Resonance Absorption of Metallic Plate with Subwavelength Hole Array

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The optical reflectance by a metallic plate arranged with array consisting of subwavelength periodic square hole is investigated by using the three-dimensional finite-difference time-domain method (3D-FDTD). There are dips in the reflectivity spectra, which indicate the absorption peaks. The absorption peaks behave differently according to the ratio of hole width and the period of the hole array. Combined with the near fields of the absorption peaks, it is found that the surface plasmon (SP) resonance on the surface of plate and localized SP in the hole play a major role for the two absorptions.

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Recently, experiments have shown the extraordinary high transmission of light through the metal subwavelength hole array and they have inspired great interest due to the unclear mechanism and the potential applications.\textsuperscript{[1-3]} It is generally admitted that the enhanced transmission is mainly attributed to the coupling of surface plasmon (SP) resonance excited on the upper and lower surfaces of the metal structure.\textsuperscript{[4-6]}

As a metal device associated to the SP resonance, the one-dimensional metal microcavity composed of metal–dielectric–metal having upper metal film arranged with slits periodically has been proposed and investigated in the optical and microwave ranges.\textsuperscript{[7,8]}

The structure (microcavity) with the surface wave resonance enlightens potential devices and it is critically important for the achievement of the compact photonic components. The underlying mechanism for the absorption is the Fabry–Perot resonance in the transverse direction in the dielectric core to form the standing waves which converts the electromagnetic power to the Joule heating of the metal. On the other hand, a metallic grating with bivalved cavities (bottle-shaped cavities), the SP resonance and the surface shape resonance also lead to the absorption of the power of incident wave at certain wavelengths.\textsuperscript{[9]}

Furthermore, there is some renewed interest in optical absorption, such as the absorption of overdense plasma to the surface plasma wave which is excited by the incident electromagnetic wave through a subwavelength diffraction grating in front of the plasma surface,\textsuperscript{[10]}

and design of a one-dimensional metallic–dielectric quasi-periodic structure to realize the absorption broadband.\textsuperscript{[11]}

In this Letter, the absorption of a metallic plate arranged with subwavelength hole array is investigated. The reflectivity spectra obtained by using the three-dimensional finite-difference time-domain method (3D-FDTD) show that there are dips at some wavelengths, which is due to the absorption of the structure. In order to find the mechanism of the absorption, the responses of the reflectivity spectra to the ratio of hole width and the period are investigated. The analysis of near fields corresponding to the dips in the reflectivity spectra is also provided.

The dispersion properties of the metal must be considered here since the absorption and permittivity of the metallic material are frequency dependent. The Drude model\textsuperscript{[12,13]} is used here to describe the dependence of the metallic permittivity on the frequency,

\begin{equation}
\varepsilon_M(\omega) = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}\right),
\end{equation}

where \( \omega \) is the angle frequency of the incident wave, \( \varepsilon_0 \) the permittivity of the vacuum, \( \omega_p \) the plasma frequency of the metal, and \( \gamma \) represents the damping rate which characterizes the ohmic absorption loss. The metal gold (Au) is used in this study,\textsuperscript{[14]} its plasma frequency is \( \omega_p = 1.236 \times 10^{16} \) and loss \( \gamma = 1.4 \times 10^{14} \).

The propagation of the light in the metal is described by the Maxwell’s equations which are coupled with the oscillations of quasi-free electrons in the metal (Drude model),\textsuperscript{[13]}

\begin{align}
\nabla \times E &= -\mu_0 \frac{\partial H}{\partial t}, \\
\nabla \times H &= \varepsilon_0 \frac{\partial E}{\partial t} + J, \\
\frac{\partial J}{\partial t} + \gamma J &= \varepsilon_0 \omega_p^2 E,
\end{align}

where \( E \) and \( H \) are the electric and magnetic field vectors, respectively; \( \nabla \) is the Nabla differential operator, \( J \) is the current density \( (A/cm^2) \) and is equal
to the time derivative of the metal polarization, i.e. \( J = \partial P/\partial t \); \( \mu_0 \) is the magnetic permeability of the vacuum.

The 3D-FDTD method is employed to simulate the interaction between the metal and the incident wave. The 3D-FDTD code is homemade. The structures are illuminated by a TE-polarized plane wave pulse \((E_z, H_y, H_z \neq 0)\) centred at \( \lambda = 600 \) nm. The spectrum width of this pulse can cover the range desired in the calculation. Two pulse responses with the structure and without the structure are written above the structure in two calculations, respectively. The reflection response is obtained by the difference between two pulse responses. The Fourier transform of the temporal reflection response of the structure is used to obtain the spectrum. Then normalization of the spectrum by the incident wave gives the reflectivity spectrum.

The schematic diagram of the structure is depicted in Fig.1. The metallic plate is arranged with square holes with period \( p \) both in the \( x \) and \( y \) directions. The hole is of width \( d_x \) (\( d_y \)) in the \( x \) (\( y \)) direction. The substrate metal with thickness \( h_2 > 200 \) nm prevents the optical wave to transmit through the structure. Here in the 3D-FDTD code, the space increments are \( \Delta x = \Delta y = \Delta z = 10 \) nm. Thus the resolution of the structure is 10 nm.

