Temporal Spectroscopic Characteristics of Terahertz Pulses Transmitted through Metal Hole Arrays

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Keywords : metal hole array, extraordinary transmission, THz time domain spectroscopy

Since Ebbesen *et al.* reported the extraordinary transmission property for the metal hole array in 1998, many studies have been carried out both experimentally and theoretically to understand the physical mechanism of this phenomenon. Until now, it is widely supported that the extraordinary optical transmission is attributed to the resonant excitation of the surface plasmon-polaritons (SPPs) by the incident light on the periodically modulated metal-air (or dielectric) boundary. Although large amount of papers have been reported, most of them are focused on the stationary transmission spectrum of periodical metal hole arrays and metallic slit gratings. Not only the stationary transmittance for the metal hole arrays but also the temporal behavior of light are very important for applying the metal hole arrays to ultrafast optical devices. In this paper, we measured the temporal transmission property of the THz pulse in order to investigate the time-dependent transmission characteristics of the metal hole array.

We measured the THz wave form transmitted through the metal hole arrays, which are aluminum slabs perforated with circular holes in the triangular structure (Fig. 1), by using the terahertz time domain spectroscopy (THz-TDS). The temporal wave form of the THz wave transmitted through the metal hole array at normal incidence is shown in Fig. 2(b). The incident THz wave is also shown in Fig 2(a) as reference. While the incident THz wave is an almost single cycle pulse, the transmitted THz wave has a sharp peak at around $t = 0$ ps followed by over ten cycle oscillations. This oscillation component corresponds to the THz wave reemitted from the SPPs which are excited on both surfaces of the metal hole array by the incident THz wave through the resonant interaction mediated by the periodic corrugation of the metal surface. The decay time of this oscillation component corresponds to the life time of the SPP, which is estimated to be $\tau=17$ ps by the numerical fitting.

The temporal spectroscopic behavior of the transmitted THz wave can also be analyzed from the temporal waveform. In order to obtain the time-dependent spectroscopic behavior of the transmitted THz wave, the Gabor transformation was performed with the variable Gaussian time window. Result is shown in Fig.2

Fig. 1. Photograph of the metal hole array

(c). In the frequency region higher than 0.30 THz, the THz wave has very short rise and decay times, and has the maximum amplitude at around $t=0$ ps. At the resonant frequency of the SPP (0.27 THz), on the other hand, the transmission intensity rises relatively slowly and becomes maximum at around $t=10$ ps, indicating that the THz wave at the resonant frequency of the SPP propagates more slowly than the THz wave directly transmitted through the metal holes at higher frequencies. This characteristic is dominated by the deceleration of the group velocity of the THz wave in the metal hole.

Fig. 2. (a) Measured waveform of the incident THz wave, (b) Measured waveform of the THz wave transmitted through the metal hole array; Inset shows the expanded waveform (open circle) in the range from 10 to 60 ps; The numerical fitted curve with a damped harmonic oscillator is also shown (solid line), (c) Gabor spectrum obtained with the variable Gaussian time window of the window width $\delta=34$ ps; Inset shows the transmission spectrum of the metal hole array

Temporal Spectroscopic Characteristics of Terahertz Pulses Transmitted through Metal Hole Arrays

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The temporal spectroscopic characteristics of the terahertz pulse transmitted through the metal hole array is investigated by using the THz time domain spectroscopy in combination with the short-time Fourier transformation. It is found that the THz wave at around the resonant frequency of the surface plasmon-polariton (SPP) delays compared with that at higher frequency region. From the dependence of the delay time on the thickness of the metal hole array and the frequency, the delay at the SPP resonant frequency is attributed to the deceleration of the group velocity of the THz wave in the metal hole.

Keywords : metal hole array, extraordinary transmission, THz time domain spectroscopy

1. Introduction

Since Ebbesen *et al.* reported the extraordinary transmission property for the metal hole array in 1998⁽¹⁾, many studies have been carried out both experimentally and theoretically to understand the physical mechanism of this phenomenon⁽²⁾⁻⁽⁵⁾. Until now, it is widely supported that the extraordinary optical transmission is attributed to the resonant excitation of the surface plasmon-polaritons (SPPs)⁽⁶⁾ by the incident light on the periodically modulated metal-air (or dielectric) boundary. Although large amount of papers have been reported, most of them are focused on the stationary transmission spectrum of periodical metal hole arrays and metallic slit gratings. Only a few papers deal with the optical pulse propagation through metallic periodic structures⁽⁷⁾⁽⁸⁾. Not only the stationary transmittance for the metal hole arrays but also the temporal behavior of light are very important for applying the metal hole arrays to ultrafast optical devices. In Ref. (7), the time delay of the optical pulse propagation through the metal aperture array has been observed, and such time delay is attributed to the resonant coupling of the incident light with the surface modes excited on the metal surface. However, the low group velocity of the optical pulse should be also included as the additional mechanism for the observed time delay in the experiment of Ref. (7). In this paper, we measured the temporal transmission property of the terahertz (THz) pulse in order to investigate the time-dependent transmission characteristics of the metal hole array, and found the significant contribution of the delay owing to the low group velocity of the THz pulse in the metal holes.

