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Ultrabroadband Detection of Terahertz Radiation up to 20 THz with an LT-GaAs Photoconductive Antenna Gated by 15-fs Laser Pulses

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Abstract – **We report on the ultrabroadband detection of terahertz radiation with a low-temperature grown GaAs photoconductive dipole antenna gated with 15-fs laser pulses. The detected spectral frequency exceeds 20 THz. This is the highest frequency detected with a photoconductive antenna reported so far.**

I. INTRODUCTION

Since the invention of the photoconductive (PC) antenna gated with ultrashort optical pulses, the generation and detection of terahertz (THz) radiation have been intensively studied during the last decade. The pulse width of commercially available mode-locked Ti:Sapphire lasers is approaching 10 fs. With such ultrashort pulses, a wider detection bandwidth is expected to be possible. Coherent detection of THz radiation based on a photoconductive antenna, however, was reported to be lower than 5 THz [1,2]. This limitation has been explained to be a result of the finite carrier lifetime and the RC time constant of the PC antenna. Therefore, interest in ultrafast detection of the radiation has recently shifted to the free-space electro-optic (EO) sampling technique because EO crystals are considered to have an instantaneous nonlinear response, and most of them are transparent in the regime from far to mid-infrared radiation. By exploiting these advantages, ultrabroadband detection of THz radiation based on EO sampling has been reported [3,4]. To obtain high-frequency response using EO sampling, the EO crystals should be thin enough to reduce the group velocity mismatch between the near-infrared probe beam and the THz radiation.

However, even with a PC antenna fabricated on slow carrier lifetime semiconductors, such as semi-insulating (SI) GaAs or SI InP, the detection of relatively broadband (~3 THz) THz radiation was reported [5,6]. This detection with a slow carrier lifetime was possibly due to the fast-rising edge of the carrier injected by the ultrashort optical pulses. This suggests that the detection bandwidth is not strongly restricted by the carrier lifetime and is possibly extended by using shorter laser pulses. Thus, it is worthwhile to investigate the high-frequency limit of a PC antenna gated with ultrashort optical pulses whose width is close to 10 fs.

In this article, we demonstrate an ultrabroadband detection of electromagnetic radiation with a PC antenna fabricated on a low-temperature-grown GaAs (LT-GaAs) substrate and gated with 15-fs laser pulses. The detected radiation frequency exceeded 20 THz. This is the highest frequency observed with PC antennas reported so far.

II. EXPERIMENTAL

A mode-locked Ti:Sapphire laser generated 12-fs laser pulses at a center wavelength of 800 nm and with a spectrum width of 90 nm (FWHM). The average output power of the laser was 320 mW. The laser beam was divided into pump and probe beams by a 1-mm glass-plate beam splitter. The average power of the pump beam was about 110 mW. The pump beam was collimated onto a SI InP (100) wafer by a silver-coated off-axis parabolic mirror with an incident angle of 45 degrees. The THz radiation from the emitter was collected in the reflection angle of the incident pump beam by a pair of off-axis parabolic mirrors and then focused on the PC detector. A silicon hemispherical lens was attached to the back side of the PC antenna to collimate the THz radiation.

The PC antenna was a 30-μm long dipole antenna with a 5-μm gap at the center, fabricated onto an LT-GaAs. The carrier lifetime of the LT-GaAs was estimated to be about 1.4 ps by a transient photo-reflectance measurement. The probe beam was focused onto the photoconductive gap with a reflection-type objective lens to avoid broadening of the optical pulses due to the dispersion and color aberration typically caused by an ordinary glass lens. The timing between the THz pulses and the probe pulses was scanned by the time delay line in the path of the probe beam with a corner reflector on a high-precision motorized translation stage.

The laser pulses were negatively chirped at the exit of the laser due to a multiple reflections between the pair of chirped mirrors. Even after the chirp of the laser pulses were positively compensated by the insertion of the beam splitters and neutral density filters, the pulse width on the semiconductor emitter and PC antenna was approximately 15 fs. The photo-current signal from the PC antenna was preamplified with a low-noise current amplifier and then detected with a lock-in amplifier referenced to an optical chopper (2 kHz) in the pump beam path.

