INSTITUTE OF PHYSICS PUBLISHING

J. Phys. D: Appl. Phys. 36 (2003) 229-235

Ring formation of focused half-cycle terahertz pulses

Rakchanok Rungsawang, Keisuke Ohta, Keiji Tukamoto and Toshiaki Hattori

Institute of Applied Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8573, Japan

E-mail: nok@laserlab.bk.tsukuba.ac.jp

Received 25 September 2002 Published 15 January 2003 Online at stacks.iop.org/JPhysD/36/229

Abstract

Studies using a terahertz (THz) imaging system have shown that focused THz electromagnetic pulses exhibit a ring-like spatial intensity distribution. In the study, almost half-cycle THz pulses were generated from a large-aperture photoconductive antenna and focused by an off-axis parabolic mirror. Time-resolved spatial distribution of the THz electric field on the focal plane was found to form a ring before and after the time region where a single peak is formed around the time origin. On the other hand, with the delay time fixed at the origin, the field distribution was also found to exhibit a ring-like profile at positions away from the focal plane. Existence of relatively low-frequency components in the power spectrum of the THz field gives these observable phenomena. Numerical simulations using diffraction integral calculations reproduced the observed features. A simpler numerical analysis based on the Gaussian beam approximation was shown to yield the observed features and also predicted the dependence on the beam parameters.

1. Introduction

Terahertz (THz) imaging has been spurred in large part by the development of imaging systems, because the imaging technique based on THz time-domain spectroscopy has the potential to be used as a portable low-frequency spectrometer. Both amplitude and phase information at any point on the sample can be extracted using THz imaging [1]. Optical rectification in a nonlinear medium [2,3], and photoconductive switching [4-6] have all demonstrated a capability for THz electromagnetic field generation by ultrashort laser pulse excitation. Among these generation techniques, large-aperture antennas have been widely used, because the devices can generate THz pulses with very high electric field [7]. By gating biased semiconductors with ultrafast optical pulses, one can generate sub-picosecond pulses of THz radiation. These THz transients consist of a single-cycle, or even a sub-cycle electromagnetic field, and consequently span a very broad bandwidth extending from dc to a few THz.

In a widely used mode of THz image measurements, an object is placed on the focal plane of a relatively weak THz beam, and it is translated for image acquisition [8]. Since the

image, in this mode, is constructed pixel by pixel, acquiring a two-dimensional image by this method consumes a lot of time. To achieve real-time detection, an expanded beam of relatively intense THz pulses is used and an object is placed in the beam path. In this method, large-area electro-optic (EO) crystals and a CCD camera are used for the detection of the THz intensity distributions of the collected beam.

To achieve real-time acquisition of THz images of objects, the spatial distribution of the observed electric field should be known first. In this paper, we report on the time-resolved measurements of the spatial profile of a focused THz field near and on the focal plane. The observed features were reproduced by diffraction integral calculations. We also showed that the paraxial Gaussian beam model is valid for the description and prediction of the tendency of ring formation.

2. Experiments and results

Figure 1 shows a schematic of the set-up used to perform the THz imaging experiment. The large-aperture photoconductive antenna consisted of a non-doped semi-insulating GaAs wafer with a $\langle 100 \rangle$ surface and two aluminium electrodes



Figure 1. Experimental set-up for the THz imaging with an expanded probe beam.

mechanically attached to it with a spacing of 30 mm. The diameter and thickness of the wafer were 50 mm and 350 μ m, respectively. Pulsed electrical voltage of 8 kV with a pulse duration of 1 μ s and repetition rate of 1 kHz was applied to the electrodes synchronously with the pump laser pulse.

