A High Performance Terahertz Photoconductive Antenna Array Detector With High Synthesis Efficiency

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A 2 × 2 terahertz photoconductive antenna (PCA) array detector with high efficiency synthesis characteristic that improves the signal-to-noise ratio (SNR) of the detected signals has been reported in this paper. By processing the substrate material through a special micromachining process, the current signal generated by the adjacent antenna elements as opposed to that generated by the antenna gap is eliminated. Experiments show that the amplitude of the current signal output by the PCA array detector is consistent with the amplitude of the synchronous superposition of the current signals output by antenna elements, and the synthesis efficiency of the device achieves 93.7%. At the same time, the antenna array detector has low current noise, and its highest SNR is 62 dB under the excitation of different light energy, which is related to the number of antenna array elements.

Keywords: terahertz wave, antenna array, signal-to-noise ratio, synthesis, reverse current

INTRODUCTION

There are mainly two ways to detect terahertz (THz) time-domain waveforms: electro-optic (EO) crystal and photoconductive antenna. The principle of the former is based on the Pockels effect of crystals [1, 2]. A thinner EO crystal can provide a wider spectrum, but at the same time it leads to a decrease in detection sensitivity [3]. Compared with the photoconductive antennas, the EO detection requires more optical elements, higher cost and larger system size. THz waves detection by PCAs is the inverse process of the THz waves generation by PCAs. The performances of large spectral width, small size and ease of use make photoconductive antennas attractive for commercialization. In addition, pasting a silicon lens on the back of antennas will improve the detector's ability to collect THz waves and obtain a higher SNR [4]. Although a single THz PCA has been widely used in THz time-domain spectroscopy systems, it still has shortcomings in detecting weak terahertz signals and improving the SNR. In theory, connecting multiple PCAs in parallel to form a PCA array detector can make use of the THz electric field as much as possible to improve the SNR and detection sensitivity of the PCA array detector. Although the PCA array detector with hundreds to thousands antenna elements have been proposed and developed [5, 6], the synthesis efficiency of PCA array was not discussed in detail in the previous work, which is important to improve the detection efficiency. When the PCA array is used as a detector, it faces the same problem when it is used as an emitter. That is, the photo-generated carriers generated in the substrate materials between adjacent antennas move directionally under the action of the terahertz electric field, forming a current opposite to the current generated in the antenna gap, the reverse current will reduce the generation efficiency of THz
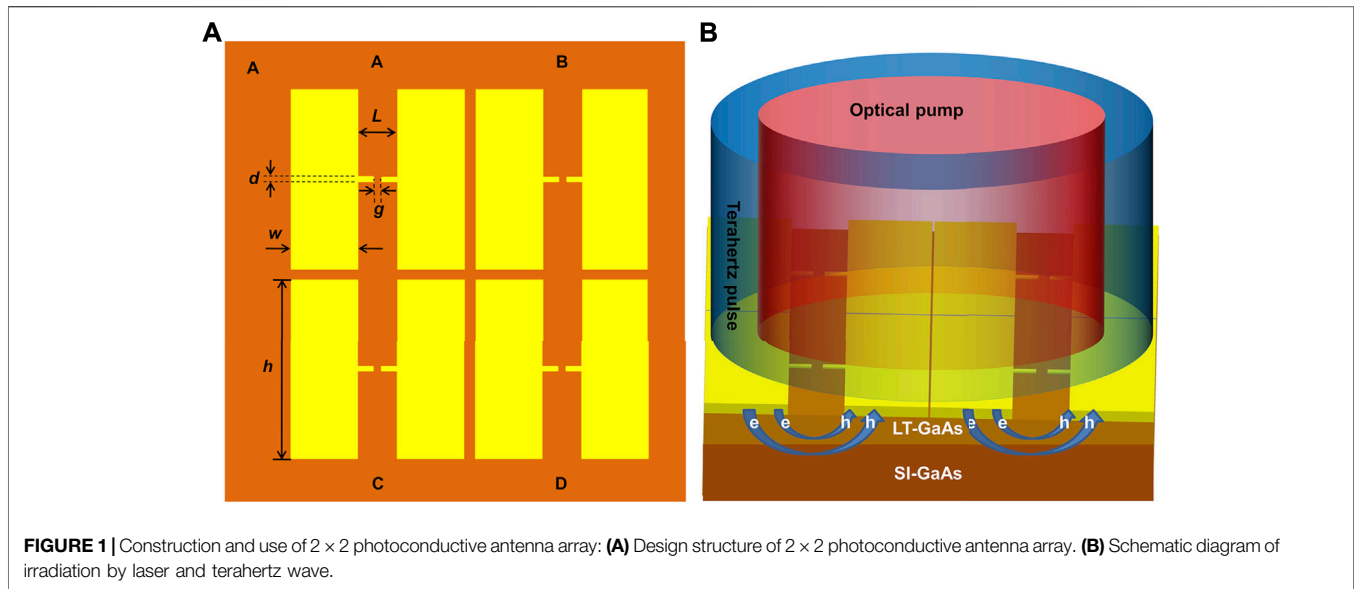
FIGURE 1 | Construction and use of 2 × 2 photoconductive antenna array: **(A)** Design structure of 2 × 2 photoconductive antenna array. **(B)** Schematic diagram of irradiation by laser and terahertz wave.

