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Intense Terahertz Pulses from Large-Aperture Antenna with Interdigitated Electrodes

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We fabricated a large-aperture photoconductive terahertz (THz) emitter array on a semi-insulating GaAs substrate. The device was composed of seven 1 cm^2 photoconductive antenna units having microstructured interdigitated electrodes with 10 μm lines and spaces. By illuminating it with amplified femtosecond optical pulses, a large THz field comparable to that obtained from conventional large-aperture photoconductive antennas was obtained at a bias voltage as low as 30 V. The coherent superposition of the output of the seven units was observed. [DOI: 10.1143/JJAP.45.L422]

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Large-aperture photoconductive antennas excited by amplified femtosecond optical pulses have been studied and used for the generation of intense terahertz (THz) pulses.[1–9] They can emit half-cycle or monocycle intense THz pulses with a large bandwidth, and have been used in real-time imaging,[5–9] time-resolved spectroscopy,[10,11] and other applications. Although the structure and usage of the conventional large-aperture antennas are simple, the requirement of a bias voltage as high as 10 kV or more has limited their usage. A practical issue concerns the use of a pulsed bias voltage, which is required to avoid electrical breakdown.[12] Pulsed voltage sources produce large electromagnetic noise, which degrades the data quality of the detected THz signals.

We fabricated a microstructured photoconductive antenna array with interdigitated electrodes that can overcome the limitations of a conventional structure. This device was operated employing a static bias voltage below 30 V, and composed of seven photoconductive antenna units. Moreover, this device was fabricated on a 2 inch semi-insulating GaAs wafer. The schematic of the entire emitter structure is shown in Fig. 1(a). Each unit had separate electrodes and could be operated independently. The structure of each unit is shown in Fig. 1(b). The size of each unit was $10 \times 10\,\mathrm{mm}^2$. It had an interdigitated electrode structure. The spacing between electrodes and the width of the electrodes were both 10 μm. The material of the electrodes was Ti, and the thickness was 200 nm. The electrode structure was fabricated by either a lift-off method or a dry etching method using SF_6. Similar results were obtained by both methods, and the experimental results shown below were obtained by the lift-off method. SiO_2 was deposited on the electrodes with a thickness of 500 nm by sputtering for the insulation between the electrodes and metal shadow masks. Shadow masks of Au(180 nm)/Ti(20 nm) were deposited on the SiO_2 layer to allow excitation light to irradiate only every other electrode spacing. This enables the constructive interference of the THz field obtained from the interdigitated electrode structure.

Our device structure essentially follows the approach of Yoneda *et al.*[13] and Dreyhaupt *et al.*[14] Yoneda *et al.* fabricated an interdigitated antenna array on diamond, which was excited by 248-nm optical pulses obtained from a high-power Kr*F excimer laser system. The emitter developed by

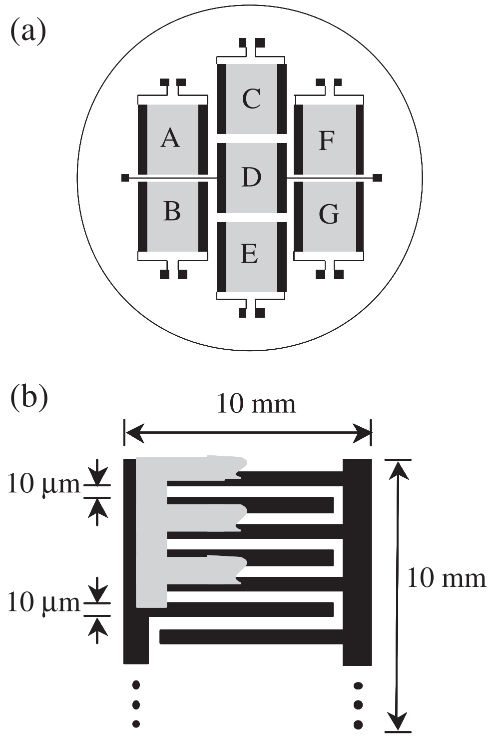

Fig. 1. (a) Schematic of THz emitter composed of seven photoconductive antenna units having interdigitated electrode structure. The units are labeled A–G for later reference. (b) Structure of electrodes and shadow mask of each unit.

Dreyhaupt *et al.* was much smaller than the present one and was excited by unamplified laser pulses. The emitter developed in this study was as large as those of conventional large-aperture antennas and was excited by amplified femtosecond Ti:sapphire laser pulses.

