

Magneto-optical features and extraordinary light transmission through perforated metal films filled with liquid crystals

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We calculate the effective dielectric tensor of a metal film penetrated by cylindrical holes filled with a nematic liquid crystal (NLC) whose director is parallel to the film and can be controlled by a static magnetic field whose direction can be rotated in an arbitrary direction in the plane of the film. We consider both randomly distributed holes (using a Maxwell-Garnett approximation) and a square lattice of holes (using a Fourier technique). Both the holes and the lattice constant of the square lattice are assumed small compared to the wavelength. The films are found to exhibit extraordinary light transmission at special frequencies, ω_{sp} , related to the surface plasmon (SP) resonances of the composite film, which depends on the direction of the applied magnetic field. © 2006 American Institute of Physics. [DOI: 10.1063/1.2158691]

The recent discovery¹ of “extraordinary transmission” of light through a metal film perforated by a periodic array of subwavelength holes has stimulated worldwide interest. This transmission is widely believed to result from the coupling of light to surface plasmons (SP) of the patterned metal film. In a recent paper,² such systems (i.e., metal/dielectric, composite films with a periodic columnar microstructure) were studied in the presence of a static magnetic field. In the quasi-static limit it was found that the frequency of the transmission peak (as well as its amplitude) depends strongly on both the magnitude and the direction of the applied in-plane magnetic field. Such sensitivity could form the basis for a new type of magneto-optical switch. Unfortunately, the materials like Ag, Au, Al, cannot be used for such magnetic field sensitive devices, since in such materials the dimensionless magnetic field is very small due to low electronic mobility.³ In order to see this effect it was proposed in Ref. 2 to use semiconductor materials like GaAs and InAs.

In this paper, we extend this idea to perforated metal film (made from metals traditionally used in such cases, such as Ag, Au, or Al), whose holes are filled by a uniaxially anisotropic dielectric, such as a nematic liquid crystal (NLC). NLCs strongly affect the optical properties of various inhomogeneous dielectrics. For example, the photonic band gap of a periodic dielectric infused with NLC can be tuned, and even made to close, by suitably orienting the principal axis \hat{n} of a NLC, known as the director, with an electric field.⁴ Similarly, the SP frequencies, ω_{sp} , of both random distributions and chains of small metal particles are altered when these systems are immersed in a NLC.^{4,5} For the present application, we assume that \hat{n} is perpendicular to the hole

axis. For this film, we again find that the transmission peak is shifted by the anisotropy, and is split for different polarizations of incident light. Since \hat{n} can be rotated by changing the direction of an applied static magnetic field \mathbf{H}_0 (the so-called Fredericksz transition⁶), this result implies that the transmission can be controlled simply by rotating \mathbf{H}_0 (see Fig. 1), even if this magnetic field has no effect on plasma frequency ω_p of the metallic film (like Ag, Au, Al, etc.).

Let us consider a geometry which corresponds to the above mentioned experiment:¹ A metal film, with a square array of identical perpendicular cylindrical holes (parallel to the y axis), is placed in a static, in-plane magnetic field \mathbf{H}_0 , whose direction can be rotated within the xz plane (see Fig. 1). A monochromatic light beam, of angular frequency ω , impinges upon this film along the perpendicular axis y , with linear polarization along the principal axis x of the array (see Fig. 1). Treating the cylindrical holes as dielectric inclusions embedded in a conducting host, we can apply a general approach developed for the discussion of a metal/dielectric composite medium in the quasistatic regime.^{2,3,7,8} In this approach, $\mathbf{E}_0^{(\alpha)} = \nabla r_\alpha = \mathbf{e}_\alpha$ is applied. The local electric potential $\phi^{(\alpha)}(\mathbf{r})$ is then the solution of a boundary value problem based upon a partial differential equation that follows from the requirement $\nabla \cdot \hat{\epsilon} \cdot \nabla \phi = 0$ (see Refs. 2, 3, 7, and 8), which can be written in the form of an integro-differential equation

