Investigation on terahertz generation by controlling the laser spot size on photoconductive antenna

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Abstract: It was experimentally investigated that the laser spot size on photoconductive antenna (PCA) gap could have a great influence on terahertz (THz) generation. Moreover, the simulation on THz generation influenced by the laser power density was carried out, which was agreed well to the experiments. It is well demonstrated that the increase of laser power density on PCA gap can enhance THz generation. However, the intensity of THz radiation reached saturation while the laser power density exceeding a certain value. The laser power density increased further by focusing harder, but the THz radiation was getting weaker due to the smaller laser excited area on PCA gap.

Key words: terahertz generation; photoconductive antenna; laser power density; spot size; saturation

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改变天线泵浦光斑尺寸对太赫兹辐射影响的研究

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摘 要:从实验上研究了光电导天线电极之间激光光斑大小对太赫兹波产生的影响。另外,理论模拟了激光功率密度与太赫兹波辐射强度之间的关系,与实验结果非常吻合。泵浦光激光功率密度的增加能够显著的提高太赫兹波辐射强度,但是当超过一定值后会趋于饱和,此时若继续减小光斑尺寸,激光功率密度的增加不会使太赫兹产生继续增强。但是,太赫兹波却会随着光斑尺寸的减小而变弱。

关键词:太赫兹产生; 光电导天线; 激光功率密度; 光斑尺寸; 饱和

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0 Introduction

In recent decades, the photoconductive antenna (PCA) has been one of the most frequently used components for terahertz (THz) technology, which could generate and detect THz radiation via transient photocarriers induced by ultrafast laser pulses[1-2]. Because of some significant advantages, such as wide frequency band, simple structure, room-temperature operation and easily fabrication, PCAs have been widespread used in the laboratory for THz researches[3-4]. A typical PCA consists of two parallel metal electrodes, which are coated on a semi-insulating semiconductor substrate. Femtosecond optical pulses with photon energy larger than the band-gap of the semiconductor are incident to antenna surface, free electron and hole pairs in the gap between the electrodes are generated. A DC bias applied across the electrodes generates a static bias field, which will accelerate the free carriers and, simultaneously, the charge density declines primarily by trapping of carriers in defect sites on the time scale of carrier lifetime[5-6]. The impulse current arising from the acceleration and decay of free carriers would radiate electromagnetic wave in the form of THz pulses.

Since the first demonstration of generating THz radiation by PCA, the PCA has been widely researched even other THz generation methods, such as nonlinear media, semiconductor surfaces, or quantum structures with femtosecond optical pulses, were developed. While the PCA factors, such as geometry, gap size, and photoconductive material, are fixed at specific conditions, the variations of pump features will significantly affect the THz emission. For example, the laser intensity and pulse width will greatly affect the amplitude and frequency spectral range of THz radiation. Usually, a stronger signal is corresponding to a higher signal to noise ratio (SNR). Therefore, it is quite attractive to improve the amplitude of THz radiation.

In this paper, we experimentally investigated that the laser spot size on PCA gap could greatly affect the intensity of THz radiation by adjusting the distance between PCA and the lens focus point. Moreover, a numerical simulation based on the theory of generating radiation from PCA was done. It was found that the laser power density on PCA gap and laser spot size could play a dominant role in generating THz radiation, which was agreed well to the experimental results.

1 Simulation

The characteristics of PCA and pump pulses are very important to generate THz signals. Assuming that the incident femtosecond laser pulse is Gaussian pulse, its power distribution $\mathbf{P}(t)$ can be expressed as:

$$\mathbf{P}(t)=\mathbf{P}_0\exp\left(-\frac{t^2}{\delta t^2}\right) \quad (1)$$

where $\mathbf{P}_0$ is the peak power of femtosecond laser; δt is the pulse width (FWHM). Combined with Maxwell equations, the generation rate of photocarriers $\mathbf{G}(t)$ can be written as:

$$\mathbf{G}(t)=\frac{\eta}{\mathbf{hv}}\mathbf{P}(t)=\frac{\eta}{\mathbf{hv}}\mathbf{P}_0\exp\left(-\frac{t^2}{\delta t^2}\right)=\mathbf{G}_0\exp\left(-\frac{t^2}{\delta t^2}\right) \quad (2)$$

where η is the quantum efficiency of photoconductive materials, $\mathbf{G}_0$ is the generation rate of photocarriers at the peak power of the incident femtosecond laser.

