Fiber laser pumped high average power single-cycle terahertz pulse source

Matthias C. Hoffmann,[1,a)] Ka-Lo Yeh,[1] Harold Y. Hwang,[1] Thomas S. Sosnowski,[2] Bradley S. Prall,[2] János Hebling,[1,b)] and Keith A. Nelson[1]
[1]*Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Clark-MXR, Inc., 7300 West Huron River Drive, Dexter, Michigan 48130, USA*

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Near single-cycle terahertz pulse generation from lithium niobate crystal by optical rectification of pulses from an Yb:fiber laser/amplifier system was investigated. The pump laser supplied 250 fs duration pulses with 14 μJ energy at up to 1 MHz repetition rate. The terahertz pulse energy and average power exceeded 0.25 nJ and 0.25 mW, respectively. The average power was more than ten times higher than corresponding values achieved by using GaP as the nonlinear crystal under similar pumping conditions. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2998609]

Ultrafast terahertz technology is being developed and used in an increasingly wide field of applications including nondestructive evaluation, pharmaceutical quality control, biological and medical sciences, and high-speed communication systems.[1] The lack of compact, high-average power, broadband terahertz sources has limited the practical deployment of terahertz radiation in these fields. An effective method for single-cycle terahertz pulse generation is based on photoconductive switches.[2] However, far higher output power can be achieved using optical rectification of ultrashort laser pulses in nonlinear optical crystals.[3,4]

Fiber laser/amplifier systems have evolved rapidly during the last decade and now offer high repetition rate output with pulse energy sufficiently high and pulse duration sufficiently short for effective single-cycle terahertz pulse generation. Fiber lasers have been demonstrated as viable pump sources for terahertz generation when semiconductors are used as nonlinear optical materials.[4,5] The 6.5 μW average terahertz power was obtained using bulk GaP (Ref. 4) and very recently 120 μW was obtained using a GaP waveguide.[6] One way to improve the generation efficiency is to use a more suitable material such as $LiNbO_3$ (LN), which has a higher figure of merit value for terahertz generation.[7] Furthermore, LN does not suffer from terahertz attenuation due to free carriers that are induced by two- or three-photon absorption, which is a limiting factor for the conversion efficiency in semiconductors.[8,9] However, despite the abovementioned advantages of LN, collinear velocity matching between the optical pump and the generated terahertz radiation is impossible in the bulk material because of its high terahertz refractive index. Noncollinear velocity matching has been demonstrated by a variety of methods,[10–12] most effectively by tilting the intensity front of the pump pulse with a grating-lens combination.[13,14] This approach has yielded single-cycle terahertz pulses with 10 μJ energy at 10 Hz repetition rate[15] and 3 μJ energy at 1 kHz repetition rate.[16] The output from LN is larger than that from ZnTe with similar pump pulse energies.[17]

In this letter, we report near-single-cycle terahertz pulse generation in LN pumped by an Yb:fiber laser/amplifier system operating at repetition rates up to 1 MHz. With pump pulse energies in the 10 μJ range, terahertz output is generated in a very different regime than at 10–1000 Hz repetition rates with multimillijoule pump pulse energies. A reliable source of broadband terahertz pulses with high average power at megahertz repetition rates could enable applications in rapid terahertz spectroscopic imaging, high throughput screening, and signal processing.

An Yb:fiber oscillator/amplifier system (Clark-MXR Impulse) producing 250 fs duration pulses at 1.035 μm, with up to 14 μJ energy at repetition rates up to 1 MHz, was used as the pump source. The intensity front of these pulses was tilted by a 1800 lines/mm grating and imaged with a 60 mm focal length lens, with a demagnification of 1.1, onto the input surface of a 0.6% MgO-doped stoichiometric $LiNbO_3$ (sLN) crystal whose output face was cut as described previously[13–16] to allow the terahertz output to leave at normal incidence. The pump spot size was adjusted through the use of a two-lens telescope prior to the grating to be about $0.3(\text{horizontal}) \times 0.2(\text{vertical})$ mm at the sLN crystal. The generated terahertz radiation was collected by a 2 in focal length, 2 in diameter off-axis parabolic reflector or by a 50 mm focal length, 30 mm diameter plastic lens. A calibrated pyroelectric detector (Microtech Instruments) was used to measure the average terahertz output power at different pump intensities and repetition rates. Electro-optic sampling using a 2 mm thick $\langle 110 \rangle$ cut GaP crystal was used to characterize the terahertz field profile and spectral content.