Regeneratively amplified Ti:sapphire laser pulses (Spitfire, Spectra Physics) with 150 fs duration were used as the light source in the experiment. The wavelength and repetition rate of the output of the amplifier were 800 nm and 1 kHz, respectively. The amplified laser beam was first split into two limbs by a beam splitter. The main portion of the beam was passed through the beam splitter and used to pump the GaAs emitter. The remainder was reflected by the beam splitter and used as the probe pulses of the EO sampling measurements. The reflected beam was guided to a delay line before passing through a polarizer. The probe beam was then expanded and collimated by a combination of a convex lens and an achromatic lens to ensure that the full area of the ZnTe crystal was being used. The pump beam was also expanded and collimated before incidence at the emitter. The energy of the pump pulse was 150 μ J. The spatial distribution of the pumping intensity on the emitter surface was measured using a knife-edge experiment, and it was found to have nearly Gaussian distribution with a 1/e radius of 9.2 mm. Therefore, the fluence of the pump pulse at the centre of the emitter is calculated to be 56.4 μ J cm⁻². In order to focus and form an image, the THz beam was brought to an off-axis parabolic reflecting mirror with a focal length of 152.4 mm, which was placed 65 mm from the emitter. The diameter of the mirror was 50.8 mm. A 1 mm thick (110) ZnTe crystal was used as an EO crystal for the EO sampling measurements of the THz field. The active area on the detection plane was $18 \times 20 \text{ mm}^2$. The EO crystal was located normal to the propagation direction (z). The crystal was oriented so that the (001) direction was parallel to the THz polarization (horizontal) direction. A polarization analyzer was placed so that the probe light is blocked when no electric field is applied to the EO crystal. The polarization direction of the analyzer was at 45° from the horizontal. In this configuration, the intensity of the light transmitted through the analyzer is proportional to the intensity of the THz field, that is, to the square of the electric field amplitude at the EO crystal. The transmitted light passed through a convex lens with



Figure 2. Experimentally obtained images of the THz intensity distribution on the focal plane at (*a*) t = -0.72 ps, (*b*) t = -0.48 ps, (*c*) t = 0 ps and (*d*) t = 0.4 ps. Each image corresponds to an area of 12×12 mm² at the EO crystal. An AVI colour movie of this figure is available.

a focal length of 26.5 mm and was incident on a CCD camera so that a 1/5 image of the THz intensity distribution at the EO crystal was obtained by the CCD camera. The background light intensity arising from the scattering of light within the EO crystal [9] was subtracted from the acquired image data.

In the present studies, we performed two series of experiments to clarify the spatio-temporal characteristics of the ring formation. In the first one, we placed the ZnTe crystal at the focal point (z = 0), and observed the time-dependent spatial distribution of the THz field on the focal plane by scanning the delay time. In the other series of experiments, we observed the dependence of the THz field distribution on the propagation distance. In this case, the whole set-up of the EO measurements, i.e. the EO crystal, the analyzer, lens and the CCD camera, was translated along the propagation axis (z-axis) from z = 0 to 50 mm. Images at positions with negative values of z could not be obtained because of contact between optical elements. The delay time of the probe pulse with respect to the pump pulse was fixed at the time when the THz field at the focus was a maximum.

Figure 2 shows the measured THz images on the focal plane with the size of $12 \times 12 \text{ mm}^2$ (or $2.4 \times 2.4 \text{ mm}^2$ on the surface of the CCD camera). Figures 2(a)-(d) show the spatial distribution of the intensity of focused THz pulses at various delay times. It is seen from figure 2(a) that at the beginning, the field distribution is ring shaped. Figure 2(b) shows that the inner rim of the ring gradually expands to the centre as time proceeds. Then, the hole of the ring is filled and the THz field comes to have the highest intensity at the centre as shown in figure 2(c). The one-dimensional intensity profile on the horizontal line that passes through the centre of this image has a (1/e) radius of 3.4 mm. Here, we take the delay time of this image to be the origin. After this the



Figure 3. Temporal intensity profiles of the THz pulses reconstructed from the set of time-resolved images as shown in figure 2. The data for each waveform are extracted from a fixed position of 100 frames of images. The dotted line represents the data at the centre (x = 0 mm) of the image. The other four waveforms (——) are taken from points shifted upward by a step of 0.37 mm.

tendency of the distribution changes in a direction opposite to that mentioned above, as seen in figure 2(d). Asymmetry seen in the images is attributed to the following two reasons. One is the misalignment of the parabolic mirror, which is difficult to steer. The other is the fundamental asymmetry of the off-axis parabolic mirror [10].

Figure 3 shows on- and off-axis temporal intensity profiles of the THz pulses obtained from the time-dependent imaging data corresponding to figure 2. The data for each pulse are extracted from a fixed position of 100 frames of images. The on-axis (x = 0 mm) waveform has the smallest pulse width. The pulses taken at the positions farther from the axis ($x \neq 0$ mm) are longer. By going away from the centre, the peak intensity becomes smaller and the pulses broadens. It is seen from the figure that at delay times larger than about 0.5 ps, the off-axis intensity is larger than the on-axis one. It is also the case with negative delay time smaller than about -0.5 ps. This means that the spatial distribution of the intensity exhibits a ring-like profile at these delay times, as seen in the images of figure 2.

