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Terahertz wave detection performance of photoconductive antennas: Role of antenna structure and gate pulse intensity

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We studied the receiver performance of two photoconductive antennas (bow tie and dipole antennas) fabricated on the same low-temperature-grown GaAs substrate to clarify the effect of the antenna structure and gate pulse intensity on terahertz wave detection. We observed the gate pulse intensity dependence of the temporal profiles of the terahertz waves or terahertz spectra. For both antennas, the sensitivity in the low-frequency regime (<0.5 THz) was enhanced compared to that in the high-frequency regime for large gate pulse intensities. This is because the carrier trap time increased due to the saturation of the GaAs defect levels. We also observed that the peak-to-peak amplitude of the terahertz wave detected by one antenna was not always larger than that detected by the other antenna, and the peak-to-peak amplitude of the bow tie antenna was larger (smaller) than that of the dipole antenna when the gate pulse intensity was high (low). This was explained by the gate pulse intensity dependence of the frequency-dependent detection sensitivity and also by the resonance frequency of the antenna structure. © *2005 American Institute of Physics*.

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I. INTRODUCTION

High-field terahertz electromagnetic waves are needed for sensing, imaging, and terahertz wave spectroscopy.[1–3] Therefore, an understanding of the temporal and spectral profiles and the amplitude of the terahertz electromagnetic waves emitted from or received by photoconductive (PC) antennas excited by femtosecond laser pulses is important for the efficient generation or detection of terahertz waves.

Excitation-intensity, excitation-position, and antenna-structure dependences of the amplitudes of terahertz waves emitted from PC antennas under a bias voltage have been studied previously.[4–10] In those works, a large bias field and a high excitation laser-pulse intensity (and laser fluence) were found to increase the terahertz wave amplitude or intensity. It was also shown that a sharp metal electrode structure enhances the dc bias field significantly due to its geometrical effects (electric-field singularity[6,7]). Additionally, the laser-pulse excitation in the vicinity of the electrode (anode) of a PC antenna with triangular tips at the antenna gap produced efficient terahertz fields when the excitation laser pulse had a small spot size (<1-μm diameter).[8] However, in contrast with the many studies of PC antennas as terahertz wave emitters, there seems to be only a few reports on the receiver characteristics of PC antennas.[8,11]

In this paper, we clarify the influence of the antenna structure and gate pulse intensity on the terahertz wave detection by measuring the performance of both dipole antenna and bow tie antenna as a function of the gate pulse intensity when they were used as receivers. The two antenna structures were fabricated on the same low-temperature (LT) grown GaAs. In general, there is a trade-off between the amplitude of the terahertz waves emitted or detected and the device lifetime of the PC antennas when high fluence laser pulses excite the PC antennas because laser pulses can damage or gradually degrade the GaAs substrate. In the present experiments, the gate pulses excited the whole area of the gap of the antennas to avoid such substrate damage or degradation. We studied the gate pulse intensity dependence of the detection sensitivity and found that the peak-to-peak amplitude of the terahertz wave received by the bow tie antenna was larger (smaller) than that of the dipole antenna when the gate pulse intensity was large (weak).

II. PC ANTENNA

LT GaAs samples of 1-μm thickness were grown by molecular-beam epitaxy (MBE) at 250 °C on a 0.5-μm-thick buffer layer of GaAs (undoped) that had been

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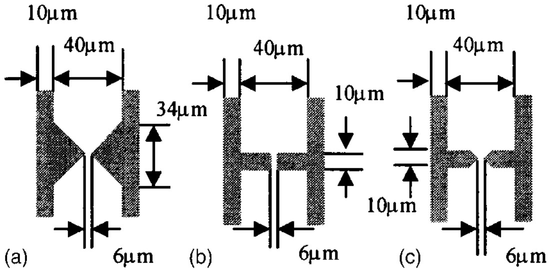

FIG. 1. Schematics of the antennas: (a) bow tie structure, (b) dipole structure, and (c) dipole structure with triangular tips at the gap. All antennas were fabricated on the same LT GaAs substrate.

