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# Mobile source of high-energy single-cycle terahertz pulses

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**Abstract** The *Teramobile* laser facility was used to realize the first mobile source of high-power THz pulses. The source is based on a tilted-pulse-front pumping THz generation scheme optimized for application of terawatt laser pulses. Generation of 50-μJ single-cycle electromagnetic pulses centered at 0.19 THz with a repetition rate of 10 Hz was obtained for incoming 700-fs 120-mJ near-infrared laser pulses. The corresponding laser-to-THz photon conversion efficiency is approximately 100%.

## 1 Introduction

THz waves have attracted considerable interest in recent years owing to their prospective applications in different scientific and industrial fields [1, 2]. Some of these applications require ultrashort THz pulses of high peak power, such as for nonlinear optics and spectroscopy in the THz frequency range and for recently developed time-resolved spectroscopy with THz pump [3–7]. To date, the highest THz peak power (100 MW) has been achieved with accelerator-based sources [3]. These sources have a number of obvious disadvantages typical for large-scale facilities. Several table-top techniques based on femtosecond lasers have been tested for obtaining high-power near-single-cycle THz pulses, including photoconductive switches, optical rectification and, more recently, four-wave mixing in air/gas plasma [8]. For most of these techniques the generation of THz pulses with an average frequency of ∼1 THz and peak power of more than 1 MW is problematic owing to the low laser-to-THz conversion efficiency and the inherently limited laser pulse power that can be applied for THz generation. In contrast to other techniques, the tilted-pulse-front pumping (TPFP) THz generation scheme [9, 10] allows an increase in pump laser power to the terawatt level while retaining relatively high energy-conversion efficiency (≥0.1%). Recently, a few TPFP schemes optimized for the generation of extremely high-power (≥100 MW) single-cycle THz pulses have been proposed [11–13].

Several THz applications, such as environmental studies, stand-off THz imaging and spectroscopy for security purposes and point-to-point communications, require mobile sources of high-power THz radiation with a central frequency of 0.1–0.5 THz [1, 2]. This spectral region is particularly attractive because of the relatively low absorption by molecular water in ambient air, which allows propagation of the THz radiation for up to several kilometers under typical atmospheres [14]. Recently, we demonstrated that 30-μJ single-cycle pulses with an average frequency of 0.3 THz can be obtained in a TPFP THz generation scheme pumped by a femtosecond terawatt laser [15]. Although generally bulky, high-intensity lasers can be made mobile and can even be used for field and outdoor experiments, as demonstrated by the pioneering work of the *Teramobile* consortium [16, 17], which performed numerous field experiments with 100-fs, 4-TW laser pulses. Therefore, such high-intensity laser sources represent good candidates for stand-off and field experiments.

In this letter we report the generation of 50-μJ single-cycle pulses centered at 0.19 THz by a TPFP scheme using the *Teramobile* laser system as the pump source. To the best

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of our knowledge, these are the highest-energy single-cycle THz pulses achieved using a laser-based technique. Moreover, as the pulses were obtained with a mobile laser system, this represents the first demonstration of a mobile source of high-power single-cycle THz pulses.

## 2 Experimental set-up

The THz generation set-up (Fig. 1) was installed inside the *Teramobile* laser container. As proposed previously [12, 15], the laser beam cross-section was elliptically shaped before pulse-front tilting to reduce the propagation distance for both the laser and THz pulses inside the lithium niobate crystal and to avoid distortion of the large-aperture laser pulse at the tilting pulse front [11, 12]. Using a telescope consisting of two cylindrical mirrors with a focal length of 550 and 175 mm, respectively for this purpose, we obtained a 40 × 10 mm ($1/e^2$) laser cross-section profile. The long dimension of the laser cross-section was mainly limited by the 30-mm height of the $LiNbO_3$ crystal. After the cylindrical telescope, the THz generation set-up was similar to that used in our previous work [15].

The absolute value of the THz pulse energy was measured using a room-temperature pyroelectric detector (Coherent, Molectron J4-05). The same detector model was previously used by other research groups to measure 100-μJ THz pulses obtained with an accelerator-based source [3] and μJ-level pulses generated by optical rectification in ZnTe [5]. Below 1 THz, diffraction and the spectral dependence of the absorber placed on the pyroelectric crystal may result in a decrease in detector sensitivity, so that our measurements provide a lower limit of the absolute energy value in this frequency range. In contrast to previous measurements [3, 5], we did not focus the THz beam on the active area of the detector. The intensity profile for the THz beam cross-section (21 × 15 mm ($1/e^2$) at a distance of 5 mm from the crystal output surface) was measured by scanning with the detector. To obtain THz pulse energy, the scanning data were deconvoluted for the active area of the detector and integrated.

