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SPECIAL TOPIC — Terahertz physics

A new nonlinear photoconductive terahertz radiation source based on photon-activated charge domain quenched mode*

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We present a high-performance terahertz (THz) radiation source based on the photon-activated charge domain (PACD) quenched mode of GaAs photoconductive antennas (GaAs PCA). The THz radiation characteristics of the GaAs PCA under different operating modes are studied. Compared with the linear mode, the intensity of THz wave radiated by the GaAs PCA can be greatly enhanced due to the avalanche multiplication effect of carriers in the PACD quenched mode. The results show that when the carrier multiplication ratio is 16.92, the peak-to-peak value of THz field radiated in the PACD quenched mode increases by as much as about 4.19 times compared to the maximum values in the linear mode.

Keywords: photoconductive antenna, terahertz time-domain spectroscopy, photon-activated charge domain quenched mode

PACS: 78.47.J−, 87.50.U−

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1. Introduction

Terahertz (THz) radiation has great scientific research value and broad application prospects. One of the key bottlenecks hindering the development of THz technology is the lack of high power THz sources.[1–3] Photoconductive switch is a kind of switching device which is formed by the combination of pulse laser and photoconductor (such as Si, GaAs, InP). It has the advantages of fast response, sub-picoseconds trigger jitter, and high output power, and has a wide application background in the field of ultrafast optoelectronics.[4–6] One of the main applications is the generation of THz radiation by using femtosecond laser to trigger a GaAs photoconductive antenna (PCA). At present, all GaAs PCAs are operated with the linear mode. Although some of the work is done by using the plasmonic contact electrodes to obtain higher output power,[7,8] but overall, its terahertz radiation intensity is still relatively small, which limits the application of PCA.[9–11]

Under different dc or pulsed bias voltage and trigger light conditions, GaAs PCAs have two distinct operating modes, namely, the linear operation mode and the nonlinear operation mode (also known as high-gain quenched mode). The characteristics and physical essence of the linear operation mode are as follows: for each incident photon absorbed by GaAs PCA, an electron–hole pair is generated at most, without the multiplier effect of photo-generated carriers. When the bias electric field and trigger light energy of GaAs PCA are both above the thresholds, it will work in a nonlinear operation mode. Its typical feature and physical manifestation is the avalanche multiplier effect for the carriers, which is equivalent to 10^3–10^5 electron–hole pairs for each incident photon absorbed by GaAs PCA, and is manifested as avalanche photo-conductance behavior. Obviously, the output power capacity of GaAs PCA in the nonlinear operation mode is much higher than that in the linear operation mode. So far, there are no reports of THz waves generated by using femtosecond laser pulses to trigger GaAs PCA in the nonlinear operation mode.

We have verified theoretically and experimentally that under certain conditions the nonlinear model of GaAs PCA can be transformed into the quenched model of the photon-activated charge domain (PACD).[12–14] In other words, firstly, GaAs PCA is triggered under the threshold condition of nonlinear mode to cause carrier avalanche multiplication. Then the external conditions needed to maintain the carrier avalanche multiplication are destroyed and the carrier quickly exits the nonlinear mode and enters the linear mode. Finally, the GaAs PCA is shut off naturally in a very short time due to the depletion of the carriers, and the obvious locking-on waveform no longer appears, and the GaAs PCA will exhibit a linear avalanche photo-conductance. The quenching mode of the PACD, which reduces the holding time of the locking-on effect to a few nanoseconds, and can generate strong THz emission under femtosecond laser trigger. This is the GaAs PCA with avalanche multiplication mechanism.

Compared with the linear mode, the power capacity of the ultrafast electric pulse output from the GaAs PCA with PACD quenched mode can be greatly enhanced due to the avalanche multiplication effect of carriers. According to the current surge model, the THz electric field intensity of GaAs PCA is directly proportional to the first derivative of the elec-

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tric pulse to time.[12,13] Therefore, it is feasible to obtain the strong THz radiation by using the PACD quenched mode of GaAs PCA.[14]

In this paper, the THz radiation characteristics of GaAs PCA with electrode gap of 0.927 mm are studied in linear operation mode and PACD quenched mode respectively. Compared with the linear operation mode, the intensity of the THz wave radiated by GaAs PCA can be greatly enhanced due to the avalanche multiplication effect of carriers in the high-gain quenched mode.