grown at 550 °C on a semi-insulating GaAs substrate.[12] The growth temperature was measured with a thermocouple at the backside of the substrate. A 2×4 reflection high-energy electron-diffraction (RHEED) pattern in the GaAs substrate observed at 580 °C was used to calibrate the thermocouple reading. The As/Ga beam equivalent pressure ratio (As/Ga flux ratio) at $x=0$ was 2.75. The growth rate of the LT GaAs sample was 1 monolayer/s (1 μm/h). The sample was annealed for 60 s at an annealing temperature of 550 °C under the face-to-face condition in an $H_2(5\%)/Ar$ ambient.

The antenna structures [Figs. 1(a)–1(c)] were fabricated on the same LT GaAs substrate to avoid any substrate dependence of the antenna characteristics. The distances between antennas were made larger than the size of each antenna structure. The antenna structure was a bow tie [Fig. 1(a)] or a rectangular [dipole type: Fig. 1(b)] structure. To examine the effect of the electrical field singularity in the whole-gap excitation condition, we used a dipole structure with triangular tips at the gap [Fig. 1(c)]. Each antenna structure had a 6-μm gap in the center and was integrated into a coplanar transmission line (strip linewidth of 10 μm and separation of 40 μm). The bow tie antenna had a 90° bow angle. The carrier trap time estimated by a reflection-type pump-probe spectroscopy[13] was ~0.44 ps.[12]

A high-resistivity Si lens is usually attached to a PC antenna to collimate the terahertz waves effectively. However, attaching a Si lens to the LT GaAs would have been problematic because the Si lens would be positioned correctly for only one of the antennas for collimating terahertz waves. To avoid such Si-lens-position-dependence problem, we did not attach a Si lens to the LT GaAs.

III. EXPERIMENTAL SETUP

In our experiments, we used an InAs wafer as a terahertz wave emitter and the three PC antennas shown in Fig. 1 as terahertz wave receivers. In the experiments, the output (center wavelength of ~790 nm, pulse width of ~300 fs, and repetition rate of 82.2 MHz) of a mode-locked $Ti:Al_2O_3$ laser was divided by a beam splitter into pump and gate pulses. The pump pulses had a 120-mW average power and were *p* polarized. They were focused by a focusing lens to the surface of the InAs (0.5-μm-thick undoped InAs grown by MBE on a GaAs substrate) to the spot size of ~100 μm (e^{-2} spot size) to generate terahertz electromagnetic waves. We estimated the average carrier densities to be $\sim 3 \times 10^{17}$ cm^{-3}, assuming that the absorption coefficient α at ~790 nm was 10^4 cm^{-1}. The main mechanisms of the terahertz wave emission from the surface of InAs were considered to be optical rectification and the photo-Dember effect.[14,15]

The polarization of the terahertz electromagnetic waves emitted from the surface of the InAs was roughly linear. The terahertz electromagnetic waves were collected and guided to the PC antennas using a pair of off-axis paraboloidal mirrors. The polarization of the terahertz waves was set perpendicular to the direction of the strip line of the antennas so that they could receive the terahertz waves effectively.

The gate pulses were focused by an objective lens to a diameter of ~6 μm (e^{-2} spot size) and excited the receiver (PC antenna). They irradiated the whole antenna gap and generated photoexcited carriers in the PC antennas. The carrier density created in the receiver (PC antenna) at 1.0-mW gate pulse intensity was estimated to be $\sim 5 \times 10^{17}/\text{cm}^3$. An optical chopper with a frequency of 1.3 kHz was used to modulate the intensity of the pump pulses. The current that flowed in the receiver (PC antenna) was proportional to the instantaneous field intensity of the terahertz waves. The current was amplified and fed to a lock-in amplifier. To obtain the temporal profile of the terahertz electromagnetic waves, we measured the output of the lock-in amplifier while changing the delay time between the pump and gate pulses.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Before discussing the antenna structure and gate pulse intensity dependence of the receiver performance, we briefly mention here why the bias field enhancement by geometrical effects (the electrical field singularity) is not important in the present case (whole-gap excitation by the gate pulse).

