Effect of hole diameter on terahertz surface-wave excitation in metal-hole arrays

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(Received 30 April 2006; revised manuscript received 11 September 2006; published 27 October 2006)

The effect of the hole diameter on the surface wave (SW) excited on the metal surface perforated periodically with circular holes has been investigated in the terahertz (THz) region. We find that the SW is localized more strongly on the metal surface with increasing the hole diameter. These results provide the evidence for the existence of the SW-like mode, having properties similar to the surface plasmon polariton in the visible region, even in the THz or lower frequency regions, where metals are regarded as the nearly perfect conductor.

DOI: 10.1103/PhysRevB.74.153416 PACS number(s): 78.20.Ek, 42.25.Ja, 42.25.Bs

The resonant light transmission phenomenon for metal-hole arrays is attracting much attention with regard to underlying physics[1–5] and the development of potential applications.[6–8] The transmittance of the metal-hole array is several times higher than that expected from the hole aperture fraction. The mechanism of such an anomalous transmission characteristic is nowadays widely understood in terms of the excitation of the surface waves (SWs)[2–5,9] on the periodically structured metal surface and Fano-like interference between the SW and directly transmitted electromagnetic wave.[4] Here, we should empasize that in the 1960s similar resonant transmission characteristics of metal meshes were reported in the millimeter wave or far infrared regimes,[10–12] and the contribution of SWs, called Zenneck waves, was discussed in Ref. 10.

The intensity of the SW is attenuated exponentially with distance from the metal-dielectric interface. The attenuation lengths both into the dielectric and metal sides are comparable to or shorter than the wavelength of light in the visible or near infrared regions. In the terahertz (THz) or lower frequency regions, on the other hand, the attenuation length of the SW into the dielectric side is several orders of magnitude longer than the wavelength for a flat metal surface, while the attenuation length into the metal side is several orders of magnitude shorter than the wavelength. In this case, one cannot recognize such a delocalized electromagnetic wave as the SW. Owing to the existence of the perforated structure, however, the attenuation length of the SW is possibly reduced to the order of the wavelength[13,14] and thus the resonant transmission phenomenon can be observed even in the THz and lower frequency regions.[15] Such SWs (called spoof surface plasmon polariton) have a possibility to cause a variety of optical characteristics of metal-hole arrays. In our previous study, for example, we observed the interesting transmission characteristics of double-layer metal-hole arrays based on the near-field coupling between the SWs excited on the two metal surfaces.[16]

The surface localization property and lifetime of the SW on the metal-hole arrays depend on some geometrical parameters, such as the hole diameter, slab thickness, lattice constant, and permittivity of metals and are important for designing the optical devices made of metal-hole arrays. In this paper, we measured the hole diameter dependence of the surface-wave characteristics on the perforated metal surface in the THz region. By using the THz time domain spectroscopy (THz-TDS), we can measure the wave form of the THz wave transmitted through the metal-hole array and hence can obtain the lifetime of the SW directly, which is strongly influenced by the periodic structure of metal surfaces. Moreover, by measuring the dependence of the transmission spectrum on the thickness of the dielectric film attached on the metal surface, the attenuation length of the SW in the direction perpendicular to the surface can be obtained.

The metal-hole arrays used in this study were Al plates (the thickness $t=0.25$ mm) perforated periodically with circular holes in the triangular lattice structure. All samples investigated had the same spacing between holes $s=1.13$ mm and the hole diameter was varied from $d=0.50$ to 0.80 mm. The permittivity of Al is about $\tilde{\varepsilon}=\varepsilon'+i\varepsilon''\approx-44900+i511000$ at around 1 THz. The attenuation length of the electromagnetic wave into the metal is estimated to be about several hundred nanometers, which is three orders of magnitude shorter than the wavelength. The transmission characteristics were measured by using the THz-TDS system,[17] which allowed the direct measurement of the wave form of the THz wave transmitted through the sample. The collimated THz wave, which was radiated from the emitter of a photoconductive antenna illuminated by a 100-fs optical pump pulse, was impinged on the sample at normal incidence. The transmitted THz wave was detected by a similar photoconductive antenna detector gated by an optical probe pulse which is divided from the pump pulse. By changing the time delay τ between the pump and probe pulses, the wave form of the electric field of the transmitted THz wave could be measured. The incident THz wave was polarized linearly parallel to one of the principal axes of the triangular structure. A 10-mm-diameter aperture was located in front of the sample. If the number of holes is finite, the coupling efficiency between the incident THz wave and the SW on the metal surface increases with increasing the number of the holes, and the transmittance at the resonant frequency reaches the saturated value when the number of holes is larger than about 20.[5] The number of the illuminated circular holes was about 70 in this experiment, being enough to avoid the finite size effect of the transmission characteristics for the metal-hole array. The transmission spectrum was obtained by comparing the Fourier-transformed spectra of the time-domain wave forms with and without the sample insertion. The total time range of the measured wave form was 136 ps, giving a spectral resolution of about 7 GHz in this experiment.

