The subwavelength tuned magneto-optical Kerr effect in $L1_0$-FePt films with perpendicular magnetic anisotropy*

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For $L1_0$-FePt films with strong perpendicular anisotropy covered by arrays of hexagonal close-packed polystyrene spheres (PSSs), fine structures are observed in magneto-optical Kerr rotation spectra in the visible spectral range. The reflection minima are found to be located at the same wavelengths as the Kerr rotation peaks. The Kerr rotation enhancement is attributed to the excitation of both the surface plasmon polariton in the dielectric PSS/metal interface and the guide waves (guide mode) in the PSS array. The two-dimensional PSSs/SiO_2/FePt system exhibiting a tunable magneto-optical Kerr effect and a high perpendicular magnetic anisotropy will be helpful for designing and fabricating magneto-optics devices.

Keywords: $L1_0$-FePt, magneto-optical Kerr effect, surface plasma polariton, guide mode

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1. Introduction

The magneto-optical Kerr effect (MOKE) has been used in magneto-optical recording media, isolators, and sensors.[1–4] In applications, a large MOKE is generally required. Fortunately, the chemically ordered $L1_0$-FePt film has a large MOKE and a high perpendicular magnetic anisotropy.[5–7,30] With spin-polarized Pt atoms and a large spin–orbital coupling, the chemically ordered $L1_0$-FePt alloy shows a broad and bell-shaped dispersion structure in the magneto-optical polar Kerr rotation θ_K spectrum in the 2.0–4.8 eV region.[9] Accordingly, a high spectral sensitivity cannot be obtained in the visible region. It is noted that although the bulk plasma resonance enhanced MOKE may occur,[10–12] the plasma edge in $L1_0$-FePt films is not located in the visible region.[7]

In the past decades, subwavelength optics in nanostructures has attracted much attention because of its wide applications in optical devices.[13–15] The electromagnetic field can be redistributed by surface plasma polariton (SPP) excitation. Magnetic nanostructures in the subwavelength scale may show peculiar properties, such as nonreciprocity,[16–18] high sensitivity, and optical anisotropy.[17,18] With an external magnetic field, the electromagnetic field is redistributed and the MOKE could be modified by the localized SPPs. For example, in Au/Co/Au trilayers, the MOKE enhancement was observed due to the localized SPP excitation.[19,20] Similar phenomena were also found in flat ferromagnetic films perforated by noble metal nanoslits,[21] nanoholes,[22] and nanodots.[23] The nature of all those phenomena is related to the subwavelength optics. In this paper, using the facile method with a two-dimensional (2D) hexagonal close-packed array of polystyrene spheres (PSSs) on the PSSs/SiO_2 (5 nm)/FePt(20 nm) films, an enhanced MOKE is achieved in the PSSs/SiO_2/FePt system.

2. Experiment

A series of PSSs/SiO_2/FePt samples with different PSSs diameters were fabricated on MgO (100) single crystal substrates. First, 20 nm $L1_0$-FePt films were prepared on MgO (100) single crystal substrates by dc magnetron sputtering at substrate temperature 620 °C. *In-situ* post-annealing was performed at the same temperature for 2 h. Subsequently, 5 nm thick SiO_2 layer was deposited to improve the 2D array of PSSs by self-assembly and to avoid the oxidization of the FePt layer. The base pressure of the sputtering system was 1.0×10^{-5} Pa, and the Ar pressure was 0.35 Pa during FePt and SiO_2 deposition. The microstructures of the films were characterized by X-ray diffraction (XRD) θ–2θ scans using a D8 Discover X-ray diffractometer with Cu $K\alpha$ radiation. The long range chemical ordering is clearly revealed by the diffraction peak around $2\theta = 24°$ in Fig. 1(a).

