Dual effect of surface plasmons in the light transmission through perforated metal films

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Abstract

The light transmission through perforated metal film has been studied both experimentally and theoretically. By taking account of plasma response of real metal on hole walls as well as metal surface, an analytical result for the transmission has been deduced, which agrees well with the experiments. The transmission involves both the diffraction modes and the surface plasmons. The surface plasmon polariton formed on the metal-dielectric interface gives rise to the transmission minima. Nevertheless, the cavity surface plasmons excited in the nanoholes contribute actively to the transmission enhancement. The results suggest a dual-effect of the surface plasmons.

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Due to the unique dielectric response of metals, the interaction between the electromagnetic waves and artificially structured metals has been a subject of a wealth of theoretical and experimental work. For example, by using the periodic arrays of conducting wires and split-ring resonators, left-handed metamaterials have been constructed [1]. In recent years, resonant excitation of surface plasmon polariton (SPP) has sparked much attention [2]. Light that usually travels in a dielectric or vacuum is, due to coupling between light and surface charges, able to propagate along the metal surface with the amplitudes decaying into both sides. This unique feature has generated the SPP-based photonics or plasmonics. Plasmonics possessing both the capacity of photonics and miniaturization of electronics enables it to be an outstanding candidate for the future optoelectronic applications [3].

Besides the propagation of light along metal surface, the light propagation normal to the metal film is another interesting issue. When the film is optically thin (~ skin depth), the energy transfer can be enhanced by the SPP mode [4], and super-resolution imaging can be achieved [5]. And when the film thickness is much larger than the skin depth, the film will be completely opaque. However, it was found by Ebbesen et al. [6] that when subwavelength hole arrays are introduced into the metal film, a surprising effect appears. That is, the transmission of light thought to be very low can be larger
than unity when normalized to the area of the holes. This unusual transmission effect has generated great interest in the scientific community [7], partly due to its wide range of potential applications, including subwavelength light sources, enhanced nonlinear processes, and so on.

The research on this issue also stems from the theoretical interest, as the physical origin of high transmission is still unclear. In such a metal system, the SPP mode can be produced by grating coupling and leads to strong enhancement of fields at the metal surface. Thus it is naturally and generally admitted that the SPP plays a crucial role [6, 8]. However, the experimental results such as the position of transmission peaks do not agree with the SPP model [8]. Even in a recent experiment [9], the indirectly deduced absorption cannot be attributed simply to the SPP mode since it occurs at all wavelengths (not only at the transmission maximum). On the other hand, no strong evidence for SPP has been presented theoretically. Previous analytical calculations bear a poor prediction of peak width as well as an obscure SPP interpretation [10]. Moreover, the numerical calculations which it is not easy to extract the underlying physics also deviate strongly from the experiments [11]. Therefore, the SPP mechanism has received a drastic debate [12-14]. These cases show that the underlying physics and the role of surface plasmons in the light transmission remains an open question rather than having been solved.

In this paper, the light transmission and the role of surface plasmons will be studied. For the purpose, here experimentally used is an \( h=220\text{nm} \) thick (much larger than the skin depth) gold film, which is coated by sputtering on the cross section of a single-mode optical fiber. Square holes arranged in a square array (14\( \mu m \times 14\mu m \)) are fabricated in the film with the focused-ion-beam system (strata FIB 201, FEI company, 30 keV Ga ions). The lattice constant and the hole side are determined respectively to be \( d=580\text{nm} \) and \( a=265\text{nm} \), with a normalized area of the holes 20.9\%. In the measurement, the incident light from an incoherent light source is coupled into the single-mode fiber for which the light can be considered to be incident normal to the metal film. And the zero-order transmission spectrum is obtained with an optical-spectrum analyzer (ANDO AQ-6315A).