2. Experiment setup

In order to detect both the THz waveform and the photocurrent flowing through the GaAs PCA at the same time, an oscilloscope (LeCroy WaveMaster 806Zi-A, 6 GHz bandwidth, 4×40 GS/s max sample rate) is used in the GaAs PCA loop and the bandwidths of the transmission line and attenuator are 18 GHz. The THz time-domain spectroscopy system (THz-TDS) is used to detect the THz radiation by the GaAs PCA. The schematic diagram of the experimental setup is shown in Fig. 1. The central wavelength of the pump laser is 800 nm, the repetition rate is 1 kHz, and the pulse width is about 100 fs. The laser spot diameter is about 1.34 mm, which completely covers the antenna gap. A 10 pF ceramic capacitor is charged by a 10 kV high-voltage dc source through a 1 MΩ resistor, which provides enough energy for the GaAs PCA to achieve avalanche multiplication, and quickly realizes the quenching of the nonlinear mode of the GaAs PCA.[15,16] The output electrical impulses through the GaAs PCA are attenuated by a 60 dB attenuator and recorded by the oscilloscope. By using a pump laser with a constant energy and different bias electric fields of the GaAs PCA, the THz radiation characteristics of the GaAs PCA in different operation modes are investigated.

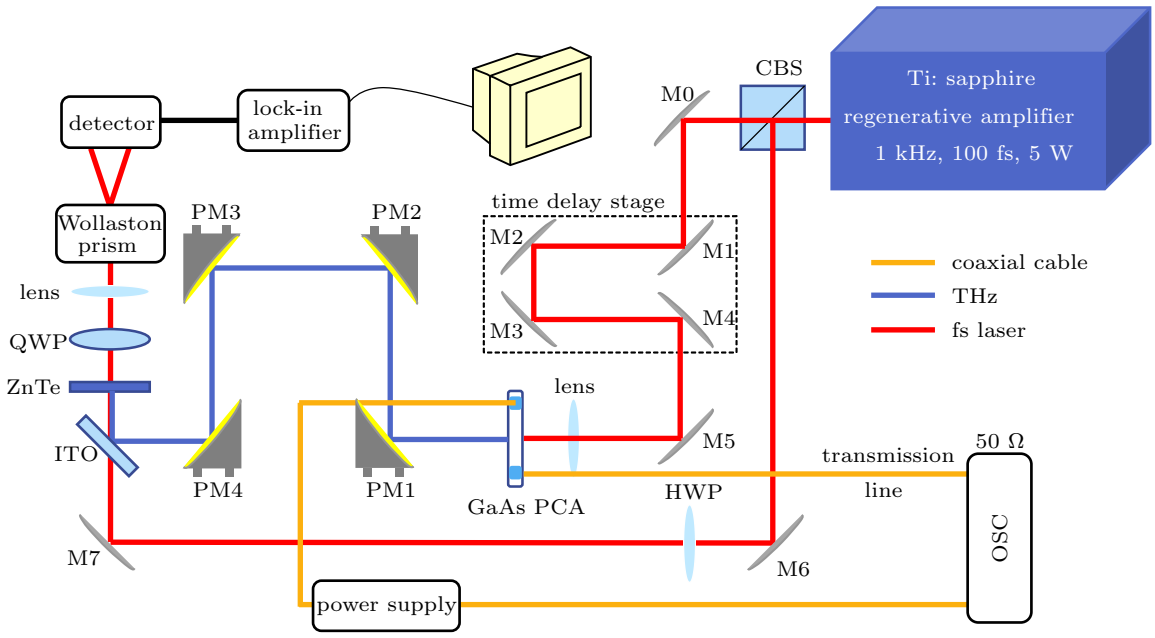


Fig. 1. The schematic of a THz-TDS with photocurrent detection function.

3. Results and discussion

3.1. Characteristics of the THz radiation in linear operation mode

When the pump laser energy is 1 μJ, and the bias electric field of the GaAs PCA is below its threshold, it works in the linear operation mode. The main feature is that each photon absorbed by the GaAs material induces at most one electron–hole pair, the conductivity of the material has a linear relationship with the photon flux on the GaAs PCA. The bias voltage of the GaAs PCA is 500 V, 1000 V, 1500 V, 2000 V, 2500 V, and 3000 V, respectively, and the corresponding bias electric field is 5.39 kV/cm, 10.79 kV/cm, 16.18 kV/cm, 21.57 kV/cm, 26.97 kV/cm, and 32.36 kV/cm. The corresponding electric pulse waveform is obtained by the single trigger mode, as shown in Fig. 2. With the increase of the bias electric field, the electric pulse waveform in the transient process of GaAs PCA increases and the maximum output electric pulse voltage is 55.7 V. However, due to the bandwidth limitation of the transmission line, the rising edge of the output pulse is about 74.2 ps, the output electrical pulse width is about 835.6 ps. Because the GaAs PCA works in the linear operation mode, its instantaneous on-resistance is large, which results in a low voltage conversion efficiency of up to 1.86%.

