Japanese Journal of Applied Physics
Vol. 45, No. 11, 2006, pp. 8714–8716

Brief Communication

Improvement of Signal-to-Noise Ratio of Terahertz Electromagnetic Waves by Bias Field Modulation of Photoconductive Antenna

Ryuzi YANO[1,2], Toshiaki HATTORI[3] and Hiroyuki SHINOJIMA[4]

[1]*Muroran Institute of Technology, 27-1 Mizumoto-cho, Muroran, Hokkaido 050-8585, Japan*
[2]*NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan*
[3]*Institute of Applied Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan*
[4]*NTT MI Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan*

(Received March 16, 2006; accepted July 14, 2006; published online November 8, 2006)

Inversion of the direction of the DC bias field applied to a photoconductive (PC) antenna produces a terahertz wave with its sign changed. We succeeded in increasing the signal amplitudes of the terahertz electromagnetic waves emitted from a pc antenna by a factor of 2 by modulating the polarization of the bias field applied to the PC antenna in the lock-in detection scheme. By this method, we were able to increase the signal-to-noise ratio of the terahertz electromagnetic waves by a factor of 2. [DOI: 10.1143/JJAP.45.8714]

KEYWORDS: terahertz electromagnetic wave, bias field modulation, photoconductive antenna

In experiments on terahertz electromagnetic waves, femtosecond laser pulses are often used to excite a photoconductive (PC) antenna that works as a terahertz wave emitter.[1)] In this case, an optical chopper is often used to modulate the intensity of the femtosecond laser pulses to obtain the temporal waveforms of the terahertz electromagnetic waves with a good signal-to-noise ratio (S/N) using a lock-in detection method.

To evaluate the response (complex refractive index) of a material in the terahertz frequency region, the temporal profiles of the terahertz electromagnetic wave before the incidence and after it passes through the material (or after it is reflected from the material) are often compared. However, the evaluation is not simple owing to the problem of the S/N when the amount of change between the two temporal profiles is small, or when the amplitude of the terahertz wave transmitted through (reflected from) the material is small.

Lock-in detection by modulating the intensity of the laser pulses with an optical chopper is often used to obtain the temporal waveform of the terahertz waves. However, another modulation technique is also possible. The modulation of a bias field applied to a PC antenna was performed by Yasui and Araki.[2)] They only modulated the magnitude of the bias field at a high frequency (100 kHz) to reduce the noise (multiplicative noise[3)]) of the terahertz waves due to the laser intensity fluctuation. If the noise is an additive noise[3)] (the noise is independent of the presence of the terahertz waves), however, it is possible to increase the S/N of the terahertz waves without employing high-frequency modulation.

In this study, instead of modulating the laser pulses that excite a PC antenna (a terahertz wave emitter), we modulated the bias field applied to the PC antenna. The inversion of the applied DC bias field to the PC antenna produces a terahertz wave with its sign changed. We succeeded in increasing the amplitudes and also the S/N of the terahertz electromagnetic waves emitted from a PC antenna by a factor of 2 by modulating the polarization of the bias field applied to the PC antenna.

The polarization modulation of a femtosecond laser pulse that excites a terahertz wave emitter is suitable for EO crystals such as ZnTe, because this method changes the sign of the terahertz electromagnetic waves.[4)] However, this method is not suitable for PC antennas as the polarization modulation only changes the amplitude of the terahertz electromagnetic waves.[5,6)]

In this experiment using a PC antenna as a terahertz wave emitter, the sign of the terahertz electromagnetic waves can be changed by reversing the direction of the bias field. As a result, the size of the signal effectively doubles. In this case, if the noise is an additive noise, we can increase the S/N of the terahertz wave by a factor of 2.

To obtain terahertz wave signals with an effectively doubled amplitude, the temporal waveform of the terahertz waves at positive and negative bias fields should be the same, and the amplitude of the terahertz waves should be proportional to the magnitude of the bias field. To obtain a linear dependence of the magnitude of the terahertz electromagnetic waves on the bias field, a spatially symmetric excitation of the antenna gap with laser pulses is favorable.

If the laser pulse does not uniformly excite the whole antenna gap of a PC antenna, the temporal waveforms and amplitudes of the waveforms with opposite bias fields may be different.[5,6)] In this case, one may suspect that the above idea cannot be applied owing to the complexity of the terahertz waves. However, as shown in the following simple consideration, even when the terahertz waveforms with opposite bias fields are different, we can apply our idea, and the magnitude of the terahertz wave effectively increases. Thus, we obtain a higher S/N. We also show that even if the terahertz waveforms with opposite bias fields are different, we can obtain complex the refractive index of the material.

