Optical and magneto-optical studies of two-dimensional metallodielectric photonic crystals on cobalt films

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We studied the optical transmission and magneto-optical effect through a subwavelength hole array fabricated on a ferromagnetic cobalt (Co) thin film in comparison to a control unperforated Co film having the same thickness. We found that the perforated film sustains extraordinary transmission bands through the hole array, which can be well explained as due to light coupling to surface plasmons on the two film interfaces. We also found that due to resonant coupling to the surface plasmons, the magneto-optical Kerr effect in the spectral range of the anomalous transmission bands of the perforated Co film is much smaller than that in the control Co film. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1712027]

On a smooth metal–dielectric interface, light does not couple to surface plasmons (SP), which are the elementary excitations of the metal surface, because conservation of energy E and momentum $\mathbf{k}$ is not obeyed.[1] On an $(E,\mathbf{k})$ plot the SP dispersion curve lies below that of the electromagnetic waves in vacuum. But in a metal film that is perforated with a two-dimensional (2D) periodic array of holes, forming a 2D metallodielectric photonic crystal (MDPC), the periodicity allows grating coupling of the SP to light.[2] This periodicity promotes zone folding of the SP excitation dispersion relation that results in the formation of SP band structure. This makes it possible for light to directly couple to the SP excitations. Indeed it was recently found[2–12] that the optical transmission through subwavelength hole arrays fabricated on optically thick metallic films is enhanced by orders of magnitude at resonances (or maxima) where light couples to the SP excitations. The optical properties of various 2D MDPC films have been extensively studied so far,[2–12] but studies of 2D hole arrays in ferromagnetic films, and in particular the influence of the periodicity on the magneto-optical properties of the film, have not as yet been performed.

We report here our study of the optical transmission and magneto-optical Kerr effect (Kerr rotation and ellipticity) through a subwavelength hole array fabricated on thin Co film; we compare the results to a control unperforated Co film having the same thickness. We found the existence of extraordinary transmission resonances in the optical spectra, which can be well explained by light coupling to SP excitations. We also found that due to resonant coupling to SP excitations, the magneto-optical Kerr effect in the spectral range of the anomalous transmission bands is much smaller in the perforated Co film compared to the continuous Co film.

The subwavelength Co hole array used in this study was in the form of a square, 5×5 mm^2 in area, which was fabricated by the Nanonex Corp. (Princeton, NJ) using a nanoimprint method. The subwavelength hole array consisted of a 70-nm-thick Co film on a glass substrate with hole size of about 150 nm and lattice constant, a_0 of about 300 nm (Fig. 1 inset). The control unperforated film was fabricated by evaporating Co on glass, with the same thickness as that of the Co hole array sample. We also measured the magnetization of the 2D MDPC and control Co film and found that the *saturation magnetization is comparable in both films*.

The optical transmission spectra through the perforated and unperforated films were obtained at room temperature using a tungsten-halogen incandescent lamp, and a homemade spectrometer. We measured the zero-order transmission at normal incidence, as well as at several other angles, φ between the incident light propagation direction and the film surface normal.

The magneto-optic studies were performed on both samples by measuring both the ellipticity, ε and polarization rotation, θ in the reflected light with an in-plane magnetic field, i.e., the magnetic-optical Kerr effect (MOKE) [Fig. 2(a)].[13] The hysteresis loops of both ellipticity and polarization rotation were measured as the first and second harmonics, respectively,[14] of the modulator output signal at each

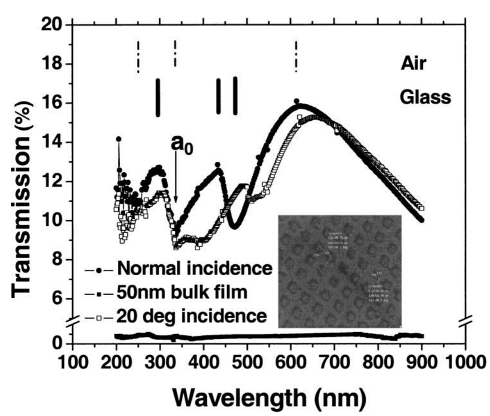

FIG. 1. The optical transmission spectra of the Co hole array film at normal incidence (full circles) and at an angle $\varphi=20°$ (empty circles) between the incident light propagation direction and the film normal. The full line at the bottom is the optical transmission of the Co control sample having the same thickness. The inset shows a SEM image of the hole array sample. The upper full and dashed vertical lines are the calculation for the transmission maxima using the model of light coupling to SP on the Co film interface with the glass and air surface, respectively.

