Spectrum control of THz radiation from InAs in a magnetic field by duration and frequency chirp of the excitation pulses

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(Received 7 January 1999; accepted for publication 1 June 1999)

The THz radiation spectrum from InAs in a magnetic field irradiated with femtosecond pulses can be controlled by varying the excitation pulse width and chirp direction of the excitation pulse. A longer excitation pulse width produces lower-frequency THz radiation. Also, positively chirped pulse excitation will generate higher power and higher frequency THz radiation. © *1999 American Institute of Physics.* [S0003-6951(99)02530-9]

Intense, compact, and simple THz-radiation sources[1–7] have been strongly needed for applications to sensing or imaging and time-resolved spectroscopy.[8–10] Zhang *et al.* reported quadratic dependence of laser-induced THz radiation on a magnetic field.[11] Previously, we reported the significant enhancement of THz-radiation power from InAs in a magnetic field irradiated with femtosecond optical pulses.[12] In most cases, the THz-radiation spectrum was strongly dependent on the emitter device structure or characteristics, therefore, spectral control was expected to be difficult without changing the emitter itself. In this letter, we report the spectrum control of this intense THz radiation by varying the width of the excitation pulses and the frequency chirp.

The experimental setup is shown in Fig. 1. The geometry was similar to the previous experiment except for the applied magnetic-field direction. The sample was nondoped bulk InAs with a (100) surface. The conduction type of nondoped bulk InAs was slightly *n*, and the carrier density of this InAs was $3.0\times10^{16}\ cm^{-3}$. The InAs sample itself is highly reflective for THz radiation, and the THz radiation was totally generated in the reflection direction. The InAs sample was placed 45° to the excitation laser beam path. A field of up to 1.7 T was applied parallel to the sample by a water-cooled electric magnet. In this geometry, the THz radiation was detected even without the magnetic field,[12] and the THz radiation was polarized horizontally. The THz-radiation power exhibits almost quadratic dependence on the excitation power and a higher magnetic field similar to the previous geometry.[12] The THz-radiation spectrum was obtained by a polarizing Michelson interferometer. A liquid-helium-cooled InSb bolometer was provided for detection. The THz-radiation spectrum differs in the magnetic-field direction because of the initial carrier acceleration direction due to the Lorentz force[11] as observed in the time-resolved measurement of the electric field of the THz radiation that will be reported elsewhere.[13]

An 82 MHz repetition-rate mode-locked Ti:sapphire laser delivered nearly transform-limited ~100 fs pulses at 800 nm with a 9 nm spectral width for the excitation. The pulses from the oscillator were almost transform limited and agreed very well with the $sech^2$ pulse-shape assumption in the temporal or frequency region. The output from the oscillator passed through a half-wave plate and an optical isolator to prevent feedback. This unit also functioned as a variable attenuator. The excitation spot size at the sample was approximately 2 mm in diameter. To simultaneously control the excitation pulse width and frequency chirp, we introduced a pulse stretcher and compressor consisting of an SF-6 prism pair separated 120 cm for fixed large negative dispersion and a closely placed SF-6 prism pair to provide adjustable positive dispersion.[14] With this pulse stretcher and compressor, the duration of pulses with a $sech^2$-shape assumption could be changed between 100 and 300 fs with positive or negative chirp without changing the other parameters. The positively chirped pulse contains a longer-wavelength component in the leading edge of the pulse and a shorter-wavelength compo-