We investigate the dependence of the lifetime of the SW on the hole diameter. The wave forms transmitted through the metal-hole arrays with several hole diameters are shown in Figs. 1(b)–1(e). The incident THz wave, which is an almost one cycle pulse, is shown in Fig. 1(a) as a reference. For the metal-hole array of $d=0.5$ mm in Fig. 1(b), the sharp peak is observed at around $\tau=0$ ps. This sharp peak corresponds to the THz wave transmitted directly through the holes without the resonant coupling with the SW. Following this peak, we can observe the component which oscillates for relatively long time. In order to evaluate the frequency of such oscillation components, we calculate the Fourier spectrum of the wave form in the range after $\tau=4$ ps, where the oscillation component is observed. The result is shown in Fig. 1(f), where the transmission peak is observed at 0.28 THz. The resonant frequency of the SW f_{SW} is expressed in the form[18]

$$f_{SW}=|\mathbf{k}_{in}+\mathbf{G}|\frac{c}{2\pi}\{(\varepsilon_m+\varepsilon_d)/\varepsilon_m\varepsilon_d\}^{1/2}, \qquad (1)$$

where $\mathbf{k}_{in}$ is the in-plane wave vector of the incident THz wave, $\mathbf{G}$ is the reciprocal lattice vector, and ε_m and ε_d are the dielectric constants of the metal and the attached dielectric, respectively. From Eq. (1), the resonant frequency of the SW is estimated to be 0.30 THz for metal-hole arrays used in this experiment, which almost agrees with the transmission peak frequency observed in Fig. 1(f). Thus, this oscillation component can be assigned to the THz wave reemitted from the SW, which is excited in the vicinity of the metal surface by the incident THz wave. The transmission peak frequency is slightly lower than the resonant frequency of the SW expected from Eq. (1). In Eq. (1), we assume that the size of the hole diameter is extremely small, corresponding to the weak perturbation of the permittivity of a metal surface from the unperturbed surface. In the present system, however, the hole diameter has a finite size and the dispersion curve of the SW in Eq. (1) is modified to some extent, leading to the low-frequency shift of the transmission peak frequency of the metal-hole arrays as observed in our experiment.

In order to fit the oscillation component of the measured wave form $E_{osc}(t)$, we utilized a damped harmonic oscillator function

$$E_{osc}(t)=A\exp(-\gamma t)\cos(2\pi\nu t+\phi_0)+\text{const.} \qquad (2)$$

Here A and γ are the amplitude and relaxation time, and ν and ϕ_0 are the frequency and phase of the oscillation component, respectively. From this fitting, we can estimate the lifetime of the SW. The lifetime of the SW can also be estimated from the spectral width of the transmission peak in the frequency domain. However, owing to the Fano-like interference effect the line shape of the transmission peak deviates from the symmetric Lorentz function,[4] making it difficult to estimate the accurate lifetime of the SW. The Fano-like interference effect is the result from the interference between the electromagnetic wave transmitted directly through metal holes and that reemitted resonantly from the SW. In Figs. 1(b)–1(e), the former wave is corresponding to the sharp pulse observed at around $\tau=0$ ps, while the latter wave is corresponding to the oscillation component. Thus, by fitting only the oscillation component in time domain, we can obtain the value of the SW's lifetime more accurately than that estimated from the transmission spectrum. The excellent numerical fittings (dotted lines) are obtained for all wave forms. From this fitting, the lifetimes of the SWs are estimated to be 16.7, 14.1, 6.0, and 4.2 ps for the hole diameters $d=0.50$ mm, 0.60 mm, 0.70 mm, and 0.80 mm, respectively. The obtained SW lifetimes are shown as a function of the hole diameters in Fig. 2. The SW lifetime decreases with increasing the hole diameter. This result agrees well qualitatively with that reported in the visible and near-infrared regions.[9,19] In Ref. 20, it is reported that the lifetime of the SW is mainly determined by the radiation loss due to scattering by the holes and, on the other hand, the ohmic loss at the metal surface plays a minor role when the conductivity of

