Terahertz Radiation from Optical Rectification of a Modulated Laser Pulse

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Abstract

A novel terahertz source has been developed based on a hybrid of optical rectification and difference frequency generation. The optical pulse from a titanium:sapphire laser system is stretched and modulated using a spatial filtering technique to produce a several picosecond long pulse modulated at the terahertz frequency. A type II phase matched interaction is realized via angle tuning in a gallium selenide crystal. A liquid helium cooled silicon bolometer was used to establish a lower bound of 2 kW on the peak power observed at 1.1 THz. Tunability was demonstrated between 0.7 and 2.0 THz.

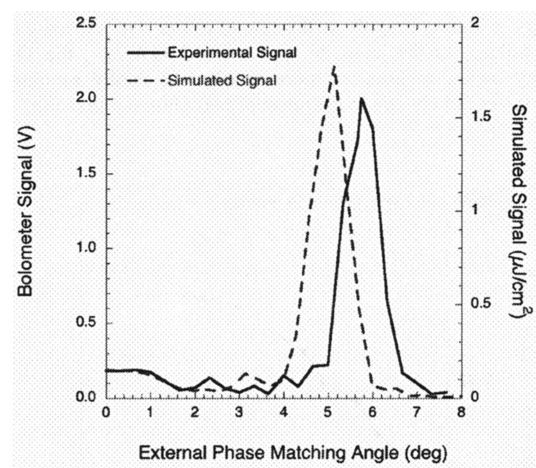
Introduction

Two methods that have often been used to generate THz radiation with lasers are difference frequency generation (DFG) and optical rectification. DFG uses two relatively long (>1 ns) pulses separated in frequency by the desired signal frequency. This approach has produced peak powers as high as 200 W (at 1.5 THz) using gallium selenide (GaSe) as the nonlinear medium [1]. Optical rectification uses a single frequency laser pulse whose pulse length is half the inverse of the desired signal frequency. This technique produces a broadband signal. Signal fields as high as 1 MV/cm have been reported based on phase matched optical rectification in GaSe [2], but only for relatively high signal frequencies (30 THz).

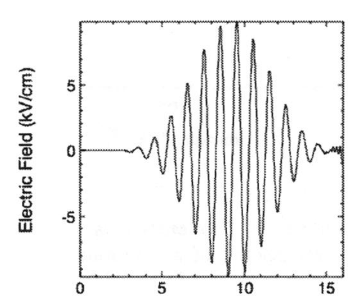
We report here on a hybrid technique where a titanium:sapphire laser system is used to generate a pulse which is modulated at the signal frequency as in DFG, but which is only a few modulation periods in length. Because the laser pulse is only a few picoseconds long, intensities of 1 GW/cm^2 can be incident on a GaSe crystal without damaging it, and therefore higher conversion efficiencies per unit length can be achieved than in the case of DFG. However, the pulse is still long enough so that phase matching can be sustained over long distances (>1 cm) without being spoiled by group velocity slippage between the ordinary and extraordinary waves. Furthermore, both the signal frequency and bandwidth can be easily adjusted.

Experimental Setup

The experiment was carried out using the Terawatt Femtosecond Laser (TFL) at the Naval Research Laboratory. The system is capable of producing 500 mJ of 800 nm radiation in a 50 fs pulse, although only a small fraction of the available energy was used for these experiments. An oscillator, grating stretcher, and regenerative amplifier produced 5 mJ of energy in a sretched (chirped) pulse. A grating and lens were used to create an image of the frequency content of the pulse. By positioning a pair of slits in this image plane, two frequency bands could be selected for transmission through the rest of the system. This included a further amplification stage and a grating compressor. In these experiments, the resulting pulse was about 5 picoseconds long, 10 mm in diameter, and had a modulation frequency that was varied between 0.7 and 2.0 THz. The modulated pulse was rotated in polarization by 45 degrees using a half-wave plate in order to more easily access a type II phase matching geometry (this meant that half the laser energy was not usable). The 10 mm diameter, 5 mm thick z-cut GaSe crystal was mounted on a rotation stage. A liquid helium cooled silicon bolometer was used as the detector. The stray laser radiation was extinguished using 3 mm of black polyethylene. An aluminum THz grating with triangular grooves spaced 700 microns apart was optionally interposed between the GaSe and the bolometer.



(a)



(b)

Fig. 1: (a) Comparison of experimental and simulated angle tuning curves for generation of 1.1 THz radiation in a 5 mm long GaSe crystal. (b) THz electric field predicted by simulation for experimental parameters.

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Experimental and Numerical Results

The THz signal as a function of the external phase matching angle is shown in Fig. 1(a) for a laser pulse with a modulation frequency of 1.1 THz and a pulse length of 5 ps. The laser intensity was approximately 1 GW/cm^2. Evidence of phase matching is clearly seen as the dramatic spike in the THz signal between 5 and 6 degrees. Also shown is a numerically calculated angle tuning curve which predicts similar behavior. The numerical model includes the effects of dispersion and pump depletion, and has been described in detail elsewhere [3]. Interestingly, both the simulation and experiment produced a secondary peak in the signal near 0 degrees. This probably corresponds to the 0.1 THz radiation produced as a result of optical rectification of each frequency band separately. Fig. 1(b) shows the simulated THz electric field corresponding to the optimum phase matching angle. The peak power implied by the simulated electric field is about 100 kW.

