# Study of terahertz pulses at an edge

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Received December 28, 2007

The propagation behaviour of terahertz (THz) pulses at an edge is characterized. The phenomenon that the amplitude oscillates periodically in the frequency spectrum is similar to Young's interference, if the absorption effect is neglected. The oscillation cycle is shorter for a thicker sample. THz pulses at an edge are analyzed by the broadband Huygens-Fresnel diffraction integral. The experimental results are in agreement with the simulation results approximately. The simulation errors are also analyzed.

*OCIS codes:* 300.6270, 320.5540.
*doi: 10.3788/COL20080609.0700.*

Electromagnetic waves at terahertz (THz) frequencies fall between the microwave and the infrared regions of the spectrum. A wide variety of experimental measurements based on THz time domain spectroscopy (THz TDS) is performed. In order to measure precisely THz electric field, it is important to understand how the propagation affects the profile of THz pulses. Many studies about the propagation of THz pulses are reported, for example, the propagation of THz pulses in random media[1,2], the propagation of THz pulses in circular waveguide[3], near-field propagation of THz pulses[4], THz pulses propagation through small apertures[5], and so on[6−14]. The location of edges in an image is an extremely well-known problem in image processing, so the precise measurement of THz pulses at the edge is very important to THz imaging. We report particularly the propagation behaviour of THz pulses at an edge and analyze the shape of THz pulses by the broadband Huygens-Fresnel diffraction integral.

The experimental setup has been given in Ref. [15]. An 805-nm femtosecond laser, with pulse duration less than 100 fs, repetition rate of 80 MHz, and average power of 700 mW is employed. The THz pulses are generated via photoconductive antenna. The THz radiation is then detected by electro-optic sampling technique in a ⟨110⟩ oriented ZnTe crystal. In consideration of the simplification, the sample with weak absorption to THz wave should be adopted in the experiments. Here the sample is polyethylene. The nitrogen is used to keep air dry during the experiments. Figure 1 shows that the THz beam scans the edges with abrupt change of refractive index or thickness. Three pulses are shown in Fig. 2 and the frequency spectra are shown in Fig. 3.

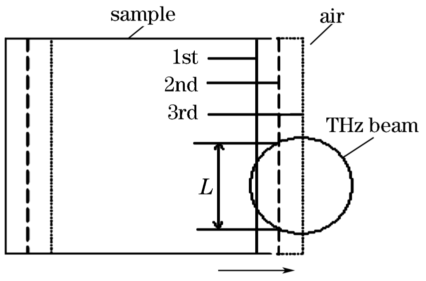

Fig. 1. Schematic of THz beam scanning the edge. The 1st position shows that only a very small part of the THz beam irradiates on the sample, whereas the 3rd position shows that a half of the THz beam irradiates on the sample and the 2nd position falls between the 1st position and the 3rd position.

A pulse can be collected when the THz beam scans the edge with abrupt change of refractive index or thickness. A common THz pulse only has one peak, whereas every pulse has two peaks in Fig. 2. Because the focus size of the THz beam is large, the beam can be divided into two parts when it scans the edge. Owing to optical path difference, two parts of the beam cannot reach the sensor simultaneously and two peaks will occur in the final pulse. A larger peak can be obtained for a larger THz beam, because a larger beam means a larger optics flow. For a thicker sample, the time difference between two peaks will become larger, but the amplitude of the pulse will change very little if the absorption effect is neglected and other conditions are uniform.

The results shown in Fig. 3 exhibit some regular phenomena. Firstly, when the length of the cross line between the sample and the THz beam $L$ becomes smaller, the amplitude is larger in the frequency spectrum. Because the absorption loss is very weak, it is concluded that the diffraction loss is stronger for a larger $L$. Secondly, the amplitude change is small at very low frequency as $L$ varies, so the very low frequency components diffract weakly. Thirdly, the amplitude oscillates periodically with the varying frequency. For a thicker sample, the oscillation cycle is shorter. The explanation is given as follows.

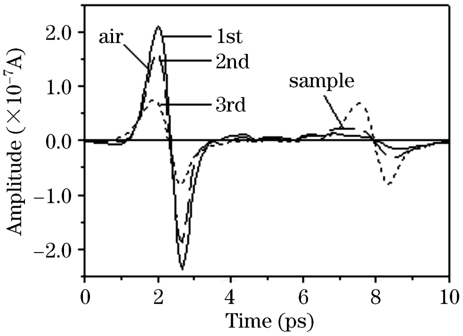

Fig. 2. Pulses of three scanning positions. The thickness of the sample is 3.4 mm and the 1st, 2nd, and 3rd pulses are coincident with the 1st, 2nd, and 3rd position in Fig. 1.