We measured the peak-to-peak amplitudes of the terahertz waves emitted or detected by the PC antennas with the dipole structure [Fig. 1(a)] and the dipole structure with triangular tips [Fig. 1(c)]. We found that their peak-to-peak amplitudes had roughly the same magnitudes. Therefore, the bias field enhancement due to geometrical effects is not important when laser pulses excite the whole antenna gap. This is discussed in more detail in Sec. IV C.

A. Antenna-structure dependence of peak-to-peak amplitudes

The length of bow tie antennas is normally of the order of millimeters,[9,16] which is much larger than the 60-μm length of our bow tie antenna. Bow tie antennas are considered to have a broad frequency-independent spectral property. The peak frequencies of terahertz waves emitted from bow tie antennas are lower than those of the terahertz waves emitted from dipole antennas.[16] This is also true when the antennas are used as receivers. The length of the bow tie antenna in Fig. 1(a) is similar to that of the dipole antenna. Therefore, we expected that both antennas would exhibit similar frequency properties or terahertz spectra as receivers, with the bow tie antenna showing a small low-frequency shift of the peak sensitivity.

We first compare the peak-to-peak amplitudes of the terahertz wave detected by the antennas with the bow tie and

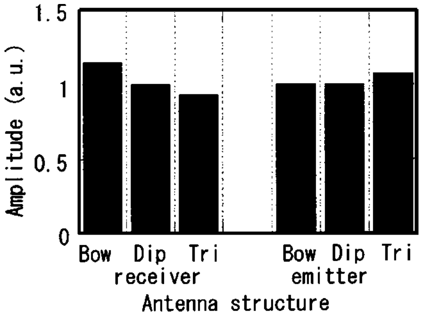

FIG. 2. Peak-to-peak amplitude of the terahertz waves (left side) detected by the PC antennas at 10-mW gate pulse intensity and (right side) emitted from them at 2.0-mW pump pulse intensity. Bow, dip, and tri stand for bow tie, dipole, and dipole with the triangular tips at the gap, respectively.

dipole structures shown in Figs. 1(a) and 1(b) at 10-mW gate pulse intensity. The result is shown on the left side of Fig. 2 (Bow: bow tie antenna and Dip: dipole antenna). The peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna was about 20% larger than that detected by the dipole antenna.

We estimated the resonance frequencies of the antennas. The resonance frequency ν is given by $\nu = c/(2\sqrt{\varepsilon^*}L)$, where c is the speed of light, $\varepsilon^* \sim 13$ the dielectric constant of GaAs,[17] and L the antenna length, including the width of the strip line. For the dipole antenna, $L = 60\ \mu\text{m}$, which gives $\nu = 0.69$ THz. The bow tie antenna is composed of dipole antennas whose directions change continuously from perpendicular to the strip line to 45° rotation. The $L = 60\sqrt{2}\ \mu\text{m}$ gives $\nu = 0.49$ THz. Therefore, the resonance frequencies are distributed from 0.5 to 0.7 THz.

Since the resonance frequency of the dipole antenna is 0.7 THz, the bow tie antenna has a higher sensitivity at frequencies below 0.7 THz. Figure 3 shows the Fourier transform of the terahertz waves detected by the two antennas. The solid curve is for the dipole antenna and the dashed one for the bow tie antenna. The amplitude of the spectrum for the bow tie antenna at frequencies less than 0.7 THz is larger than that of the dipole antenna. This result explains qualitatively why the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna was larger than that detected by the dipole antenna.

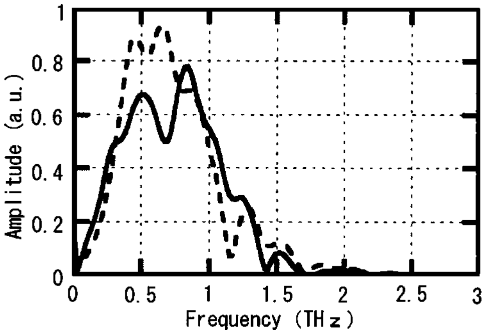

FIG. 3. Terahertz spectra detected by the PC antennas with the bow tie structure (dashed curve) and the dipole structure (solid curve) at the gate pulse intensity of 10 mW.

