EO sampling methods for real-time THz imaging

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***Abstract*—We have developed a method of real-time terahertz (THz) imaging in which image deformation due to nonuniformity of residual birefringence in the electro-optic (EO) sampling crystal is corrected. Real-time THz imaging using intense THz pulses and two-dimensional EO sampling can suffer from birefringence nonuniformity of the EO crystal since the birefringence is explicitly used for the linear detection of the THz field. In the proposed method, the distribution of the residual birefringence of the EO crystal is measured and used for image correction. Deformation-free images of the spatial profile of a focused THz pulse were obtained.**

Imaging using terahertz (THz) radiation has been attracting considerable interest since the demonstration by Hu and Nuss [1]. Use of intense THz pulses and a two-dimensional electro-optic (EO) sampling method enables real-time acquisition of THz images [2]–[10]. Typical setup uses amplified femtosecond mode-locked Ti:sapphire laser pulses to pump a large-aperture photoconductive antenna for generation of intense THz pulses. Detection of spatial distribution of THz electric field is made using a large EO crystal, an expanded probe beam, and an optical image detector. Two configurations of the optical setup have been used for the detection of the polarization change of the probe light due to the EO effect induced by the THz field. One configuration is composed of crossed polarizer and analyzer [2]–[5], and an EO crystal between them. Detection of signal that is linear to the THz field is enabled using residual birefringence of the EO crystal [11]. The other configuration uses a quarter-wave plate (QWP) and an analyzer that is oriented at a small angle from the crossed position [7]–[10]. In both configurations, nonuniformity of residual birefringence of the EO crystal affects the image quality. In this report, we present a method of real-time detection of two-dimensional distribution of THz field, in which birefringence nonuniformity of the EO crystal is directly measured and the obtained THz image is corrected for it.

In the configuration of EO sampled imaging using crossed polarizers, the intensity of the probe light transmitted through the analyzer can be expressed as [11]

$$I = I_0[(\theta + \Gamma)^2 + \eta], \tag{1}$$

where I_0 is the incident light intensity, θ is the phase retardation due to the EO effect, which is proportional to the THz field, Γ is the phase retardation due to residual birefringence of the EO crystal, and η is depolarization factor due to scattering and other types of imperfection in the optics. It is assumed here that $|\theta|$ and $|\Gamma| \ll 1$. In this method, nonuniformity of Γ directly affects the uniformity of the obtained image, and the magnitude of Γ cannot be controlled although there is an

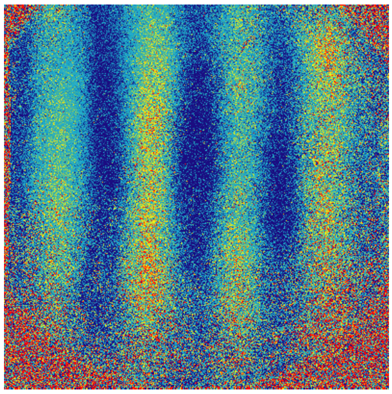

Fig. 1. Frequency-resolved THz image of 2 mm lines and spaces of aluminum at 0.5 THz. Distribution of Fourier amplitude divided by that of a reference image is shown. The image area corresponds to the crystal size of 20 × 20 mm^2.

appropriate value of Γ for the largest signal modulation depth [11]. In the configuration using a QWP and a tilted analyzer [7], [8], on the other hand, the transmitted light intensity becomes

$$I = I_0[(\theta + \delta)^2 + \eta], \tag{2}$$

which is the same as above except that Γ is replaced by the tilt angle of analyzer, δ. Derivation of Eq. (2) is detailed in the appendix of Ref. [8], where residual birefringence of the EO crystal is not taken into account. By taking into account the phase retardation due to residual birefringence of the EO crystal, we obtain

$$I = I_0[(\theta + \delta + \Gamma)^2 + \eta]. \tag{3}$$

In Eqs. (2) and (3), it is assumed that $|\theta|, |\delta|$, and $|\Gamma| \ll 1$. In the linear region, *i.e.*, when $|\theta| \ll |\delta+\Gamma|$, the phase retardation due to the THz field is obtained as

$$\theta = (I - I_b)/[2(\delta + \Gamma)I_0], \tag{4}$$

where I_b is background light intensity obtained without THz field. It is seen from this expression that the sensitivity of the measurement is a function of the residual birefringence at each point. For spectroscopic object imaging [4], [5], the signal intensity can be divided by a reference intensity, which leads to images immune to the nonuniformity. For the measurements, however, of THz field profiles, the influence cannot be removed.