First, we consider the lock-in detection scheme using an optical chopper. We write the detected terahertz waveform without a sample (with a sample) as $f(t)^{\mathrm{OUT}}$ [$f(t)^{\mathrm{IN}}$]. Here, the superscript "OUT" means that the sample is out of the propagation path of the terahertz wave and "IN" means that the sample is in the propagation path of the terahertz wave. (Here, we consider a transmission experiment, where a sample is inserted in the path of the terahertz pulses.) Then, the Fourier transform $E^{\mathrm{OUT}}(\omega)$ [$E^{\mathrm{IN}}(\omega)$] of $f(t)^{\mathrm{OUT}}$ [$f(t)^{\mathrm{IN}}$] is written as

$$E^{\mathrm{OUT(IN)}}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f^{\mathrm{OUT(IN)}}(t)\exp(i\omega t)\,dt, \qquad (1)$$

For $E^{\mathrm{OUT}}(\omega)$ and $E^{\mathrm{IN}}(\omega)$, the following relation holds:

$$E^{\mathrm{IN}}(\omega) = E^{\mathrm{OUT}}(\omega)t(\omega), \qquad (2)$$

where $t(\omega)$ contains the information of the response (complex refractive index) of the sample.

Next, we consider the lock-in detection scheme using a bias field modulation. We assume that for the positive (negative) bias field, we have a terahertz waveform of $f_1^{\mathrm{OUT}}(t)$ $[-f_2^{\mathrm{OUT}}(t)]$ without a sample. Here, for simplicity, the temporal waveform of the terahertz wave is only dependent of the sign of the bias field and is independent of the magnitude of the bias field. Of course, the amplitude of the terahertz wave depends on the amplitude of the bias field.[7] Similarly, we have a terahertz waveform of $f_1^{\mathrm{IN}}(t)$ $[-f_2^{\mathrm{IN}}(t)]$ with a sample for the positive (negative) bias field.

If we follow the above assumptions, the detected waveform (the effective temporal waveform of terahertz pulses) is the sum of the two waveforms: $f_1^{\mathrm{IN}}(t) + f_2^{\mathrm{IN}}(t)$ or $f_1^{\mathrm{OUT}}(t) + f_2^{\mathrm{OUT}}(t)$. Here, we assume that $f_1^{\mathrm{IN(OUT)}}(t)$ is in phase and $-f_2^{\mathrm{IN(OUT)}}(t)$ is out of phase with the reference signal. Therefore, we obtain the effective waveform of the terahertz pulse with a sample $[f_{\mathrm{SUM}}^{\mathrm{IN}}(t)]$ and without a sample $[f_{\mathrm{SUM}}^{\mathrm{OUT}}(t)]$ in the following.

$$f_{\mathrm{SUM}}^{\mathrm{OUT}}(t) = \sum_{j=1}^{2} f_j^{\mathrm{OUT}}(t), \quad f_{\mathrm{SUM}}^{\mathrm{IN}}(t) = \sum_{j=1}^{2} f_j^{\mathrm{IN}}(t). \tag{3}$$

In the femtosecond laser pulse excitation of a PC antenna with a bias field, both $f_1^{\mathrm{OUT}}(t)$ and $f_2^{\mathrm{OUT}}(t)$ take their maximum at a certain time t_{max}. Therefore, we can safely assume that $|f_1^{\mathrm{OUT}}(t_{\mathrm{max}}) + f_2^{\mathrm{OUT}}(t_{\mathrm{max}})| > |f_j^{\mathrm{OUT}}(t_{\mathrm{max}})|$ for $j =$ 1 and 2. This means that the amplitude of the terahertz wave $f_{\mathrm{SUM}}^{\mathrm{OUT}}(t) \equiv f_1^{\mathrm{OUT}}(t) + f_2^{\mathrm{OUT}}(t)$ detected by the bias field modulation is larger than that detected by the optical chopper modulation. If $f_1^{\mathrm{OUT}}(t) = f_2^{\mathrm{OUT}}(t)$, then the amplitude of the signal effectively doubles.

Next, we consider the complex refractive index measurement of a sample. If we define

$$E_j^{\mathrm{OUT(IN)}}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f_j^{\mathrm{OUT(IN)}}(t)\exp(i\omega t)\,dt, \tag{4}$$

as in the case of the optical chopper modulation scheme, the relation

$$E_j^{\mathrm{IN}}(\omega) = E_j^{\mathrm{OUT}}(\omega)t(\omega) \tag{5}$$

holds for $j = 1$ and 2. Therefore, the Fourier transform $E_{\mathrm{SUM}}^{\mathrm{OUT}}(\omega)$ of $f_{\mathrm{SUM}}^{\mathrm{OUT}}(t)$ is given by

$$\begin{aligned} E_{\mathrm{SUM}}^{\mathrm{IN}}(\omega) &= \frac{1}{2\pi}\int_{-\infty}^{+\infty} \left\{ \sum_{j=1}^{2} f_j^{\mathrm{IN}}(t) \right\} \exp(i\omega t)\,dt \\ &= \sum_{j=1}^{2} E_j^{\mathrm{OUT}}(\omega)\cdot t(\omega) = E_{\mathrm{SUM}}^{\mathrm{OUT}}\cdot t(\omega). \end{aligned} \tag{6}$$