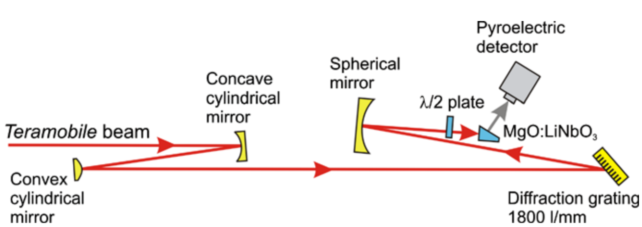


**Fig. 1** Schematic of the tilted-pulse-front pumping terahertz generation set-up optimized for application of terawatt laser pulses

## 3 Results and discussion

The maximum laser pulse energy of 120 mJ used for THz generation in these experiments was limited by the dimensions of the $LiNbO_3$ crystal. Figure 2 shows the dependence of the THz pulse energy on the duration of 120-mJ laser pulses. The laser pulse duration was varied by shifting the diffraction grating of the laser compressor (i.e. by laser pulse chirping) as previously described [16].

THz pulses with the highest energy (50 μJ) were achieved with negatively chirped laser pulses of 120 mJ for 700 fs. The use of close to transform-limited 140-fs laser pulses results in a 30% decrease in generation efficiency. One of the most probable explanations for this behavior is self-phase modulation of a 140-fs laser pulse along the propagation distance of 6 m in air from the laser compressor to the THz generation set-up. The presence of self-phase modulation of 140-fs laser pulses is unambiguously indicated by a decrease at 804 nm and increases at 789 and 814 nm in the laser pulse spectra measured just before the THz generation set-up (Fig. 3). These spectral features disappeared when the laser pulses were chirped; moreover, they were not observed immediately after the compressor output. The specific mechanism of the decrease in THz generation efficiency resulting from self-phase modulation is beyond the scope of the present study.

Measurements of the THz pulse energy as a function of the 140-fs laser pulse energy reveal a quadratic dependence up to laser pulse energy of 70 mJ (Fig. 4). A further increase in pulse energy results in saturation of the quadratic dependence (not shown in Fig. 4), which is most probably related to self-phase modulation of the laser pulse, as discussed above.

The temporal profile of the THz pulses was characterized by electro-optic sampling using a 0.5-mm ZnTe crys-

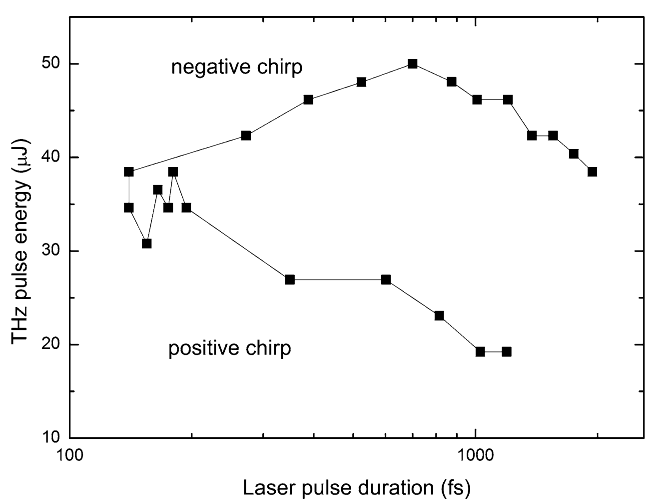


**Fig. 2** THz pulse energy as a function of the duration of 120-mJ laser pulses

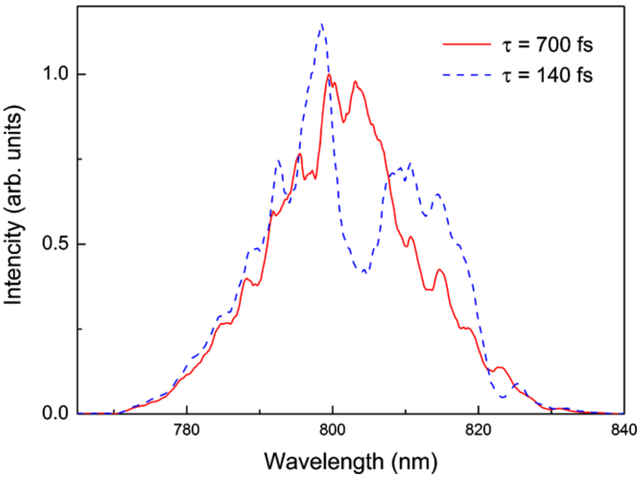


**Fig. 3** Spectra of close to transform-limited 140-fs laser pulses (*solid line*) and negatively chirped 700-fs lased pulse (*dashed line*) after propagation over a distance of 6 m in air