waves. The same phenomena will also reduce the synthesis efficiency of the PCA array detector [7]. At present, techniques to avoid the reverse current between adjacent antenna elements include employing shielding substrate between adjacent elements or using a micro-lenses array to split and focus the probe beams on the gaps [8, 9]. However, electrons transition from the valence band to the conduction band with the excitation of laser, the electrons generated in the antenna gap still can move to other antenna gaps due to the diffusion motion and the drift motion in response to the THz electric field. Therefore, these solutions cannot fundamentally solve the problem of reverse current between antenna elements.

In this work, a THz PCA array detector that eliminates the reverse current between the adjacent antenna elements is designed and fabricated, and its outstanding synthesis efficiency and signal-to-noise ratio have been demonstrated by comparing with a single antenna element.

ANTENNA DESIGN AND EXPERIMENTAL SETUP

Antenna Design

The structure diagram of the 2 × 2 PCA array detector is shown in **Figure 1A**. Its substrate is low-temperature-grown GaAs (LT-GaAs) with a thickness of 1 μm grown on (100) semi-insulating (SI)-GaAs at 250°C using MBE system. AuGeNiAu electrodes were deposited on the substrate by e-beam evaporation, and was metalized by rapid annealing to form an ohmic contact. The antenna element has a dipole length (L) of 250 μm, a dipole gap (g) of 50 μm, a dipole antenna