$$\phi^{(\alpha)}(\mathbf{r}) = r_\alpha + \int dV' \theta(\mathbf{r}') \nabla' G(\mathbf{r}, \mathbf{r}') \cdot \delta \hat{\epsilon} \cdot \nabla' \phi^{(\alpha)}(\mathbf{r}'), \quad (1)$$

where r_α is the α component of \mathbf{r} and $G(\mathbf{r}, \mathbf{r}') = [4\pi(\epsilon_{xx}\epsilon_{yy}\epsilon_{zz})^{1/2}]^{-1} [(x-x')^2/\epsilon_{xx} + (y-y')^2/\epsilon_{yy} + (z-z')^2/\epsilon_{zz}]^{-1/2}$ is a Green function, $\theta(\mathbf{r}')$ describes the location and

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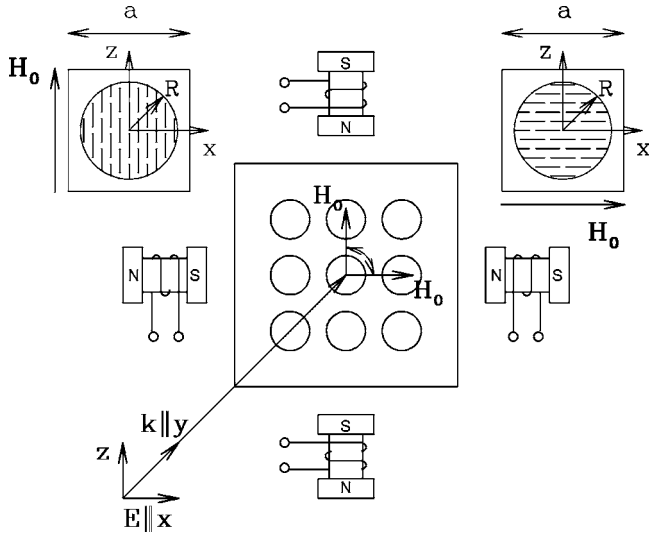


FIG. 1. Schematic drawing of a metal film with a periodic array of holes filled with a nematic liquid crystal (NLC) whose director is parallel to the film and can be rotated in the film plane by a static magnetic field \mathbf{H}_0 . The coordinate axes x , y , z , are always directed along the principal axes of the simple square lattice, and the applied static magnetic field \mathbf{H}_0 (created by a system of solenoids) always lies in the film plane. The incident light beam is normal to the film surface, i.e., the ac electric field \mathbf{E} is parallel to the film plane, while the wave vector is normal to it (i.e., $\mathbf{k} \parallel \mathbf{y}$). Note that the ac magnetic field \mathbf{B} of the light wave ($\mathbf{B} \perp \mathbf{E}$) is not important in our considerations and we omit it everywhere. Insets: The $a \times a$ unit cell of the periodic composite film with a cylindrical hole of radius R at its center filled with the NLC whose director is parallel to the film and can be rotated by application of a static magnetic field \mathbf{H}_0 whose direction can be rotated within the xz plane.

the shape of the inclusions ($\theta=1$ inside inclusions and $\theta=0$ outside of them).

The further treatment depends on whether we consider single or multiple inclusions. In the case of periodically arranged inclusions, we can subtract the linear part $r^{(\alpha)}$ from the electrical potential $\phi^{(\alpha)}$ and expand the remaining periodical part $\psi^{(\alpha)} = \phi^{(\alpha)} - r^{(\alpha)}$, as well as θ and G in Fourier series. Solving the system of linear equations obtained in this way from (1) we find the Fourier coefficients of $\psi(\mathbf{r})$ and then calculate³ the bulk effective macroscopic electrical permittivity tensor ϵ_e .

