0.4 mJ THz Pulses by Optical Rectification

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Abstract: THz pulses with more than 0.4 mJ energy were generated with 0.77% efficiency by optical rectification of 785-fs laser pulses in $LiNbO_3$ using tilted-pulse-front pumping. The spectral peak is at about 0.2 THz, suitable for charged-particle manipulation.

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1. Introduction

Interesting new applications, such as THz-enhanced attosecond-pulse generation [1], the manipulation of electron beams [2], or the post-acceleration of laser-driven protons and ions [3], with the potential for hadron therapy applications, will require THz pulses with extremely high peak electric field strengths up to the 100 MV/cm level. For most of these applications the low-frequency part of the THz spectrum, i.e. the 0.1 to 3 THz frequency range is more advantageous since the corresponding wavelengths naturally fit to practical sizes of charged-particle beams. In this spectral range $LiNbO_3$ (LN) with tilted-pulse-front pumping (TPFP) [4] demonstrated potential for high-energy pulse generation [5–8]. It was proposed that OR in LN could be significantly improved by using pump pulses with optimal Fourier-limited duration of about 500 fs, and cooling LN to cryogenic temperature to reduce its THz absorption [9]. Recent experimental studies confirmed these predictions. The highest reported THz pulse energy from OR (125 μJ) could be reached with somewhat longer than optimal pump pulses [7]. The highest conversion efficiency (3.8%) was demonstrated by cryogenic cooling of congruent LN and using close-to-optimal pump pulse duration [8].

Here we present experimental results on a substantial increase of the THz pulse energy by OR of femtosecond laser pulses in LN using TPFP. A comparison of different experimental conditions (crystal temperature, imaging optics, pumped area) is given.

2. Experimental setup

A diode-pumped high-energy picosecond Yb:YAG chirped-pulse amplification system was used as the pump laser with 10 Hz repetition rate, 1030 nm central wavelength, and 785 fs compressed pulse duration [10]. Up to about 60 mJ energy was used in the experiment. 0.6% MgO-doped stoichiometric LN prisms with up to 8.1×20 mm^2 (horizontal×vertical) useful input surface were used for OR. Three different TPFP setups (all with 1400-lines/mm grating) were used to compare different experimental conditions. *Setup 1* consisted of a 20-cm focal length NIR achromat lens satisfying conditions for optimal imaging [11]. The pumped area (A) on the input surface of LN was large, 8.1 mm in the horizontal direction and 15.3 mm in the vertical direction (FWHM). The LN crystal was placed inside a cryostat with a fused silica input window for the pump and a TPX exit window for THz to enable measurements both at room temperature (RT) and cryogenic temperature (CT, with $T \approx 23$ K). *Setup 2* consisted of a telescope with 25 cm and 15 cm focal length lenses, and a vacuum tube between them. The pumped area was large, approximately the same as for Setup 1. *Setup 3* contained the same telescope but the pumped area was small ($A = 5.7\times7.0$ mm^2 FWHM).

A calibrated pyroelectric detector (Microtech Instruments) with 2×3 mm^2 active area and a cone-shaped input opening with 15 mm diameter was used for measuring the energy of the THz pulses. A silicon wafer and a varying number of cardboard plates were used to attenuate the THz pulses to avoid detector saturation, and to block the optical radiation. For electro-optic sampling (EOS) a 0.1 mm thick (110)-oriented ZnTe plate was used attached to a 1 mm thick inactive ZnTe substrate. A small fraction of the pump beam was taken as the probe. Due to space constraints in the setup we have used reflection-type EOS geometry, where THz (collimated and focused by off-axis paraboloid mirrors) and pump entered the detector crystal from opposite directions. It was the probe reflected from the back side of the active layer and (after reflection) co-propagating with THz, which was detected.