width (d) of 30 μm, an electrode width (w) of 370 μm, and an electrode length (h) of 990 μm. The activation area of antenna element is 0.03 mm × 0.05 mm and the distance between adjacent antenna elements is about 10 μm. The pickup circuit designed in the experiment can not only output the synthetic signal of a PCA array detector, but also
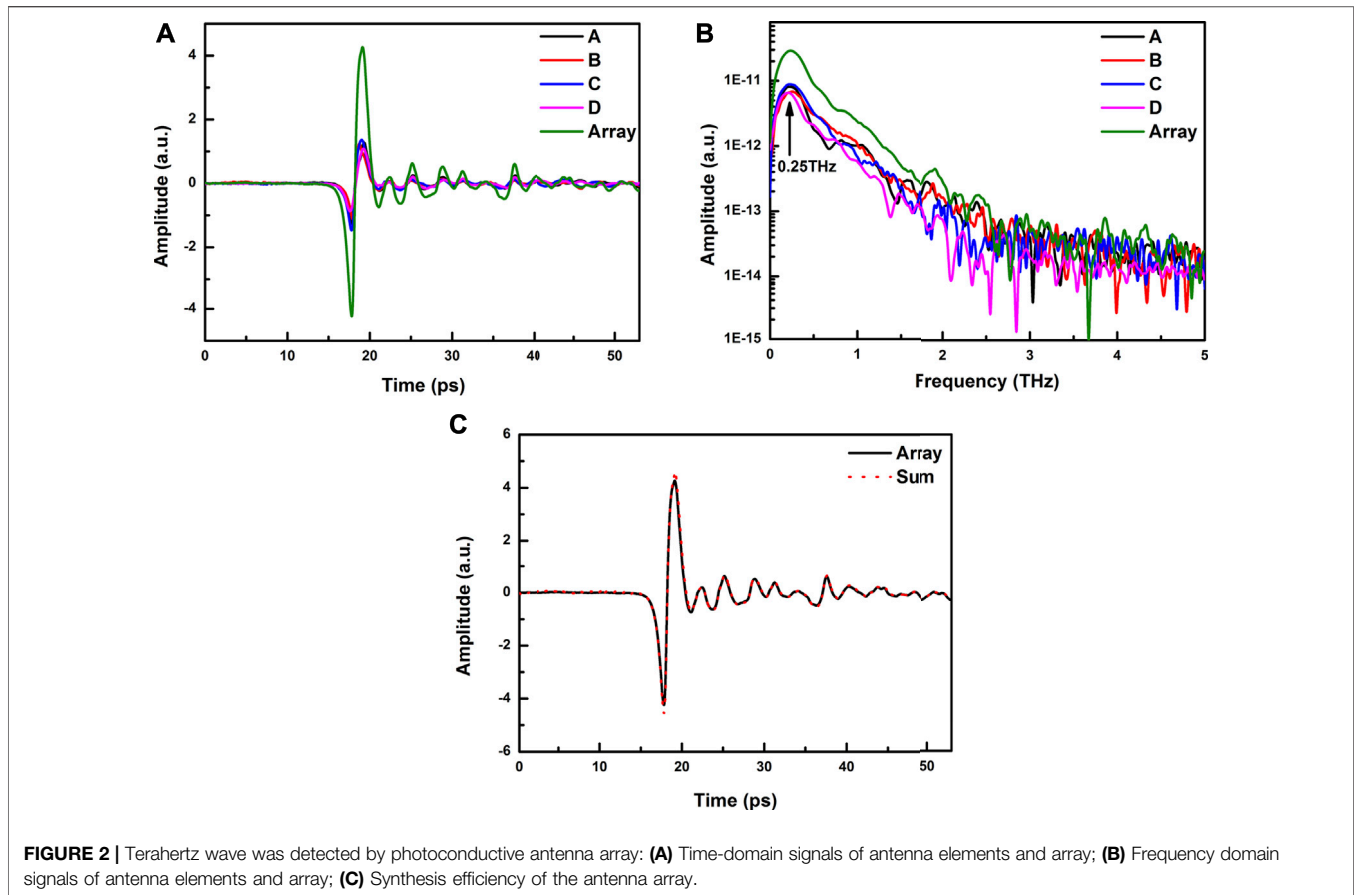
each signal of each antenna element by connecting different output ports.

Experimental Setup

In this paper, a THz time-domain spectroscopy system is used for measure the performance of the THz PCA array detector. A Ti: sapphire laser (Spectra-physics, MaiTai XF–1) with a center wavelength of 800 nm, a pulse width of 70 fs, and a repetition frequency of 80 MHz is used to excite the detector and the emitting antenna. The LT-GaAs PCA emitter with a gap of 150 μm was excited by a pump beam with the power of 200 mW and the voltage applied to the emitter was 300 V. The polarization direction of the THz electric field was parallel to the electrode gaps of the PCA array detector. The THz wave was focused on the PCA array detector through an off-axis parabolic mirror, and the diameter of focused THz beam measured by the knife edge method is 2.09 mm. The probe beam was focused to a spot with the diameter of 3 mm on the PCA array detector. The THz pulse and the laser pulse illuminate the PCA array detector vertically on the same side, as shown in **Figure 1B**. The output signal was recorded by a lock-in amplifier (SR830).