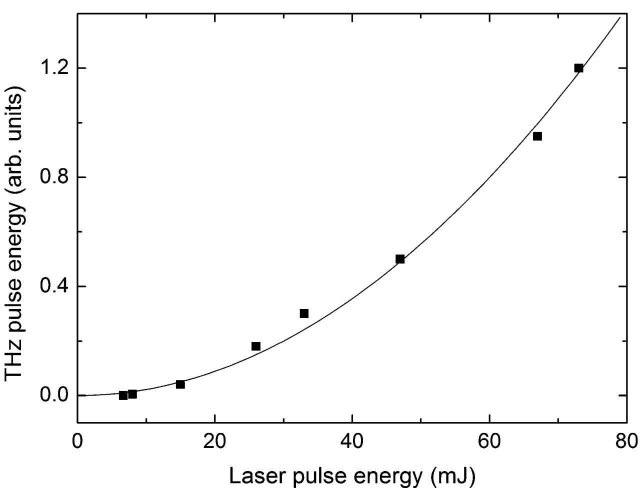


**Fig. 4** THz pulse energy as a function of the energy of incident 140 fs transform-limited pulses

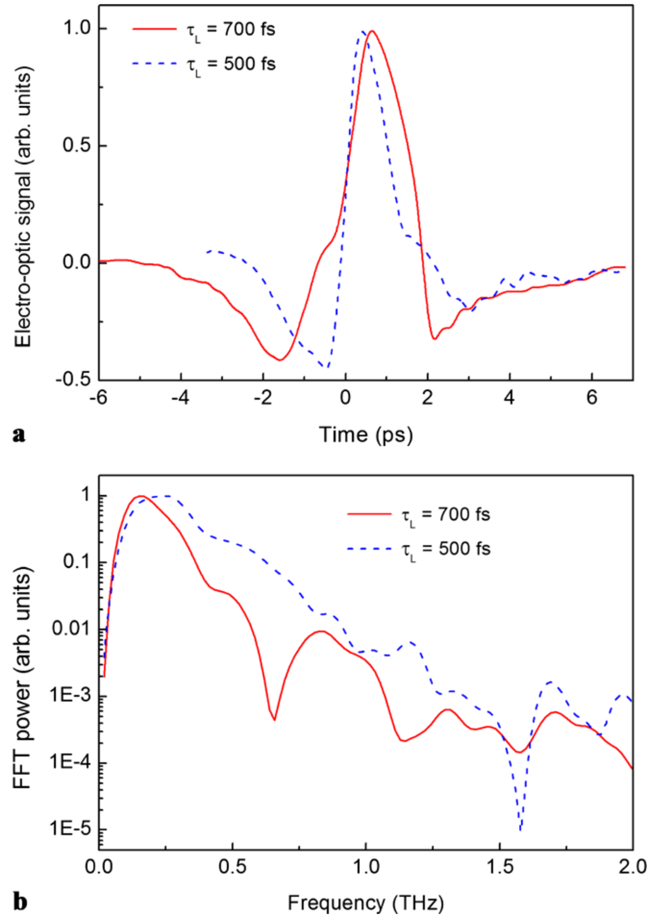


**Fig. 5** (**a**) Normalized electro-optic signals and (**b**) power spectra obtained for incident laser pulses of 120 mJ for 700 fs (*solid line*) and 80 mJ for 500 fs (*dashed line*)

tal as a sensor, which was placed at a distance of 150 mm from the THz output surface of the $LiNbO_3$ crystal. Figure 5 shows electro-optic signals and the corresponding spectra of 50- and 44-μJ THz pulses generated by 700-fs, 120-mJ and 500-fs, 80-mJ laser pulses, respectively.

The THz pulse spectra observed in our experiments are slightly narrower and red-shifted compared with spectra obtained by model calculations for transform-limited laser pulses [13]. The red-shift and spectral narrowing probably result from the pulse chirping applied for THz generation. It should also be noted that according to model calculations [13], the average frequency and width of THz pulse spectra can be increased by up to 1.2 and 1.6 THz (FWHM), respectively, by decreasing the laser pulse duration to 50 fs.

The laser-to-terahertz energy-conversion efficiency calculated from the laser pulse energy incident on the crystal surface and the THz pulse energy measured was $5.0 \times 10^{-4}$. This value is comparable with the conversion efficiencies reported for generation of 10-μJ-scale near-single-cycle THz pulses by TPFP [4, 15]. The photon conversion efficiency was approximately 100%. Note that this value could exceed 100% due to cascaded $\chi^{(2)}$ processes [18, 19].

## 4 Conclusions

In summary, we have demonstrated the first mobile source of high-power THz pulses based on a TPFP THz generation scheme combined with the *Teramobile* laser facility. Application of 700-fs, 120-mJ laser pulses yielded 50-μJ single-cycle THz pulses with an average frequency of 0.19 THz. This source can be used for stand-off applications such as nonlinear THz atmospheric research and THz LIDAR systems.

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