Transmission properties of terahertz radiation through a single sub-wavelength circular hole in the metal foil

Weili Cui (崔伟丽), Zhenwei Zhang (张振伟), Guozhong Zhao (赵国忠), Yan Zhang (张 岩), and Cunlin Zhang (张存林)

Department of Physics, Capital Normal University, Beijing 100037

The terahertz (THz) transmission properties of a single sub-wavelength circular hole in the free-standing metal foil are experimentally investigated. A THz time-domain spectroscopy (THz-TDS) is utilized to measure the transmission coefficient from 0.2 to 2.2 THz. The transmission coefficients for the aperture with different diameters ranging from $d = 150$ to 500 μm are presented. The results indicate that the samples change the temporal and spectral characteristics of the incident THz pulses. In particular, there is a remarkable stop band for $d = 150$ μm in the transmission spectrum which the conventional diffraction theory cannot explain. Further theoretical analysis is necessary.

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Recently, electromagnetic transmission properties through sub-wavelength apertures have attracted a lot of interest[1−7]. Among these studies, much attention has been paid to two kinds of sub-wavelength apertures structures — periodic array of sub-wavelength apertures and a single sub-wavelength aperture surrounded by a periodic surface topography in the metal films. Enhanced electromagnetic transmission efficiencies through them have been observed. These results are attributed to the resonant interaction of the incident radiation with the surface plasmon polaritons at metal surface or corrugated metal surface surrounding the aperture[7]. Conversely, as described by the conventional diffraction theory[8], a single sub-wavelength circular hole is considered to possess quite poor transmission properties, and the transmission of a single sub-wavelength aperture in an ideal-metal sheet is proportional to $(d/\lambda)^4$, where d is the aperture diameter. However, transmission properties of a single aperture are related to the dielectric constant of metals due to the fact that ideal metal does not exist. Grupp *et al.* have drawn a conclusion that in the optical frequency range, the magnitude of the real component for the dielectric constant of the metal must be much larger than that of the corresponding imaginary component of the dielectric constant[9]. In the terahertz (THz) frequency range, the findings are opposite to that in the optical frequency range for most metals[10]. Furthermore, it is still not explicit that metals have impact on the results in this frequency range. Consequently, to investigate the transmission properties of the single hole in the THz frequency range is quite important to fabricate micro device with metals in this range.

In this letter, we present experimental investigations of the transmission properties of THz pulse through a single sub-wavelength circular hole in the metal foil in the far-field zone. Transmission coefficient as a function of the frequency in the range of 0.2–2.2 THz is experimentally measured via a THz time-domain spectroscopy (THz-TDS)[11].

The THz-TDS has been widely applied to characterize various materials — chemical vapors, conducting polymers, and biomaterials, and to image optically opaque materials. Our experimental setup, shown in Fig. 1, is a typical THz-TDS system. The THz radiation is generated from the semiconductor surface of p-InAs, and detected by using electro-optical crystal. A succession of pulses with duration of 100 fs, wavelength of 810 nm, and output power of 910 mW from Ti:sapphire laser is separated into two beams, one serves as the probe beam while the other is the pump beam. The THz pulses are generated by illuminating the < 100 > InAs wafer with pump pulses, then, are collimated and focused with two pairs of off-axis gold-coated parabolic mirrors. The probe pulses receive the THz pulse signal through < 110 > ZnTe. By varying the time delay between two pulses, the THz pulse waveform can be detected. In this experiment, the effective bandwidth is about 0.2–2.2 THz, frequency resolution is approximately 50 GHz and signal-to-noise ratio (SNR) is about 600. Because we study the transmission properties in the far-field zone and there is high energy at the focal spot, the samples are mounted directly at the focal spot after the second parabolic mirror and the THz pulses are normally incident on the samples. The spot diameter at the focal point is approximately 1.1 mm which is much larger than the diameter of circular hole.

The samples are copper foils with different diameters of circular holes. All of the circular holes are fabricated by solid-state semiconductor laser in the free-standing copper foils of thickness 150 μm. The apertures range from $d = 150$ to 500 μm, d is the hole diameter. The time-domain waveform of the THz field is acquired

