Real-Time Calibrated Terahertz Field Profile Imaging

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A method of real-time terahertz imaging with built-in field calibration is presented for measurement of spatial profiles of electric field of terahertz pulses. This method has been applied for the characterization of a photoconductive terahertz-wave emitter with interdigitated electrodes.

I. Introduction and Method

IMAGING of terahertz wave spatial profiles in short time is required in many application fields of terahertz waves. Terahertz imaging method enabling calibrated measurements of terahertz field profile is especially useful in characterization of terahertz-wave emitters and other terahertz devices. We have previously reported a real-time terahertz imaging technique which enables correction for image deformation due to intrinsic birefringence of the electro-optic (EO) crystal used in the EO sampling method[1]. We present here a modification of the method which enables real-time calibrated measurements of terahertz field profiles.

The measurement is based on the EO sampling method near zero bias[2], and a quarter-wave plate (QWP) and a rotatable polarization analyzer are incorporated[1,3]. A schematic of the setup is depicted in fig. 1. Power of the probe light transmitted through the EO sampling setup is detected by a CCD camera. In this method, the polarization component of the probe light generated by the EO effect, which is $\pi/2$ phase-shifted from the incident probe field, is reversely phase-shifted using the QWP and then mixed with the incident probe light with a ratio determined by the analyzer rotation angle. The controllable mixing is only possible by the use of the wave plate. The detected light power with (I) and without (I_b) terahertz field is expressed as

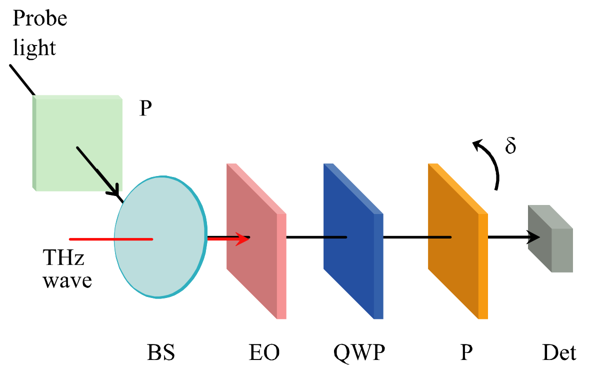


Fig. 1. Experimental schematic of the polarization optics for the terahertz electric field detection. BS: beamsplitter, EO: EO crystal, QWP: quarter-wave plate, P: polarizer, Det: light detector. In the actual measurement, components for imaging are added and the spatial distribution at the EO crystal is imaged onto the detector surface.

$$I = [(\delta + \theta + \Gamma)^2 + \eta] I_0, \qquad (1)$$

$$I_b = [(\delta + \Gamma)^2 + \eta] I_0. \qquad (2)$$

In these expressions, δ is rotation angle of the analyzer, 2θ the phase shift of the probe light due to the EO effect induced by the terahertz field, η a scattering factor, I_0 the incident light power, and Γ the phase shift due to residual birefringence of the EO crystal. All of them except δ can be independent at each pixel of the CCD camera. The expressions above are only valid when $|\delta|, |\theta|, |\Gamma| << 1$.

In the experiments, I_b is first measured as a function of δ by turning off the terahertz waves. Then parameters Γ and η are obtained by fitting the data to a quadratic function, which provides the calibration curve for θ at each pixel of the image since δ and θ have the same effect in eq. (1). The electric field can be calculated as

$$E_{\mathrm{THz}} = \frac{\lambda}{\pi r_{41} n^3 L}\theta = 28.8 \times \theta \ \ \mathrm{kV/cm}.$$

Here, r_{41}, n, and L are the electro-optic coefficient, refractive index, and thickness of the crystal and λ is the wavelength of the probe light. (L = 1 mm was assumed for the numerical expression.) This procedure is schematically depicted in fig. 2. After this procedure, the terahertz waves are turned on, and δ is fixed so that $\delta + \theta + \Gamma$ has the same sign at all pixels and all delay times. Then the probe power is measured, and phase shift θ is calculated from the observed data using the calibration curve.

II. Results

This method was applied to characterization of a newly fabricated large-aperture photoconductive emitter device with

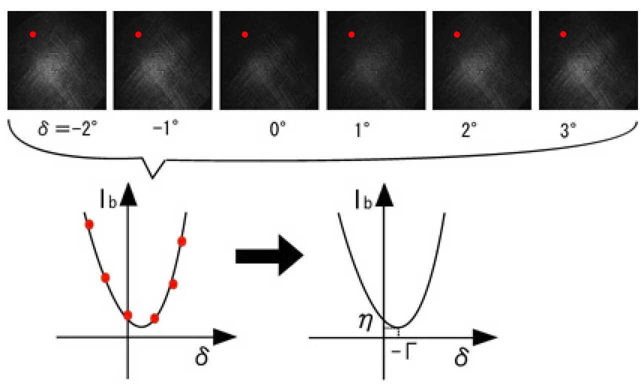
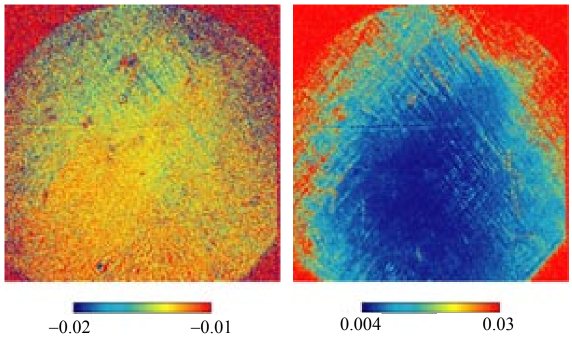


Fig. 2. Schematic of the determination procedure of the calibration curve of electric field from the measurement.