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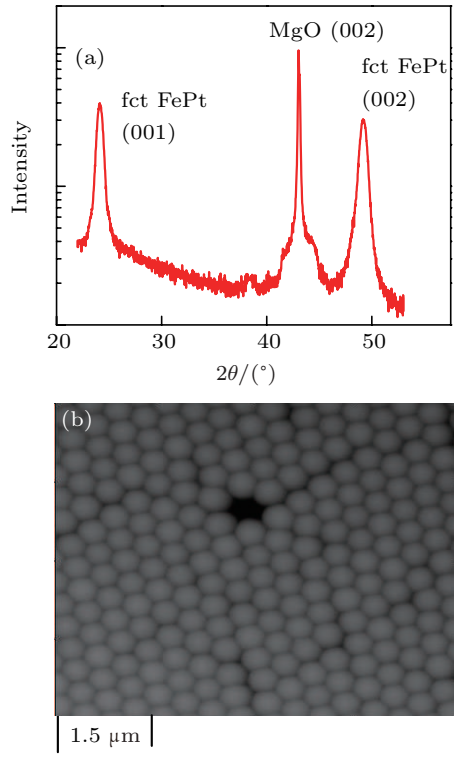


Fig. 1. (color online) (a) XRD pattern of SiO_2/FePt films and (b) top-view AFM image of the monolayer array of self-assembled PSSs on SiO_2/FePt films, with $d = 400$ nm.

The 2D arrays of PSSs were formed by self-assembly on the SiO_2/FePt films. A channel was made by an FePt film, a parallel quartz slide, and a Cu line U-shaped spacer, where the FePt film (bottom) and the parallel quartz (up) were separated by the U-shaped spacer and clipped by two clamps. An aqueous solution of PSSs was injected into the channel. After drying in air, PSSs were aligned on the FePt films. In experiments, PSSs with $d = 400$ nm, 500 nm, 600 nm were employed. Atomic force microscopy (AFM) was used to characterize the structures of the samples. Figure 1(b) shows the morphology of the PSSs/SiO_2/FePt sample with $d = 400$ nm. It can be seen that a well defined hexagonal close-packed array is formed, where the lattice constant is determined by d.

3. Result and discussion

The magneto-optical polar θ_K and Kerr ellipticity ϵ_K spectra were measured at room temperature by using a home-made Kerr spectrometer with a rotating analyzer. A $\lambda/4$ waveplate was put in front of the analyer when the ϵ_K spectra were measured. The incident angle was 5° in Fig. 2(a). Optical reflection R was measured by a reflectometer and normalized to that of an Al mirror. The Kerr loops of SiO_2/FePt (red line) and PSSs/SiO_2/FePt (black line) were measured at $\lambda = 510$ nm, and the results are displayed in Fig. 2(b). With the PSSs ($d = 600$ nm) array on SiO_2/FePt, θ_K at the wavelength of 510 nm is enhanced by a factor of 2. The coercivity of the sample is about 3.6 kOe.

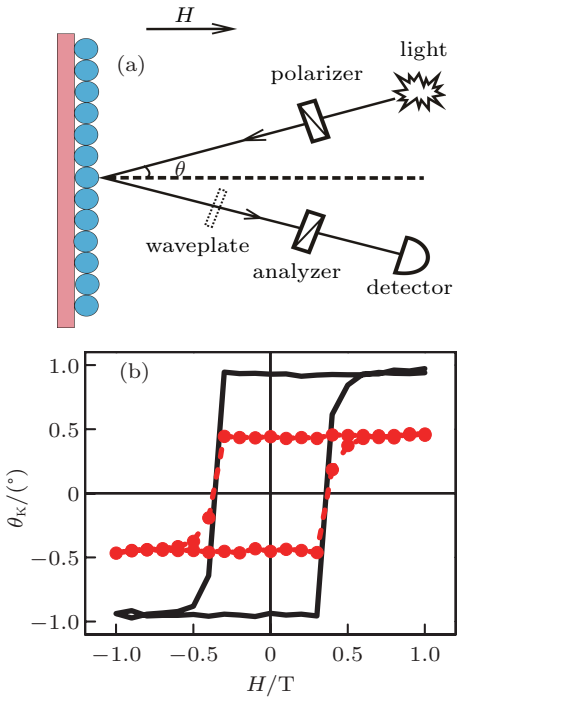


Fig. 2. (color online) (a) Schematic plot of magneto-optical polar θ_K and ϵ_K measurements and (b) polar Kerr loops of SiO_2/FePt without (dashed, red line) and with PSS array ($d = 600$ nm)(solid, black line), where the wavelength is 510 nm.