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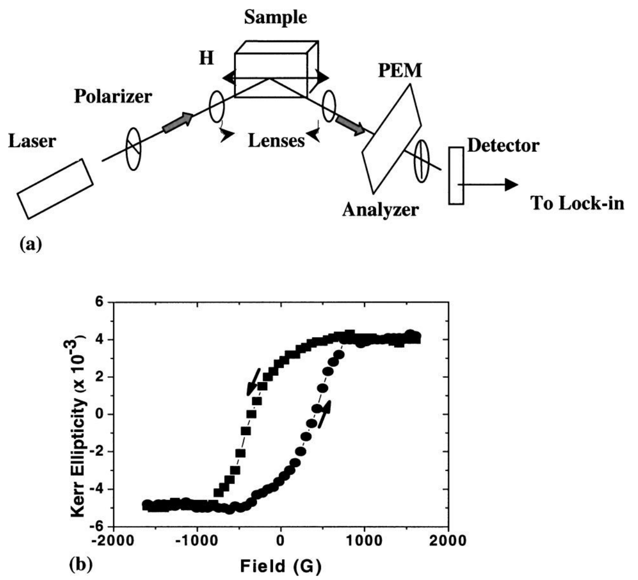

FIG. 2. MOKE measurements. (a) The experimental set up for measuring the MOKE changes. (b) The hysteresis in MOKE ellipticity versus the external applied magnetic field for the Co hole array at $\lambda = 824$ nm; the full circles (squares) are for the increasing (decreasing) field strength.

laser wavelength [see Fig. 2(b) for $\lambda = 824$ nm]. To cover the MOKE wavelength response within the visible spectral range we used several laser lines from three laser systems.

The zero-order optical transmission through the Co hole arrays in the visible/near-IR spectral range is shown in Fig. 1 for two incident angles, $\varphi = 0°$ and $\varphi = 20°$, respectively. Each spectrum is composed of several transmission band resonances occurring at λ_{max}, that ride on a transmission baseline. The features at λ_{max} are due to extraordinary transmission bands that are formed as the result of resonant light coupling to SP excitations of both interfaces.[2–12] This can be verified from the angle dependence, where a red shift in λ_{max} is apparent.

In the standard aperture theory of Bethe[15] the transmission through a subwavelength aperture follows a $(d/\lambda)^4$ dependence, where d is the hole diameter and λ is the incident light wavelength. Diffraction limits the transmission through such a hole so that the transmission in our case should have been about 0.4%. However the zeroth-order transmission through a subwavelength array of holes shows ''anomalous'' behavior. The transmission spectrum shows significant transmission at wavelengths much longer than d (Fig. 1). Also we note that the transmission is much stronger than that of the control Co film of comparable thickness (Fig. 1). The resonant interaction between the incident light and SP excitations on the two metallic film surfaces leads to the enhancement of transmission through such holes.

A normal incident light impinging on a metallic surface cannot excite the SP excitations, as the SP exist only in the transverse mode on such a metallic surface.[1] The periodicity of holes on the metallic surface allows coupling between the incident light and the SP excitations on both sides of the film. The conservation of momentum in this case can be written as[2]

$$\mathbf{k}_{SP} = \mathbf{k}_x \pm m\mathbf{u}_x \pm n\mathbf{u}_y, \tag{1}$$

where $|\mathbf{k}_x| = (2\pi/\lambda)\sin\theta$ is the component of incident wave vector of light in the plane of the hole array, $\mathbf{u}_x$ and $\mathbf{u}_y$ are the reciprocal lattice vectors (for a square lattice as in our case we have $|\mathbf{u}_x| = |\mathbf{u}_y| = 2\pi/a_0$), and m and n are integers. From the conservation of energy we get for the SP wave vector k_{SP} on a smooth metallic film

$$|\mathbf{k}_{SP}| = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}, \tag{2}$$

where ε_m and ε_d are the dielectric constants for the metal and the substrate (glass in our case). λ_{max} varies with the angle φ between the normal of the sample plane and the incident wave vector $|\mathbf{k}_x|$. The SP dispersion relations can be thus mapped out by a relation between λ_{max} and φ,[2] since at different angles of incidence different modes of surface plasmons can be excited.

For normal incidence Eqs. (1) and (2) above are reduced to

$$\lambda_{max} = \frac{a_0}{\sqrt{m^2+n^2}}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}. \tag{3}$$

Using Eq. (3) λ_{max} in the spectrum can be associated with the SP modes on different interfaces. In Fig. 1 the vertical full and dotted lines represent the different SP modes on metal–glass and metal–air interface, respectively. In the calculations performed using Eq. (3), the complex dielectric constant of Co (ε_m) was used as a fitting parameter, unlike the procedure described in the literature[2–4] that uses the standard database values of variation of dielectric constant with frequency, because the optical properties of the thin Co film were found to depend on the preparation methods. ε_d of glass and air were set constant at values of 2 and 1, respectively. We also note that there might be a different dispersion relation for surface plasmons with relatively high filling fraction of holes (25% in our case). In general there is good agreement between the calculated and experimental λ_{max}, where the maxima are either due to one interface or the other (Fig. 1). However we note that the exact λ_{max} is due to a combination of both film surfaces, and thus is difficult to predict without a detailed theoretical insight.[7,16]

Figure 2(b) shows the standard MOKE hysteresis measurements in ellipticity ε of the 2D MDPC sample at $\lambda = 824$ nm. It is seen that ε saturates at an applied field of about 1000 Gauss, and we took the difference between the two saturated values to compare with that for the control unperforated Co film. We found that whereas the MOKE ellipticity in the MDPC film showed a measurable value in the entire visible to near-IR spectral range, the MOKE polarization rotation was very small in the spectral range that corresponds to the anomalous transmission bands (at about 450 and 600 nm, respectively). For example, at $\lambda = 458$ nm we found that MOKE polarization rotation angle measured on the control Co film is a sizable 60 mdeg, in agreement with previous MOKE measurements on FCC Co crystal;[14] whereas that obtained on the MDPC sample was in the noise level of about 0.1 mdeg.

