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RESEARCH ARTICLE

Oscillation effect in frequency domain current from a photoconductive antenna via double-probe-pulse terahertz detection technique

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Abstract Via constructing a special terahertz time domain spectroscopy (THz-TDS) system in which two femtosecond (fs) laser pulses were used as probe pulses to excite a photoconductive (PC) THz detector, the time behavior of the current from the detector was measured. The corresponding theoretical analysis was performed by a well-known equivalent-circuit model. When the time domain current was transformed to frequency domain, an oscillation effect was observed. The oscillation frequency was decided by the time delay between the two probe pulses. The number of the extrema in the frequency domain current curve was proportion to the pulse interval in 0.1 – 2 THz. A method to measure the interval of fs laser pulses was proposed. It is important for applications of fs laser pulses or train.

Keywords terahertz (THz), photoconductivity, frequency oscillation

1 Introduction

Photoconductive (PC) antenna has been widely used as terahertz (THz) emitter or detector for a long time. In the past, many researchers have concentrated on field screening effects of PC antennae, including space-charge field and radiation field screening effects [1–11]. When a PC antenna used as a THz emitter, the radiation field screening effect is the principal cause for saturation of THz emission observed if the emitters are driven hard with high-repetition-rate femtosecond (fs) laser pulses [7]. When used as a THz detector, the radiation field screening effect is also the main factor to cause the distortion for THz pulse field detection [10]. Compared with the radiation field screening effect, the space-charge field screening effect is usually too weak to be considered when the spot diameter is above 0.1 mm [11].

An approach named double-pump-pulse THz emission technique was presented to study the field screening effects of a PC THz emitter in a special THz time domain spectroscopy (THz-TDS) system, in which two fs laser pulses were used as pump pulses to excite the THz emitter [5–8]. Such a double-pump technique was developed into a double-probe-pulse THz detection technique used to study the field screening effects of a PC THz detector in another kind of special THz-TDS system, in which two fs laser pulses were used as probe pulses to excite the THz detector [10]. Such a double-probe technique was used to perform a wave shape recovery for THz pulse field detection, in which the interval of the two probe pulses was taken at a fixed value [10]. The unknown phenomenon stays while different pulse intervals are taken.

In this paper, we use the double-probe-pulse THz-TDS system to measure the current of the PC THz detector in time domain with different probe pulse intervals. When the measured time domain current is Fourier transformed to frequency domain, we find an oscillation effect in the frequency domain current curves. The oscillating frequency is proportional to the pulse interval. By the use of the theoretical model presented in Ref. [10], which was developed from the equivalent-circuit model [5,8], the current curves are calculated. The calculated curves and the measured ones are coincident in both time and frequency domains. We find that the interval of the two probe pulses is strictly proportional to the number of the minima in the frequency domain current curve in 0.1 – 2 THz, which is the effective detection range of this THz-TDS system. Via assuming the current pulse as a δ

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function, a simple model is built, which can effectively describe the relation between the number of minima and the pulse interval. Based on these theoretical and experimental results, we can propose a new method to measure the interval of fs laser pulses while the interval is a few picoseconds. This method is useful in the areas of fs laser applications, especially those systems which are concerned with several fs pulses or train.

2 Experimental observation

Figure 1 shows our experimental setup, which is a double-probe-pulse THz-TDS system [10]. The excitation source is a mode-locked Ti: sapphire laser (Coherent, Micra-5) providing 40 fs pulse width at a center wavelength of 800 nm and repetition rate of 80 MHz. By using beam splitters (BSs), the laser pulse is divided into three parts (pump, probe 1 and probe 2). The pump pulse is focused on a PC emitter to create THz pulse. The two probe pulses and the THz pulse are focused on a PC detector. The power ratio of the probe 1 and probe 2 can be controlled by a half-wave plate (HWP). The polarizations of the probe 1 and probe 2 are vertical. The time delay τ between the pump pulse and the probe pulse 2 is adjusted by a delay line. The interval between probe 1 and probe 2, denoted as $\tau_{1,2}$, is adjusted by a delay stage.