RESULTS

In order to explain that photo-generated carriers move freely throughout the semiconductor, an unmicromachined antenna array, which is similar to the interdigitated PCA detectors, was used for the verification experiment, we focused the laser with a power of 800 mW laser on the gap of one antenna element, and the diameter of the focus is 93 μm, the dark state resistance of the antenna was reduced from 1.1 GΩ to several MΩ. The resistance of other antenna elements in the unlit area was reduced by two orders of magnitude. In addition, the resistance between adjacent antenna elements was also reduced by two orders of magnitude,

FIGURE 2 | Terahertz wave was detected by photoconductive antenna array: **(A)** Time-domain signals of antenna elements and array; **(B)** Frequency domain signals of antenna elements and array; **(C)** Synthesis efficiency of the antenna array.

indicating that the photo-generated carriers generated in one antenna gap are not limited to movement in this antenna gap. On the contrary, due to the THz electric field, the reverse current can be formed between the adjacent antenna elements, which causes the synthesis efficiency of the PCA array detector decrease. Therefore, the masking process between the array elements for the interdigitated PCA array detector cannot prevent the reverse current between the array elements. In this experiment, we cutting the substrate material of adjacent elements by high power laser, and rearranged the elements with proper distance to eliminate the reverse current between adjacent antenna elements, and the photo-generated carriers generated by the antenna elements were restricted from moving to other antennas. When one antenna element was triggered by laser, the resistance of other antenna elements does not change.

When the PCA array detector was excited by the probe beam with the power of 120 mW, the THz time-domain waveforms of the each antenna element and PCA array detector are shown in **Figure 2A**. The amplitude of THz time domain waveform of the PCA array detector is far greater than that of the antenna elements A, B, C and D when they work alone. Due to the difference of the antenna elements' performance and the uneven irradiation of laser and THz waves, the amplitudes of the time-domain waveforms output from each element antenna are different. At the same time, there is a time difference among the waveforms of antenna elements, and the largest one is about

300 fs between A and D. The reason is caused by the optical path difference between the probe beam and the THz beam received by each antenna element.

In addition, the bandwidth of the PCA array is same as that of the antenna elements. The resonant frequency of the antenna elements is the same as that of the antenna array, and all of them are 0.25 THz, which is marked in **Figure 2B**.

The output photocurrent of the PCA array detector under THz wave excitation can be calculated as,

$$J_i(t) = e\mu \int E_{THz}(t')N_i(t - t')dt'$$

Where, e is the electronic charge, μ is the electron mobility of LT-GaAs, E_{THz} is the incident THz electric field, and $N_i(t)$ is the number of photo-generated carriers on the ith photoconductive antenna element. Due to the low carrier lifetime of LT-GaAs, $J_i(t) \propto E_{THz}$ [10, 11]. Since the PCA array detector is a parallel structure, the theoretical output current is:

$$J_{Array}(t) = \sum_{i=1}^{n} J_i(t)$$

Where n is the number of element antennas, $J_{Array}(t)$ is the current output by the PCA array detector, $\sum_{i=1}^{n} J_i(t)$ is the synchronous superposition of the output current when that each antenna element works independently, as shown in **Figure 2C**. But in the experiment, $J_{Array}(t)$ is always smaller

TABLE 1 | The amplitude and RMS noise of the time domain signal of the antenna elements and the array detector.