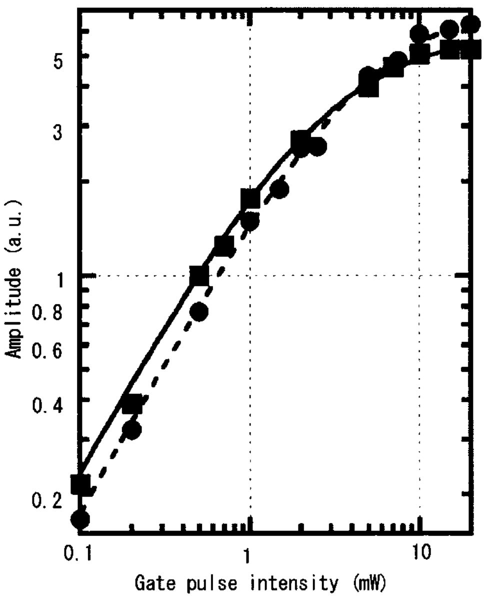

FIG. 4. Gate pulse intensity dependence of peak-to-peak amplitudes $A_{\text{p.-p.}}$'s of the terahertz wave detected by the bow tie antenna (●) and the dipole antenna (■). The solid and dashed curves are fittings based on the equation $A_{\text{p.-p.}} = BF/(F+F_0)$, where F is the average gate pulse intensity and B and F_0 are fitting parameters.

However, it is not certain whether the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna is always larger than that detected by the dipole antenna regardless of the gate pulse intensity.

B. Gate pulse intensity dependence of peak-to-peak amplitude

To investigate this, we measured the terahertz waves detected by the PC antennas with the bow tie and dipole structures as a function of the gate pulse intensity and examined the peak-to-peak amplitudes and the spectra of the terahertz waves.

Figure 4 shows the peak-to-peak amplitudes of the terahertz waves detected by the bow tie (circles ●) and dipole (squares ■) antennas as a function of the gate pulse intensity from 0.10- to 20-mW average powers. The dotted (bow tie antenna) and solid (dipole antenna) curves are fittings performed assuming that the peak-to-peak amplitude $A_{\text{p.-p.}}$ is given by $A_{\text{p.-p.}} = BF/(F+F_0)$, where F is the laser-pulse intensity (laser fluence) and B and F_0, the saturation parameters, are constants.[11,18] This equation was originally derived for a large-aperture PC antenna with a distance between the two electrodes that was larger than the typical wavelength of the terahertz waves, and the saturation parameter F_0 did not have any dependence on the antenna structure.[18] However, the saturation parameter F_0 should contain a factor that depends on the antenna structure in the present case. The equation, $A_{\text{p.-p.}} = BF/(F+F_0)$ is, strictly speaking, applicable not to the peak-to-peak amplitude but to the peak amplitude of the terahertz waves. However, since the temporal profiles of the terahertz wave detected by the antennas showed almost the same behavior regardless of the gate pulse intensity, the peak-to-peak amplitude of the terahertz wave can be fitted by the above equation. Therefore, to avoid a poor signal-to-

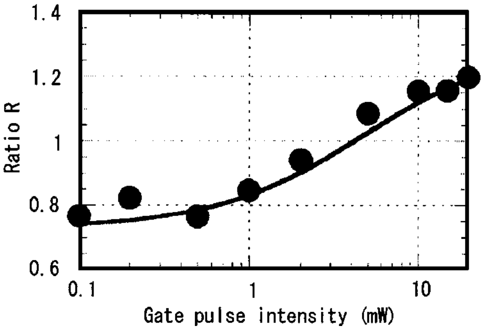

FIG. 5. Gate pulse intensity dependence of the ratio R defined as (the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna)/(the peak-to-peak amplitude of the terahertz wave detected by the dipole antenna). The curve was obtained from the fitting curves in Fig. 4. The circles show the ratio R obtained from the data in Fig. 4.

noise (S/N) ratio in the data at low gate pulse intensities, we measured the peak-to-peak amplitudes instead of the peak amplitudes. The fitting values are $B=7.9$ and $F_0=4.5$ mW for the bow tie antenna, and $B=6.1$ and $F_0=2.5$ mW for the dipole antenna.