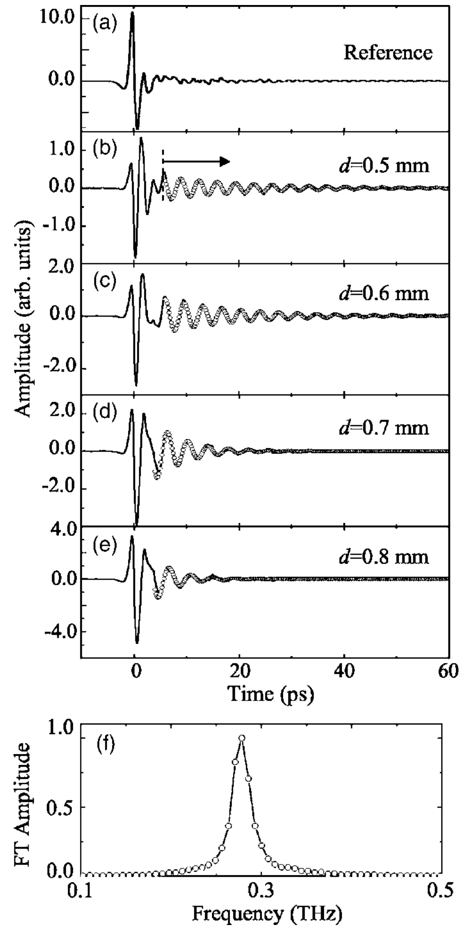

FIG. 1. (a) The incident THz wave form and (b)–(e) THz wave forms (solid lines) transmitted through the metal-hole arrays with several hole diameters d. Circles are numerical fittings with the damped harmonic oscillator model for the oscillation components. (f) The Fourier-transformed intensity of the THz wave forms of (b) in the time range after 4 ps.

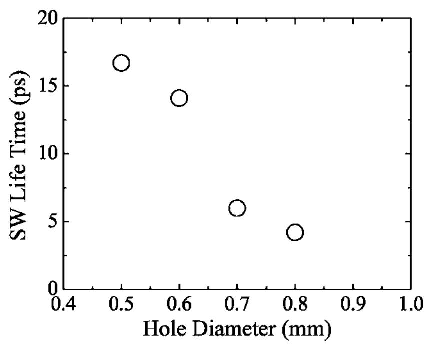

FIG. 2. The SW lifetime as a function of the hole diameter.

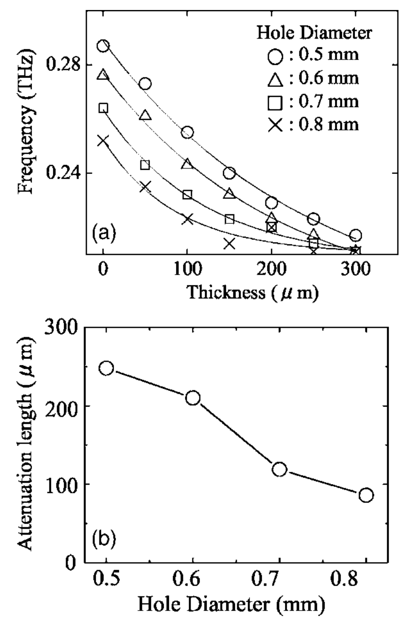

FIG. 3. (a) Transmission peak frequencies as a function of the dielectric film thickness attached on the output surfaces of the metal-hole arrays for hole diameters, $d=0.50$ mm (circle), 0.60 mm (triangle), 0.70 mm (square), and 0.80 mm (cross). (b) The estimated attenuation length of the SW versus the hole diameter.

metals is relatively high. Since the scattering cross section due to the holes becomes larger with increasing the hole diameter, the SW lifetime is expected to become shorter with the hole diameter, as observed in Fig. 2.

