Tuning the extraordinary optical transmission through subwavelength hole array by applying a magnetic field

Arvind Battula,[1] Shaochen Chen,[1,*] Yalin Lu,[2] R. J. Knize,[2] and Kitt Reinhardt[3]

[1]*Department of Mechanical Engineering and Center for Nano & Molecular Science and Technology, The University of Texas, Austin, Texas 78712 USA*

[2]*Laser Optics Research Center, the Physics Department, U.S. Air Force Academy, Colorado 80840, USA*

[3]*AFOSR/NE, 875 North Randolph Street, Suite 326, Arlington, Virginia, 22203, USA*

**Corresponding author: scchen@mail.utexas.edu*

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The transmission of light through a thin Ag film with a periodic subwavelength hole array can be influenced by the presence of the externally applied magnetic field **H**. Using a three-dimensional finite element method, we show that the spectral locations of the transmission peak resonances can be shifted by varying the magnitude and direction of the **H**. The transmission peaks have blueshift, and the higher the magnitude of **H** the larger the blueshift. The shift is due to the change of cavity resonance condition as a result of the magneto-induced anisotropy in the optical properties of the Ag film. Hence, high transmittance for any desired wavelength can be achieved by applying an appropriate **H** to the metallic film of optimized material and hole parameters. © 2007 Optical Society of America

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Theoretical description by Bethe [1] says that the transmission through a subwavelength circular hole ($r \ll \lambda$) in an infinitely thin, perfectly conducting metal sheet would scale proportionally to $(r/\lambda)^4$. So, according to this theory the transmission through subwavelength holes would be very small. But an extraordinary transmission of several orders of magnitude more than Bethe's prediction has been reported through an array of subwavelength holes milled in an opaque metal screen [2]. The underestimation of transmission by Bethe's theory is because it is too idealized to consider the surface modes that might be involved and also of propagation of evanescent modes that could be excited inside the holes [3]. Subsequently, enhanced transmission through hole arrays in metal films has been studied in great detail both theoretically and experimentally. The transmission peaks are because of light coupling to the surface plasmons (SPs) on the incident surface, which would then be transmited through the holes to the rear surface where re-emission of light would take place. These SPs are attracting much attention due to their possible applications for light control at nanoscale. For example, the plasmon resonance condition of a nanoshell is sensitive to the relative size of the core and shell layers [4].

Similarly gryotropic media with magneto-optical Faraday and Kerr effects have derived a great interest for applications in submicrometer scale to control the light [5,6]. In recent times, both the magnetized films with perforated holes and magnetized pillars included in a dielectric have been studied for their plasmonic aspects [7–10]. Also, following the report of extraordinary transmission through subwavelength holes [2], a study was conducted on the idea of how the transmission peaks would depend in the presence of a static, in-plane magnetic field [9]. It was concluded in the study that the transmission peaks depend not only on the plasma frequency but also on the magnitude of an applied static magnetic field **H** and on its direction. However, the study has treated the cylindrical holes as dielectric inclusions in a conducting host that occupies the entire volume in between the infinitely conducting plates of a large capacitor. Lately, a study [11] has been reported with simultaneous enhancement of both transmittance and MO Faraday and Kerr effect in a bilayer system of a metallic film perforated with subwavelength hole arrays, which is placed on a uniform dielectric film magnetized perpendicular to its plane. Nevertheless none of the above studies have considered a finite metal film with the effect of different directions of the **H** on the transmission peaks.

In this Letter we study the transmission peaks through a thin Ag film perforated with a hole pair under different externally applied **H**. The holes are rectangular in shape and are in square array with a periodicity d (Fig. 1). The thickness of the Ag film is h with the holes having width w, length l, and spacing between the holes given by s. Throughout the current study, we choose $d=600$ nm, $h=300$ nm, $s=60$ nm, and $l=400$ nm. The three-dimensional numerical modeling is carried out by finite element software (COMSOL 3.2a) [12]. The Ag dielectric constant is fitted into Drude model $\varepsilon=\varepsilon_\infty-\omega_p/(\omega^2+i\gamma\omega)$ by taking $\varepsilon_\infty=7.9$, $\omega_p=1.29\times10^{16}$, and $\gamma=3.21\times10^{13}$ to fit the empirical data given by [13]. The optical properties of the Ag have a directional sensitivity to the externally applied **H** and result in strong anisotropy. The applied **H** enters through the Hall-to-Ohmic resistivity ratio [9]. The local permittivity tensor (ε) of the Ag dielectric function can be obtained from [9,14]. The