Equation (1) can be solved also for the single inclusion problem. Differentiating it by \mathbf{r} , and taking into account that the internal electric field, \mathbf{E} , is uniform inside a single elliptical inclusion^{8,10} we get: $E_\alpha = E_{0,\alpha} + (N_\alpha / \epsilon_{\alpha\alpha}) \delta \epsilon_{\alpha\beta} E_\beta$, where N_α is the depolarization factor in the α direction: $N_y = 0$, $N_x = 1 / (1 + \sqrt{\epsilon_{zz} / \epsilon_{xx}})$, $N_z = 1 - N_x$, and $\delta \hat{\epsilon} = \hat{\epsilon}_2 - \hat{\epsilon}_1$. Solving this system of linear equations, we find

$$\mathbf{E} = \hat{\gamma}(\hat{\epsilon}_{\text{incl}}, \hat{\epsilon}_{\text{host}}) \cdot \mathbf{E}_0, \quad (2)$$

where $\hat{\gamma}(\hat{\epsilon}_{\text{incl}}, \hat{\epsilon}_{\text{host}})$ is a diagonal 3×3 matrix with components $\gamma_{\alpha\alpha} = \epsilon_{\text{host},\alpha\alpha} / [(1 - N_\alpha) \epsilon_{\text{host},\alpha\alpha} + N_\alpha \epsilon_{\text{incl},\alpha\alpha}]$.

Taking Eq. (2) into account and considering the change in the average current, $\langle \mathbf{J} \rangle$, caused by a single inclusion, $\langle \mathbf{J} \rangle - \hat{\sigma}_{\text{host}} \cdot \mathbf{E}_0$, it is possible to get a simple equation for determining the bulk effective permittivity tensor $\hat{\epsilon}_e \cdot \langle \mathbf{E}(\mathbf{x}) \rangle = \langle \hat{\epsilon}(\mathbf{x}) \cdot \mathbf{E}(\mathbf{x}) \rangle$ [where $\langle \dots \rangle$ denotes a volume average, and $\hat{\epsilon}(\mathbf{x})$ is the local dielectric tensor] in the Maxwell Garnett (MG) (or Clausius-Mossotti) approximation⁸

$$(\hat{\epsilon}_e - \hat{\epsilon}_{\text{host}}) \cdot \hat{\gamma}(\hat{\epsilon}_e, \hat{\epsilon}_{\text{host}}) = \sum_{j \neq \text{host}} p_j \langle (\hat{\epsilon}_j - \hat{\epsilon}_{\text{host}}) \cdot \hat{\gamma}(\hat{\epsilon}_j, \hat{\epsilon}_{\text{host}}) \rangle_j, \quad (3)$$

where the sum is over the different types of inclusions j , excluding the host component, each with its particular volume fraction p_j , $\hat{\gamma}(\hat{\epsilon}_e, \hat{\epsilon}_{\text{host}})$ is a matrix similar to the given one in Eq. (2) where only the permittivities $\hat{\epsilon}_e$ and $\hat{\epsilon}_{\text{host}}$ should be interchanged.

A single cylindrical hole in a metallic host (see inset to Fig. 1) is assumed to be filled by an anisotropic material having a dielectric tensor with principal components ϵ_{ii} , ($i = x, y, \text{ or } z$): $\epsilon_{zz} \neq \epsilon_{xx} = \epsilon_{yy}$.

For simplicity, we assume the host has a Drude dielectric function

$$\epsilon_m = 1 - \frac{\omega_p^2}{\omega(\omega + i/\tau)}, \quad (4)$$

where $\omega_p = (4\pi n_0 e^2 / m)^{1/2}$ is the plasma frequency (n_0 is the density of charge carriers, e is the charge of one carrier, and m is its effective mass, see Ref. 7) and τ is a relaxation time.

From Eq. (3) we find expression for $\hat{\epsilon}_e$ in the MG approximation^{8,9}

$$\epsilon_{e,ii} = \epsilon_m \left(1 - p \frac{\delta \epsilon_{ii}}{\epsilon_m - N_i (1 - p) \delta \epsilon_{ii}} \right), \quad (5)$$

where p is the volume fraction of inclusions. When $\epsilon_m(\omega) - N_i (1 - p) \delta \epsilon_{ii} = 0$, then in the limit $\omega_p \tau \rightarrow \infty$ we obtain the following expression for the surface plasmon resonance frequency, ω_{sp} :

$$\omega_{\text{sp},i} = \frac{\omega_p}{\sqrt{\{1/[N_i(1-p)] - 1\} + \epsilon_{ii}}}, \quad (6)$$

where $i = x, z$. The resonant frequency depends on ϵ_{ii} and the volume fraction of the holes, p .