The curve in Fig. 5 shows the ratio R (the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna)/(the peak-to-peak amplitude of the terahertz wave detected by the dipole antenna) obtained from the fitting curves in Fig. 4. The circles show the ratio R obtained from the data in Fig. 4. The peak-to-peak amplitude of the bow tie antenna was smaller than that of the dipole antenna for the gate pulse intensities of less than 5.0 mW. The peak-to-peak amplitude of the bow tie antenna was ~80% of dipole antenna at the gate pulse intensity of less than 1.0 mW. This relation was inverted and the peak-to-peak amplitude of the bow tie antenna was larger than that of the dipole antenna when the gate pulse intensity was larger than 5.0 mW. The peak-to-peak amplitude of the bow tie antenna was ~120% of that of the dipole antenna at 20-mW gate pulse intensity. The ratio R between the peak-to-peak amplitudes $A_{\text{p.-p.}}$'s increased about 40% with increasing gate pulse intensity from 0.10 to 20 mW.

The value of the peak-to-peak amplitude $A_{\text{p.-p.}}$ of the terahertz wave detected by the dipole antenna became smaller than that detected by the bow tie antenna when the gate pulse intensity was larger than 5.0 mW because $A_{\text{p.-p.}}$ saturated earlier in the dipole antenna ($F_0=2.5$ mW) than it did in the bow tie antenna ($F_0=4.5$ mW). In what follows, we consider the reasons why the ratio R changed from less than unity to larger than unity when the gate pulse intensity increased and why the F_0 value of the bow tie antenna was larger than that of the dipole antenna.

In general, the antenna structure determines the spectral characteristics of the terahertz waves. Therefore, we consider that the above inversion of the peak-to-peak amplitudes between the two antenna structures has a relation with the spectral properties of the terahertz waves detected with our experimental procedure (measuring current in PC antennas while changing the pump-to-gate pulse separation time).

We Fourier transformed the terahertz waves at several gate pulse intensities. Figures 6(a)–6(d) show terahertz spectra at the gate pulse intensities of 0.10, 1.0, 5.0, and 20 mW, respectively. The solid curves are the spectra for the dipole antenna and the dashed curves those for the bow tie antenna.

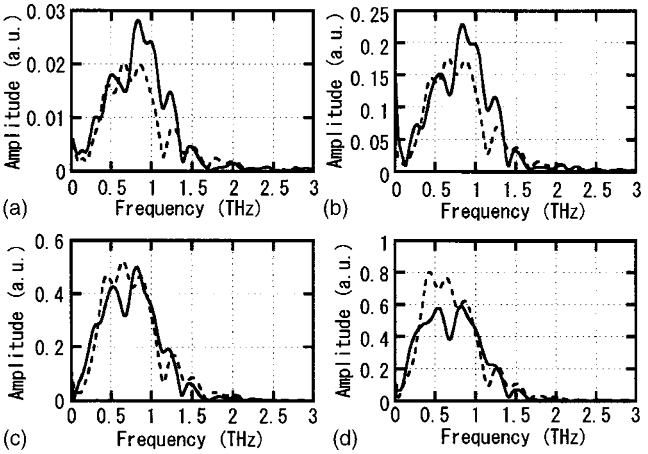

FIG. 6. Terahertz spectra detected by the bow tie antenna (dashed curve) and the dipole antenna (solid curve) at gate pulse intensities of (a) 0.10, (b) 1.0, (c) 5.0, and (d) 20 mW.