The spatial intensity distribution on the planes at z = 0, 20, 40 and 50 mm as a function of change of image position in the other experiment has been shown in figure 4. Here, z = 0 mm corresponds to the focal plane. The images correspond to an area of 12×12 mm² at the EO crystal. The delay time of the probe pulse of the EO measurement with respect to the pump pulse was fixed at the time (t = 0 ps) of the peak of the temporal waveform at the focus. Interestingly, we obtained a ring-like intensity distribution again.

3. Simulations

In order to confirm the ring formation phenomena observed in the experimental images, we performed numerical simulations of two-dimensional images based on the diffraction integral formula. The merit of this model is that we need no assumption about the characteristic of wave propagation. Moreover, it can include various details of the experimental set-up such as the shapes of the emitter or the other optical elements and the

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Figure 4. Experimentally obtained images of THz intensity distribution at a fixed delay time, t = 0 ps, on the plane at (a) z = 0 mm, (b) z = 20 mm, (c) z = 40 mm and (d) z = 50 mm.

spatial distribution of the bias field on the emitter surface. We developed a new computer code of the vector-field diffraction integral to simulate the focusing by an off-axis parabolic mirror using the geometrical shape of the mirror surface. On the other hand, one can also model using the necessary assumption that each frequency component contained in a THz pulse conducts itself like a Gaussian beam. This model is simple compared with the preceding one and includes only some details of the experiment set-up but can visualize the characteristics of THz pulse focusing.

3.1. Current surge model

The simulation starts from the calculation of the THz field at the antenna surface, which we call the surface field. We adopted the current surge model, which is widely applied to describe the THz radiation generation process [11, 12]. In this model, the time-dependent surface field is given by

$$E_{\text{surf}}(t) = -E_{\text{bias}} \frac{\sigma_{\text{s}}(t)\eta_0}{\sigma_{\text{s}}(t)\eta_0 + (1+\sqrt{\epsilon})},\tag{1}$$

where E_{bias} is the bias field, $\sigma_{\text{s}}(t)$ the time-dependent surface conductivity, ϵ the dielectric constant of the emitter medium, and η_0 the impedance of vacuum. We adopted the phenomenological distribution of the bias field on the emitter surface in the form [11]

$$E_{\text{bias}}(x) = E_{\text{c}} + (E_{\text{e}} - E_{\text{c}}) \left(\frac{2x}{a}\right)^n.$$
 (2)

Here, the x-axis is set in the direction of the biased field with its origin located at the centre of the emitter, a = 30 mm is the emitter width and n = 6. The surface conductivity is given by [11]

$$\sigma_{\rm s}(t) = \frac{e(1-R)}{h\nu} \int_{\infty}^{t} \mu(t-t') I_{\rm opt}(t') \exp\left[-\frac{t-t'}{\tau_{\rm car}}\right] \mathrm{d}t',$$
(3)

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where *e* is the elemental charge, *R* the reflectance of the optical pump beam that has the intensity of $I_{opt}(t)$, τ_{car} the carrier lifetime. The time-dependent electron mobility, $\mu(t)$, is expressed as

$$\mu(t) = \mu_{\rm dc} - (\mu_{\rm dc} - \mu_{\rm i}) \exp(-\Gamma t).$$
(4)

Here, the initial mobility, μ_i , of hot carriers photoexcited to a state above the bottom of the conduction band increases to the steady-state mobility, μ_{dc} , of the carriers at the bottom of the conduction band with the carrier relaxation time of Γ^{-1} .

3.2. Diffraction integral

The diffraction integral formula for the full electric field vector is known as the Smythe–Kirchhoff diffraction integral. The time-domain version of the electric field at position x and time t is given by [11]

$$\boldsymbol{E}(\boldsymbol{x},t) = \nabla \times \int_{S} \frac{1}{2\pi r'} \left[\boldsymbol{n} \times \boldsymbol{E}\left(\boldsymbol{x}',t-\frac{r'}{c}\right) \right] \mathrm{d}\boldsymbol{x}'.$$
 (5)

Here, *S* is the surface from which the THz radiation is emitted, *n* is the inward normal of the emitter surface and x' is the integration vector on the emitter. Vector r' is defined by r' = x' - x and r' = |r'|.