Figure 3(a) shows θ_K (black line) and ε_K (red line) spectra of the $L1_0$-FePt covered by 5 nm thick SiO_2. In experiments, the spectra of SiO_2/$L1_0$-FePt are similar to those of $L1_0$-FePt,[6] and the 5 nm thick SiO_2 has no impact on the MOKE of $L1_0$-FePt. Both the θ_K (black line) and ε_K (red line) spectra exhibit an s-shaped dispersion in the visible region, with a broad valley centered at $\lambda = 410$ nm in the θ_K spectrum and at $\lambda = 340$ nm in the ε_K spectrum. Since θ_K and ε_K obey the K–K relationship, we just focus on the θ_K results.[4] With 2D PSSs arrayed on the SiO_2/FePt film with $d = 400$ nm, fine structures appear in the θ_K spectrum with alternative maxima and minima, as shown in Fig. 3(b). The θ_K peaks and a resonance-like θ_K spectral structure appear. In the whole measured spectral region, θ_K is enhanced. For clarity, the θ_K peaks are marked. The 5^{th} peak near $\lambda \approx d$ has a full width at half maximum (FWHM) as small as 10 nm, and the 1^{st}, the 4^{th}, and the 6^{th} peaks locating at 676 nm, 428 nm, and 331 nm, respectively, are much broader than the 5^{th} peak. A resonant-like structure centered at 498 nm apears, where the spectral difference between the peak (2^{nd}) and the dip (3^{rd}) is about 20 nm and the θ_K has a very steep spectral slop. The reflection spectrum of PSSs/SiO_2/FePt (400 nm) is displayed in Fig. 3(c) (black line). The reflection dips are marked corresponding to the θ_K peaks. This suggests that the θ_K enhancement and the fine structure in the θ_K spectrum arise from the optical property modification. The wide and narrow R dips are suggested to be induced by the SPP excited at the FePt/PSS interface and the guide mode in the PSS array, respectively.[24,25] Additionally, the sharp and large peak at 360 nm is resulted from the

substrate $L1_0$-FePt film covered by 5 nm thick SiO_2, its reflection spectrum is also displayed in Fig. 3(c) (red thin line).

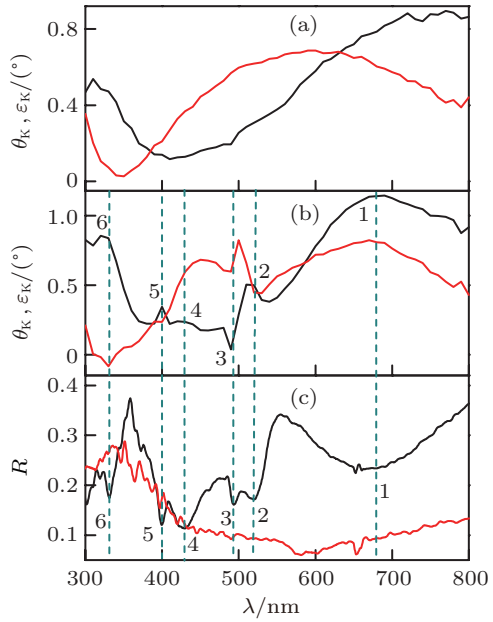


Fig. 3. (color online) The θ_K (black line) and ϵ_K (red line) spectra of (a) SiO_2/FePt and (b) PSSs/SiO_2/FePt, and (c) the reflection spectra of PSSs/SiO_2/FePt (black line) and SiO_2/FePt (red thin line). Here the external magnetic field $H = 10$ kOe and $d = 400$ nm.