The temporal shape of the terahertz pulses generated at 1 MHz repetition rate is depicted in Fig. 1. The near-single-cycle pulse has a duration of about 1 ps. The spectrum reaches maximum at 1.0 THz and extends above 2 THz. The effective sensitivity of the pyroelectric detector was calculated by weighing the detector sensitivity curve with the measured spectrum of the generated terahertz radiation.

The dependence of the terahertz pulse energy on the pump pulse energy at repetition rates of 500 kHz and 1 MHz is shown in Fig. 2. The optical pump power was attenuated using a polarizer cube and a half wave plate in these measurements. At a 1 MHz repetition rate, the 14 μJ pump pulse energy corresponds to 14 W average pump power. Neither the dependence of the terahertz energy on the pump pulse energy nor its dependence on the repetition rate indicates any heating effect. In fact, for a given pump energy the generated terahertz energy is higher at higher repetition rate. This is

[a)]Electronic mail: mch@mit.edu.
[b)]On leave from Department of Experimental Physics, University of Pécs, 7624 Hungary.

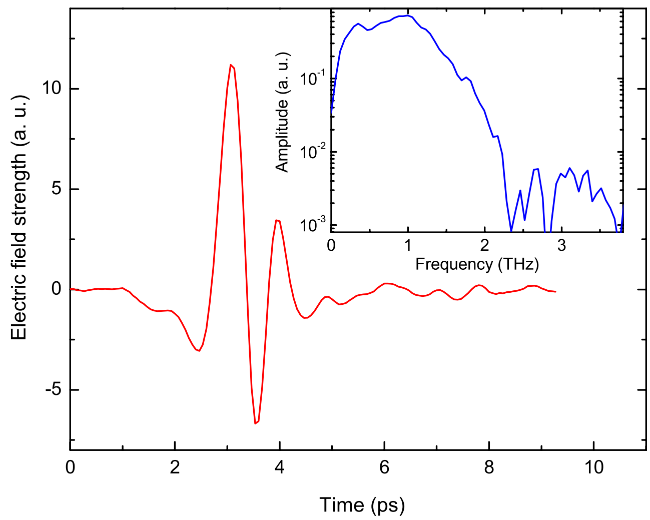

FIG. 1. (Color online) Temporal shape of the terahertz pulse generated at 1 MHz repetition rate and (inset) corresponding amplitude spectrum.

probably due to a slight shortening of the fiber system pulse duration that was observed at the higher repetition rate.

The terahertz pulse energy measured at 3 μJ pump energy was only about half of that measured earlier,[18] using 2.6 μJ pulses from a Ti:sapphire laser. Several factors could account for this. First, the pump spot size on the sLN crystal may not have been optimal. In addition, the pump pulse duration in the present case was 220 fs (see the inset of Fig. 3), which is significantly longer than the 170 fs pump pulses from the Ti:sapphire laser. Theory[19] predicts a 15% higher efficiency for 1 THz pulse generation when 170 fs long pump pulses are used rather than for 220 fs pulses. Finally, the autocorrelation trace of the pump pulse reveals a pedestal, which is not optimal for terahertz generation.

Figure 3 depicts the dependence of the square root of the terahertz pulse energy on the average pump pulse energy. For 14 W pump power, the average terahertz output power exceeded 0.25 mW. This is the highest output power reported to date in the generation of single-cycle terahertz pulses using fiber laser pumping. In fact, it is only a factor of 4 smaller than the highest average power obtained from multicycle terahertz pulses[20] and more than two times higher than what was obtained very recently using a fiber laser pumped GaP waveguide.[6] Within our measurement uncertainty, the quadratic fit displayed in Fig. 3 matches the measured data quite well, up to more than 12 W, indicating the absence of saturation in the conversion efficiency in this pumping range.

