Compact THz-radiation source consisting of a bulk semiconductor, a mode-locked fiber laser, and a 2 T permanent magnet

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A compact THz-radiation source using an InAs semiconductor is demonstrated with a turn-key femtosecond fiber laser as an excitation source and a newly designed 2 T permanent magnet. By using a newly designed magnetic circuit, a compact permanent magnet which can exceed the remanence magnetic field was obtained. This compact source is sufficiently intense for absorption spectroscopy. © *2000 American Institute of Physics.* [S0034-6748(00)02302-9]

To date, various THz-radiation sources have been intensively studied including photoconductive switches irradiated with ultrashort optical pulses.[1–3] The average power of THz-radiation source excited by short optical pulses has been microwatt level at most, mostly limited by the electric breakdown of the photoconductive antennas. An intense, compact, and simple light source is required for applications in sensing or imaging. Zhang *et al.* reported a compact THz-radiation source consisting of a biased photo conductive antenna and a mode-locked fiber laser as an excitation source.[4] They have also reported the quadratic dependence of the laser induced THz radiation on the magnetic field.[5] We have also demonstrated the strong enhancement of THz-radiation power with a magnetic field by using an InAs semiconductor instead of GaAs.[6] This remarkable enhancement was also confirmed by many groups, such as Zhang *et al.*[7] and Beigang *et al.*[8] The advantage of the magnetic-field-enhanced scheme is flexibility of the geometry. In this article, we report on a compact THz-radiation source consisting of a fiber femtosecond laser and a newly designed 2 T permanent magnet.

The photograph of the compact THz-radiation source is shown in Fig. 1. A mode-locked frequency-doubled Er-doped fiber laser delivered 170 fs pulses at 780 nm with a 48.5 MHz repetition rate (IMRA model FA7850/10SA) with 30 mW average power and 4.1 kW peak power. The mode-locked fiber laser is a completely turn-key system. It is much smaller than a mode-locked Ti:sapphire laser that requires daily alignment. The used semiconductor sample was undoped bulk InAs with a (100) surface. The InAs sample itself is highly reflective, unlike transparent GaAs, and the THz radiation was totally generated in the reflection direction. The 2 T permanent magnet unit consisted of eight Nd–Fe–B magnet pieces. Each of them was magnetized in different ways as shown in Fig. 2. The remanence magnetic field of the Nd–Fe–B material itself was 1.3 T (NEOMAX-44H). Owing to the new magnetic circuit design,[9] the magnetic field in the center exceeded the remanence magnetic field of the material. The permanent magnet only weighs about 5 kg. The 2 T permanent magnet unit is cylindrical in shape, 128 mm diameter and 56 mm thick, which makes it smaller and much lighter than an electromagnet. In the far field, the vector sum of magnetic moments is close to zero. Therefore, the magnet has a very small leak magnetic field owing to the new magnetic circuit. This is an advantage of this radiation source for further system integration.

The experimental setups are shown in Figs. 3(a) and 3(b). The THz radiation is generated from an InAs emitter irradiated with femtosecond pulses in a magnetic field. The magnetic field direction can be reversed by rotating the magnet. In Figs. 3(a) and 3(b), the magnetic field was parallel to the sample surface, and the excitation laser was vertical to

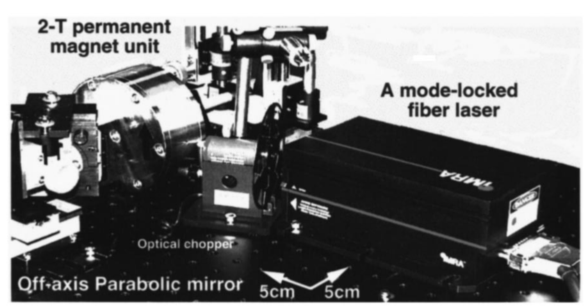

FIG. 1. Photograph of a compact THz-radiation source with a bulk semiconductor, a fiber femtosecond laser, and a 2 T permanent magnet. Including the laser, the size is less than 40×30×15 cm.

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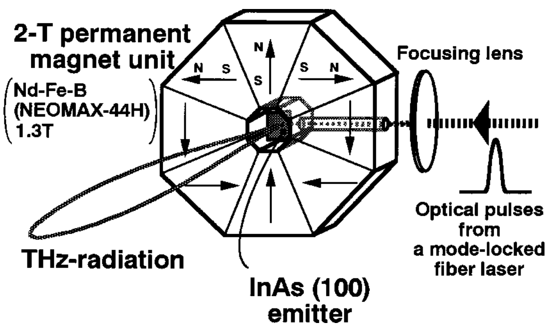

FIG. 2. Experimental setup of the compact THz-radiation source. This illustration indicates the geometrical layout with an InAs sample placed 45° to the excitation laser.