III. RESULTS AND DISCUSSIONS

Figure 1(a) shows the waveform of THz radiation from a SI-InP (100) emitter for a single scan. The time constant of the lock-in amplifier was 0.1 sec, and the scanning time for a 3-ps time window was about 3 minutes with a 1-μm step resolution in the delay-line translation stage. There was a single THz pulse centered around 0.5 ps,

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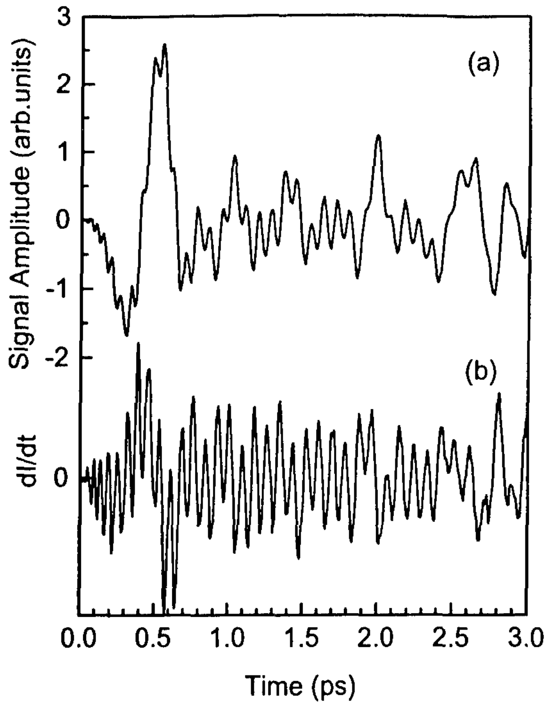

Fig. 1 (a) Time-resolved waveform of THz radiation from InP (100) surface. (b) Calculated time-derivative of the waveform (a).

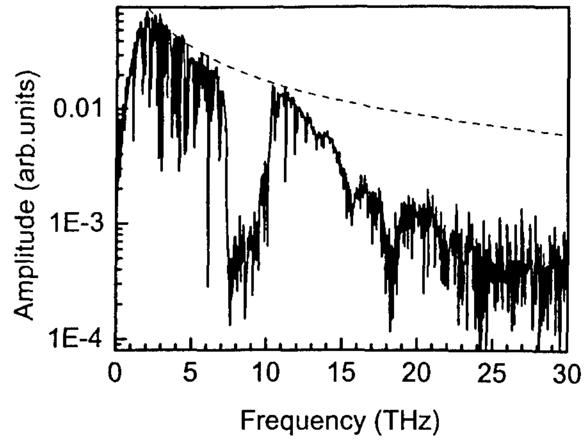

Fig. 2 Fourier transformed spectra of THz radiation wave form in Fig. 1 (a) for a longer time window. The dashed line represents the RC response function with the RC time constant of 0.2 ps.

which is attributed to the radiation due to the real current modulation at the emitter surface. Very fast oscillations were superposed on this pulse. The shortest oscillation period was about 45 fs. These fast oscillations were attributed to the radiation generated by the optical rectification effect in the emitter. Figure 1(b) shows the calculated first time-derivative for the waveform in Fig. 1(a). The fast oscillations are clearly visible in Fig.1(b) because the slow component was suppressed while the fast oscillation component was enhanced by differentiation. The ringings after the first single and large cycle of oscillation were mainly attributed to dispersion and absorption in the GaAs substrate of the detector and absorption by water vapor in the ambient air.

Figure 2 shows the Fourier transformed spectrum of the THz radiation waveform shown in Fig. 1(a) for a longer time window. The spectrum was extended more than 20 THz. This bandwidth is four times wider than the widest bandwidth achieved by a PC antenna ever reported. The absorption band from 7 to 9 THz was due to the phonon resonance in the 0.4-mm thick GaAs substrate of the PC detector (Reststrahlen band). The peak at 10.5 THz corresponds to the LO phonon frequency of InP. Many of the absorption lines observed in the spectrum were due to the water vapor in the ambient air.