Figure 4 shows the θ_K and the reflection each as a function of the ratio d/λ for the PSSs/SiO_2/FePt with different d. For clarification, the orders of all θ_K peaks and the reflection minima are marked. For $d = 600$ nm, the strong 2nd and 5th θ_K peaks are located near $d/\lambda = 0.79$ and 1.02, respectively. The weak 4th and 6th θ_K peaks are located near $d/\lambda = 0.95$ and 1.3, respectively. For all samples, the d/λ position for a specific order θ_K peak is almost fixed when d changes from 400 nm to 600 nm. The wavelength of the specific θ_K peak is approximately proportional to d. The peaks move in the short wavelength direction with increasing PSS diameter, which may due to the PSS dispersion.[26] The marked dips in the reflection spectra show the same wavelength dependence as the θ_K peaks with varying d. For $d = 600$ nm, the narrow 2nd and 5th dips appear at $d/\lambda = 0.778$ and 1.0, respectively. The 3rd one is located at $d/\lambda = 0.81$, close to the 2nd R dip. The 4th and 6th shallow R dips are located at $d/\lambda = 0.93$ and 1.2, respectively. In Figs. 4(c) and 4(f), we can deduce that for all samples, the θ_K peaks correspond to the reflection dips one by one and the θ_K enhancement should be related to the changes in the optical properties of the PSSs/SiO_2/FePt system.

The MOKE is sensitive to the optical properties of surroundings and the sensitivity can be described by $S = \partial\theta_K/\partial\tilde{n}(\lambda) = \partial\theta_K/\partial\lambda(\partial\tilde{n}(\lambda)/\partial\lambda)^{-1}$,[27–30] where $\tilde{n}(\lambda)$ is the complex index of the material and depends on the wavelength, that is, the sensitivity should be related to $\partial\theta_K/\partial\lambda$. For the θ_K spectra of the PSSs/SiO_2/FePt system in Figs. 4(a)–4(c), the 5th peaks near $\lambda = d$ are narrow and the larger $\partial\theta_K/\partial\lambda$ and high sensitivity are expected, which may make the detection substantially feasible. In addition, the resonance-like θ_K structure near the 2nd peak and the 3rd dip has a narrow width for all the three samples, implying the high sensitivity of the material.

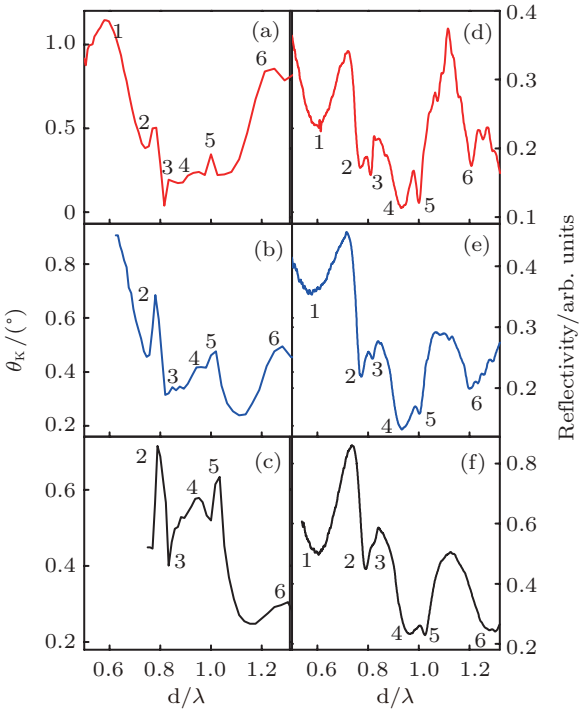


Fig. 4. (color online) The (a)–(c) θ_K and (d)–(f) reflection of PSSs/SiO_2/FePt with $d = 400$ nm ((a) and (d)), 500 nm ((b) and (e)), 600 nm ((c) and (f)). Here, $H = 10$ kOe.

4. Summary

Using the facile method of PSSs self-assembly on a hard magnetic $L1_0$-FePt film, both the perpendicular anisotropy and the high sensitive MOKE signal can be acquired. With the SPP mode and the guide mode excited in the PSSs/SiO_2/FePt subwavelength structure, the optical properties of PSSs/SiO_2/FePt are changed, and a high sensitivity is acquired, which may facilitate sensor fabrication.