the magnetic field. The InAs sample was placed 45° and 0° to the excitation laser in Figs. 3(a) and 3(b), respectively. The excitation laser irradiated the sample with a 2-mm-diam spot. The intensity of the THz radiation obtained by a liquid-helium-cooled InSb bolometer (QMC model QFI/2BI) is shown in Fig. 4. The highest power was obtained by the setup shown in Fig. 3(a). The significant difference of the radiation power by inverting the magnetic field is partly attributed to asymmetric enhancement of THz radiation for magnetic direction that was observed in high field case.[10] At present the intensity is about a thousand times smaller than the intensity which is generated by using a 1.5 W femtosecond mode-locked Ti:sapphire laser and a huge 1.7 T electromagnet.[6] Believing the calibration of manufacturer, the average power is estimated to submicrowatt level. The spectra of the THz radiation were obtained by a Polarizing Michelson interferometer with the bolometer as shown in Fig. 5. Many water vapor absorption lines were clearly observed. Therefore, the THz-radiation source is already usable for spectroscopy. The center frequency of the radiation was shifted by inverting of the magnetic field direction due to the

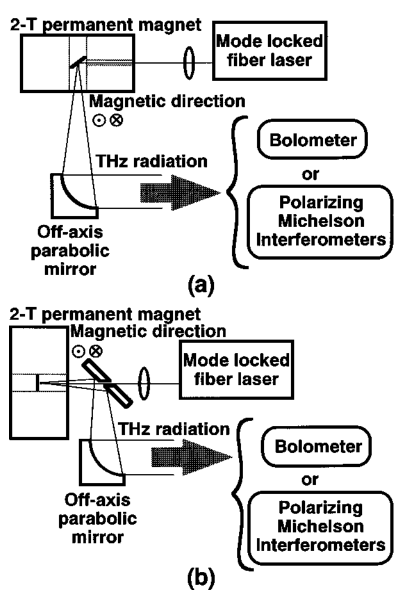

FIG. 3. Geometrical layout. The InAs sample surface was parallel to the magnetic field, and the excitation laser was vertical to the magnetic field. (a) The InAs sample was placed 45° to the excitation laser. (b) The InAs sample was placed 0° to the excitation laser (Fig. 2).

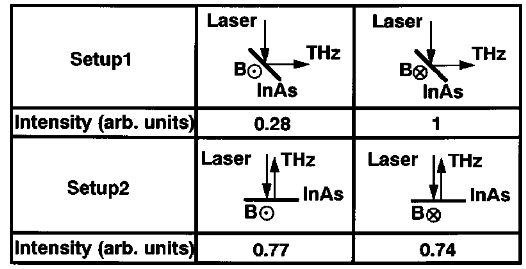

FIG. 4. Comparison of intensity of THz radiation in four geometrical layouts.

difference of the electron acceleration direction.[10]

In conclusion, a compact THz-radiation source using an InAs semiconductor was demonstrated with a genuine turn-key fiber femtosecond laser as an excitation source and a newly designed 2 T permanent magnet. Such a simple and compact source will open up new application for THz radiation. After further optimization, a higher power can easily be obtained because of the quadratic magnetic field and excitation power dependence of THz-radiation intensity.[6] In the near future, a 3 T magnetic field will be realized by having a smaller center gap in the magnet. A 3 T magnetic field is sufficient for the high power THz-radiation source because of the saturation of THz-radiation power around a 3 T magnetic field.[10] The power of mode-locked fiber lasers will be dramatically increased. Therefore, the compact THz-radiation source will be much improved.

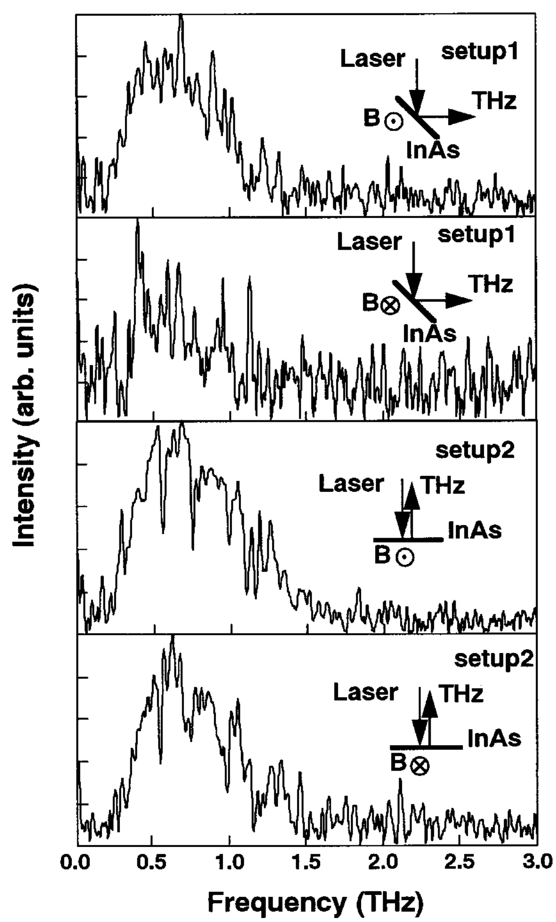

FIG. 5. Spectrum of THz radiation from the compact source for different geometry.

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