Since the field of THz radiation obtained from photoconductive antennas is saturated at a relatively small excitation fluence, the emitted field E_{THz} is expected to follow a simple scaling law:

$$E_{\mathrm{THz}} \propto A_{\mathrm{eff}} E_{\mathrm{bias}}. \tag{1}$$

Here, A_{eff} is the effective emitter area used for THz field generation and E_{bias} is the bias field applied between the electrodes. The bias field applied to the small spacing between electrodes can easily be increased up to 100 kV/cm, and a bias field of 500 kV/cm can be obtained using the state-of-the-art microprocessing technology. In contrast, the

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bias field of a conventional large-aperture antenna is limited at around 10 kV/cm due to discharge on the semiconductor surface. Although the effective emitter area of the microstructured antenna is about 25% of the entire area, it is easily scalable using large wafers. Thus, the microstructured antenna pumped by amplified laser pulses is the choice for the generation of intense broadband THz pulses.

The properties of the emitter were characterized by measuring the waveforms of the emitted THz field as a function of bias voltage and excitation light fluence. The results were compared with those of a conventional large-aperture antenna,[5] which had a 3-cm-spacing between electrodes. The antennas were excited by amplified 150 fs, 800 nm Ti:sapphire laser pulses at a repetition rate of 1 kHz. The pump beam had an almost Gaussian spatial profile and the $1/e$ beam diameter on the emitter surface was 18 mm. The center of the pump beam coincided with the center of the antennas. The emitted THz field was focused by a TPX lens of 98.3 mm focal length, and the field waveform was measured using an electrooptic sampling method employing a 1-mm-thick ZnTe crystal. The microstructured antenna was biased by a dc voltage up to 30 V, which corresponds to a bias field of 30 kV/cm. It was observed that the THz field becomes unstable above this voltage. The output THz field depended linearly on the bias voltage in the range below 30 V.

The waveforms of the THz field obtained from the microstructured and conventional large-aperture antennas under typical operation conditions are shown in Fig. 2. The thick line shows the THz waveform from the conventional antenna under a bias voltage of 6 kV and a pump fluence of 76 μJ/cm^2. The thin line shows the waveform from the microstructured antenna under a bias voltage of 30 V and a pump fluence of 7.6 μJ/cm^2. Both of these pump fluences are above the saturation level of each emitter. The saturation fluence of the conventional antenna was about 5 μJ/cm^2, which is consistent with that for the near-field screening[5] of a current surge model. The THz field from the microstructured antenna was observed to be saturated slowly around 0.5 μJ/cm^2 and above, which is attributed to the fact that the charge supply becomes insufficient at high excitation levels due to the CR time constants distributed in the interdigitated electrode structure. The peak THz field obtained from the microstructured antenna was about half of that obtained from the conventional antenna, as shown in Fig. 2, which is about seven times lower than that predicted using the scaling law. This discrepancy is attributed to the saturation due to insufficient charge supply as mentioned above. The waveform of the THz pulse from the microstructured emitter shows a monocycle profile, which is in contrast to the half-cycle pulse shape obtained from the conventional large-aperture antenna. The Fourier amplitudes of the temporal waveforms in Fig. 2 are plotted in Fig. 3, which reflect the difference in waveform. The spectrum from the microstructured antenna has a negligibly small Fourier amplitude at zero frequency and a peak at a frequency higher than that for the spectrum obtained from the conventional antenna. This difference is attributed to the effect of the electrode structure on the propagation of the THz waves.

We also measured the THz waveforms from each unit of the microstructured antenna array. For this measurement, the

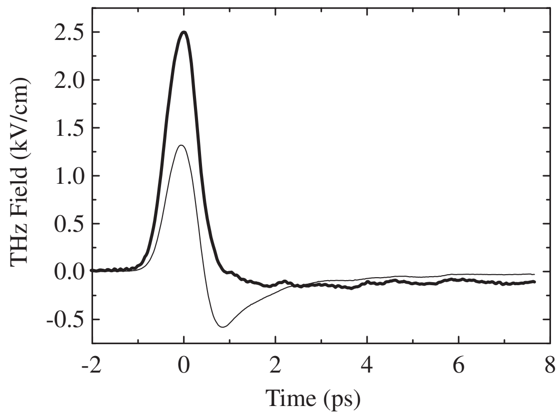

Fig. 2. THz field waveforms obtained from conventional large-aperture emitter (thick line) and microstructured antenna array (thin line) under typical operation conditions. The excitation fluence was over the saturation level, and the bias field was set at 2 and 30 kV/cm for the conventional and microstructured antennas, respectively.

