Generation of High-Power Terahertz Pulses at the Advanced Laser Light Source (ALLS)

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Abstract: We report on terahertz pulse generation by optical rectification in a large aperture ZnTe single-crystal wafer. Terahertz pulse energies up to 0.76 μJ are measured, the highest ever observed from an optical rectification source.

1. Introduction

Terahertz (THz) pulses are picosecond-long electromagnetic transients propagating in free-space with a corresponding frequency spectrum in the range of 0.2 - 4 THz. Terahertz time-domain spectroscopy (THz-TDS) is now a well-established tool that uses THz pulses to probe the nature of conductivity in various materials, and has also been used for novel THz imaging applications [1]. Even though the THz pulse energies used in most of these studies are quite low, gated detection of THz pulse electric fields affords excellent signal-to-noise, which is typically superior to that of traditional Fourier transform infrared spectroscopy (FTIR) techniques. For example, THz-TDS uses mode-locked Ti:sapphire laser sources and Auston switch antennas to generate THz pulses with pulse energies around 0.1 fJ and peak electric fields less than 10 V/cm at a 1 mm focus [1]. Time resolved THz spectroscopy studies (TRTS), which use amplified laser sources with ~ 1 kHz repetition rates, can generate THz pulses by optical rectification [2] in nonlinear crystals with peak electric fields from 1 - 10 kV/cm [3]. However, such electric field amplitudes are still too low for exploring nonlinear effects in materials at THz frequencies, in spite of the fact that these effects are of great interest [4,5]. Much larger THz electric fields can be generated using large-aperture photoconductive switches. THz pulse energies (and estimated peak electric fields at the focus) as high as 0.8 μJ (~ 150 kV/cm) [6] and 0.4 μJ (~ 350 kV/cm) [7] have been reported. In this paper, we show preliminary results from the initial development phase (June 2006 and October 2006) of the THz pulse source at the Advanced Laser Light Source (ALLS), where we recently observed THz pulse energies up to 0.76 μJ from a large-aperture ZnTe optical rectification source. To the best of our knowledge, this represents the highest THz pulse energy measured from an optical rectification source. Clearly, these results may open up new research opportunities in nonlinear THz photonics, THz source development, and other applications such as full-field, single-shot THz imaging.

2. Experimental

The ALLS beam line used in these experiments provided 800 nm, 30 fs laser pulses with energies as high as 40 mJ at a repetition rate of 100 Hz. The THz source consisted of a single crystal [110] ZnTe wafer with a diameter of 70 mm and a thickness of 0.5 mm (Nikko Materials). The 800 nm pulse from the ALLS source was expanded and collimated to a diameter of about 52 mm, and illuminated the ZnTe wafer at normal incidence. Any 800 nm pulse energy transmitted through the ZnTe wafer was blocked using a black polyethylene absorber which was transparent to the THz radiation. The ZnTe crystal could be rotated in its mount to maximize the THz pulse emission via optical rectification. Gold-coated off-axis parabolic reflectors with 4” clear apertures were used to focus and collimate the freely-propagating THz pulse. Beam reduction to 2” off-axis parabolic reflectors were then used to facilitate handling of the THz beam. A chopper at the first focus allowed modulation of the THz beam. Free-space electro-optic sampling in a second [110] ZnTe crystal with a thickness of 0.02 mm was used to detect the THz pulse waveform, which could be scanned using a delay stage. A lock-in amplifier referenced to the chopper was used to

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acquire the THz wave forms. By properly setting the delay stage to the main peak of the THz pulse, it was possible to display the modulated signal directly on an oscilloscope, which was then used to estimate the THz electric field amplitude at the focus in the ZnTe detection crystal. We used two pyroelectric detectors for measuring the total THz pulse energy emitted from the ZnTe source: 1) a Coherent-Molectron pyroelectric detector with a sensitivity of 2624 V/J calibrated at 1.06 µm, and 2) a Microtech Instruments pyroelectric detector with a sensitivity of about 2100 V/W calibrated at terahertz frequencies.

3. Results

Figure 1 shows the total THz pulse energy measured using both the Coherent-Molectron and Microtech Instruments pyroelectric detectors. We note that the 800 nm excitation laser fluence we use is well above typical saturation fluences for optical rectification in ZnTe [3], but we still see an approximately linear increase in THz pulse energy with 800 nm excitation pulse energy. At 40 mJ excitation, the Coherent-Molectron pyroelectric detector gave a voltage pulse with a peak height of 1.07 mV, corresponding to a total energy of 0.41 µJ. This provides a lower estimate of the THz pulse energy since this detector was calibrated at 1.06 µm rather than at THz frequencies, and we expect the sensitivity to THz radiation to be less [7]. At the same excitation fluence, the Microtech Instruments detector showed 159 mV peak to peak with 10 Hz chopping, giving a total calibrated THz pulse energy of 0.76 µJ. At this THz pulse energy, the peak THz electric field measured at the ZnTe detection crystal was about 25 kV/cm. We should expect a much higher value on the order of 95 kV/cm since the focus of the THz pulse was about 2 mm (similar to or better than previous studies performed using large-aperture photoconductive switch sources). We are currently investigating this further. We are currently investigating further. We note that at 0.76 µJ at 100 Hz, the average THz power is 76 µW and the conversion efficiency at the ZnTe source is 1.9×10^{-5}. Finally, we conclusively show that the THz pulses are generated by optical rectification in the ZnTe crystal by measuring the THz pulse energy as a function of azimuthal crystal orientation with respect to the polarization of the 800 nm excitation beam, as shown in Fig. 2. The solid line is the predicted behaviour according to Ref. [2].

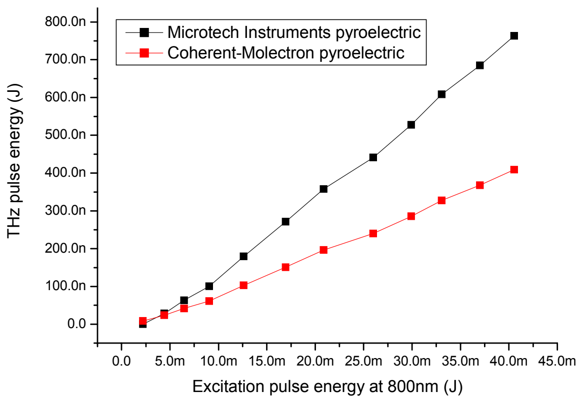

Fig. 1. THz pulse energy as a function of 800 nm excitation.

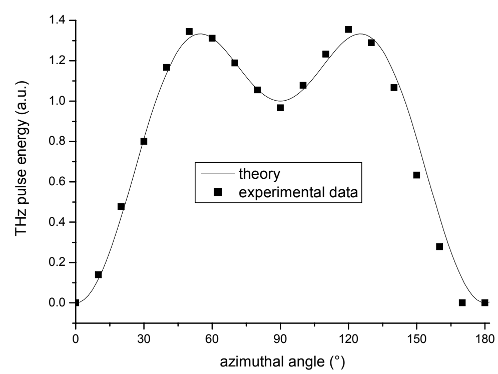

Fig. 2. Azimuthal angle dependence of THz pulse energy.

4. Conclusion

In summary, we report the highest THz pulse energy observed so far from an optical rectification source. The ALLS THz source will allow the exploration of nonlinear THz photonics as well novel THz imaging applications.

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