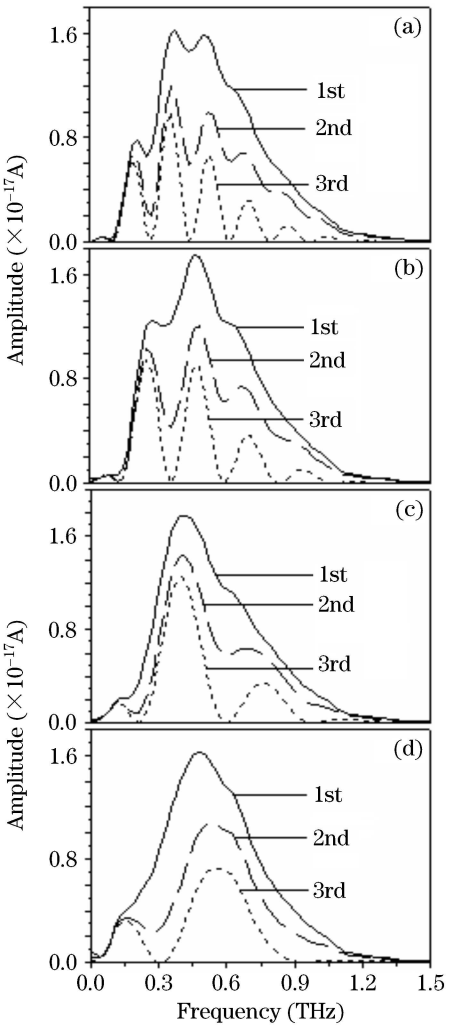

Fig. 3. Frequency spectra of three scanning positions. The thickness of the sample is (a) 3.4, (b) 2.6, (c) 1.6, (d) 0.95 mm, respectively. The 1st, 2nd, and 3rd spectra are coincident with the 1st, 2nd, and 3rd position in Fig. 1.

When the THz beam is divided into two parts after transmitting the edge, the phase difference $\Delta\Phi_i$ between two parts has the following relationship with the frequency $f_i$:

$$\Delta\Phi_i = \frac{(n_1-1)df_i}{c} \times 2\pi, \tag{1}$$

where $d$ is the thickness of the sample, $c$ is the speed of light in vacuum, $n_1$ is the refractive index of the sample. The following equation is defined:

$$\Delta\Phi_i = q_i\pi. \tag{2}$$

When the value of $q_i$ is odd, the minimum value in the frequency spectrum will be obtained at the frequency $f_i$. Similarly, when the value of $q_i$ is even, the maximum value will be obtained. Moreover, $\Delta f_i \approx c/((n_1-1)d)$, where $\Delta f_i$ is the oscillation cycle. The analyses are in good agreement with the experimental results in Fig. 3. This phenomenon is similar to Young's interference. The principle can be outlined as: a THz pulse is split into two pulses in time domain as irradiating on the edge, so the two pulses will interfere with each other in frequency spectrum, finally the amplitude will oscillate periodically in the frequency spectrum if the absorption effect is neglected.

The shape of THz pulses at the edge can be explained by the use of the broadband Huygens-Fresnel diffraction integral[4]:

$$u(P_0,t) = \iint_S \frac{\cos(\vec{n},\vec{r_{01}})}{2\pi c|r_{01}|}\frac{\mathrm{d}}{\mathrm{d}t}u(P_1,t-\frac{|r_{01}|}{c})\mathrm{d}S, \tag{3}$$

where $|r_{01}|$ is the optical path. The simulation model is shown in Fig. 4 when the THz beam is divided into two parts symmetrically. In the experiments, the profiles of paraxial points are measured. The simulation model reproduces the experimental course accurately.

In simulation model, the absorption effect is neglected. Because $|r_{01}|$ in the sample is different from $|r_{01}|$ in the air, the calculation should be divided into two parts:

$$\begin{aligned} u(P_0,t) = & \iint_{S_1} \frac{\cos(\vec{n},\vec{r_{01}})}{2\pi c|r_{01}|_{\text{sample}}}\frac{\mathrm{d}}{\mathrm{d}t}u(P_1,t-\frac{|r_{01}|_{\text{sample}}}{c})\mathrm{d}S_1 \\ & + \iint_{S_0} \frac{\cos(\vec{n},\vec{r_{01}})}{2\pi c|r_{01}|_{\text{air}}}\frac{\mathrm{d}}{\mathrm{d}t}u(P_1,t-\frac{|r_{01}|_{\text{air}}}{c})\mathrm{d}S_0. \end{aligned} \tag{4}$$

The experimental and the simulation results of the output pulses are shown in Fig. 5. Similarly, when the THz beam is not divided into two parts symmetrically, the experimental and the simulation results are shown in Fig. 6, where the beam irradiating on the sample is larger than the beam irradiating on the air.