Next, we investigate the spatial attenuation length of the SW in the direction normal to the metal surface into the air. In order to obtain the attenuation length experimentally, we measured the frequency shift of the transmission peak with increasing the thickness t_d of the thin dielectric film attached on the output side of the metal surface. In our previous study,[21] we observed that the transmission peak shifts to the lower frequency side with increasing the thickness of the film attached on the output side of the metal surface. Such a peak shift is attributed to the shift of the resonant SW frequency on the output side. Since the electric field of the SW is attenuated exponentially in the direction perpendicular to the surface, this frequency shift shows the tendency of saturation when the film thickness becomes comparable to the attenuation length of the SW, and thus we can estimate roughly the attenuation length of the SW from the dependence of the peak frequency on the film thickness.[12] Figure 3(a) shows the transmission peak frequencies for the several hole diameters as a function of the thickness of the attached dielectric film. The peak frequency decreases exponentially and shows the tendency of saturation with increasing the film thickness. The solid lines are numerical fittings by the exponential damping function approaching the constant value with increasing film thickness. The film thickness t_a, where the frequency becomes $1/e$ of the initial frequency (at $t_d=0$), is a measure of the SW attenuation length in the direction normal to the surface. The attenuation lengths estimated from this analysis are plotted as a function of hole diameter in Fig. 3(b). The attenuation length of the SW is 250 μm for $d=0.5$ mm. With increasing the hole diameter, the attenuation length decreases monotonically and at $d=0.8$ mm becomes shorter than 100 μm, which is about ten times shorter than the wavelength of the THz wave ($\lambda \sim 1.0$ mm).

We note that the intensity of the SW is localized within the wavelength of the THz wave in the direction normal to the metal surface for the metal-hole arrays used in our experiment. These results confirm Pendry's theory,[13] which insists that the SW can be excited on the structured metal surfaces even though the metal is regarded as a perfect conductor. For the flat surface of the perfect conductor, the intensity of the electromagnetic wave extends from the metal surface into the semi-infinite space of the air or dielectric side, and in this case the SW cannot exist. When the surface of the perfect conductor is periodically structured, the effective plasma frequency is reduced and thus the electric field of the electromagnetic wave can be localized on the metal surface, meaning the existence of the SW-like mode. As the conductor area decreases, i.e., the hole diameter becomes larger, the attenuation length becomes shorter and consequently, the SW is localized more strongly at the surface. Such an SW excited on the surface of the perfect conductor may contribute to the resonant transmission of the metal-hole array, as observed experimentally in the THz region.[15] Finally, we mention the relationship between the resonant transmission frequency and the cutoff frequency in some detail. The resonant frequencies for the samples with $d=0.5$, 0.6, 0.7, and 0.8 mm are 0.288, 0.276, 0.265, and 0.252 THz, respectively. On the other hand, the cutoff frequencies of the corresponding samples are 0.352, 0.293, 0.251, and 0.220 THz. Since the cutoff frequency corresponds to the plasma frequency in the Pendry's spoof surface plasmon polariton (SPP), the spoof SPP theory can be applied to the samples with $d=0.5$ and 0.6 mm. However, the spoof SPP theory cannot be applied directly to the samples with $d=0.7$ and 0.8 mm, since the resonant frequencies are above the cutoff frequencies. The consideration of the coupling between the SW and standing cavity modes will be needed for accurate analysis.[15]

In conclusion, the effects of the hole diameter on the lifetime and the attenuation length normal to the surface of the SW excited on the nearly perfect conductor surface have been investigated in the THz region. The lifetime decreases with increasing hole diameter.

This work is supported partly by the Grant-in-Aid for Scientific Research from the Japan Society of Promotion of Science (JSPS) and the Terahertz Optics Project for Medical Application led by J. Nishizawa, organized by the Ministry of Education, Culture, Sports, Science, and Technology, Japan. F.M. also acknowledges the JSPS for financial support.

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