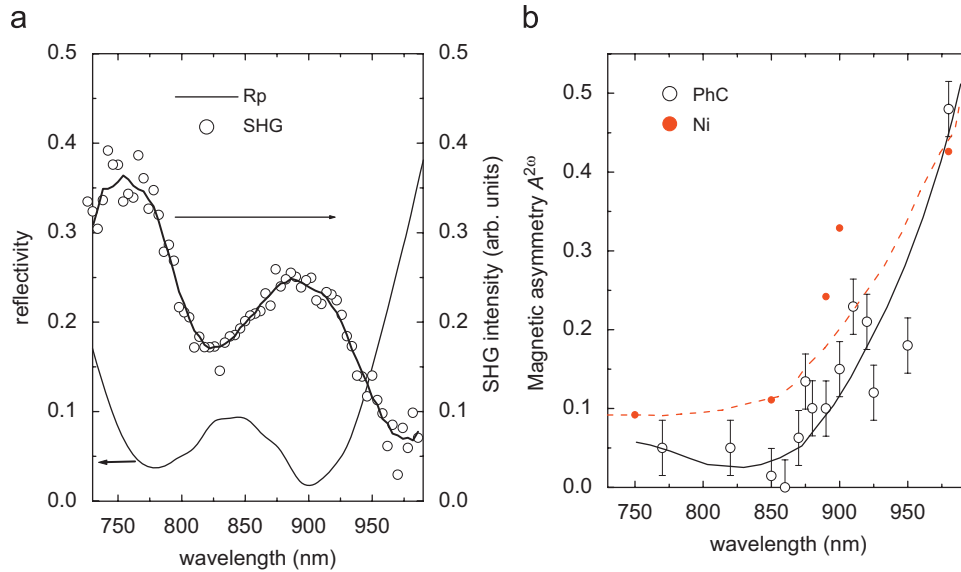


Fig. 3. (a) Reflectivity (left scale) and SHG (right scale) spectra in p-polarization, (b) MSHG magnetic asymmetry in p-s-polarization combination, solid line—guide for eye.

nickel film LKE rotation angles at 400 and 800 nm are of the same order of magnitude. In our measurements for PhC in the “blue” range a strong enhancement up to 10 min of the LKE rotation angle was observed near the λ_3 minimum at 410 nm. Oppositely to the “red” range, in the “blue range” the spectral dependence of the Kerr rotation angle was quite pronounced with the minimum close to the maximum of the reflectivity. Thus, a pronounced enhancement of LKE exists only in the “blue” spectral range, i.e. near photonic bandgaps (maxima of reflectivity) of higher order.

The second harmonic generation spectra without magnetic field are consistent with the reflectivity spectra: a strong enhancement is observed around the metal resonator eigenmodes $\lambda_{11}^{\text{SHG}} = 890 \text{ nm} \approx \lambda_{12}^{\text{p}}$ and $\lambda_{12}^{\text{SHG}} = 760 \text{ nm} \approx \lambda_{12}^{\text{p}}$ (Fig. 3(a)).

In order to characterize the nonlinear magneto-optical properties the spectral dependence of the magnetic SHG asymmetry was determined as [22]

$$A^{2\omega} = \frac{I^{2\omega}(H^+) - I^{2\omega}(H^-)}{I^{2\omega}(H^+) + I^{2\omega}(H^-)}$$

and plotted in Fig. 3(b) both for a Ni film and the Ni PhC. For the PhC, the data are quite noisy but not very different from the data for the nickel film (also consistent with the data from Ref. [22]) and do not reveal any obvious correlation with neither SHG nor reflectivity spectra.

Thus, among all the measured magneto-optical effects the strongest correlation with photonic properties was found for TKE (in the whole spectral range) and LKE (in the blue spectral range), and the poorest correlation was found for MSHG.

In conclusion, it was demonstrated that magnetic metal inverse opals possess clear magnetophotonic crystal properties in the UV and visible ranges, in spite of their high absorption. Enhancements of linear magneto-optical effects (both transversal and longitudinal) were found to be stronger in the blue rather than in the red spectral range. No enhancement was found for MSHG in the studied red spectral range.

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