Figure 1 shows both measured (the open circles) and calculated (the solid line) transmission spectra for the perforated gold film (inset is the focused-ion-beam image of the square holes), which is characterized by the transmission dips and peaks. In the analytical calculation (see the following), the refractive index for air and glass is set as 1 and 1.46 respectively, and a frequency-dependent permittivity for gold is used [15]. One can see that the experimental results, including the spectrum shape, the transmission minima and maxima are well reproduced by the calculations. In the experimental transmission spectrum, two dominant dips locate at the wavelengths 606 and 870nm, which is very close to the calculated 598 and 870nm (a small dip at 658nm is due to reciprocal vector \( G_{1,1} \) which is neglected in the theory). And the transmission efficiency is greatly enhanced with the peaks positioned at 710 and
945nm, which agrees respectively with the theoretical values 694 and 946nm. Moreover, good agreement can also be extended to the width of transmission peaks (or dips), as can be seen from the spectra. So far, the numerical calculation based on the Fourier modal method has been found in the literature to be most successful [11], nevertheless the deviation of peak position (and peak width) between theory and experiment is still up to about 80nm (and 40%). Comparing with previous work, our analytical results appear to be more preferable. In addition, the locations of Wood’s anomaly and SPP resonance have been marked in the transmission spectra by the thinner and thicker arrows, respectively. It is found for the first time that the Wood’s anomaly corresponds not to the transmission minimum but to a small step located near the transmission dip, where the detail is exhibited in both measured and calculated spectra. Overall, the calculation captures quantitatively the transmission properties and thus reveals the underlying physics of the light transmission.

It is a common knowledge that diffraction modes can be generated when the incident light impinges on the structured metal surface. These diffraction modes will be of great importance in the light transmission as stressed by the CDEW model [14]. In addition, for the metal film, the surface charges can be excited and couple strongly to the electromagnetic fields. These surface plasmons, being of either positive or negative effect, will participate in shaping and simultaneously be marked in the transmission spectrum. Actually, besides the SPP mode formed on the metal-dielectric interface, the surface plasmons also involve the light-electron interaction inside the nanoholes. In the transmission, the electromagnetic waves are strongly confined in the subwavelength holes, which act as the unique channel for the photon tunneling. Then, strong coupling between light and electrons on the hole walls can be induced, giving rise to cavity surface plasmons (CSP) in the nanoholes.

By using Maxwell’s equations and surface-impedance boundary condition (SIBC) imposed on the subwavelength hole walls, the wave fields inside the holes can be approximated by (the surface normal is in the y direction)

\[
H_y^h = (A_0 e^{i h y} + B_0 e^{i h y}) \cos(\alpha x) \cos(\beta z), \\
(-a/2 \leq x, z \leq a/2; -h \leq y \leq 0)
\]  

(1)

Here, \( A_0 \) and \( B_0 \) are the unknown amplitudes of the downward and upward waves in the nanoholes; \( q_0 = \sqrt{k_n^2 - \alpha^2 - \beta^2} \) is the propagation constant, where \( k_n = k_0 \sqrt{\varepsilon_n} \) \( (\varepsilon_n \) is the permittivity of any material filled in the holes); \( \alpha \) and \( \beta \) are determined respectively by

\[
\frac{\alpha a}{2} = \frac{k_n \varepsilon_n}{i\alpha \sqrt{\varepsilon_m}}, \quad \frac{\beta a}{2} = \frac{k_0 \sqrt{\varepsilon_m}}{i\beta}
\]  

(2)

When the hole walls are perfect conducting as was considered previously [10, 16],
equations (2) lead to $\alpha \approx 0$ and $\beta \approx \pi / a$. Correspondingly, the fundamental eigenmode in the square holes are just simplified to the $TE_{01}$ mode. But when the real metal is considered, it is found that $\alpha$ becomes a purely imaginary number $(\alpha = i \sqrt{2k_0\varepsilon_n h} (-\varepsilon_m)^{1/2} a)$, and $\beta$ is real but smaller than $\pi / a$ (the absorption of metal is neglected). That means, the fields in the holes are propagating in the $z$ direction but evanescent in the $x$ direction; i.e., they are bounded to the hole walls $(x = \pm a / 2)$. This surface mode confined in the nanoholes, originating from coupling of light to collective oscillation of electrons, can be termed as the CSP mode. In addition, the $y$-component of wavevector $q_y$ is also imaginary when the wavelength is much larger than the hole size. Comparing with the tunneling effect of electrons where the electron energy is lower than the potential and the wavevector of de Broglie wave is imaginary, here the photon tunneling effect in the nanoholes can be expected. However, due to the presence of CSP mode, $|q_y|$ becomes smaller and thus the photons are easier to pass through the subwavelength holes than that in a perfect-metal case. This efficient channel has been proposed by Popov et al. [17], but the origin was not clarified. Now, it is clear that this CSP-assisted and enhanced photon tunneling effect will contribute actively to the transmission of light.