Then the THz time domain waveform is detected by using the THz-TDS, the results are shown in Fig. 3. With the increase of the bias electric field, the THz radiation field is also increased.

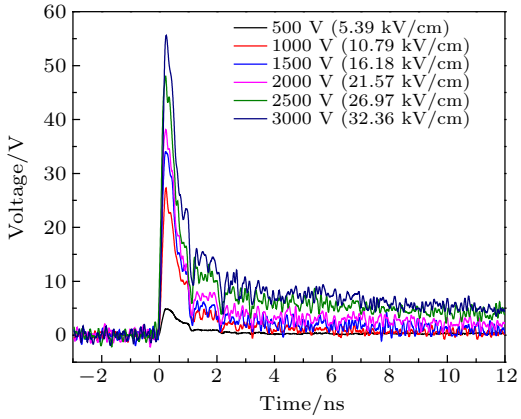


Fig. 2. Electric pulses of GaAs PCA under different bias electric fields.

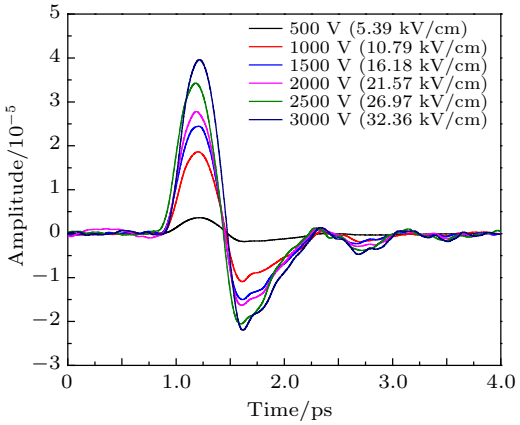


Fig. 3. Terahertz time-domain spectra under different bias electric fields in linear mode.

3.2. Characteristics of the THz radiation in PACD quenched mode

When the bias electric field and the trigger laser energy are higher than their thresholds, the GaAs PCA will work in a nonlinear operation mode, as shown in Fig. 4. Comparing with the linear mode in which only one electron–hole pair is generated when one photon is absorbed, the high-gain mode can produce as many as 10^3–10^5 electron–hole pairs because of the avalanche multiplication effect. When the bias electric field exceeds 32.36 kV/cm, the electric pulse begins the avalanche multiplication, and the output ultrafast electric pulse amplitude and power capacity exceed the linear increase. When the bias electric field is greater than or equal to 33.44 kV/cm, the avalanche multiplier effect of the photo-induced carriers is formed, and then the quenched mode of PACD is entered. The amplitude of the output electric pulse is 157 V, and the pulse width is about 3.69 ns. When the bias electric field is 34.52 kV/cm, the amplitude of the output electric pulse is 518 V, and the pulse width is about 2.84 ns.

Based on the characteristics of the linear and nonlinear operation modes and the principle of the test circuit used in the experiment, the multiplication rate can be proposed to characterize the degree of the GaAs PCA operated with the high multiplication operation mode as follows:

$$M = N_{\mathrm{g}}/N_{\mathrm{o}}, \tag{1}$$

where M is the multiplication rate, N_{g} is the number of photo-generated carriers generated in the GaAs material and crossing the antenna gap to form current in the circuit, and N_{o} is the number of photons in the pump laser. The N_{g} is expressed as follows:

$$N_{\mathrm{g}} = \int I\mathrm{d}t/e = S/(R_{\mathrm{g}} \cdot e), \tag{2}$$

where S is the area under the electric pulse waveform detected by the oscilloscope, R_{g} is the internal resistance of the oscilloscope (50 Ω), and e is the electron charge. The total charge is obtained by integrating the current with time, and the number of photo-generated carriers of the transition GaAs PCA is obtained. It is expressed as follows:

$$N_{\mathrm{o}} = \frac{E\lambda}{hc}, \tag{3}$$

where E is the pump laser energy, λ is the center wavelength of the laser, h is the Planck constant, and c is the speed of light. However, not all photo-generated carriers can be absorbed by the GaAs PCA. The actual situation is that the multiplication rate under the linear mode is much less than 1, indicating that some of the photo-generated carriers are compounded inside the GaAs material. Through the calculation of the above formula, the multiplication rates of the bias voltages of 3000 V, 3100 V, and 3200 V are obtained respectively. The final results are shown in Table 1.