The anomalously high band-pass transmission property for the metal hole arrays has been reported experimentally in the millimeter and THz regions⁽⁹⁾⁻⁽¹⁴⁾. In most of the experiments in these regions, the band-pass peak frequency is located above the cutoff frequency of circular metal holes, indicating that the electromagnetic wave is propagation mode in the metal hole. This situation is different from that of the sub-wavelength metal hole

arrays in the visible region⁽¹⁾ where the electromagnetic wave is the evanescent mode in the metal hole. Despite of such the difference, the mechanism of the high band-pass transmission property in the THz region is analogous to that of the Ebbesens' experiment in the visible region⁽²⁾⁽¹¹⁾⁽¹⁵⁾.

2. Experiment

We measured the THz wave form transmitted through the several types of a metal hole array, which are aluminum slabs perforated with circular holes in the triangular structure (Fig. 1), by using the THz time domain spectroscopy (THz-TDS). The fundamental measurement principle of this system is as follows. The THz wave was generated by illuminating a photoconductive antenna evaporated on a low-temperature-grown gallium arsenide (LT-GaAs) substrate with 100 fs pump laser pulses. The THz wave was collimated by an off-axis paraboloidal mirror and impinged on the sample. After transmitted through the sample, the THz wave was focused on another photoconductive antenna which was illuminated by gate laser pulses separated from the pump laser pulses. By changing the delay between the pump and gate laser pulses, the temporal behavior of the electric field of the THz wave were measured. The transmission spectrum was obtained by dividing the Fourier component of the transmitted THz wave by that of a reference THz wave.

3. Results and Discussion

The temporal waveform of the THz wave transmitted through the metal hole array at normal incidence is shown in Fig. 2(b). The

Fig. 1. Photograph of the metal hole array

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incident THz wave is also shown in Fig 2(a) as reference. The geometrical parameters of the metal hole array are as follows: a diameter $d=0.68$ mm, a lattice constant $s=1.13$ mm, and a slab thickness $l=0.50$ mm. While the incident THz wave is an almost single cycle pulse, the transmitted THz wave has a sharp peak at around $t = 0$ ps followed by over ten cycle oscillations. The first sharp peak at around $t=0$ ps corresponds to the THz wave transmitted through the metal hole directly without the resonant coupling to the SPPs. Below the cutoff frequency ($f_c=0.26$ THz), an electromagnetic wave becomes an evanescent wave in the metal hole, and therefore, the transmittance becomes extremely low⁽¹⁶⁾. Such a high-pass filtering effect makes the pulse width of the transmitted THz wave at $t \sim 0$ ps shorter than that of the incident THz wave as seen in Fig. 2(a). The oscillation following the sharp pulse at around 0 ps corresponds to the THz wave reemitted from the SPPs⁽¹⁷⁾ which are excited on both surfaces of the metal hole array by the incident THz wave through the resonant interaction mediated by the periodic corrugation of the metal surface. The decay time of this oscillation corresponds to the lifetime of the SPP. In order to estimate the lifetime of the SPP, we performed the numerical fitting to the transmitted THz waveform with the damped harmonic oscillation in the time range after $t=8$ ps. As shown in the inset of Fig. 2(b), the oscillation component can be fitted well with the damped harmonic oscillator, and the decay time τ is estimated to be $\tau=17$ ps which is 4.6 times as long as the oscillation period.

Next, we investigate the temporal spectroscopic behavior of the transmitted THz wave. The transmission spectrum of the metal hole array is shown in the inset of Fig. 2(c). The transmission peak is observed at 0.27 THz which corresponds to the oscillation component observed in the transmitted THz wave form, and below 0.25 THz the transmittance is almost zero because of the cutoff effect of the metal hole. In the frequency region above 0.30 THz, the THz wave transmits directly through the metal hole. In this region, the transmittance is expected to be same with the air fraction F_{air} of metal holes given by

$$F_{air} = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{s} \right)^2 \dots\dots\dots (1)$$