In the weak gate pulse intensity case (0.10-mW gate pulse intensity), the peak-to-peak amplitude of the dipole antenna was larger than that of the bow tie antenna. This can be understood from the fact that the spectral amplitude of the terahertz wave detected by the dipole antenna was larger than that detected by the bow tie antenna in the spectral regime from ~0.6 to ~1.3 THz. This tendency still held at the 1.0-mW gate pulse intensity, as shown by Fig. 6(b).

However, at 5.0-mW gate pulse intensity [Fig. 6(c)], the spectral amplitudes of the terahertz waves detected by the two antennas were almost the same. This gate pulse intensity corresponds to the crossing point of the peak-to-peak amplitudes of the two antennas, as shown in Fig. 5. At 20 mW [Fig. 6(d)], the spectral amplitude of the terahertz wave detected by the bow tie antenna was larger than that detected by the dipole antenna in the spectral regime from 0.25 to 0.8 THz.

In addition to the relative change of the spectral amplitudes between the two antenna structures, we notice the common characteristic that the relative amplitude of the spectrum of the detected terahertz waves in the low-frequency regime (0.7 THz) became larger than that in the high-frequency regime (0.7 THz) as the gate pulse intensity increased. This spectral change cannot be explained simply in terms of the antenna structure.

We consider that the peak frequency of the amplitude of the terahertz wave was in the high frequency regime (0.5 THz), as shown by the solid curve in Fig. 6(a), because the shape of the terahertz spectrum detected by the dipole antenna showed no clear change between 0.10- and 0.50-mW gate pulse intensities. At 0.10 mW, the peak-to-peak amplitude of the dipole antenna became larger than that of the bow tie antenna because the resonance frequency of the dipole antenna was larger than that of the bow tie antenna. However, at 20 mW, the peak sensitivity shifted to the low-frequency regime. The resulting peak-to-peak amplitude of the bow tie antenna became larger than that of the dipole antenna because the resonance frequency of the bow tie antenna was smaller than that of the dipole antenna. Therefore, the antenna-structure dependence of the resonance frequency and the gate pulse intensity dependence of the sensitivity are the reasons that the ratio R changed from less than unity to larger than unity when the gate pulse intensity increased.

We next consider the reason why the sensitivity in the low-frequency regime became larger than that in the high-frequency regime as the gate pulse intensity increased even when the emitted terahertz wave did not change.

Pump-probe spectroscopy of LT GaAs samples showed that the carrier trap time increases as the excitation pulses cause the saturation of the defect levels.[19] We also obtained similar results from pump-probe terahertz wave emission spectroscopy performed at several pump pulse intensities.

The carrier trap time works as the gate time for PC antennas when they are used as receivers. When the gate time increases, the amplitudes of the high-frequency components are averaged and canceled out, and the amplitudes of the low-frequency components increase. In this way, the detected terahertz spectrum is expected to change, and the sensitivity in the low-frequency regime increases compared to that in the high-frequency regime as the gate pulse intensity increases. Therefore, the spectrum of the detected terahertz wave changes when the gate pulse intensity increases, and the detection sensitivity in the low-frequency regime increases compared to that in the high-frequency regime.

The saturation of the peak-to-peak amplitude occurred at low gate pulse intensity for the dipole antenna because the resonance frequency of the dipole antenna was larger than that of the bow tie antenna, and because PC antennas were tend to be less sensitive in the high-frequency regime due to the saturation of the defect levels (increase of gate time) caused by the increase of the gate pulse intensity. This explains the smaller F_0 value for the dipole antenna.

Therefore, the larger saturation parameter F_0 for the bow tie antenna compared to that for the dipole antenna and the gate pulse intensity dependence of the carrier trap time (gate time), or equivalently the spectral shift of the detection sensitivity to the low-frequency regime, are the reasons for the inversion of the peak-to-peak amplitudes of the terahertz waves detected by the two antennas.

Here, we comment on the terahertz wave emitted from the surface of the InAs wafer. If the terahertz wave has only frequency components that are less than 0.5 THz (or larger than 1 THz), the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna should be larger (smaller) than that of the terahertz wave detected by the dipole antenna.