In the simulation, the time-dependent electric field $E(\mathbf{x}', t)$ on the emitter surface was obtained using equation (1). The Gaussian spatial distribution of the pump pulse fluence with a 1/e radius of 9.2 mm was incorporated in the calculation. THz field waveforms on the surface of the parabolic mirror were, then, calculated using the diffraction integral. Finally, the waveforms at the observation points and the electric fields on the observation plane were calculated using the integral again. The source field for this step was the field reflected from the parabolic mirror surface, which has a tangential component equal to -1 times that of the incoming field. The surfaces of the emitter and the parabolic mirror were divided into 128×128 sections in the numerical integration. The pulse shape of the pumping light was assumed to be Gaussian:

$$I_{\rm opt}(t) \propto \exp\left(-\frac{t^2}{\tau_{\rm las}^2}\right).$$
 (6)

To simulate the THz images, we used the following values [11]: R = 0.3, $\epsilon = 12.25$, $\eta_0 = 377 \Omega$, $\Gamma = 2$ THz, $\mu_i = 500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\mu_{dc} = 8000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $\tau_{car} = 600 \text{ ps}$. The parameter describing the pump laser pulse width, τ_{las} , should be equal to the pump pulse duration divided by $2\sqrt{\ln 2}$. In the simulation, this value was modified from the experimental pulse width of 150 fs to an effective pulse width, as described below, in order to make the simulated THz pulse width consistent with the experimental one.

When a value of τ_{las} equal to the experimental one is used in the simulation, the calculated pulse durations of the temporal waveforms are much shorter than those observed in the experiments. This is probably because the carrier dynamics model used in this simulation is not appropriate. In the actual experiments, high-density carriers are created in the emitter for intense THz pulse generation. Because the simple dynamic model described in the previous section is based on the carrier dynamics at a low excitation level [13], it



Figure 5. Temporal intensity profiles of the THz pulse at the focus obtained from the experimental data (—— and +) and a simulation with an effective pump pulse width of 550 fs (——).

is reasonable to assume that it cannot be applied under actual experiment conditions. Pump pulse broadening due to the propagation through optics such as beam splitters and lenses is estimated by calculation to be less than 1 fs, and cannot be the origin of the disagreement [14]. Since carrier dynamics modelling is not the main purpose in this study, we adopted an effective pump laser pulse width of 550 fs, which resulted in the simulated THz pulse width being equal to the experimental one at the focus. The experimental and simulated temporal waveforms of the THz field at the focus are plotted in figure 5. It is seen from the figure that the pulse widths agree with each other but the pulse shapes are slightly different. The simulated waveform increases faster in the rising stage but decreases slower in the decay state. It may be attributed to the screening of the bias field by carriers and the scattering of carriers to the intra-band states, which are not included in the model of the THz generation described above. We leave the work of elaboration of the dynamic model for later studies, and use this model of the generation process of the THz field. In the simulations, no variable parameters were used except for the pump pulse width. The results of the simulations using the diffraction integral formula for the time dependence and the position dependence of the spatial distribution of the THz intensity are shown in figures 6 and 7, respectively. The simulated images are in qualitative agreement with those of the corresponding experimental images of figures 2 and 4. It is apparent that the ring shapes before and after t = 0 are different, as seen in figure 6. This can be attributed to the asymmetry of the simulated temporal pulse shape as shown in figure 5. Figure 8 shows the simulated version of figure 3 for a qualitative comparison of time-dependent intensity at off-axis positions. It is seen that the pulse shapes at points closer to the centre are narrower. Inversion of the intensity order is clearly observed at large |t|. This contributes to the fast decrease in magnitude at $t \neq 0$.

3.3. Gaussian beam model

Focusing characteristics, such as focused spot size (1/e radius) and confocal length, generally depend on the frequency. Here, for the sake of simplicity, we assume that each frequency component of the THz pulses emitted from the large-aperture



Figure 6. Time dependence of the spatial distribution of the THz intensity obtained by the simulations based on the vectorial field diffraction integral. Images (a)-(d) correspond to the experimental images of figures 2(a)-(d). The grey scale images indicate the calculated THz intensity distributions on the focal plane at (a) t = -0.72 ps, (b) t = -0.48 ps, (c) t = 0 ps and (d) t = 0.4 ps. An AVI colour movie of the spatial distribution from t = -0.72 to 0.4 ps is available.