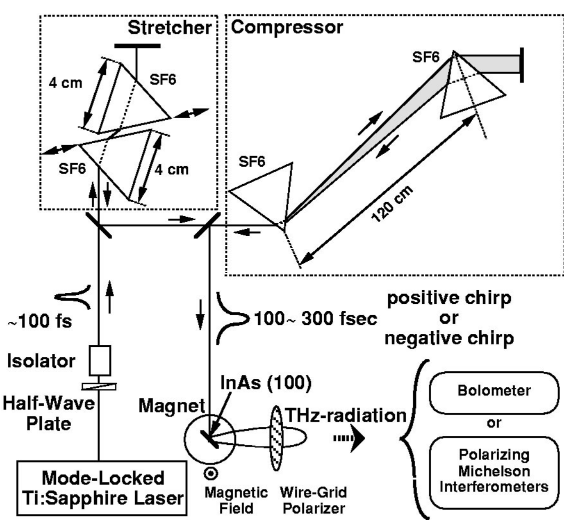

FIG. 1. The sample was nondoped bulk InAs with a (100) surface. The InAs sample was placed 45° to the excitation laser beam path. A field of up to 1.7 T was applied parallel to the sample by a water-cooled electric magnet. The spectrum of the THz radiation was obtained by a polarizing Michelson interferometer. A mode-locked Ti:sapphire laser delivered 100 fs pulses at 800 nm with an 82 MHz repetition rate. To simultaneously control the excitation pulse width and frequency chirp, we introduced a pulse stretcher and compressor consisting of an SF-6 prism pair separated 120 cm for fixed, large, and negative dispersion, and a closely placed SF-6 prism pair to provide adjustable positive dispersion. With this pulse stretcher and compressor, the pulse duration could be changed between 100 and 300 fs with positive or negative chirp, without changing the other parameters.

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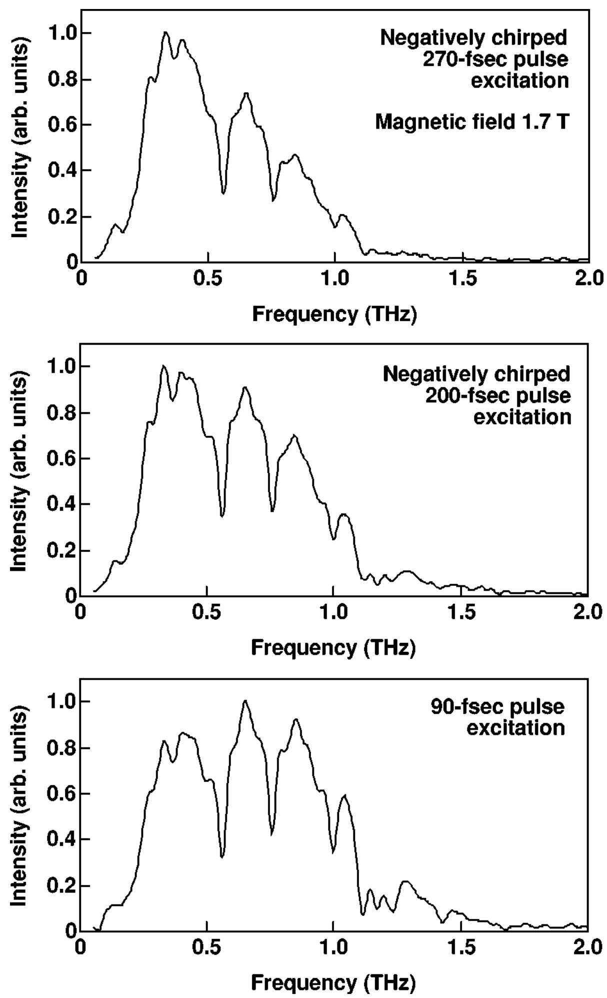

FIG. 2. Frequency spectrum of THz radiation from InAs in a 1.7 T magnetic field with different excitation pulse durations with negative chirp.