When femtosecond pulses excite photoconductive material, the photocarriers are generated and recombined simultaneously. Electrons usually have much higher mobility than holes, so the contribution of holes can be ignored in most cases. Assuming that carrier's lifetime is τ_c, so the carrier's attenuation rate is $\mathbf{N}(t)/\tau_c$. Generation and recombination processes codetermine photocarrier's dynamic density changing over time $-d\mathbf{N}(t)/dt$. Thus, photocarrier's dynamic density can be expressed as:

$$\mathbf{N}(t)=-\frac{\mathbf{N}(t)}{\tau_c}+\mathbf{G}(t)=-\frac{\mathbf{N}(t)}{\tau_c}+\mathbf{G}_0\exp\left(-\frac{t^2}{\delta t^2}\right) \quad (3)$$

When the PCA substrate is excited, it is no longer a semi-insulating material, but rather a conductive medium. According to the basic physical theory, the current density is described as

$$\mathbf{J}(t)=\mathbf{N}(t)\mathbf{e}\mu\mathbf{E}_b \tag{4}$$

where **e** donates the elementary charge, μ is the mobility of electron, and $\mathbf{E}_b$ is the bias electric field. According to the classical electromagnetic radiation theory, a transient photocurrent pulse will radiate an electromagnetic pulse wave.

Since the photocurrent varies in time, the generated terahertz electric field can be approximately expressed as

$$\mathbf{E}_{THz}=\frac{1}{4\pi\varepsilon_0}\frac{\mathbf{A}}{\mathbf{c}^2\mathbf{z}}\frac{\partial \mathbf{J}(t)}{\partial t}=\frac{\mathbf{Ae}}{4\pi\varepsilon_0\mathbf{c}^2\mathbf{z}}\frac{\partial \mathbf{N}(t)}{\partial t}\mu\mathbf{E}_b \tag{5}$$

where **A** is the effective area of antenna gap illuminated by laser, ε_0 is the permittivity in vacuum, **c** is the light speed in vacuum, and **z** is the distance between field point and terahertz source. To derive Eq. (5), the distance between field point and THz source is assumed much larger than the dimension of antenna.

Without excitation, a balance is reached between the drift and the diffusion of free carriers in semiconductor, including the depletion layer. Therefore, net charge movement is observed in a macro scale. When a laser pulse is absorbed in the depletion layer, the photo induced electron-hole pairs will be accelerated by the exciting electric field. In n-type GaAs, for instance, electrons are driven toward inside of the wafer, while holes are driven in the opposite direction. Dipole oscillations occur until a new balance is reached. Terahertz radiation can also be estimated using dipole radiation as shown above.

To obtain the terahertz pulse shape, the antenna surface electric field and magnetic field boundary conditions should be used[7]. Here we suppose the carrier lifetime τ_c is 1 ps, the electron mobility μ is 8 000 cm^2/Vs, laser pulse width δt is 20 fs, and the electric field $\mathbf{E}_b$ is about 2×10^6 V/m. The THz signal's variation tendency under different incident laser powers is shown in Fig.1.

In Fig.1, it's clear that the increase of terahertz signal amplitude with the incident laser power is not infinite, but tends to be saturated. This phenomenon is known as the radiation field screening effect. The energy of terahertz pulse comes from the electric energy stored across the gap rather than the optical pulse energy. The more photocarriers being generated, the more stored energy is converted into terahertz radiation. Under weak excitation condition, pulse energy of the terahertz wave is proportional to the excitation laser. In reality, linear relationship between the biased field and terahertz field, as well as between the excitation pulse energy and terahertz field, is only true under weak excitation and low bias field. When the laser intensity exceeds a certain value, the generated terahertz pulse will not change significantly[8].