A lower bound on the experimental peak power is 2 kW. This estimate is based on using the bolometer responsivity quoted by the manufacturer, which is in turn based on measurements using near or mid-infrared radiation. The responsivity at THz frequencies is thought to be significantly less, which would lead to a higher estimate of the THz power.

The scaling of the energy in the THz pulse with the intensity of the pumping laser is shown in Fig. 2. The measurement was obtained using the 1.1 THz modulation, with the GaSe crystal tuned to the optimum angle. Combinations of NG filter glasses were used to vary the laser intensity. As expected, the THz energy increases roughly as the square of the laser intensity up to a point. As the intensity approaches 1 GW/cm^2, the THz energy begins to increase more slowly and finally saturates. This is very likely due to the onset of two-photon ionization.

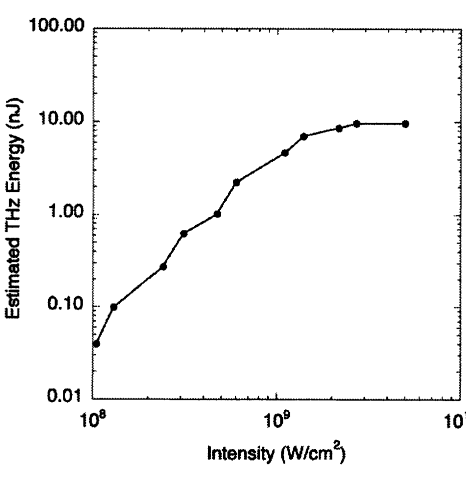
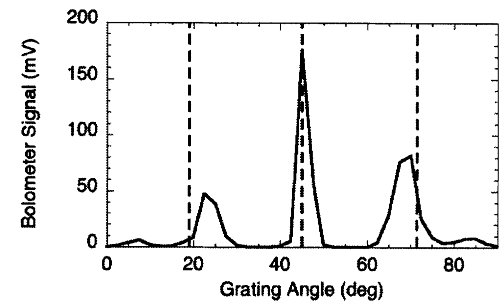
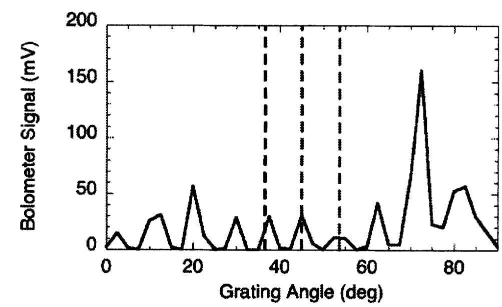


Fig. 2: Measurement of THz energy vs. laser intensity for optical rectification of a THz-modulated, 5 ps long, 800 nm laser pulse in a 5 mm thick GaSe crystal. The energy was estimated using a bolometer calibration based on the near and mid-IR responsivity. The actual THz energy is expected to be higher.

Finally, Fig. 3 illustrates the tunability of the source. The THz grating was placed between the GaSe crystal and the bolometer such that a ray reflecting off the grating entered the bolometer if the angle of incidence plus the angle of reflection was 90 degrees. Thus, by rotating the grating, different diffracted orders could be swept through the collection aperture of the bolometer. The angular spacing between diffraction orders is a measure of the center frequency of the THz radiation. Fig. 3(a) shows such a scan for a laser pulse modulated at 0.7 THz. The diffraction peaks occur approximately in the expected locations. Fig. 3(b) shows a similar scan for a 2.0 THz modulation. Again, the diffraction peaks occur in the expected locations. Similar plots were produced for 1.0 and 1.5 THz modulations.



(a)



(b)

Fig. 3: Bolometer signal vs. angle of incidence on the THz grating, demonstrating tunability. (a) laser pulse modulated at 0.7 THz (b) laser pulse modulated at 2.0 THz. The dashed lines indicate the expected locations of the zero and first order diffracted beams. Similar results were obtained for 1.0 and 1.5 THz.

Conclusions

We have demonstrated a new approach to THz generation based on optical rectification of a modulated laser pulse where the pulse length is only a few modulation periods long. Using a relatively thin (5 mm) crystal, we have obtained a peak power of at least 2 kW at a frequency of 1.1 THz. We have demonstrated tunability between 0.7 and 2.0 THz.

References

[1] W. Shi and Y.J. Ding, "A monochromatic and high-power terahertz source tunable in the ranges of 2.7-38.4 and 58.2-3540 μm for variety of potential applications", Appl. Phys. Lett. Vol. 84, No. 10, 2004, 1635-1637.

[2] K. Reimann et al., "Direct field-resolved detection of terahertz transients with amplitudes of megavolts per centimeter", Opt. Lett. Vol. 28, No. 6, 2003, 471-473.

[3] D.F. Gordon et al., "Analysis and Simulation of Optical Rectification as a source of Terahertz Radiation", NRL Memorandum Report No. 8869, 2005.