References

[1] Hashimoto S, Matsuda H and Ochiai Y 1990 *Appl. Phys. Lett.* **56** 1069
[2] Pištora J, Yamaguchi T, Foldyna M, Mistrík J, Postavaa K and Aoyama M 2001 *Sensors and Actuators A* **110** 87
[3] Wang Z and Fan S H 2005 *Opt. Lett.* **30** 1989
[4] Wohlfarth E P and Buschow K H J 1990 *Handbook of Magnetic Materials* Vol. **5** (Holland: Elsevier)
[5] Lairson B M and Clemens B M 1993 *Appl. Phys. Lett.* **63** 1438
[6] Cebollada A and Weller D 1994 *Phys. Rev. B* **50** 3419
[7] Yamaguchi M, Kusakabe T, Kyuno K and Asano S 1999 *Physica B* **270** 17
[8] Zhou S M, Zhai H R, Song J T, Zhang H Y, Lu M and Jiang S L 1992 *Chin. Phys. Lett.* **9** 379
[9] Oppeneer P M 1998 *J. Magn. Magn. Mater.* **188** 275
[10] Reim W, Hüsser O E, Schoenes J, Kaldis E, Wachter P and Seiler K 1984 *J. Appl. Phys.* **55** 2155
[11] Feil H and Haas C 1987 *Phys. Rev. Lett.* **58** 65
[12] De A and Puri A 1984 *J. Appl. Phys.* **92** 5401
[13] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 *Nature* **391** 667

[14] Pendry J B, Martín-Moreno L and Garcia-Vidal F J 2004 *Science* **305** 847
[15] Barnes W L, Dereux A and Ebbesen T W 2003 *Nature* **424** 824
[16] González-Díaz J B, García-Martín A, Armelles G, García-Martín J M, Clavero C, Cebollada A, Lukaszew R A, Skuza J R, Kumah D P and Clarke R 2007 *Phys. Rev. B* **76** 153402
[17] Khanikaev A B, Mousavi S H, Shvets G and Kivshar Y S 2010 *Phys. Rev. Lett.* **105** 126804
[18] Temnov V V, Armelles G, Woggon U, Guzatov D, Cebollada A, Garcia-Martin A, Garcia-Martin J M, Thomay T, Leitenstorfer A and Bratschitsch R 2010 *Nat. Photonics* **4** 107
[19] Martín-Becerra D, González-Díaz J B, Temnov V V, Cebollada A, Armelles G, Thomay T, Leitenstorfer A, Bratschitsch R, García-Martín A and González M U 2010 *Appl. Phys. Lett.* **97** 183114
[20] Clavero C, Yang K, Skuza J R and Lukaszew R A 2010 *Opt. Lett.* **18** 7743
[21] Belotelov V I, Akinov I A, Pohl M, Kotov V A, Kasture S, Vengurlekar A S, Gopal A V, Yakovlev D R, Zvezdin A K and Bayer M 2011 *Nat. Nanotechnol.* **6** 370
[22] Ctistis G, Papaioannou E,Patoka P, Gutek J, Fumagalli P and Giersig M 2009 *Nano Lett.* **9** 1
[23] Torrado J F, González-Díaz J B, González M U, García-Martín A and Armelles G 2010 *Opt. Express* **18** 15635
[24] Shi L, Liu X H, Yin H W and Zi J 2010 *Phys. Lett. A* **374** 1059
[25] Zhang X, Shi L, Li J, Xia Y J, Shi Z, Zi J and Zhou S M 2012 *J. Phys. D: Appl. Phys.* **45** 405002
[26] Hu X S, Shin K W, Rafailovich M, Sokolov J, Stein R, Chan Y, Williams K, Wu K L and Kolb R 2000 *High Perform. Polym.* **12** 621
[27] Fumagalli P, Spaethand C and Tudiger U 1995 *IEEE Trans. Magn.* **31** 3319
[28] Sepúlveda B, Calle A, Lechuga L M and Armelles G 2006 *Opt. Lett.* **31** 1085
[29] Hauser H, Hochreiter J, Stangl G, Chabicovsky R, Janiba M and Riedling K 2000 *J. Magn. Magn. Mater.* **215–216** 788
[30] Klank M, Hagedorn O, Shamonin M and Dotsch H 2002 *J. Appl. Phys.* **92** 6484