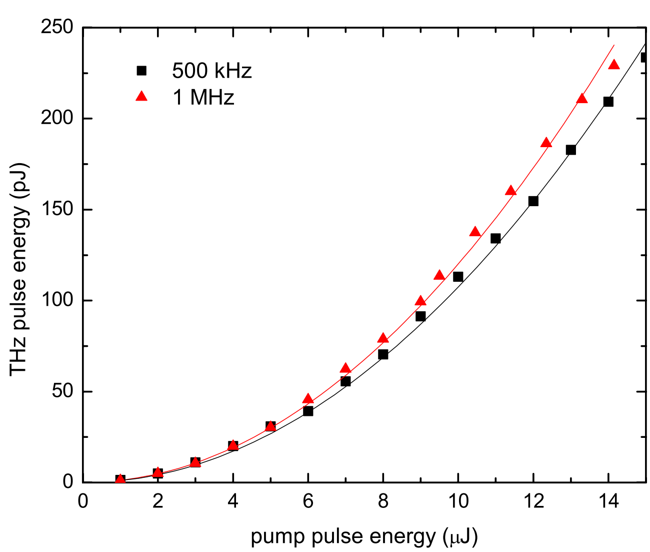

FIG. 2. (Color online) Dependence of terahertz pulse energy on the pump pulse energy at 500 kHz (squares) and 1 MHz (triangles) pump pulse repetition rates. The solid lines are the respective parabolic fits to the data.

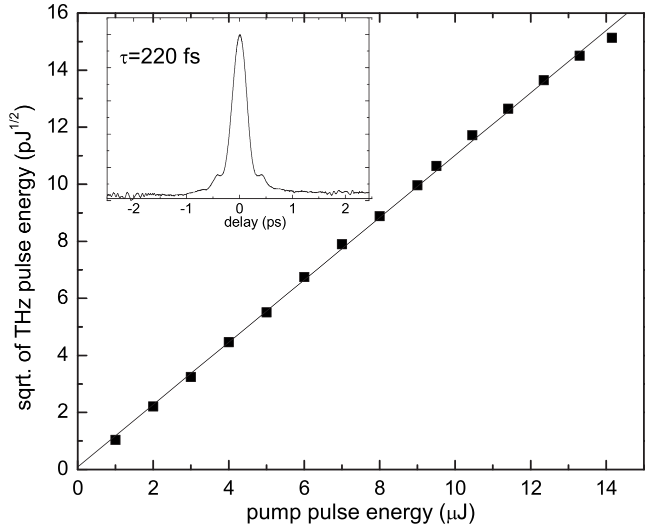

FIG. 3. Dependence of the average generated terahertz pulse energy on the pump pulse energy at 1 MHz repetition rate (squares). The line is a quadratic fitting curve. The inset depicts the autocorrelation curve of the pump pulses measured at 10 W average pump power.

GaP was used in previous terahertz generation with an Yb:fiber pumping system.[6] For comparison, we focused the present pump output into a 2 mm GaP crystal and found that with optimized pump focusing into the crystal, the terahertz output was more than an order of magnitude lower than the output from LN with the same pump power. This result is consistent with a recent extensive comparison between the terahertz generation efficiencies of LN and GaP using a conventional (not fiber) Yb laser/amplifier as the pump.[8] Over a wide range of pump intensities including those used here and far higher, the LN output was at least an order of magnitude higher than that achieved with GaP or ZnTe. In addition, the GaP output went from quadratic to linear within the present range of pump energies and from linear to saturated (no further increase with pump intensity) at far lower intensities than the LN output. This was attributed to terahertz attenuation by carriers that are produced through indirect two-photon absorption and direct three-photon absorption of the pump light in GaP while LN requires four-photon absorption as the lowest-order carrier production mechanism. The higher figure of merit of LN for optical rectification[7] explains its higher terahertz output at low pump intensities.

We have demonstrated the generation of 0.25 mW of terahertz average power by tilting the intensity front of pulses from a 1 MHz repetition rate fiber laser/amplifier system at 1.035 mm using LN as the nonlinear optical crystal. A comparison was made with GaP in which collinear phase matching can be achieved. The output from GaP was about an order of magnitude lower than that from LN. Further developments in fiber laser technologies should result in average terahertz power in the multimilliwatts range in the near future.

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