3. Results and discussion

The measured pump-to-THz energy conversion efficiency is shown in Fig. 1(a) as function of the pump intensity for the different experimental conditions. The highest efficiency (0.77%, Fig. 1(a), green symbols) and THz energy (436 µJ, inset of Fig. 1(a)) were achieved with Setup 3 at the highest pump intensity (233 GW/cm^2). The increase of the THz energy with pump energy shows power-law dependence with exponents varying from 1.4 to about 1.7, the latter value corresponding to highest energies. The observed efficiencies at RT are in good agreement for all three setups up to about 10 GW/cm^2. For higher pump intensities, using the telescope with large pumped area (Setup 2) gives significantly higher efficiencies (Fig. 1(a), black symbols). If we depict the efficiency vs. the estimated THz intensity, this discrepancy gets reduced but still persists for higher THz intensities (Fig. 1(b)). As possible explanation for the higher efficiency we consider that larger *A* allows larger effective THz generation length resulting in larger in-medium THz field strength. This may lead to a reduction of the THz absorption, similarly to what was observed for ZnTe [12]. The increasing exponent for the energy dependence mentioned above allows similar reasoning. To understand the underlying processes, which is quite important for further development of high-energy THz sources, requires more detailed study.

In good accordance with theoretical predictions [9] and previous measurements at much lower energies [13], we observed an increase of the efficiency by about 2.4 to 2.7 times when cooling LN to CT (Fig. 1(a) blue and red symbols). This increase is due to the reduced absorption of LN at CT. THz pulse spectra at CT obtained from measured waveforms are shown in the inset of Fig. 1(b) for small, medium, and high pump energies. In all cases the spectra extend up to about 1 THz with a strong drop in the spectral amplitudes at around 0.5 THz. Another feature is the decrease of the frequency for the amplitude peak from about 0.25 to 0.15 THz with increasing THz energy.

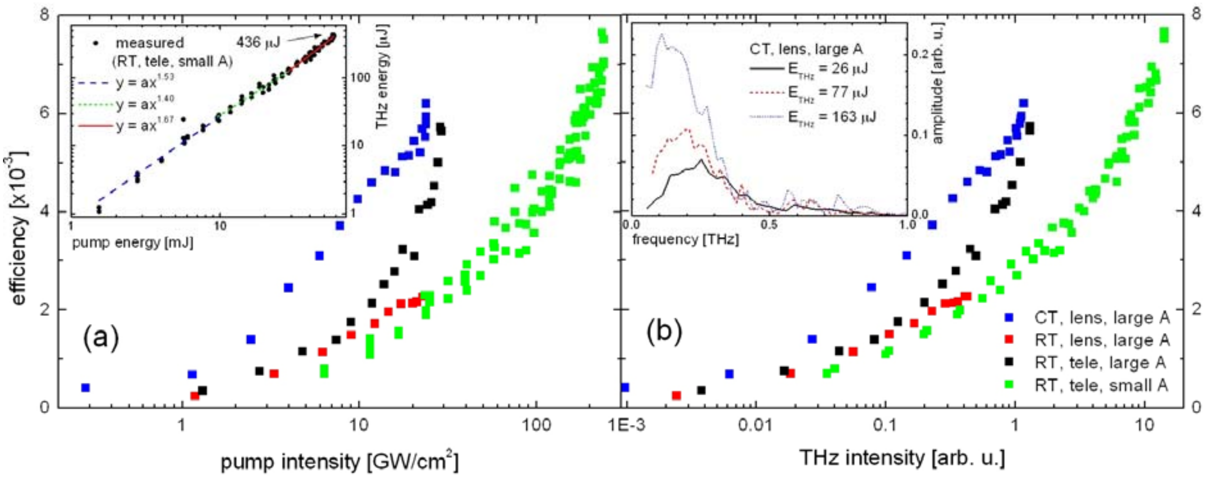

Fig. 1. (a) Measured THz generation efficiency vs. pump intensity (legend: see right panel). Inset: Measured THz energy vs. pump energy. (b) Measured THz generation efficiency vs. THz intensity. Inset: THz spectra obtained from the measured waveforms.

4. Conclusion

The achieved THz pulse energies are, to our knowledge, the highest so far published values for optical rectification of laser pulses (almost 3.5-times higher than the previously reported maximum). Owing to the closer-to-optimum pump pulse duration, the achieved THz generation efficiency is the highest one measured for high THz energies. Based on these measurements it can be expected that by using CT and optimized TPFP setups, possibly with a contact grating, the THz energy can be increased beyond 1 mJ from such a compact and simple setup.

5. References

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