Terahertz radiation from a shallow incidence-angle InAs emitter in a magnetic field irradiated with femtosecond laser pulses

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The optimized incidence angle and magnetic field direction geometry of an InAs terahertz radiation emitter irradiated with femtosecond laser pulses in a magnetic field is reported. The optimum geometric layout is the magnetic field direction parallel to the semiconductor surface and at an incidence angle that is slightly larger than the Brewster angle. Additionally, we also observed a center frequency shift of terahertz radiation spectrum by changing the incidence angle of the excitation laser. © 2001 Optical Society of America

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There has been a strong need for an intense, compact, and stable terahertz (THz) radiation source for applications to sensing, imaging, and spectroscopy.1–6 Among the numerous THz radiation generation schemes, THz radiation generation from a semiconductor surface in a magnetic field has attracted much attention because of its simplicity and intensity. Zhang et al. reported the quadratic magnetic field dependence of THz radiation power from GaAs irradiated with femtosecond laser pulses.7 Previously, we reported approximately one-order higher enhancement of THz radiation power from an InAs at higher magnetic field and excitation power.8–10 Liquid-helium-cooled bolometers, time-gated dipole antennas, and electro-optic sampling have been widely used for the detection of THz radiation. However, experimental flexibility was largely restricted by the detection system because of the use of liquid helium or the precise time-delay adjustment. Significant enhancement of the THz radiation power from the THz radiation emitter has already been achieved with the magnetic-field enhancement scheme. If we were to obtain more intense THz radiation, we could utilize less sensitive, inexpensive detectors at room temperature, for example, a deuterated triglycine sulfate pyroelectric thermal receiver. Here we report on the optimized incidence angle and magnetic field direction of the THz radiation source. We also observed the incidence-angle dependence of the THz radiation power and spectrum.

The experimental setup is shown in Fig. 1. A mode-locked Ti:sapphire laser delivered 100-fs pulses at 800 nm with an 82-MHz repetition rate and 1-W average power for excitation. The sample was nondoped bulk InAs with a (100) surface. The surface of the InAs was parallel to the magnetic field, and the excitation laser irradiated the sample with a 1-mm-diameter beam. A magnetic field of as much as 1.7 T was applied with an electromagnet. The THz radiation was detected by a liquid-helium-cooled InSb bolometer, and the THz radiation spectra were taken by a polarizing Michelson interferometer. Previous experiments demonstrated that the THz radiation power from an InAs with the magnetic field direction parallel to the semiconductor surface was higher than that from four other possible geometries as reported in Ref. 10. THz radiation was generated only in the reflection direction because InAs has high reflectivity in the THz frequency region.7 Therefore,
the remaining parameter for geometric layout was the incidence angle of the excitation laser. We measured THz radiation power at each incidence angle by rotating the InAs and the bolometer simultaneously, as shown in Fig. 1. The angular dependence of reflectance for InAs around the 800-nm wavelength region is shown in Fig. 2(a) for horizontal and vertical polarization for the incidence-angle plane. The solid and dotted curves indicate theoretical calculations for \( n = 3.729 \) and \( k = 0.448 \), for which the Brewster angle was 78 deg. The angular dependence of the THz radiation power is shown in Fig. 2(b) for horizontal and vertical polarization. As expected, horizontal polarization excitation yielded higher power because of higher absorption, inasmuch as the radiation power has been shown to have quadratic dependence on excitation power as reported in Ref. 8. The THz radiation power is the most enhanced at nearly Brewster angle, and this information is important for the design of a practical THz radiation source. The highest THz radiation power was greater than five times the 0-deg incidence-angle power, which is due partly to the higher photoinjected carrier density that generates THz radiation from the higher absorption efficiency of excitation power. Deviation from the Brewster angle and the optimum efficiency angle might be connected to the coupling-out efficiency of the THz radiation that is not evaluated here. For a detailed explanation of this dependence, one should take into consideration the drop in power density of the exciting pulse, the emitter area change, and the diffraction effect when the angle increases.

For practical spectroscopic applications, it is also necessary to know the geometric dependence of the THz radiation spectra. For three angles, the spectral shape changes for various magnetic fields were observed as shown in Fig. 3. To extract the features of the THz radiation spectra in various cases, the center frequency of the THz radiation was defined as the integral average of the frequency between 0.05 and 3 THz. We can observe the asymmetrical center frequency shift with respect to the magnetic field direction. The amount of center frequency shift is also pronounced in the case of a shallower incidence angle, which is due to the difference in carrier acceleration direction that is induced when the magnetic field direction is changed as previously reported. The center frequency shift of the THz radiation spectrum increases for larger incidence angles, as shown in Fig. 4, because of the asymmetry of the carrier motion. In contrast with the earlier Brewster geometry excitation results reported by Weiss et al., it should be noted that one can change the spectrum shape by flipping the magnetic field direction. This result is qualitatively in good agreement with previous explanations. We believe such detailed information should be helpful for further discussion about the enhancement mechanism together with other experimental and theoretical reports. To explain the result quantitatively, we need more precise experiments including time-resolved fluorescence measurements in a magnetic field to clarify the actual carrier dynamics. Also note that, for practical applications, the THz radiation from such an emitter is intense enough to be detected by a pyroelectric thermal receiver. Its sensitivity is approximately four orders lower than that of a liquid-helium-cooled Si bolometer.

In conclusion, we have determined the best incidence angle to generate THz radiation. The final geometric conditions are the magnetic field direction...
parallel to the semiconductor surface and the close to Brewster incidence angle of the excitation laser. This optimization enhanced the THz radiation power approximately four times compared with the 45-deg incidence-angle case. Such a qualitative advance in emitters will have a significant effect on the future design of a compact absorption measurement system in the THz radiation or the far-infrared region.

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References