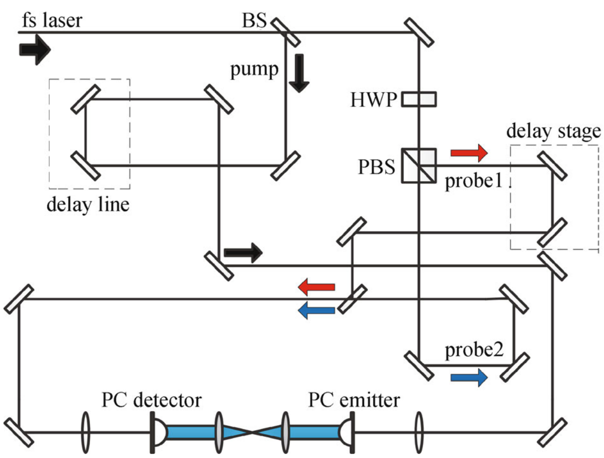

Fig. 1 Experimental setup. fs: femtosecond; BS: beam splitter; HWP: half-wave plate; PBS: polarization beam splitter; PC: photoconductive

The PC THz detector has two metal electrodes on a semi-insulating low-temperature-grow GaAs substrate with a gap between the electrodes. When the probe pulses and the THz pulse are focused on the THz detector, the probe pulses will generate transient photocarriers in the substrate, and then the THz pulse can drive the photocarriers to form a steady electric field, which will lead a measurable current J between two electrodes of the PC THz detector [12]. By scanning the delay line, the current J as a function of τ can be measured in time domain under different values of $\tau_{1,2}$. The current can be denoted as $J(\tau,\tau_{1,2})$, in which τ is the independent variable and $\tau_{1,2}$ is a parameter. The corresponding frequency domain curve $J(\nu,\tau_{1,2})$ can then be obtained by Fourier transformation. The credible frequency range is mainly determined by the THz detector, which is 0.1 to 2 THz for this THz-TDS system.

By setting the average power of both probe 1 and probe 2 to 11 mW, the time domain current $J(\tau,\tau_{1,2})$ is measured in the condition of $\tau_{1,2}=0,\pm 0.5,\pm 1,\pm 1.5,\pm 2,\pm 2.5,\ldots,\pm 5$ ps, respectively. Here we define that $\tau_{1,2}>0$ when probe pulse 1 comes ahead of probe pulse 2. The results of $\tau_{1,2}=0$ and each positive integer are shown in Fig. 2. As can be seen there are two current pulses in the time domain curves, which are excited by the two probe pulses, respectively. An oscillation phenomenon occurs in the frequency domain curves and the oscillating frequency is proportional to the pulse interval. The similar phenomena is observed for the other taken values of $\tau_{1,2}$.

3 Theoretical simulation

In this section, we will perform a theoretical analysis to simulate the observed results based on the model built in Ref. [10]. When the radiation field screening effects and the time dependence of the photocarriers density n_f are considered, the THz field induced current $J(\tau,\tau_{1,2})$ can be expressed as

$$J(\tau,\tau_{1,2})=\frac{e\mu_\mathrm{e}}{T_\mathrm{rep}}\int_0^{T_\mathrm{rep}} n_\mathrm{f}(t,\tau,\tau_{1,2})E(t,\tau,\tau_{1,2})\mathrm{d}t, \quad (1)$$

where T_rep is the repetition time of the fs laser, e is the elementary charge, μ_e is the mobility of the electron, $E(t,\tau,\tau_{1,2})=E_\mathrm{THz}(t)-E_\mathrm{rad}(t,\tau,\tau_{1,2})$, E_THz is the THz field, and E_rad is the radiation field.

According to the equivalent-circuit model [5,7], the radiation field can be expressed by the impedance Z_a of the antenna.

$$E_\mathrm{rad}(t,\tau,\tau_{1,2})=\frac{e\mu_\mathrm{e}n_\mathrm{f}(t,\tau,\tau_{1,2})E(t,\tau,\tau_{1,2})A}{d}Z_\mathrm{a}, \quad (2)$$

where A is the effective contact area of the PC gap, d denotes the width of the gap. For double-probe pulses, the time dependence of $n_\mathrm{f}(t,\tau,\tau_{1,2})$ can be expressed as

$$n_\mathrm{f}(t,\tau,\tau_{1,2})=\frac{1}{2}\frac{\eta}{h\nu V\nu_\mathrm{p}}\exp\left(\frac{T_0^2}{4\tau_\mathrm{c}^2}-\frac{t+\tau}{\tau_\mathrm{c}}\right)$$

$$\cdot\left\{W_\mathrm{p1}\left[1+\mathrm{erf}\left(\frac{t}{T_0}-\frac{T_0}{2\tau_\mathrm{c}}+\frac{\tau+\tau_{1,2}}{T_0}\right)\right]\right.$$