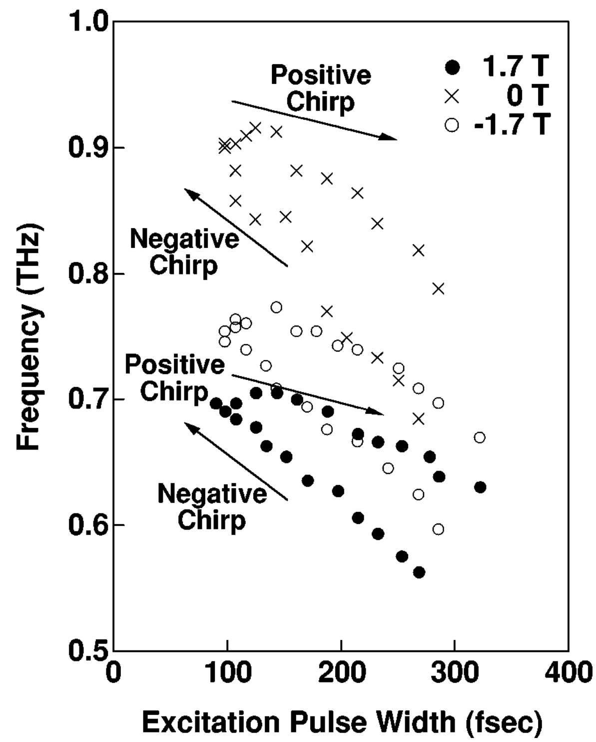

FIG. 3. Center frequency spectrum dependence of THz radiation with different excitation chirp, pulse duration, and magnetic field. Since the output pulse duration from the oscillator was nearly transform limited ~100 fs, the shortest pulse duration was limited to around 100 fs in this experiment. The pulses around the shortest duration in this experimental setup were rather close to the transform limit, and the difference between the positively and negatively chirped pulse excitations was not large. In the longer excitation pulse duration, the excitation with the positively and negatively chirped pulses showed a clear difference.

nent in the trailing edge of the pulse. The wavelength shift in the negatively chirped pulse is the opposite. Since the output pulse duration from the oscillator was nearly transform limited ~100 fs, the shortest pulse duration was limited to around 100 fs in this experiment. The longer pulse-duration side was limited by the separation of the compressor prism pair and the second prism size to collimate the widely dispersed spectrum of the 100 fs pulses. The average power of irradiation was finely controlled to 700 mW by the previously mentioned half-wave plate and an isolator placed before the pulse stretcher and compressor. The spectra of the pulses were also monitored to confirm there was no spectral clipping. Since there were intense water-vapor absorption lines in the THz-radiation spectrum, the peak position of the spectra was not easily determined. To extract the features of the THz-radiation spectra in various cases, the center frequency of the THz radiation was defined as the average of intensity at each spectral component between 0.05 and 1.8 THz by integration. This center frequency can be controlled with different excitation pulse widths as shown in Fig. 2. A longer excitation pulse width resulted in a lower center frequency as shown in Fig. 3, due to the corruption of the impulse response of the semiconductor in the longer pulse width region. Furthermore, the spectral shape of the radiation strongly depends on the chirp direction as shown in Fig. 4. This unexpected difference with the same excitation peak power and the same pulse duration with different chirp direction is rather surprising. Since the sample is excited well above the band gap (0.42 eV) with excitation photon energy of 1.55 eV, and the photon energy width of excitation pulses were only 20 meV. However, the THz radiation from InAs was found to contain still some information of the relaxation process that might occur within the duration of excitation pulses, and the radiation could be controlled just by the time sequences of photons with only a 20 meV energy difference. This difference of THz radiation for the chirping of the excitation pulses might be attributed to the difference of the photocarrier relaxation process in the conduction band with oppositely chirped-pulse excitation. Excitation of the carrier from the lower-energy side with a positively chirped pulse is more efficient for creating carriers and less sensitive to the carrier-scattering effect considering the carrier relaxation in the conduction band. This is favorable for intense, higher-frequency THz-radiation generation, as shown in Fig. 3. In contrast, excitation of the carrier from the higher-energy side with a negatively chirped pulse will be sensitive to the carrier-scattering effect due to the carrier relaxation in the conduction band. This would result in the lower power of THz-radiation generation with lower frequency. This hypothesis is partly supported by the fact that the positively chirped pulse excitation yielded higher radiation power, as shown in Fig. 5. To discuss this in more detail, it is necessary to observe dynamic carrier relaxation in a magnetic field by time-resolved luminescence up-conversion.[15] This unexpected dif-