Antenna	Amplitude (A)	RMS noise (A)	SNR
Unit A	2.55624E-10	4.40724E-13	55
Unit B	2.37891E-10	8.67724E-13	49
Unit C	2.8485E-10	9.18471E-13	50
Unit D	1.96796E-10	7.01004E-13	49
Antenna array	8.5384E-10	6.45848E-13	62

$$i = \sqrt{4k_B T \overline{G_p(t)} \Delta f} = \sqrt{\frac{4k_B T}{\frac{h\nu L^2}{\eta_e\left(\tau_n\mu_n + \tau_p\mu_p\right)P_0}} \Delta f}$$

where k_B is the Boltzmann constant, T is operation temperature in kelvin, $h\nu$ is the energy of the probe photons, η_e is the photoconductor external quantum efficiency, τ_n and τ_p are lifetimes of electrons and holes in the semiconductor, μ_n and μ_p are electron and hole mobility, P_0 is the DC component of the envelope surface of the optical probe, and Δf is the detection bandwidth. The data of RMS noise of the antenna elements and PCA array are listed in **Table 1**. The noise of the array antenna is lower than the average noise of the elements, that means the PCA array plays the role in reducing the overall noise.

Figure 3A and **Figure 3B** show the time-domain waveforms and frequency-domain spectra detected by the PCA array detector under different probe power, the signal amplitude increases with the increase of the probe power. When the probe power is only 1 mW, the PCA array detector still shows a good response curve. When the probe power increases from 1mW to 120 mW, the THz linear increases. When the probe power is greater than 120 mW, the amplitude tends to be saturated. This saturation is caused by the screening effect,
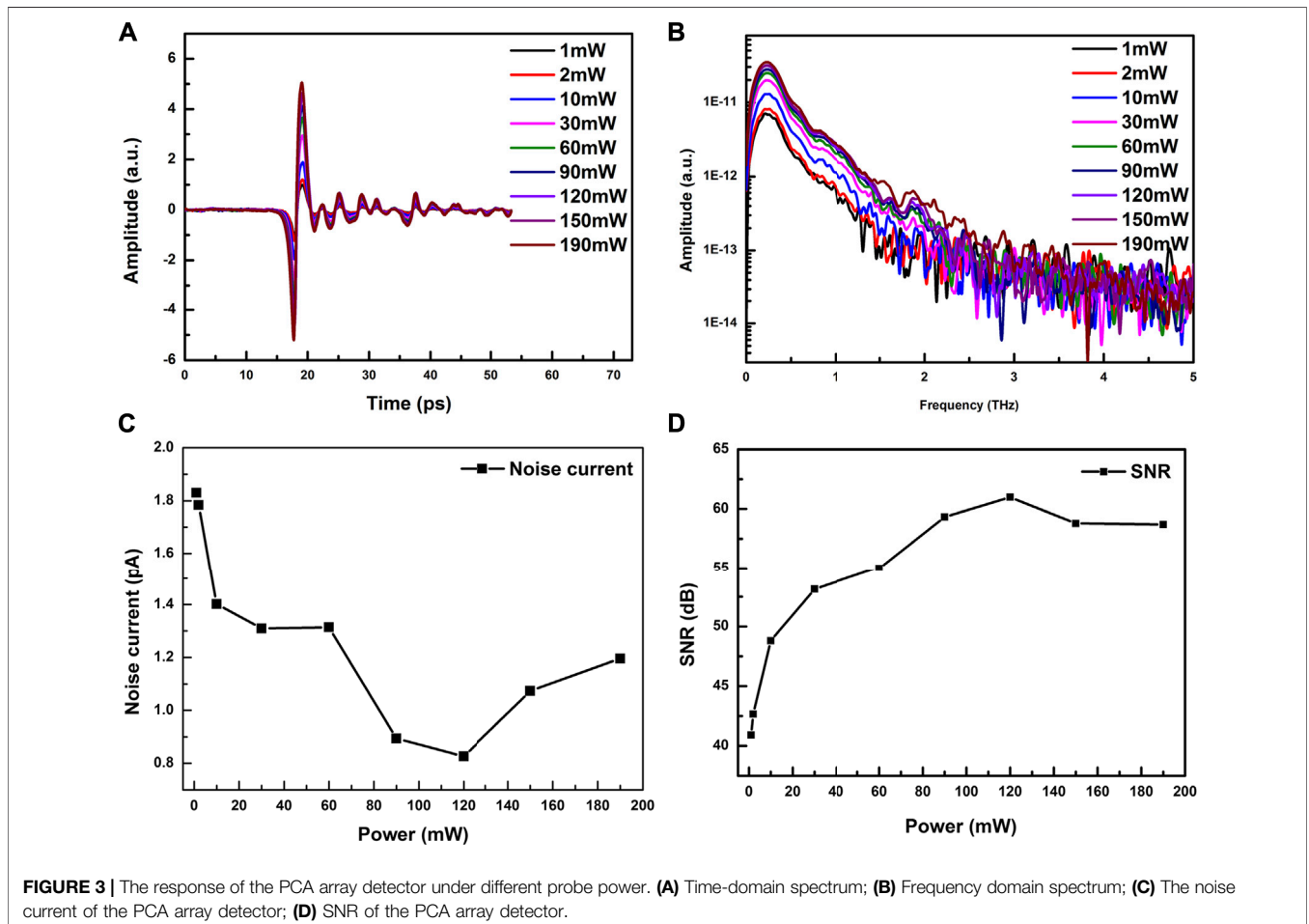
than $\sum_{i=1}^{n} J_i(t)$. Since there is no reverse current between adjacent antenna elements, $J_{Array}(t)/\sum_{i=1}^{n} J_i(t)$ is the synthesis efficiency of the antenna array, and its efficiency reaches 93.7% in this paper. Since there is no reverse current between adjacent antenna elements, the time-domain signal output by the PCA array detector is approximately equal to the synchronous superposition of the time-domain signal output by all antenna elements.