C. Effect of bias field enhancement due to geometrical effects of antenna structures

Here, we discuss why the bias field enhancement due to the geometrical effects (electrical field singularity) is not important for the present case (whole-gap excitation by the gate pulse).

We measured and compared the peak-to-peak amplitudes of the terahertz waves detected by the dipole antenna [Fig. 1(b)] and the dipole antenna with triangular tips at the gap [Fig. 1(c)]. We found that the peak-to-peak amplitudes between them (Dip: dipole antenna and Tri: dipole antenna with triangle tips) had roughly the same magnitudes, as shown in the left side of Fig. 2, and no clear evidence of peak-to-peak amplitude enhancement was found.

To make certain experimentally that whole-gap excitation reduces the importance of the bias field enhancement, we measured the peak-to-peak amplitude of the terahertz waves emitted from the antennas shown in Fig. 1. The bias voltage of 5 V was applied to the PC antennas. The pump pulse intensity was 2.0 mW and an objective lens was used to excite the whole gap of the antennas. The receiver was a PC antenna with a Si lens attached. The result shown in the right side of Fig. 2 is similar to the case of the receiver shown in the left side of Fig. 2. The main reasons we did not observe any clear effect of the bias field enhancement (enhancement of current that flow in the receiver by the bias field of the terahertz waves) are as follows:

(1) Difference of the excitation area. The bias field enhancement is considered to be limited to a small region of the antenna gap,[8] and the distribution of the strength of the electric field created by the terahertz field is not uniform within the antenna gap; it varies from high to low even if the antenna has triangular tip pairs. The carriers generated by the gate pulse in each subarea within the gap area will see the electric field in the subarea. Since the current is proportional to the summation of the product of the carrier density and the electric field in the subarea, the magnitude of the current is not necessarily determined by the highest electric field and the electrical field singularity becomes less important.

(2) Difference of emitters and receivers. The bias field is very large for emitters. (It is of the order of ~kV/cm or more on average.) For example, the application of 10 V to an antenna gap of 5 μm gives 2-kV/cm average electrical field, whereas a much smaller electrical field by the terahertz wave is applied to the gap for receivers. (A current amplifier is usually used to increase the detected signal.) This difference results in carrier dynamics (strong electric-field-related phenomena such as carrier transfer between valleys), and the screening field generated by the photogenerated carriers is considerably different between emitters and receivers. Indeed, Cai *et al.* obtained only about a 1.4-fold enhancement for receivers even when a very small excitation area (<1-μm diameter) was used.[8]

V. SUMMARY

We have shown that the peak-to-peak amplitudes and spectra of the terahertz waves detected by PC antennas depend on both the antenna structure and the gate pulse intensity. We also found a spectral shift of the sensitivity of the detected terahertz wave to the low-frequency regime when the gate pulse intensity is increased. The spectral shift is attributed to an increasing carrier trap time, which acts as the gate time for PC antennas when they are used as receivers. Contrary to the peak-to-peak amplitude enhancement of terahertz waves due to the electric-field singularity for emitters, we observed no such effect for receivers. This is due to the large spot size of the gate pulses and the different carrier dynamics. We also observed that the peak-to-peak amplitude of the terahertz wave detected by the bow tie antenna was initially smaller and then became larger than that detected by the dipole antenna as the gate pulse intensity increased. This phenomenon is attributed to the gate pulse intensity dependence of the spectral sensitivity and the antenna-structure dependence of the resonance frequency. To avoid a peak frequency shift of the detected terahertz spectrum to the low-frequency side, the gap structure of the antenna has to be designed appropriately along with a suitable spot size and excitation position of the gate pulse. On the other hand, if the terahertz wave contains only low-frequency components, a high intensity gate pulse will be suitable to increase the carrier trap time and thereby increase the amplitude of the detected terahertz wave. To increase the peak-to-peak amplitude of the detected terahertz waves, it is important to control the carrier trap times by gate pulses as well as design antenna structures that take into account of the resonance frequencies.

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