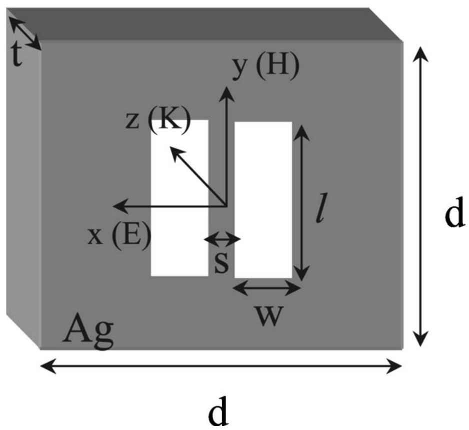

Fig. 1. Schematic of light incident on a thin Ag film perforated with square array of rectangular holes pair having $d=600$ nm, $t=300$ nm, $w=60$ nm, $l=400$ nm, $s=60$ nm.

computational domain considered is a single unit cell, and the light is incident normal to the film surface ($\mathbf{k}\|z$) with transverse magnetic (TM) polarization, i.e., the incident polarization (electric field $\mathbf{E}$) is parallel to the width of the rectangular hole as shown in Fig. 1. The unit cell has periodic boundary conditions and the computational domain is terminated with a perfect matching layer [15].

Figure 2 shows the transmission spectra in the visible and near IR region for various long and narrow rectangular hole arrays. The two high transmission peaks observed are due to the cavity resonance in the rectangular holes, which can be regarded as a slit of definite length that can support standing waves [16]. At the first transmission peak ($\lambda=814$ nm), the hole has a resonance that is very close to a complete standing wave or a second harmonic and at the second transmission peak ($\lambda=1118$ nm) the hole has a resonance that is almost like a half standing wave or a first harmonic. The location of both transmission peaks have a blueshift when the single hole array width is increased from $w=60$ nm to $w=120$ nm. This is due to the decrease in effective index (n_{eff}) with the increase in width of the hole or slit [17] that would then shift the resonance condition to lower wavelengths. However, when a single hole ($w=120$ nm) is split into two holes with a smaller width ($w=60$ nm) and has a space ($s=60$ nm) between them, then the transmission peaks would have redshift. This can be explained by an increase in n_{eff} due to the decrease in hole width. But, the new n_{eff} of the hole pair is not the same as that of a single hole array with the same width. Because the hole pair array would have a resonance mode with a z component wave vector ($\mathbf{k_z}$) different from the single hole array, which then would lead to a different n_{eff} ($=\mathbf{k_z}/\mathbf{k_o}$, where $\mathbf{k_o}$ is the free space wave vector [17]). Also, it is to be noted that the double hole array has transmission peak magnitudes bigger than the single hole array having the same width. In addition, the double hole array has transmission peaks that are well separated in comparison to the single hole array having an equivalent width ($w=120$ nm). Also, it was found that there is no transmission when the incident light has transverse electric (TE) polarization, i.e., when the incident light polarization is parallel to the hole length.

The effect of applied $\mathbf{H}$ with different orientation and magnitude on the TM polarized light transmission spectra through a thin Ag film perforated with a rectangular hole pair can be seen in Figs. 3(a)–3(d). When the $\mathbf{H}$ direction is parallel to the incident polarization ($\mathbf{H}_{\|}$), then as the magnitude is increasing the locations of both the transmission peaks have a blueshift. This is in accordance with results presented in [9,14,18], which reported that the transmission peaks appearing at SP's resonance locations would move to lower wavelengths with increasing $|\mathbf{H}|$, whereas in the current study, the transmission peaks are mainly due to the cavity resonance. The increase in applied $\mathbf{H}$ would lower the ε tensor components except for the diagonal element that is in the direction of applied $\mathbf{H}$, and this might result in smaller n_{eff}, which would shift the transmission peak resonances to lower wavelengths. The shift in the first transmission peaks is approximately 35 nm for the $\mathbf{H}$ range considered, and the shift in second transmission peaks is much bigger, in the range of 110 nm for the same $\mathbf{H}$ range considered. When the applied $\mathbf{H}$ is in the direction perpendicular ($\mathbf{H}_t$) to the incident polarization but in-plane to the metal surface, it would result in a similar blueshift for the second transmission peak, whereas the first transmission peak has a very small shift and a new small transmission dip seems to evolve with the increase in $\mathbf{H}_t$. This can be seen clearly in Fig. 3(c). The transmission peak on the lower wavelength side of the dip has a strong cavity resonance similar to the second harmonic, whereas the transmission peak on the higher wavelength side of the dip has an off-cavity resonance. This suggests that the high transmission might be due to a resonance of in-plane SPs excited on the front and back surfaces of the metal film. Hence the dip near the first transmission peak is due to the off resonances of both the cavity and in-plane SPs. Figure 3(d) shows that when the applied $\mathbf{H}$ is in the direction of the propagation of the incident light ($\mathbf{H}_k$) then the increase in its magnitude would result in a similar shift of the transmission peaks to lower

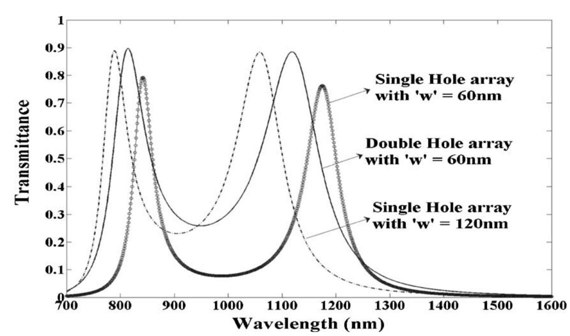

Fig. 2. Transmission spectrum of a TM polarized light through a thin Ag film perforated with rectangular hole array having $w=60$ nm (continuous curve with open circle), rectangular hole pair array having $w=60$ nm and $s=60$ nm (continuous curve) and rectangular hole array having $w=120$ nm (dashed curve).

