High-power source of THz radiation based on orientation-patterned GaAs pumped by a fiber laser

G. Imeshev and M. E. Fermann

IMRA America, Inc., 1044 Woodridge Ave., Ann Arbor, Michigan 48105, USA
mfermannv@imra.com

K. L. Vodopyanov and M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

X. Yu and J. S. Harris

Solid State Photonics Laboratory, Stanford University, Stanford, California 94305, USA

D. Bliss and C. Lynch

Hanscom Air Force Research Laboratory, Bedford, Massachusetts 01731, USA

Abstract: We demonstrate a new source of frequency-tunable THz wave packets based on parametric down-conversion process in orientation-patterned GaAs (OP-GaAs) that produces µW-level THz average powers at the repetition rate of 100 MHz. The OP-GaAs crystal is pumped by a compact all-fiber femtosecond laser operating at the wavelength of 2 µm. Such combination of fiber laser and OP-GaAs technologies promises a practical source of THz radiation which should be suitable for many applications including imaging and spectroscopy.

OCIS codes: (140.3510) Lasers, fiber; (190.2620) Frequency conversion; (190.7110) Ultrafast nonlinear optics; (320.7090) Ultrafast lasers.

References and links

1. D. M. Mittleman, R. H. Jacobsen, and M. C. Nuss, "T-ray imaging," IEEE J. Sel. Topics Quantum Electron. **2**, 679-692 (1996).
2. B. Ferguson and X.-C. Zhang, "Materials for terahertz science and technology," Nat. Mater. **1**, 26-33 (2002).
3. D. van der Weide, "Applications and outlook for electronic Terahertz technology," Opt. Photonics News **14**, 48-53 (2003).
4. K. Kawase, "Terahertz imaging for drug detection and large-scale integrated circuit inspection," Opt. Photonics News **15**, 34-39 (2004).
5. K. H. Yang, P. L. Richards, and Y. R. Shen, "Generation of far-infrared radiation by picosecond light pulses in $LiNbO_3$," Appl. Phys. Lett. **19**, 320-323 (1971).
6. T. J. Carrig, G. Rodriguez, T. S. Clement, A. J. Taylor, and K. R. Stewart, "Scaling of terahertz radiation via optical rectification in electro-optic crystals," Appl. Phys. Lett. **66**, 121-123 (1995).
7. P. Y. Han, M. Tani, F. Pan, and X.-C. Zhang, "Use of the organic crystal DAST for terahertz beam applications," Opt. Lett. **25**, 675-677 (2000).
8. J. Ahn, A. V. Efimov, R. D. Averitt, and A. T. Taylor, "Terahertz waveform synthesis via optical rectification of shaped ultrafast laser pulses," Opt. Express **11**, 2486-2496 (2003).
9. M. Nagaia, K. Tanaka, H. Ohtake, T. Bessho, T. Sugiura, T. Hirosumi, and M. Yoshida, "Generation and detection of terahertz radiation by electro-optical process in GaAs using 1.56 µm fiber laser pulses," Appl. Phys. Lett. **85**, 3974-3976 (2004).
10. A. G. Stepanov, J. Hebling, and J. Kuhl, "Generation, tuning, and shaping of narrow-band, picosecond THz pulses by two-beam excitation," Opt. Express **12**, 4650-4658 (2004).
11. J. Hebling, A. G. Stepanov, G. Almási, B. Bartal, and J. Kuhl, "Tunable THz pulse generation by optical rectification of ultrashort laser pulses with tilted pulse fronts," Appl. Phys. B **78**, 593-599 (2004).

