Exploring magnetic plasmon polaritons in optical transmission through hole arrays perforated in trilayer structures

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Optical transmission properties through hole arrays in metal/dielectric/metal trilayer structures were demonstrated. Besides the surface plasmon induced strong transmission and well-recognized negative refraction band, a higher mode was observed and elaborately investigated. Detailed results showed that this mode belongs to a higher magnetic excitation related to the reciprocal vector \( G_{1,1} \) of the lattice, and a “magnetic plasmon polariton (MPP)” model was proposed to describe such magnetic excitations in periodically modulated structure. By adjusting the structural parameters, the authors can conveniently control the MPPs’ properties, which provide us another way to tailor the light propagation properties in subwavelength structures. © 2007 American Institute of Physics. [DOI: 10.1063/1.2750394]

The desire to manipulate the photon’s behavior in a controlled manner in micro-nanoscale has inspired good many researches and leads to a new discipline—plasmonics owing to its ability to merge electronics and photonics. Surface plasmon polaritons (SPPs) stemmed from the coupling of electromagnetic wave and the collective electronic excitations on metal surface especially attracted many interests considerably due to its important role in the extraordinary optical transmission (EOT) phenomena since Ebbesen’s report in 1998. Although SPP excitation is recognized as not the only mechanism responsible for EOTs in recent studies, its remarkable contribution in the interaction between the light and metallic nanostructures is undoubted. At the same time, in another very active topic of negative index metamaterials (NIM), great efforts have been made to seek smart structures to have high coupling to the magnetic-field component of light, which produces a negative permeability to meet the negative refractive (NR) property. In a common sense, one would imagine could a plasmonic behavior be formed via the coupling to the magnetic component of incident wave in a proper metamaterial? Here, we reintroduce the metal/dielectric/metal trilayer structure perforated with square-hole arrays [or so-called “fishnet” structure, sketched in Fig. 1(a)], which was well developed in recent NIM studies.

The proposed structure was proved to exhibit magnetic response via two coupled metal layers referred as “magnetic atoms.” In the top view [Fig. 1(b)], the horizontal blocks filled with red diagonal patterns (type M1) are the commonly identified magnetic atoms, and the longitudinal stripes are regarded as the electric atoms to produce the negative permittivity. However, from another point view, magnetic resonance may not be always localized but coupled to its neighborhoods by magnetic inductions. So in our considerations, when magnetic resonances are excited in the region M1, they will most possibly spread away into those “electric atoms.” Thus, more magnetic atoms would be formed inside the middle layer of the longitudinal strips, which are sketched as types M2 and M3 (it is only a schematic, more types may exist for higher modes). Thus, a plasmonic behavior comes into being in a magnetic induction way. Different plasmon modes will be excited as is coupled to appropriate incident light. So we call such magnetic excitations as “magnetic plasmon polaritons” (MPPs).

To verify this idea, trilayer (Ag/SiO2/Ag) samples with square-hole arrays are fabricated on polished K9-glass substrates. Experimentally, the trilayer films are prepared by sputtering, and then followed with the milling of focused-ion beam (Strata FIB 201, FEI Company, 30 keV Ga ions). By controlling the sputtering condition and focused-ion beam (FIB)-milling treatment, the sample structural parameters can be adjusted conveniently. Here, two series of samples are addressed, both of whose Ag film thickness (t=35 nm) and hole size (d=250 nm) are kept unchanged, but various SiO2...
FIG. 2. (Color online) Experimentally measured (a) and numerical calculated (b) transmission spectra of the samples A, B, and C with various SiO$_2$ spacers, in which mode 1 and mode 2 are marked out as two MPP modes.

The subsequent numerical simulations confirm this assumption. High frequency structure simulator (HFSS), a commercial software package based on the finite elemental method, is employed in simulations. The dielectric constant of silver is defined by the Drude model \[ \varepsilon = \varepsilon_0 - \omega^2/\omega_p^2 + i\omega\gamma \], with the plasma frequency \( \omega_p = 1.38 \times 10^{16} \text{s}^{-1} \) and collision frequency \( \gamma = 8.5 \times 10^3 \text{s}^{-1} \). The refractive indices of SiO$_2$ spacer and glass substrate are set as 1.47 and 1.5, respectively, according to the material’s data. From simulations, the transmission spectra are well reproduced, as shown in Fig. 2(b), except for a little difference in intensities. The characteristic peaks or dips also demonstrate the ratio of \( \lambda_{\text{mode 1}}/\lambda_{\text{mode 2}} \) approximately equals 1.4. To get a clear cognition, Figs. 3(a) and 3(b) reveal the simulated magnetic field \( H_z \) distributions in the xy plane (z=0) lying in the center of the SiO$_2$ spacer for those two modes. Wavelike features of magnetic field are well presented in the y direction for mode 1 and in both the x and y directions for mode 2. It confirms the plasmonic character of MPPs modulated by the lateral periodic structure. As well as the reciprocal vector \( G_{0,1} \) associated mode 1 (MPP1), mode 2 (MPP2) is apparently related to \( G_{1,1} \) [as illustrated in Fig. 3(b)]. For the normal incidence, we can presumably propose the MPP excitation condition in the form analogous to that of the SPPs on perforated metal surface as

\[
\lambda_{\text{MPP}} = \frac{2\pi c}{|G_{m,n}|} \frac{1}{\omega_{LC}},
\]

where

\[
G_{m,n} = m\frac{2\pi}{P_x} + n\frac{2\pi}{P_y}
\]

is the \((m,n)\) ordered in-plane reciprocal vector of the hole lattice, and \( \omega_{LC} \) is the eigenfrequency of the LC circuit induced magnetic resonance. It should be noted that, as the magnetic excitation is polarization dependent, the orthogonal modes cannot be excited for a polarized incidence. For example of y polarization, all \((m,0)\) modes are extinct. As for the concerned samples with a square lattice \( P_x = P_y \), we have \(|G_{1,0}| = |G_{0,1}| \) and \(|G_{1,1}| = \sqrt{2}|G_{0,1}| \). It truly verifies the \( \sqrt{2} \) relation of these two modes, indicating a feature very analogous to the SPPs. From the \( H_z \) maps, we also can identify the exact “moment” arrangements of the magnetic atoms M1, M2, and M3 schemed in Fig. 1(b) in correspondence to these two MPP modes.
From these results and interpretations, a clear physics picture is presented. When a light normally incidents into a perforated metal film, optical field is enhanced at proper wavelengths due to the excitation of the SPPs (or other surface waves). These em energies will reradiate through the holes array leading to a strong broad transmission band if only one metal layer is presented. However, the trilayer structure composes many magnetic resonators by LC circuits, which will absorb the em energies around their resonant frequency with relative narrow linewidth. If this mode is rightly located inside or near the transmission band, it will appear as a dip or a step in spectrum correspondingly. Notably, these magnetic responses are actually modulated by the periodic structure via the lateral coupling, thus multi-MPP modes are excited as different reciprocal vectors $G_{m,n}$ are involved, which behave in a similar manner of the $G_{m,n}$ associated SPP excitations.

In summary, by elaborately investigating the transmission property of perforated trilayer structure, we proposed a remarkable MPP model as a more basic cognition on the well-known magnetic response in this system. A higher magnetic mode that is emphatically illustrated as a MPP excitation associated SPP excitations.

Additional references include:


Here, we do not want to be involved in the detailed discussions on the multicauses of the strong EOT, only regarded it as the SPP mode for simplifications.