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Detection of up to 20 THz with a low-temperature-grown GaAs photoconductive antenna gated with 15 fs light pulses

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We report on the ultrabroadband coherent detection of radiation in wavelengths spanning from far to midinfrared with a low-temperature-grown GaAs photoconductive dipole antenna gated with 15 fs light pulses. The detected spectral frequency exceeds 20 THz. © *2000 American Institute of Physics.* [S0003-6951(00)05451-6]

The generation and detection of terahertz (THz) radiation using ultrashort optical pulses has 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 (PC) antenna, however, was reported to be lower than 7 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 assumed to have an instantaneous nonlinear response, and most of them are transparent in the far to midinfrared radiation regime. 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 has been 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 letter, we report on the ultrabroadband detection of electromagnetic radiation, extending up to the midinfrared regime, 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 by PC antennas reported so far.

The 12 fs light pulses were delivered from a mode-locked Ti:sapphire laser (Femtolasers Produktions, Femtosource PRO) at a center wavelength of 800 nm and with a spectral width of 90 nm (full width at half maximum). The average output power of the laser was 320 mW. The laser beam was divided into pump and probe beams by a 1-mm-thick glass-plate beam splitter. The average power of the pump beam was about 110 mW. The pump beam was focused onto a SI InP (100) wafer by a silver-coated off-axis parabolic mirror with an incident angle of 45°. The THz radiation from the emitter was collected at the reflection angle of the incident pump beam by a pair of off-axis parabolic mirrors and then focused onto the PC detector. A silicon aplanatic hemispherical lens whose diameter was 12 mm was attached to the PC antenna to focus the THz radiation.

The PC antenna was a 30-μm-long dipole antenna with a 5 μm gap at the center, fabricated on an LT GaAs wafer. The 1.5-μm-thick LT GaAs layer was grown at 250 °C on the GaAs substrate whose thickness was 0.4 mm. The carrier lifetime of the LT GaAs was estimated to be about 1.4 ps by a transient photoreflectance 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 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 photocurrent 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.

Figure 1(a) shows the wave form of the THz radiation from the SI InP (100) emitter for a single scan. The time constant of the lock-in amplifier was 0.1 s, and the scanning time for the 3 ps time window was about 3 min with a 1 μm step resolution in the delay-line translation stage. There is a single THz pulse centered around 0.5 ps, which is attributed to the radiation due to the current modulated from the surface field of the InP. Very fast oscillations are superimposed on this pulse. The shortest oscillation period is about 45 fs and the periods of the oscillations are not constant. We did

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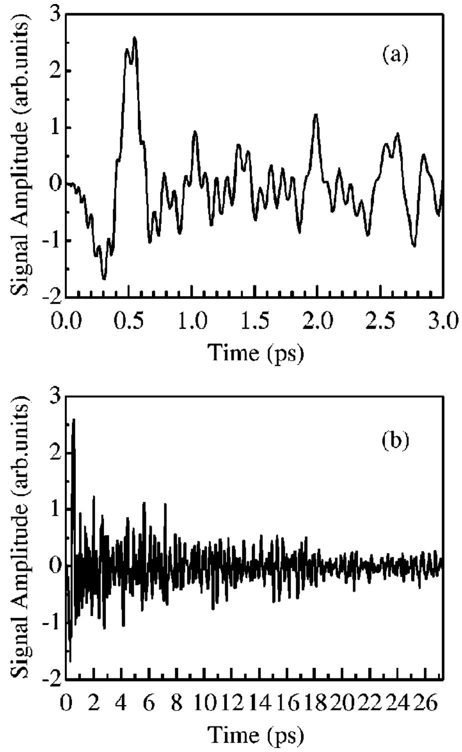

FIG. 1. (a) Beginning of the time-resolved wave form of THz radiation from the InP (100) surface. (b) The entire time-resolved THz wave form. This wave form was used for the calculation of the Fourier transformed spectra shown in Fig. 2.