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12. A. G. Stepanov, J. Kuhl, I. Z. Kozma, E. Riedle, G. Almási, and J. Hebling, "Scaling up the energy of THz pulses created by optical rectification," Opt. Express **13**, 5762-5768 (2005).
13. Y.-S. Lee, T. Meade, V. Perlin, H. Winful, T. B. Norris, and A. Galvanauskas, "Generation of narrow-band terahertz radiation via optical rectification of femtosecond pulses in periodically poled lithium niobate," Appl. Phys. Lett. **76**, 2505-2507 (2000).
14. Y.-S. Lee, T. Meade, M. DeCamp, T. B. Norris, and A. Galvanauskas, "Temperature dependence of narrow-band terahertz generation from periodically poled lithium niobate," Appl. Phys. Lett. **77**, 1244-1246 (2000).
15. C. Weiss, G. Torosyan, Y. Avetisyan, and R. Beigang, "Generation of tunable narrow-band surface-emitted terahertz radiation in periodically poled lithium niobate," Opt. Lett. **26**, 563-565 (2001).
16. K. L. Vodopyanov, M. M. Fejer, D. M. Simanovskii, V. G. Kozlov, and Y.-S. Lee, "Terahertz-wave generation in periodically-inverted GaAs," CLEO 2005, paper CWM1.
17. G. Imeshev and M. E. Fermann, "230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber," Opt. Express **13**, 7424-7431 (2005).
18. L. A. Eyres, P. J. Tourreau, T. J. Pinguet, C. B. Ebert, J. S. Harris, M. M. Fejer, L. Becouarn, B. Gerard, and E. Lallier, "All-epitaxial fabrication of thick, orientation-patterned GaAs films for nonlinear optical frequency conversion," Appl. Phys. Lett. **79**, 904-906 (2001).
19. K. L. Vodopyanov, "Optical generation of narrow-band terahertz packets in periodically-inverted electro-optic crystals: conversion efficiency and optimal laser pulse format," Opt. Express, in press (2006).
20. P. E. Powers, T. J. Kulp, and S. E. Bisson, "Continuous tuning of a continuous-wave periodically poled lithium niobate optical parametric oscillator by use of a fan-out grating design," Opt. Lett. **23**, 159-161 (1998).

1. Introduction

Compact sources of THz radiation have many important industrial, medical, scientific and security applications, including gas sensing, bio-sensing, spectroscopy, imaging, quality control, nondestructive testing and explosives detection [1-4]. Most broadband THz sources rely on excitation of electro-optic or photoconductive materials with ultrashort optical pulses. Despite a lot of progress in recent years, much of the THz source complexity is still associated with the pumping laser. A compact, high power, high repetition rate, practical source of broadband THz radiation still remains elusive.

Optical pulse rectification through parametric down-conversion [2, 5] is an established technique for THz generation, it offers power scalability, broad spectral coverage and room temperature operation. Typically the lack of phase-matching and non-negligible THz absorption limits the length of the nonlinear crystal to about 1 mm [6-9]. Because of the short interaction length the generated THz average powers are generally low, in the 100-nW range, while achieving higher powers generally requires pump sources delivering femtosecond pulse energies higher than 1 μJ [10, 11].

A way to increase the interaction length is to use the tilted front pump pulses as was demonstrated very recently in Ref. [12] where the authors achieved 240 μW THz average power from a lithium niobate crystal when pumped by a Ti:Sapphire regenerative amplifier that produced 500 mW average power (500 μJ pulse energy). Another way to increase the efficiency of pulse rectification through parametric down-conversion is the use of quasi-phase-matched (QPM) nonlinear materials as was demonstrated with periodically-poled lithium niobate crystals [13-15].

Gallium arsenide (GaAs) is another promising QPM material for THz generation. In has a wide optical transparency range (0.9-17 μm) and excellent mechanical and thermal properties. In the THz region, GaAs is characterized by low (<5 cm^{-1}) absorption below 3 THz, and high nonlinear coefficient, comparable to that of other materials (ZnTe, GaP, GaSe) used for THz-wave generation by optical rectification. Because of the two-photon-absorption edge in GaAs at about 1.75 μm, pumping at longer wavelengths is required. Efficient QPM generation of THz radiation in periodically-inverted diffusion-bonded GaAs stacks had been recently demonstrated [16] using a table-top pump source that produced femtosecond pulses in the 3 - 4 μm wavelength range with 1 - 2 μJ pulse energies at 1 kHz repetition rate.