The distribution of wave fields in the space has been deduced analytically, which is found to be strongly dependent on a resonance factor $F(\lambda)$, where

$$F(\lambda)^{-1} = (1 + \theta_1^-)(1 + \theta_3^-) - (1 - \theta_1^+)(1 - \theta_3^+) e^{2ihb}.$$  

Here $\theta_j^\pm (j = 1, 3)$ is given by

$$\theta_j^\pm = \frac{\sigma \pm i \varepsilon_m^{-1/2}}{\sin c(\alpha a / 2)} \sum_{n=\pm}^{n} \frac{w\varepsilon_j g_n s_n}{(\varepsilon_j - \gamma_n)^{1/2} + \varepsilon_m^{-1/2}},$$

where, $\sigma = k_0 q_y^{-1}(1 - \alpha^2 k_n^{-2})$ is associated with the CSP mode, $w = a^2 / d^2$ is the duty cycle of the subwavelength holes. The summation on $n (n = 0, \pm 1, \pm 2, ...)$ involves all the diffraction orders above or below the metal film, with $g_n = \sin c(k_0\gamma_n a / 2)$, $s_n = (1 / a) \int_{a/2}^{a/2} e^{-ik_0\gamma_n x} \cos(\alpha x) dx$, and $\gamma_n = \sqrt{\varepsilon_1 \sin \varphi + G_n} / k_0$; where $G_n = 2\pi n / d$ is the reciprocal vector, $\varepsilon_j$ is the dielectric constant of the surrounding medium, and $\varphi$ the incident angle.
With the resonance factor \( F(\lambda) \), the zero-order transmission can be expressed as

\[
t_0 = \sqrt{\varepsilon_3 |\tau F(\lambda)|^2}.
\]  

(5)

Here, \( \tau \) is a coefficient related to the incident angle, which can be simplified at normal incidence to

\[
\tau = \frac{4\omega \sigma e^{-qh}}{(1 + \varepsilon_1^{1/2} - \varepsilon_m^{1/2})/(1 + \varepsilon_3^{1/2} - \varepsilon_m^{1/2})}.
\]  

(6)

It is noticed that the light transmission is governed by the resonance factor, where the transmission dips and peaks correspond respectively to the minima and maxima of \( |F(\lambda)| \) (the open circles in figure 2). When the denominator in equation (4) approaches zero, i.e., \( (\varepsilon_j - \gamma_n^{1/2}) + \varepsilon_j m^{1/2} = 0 \), the transmission dip can be reached \( (F(\lambda) \to 0) \). The equality can be rewritten in a familiar form

\[
k_0 \sqrt{\varepsilon_1 \sin \varphi} + G_n = \pm k_{app},
\]  

(7)

with

\[
k_{app} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_j (\varepsilon_m^{1/2} - \varepsilon_j^{1/2})}{\varepsilon_m (\varepsilon_m + \varepsilon_j)}} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_j}{\varepsilon_m + \varepsilon_j}}.
\]  

(8)

Where \( \varepsilon_j^{2/3} \) is much smaller than \( \varepsilon_m^{2/3} \). This is just the condition for SPP resonance on the metal-dielectric interface (the approximated SPP dispersion is caused by the SIBC imposed on the metal surface). Therefore, the SPP mode is responsible for the transmission dip (the SPP minima), which is identical to the experiment (see the thicker arrows in figure 1).

We notice in a recent calculation that the dispersion of SPP on a perforated metal film has been proposed to be strongly modified [18]. There, the so-called dispersion curve obtained by searching for the poles of scattering matrix is linked not merely to the SPP mode [19]. Moreover, the change of dispersion by more than 10% [18] is difficult to understand, considering the fact that the SPP dispersion on slit arrays is within 1% of the flat case [14]. Here the theory and experiment show that when the resonance condition (equation (7)) is satisfied a sudden decrease in the transmission will be induced. The results strongly suggest that the SPP mode (the inherent surface resonance) of a flat metal surface still survives and acts on the perforated metal film, i.e., the residual metal surface.

The negative role of SPP mode has been suggested in the subwavelength slits [13, 20] and admitted by Ebbesen et al. [6]. This point hold even for two-dimensional holes is not difficult to understand. When the resonance condition is satisfied, some
evanescent diffraction mode will couple strongly to the SPP wave and others are suppressed, where the photons seem to be absorbed on the surface. Nevertheless, the SPP wave is limited to the metallic boundary (the hole opening is not favored) due to the coupling between light and electrons. Moreover, the electromagnetic fields of the SPP yield two flow of energy: one is strong and proceeds along the metal surface, while the other is weak and travels normal to the metal film. However, the former cannot supply the energy flow for the transmission; and the latter can work only when the metal film is very thin \[4, 5\], which is not hold here. Hence, the SPP mode contributes negatively to the transmission.

