Coherent synthesis of THz wave profiles

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***Abstract*—Coherent synthesis of THz wave spatial profiles was observed using real-time THz imaging. We used an array of photoconductive antennas pumped by femtosecond optical pulses as a THz wave source. Emitted THz pulses were focused and the spatial profile on the focal plane, which is a coherent superposition of output from each unit, was observed by real-time THz imaging using the EO sampling method. By inverting the bias voltage applied to the central unit of the antenna array, a super-resolution effect was observed, where the THz spot sizes was smaller than when a voltage was applied to all the unit in the same direction.**

Control of spatial profiles of THz waves is required for wider applications of THz waves in imaging, nonlinear optics, coherent control, and other areas. We used a photoconductive antenna array (Fig. 1) [1] as a THz wave source, and controlled the THz wave profile by controlling the bias voltages of the seven independently operated antenna units. The whole area of the antenna array was pumped by amplified femtosecond Ti:sapphire laser pulses at a repetition rate of 1 kHz. The pump intensity profile was almost Gaussian and had a $1/e$ radius of 4.6 mm. The emitted THz pulses were focused by a TPX lens ($f = 98.3$ mm) and the THz field profile on the focal plane was measured by real-time THz imaging using the EO sampling method [2]–[4]. Effects of nonuniformity of residual birefringence in the EO crystal (1-mm thick ZnTe) was corrected using a newly-developed method [5]. The distances between the emitter and the lens and between the lens and the EO crystal were both f.

When all the units were biased at 15 V in the same direction, we observed a Gaussian-like profile at $t = 0$, and a ring-like one at negative and positive times (Fig. 2(a)), which were similar to the results obtained using a conventional large-aperture photoconductive antenna [6]. The spot size (FWHM) at $t = 0$ was 4.4 mm. When the voltage applied to the central unit was inverted, a smaller spot size of 3.4 mm was observed at $t = 0$ (Fig. 2(b)).

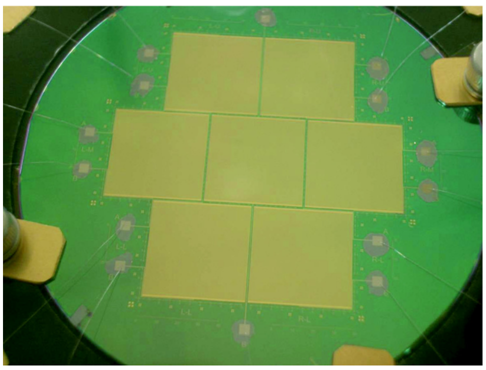

Fig. 1. Picture of the large-aperture antenna array, consisting of seven units of photoconductive antennas having interdigitated electrodes. Each unit has an area of 10 × 10 mm^2, and can be operated independently.

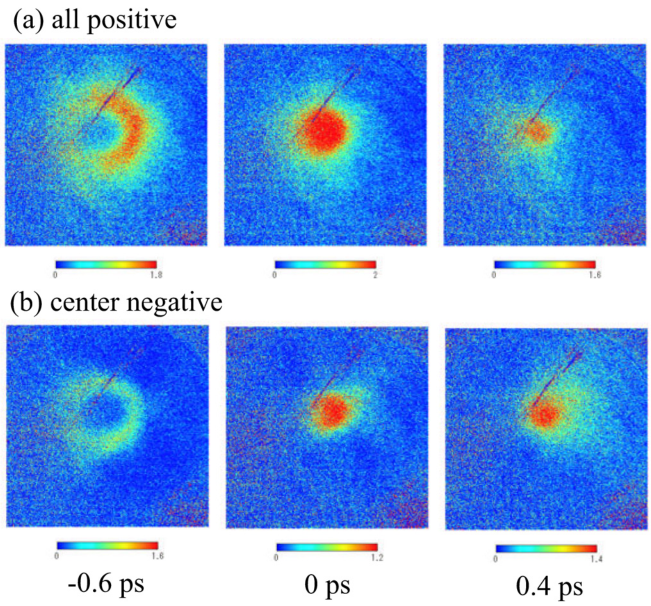

Fig. 2. Time-resolved spatial profiles of the focused THz electric field on the focal plane. The whole image size corresponds to an area of 20 × 20 mm^2. (a) The THz profiles obtained when +15 V was applied to all the units. (b) The THz profiles obtained when −15 V was applied to the central unit and +15 V was applied to the other units.

Frequency-resolved THz amplitude profiles were obtained by scanning the delay of the probe pulse and Fourier transforming the THz waveform at each pixel of the images (Fig. 3). It is clearly seen in these images that the THz spot sizes obtained by inverting the central unit voltage are smaller than those obtained when the applied voltages were all in the same direction. Annular profiles are also seen in images obtained with inverted central unit bias.