not clearly observe the expected 95 fs oscillation due to the coherent oscillation of the longitudinal optical (LO) phonon of the InP emitter, as shown in Fig. 3(a) of Ref. 4. Thus, these fast oscillations may be attributed to the radiation generated by the optical rectification effect in the emitter. The rings after the peak signal are mainly attributed to the beats between the coherent oscillation of the LO phonon in the InP emitter and the fast oscillation due to the optical rectification effect because the periods of the rings are not constant. These beats are, at the same time, affected by the 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 wave form shown in Fig. 1(b). The spectrum extends beyond 20 THz. This bandwidth is almost three times wider than the widest bandwidth ever achieved by a PC antenna. The absorption band from 7 to 9 THz is due to

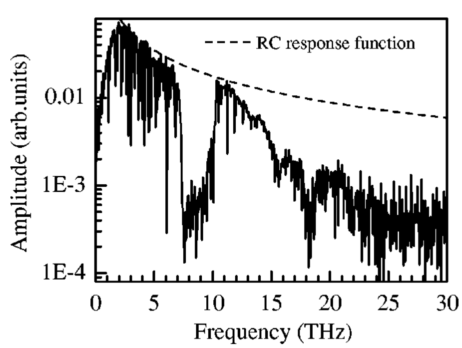

FIG. 2. Fourier transformed spectra of THz radiation waveform in Fig. 1 (b). The dashed curve represents the RC response function of the receiver antenna with an RC time constant of 0.2 ps.

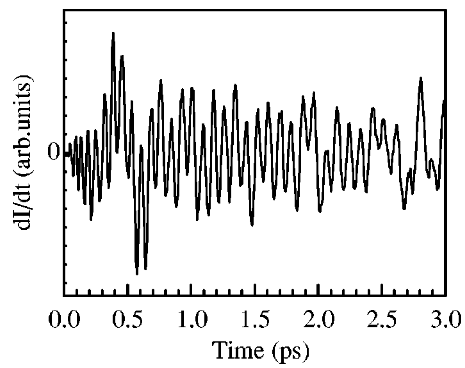

FIG. 3. Calculated time derivative of the THz-radiation wave form of the THz radiation shown in Fig. 1(a).

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. The fast oscillations due to the optical rectification effect extend the tail of the spectrum higher than this LO-phonon resonance. Many of the absorption lines observed in the spectrum are due to the water vapor in the ambient air. The strong absorption lines at 6.08, 11.24, and 11.83 THz correspond to the water vapor absorption lines in the literature [7] within the spectral resolution of 36.6 GHz. The absorption centered at 15.5 THz is due to the phonon oscillation in the Si hemispherical lens.[8] The absorption band centered at about 18.2 THz is mainly attributed to the two-phonon absorption due to the combination of a transverse optical and a transverse acoustic phonon in the Si hemispherical lens.[9]

It is rather surprising that the bandwidth of the PC antenna exceeded 20 THz. We need to explain the origin of this ultrabroadband 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 subpicosecond carrier lifetime.[5,6] 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. 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. Figure 3 presents the calculated time derivative of the wave form shown in Fig. 1(a). This time-differentiated wave form is similar to Fig. 3 of Ref. 3. This supports the theory that the PC antenna was working in an integration mode. The physical origin of the fast photocurrent within the initial ~100 fs still needs to be investigated. However, it may be explained by the ballistic transport of the photoexcited electrons in the biased electric field, which was experimentally observed by Hu *et al.* in the same time range.[10]

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 approximately 0.2 ps.[11] This finite RC time constant restricts the bandwidth of the PC antenna and reduces its responsivity at higher frequencies. Our observation of radiation at unexpectedly high frequencies with a PC antenna can be explained by the relatively slow decay of the frequency response for the RC time constant. 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 cutoff 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 cutoff frequency. The circuit response function in the frequency domain calculated with an RC time constant of 0.2 ps is indicated by the dashed curve in Fig. 2. The RC response function reproduces the spectral profile for the frequency range from 2 to 11 THz, except for the Reststrahlen absorption band. We need to include other factors, such as the emitter bandwidth and absorption or reflection loss, for better reproduction of the overall spectral profile.

In conclusion, we demonstrated that a PC antenna gated with 15 fs laser pulses was capable of ultrabroadband detection up to 20 THz, comparable to that reported with EO sampling using a thin EO crystal. In the EO sampling technique, the strong absorption and dispersion at the phonon resonance frequencies of EO crystals is a disadvantage. We also observed strong phonon absorption in the GaAs substrate but this problem can be avoided by fabricating the LT GaAs on a suitable substrate material, such as high resistivity silicon.

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