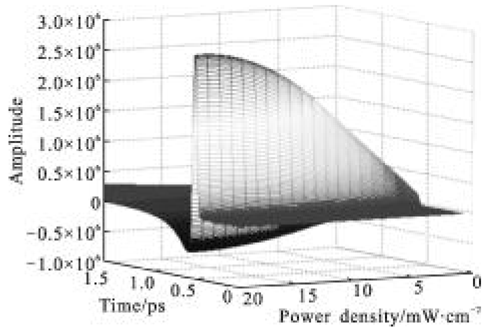


Fig.1 Terahertz generation under different incident laser powers

For small-aperture antennas, the space-charge screening arises from the separation of the photo-generated electrons and holes in the biased electric field. When the electrons and holes drift in the opposite direction, regions of net positive and negative space charge develop. The electric field induced by this space charge is in the opposite direction to the biased field and screens it. This space screening is important for small-aperture dipole antennas, but for large-aperture antennas, radiation screening is the major source of the saturation [9]. In large-aperture photoconducting antenna, saturation is mainly caused by the boundary conditions of the electromagnetic field at the surface of the illuminated region. The peak electric field amplitude of the sub-millimeter electromagnetic pulse is expected to saturate at a value comparable to the biased field when the surface photoconductivity becomes comparable to the reciprocal of the radiation resistance.

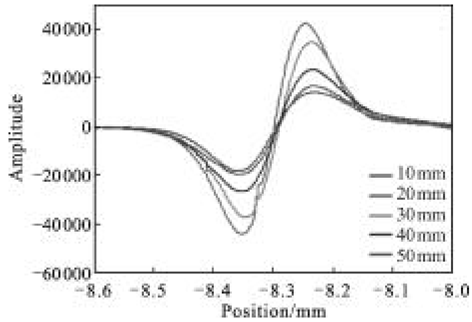
2 Experiment

In our experiment, a mode-locked Ti:Sapphire laser which generates 12 fs ultrafast pulses at a central wavelength of 790 nm with a repetition rate of 72 MHz is used to excite the terahertz emitter. The laser beam is split into pump and probe beams by a splitter. The pump beam is focused onto the photoconductive antenna to generate terahertz radiation, which is collimated and focused by a pair of off-axis parabolic mirrors. The antenna is biased with 10 kHz bipolar square wave that generated by a function waveform generator and a high voltage amplifier. After interaction with a ZnTe crystal, the generated terahertz signal is transmitted from a home-made differential detector to a lock-in amplifier, and then sent to the computer for analysis.

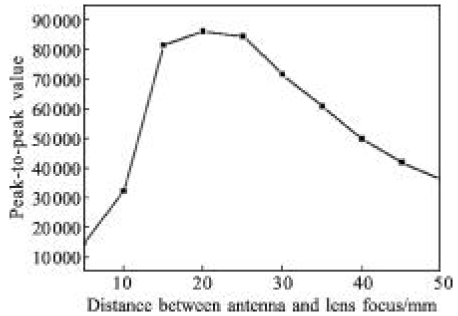
Usually, the PCA is fixed around the focus of lens in terahertz time-domain spectroscopy, but the maximum peak-to-peak value of THz radiation may not be obtained. Here, we experimentally observed the influence of the laser spot size and the power density to terahertz radiation by changing the position of lens in front of photoconductive antenna.

Figure 2 shows different signals while changing the laser spot size and its variation of peak-to-peak values. It's clear shown in Fig.2 (b) that the terahertz signal's amplitude increases at the beginning when the lens focus is moved closer to the PCA surface, and after reaching the maximum, they become weak again. During this progress, the laser power intensity is getting stronger with the laser focused harder.

Figure 3 shows the frequency spectra of THz signals in Fig.2 (a). Since a stronger signal is corresponding to a higher SNR, the spectral range will broaden with the power density being enhanced. Therefore, we can see in Fig.3 (b) that the frequency spectral range follows the same variation with peak-to-peak value.

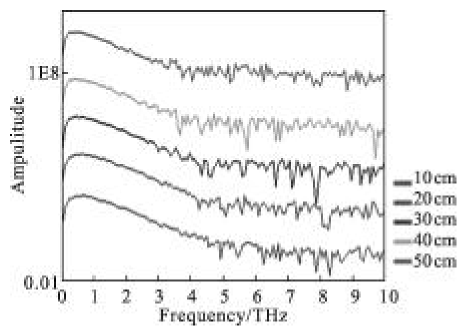


(a) Different signals while changing the position of focusing lens

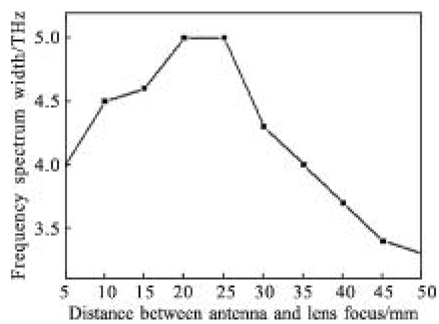


(b) Variation tendency of THz peak-to-peak value with different distance between antenna and lens focus

Fig.2 Terahertz time-domain signals



(a) Different spectra got from Fig.2(a)



(b) Variation tendency of THz frequency spectrum range with different distance between the PCA and the lens focus

Fig.3 Terahertz frequency spectra

In our experiment, we measured the laser spot size for further observation of laser power density. Many methods have been developed to measure laser spot size, among which, the knife-edge method is often used. The intensity profile of the laser beam is Gaussian generally, and the total intensity of the transmitted laser beam changes according to the error function[10]. As a result, determining the spot size requires differentiating or evaluating this error function.