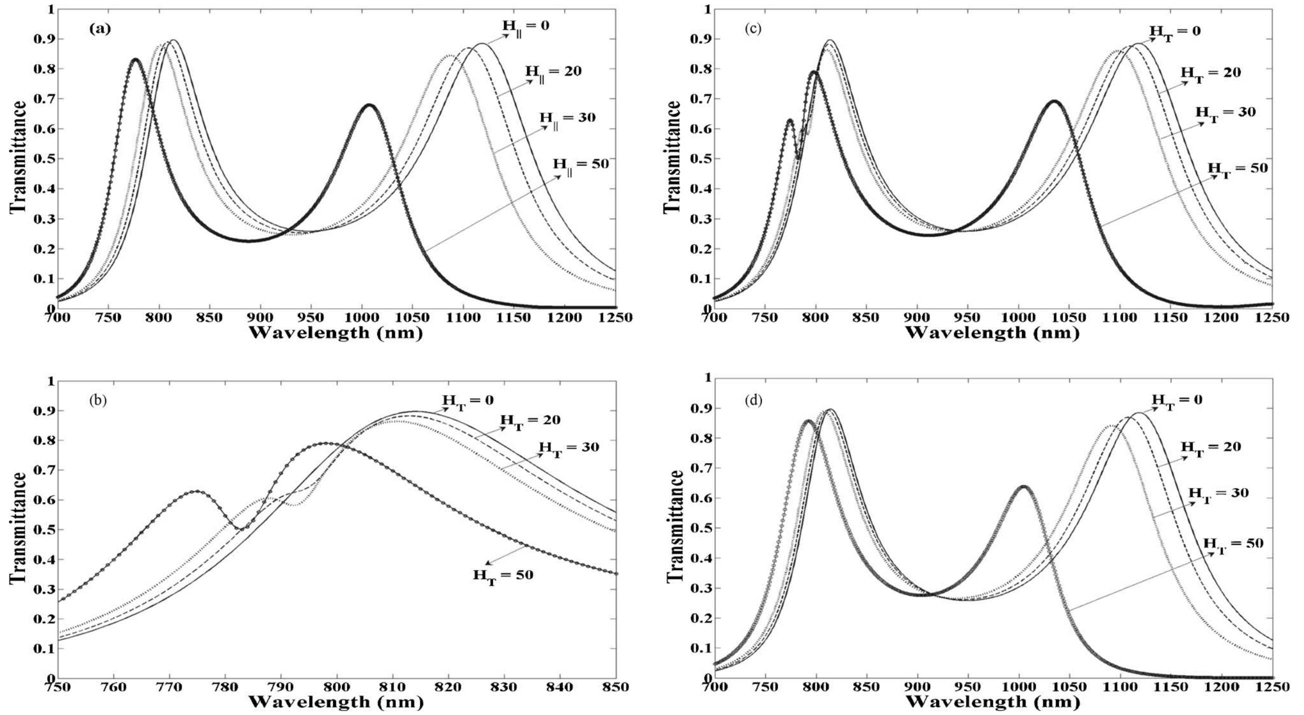

Fig. 3. Transmission spectrum of a TM polarized light through a thin Ag film perforated with a rectangular hole pair array having $w=60$ nm and $s=60$ nm for magnetic field $|\mathbf{B}_o|$ ($=H/\mu$, where μ is Hall mobility) applied in the direction (a) parallel to the incident polarization, (b) and (c) perpendicular to the incident polarization but in-plane to the metal film, and (d) parallel to the propagation direction of the incident light.

wavelengths. Except for now the range of shift for the first transmission peak is smaller for $\mathbf{H}_k$ when compared with $\mathbf{H}_{\parallel}$. Also, it is to be noted from Figs. 3(a)–3(d) that the transmission peaks are reducing in strength with the increase in **H** magnitude and the rate of decrease is more for the second transmission peak when compared with the first peak. But the strength of the transmission peaks is similar for different **H** orientations.

In conclusion it is shown that an Ag film with an array of rectangular hole pairs under the presence of externally applied magnetic field **H** would have the transmission peak locations shifted. This is due to the shift of the cavity resonance condition as a result of the magneto-induced anisotropy in the optical properties of the metallic film. The transmission resonances have blueshift in the locations with the increase in **H**. The $\mathbf{H}_{\parallel}$ case has more blueshift when compared with other directions of the **H**.

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