An important result predicted by the theory is that the Wood’s anomaly does not give rise to transmission minimum, which is contrary to the conventional idea \[8\]. Since \[\varepsilon_j e_m^{-1/2} \ll 1\], when \(\varepsilon_j - \gamma_n^2 = 0\) (this is the condition for Wood’s anomaly), the transmission is low as shown to be a step in figure 1. Physically, in the case of Wood’s anomaly the related diffraction order becomes tangent to the metal surface and unable to transmit. But the remaining diffraction modes have not been suppressed completely, which couple with the CSP mode and result in a weak transmittance. In fact, the position of Wood’s anomaly is always slightly smaller than that of transmission dip. When the metal film is perfect conducting, they turn out to be identical. Therefore, the Wood’s anomaly is actually an approximation to the transmission minimum.

In addition, the analytical results show that the wave amplitudes in the nanoholes (\(A_0\) and \(B_0\) in equation (1)) are proportional to \(F(\lambda)\). Thus the CSP mode is greatly suppressed when the SPP wave is resonantly excited. However, when the wavelength is far from the SPP resonance, a strong coupling between the evanescent diffraction modes and the CSP mode will be established. The evanescent diffraction modes can propagate along the whole surface, including the nonmetallic interface at the hole opening, where coupling occurs through the matching of the fields. Then the diffraction modes on the incident side will emit the photons that tunnel via the CSP mode to the other side, which further couples to the outgoing light. This coupling can be strongly resonant when \(|F(\lambda)|\) reaches its maximum. In general, the second term on the right-hand side of equation (3) is much smaller and can be neglected. Then the condition for resonance can be simplified to \(1 + \theta_1^- = 0\) or \(1 + \theta_3^- = 0\), which corresponds to strong coupling of CSP mode to upper- or lower-side diffraction modes, respectively. Both cases can lead to great enhancement of CSP mode and evanescent diffraction modes on either side. Consequently, a strong power flow normal to the metal film is supported and the energy is transferred efficiently from one side to the other side, which differs significantly from the case when the SPP is resonantly excited. Therefore, the transmission enhancement is due to the coupling of diffraction modes to CSP mode (or CSP excitation) rather than coupling between SPP
modes on both sides of the metal film (or SPP excitation [10]).

The optical transmission through a perfect metal film perforated with square holes has also been calculated (the thinner solid line in figure (2)), where the SPP and CSP modes are both absent. One can see that the transmission dips and peaks are still supported, implying that the surface plasmons are not necessary for transmission. However, the case is indeed different when they are present (the thicker solid line in figure (2)). On the one hand, the dip position is shifted from Wood’s anomaly to SPP resonance (the SPP contribution). On the other hand, the position of peaks is red-shift and simultaneously the peak width is greatly enlarged (the CSP contribution). It is also found that when the metal film becomes thicker, the transmission efficiency for a real metal is much higher than that of a perfect one, which confirms that the CSP mode plays an active role in the transmission.

Although the results presented here are based for convenience on square holes, the underlying physics is general. In the light transmission, the diffraction modes interact with the surface plasmons: strong coupling of diffraction modes to SPP results in the transmission minima and to CSP the transmission maxima. This dual-effect of surface plasmons is critical for the transmission properties. Certainly, these useful elements, including the diffraction modes, the SPP mode, and the CSP mode, provide us with more degrees of freedom for the applications, with which the near- and far-field optical properties can be manipulated and novel devices may be constructed.

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References


Figure captions

Fig.1 Measured (the open circles) and calculated (the solid line) zero-order transmission spectra of the gold film perforated with the subwavelength holes, where d=580nm, a=265nm, and h=220nm. Inset is the focused-ion-beam image of the square holes. The thicker and thinner arrows indicate the positions of SPP resonance and Wood’s anomaly, respectively.

Fig.2 The dependence of resonance factor $|F(\lambda)|$ (the open circles) and transmission efficiency (the thicker solid line) on the wavelength, where the gold film is characterized by a frequency-dependent permittivity. As a comparison, the transmission spectrum for a perfect metal is also presented (the thinner solid line). Here the hole size are set as $d=1000nm$, $a=400nm$, and $h=250nm$. 
Figure 1

Figure 2