We used a translation stage with step size of 20 μm to move the knife and cut the laser beam. During this process, a power-meter (Newport 1918C) behind the blade is used to record the laser power at each position of blade. Because the complementary error function cannot be integrated analytically for arbitrary blade position, the common practice is to numerically differentiate the measured power with respect to the blade position. Therefore, the laser spot diameter can be obtained through the differential coefficient.

Figure 4 shows the laser spot size measured by knife-edge method when the distance between lens focus and antenna is 20 mm (i.e. the maximum point of the curve in Fig.2(b). In Fig.4(b), we can see that the actual diameter of laser spot is around 400 μm, which is roughly equal to the gap size of PCA used. This means that in our experiment, while the distance between the lens focus and the PCA is shorter than 20 mm, the laser spot size will be smaller than the dimension of antenna gap, so the illuminated region of antenna will become smaller by moving the lens focus closer to the PCA surface. On the other hand, while the distance between the lens focus and the PCA is in the range of 20-50 mm, the focus level of pump laser is much lower, and the laser spot diameter is wider than the antenna gap. Thus, the measurement by changing the spot size will not influence the generated radiation significantly.

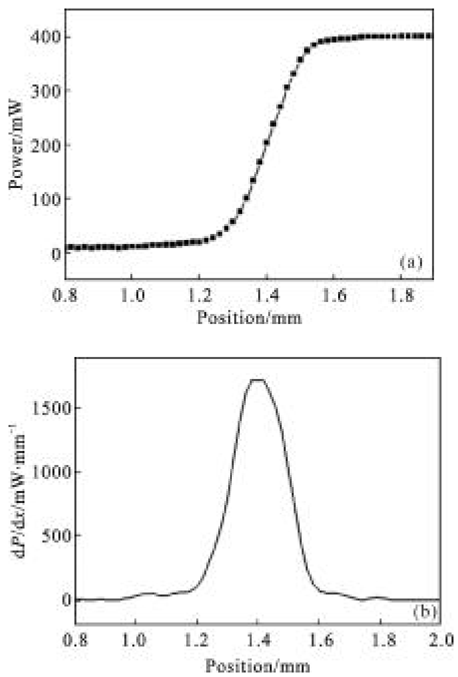


Fig.4 (a) Different laser powers by changing the position of blade (b) Differential coefficient of (a)

Above all, we can get a reasonable explanation of the phenomenon in Fig.2 that with the distance between the lens focus and the antenna surface is changing from 50 mm to 5 mm, the laser will be focused harder, and the laser power density will increase progressively. According to our simulation, the generated terahertz signal will increase continuously and reach saturation finally.

However, while continuing to focus the pump laser harder, the spot size on the PCA surface will be getting smaller than the gap between two electrodes, and the area of occurring photoelectric effect will decrease with smaller spot size, for which reason, the number of photocarriers could decrease eventually. As a consequence, the terahertz signal will be getting weak. Therefore, during the process of moving the lens in front of the PCA, the generated THz signal is influenced by two factors: the laser power density and the spot size on the antenna gap, which eventually lead to the THz amplitude increased at the beginning and then decreased at the end, as shown in Fig.2(b).

3 Conclusion

We have experimentally investigated that controlling laser spot size on PCA gap could greatly affected the intensity of THz radiation by adjusting the distance between the PCA and the lens focus. The laser power density will increase when the lens focus is moved closer to the antenna surface due to the laser spot size smaller. According to the simulation, the increase of laser power density on PCA gap could enhance the THz radiation. However, the intensity of THz radiation will reach saturation while the laser power density exceeding a certain value. After reaching the saturation, the increase of laser power density will not influence THz radiation significantly. However, THz radiation will become weak due to the decrease of photocarriers because a further reduction of laser spot size could reduce the effective illuminated region on PCA gap.

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