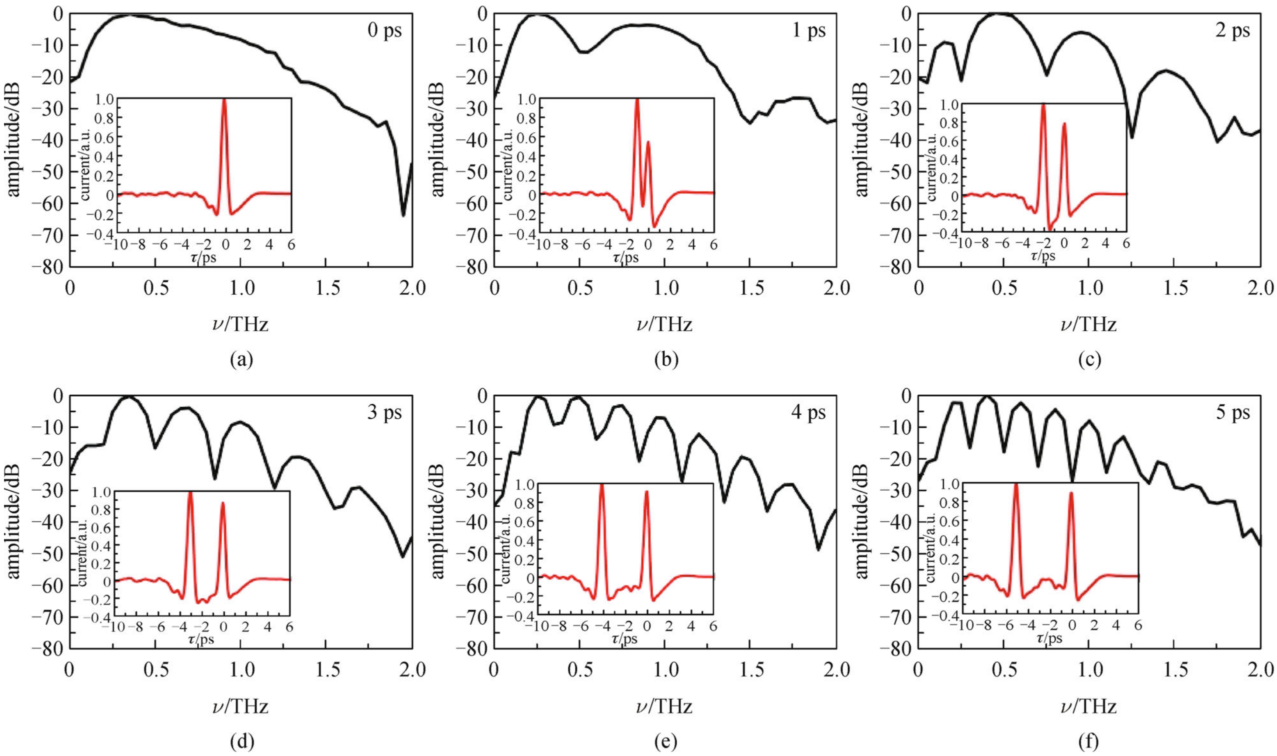

Fig. 2 Normalized measured time domain current (inset red lines) and the corresponding normalized frequency domain current (black lines) under different $\tau_{1,2}$. (a) 0 ps; (b) 1 ps; (c) 2 ps; (d) 3 ps; (e) 4 ps; (f) 5 ps

$$\cdot \exp\left(-\frac{\tau_{1,2}}{\tau_c}\right) + W_{p2}\left[1 + \mathrm{erf}\left(\frac{t+\tau}{T_0} - \frac{T_0}{2\tau_c}\right)\right]\Bigg\}, \quad (3)$$

where η is the quantum efficiency, $h\nu$ is the photon energy of the laser, V is the active volume, ν_p is the laser repetition rate, T_0 is the pulse width, and τ_c is the trapping time. The THz field from the PC emitter can be written as [10]

$$E_{\mathrm{THz}}(t) = A_0 t[a(t+t_0) + b]\exp\left(-\frac{t^2}{T^2}\right), \quad (4)$$

wherev A_0, b, T, andv a vare vselected vparameters, vand $t_0 = (2\pi + b)/a$. The parameter values used to the calculation are: $A_0 = 1$ V/(cm·ps), $b = 2.05$, $T = 0.475$ ps, $a = 1.94/T$, $\tau_c = 0.65$ ps, $T_0 = 40$ fs, $\mu_e = 32\ \mathrm{cm}^2/\mathrm{Vs}$, and $Z_a = 70\ \Omega$. Simultaneously solving Eqs. (1)–(4), $J(\tau,\tau_{1,2})$ can be calculated and its Fourier transformation $J(\nu,\tau_{1,2})$ can then be obtained.