978-1-4244-5417-4/09/$26.00



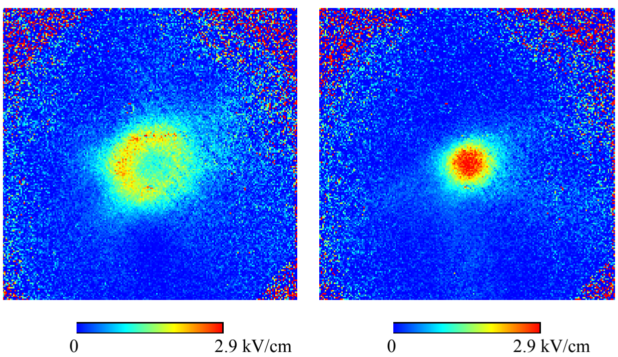
(a) (b)

Fig. 3. Spatial distribution of (a) phase shift due to residual birefringence Γ, and (b) scattering factor η. The area of the images is the same as those of fig. 4.

interdigitated electrodes[4]. The emitter was irradiated by amplified 150-fs, 800-nm Ti:sapphire laser pulses, and the terahertz waves emitted from the device were focused onto an EO crystal with an f/4.5 focusing lens. The EO crystal was a 1-mm-thich (110) ZnTe.

First, parameters Γ and η were obtained following the procedure above. Results are shown in fig. 3. It was found that with this crystal Γ was distributed mostly between –0.015 and –0.010, and η between 0.004 and 0.008. The crystal used in the present measurement shows much less birefringence than that used in the previous report[1], resulting in better sensitivity of the measurements and better image quality. With this crystal, phase shift of θ = 0.003, corresponding to terahertz electric field of 100 V/cm, was clearly observed in real time. Analyzer rotation angle δ was set at 0.052 rad for the following terahertz field imaging.

Performance of a newly fabricated terahertz-wave emitter was studied using the present method. The emitter was a large-aperture photoconductive antenna with interdigitated electrodes[4]. Fabrication processes and device structure have been modified from the previously reported emitter[5]. The active area of the emitter was 448 mm^2, and the electrode gap was



(a) (b)

Fig. 4. Time-resolved field profiles of a focused terahertz pulse at (a) –0.4 ps and (b) 0 ps. The image size of the CCD is 400 x 400 pixels, which corresponds to a physical area of 20 x 20 mm^2 at the EO crystal.

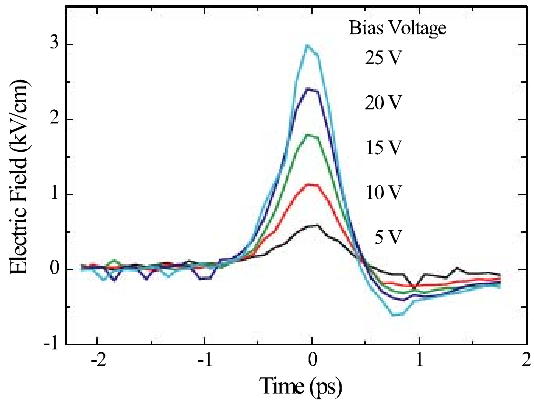


Fig. 5. Bias voltage dependence of the temporal waveforms of the terahertz pulses.

10 μm. The emitter was irradiated by 180 fs, 800 nm optical pulses at a repetition rate of 1 kHz. Pump fluence was set at 5.5 $\mu J/cm^2$ in the measurements reported here. Emitted terahertz pulses were focused by a f = 98.3 mm TPX lens onto the EO crystal, and the terahertz field profile on the EO crystal was obtained using the procedure described above. Examples of images of the field profile are shown in fig. 4, which were obtained at a bias voltage of 25 V. Time zero is the delay time when the field peak was obtained. Peak field observed was 3.0 kV/cm, which corresponds to about 0.1 rad phase shift of the probe light. The obtained terahertz field was larger by a factor of three than obtained from the previously reported emitter[5].

Bias voltage dependence of the temporal waveforms of the emitted terahertz pulses are plotted in fig. 5. For this purpose, terahertz images were obtained at every 100 fs of probe delay, and the average of field in the central area of 10 x 10 pixels was extracted from each image. It is seen that the peak field is almost proportional to the bias field, and growth of a negative overshooting at large bias voltages is observed. These features have also been observed with the previous emitters[5].

III. SUMMARY

We have developed a method of real-time imaging of terahertz field profiles with field calibration. Electric field less than 100 V/cm was clearly observed using the method. The method was used for the characterization of a newly fabricated photoconductive emitter.

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