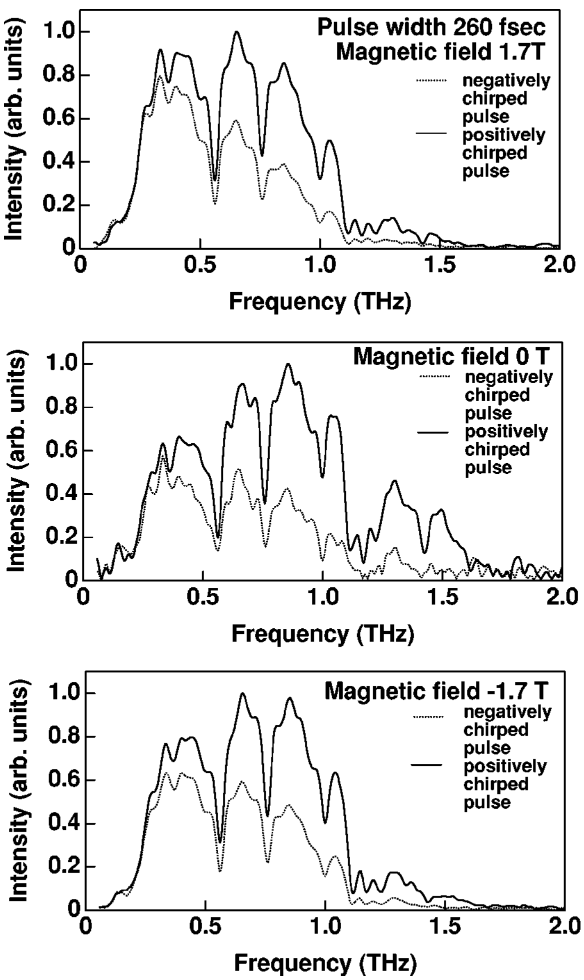

FIG. 4. Frequency spectrum of THz radiation from InAs with different excitation chirp and magnetic field. The excitation pulse duration is 260 fs in all cases. The solid line is the positively chirped pulse excitation; the dotted line is the negatively chirped pulse excitation.

ference with different chirp direction is significant on two points. In the engineering point of view, this experimental result suggested a new way of spectral control of the THz radiation that was expected to be difficult without some modification of the emitter itself. In the spectroscopic point of view, this experiment revealed that the observation of THz radiation from semiconductors irradiated with ultrashort pulses will provide new information on dynamic carrier relaxation processes.

In conclusion, we have demonstrated a simple scheme to control the THz-radiation spectra by varying the excitation pulse width and chirp direction of the excitation pulse. Development of such simple and intense radiation sources with spectral controllability will open up new applications of THz radiation.

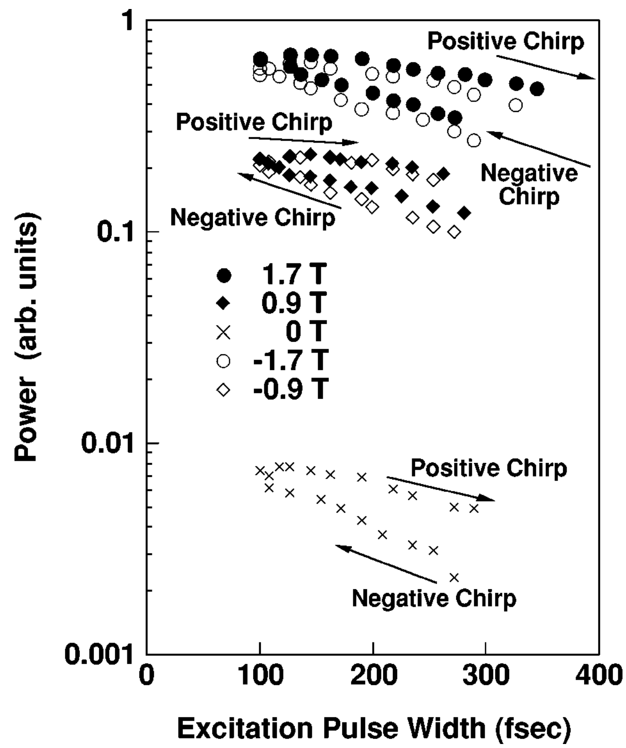

FIG. 5. Dependence of THz-radiation power on different excitation chirp, pulse duration, and magnetic field.

The authors would like to express their gratitude to Professor T. Suemoto at Tokyo University, Professor M. Ikezawa and Professor Y. Kondo at Tohoku University and Dr. Y. Segawa at the Institute of Physical and Chemical Research, for their discussions, and Dr. M. Tani and Dr. K. Sakai at the Communications Research Laboratory for the time-resolved measurements. This research was partially supported by a Scientific Research Grant-in-Aid from the Ministry of Education, Science, Sports, and Culture of Japan and the Sasakawa Scientific Research Grant from The Japan Science Society.

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