An \( x \)-polarization TE wave is incident on the upper surface of the structure normally. The depth of the hole is \( h_1 = 200 \) nm, the width in the \( y \) direction is \( 200 \) nm, and the period is \( 480 \) nm. The reflectivity spectrum varies as the width of the hole in the \( x \) direction decreases, as shown in Fig.2. One can see that there are two dips in the reflectivity spectra. When \( d_x = 200 \) nm, there are two dips: a strong one around \( \lambda = 490 \) nm and another one around \( \lambda = 568 \) nm.

As \( d_x \) decreases, the dip around \( \lambda = 568 \) nm becomes deeper and has a red-shift, while the other one only becomes narrower. The response of reflectivity spectra to the period of the hole array is studied. The hole width is selected to be \( d_x = 60 \) nm and \( d_y = 200 \) nm, the depth is \( 200 \) nm. Three hole arrays with \( p = 430, 480, 530 \) nm are calculated as shown in Fig.3. It is obvious that the absorption peak on the left has a red-shift with the increasing period. In contrast, the right one has little red-shift. Both the dips become deeper when the period increases.

![Fig. 1. Schematic diagram of the metallic structure: (a) \( zz \) cross section and (b) top view. The depth of the holes is \( h_1 \) and the substrate metal with the thickness \( h_2 > 200 \) nm is opaque to the optical waves.](image1)

![Fig. 2. Reflectivity spectra of the hole array with different hole widths in the \( x \) direction.](image2)

![Fig. 3. Influence of the period of the hole array on the dips.](image3)

The dips in the reflectivity spectra are smaller than the metal porosity of the upper metal film. It is indicated that the incident waves are absorbed not only onto the part of hole but also onto the part of metal. Furthermore, the hole width is smaller than half the wavelength of the optical spectrum range we are interested in. Therefore the absorption phenomenon is very interesting. The field amplitude distributions at the dips are provided to understand the absorption
phenomenon of the incident waves by the structure.

The holes in widths $d_x = 60 \text{ nm}$ and $d_y = 200 \text{ nm}$ are engraved in the plate with a depth of $h_1 = 200 \text{ nm}$, the period is chosen to be 480 nm. There are two dips on the reflectivity spectra at $\lambda = 490 \text{ nm}$ and $\lambda = 638 \text{ nm}$. The amplitudes of electric and magnetic fields corresponding to the dip at $\lambda = 490 \text{ nm}$ are presented in Fig. 4. The first row shows that the electric field $E_x$ inside the hole is larger as compared to the other places.

The magnetic field $H_y$ shown in the second row mainly concentrates on the surface of the plate and the bottom of the hole. The characters of the fields indicate the excitation of SP resonance. Moreover, the absorption peak is sensitive to the period of the hole array but independent of the hole width in the direction (see Figs. 2 and 3). Therefore, it is believed that the SP

Fig. 4. Field amplitude distribution for the dip at $\lambda = 490 \text{ nm}$ for $p = 480 \text{ nm}$, $h_1 = 200 \text{ nm}$, $d_x = 60 \text{ nm}$, and $d_y = 200 \text{ nm}$.

Fig. 5. Field amplitude distribution for the dip at $\lambda = 638 \text{ nm}$ for $p = 480 \text{ nm}$, $h_1 = 200 \text{ nm}$, $d_x = 60 \text{ nm}$, and $d_y = 200 \text{ nm}$.
plays a major role in the absorption phenomenon. The SP is the wave propagating along the surface of the conductor with the wave vector,

$$k_{SP} = k_0 \sqrt{\frac{\epsilon_d \epsilon_M}{\epsilon_d + \epsilon_M}},$$

where $k_0 = \omega/c$ is the wave vector of the incident wave and $\epsilon_d = 1$ is the permittivity of vacuum on the plate. The momentum of the incident wave is enhanced to match that of the SP on the metallic surface through the diffraction of subwavelength hole array. Then the incident wave is changed to the SP resonance on the metallic surface but not reflected by the plate. Finally the energy of the SP are absorbed via Joule heating of the metal.

The amplitudes of electric and magnetic fields corresponding to $\lambda = 638\,\text{nm}$ are shown in Fig.5. The first row shows that the electric field $E_x$ at the entrance of the hole is larger than the field at other places. The magnetic field shown in the second row is strong inside the hole. Combined with the sensitivity of the absorption mode to the width $d_x$ as shown in Fig.2, it is implied that the localized SP mainly contributes to the absorption. The incident wave is coupled to the localized SP inside the hole, then the energy of the localized SP is changed to the Joule heating of the metal wall.

The effect of the hole depth on the absorption is analysed in Fig.6. For very small hole depth, the right dip has a large red-shift when the hole becomes deeper. However, the dip is almost independent of the hole depth for large values of hole depth. This indicates that the dip is due to the localized SP at the entrance of the hole.

In conclusion, the optical absorption of the metallic plate arranged with subwavelength hole array has been studied by using the 3D-FDTD. The dips in the reflectivity spectra indicate the existence of absorption modes. By changing the parameters of the hole and the period and by combining with the electric and magnetic field distributions, the main mechanisms for two different absorption modes are identified. The SP resonance and localized SP play different roles in the transition of the energy of incident waves to the Joule heating.

References


Fig. 6. Influence of the depth of the hole on the absorption. The period is 480\,\text{nm} and the hole width is $d_x = 60\,\text{nm}$ and $d_y = 200\,\text{nm}$. 