As an example, suppose that the material within the hole is the NLC known as BEHA, a uniaxial dielectric with principal dielectric constants 1.96, 1.96, and 2.56.¹¹ If $\hat{n} \parallel \hat{x}$, then Eq. (6) shows that the SP frequencies are split (in the limit $p \rightarrow 0$) by $\sim 0.06 \omega_p$.

In Fig. 2(a), we show the calculated $\text{Im} \epsilon_e(\omega)$ for several cases. In all cases, we assume that the cylindrical holes are filled by BEHA, and that $\hat{n} \parallel \hat{x}$. For the metal film, we assume $\omega_p \tau = 40$. The full curves without circles are the two principal components of $\text{Im} \epsilon_e$, denoted $\text{Im} \epsilon_{e,\parallel}$ and $\text{Im} \epsilon_{e,\perp}$, corresponding to the in-plane components parallel and perpendicular to \hat{n} , as obtained in the MG approximation. We take the $\hat{n} \parallel \hat{x}$, while cylindrical inclusions are assumed $\parallel \hat{y}$. The filled and open circles in Fig. 2(a) (connected by the dashed and dotted lines, respectively) denote the same quantities, but now for a square lattice of holes in the shape of right-circular cylinders. This value corresponds to the holes of radius $0.1a$ on a square lattice of lattice constant a . In this case, $\text{Im} \epsilon_{\parallel}$ and $\text{Im} \epsilon_{\perp}$ are calculated by a Fourier expansion technique mentioned above, and described in detail in Ref. 2. In Fig. 2(b), we show the $\text{Re} \epsilon_e(\omega)$ for the same cases as in Fig. 2(a). Finally, in Fig. 2(c), we show the transmission coefficient $T(\omega)$ [see Fig. 2(c)], and the characteristic "ex-