The spectra of the obtained MOKE changes in the ellipticity ε and polarization rotation θ of the MDPC and control Co films are shown in Fig. 3. The $\Delta\varepsilon$ and $\Delta\theta$ spectra of the control film are relatively flat, in agreement with previous measurements.[14] The $\Delta\theta$ spectrum of the perforated film, on

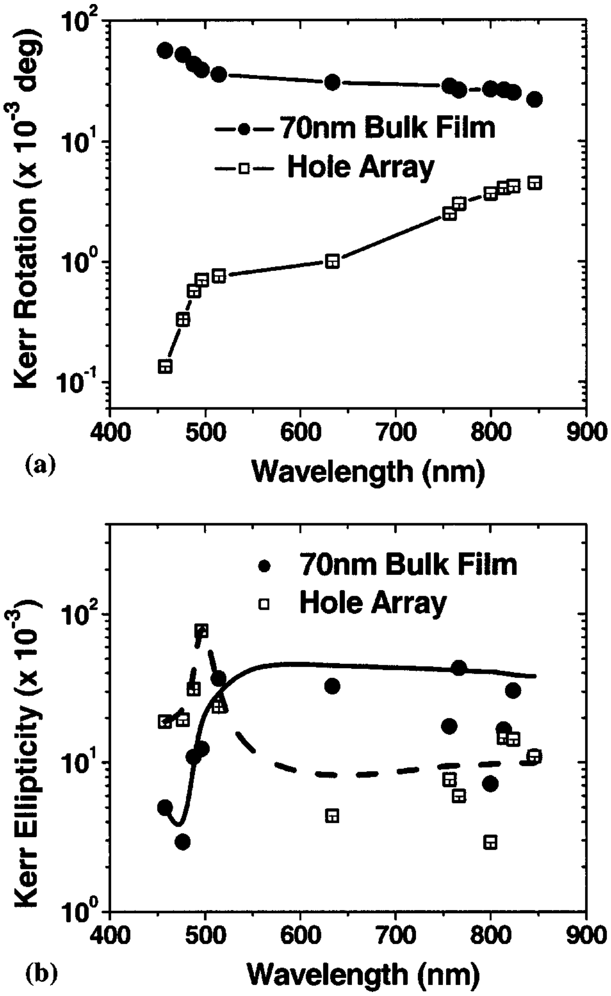

FIG. 3. MOKE spectra measured on the Co hole array film (empty squares) compared with those of the control Co film (full circles). (a) MOKE polarization rotation $\Delta\theta$; (b) MOKE ellipticity $\Delta\varepsilon$.

the contrary is about two orders of magnitude smaller in the spectral range of the anomalous transmission bands [$\approx$450 and $\approx$600 nm (Fig. 1)]. It partially recuperates in the near-IR range away from the anomalous transmission band, and has a pronounced shoulder at $\lambda_{min} \approx 500$ nm. The $\Delta\varepsilon$ spectrum of the perforated film is also small in the vicinity of the first anomalous transmission band at $\approx$600 nm, but recuperate at 500 and 800 nm, respectively, away from λ_{max}. It is thus tempting to interpret the MOKE results in the MDPC film as due to coupling to SP excitations on the metallic surfaces. The transmission maxima are due to SP resonance coupling, and whenever the transmission is enhanced the MOKE effect diminishes. In the unperforated control sample the impinging light induces oscillatory currents on the metal surface, and the direction of the currents is determined by the film magnetization. Consequently the polarization of the reflected light is rotated away from that of the incident light, and the rotation angle θ is proportional to the magnetization. In contrast, light resonant coupling to the SP excitations of the two MDPC film interfaces also induces currents *through the holes*, i.e., perpendicular to the film surface.[17,18] Such induced currents do not couple well to the film magnetization, and consequently the induced rotation θ of the incident light polarization direction is much smaller compared to that in the unperforated metal film. The MOKE effect is partially restored away from λ_{max}, where light coupling to the SP excitations is reduced. This explains both the weakness of the MOKE intensity in the spectral range of the anomalous transmission bands in the visible range of the 2D MDPC and its partial restoration at wavelengths that correspond to the Wood's anomaly, or far from λ_{max} in the near-IR spectral range (Fig. 3).

In conclusion, we measured extraordinary optical transmission through a subwavelength hole array on a ferromagnetic Co film that forms 2D MDPC. The anomalous transmission is well explained using the model of resonant light coupling to SP excitations on the two film interfaces. We also found that the magneto-optic Kerr effect is quenched in the spectral range that corresponds to the anomalous transmission, and we explained it as due to the resonance coupling to the SP excitations.

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