Figure 3 shows the calculated results together with the observed results for $\tau_{1,2} = 2$ and 5 ps. The theoretical simulations present agreements with the experimental observations. From the frequency domain curves, we can clearly see that there is a remarkable consistency in both the number and the position of the minima between observation and simulation, indicating that the theoretical model can effectively describe the frequency oscillation effect. The number of the minima has a simple relation with the pulse interval in $0.1-2$ THz, which is the effective detection range of our THz-TDS system, thus allowing us to propose a method to measure the interval between two fs laser pulses.

4 A proposed method to measure the pulse interval

For all the taken values of $\tau_{1,2}$, both the experimental observations and the theoretical simulations show that the pulse interval has a linear relation with the number of the minima in frequency domain current curves in the range $0.1-2$ THz, as shown in Fig. 4. Based on this, we can propose a method to measure the interval of two fs laser pulses. That is, the interval can be determined via counting the number of the minima (or maxima) in frequency domain current curves. In what follows we will build a simplified model to describe the method by assuming the time domain current pulse as a $\delta(t)$ function.

By regarding the measured current pulse as a $\delta(t)$ function instead of emphasizing its certain width, we believe that the key mechanism of the frequency oscillation effect can be revealed clearly. Thus, the time domain current can be phenomenologically expressed as