However, the transmittance is at most 10% which is considerably smaller than the expected value of our metal hole arrays ($F_{air} \sim 0.33$). This discrepancy is due to the diffraction loss to the higher diffraction orders⁽⁹⁾, because in our experimental setup only the zeroth order transmission component can be detected. In order to obtain the time-dependent spectroscopic behavior of the transmitted THz wave, the Gabor transformation is performed with the variable Gaussian time window. By changing the delay time of the Gaussian time window, the time evolution of the transmittance (Gabor spectrum) can be obtained as shown in Fig. 2(c). In this analysis, the window width δ of the Gaussian time window determines both the time and frequency resolutions of the Gabor spectrum. The time resolution increases proportionally with decreasing δ , while the frequency resolution decreases with decreasing δ . In order to obtain the appropriate time and frequency resolutions, we select the window width to be $\delta=34$ ps in this analysis. At 0.50 THz, the THz wave has very short rise and decay times, and has the maximum amplitude at around $t=0$ ps. At the resonant frequency of the SPP (0.27 THz), on the other hand, the transmission intensity rises relatively slowly and becomes maximum at around $t=10$ ps, indicating that the THz wave at the

Fig. 2. (a) Measured waveform of the incident THz wave, (b) Measured waveform of the THz wave transmitted through the metal hole array; Inset shows the expanded waveform (open circle) in the range from 10 to 60 ps; The numerical fitted curve with a damped harmonic oscillator is also shown (solid line), (c) Gabor spectrum obtained with the variable Gaussian time window of the window width $\delta=34$ ps; Inset shows the transmission spectrum of the metal hole array

resonant frequency of the SPP propagates more slowly than the THz wave directly transmitted through the metal holes at higher frequencies.

Two mechanisms can be considered as the reason for the propagation delay of the THz wave at 0.27 THz. One is the delay due to the conversion time from the incident THz wave to the SPP at the input surface and from the SPP to the outgoing THz wave at the output surface. Another possible mechanism is the deceleration of the group velocity of the THz wave when the THz wave propagates in the metal holes⁽¹⁶⁾. In order to investigate which mechanism is dominant for the delay time observed in Fig. 2(c), we measured the dependence of the delay time on the thickness of the metal hole array. If the former mechanism is dominant, the delay time should be almost independent of the thickness because the conversion time of the SPP is considered to be sensitive only to the structure of the metal surface. If the latter mechanism, on the other hand, is dominant, the increase of the delay time should be observed with increasing the thickness of the metal hole array. Figures 3(a)-(d) show the Gabor spectra of the THz waves transmitted through the metal hole arrays for the thicknesses of $l=0.20, 0.50, 1.00$ and 2.00 mm, respectively. The hole diameter

Fig. 3. Gabor spectra for metal hole arrays with several thicknesses of (a) 0.20 mm, (b) 0.50 mm, (c) 1.00 mm and (d) 2.00 mm

and the lattice constant are $d=0.70$ and $s=1.12$ mm, respectively, for all samples. From these figures, it is clearly observed that the delay time between maximum points of the transmission peak frequency (0.27 THz) and the higher frequency region increases systematically from $\Delta t=3.5$ to 18 ps with increasing the thickness from 0.20 to 2.00 mm. This result demonstrates that the dominant contribution to the delay is the deceleration of the THz wave group velocity at the transmission peak frequency. In the microwave theory⁽¹⁵⁾, the group velocity of the electromagnetic wave in the perfect conductor circular hole is expressed by

$$v_g(f) = c\sqrt{1 - (f_c/f)^2} \quad (2)$$

Here, $f_c=1.841c/\pi d$ is the cutoff frequency of the TE_{11} mode which is the lowest order of the waveguide mode of the metal hole. f and c are the frequency of the electromagnetic wave and the velocity of light in vacuum, respectively. Figure 4 shows the frequency dependence of the measured (closed triangle) and calculated (open circle) delay times of the THz wave with respect to that at 0.50 THz for the metal hole array ($d=0.70$ mm, $s=1.12$ mm, $l=2.00$ mm). The delay time Δt is calculated from $\Delta t(f)=l(1/v_g(0.50\text{THz}) - 1/v_g(f))$. The cutoff frequency f_c (0.25 THz) is shown as a vertical dashed line in the figure. The good agreement between the experiment and theory is observed. This result also indicates that the deceleration of the THz wave group velocity is the dominant mechanism for the propagation delay of the THz wave. The discrepancy at around 0.32 THz might be due to the effect of the resonant excitation of the SPP, which induces the negative group

Fig. 4. Measured (triangle) and calculated (circle) delay time of the THz wave as a function of the frequency with respect to that at 0.50 THz for the metal hole array of $d=0.70$ mm, $s=1.12$ mm, and $l=2.00$ mm

delay for the electromagnetic wave at around the resonant frequency. Details about such a negative group velocity delay effect for the THz wave transmitted through the metal hole array will be discussed elsewhere.

4. Summary

In summary, we investigated the temporal spectroscopic behavior of the THz wave transmitted through the metal hole array by using the Gabor transformation. In the Gabor spectrum, the propagation delay of the THz wave at the transmission peak frequency compared with that of the higher frequency range is observed. The dominant mechanism of this delay is the deceleration of the group velocity of the THz wave in the metal hole. The conversion time between the SPPs and free-space THz waves plays a minor role for the propagation delay time.

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