There are also some discrepancies between the experimental results and the simulation results. Apparently some small peaks appear near the main peaks in the simulation results, and the main peaks are smaller in the

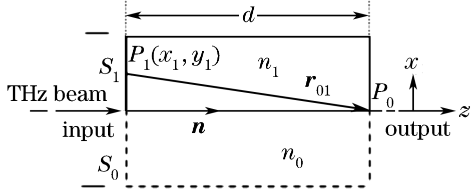

Fig. 4. Schematic of simulation mode. $n_0$ is the refractive index of the air, $S_1$ is the area of the THz beam irradiating on the sample and $S_0$ is the area of the THz beam irradiating on the air.

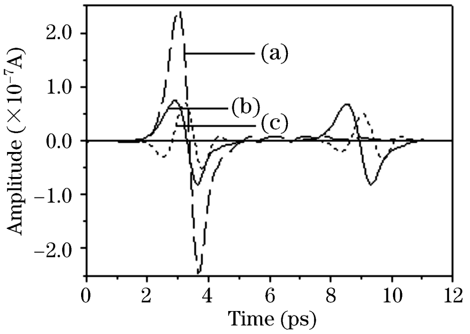

Fig. 5. (a) Input pulse; (b) experimental result; (c) simulation result. The THz beam is divided into two parts symmetrically and the thickness of the sample is 3.4 mm.

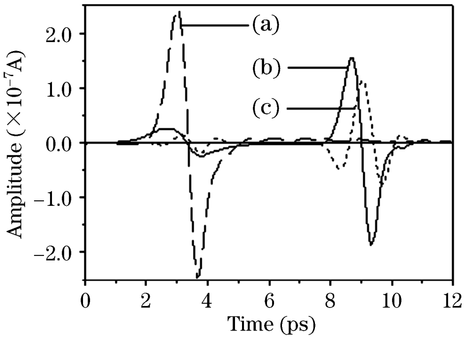

Fig. 6. (a) Input pulse; (b) experimental result; (c) simulation result. The THz beam is not divided into two parts symmetrically and the thickness of the sample is 3.4 mm.

simulation results than those in the experimental results. The positions of the main peaks have differences between the experimental and the simulation results. Otherwise, the experimental and the simulation results show different phase information, for example at $t = 3$ ps. The discrepancies result from several factors. Firstly, the weak absorption effect is neglected in the simulation. Secondly, when the THz pulses irradiate on the edge, the photons may be divided into several parts: most photons only transmit in the air or in the sample; a small number of photons transmit from air to sample or from sample to air. Because the small number of photons is not very important to the change trend of the THz pulses, it is neglected in the simulation. But this also brings the effect that the main peaks are smaller in the simulation results than in the experimental results. Thirdly, though Huygens-Fresnel diffraction integral can be used to analyze the change trend of THz pulses at the edge, it is not very accurate, especially for the phase analysis. Because of the error of optical path $|r_{01}|$ in the simulation, the phase discrepancy in the experimental and the simulation results will occur. Fourthly, the initialization of $u(P_1, t)$ is not very accurate in the simulation. In time domain, the input pulse can be measured accurately. In space domain, for our experimental setup, the spatial distribution at the input surface is analogous base mode Gaussian distribution, but the exact spatial distribution equation cannot be measured. In the simulation, out of consideration for the simplification the base mode Gaussian distribution is given, so some discrepancies will occur.

When the absorption is not very weak, the absorption effect cannot be neglected in the simulation. The theoretical calculation will be comparatively complicated. The following equation shows the simulation method:

$$u(P_0, t) = \mathrm{FFT}^{-1}\{\exp[-\alpha(\omega)d] \\ \times \mathrm{FFT}[u_1(P_0, t)]\} + u_2(P_0, t), \qquad (5)$$

where FFT and FFT$^{-1}$ are Fourier transform and inverse Fourier transform respectively, $\alpha(\omega)$ is the absorption coefficient, $u_1(P_0, t)$ and $u_2(P_0, t)$ can be solved by Eq. (3). Because of the absorption effect, aperiodic oscillation can happen in the frequency spectrum.

In conclusion, the propagation behaviour of THz pulses at an edge is investigated. If the absorption effect is neglected, the phenomenon that the amplitude oscillates periodically in the frequency spectrum is similar to Young's interference. Shape of THz pulses at an edge is analyzed by the broadband Huygens-Fresnel diffraction integral.

This work was supported by the National Natural Science Foundation of China under Grant No. 10574134. Z. Xi's e-mail address is xizaijun@sinap.ac.cn.

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