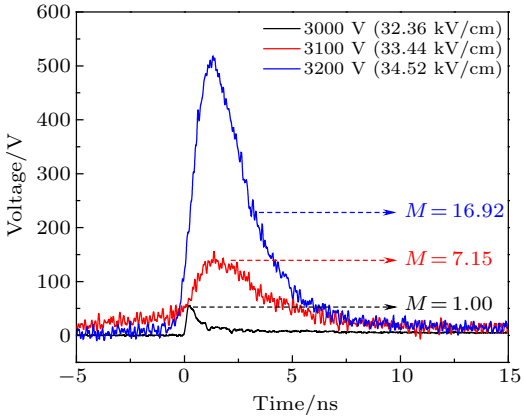


Fig. 4. Electric pulse curves of GaAs PCA in linear mode and high-gain quenched mode.

Table 1. The multiplication rate and THz radiation in different working modes.

Biased voltage	3000 V (32.36 kV/cm)	3100 V (33.44 kV/cm)	3200 V (34.52 kV/cm)
Multiplication rate	1	7.15	16.92
THz_{pp} amplitude	6.16×10^{-5}	6.02×10^{-5}	2.58×10^{-4}
THz_{pp} amplitude normalized	1	0.98	4.19

The THz radiations in different operation modes of GaAs PCA are detected by using the THz-TDS, as shown in Fig. 5. The THz peak-to-peak amplitude of the linear operation mode is about 6.15×10^{-5} when the bias voltage is 3000 V, and the THz peak-to-peak amplitude of the PACD quenched mode is about 2.58×10^{-4} when the bias voltage is 3200 V, so the peak-to-peak value of THz field radiated by the PACD quenched mode is about 4.19 times of that by the linear mode. The 3100 V is in the critical zone from linear operation mode to PACD quenched mode and the corresponding output electrical pulse is extremely unstable.

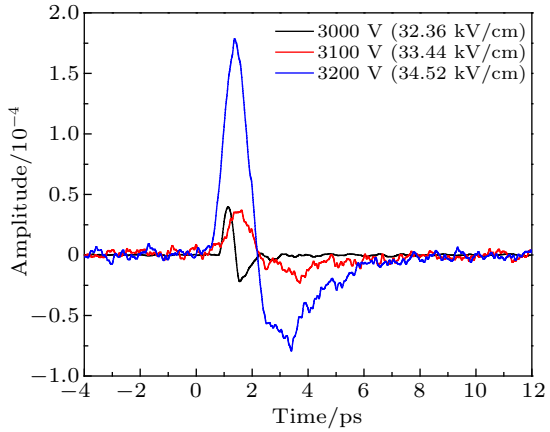


Fig. 5. The THz time-domain waveforms in different operation modes.

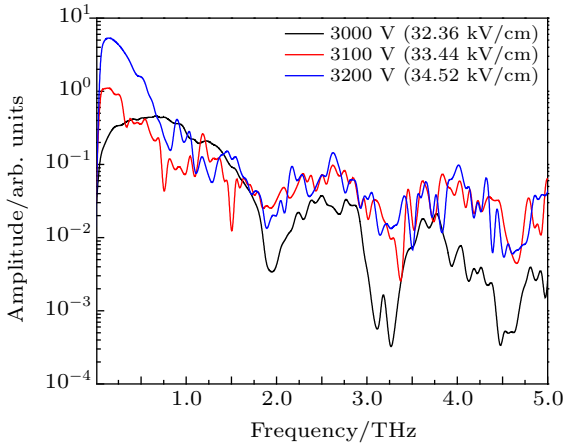


Fig. 6. The THz spectra from high-gain quenched mode and linear mode, the corresponding bias voltages are 3200 V, 3100 V, and 3000 V, respectively.

Finally, the THz spectra under different bias electric fields are obtained by fast Fourier transform (FFT), as shown in Fig. 6. When the GaAs PCA is working in the linear operation mode, the peak amplitude of the spectrum is about 0.48 (arb. units), the effective spectral width is 0.1–2.5 THz, and the center frequency is about 0.82 THz. When the GaAs PCA works in the PACD quenched mode, the peak amplitude of the spectrum increases by about 11.16 times compared to the maximum value in the linear mode.

4. Conclusion and perspectives

In summary, a high-performance THz radiation source based on the PACD quenched mode of GaAs PCA is presented. We experimentally obtain the THz time-domain spectra of the GaAs PCA in different operation modes, and the PACD quenched mode is achieved at the bias electric field of 34.52 kV/cm. The results indicate that the amplitude of THz wave radiated by GaAs PCA can be greatly enhanced due to the avalanche multiplication effect of carriers in the PACD quenched mode. When the multiplication ratio is 16.92, the peak-to-peak amplitude of THz radiated in the PACD quenched mode is about 4.19 times of the maximum peak-to-peak values in the linear mode. In fact, we have experimentally realized a nonlinear GaAs PCA with a carrier multiplier of 10^3, and are currently in the process of preparing the new antenna system, which will be reported in the near future.

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