Thus, we can effectively regard the temporal waveform detected by the lock-in detection with the bias field modulation as the terahertz pulse. These results show that even if the temporal waveform of the terahertz wave depends on the bias field, we can effectively regard the detected waveform as the terahertz waveform. In this way, we can obtain the complex refractive index from eq. (6).

The excitation source was a mode-locked Ti:Al_2O_3 laser with a pulse width of $\sim$200 fs and a repetition of 100 MHz. The center laser wavelength was set to 800 nm. The output of the laser was divided by a beam splitter into pump and probe pulses. The pump pulses were guided and focused by an objective lens to a PC antenna (a terahertz wave emitter).

The PC antenna[7] had a 30-μm-long and 5-μm-wide dipole with a 5-μm-gap in the center, and was integrated into a coplanar transmission line (the strip line width of 10 μm and a separation of 30 μm). The antenna structure was fabricated on low-temperature grown GaAs with metal layers. A high-resistivity Si lens was attached to the antenna to collimate the terahertz waves. The spot size (e^{-2}) of the pump pulses at the PC antenna was $\sim$10 μm. This spot size is enough for the symmetric excitation of the PC antenna with laser pulses. This excitation condition was favorable also to avoid the shortening of the device lifetime of the PC antennas.[8] The carrier density estimated at the LT-GaAs was $\sim 10^{17}$ cm^{-3}/pulse at 1 mW average power. The bias voltage applied to the PC antenna was typically 14 V.

The terahertz waves emitted from the PC antenna were collimated using two off-axis mirrors and were detected by an electro-optic (EO) sampling technique using a 1-mm-thick $\langle 110 \rangle$ ZnTe crystal and a quarter-wave plate.[9] The terahertz waves were collimated using a 150-mm-focal-length off-axis parabolic mirror and were focused on the ZnTe crystal. The probe pulses of 0.4 mW average power were also focused on the ZnTe crystal using a pellicle beam splitter. For the lock-in detection, an optical chopper modulated the pump pulses, or the bias field applied to the PC antenna was modulated.

To measure the peak amplitude of the terahertz electromagnetic waves, the probe pulse was set temporally to the peak of the terahertz waves. In measuring the temporal profiles of terahertz electromagnetic waves, the output of the lock-in amplifier was measured as a function of the time separation between the pump and probe pulses.

Figure 1 shows the bias field dependence of the peak amplitude (including the sign) of the terahertz wave at a bias voltage from -14 to $+14$ V. The peak amplitude of the terahertz electromagnetic wave depends almost linearly on the bias voltage. The deviation from a perfect linear dependence may be attributed partly to the size of the laser spot size and also to the position of the excitation point within the gap of the PC antenna.

The terahertz electromagnetic waves detected by optical chopper modulation (dashed gray curve) and bias field modulation (solid curve) are shown in Fig. 2(a). To make clear the difference in the magnitudes of the amplitudes of both signals, an offset of -3 was added to the terahertz wave detected by optical chopper modulation (dashed gray curve). The modulation frequency was 1.2 kHz for both methods, and the other parameters were the same. The amplitude of the terahertz waveform detected by the bias field modulation

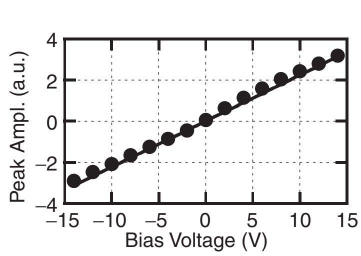

Fig. 1. Bias field dependence of peak amplitude (including sign) of terahertz wave at bias voltage from -14 to $+14$ V.