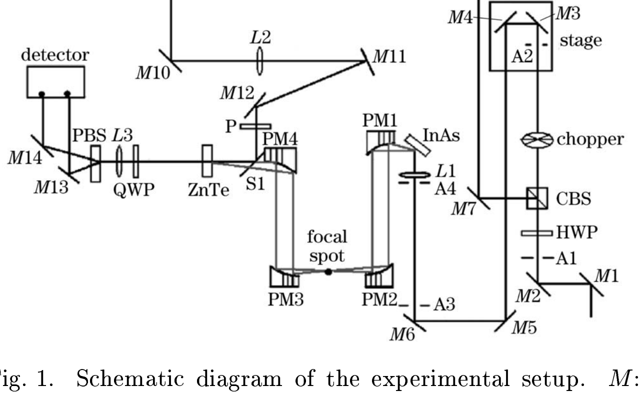

Fig. 1. Schematic diagram of the experimental setup. M: mirror; L: lens; A: aperture; P: polarizer; PBS: polarizing beam splitter; CBS: cubic beam splitter; PM: parabolic mirror; HWP: half-wave plate; QWP: quarter-wave plate.

by using THz-TDS. The transmission coefficient, $T(\nu)$, is derived from the time-domain data via the fast Fourier transformation (FFT)

$$T(\nu) = \frac{E_{\text{transmitted}}(\nu)}{E_{\text{reference}}(\nu)}, \quad (1)$$

where ν is the frequency of the incident pulses, $E_{\text{transmitted}}(\nu)$ is the Fourier transform of the incident THz field and $E_{\text{reference}}(\nu)$ is that of the transmitted THz field.

The experiment is achieved in the environments of humidity of 30% and temperature of 22 °C. Typical THz pulses before and after propagating through the samples are shown in Fig. 2. For each waveform, the total measuring time is 21 ps. However, only part of waveform (4.5 ps) is shown in figure for clarity. It is apparently found from Fig. 2 that the transients of the transmitted pulses are shifted forward horizontally compared with the incident THz pulse. The phenomenon of temporal advancement of the peak for the transmitted THz pulses is more obvious with decrease of the aperture diameter. In addition, there is the temporal pulse deformation, related to the high-pass property of the sub-wavelength circular hole.

The time-domain waveforms are Fourier transformed to get spectral information about the reference and the samples. The amplitudes of the spectra for the reference and samples are compared in Fig. 3. The strong water-absorption peaks located at about 0.54, 0.73, 0.98, 1.17, 1.40, and 1.70 THz can be observed. The fluctuations of the spectra are not only linked to noise, but also arise from reflections of the optical element's surface. Putting the system into a glass box full with pure nitrogen, the spectra will be smoothed relatively since the humidity decreases. To compare the spectral characteristics of the different samples, the transmitted spectral data are normalized to the peak of reference signal. It is clear that the spectrum of the transmitted pulse for the aperture diameter of 150 μm largely differs from the spectra of the reference and other samples.

As shown above, a single aperture in the metal foil can be considered to be a high-pass filter[12]. We are more interested in the transmission properties below and above the filter's cutoff frequency, $\nu_c = c/2d$, where d is the aperture diameter. Figure 4 shows the magnitude and phase of the transmission coefficient versus THz frequency for the single apertures with different diameters in the free-standing copper foils. If the metal foil's thickness is less than the cutoff wavelength, there is no obvious cutoff frequency for any single circle hole. In contrary, the circle hole with the same size in the metal foil whose thickness is greater than the cutoff wavelength has a much sharper cutoff transition. In Fig. 4(a) it can be seen that all of the transmission coefficient spectra posses a roll-off frequency νr. For the diameter of $d = 150$, 200, 300, 400, and 500 μm, the high pass band rolls off at about 0.75, 0.8, 0.6, 0.5, and 0.4 THz, respectively. Fabrication technique seems to make the roll-off frequency of $d = 200$ μm some error. For frequencies $\nu > \nu_r$, magnitude of transmission coefficients through the

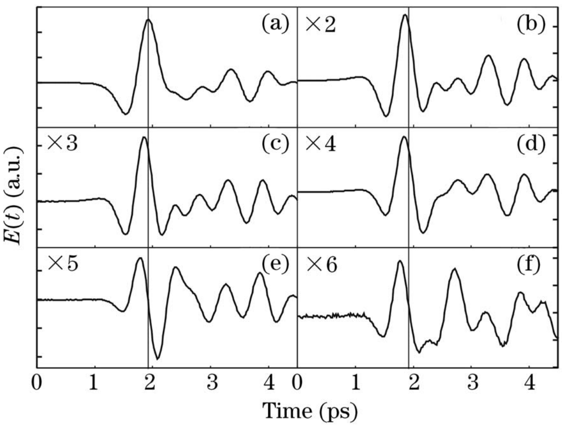

Fig. 2. Time-domain waveforms of the incident pulse (a) and the transmitted pulse through the circle holes with diameter $d = 500$ (b), 400 (c), 300 (d), 200 (e), and 150 μm (f).