Generally, the output noise current of the photoconductive detector mainly comes from Johnson-Nyquist noise and shot noise [12, 13]. The root mean square (RMS) value of the noise current output form the symmetrically pumped PCA array detector is as follows:

FIGURE 3 | The response of the PCA array detector under different probe power. **(A)** Time-domain spectrum; **(B)** Frequency domain spectrum; **(C)** The noise current of the PCA array detector; **(D)** SNR of the PCA array detector.

which is related to the carrier density generated on the GaAs surface. The influence of the screening effect on the PCA emitter has been reported [14, 15], and its influence on the PCA detector can be expressed as [16].

$$E(t) = E_{THz}(t) - \frac{P(t)}{\alpha\varepsilon}$$

$E_{THz}(t)$ is the incident THz electric field, ε and α are the dielectric constant and geometric factor of GaAs, respectively. $P(t)$ is the polarization caused by the separation of electron-hole pairs, and it increases as the density of photo-generated carrier increases. The detection bandwidth of the PCA array detector is about 2.5 THz, which is the same as that of a single antenna. At the same time, the noise data of the detector was measured while the terahertz source was working normally. The SNR is proportional to the laser power when the probe power is lower than 120 mW, and the maximum SNR of the detector reaches 62 dB at 120 mW. When the power of probe beam exceeds 120 mW, the noise of the detection current increases and the SNR decreases due to the carrier shielding effect, as is shown in **Figure 3C** and **Figure 3D**.

CONCLUSION

In summary, we proposed a PCA array detector with high synthesis efficiency. According to experimental verification and theoretical analysis, the reverse current between the array elements is eliminated, and the synthesis efficiency of the PCA array detector reaches 93.7%. At the same time, the results show that the detector has a low noise, which is lower than the average noise of the elements. The bandwidth of the PCA array detector is about 2.5 THz. Within the probe power of 0–120 mW, the THz amplitude of detector shows a linear

growth trend. When the probe power exceeds 120 mW, the signal amplitude tends to be saturated and the current noise increases due to the carrier shielding effect. The detector has a maximum SNR of 62 dB at the probe power of 120 mW power. The concept of the proposed PCA array detector can be widely used in both large size and small size PCA array detector to improve its detection efficiency.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Conceptualization, WS; methodology, LH; formal analysis, ZW; data curation, MW and CL; writing—original draft preparation, ZW; writing—review and editing, WS. All authors have read and agreed to the published version of the manuscript.

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