Figure 7. Position dependence of the spatial distribution of the THz intensity obtained by the simulations. Images (a)-(d) correspond to the experimental images of figures 4(a)-(d). The grey scale images indicate the calculated THz intensity distributions on the plane at (a) z = 0 mm, (b) z = 20 mm, (c) z = 40 mm and (d) z = 50 mm.

photoconductive antenna behaves as a Gaussian beam [15]. We use a simple model for the optical configuration, where an ideal lens with a focal length of f is placed at a distance $z_{\rm L}$ from the emitter. The Gaussian beam of each frequency is assumed to have a frequency-independent initial beam size A at the surface of the emitter. Then, the beam size of the



Figure 8. Simulated temporal intensity profiles of the THz pulses reconstructed from the set of time-resolved images as shown in figure 6. The dotted line represents the data at the centre (x = 0 mm) of the image. The other four waveforms (——) are taken from points shifted upwards by a step of 0.37 mm.

component with frequency ν at the lens is expressed as

$$w_{z_{\rm L}}(\nu) = A \left[1 + \frac{z_{\rm L}^2}{z_0^2(\nu)} \right]^{1/2},\tag{7}$$

where $z_0(v)$ is defined as

$$z_0(\nu) \equiv \frac{\pi A^2 \nu}{c}.$$
 (8)

The radius of curvature of the wave front at the lens is

 $R_{z_{\rm L}}(\nu) = z_{\rm L} \left(1 + \frac{z_0^2(\nu)}{z_{\rm L}^2} \right).$ (9)

The radius of curvature is changed from R to R' by passing through an ideal lens:

$$\frac{1}{R'(\nu)} = \frac{1}{R_{z_{\rm L}}(\nu)} + \frac{1}{f}.$$
 (10)

The effect of the finite size of the lens is taken into account by assuming that the beam size is changed from w to w' by passing through a lens of diameter D [16]:

$$\frac{1}{w^{\prime 2}(v)} = \frac{1}{w_{z_{\rm L}}^2(v)} + \frac{2}{D^2}.$$
 (11)

The beam waist and its location for the beam focused by the lens can be written as

$$w'_{0}(\nu) = w'(\nu) \left[1 + \left(\frac{\pi \nu w'^{2}(\nu)}{c R'(\nu)} \right)^{2} \right]^{-1/2}, \qquad (12)$$

$$z'_{\rm f}(\nu) = z_{\rm L} - R'(\nu) \left[1 + \left(\frac{c R'(\nu)}{\pi \nu w'^2(\nu)} \right)^2 \right].$$
(13)

For the calculations, we use the parameters similar to those of the experimental set-up, i.e. A = 9.2, $z_L = 65$, f = 152.4 and D = 50.8 mm. The focusing characteristics of Fourier components with several frequencies are visualized in figure 9 by plotting the propagation distance dependence of



Figure 9. Propagation lines (positions where the electric field has 1/e peak value) calculated using the Gaussian beam model. The three pairs of lines starting from the position of the ideal lens represent three different frequency components: 0.3 THz (-----), 1.0 THz (------) and 2.5 THz (------).

the beam size. The figure shows the propagation lines of beam frequency of 0.3, 1.0 and 2.5 THz. In this figure, we locate the focal point of the lens at z = 0, i.e. the lens is positioned at z = -152.4 mm. The positions of the beam waists of these beams are at z = -30.80 mm, -3.15 mm and -0.51 mm, respectively. It is clearly seen that the confocal length of the low-frequency component (solid lines) is quite longer than the others, and the corresponding beam waist is larger.

4. Discussion

In the following, we explain the ring formation phenomenon qualitatively, using a Gaussian beam model. When we focus our attention on the focal plane (z = 0), and consider the spatial distributions, it is seen that the high-frequency components are tightly compressed near the *z*-axis while beams of low frequency distribute in a larger area as shown in figure 9. This frequency-dependent spatial distribution results in the position dependence of the THz pulse width in the time domain as evidenced by the experimental result shown in figure 3. Briefly, the on-axis pulse width is shortest because it is composed of a broad spectrum including a significant contribution of high-frequency components, whereas pulse widths at off-axis positions are larger due to the loss of high-frequency components.