It is rather surprising that the bandwidth of the PC antenna exceeded 20 THz. We need to explain the origin of this ultrabroadband band response. It has been reported that a PC antenna with a very long carrier lifetime (~100 ps) was able to detect THz radiation with almost the same detection bandwidth of a PC antenna with a subpicoseond carrier lifetime. The fast temporal response of a slow photoconductive antenna can be explained by the fast rise of its photocurrent on excitation by the ultrashort laser pulse. As described in Ref. [5,6], if the response function of the PC antenna with a slow carrier lifetime is a step-function, the PC antenna works as a sampling detector in an integration mode. This appear to be the case in the present experiment: the carrier lifetime of the LT-GaAs (~1 ps) was much longer than the gating pulse width. The fact that the time derivative of the THz waveform shown in Fig.1(b) is similar to that of Ref. [3] also supports our interpretation. The physical origin of the fast photocurrent within the time scale of ~100 fs still needs to be investigated. However, it may be explained by the ballistic transport of the photo-excited electrons in the biased electric field, which was reported by Hu et al. in the same time range [7].

In addition to the carrier lifetime, the RC constant of the antenna is an important parameter in determining the frequency response. In a previous report, we estimated an RC time constant for the same type of antenna to be of the order of subpicoseconds (~0.2 ps) [8]. This finite RC time constant restricts the bandwidth of the PC antenna and reduces its responsivity at higher frequencies. The frequency response of the PC antenna was approximated by the equation of the differential circuit $G(\omega)=X_C/\sqrt{R^2+X_C^2}$, where $X_C=1/\omega C$, R is the resistance of the PC antenna, and C is the capacitance formed between the antenna electrodes. For example, for a 0.2 ps RC time constant, the cut-off frequency was calculated to be about 0.8 THz. The responsivity of the antenna at 5 and 10 THz respectively decreases to 25 and 13 % of that at the cut-off frequency. The circuit response function in the frequency domain calculated with an RC time constant of 0.2 ps is indicated by the dashed line in Fig. 2. The RC response function reproduces the spectral profile at the frequency range lower than 5 THz. In spite of the reduction of the circuit responsivity due to the carrier lifetime, this slow decay of the frequency response can be one of the reasons of our observation of radiation at unexpectedly high frequencies with a PC antenna. Other factors, such as the emitter bandwidth and absorption or reflection loss, will be necessary for better reproduction of the overall spectral profile.

IV. CONCLUSION

In conclusion, we demonstrated that a PC antenna gated with 15-fs laser pulses was capable of ultrabroadband detection up to 20 THz. This is the highest frequency detected with PC antennas than ever reported. PC antenna is also promising for ultrabroadband detection as well as the EO sampling technique. In the EO sampling technique, the strong absorption and dispersion at the phonon resonance frequencies of EO crystals is a disadvantage. Although we also observed the strong phonon absorption in GaAs substrate, this problem can be avoided by fabricating the LT-GaAs on another substrate material, such as high resistivity silicon.

References

1. N. Katzennellenbogen and D. Grischkowsky, "Electrical characterization to 4 THz of N- and P-type GaAs using THz time-domain spectroscopy," Appl. Phys. Lett. 61, 840-842 1992
2. M. Tani, R. Fukasawa, H. Abe, S. Matsuura, K. Sakai, and S. Nakashima, "Terahertz Radiation from Coherent Phonons Excited in Semiconductors," J. Appl. Phys. 83, 2473-2477 1998
3. Q. Wu, and X.-C. Zhang, "Free-space electro-optics sampling of mid-infrared pulses", Appl. Phys. Lett. 71, 1285-1287 1997
4. A. Leitenstorfer, S. Hunsche, J. Shah, M. C. Nuss, and W. H. Knox, "Detectors and sources for ultrabroadband electro-optic sampling: Experiment and theory", Appl. Phys. Lett. 74, 1516-1518 1999
5. F. G. Sun, G. A. Wagoner, and X.-C. Zhang, "Measurement of free-space terahertz pulses via long-lifetime photoconductors," Appl. Phys. Lett. 67, 1656-1658 1995
6. M. Tani, K. Sakai and H. Mimura, "Ultrafast Photoconductive Detectors Based on Semi-Insulating GaAs and InP" Jpn. J. Appl. Phys., 36, L1175-L1178 1997
7. B. B. Hu, E. A. de Souza, W. H. Knox, J. E. Cunningham, M. C. Nuss, A. V. Kuznetsov, and S. L. Chuang, "Identifying the distinct phases of carrier transport in semiconductors with 10 fs resolution", Phys. Rev. Lett. 74, 1689-1692 1995
8. Shuji Matsuura, Masahiko Tani and Kiyomi Sakai, "Generation of coherent terahertz radiation by photomixing in dipole photoconductive antennas," Appl. Phsy. Lett. 70, 550-561 1997