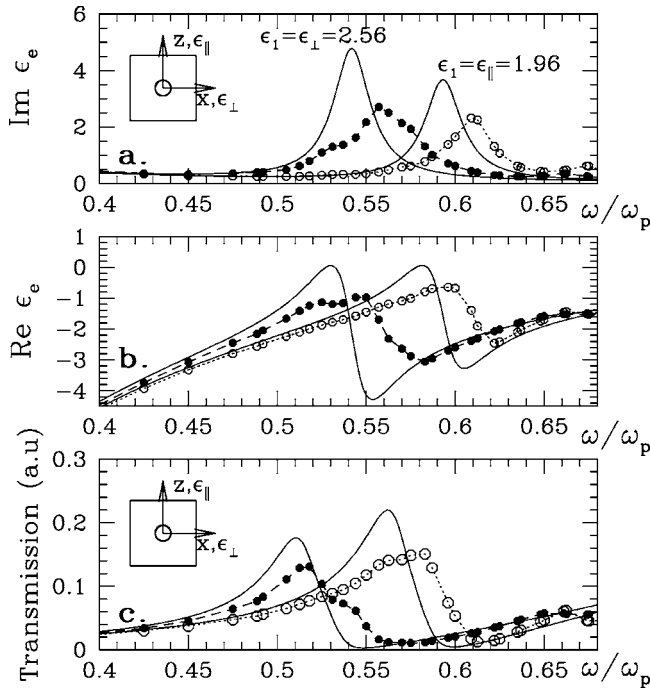


FIG. 2. (a) $\text{Im } \epsilon_{\perp}^{(e)}$ and $\text{Im } \epsilon_{\parallel}^{(e)}$ vs ω/ω_p . (b) $\text{Re } \epsilon_{\perp}^{(e)}$ and $\text{Re } \epsilon_{\parallel}^{(e)}$ vs ω/ω_p . (c) Transmission coefficient T vs frequency ω , for different polarizations $\mathbf{E}_{\parallel x}$ and $\mathbf{E}_{\parallel y}$. The analytical results obtained using a Clausius-Mossotti approximation [cf. Eqs. (5)] are indicated by full curves. The filled ($\epsilon=2.56$) and empty ($\epsilon=1.96$) circles denote the results obtained numerically using the method of Ref. 3 for a square array of holes in the shape of right circular cylinders. The dashed and the dotted lines, connecting, respectively, the filled and empty circles, are guides to the eye. We assume that the ratio of the hole radius R to the lattice constant a is 0.1 (see insets), corresponding to a volume fraction of holes of $p=0.031$, and we take $\omega_p\tau=40$, and $\omega_p h/c=5/3$. The latter means that when $\omega_p=10^{15}$ rad/s (a typical for Al value¹), the film thickness is $h=0.5$ μm , respectively, when $\omega_p=10^{16}$ rad/s (typical for the Ag value¹), the film thickness is $h=0.05$ μm , when $\omega_p=10^{14}$ rad/s [a value typical for GaAs and InAs (see Ref. 7)], then $h=5$ μm .

traordinary transmission" peaks expected on the basis of Figs. 2(a) and 2(b). Both approximations show rather sharp SP peaks in the transmission, which occur at different frequencies depending on the polarization of the incident radia-

tion. The curves are obtained for the dimensionless value $\xi = \omega_p h/c = 5/3$. When $\omega_p = 10^{15}$ rad/s (typical for the Al value) it corresponds to the film thickness $h = 0.5$ μm (cf. with 200–300 nm in the experiments¹). The wavelength of the light corresponding to the resonance frequency ω_{sp} [see Eq. (6)] is of the order $\lambda = 2\pi c/\omega_{\text{sp}} \sim 3770$ nm. Since we have used the quasistatic approximation, the wavelength should be much larger than the hole (cf. this value of the wavelength $\lambda \sim 3770$ nm with the hole sizes used in the experiments ~ 150 – 700 nm, see Ref. 1).

In summary we suggest that extraordinary transmission through perforated metal films can easily be controlled by filling the holes with an NLC such as BEHA. Since the transmission would differ substantially for \hat{n} parallel and perpendicular to the polarization of the incident wave, $T(\omega)$ through the film could be controlled simply by rotating \mathbf{H}_0 .

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- ¹T. W. Ebbesen, H. H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, *Nature (London)* **391**, 667 (1998); H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, *Phys. Rev. B* **58**, 6779 (1998); J. A. Porto, F. J. Garcia-Vidal, and J. B. Pendry, *Phys. Rev. Lett.* **83**, 2845 (1999).
- ²Y. M. Strelniker and D. J. Bergman, *Phys. Rev. B* **59**, R12763 (1999).
- ³Y. M. Strelniker and D. J. Bergman, *Phys. Rev. B* **50**, 14001 (1994).
- ⁴K. Busch and S. John, *Phys. Rev. Lett.* **83**, 967 (1999); J. Müller *et al.*, *Appl. Phys. Lett.* **81**, 171 (2002); H. Takeda and K. Yoshino, *Phys. Rev. B* **66**, 115207 (2002).
- ⁵S. Y. Park and D. Stroud, *Appl. Phys. Lett.* **85**, 2920 (2004); S. Y. Park and D. Stroud, *Phys. Rev. Lett.* **94**, 217401 (2005).
- ⁶V. Friedericksz and V. Zolina, *Z. Kristallogr.* **72**, 255 (1931); *Trans. Faraday Soc.* **29**, 919 (1933).
- ⁷D. J. Bergman and Y. M. Strelniker, *Phys. Rev. Lett.* **80**, 857 (1998); Y. M. Strelniker and D. J. Bergman, *Eur. Phys. J.: Appl. Phys.* **7**, 19 (1999).
- ⁸D. J. Bergman and Y. M. Strelniker, *Phys. Rev. B* **60**, 13 016 (1999), and references therein.
- ⁹D. Stroud, *Phys. Rev. B* **12**, 3368 (1975).
- ¹⁰L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii, *Electrodynamics of Continuous Media*, 2nd ed. (Pergamon, Oxford, 1993).
- ¹¹L. M. Blinov, V. A. Kizel, V. G. Rumyantsev, and V. V. Titov, *J. Phys. (Paris), Colloq.* **36**, C1 (1975).