A qualitative explanation of the *z*-dependent ring formation phenomenon in the second experiment is as follows. On the focal plane (z = 0 mm), the intensity distribution forms a single peak at t = 0 ps, and exhibits a ring-like profile at times larger than about 0.5 ps and less than about -0.5 ps, as shown above. On the other hand, the position dependence of the temporal waveforms of the THz pulse on the *z*-axis has been reported in our previous paper [16]. The pulse peak time was found to be shifted in the negative direction for larger positive values of *z*, which has been attributed to the difference in the optical path length for the on-axis and off-axis rays. Because of this peak shift at positions of large *z*, the delay time region when the ring profile appears is also shifted in the negative direction. This has been confirmed by simulation calculations using the



Figure 10. The second derivative of the THz intensity with respect to the radial parameter, r, as a function of time. They were obtained by the calculations using the Gaussian beam model. Each line is for the optical pump beam radius of 3 mm (----), 6 mm (----) and 9 mm (----), respectively.

diffraction integral method as described in section 3.2. Thus, a ring-like distribution is observed even at t = 0 ps at positions sufficiently far away from the focus.

We also used a more analytic approach to study the condition for ring formation. A ring-like intensity distribution occurs when the following inequality is satisfied:

$$\left. \frac{\mathrm{d}^2 I(t,r)}{\mathrm{d}r^2} \right|_{r=0} > 0.$$
 (14)

Here, I(t, r) represents the THz intensity at time t and radial position r. We used the Gaussian beam model for the calculation of I(t, r) at the focus with the surface field parameters described in section 3.2. The left-hand side of equation (14) was calculated as a function of time for different values of pump beam radius. The results are shown in figure 10. The plots indicate that a ring-like spatial distribution is formed in the time region when the plotted value is positive. The result with a pump radius of 9 mm shows good agreement with the experimentally obtained time dependence. It is of importance that the ring formation is reproduced not only by the diffraction integral but by the Gaussian beam model. It shows that the ring formation is a very fundamental phenomenon.

It is seen from the figure that a smaller size of the optical pump beam yields a shorter duration of ring formation. Under the Gaussian beam approximation, the contribution of a single frequency component to the left-hand side of equation (14) is simplified to

$$\left. \frac{\mathrm{d}^2 I(t,r)}{\mathrm{d}r^2} \right|_{r=0} \propto \frac{1}{w_0^{'2}},\tag{15}$$

where the beam waist at the focal point is approximately expressed as [16]

$$w_0' = \frac{cf}{A\pi\nu}.$$
 (16)

Here, it is assumed that the beam radius does not change when the beam propagates from the emitter to the focusing element and that $\lambda \ll (\pi A^2)/f$. From equation (16), we can obtain the conclusion that smaller optical pump beam sizes and/or larger focal lengths, f, give larger beam waists and result in smaller changes in the THz pulse width at off-axis positions.



Figure 11. Normalized second derivative of the intensity of focused light pulses with respect to the radial parameter, r, as a function of time. It was obtained by the calculations using the Gaussian beam model. The inset shows the expanded vertical scale around the zero line (- - - -).

This leads to a shorter time duration for the ring formation or no ring formation at all.

With ultrashort optical pulses of many-cycle duration, for example, the ring formation phenomenon has been rarely observed. We again used the Gaussian beam model to calculate the electric field at the focus of the ideal lens and verified it with the condition in equation (14). The time-dependent second derivative of intensity with respect to r of a 150 fs pulse at 800 nm is plotted in figure 11. The inset shows the time region when the on-axis intensity is less than the off-axis one (positive values). It indicates that the ring formation effect is negligible with optical many-cycle pulses on account of very little contribution from low-frequency components.

5. Conclusion

In conclusion, with a THz imaging system, it has been observed that the two-dimensional spatial intensity distribution of focused half-cycle THz pulses forms a ring-like profile at a certain region of space and time. This has been confirmed by the numerical simulations based on the vectorial diffraction integral formula and the Gaussian beam approximation. This observed phenomenon is attributed to the broad spectrum of half-cycle THz pulses, which include a significant contribution of low-frequency components and the corresponding large central wavelength compared with optical elements. It was shown that the time duration of the ring can be controlled by changing the beam size of the optical pump pulses and the focal length of focusing elements.

Acknowledgment

This study was partly supported by the Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science.

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