In a method presented here, we measured the distribution of the residual birefringence by acquiring the background

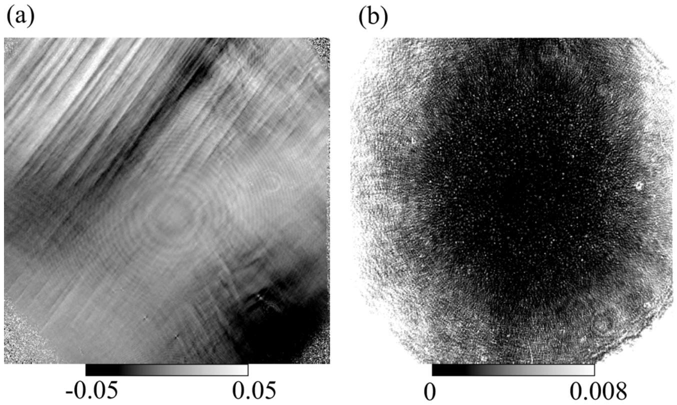

Fig. 2. (a) Distribution of the phase retardation of the probe light, Γ, due to residual birefringence of the EO crystal. (b) Distribution of the scattering term, η. In both images, the area corresponds to the crystal size of 20×20 mm^2. Data quality of the four corners are poor because of low probe intensity.

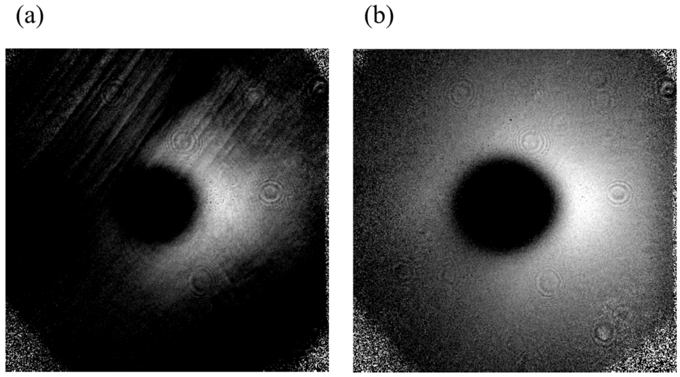

Fig. 3. Distribution of the electric field of a focused THz pulse at a positive delay time. (a) Image obtained without taking into account the influence of residual birefringence of the ZnTe crystal. (b) Image corrected for the residual birefringence.

intensity, I_b, at several rotation angles, δ, of the analyzer. By fitting the data to a quadratic function of δ according to Eq. (3), I_0, Γ, and η were obtained at each pixel of the image.

Experiments were performed using a setup similar to that reported previously [7]. Regeneratively amplified Ti:sapphire laser pulses at 800 nm irradiated the 3-cm gap between the electrodes of a large-aperture semi-insulating GaAs photoconductive antenna at a repetition rate of 1 kHz. The probe beam was split from the pump beam and passed through a polarizer before combined with the THz beam by a pellicle beamsplitter. Then it passed through a 1 mm thick, 20×20 mm^2 $\langle 110 \rangle$ ZnTe crystal, a QWP, an analyzer, and an imaging optics before detected by a CCD camera.

Before describing the effect of nonuniformity correction, we present first a result of frequency-resolved object imaging in Fig. 1. The object was 2 mm lines and spaces of aluminum foils on paper. The spatial profile of the object was imaged by a TPX lens of a focal length of $f = 98.3$ mm to the ZnTe crystal. Distances between the object and the lens and between the lens and the ZnTe crystal were $9f/4$ and $9f/5$, which leads to 5:4 imaging. The probe delay was scanned and the obtained temporal THz waveform at each pixel was Fourier transformed to obtain frequency-resolved images, which were then divided by a reference image that was obtained using a blank sample. Figure 1 shows the distribution of the Fourier amplitude of the THz field at 0.5 THz. Because of the division by the reference, any image deformation due to EO crystal birefringence is automatically corrected. Thus it is seen that EO crystal nonuniformity is not a serious problem in object imaging, and that resolution better than 1 mm is obtained using this imaging setup.

We obtained the distribution of the phase retardation due to the residual birefringence of the ZnTe crystal used in the measurements and that of the scattering term following the procedure described above. Results are shown in Fig. 2. It was found that Γ ranged from -0.05 to 0.05 in this crystal and stripe structures were clearly seen. Scattering factor, η, was distributed around 0.001 in the major central part of the image area, and reached $\eta \simeq 0.005$ at some bright spots. In the following THz image measurements, δ was set at 3° (0.052 rad) to avoid the condition that $\delta + \Gamma = 0$ and ensure linear detection of THz field.

For the field profile imaging, THz pulses were focused by the TPX lens, and the ZnTe crystal was placed at the focal point. The probe delay was set at a time after the peak to observe a ring profile [6]. In Fig. 3(a) is shown the THz field distribution obtained by assuming no residual birefringence. It is seen that the image is seriously affected by the nonuniformity of the residual birefringence. Figure 3(b) shows an image corrected for the residual birefringence, which is almost free from the effect of birefringence nonuniformity.

In conclusion, we proposed and demonstrated a method for real-time THz imaging in which image deformation due to nonuniformity of the residual birefringence of the EO crystal is corrected. Distribution of residual birefringence and scattering factor were directly measured and used for the image correction. Clean images of THz pulse profiles almost free from deformation were obtained using this method.

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