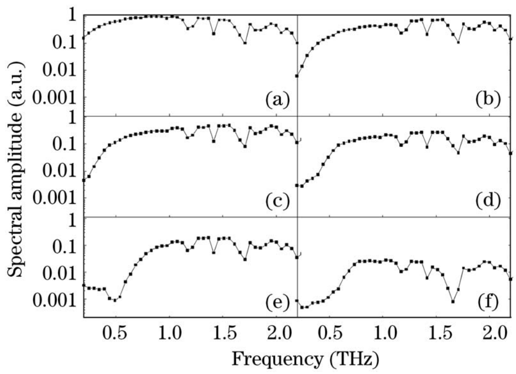

Fig. 3. The frequency spectra of the reference (a) and the samples with $d = 500$ (b), 400 (c), 300 (d), 200 (e), and 150 μm (f).

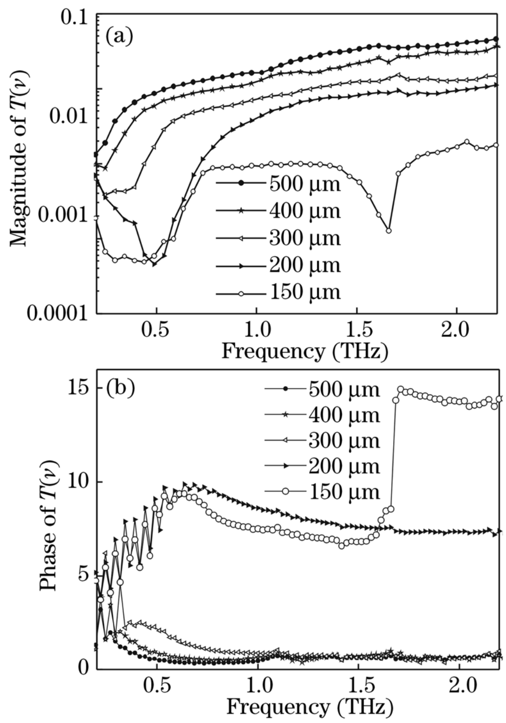

Fig. 4. (a) Magnitude and (b) phase of the transmission coefficient through the aperture diameters $d = 500$, 400, 300, 200, and 150 μm.

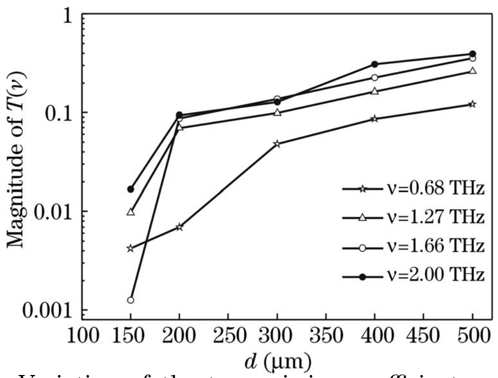

Fig. 5. Variation of the transmission coefficient versus the aperture diameter d for different frequencies ν = 0.68, 1.27, 1.66, and 2.0 THz.

aperture from d = 200 to 500 μm almost retain constant. To our surprise, there is a remarkable stop band for $d = 150$ μm at the frequency of about 1.66 THz, corresponding to the wavelength of 181 μm. In Fig. 4(b) the phase shows a suddenly jump at this frequency. We have repeated this measurement in nitrogen environment and got the same results. The conventional diffraction theory cannot explain this phenomenon. While the frequencies $\nu < \nu_{\rm r}$, the magnitude of $T(\nu)$ falls off with frequency, resulting from the severe diffraction. It also appears in Fig. 4 that transmission coefficient at THz region is enhanced with increase of the diameter of circular hole, which is in agreement with the conventional diffraction theory.

In Fig. 5, magnitude of transmission coefficients as a function of d for different frequencies $\nu = 0.68, 1.27, 1.66$, and 2.0 THz are plotted. However, the magnitude of $T(\nu)$ is not linear with the diameter in Fig. 5, distinguishing from the linear relation by conventional diffraction theory.

In summary, we have presented an experimental study of transmission properties of the THz pulse through a single sub-wavelength circle hole in the free-standing metal foil. The transmission process through the circle hole can shape the THz pulse waveform and change the spectrum of the incidence THz pulses. In fact, these findings are independent of the aperture shapes. Results of the transmission coefficient do not entirely conform to conventional diffraction theory. Firstly, transmission coefficient is not linear with the aperture diameter. Secondly, the especial feature of a stop band at about 1.66 THz, corresponding to the wavelength of 181 μm, for the circle hole with $d = 150$ μm cannot be explained with the existing theories. Thus, to gain a better insight into these extraordinary transmission phenomena, theoretical analysis of the results would be very important. Perhaps only then can we grasp the full implication of these findings.

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