$$f(t,\tau_{1,2}) = A_1\delta(t) + A_2\delta(t+\tau_{1,2}), \quad (5)$$

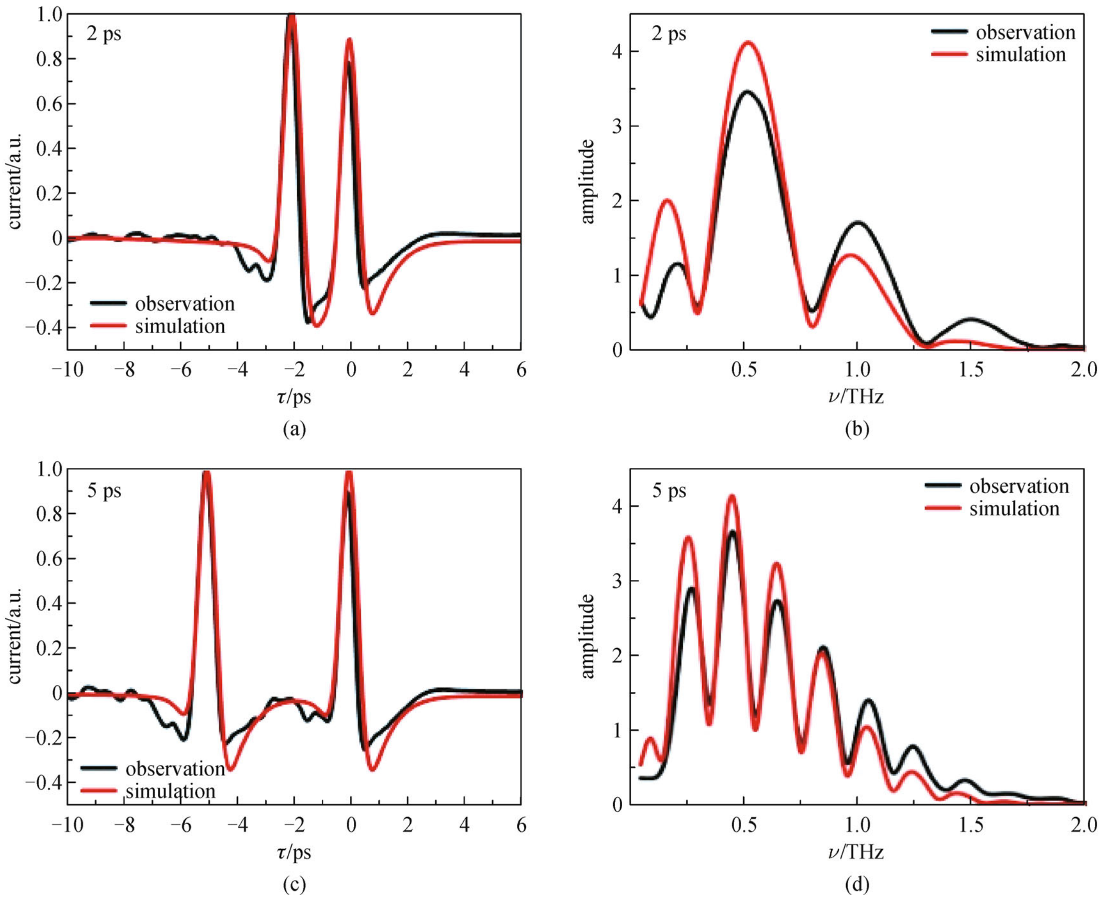

Fig. 3 Normalized current J as a function of τ and its corresponding Fourier transform amplitude (Observation: black lines, and simulation: red lines). (a) and (b) for $\tau_{1,2} = 2$ ps, (c) and (d) for $\tau_{1,2} = 5$ ps

where A_1 and A_2 denote the amplitude of the two pulses, and $\tau_{1,2}$ is the pulse interval. By Fourier transformation, the frequency domain current can be obtained as

$$f(\nu,\tau_{1,2}) = A_1 + A_2 e^{i2\pi\nu\tau_{1,2}}, \tag{6}$$

$|f(\nu,\tau_{1,2})|^2$ is then given by

$$|f(\nu,\tau_{1,2})|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(2\pi\nu\tau_{1,2}). \tag{7}$$

The key physical mechanism of the oscillation effect can be seen through Eqs. (5)–(7). For two current pulses with an interval $\tau_{1,2}$, if the time width of the pulses is narrow enough, the corresponding frequency domain curve includes the function of $\cos(2\pi\nu\tau_{1,2})$ that can result in oscillation. Equation (7) indicates that $|f(\nu,\tau_{1,2})|^2$ has the same number of the minima as that of $\cos(2\pi\nu\tau_{1,2})$. For $\tau_{1,2} = m$ ps, $m = 0, \pm 0.5, \pm 1, \pm 1.5, \pm 2, \pm 2.5, ..., \pm 5, ...$, $\cos(2\pi\nu\tau_{1,2})$ has $n = 2|m|$ minima when ν changes from 0.1 to 2 THz, which is consistent with the experimental results in Fig. 4. According to the analysis above, we can get the relation between the pulse interval $\tau_{1,2}$ and the number of minima n as $\tau_{1,2} = n/2$ ps, thus allowing us to count n to determine $\tau_{1,2}$. In fact, we can also take maxima into consideration to lead the same consequence.

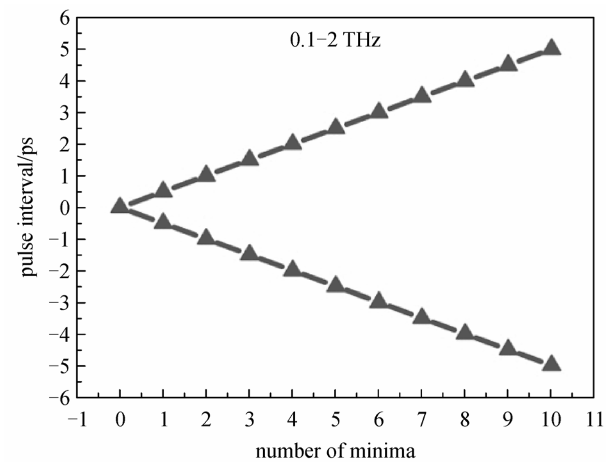

Fig. 4 Relation between the pulse interval and the number of minima in frequency domain current curves

5 Conclusion

In conclusion, for a THz-TDS system with double fs laser pulses to excite a PC THz detector, the current from the detector presents an oscillation effect in frequency domain. There is a linear relationship between the pulse interval and the number of the extrema in the frequency domain current curve. For fs laser pulses with their interval to be a few picoseconds, via counting the number, the interval can be determined. This way is significant for applications of fs laser pulses or train.

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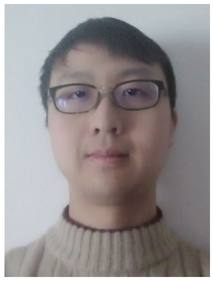

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