Since spot sizes obtained with all positive biases are almost diffraction limited [2], the present results show that THz field spot sizes smaller than the diffraction limit are obtained

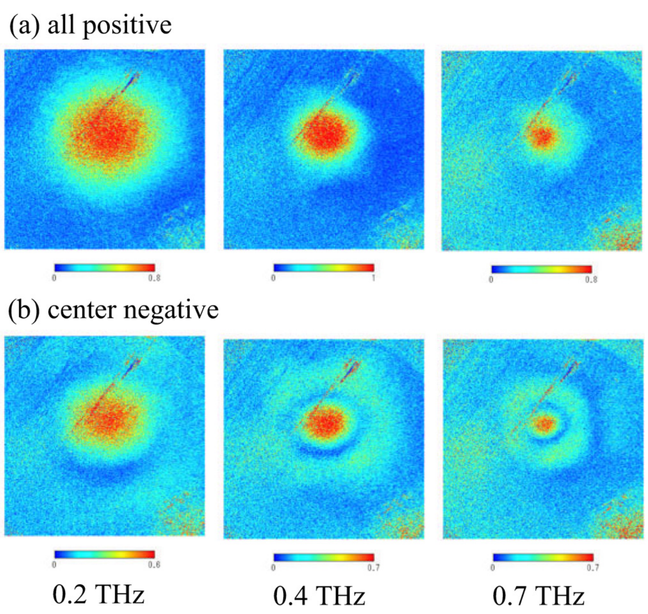

Fig. 3. Frequency-resolved spatial profiles of the focused THz electric field on the focal plane. Spatial distribution of the Fourier amplitude at each frequency is shown. (a) The THz profiles obtained when $+15$ V was applied to all the units. (b) The THz profiles obtained when -15 V was applied to the central unit and +15 V was applied to the other units.

by inverting the direction of THz waves emitted from the central part of the emitter. Super-resolution effects using annular spatial filter have been known [7]–[10], and studied for applications in microscopy and photolithography. The effect of inverted central bias is equivalent to that of an annular phase filter. The THz profile obtained with uniform bias, $E_u(\mathbf{r})$, has a Gaussian-like shape, while a profile of THz waves emitted from the central unit alone, $E_c(\mathbf{r})$, should have a Gaussian-like shape with a lower amplitude and a larger size. Since a THz profile obtained with inverted central bias, $E_i(\mathbf{r})$, can be calculated by

$$E_i(\mathbf{r}) = E_u(\mathbf{r}) - 2E_c(\mathbf{r}),$$

larger side lobes with inverted field direction and a smaller central peak are expected.

THz spot sizes of frequency-resolved images are plotted in Fig. 4 as a function of frequency. In the figure, spot sizes obtained from [2], [11]

$$w_0 = \frac{cf}{A\pi\nu}$$

is also shown, where w_0 and A are the $1/e$ radii of THz beam waist and pump intensity profile, and ν is the frequency. This equation neglects effects of increase in THz beam size at the lens due to diffraction, and is correct only in the high-frequency limit. The figure shows that the THz spot size under uniform bias is already diffraction limited and that we obtain super-resolution beyond the diffraction limit using inverted central bias.

In conclusion, we have observed super-resolution effects on the spot size of focused THz pulses emitted from a photoconductive antenna array composed of seven units which can be operated independently. By inverting the bias voltage applied to the central unit, coherent synthesis of output from the seven units leads to annular profiles and smaller spot sizes of the focused THz field. Putting the present results together with the previous observation on time-domain coherent superposition [1], it is shown that spatio-temporal coherent systhesis can be performed using THz emitter arrays.

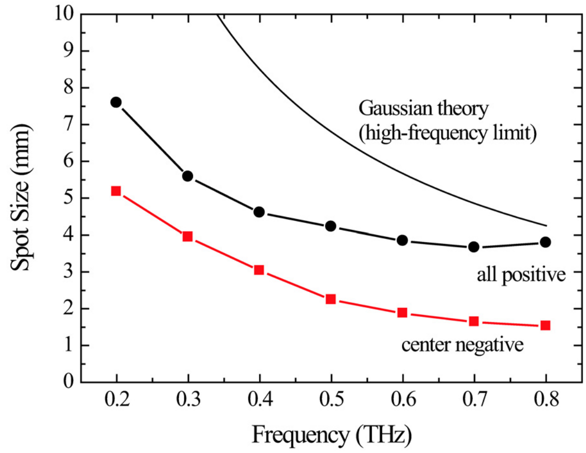

Fig. 4. THz spot sizes (FWHM) as a function of frequency. Calculation using a Gaussian theory neglects diffraction of the THz beam at the lens, resulting in overestimated spot sizes at low frequencies.

Acknowledgment

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