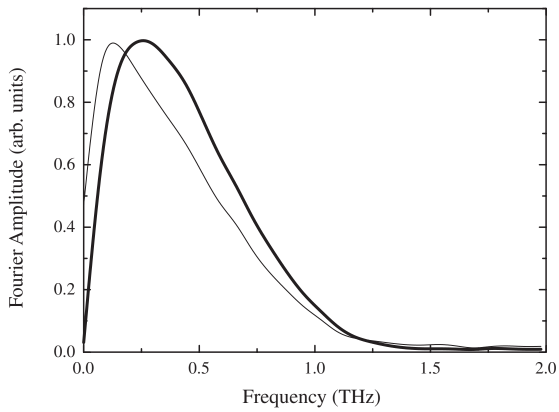

Fig. 3. Normalized Fourier amplitudes of THz fields obtained from conventional large-aperture emitter (thick line) and microstructured antenna array (thin line).

experimental setup was maintained except that only one of the seven units was biased. The obtained waveforms are shown in Fig. 4. The observed difference in waveform is attributed to the differences in the pump fluence and propagation geometry of the emitted THz pulses for each unit. The central unit (unit D) is pumped with the largest fluence, which leads to a high peak field and a fast decay of the waveform owing to near-field saturation[5] and faster carrier scattering. Figure 5 shows that the summation of these waveforms almost overlaps the waveform obtained from the seven units operated simultaneously. This observation confirms the coherent superposition of THz waves obtained from separate antennas. Note that this data were acquired under conditions different from those used in obtaining the data shown in Fig. 2. Since the present device setup allows the independent control of the amplitude and phase of the bias voltage of each emitter unit, unique applications, such as phase-sensitive THz pulse detection[7] and super-resolution THz imaging,[15] are expected.

In conclusion, a large-aperture microstructured photoconductive antenna array having interdigitated electrodes with 10 μm lines and spaces was fabricated on a semi-insulating GaAs substrate, and its properties were charac-

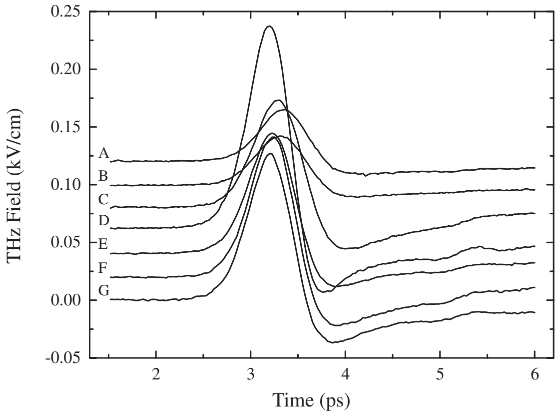

Fig. 4. Waveforms of THz pulses obtained from units A–G obtained by operating each unit separately. Each waveform is shifted by 0.02 kV/cm.

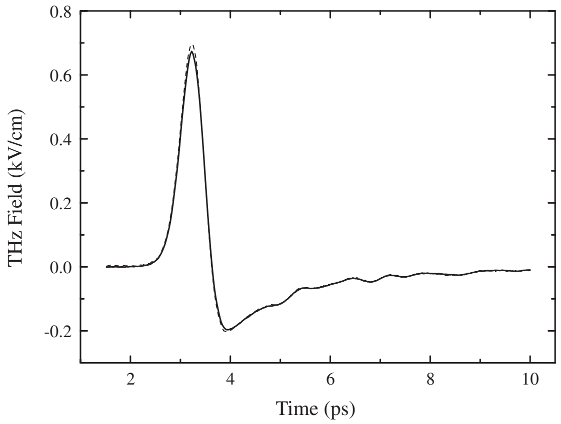

Fig. 5. The waveform of THz pulses obtained by operating the seven units simultaneously (thick solid line) is compared with the summation of the THz waveforms obtained from each unit separately (thin dashed line). The two lines almost overlap each other.

terized. The generation of THz pulses with a field amplitude comparable to those obtained with conventional large-aperture antennas was observed. The obtained field was not as high as that expected from a scaling law, and the properties are expected to be improved by optimizing the microprocessing procedure. The coherent superposition of the output THz field was observed.

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