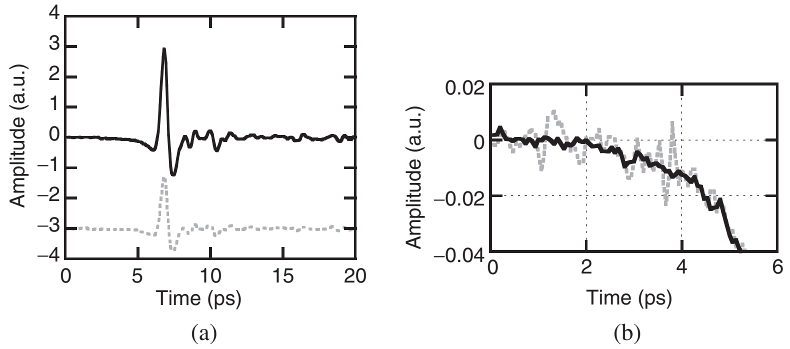

Fig. 2. (a) Terahertz electromagnetic waves detected by optical chopper modulation (dashed gray curve) and bias field modulation (solid curve). The modulation frequency was 1.2 kHz for both methods. An offset of -3 was added the signal detected by the optical chopper modulation (gray dashed curve) to make clear the difference in the amplitudes of both terahertz waves. (b) Section (time region from 0 to 6 ps) of terahertz electromagnetic waves shown in Fig. 2(a). Both waveforms were normalized to unity and were then vertically expanded.

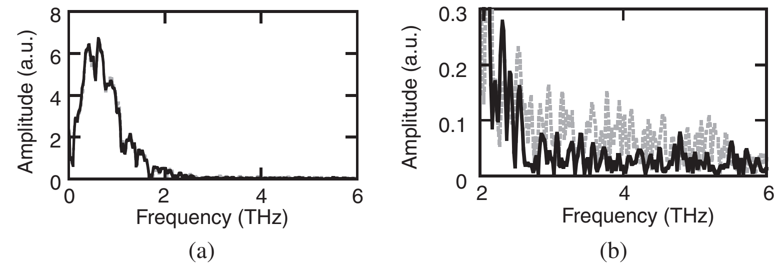

Fig. 3. (a) Spectra (Fourier transform) of terahertz waves shown in Fig. 2. The solid (dashed gray) curve is the spectrum of the terahertz wave detected by bias field (optical chopper) modulation. (b) Spectra of terahertz waves shown in Fig. 3 from 2 to 6 THz region expanded vertically.

was a factor of ~2 larger than that detected by optical chopper modulation. The magnitudes of the noises of both the terahertz waves were observed to be the same. Figure 2(b) is a section (time region from 0 to 6 ps) of the terahertz electromagnetic waves expanded vertically to show the difference in the S/N between the waveforms detected by the two methods. In this case, both waveforms were normalized to unity and were then vertically expanded. We clearly see that the S/N of the signal detected by bias field modulation is higher than that detected by optical chopper modulation. Thus bias field modulation improved the S/N of the waveform compared with optical chopper modulation.

Figure 3(a) shows the spectra (Fourier transform) of the terahertz waves shown in Fig. 2(a). The solid curve is the spectrum of the terahertz wave detected by bias field modulation, and the dashed gray curve is the one of the terahertz wave detected by optical chopper modulation. In obtaining the spectra, we first normalized the terahertz waveforms and Fourier transformation was performed. Figure 3(b) is the expanded spectra of the same terahertz waves with the spectral range from 2 to 6 THz. We clearly see that the amplitude of the spectrum of the terahertz wave detected by bias field modulation is smaller than that detected by optical chopper modulation. These small amplitudes at each frequency in the high-frequency region (2 to 6 THz) were attributed to the increase of the S/N.

If the noise is multiplicative, the amplitude of the noise component will also increase, and no improvement of the S/N will be achieved. However, by increasing the amplitude of the terahertz wave, we obtained a waveform with a higher S/N. This means that the noise component was additive.

In the generation of the terahertz waves, the laser pulses excited the whole gap of the PC antenna. Therefore, the spatial fluctuation of the excitation position of the laser pulses due to the mechanical vibration of the optical components was considered to be small. Therefore, we concluded that the noise component was created mainly during the detection process of the terahertz waveform. This means that the spatial overlap of the terahertz waves and probe pulses is a serious problem in measuring the terahertz waveform, as suggested by ref. 10.

The absorption frequencies of the water vapor and other gases detected by both optical chopper and bias field modulations are shown by the dips of the terahertz spectra in Fig. 3. The frequency positions and the depths of these dips are the same for both detection methods. This is an experimental verification of eq. (6) for the imaginary part of the refractive index (the extinction ratio).

To summarize, by using bias field modulation, we have increased the amplitude of the terahertz wave by a factor of 2. When the DC bias field applied to the PC antenna changes its sign, the terahertz electromagnetic wave emitted from the PC antenna changes its sign. By this method, we also succeeded in increasing the S/N of the terahertz waves emitted from a PC antenna by a factor of 2. We have also shown by a simple calculation that even if the temporal waveforms of the terahertz waves are bias-field dependent, we can effectively regard the waveform measured by a lock-in detection as the actual terahertz waveform.

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