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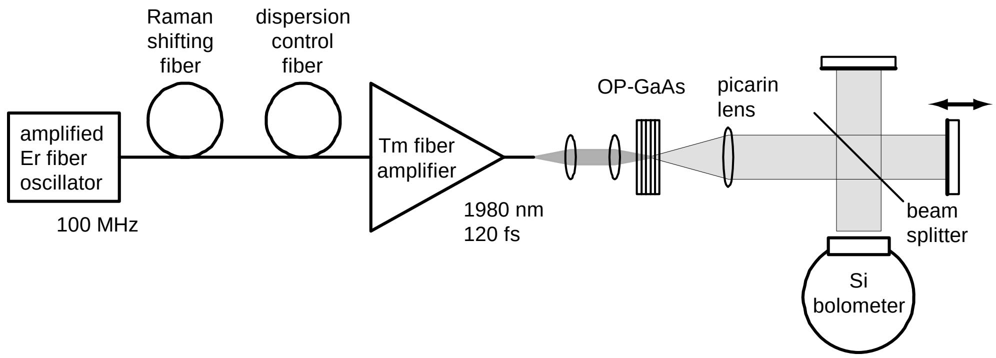

Fig. 1. Schematic of the THz generation and characterization setup.

In this paper we demonstrate a source of frequency-tunable THz wave packets based on QPM parametric down-conversion in an orientation-patterned GaAs (OP-GaAs) crystal that produces μW-level THz average powers. For pumping the OP-GaAs crystal we use a recently developed compact all-fiber source that generates femtosecond pulses at the wavelength of about 2 μm. Fiber-based sources of short optical pulses have well-known benefits of compactness and environmental reliability compared to their bulk counterparts, as particularly advantageous for practical applications. The demonstrated combination of fiber laser and OP-GaAs technologies promises a truly practical source of THz radiation.

2. THz generation using OP-GaAs pumped by a fiber laser

The experimental setup for THz generation and characterization is shown in Fig. 1. The optical pump source was an all-fiber laser that produced 120-fs pulses at 100 MHz repetition rate with the average power of 3 W (30 nJ pulse energy) at the wavelength of 1980 nm. Briefly, output of a mode-locked Er-fiber oscillator at 1557 nm was amplified in an Er/Yb-doped fiber amplifier, then Raman-shifted to 1980 nm, and finally amplified a large-mode-area Tm-doped fiber amplifier. The details of the system architecture and the performance achieved are reported elsewhere [17].

We used two OP-GaAs samples (designated as samples A3 and B3 henceforth) that were grown by a combination of molecular beam epitaxy and hydride vapor phase epitaxy [18]. Both samples were 0.4-mm-thick and 3-mm-long, and had lithographically-defined QPM periods of 1277 μm (sample A3) and 759 μm (sample B3). The pump beam was propagating along the <110> direction of GaAs and was polarized along <111> to maximize the effective nonlinear optical coefficient.

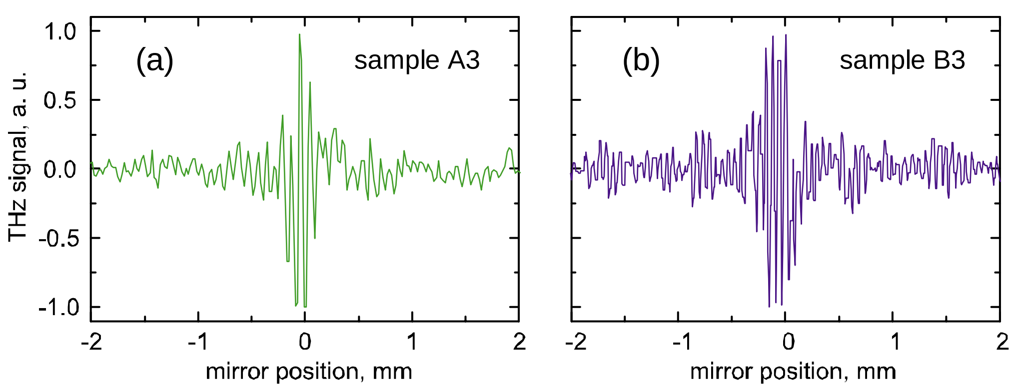

Fig. 2. Michelson interferograms obtained from (a) sample A3 with QPM period of 1277 μm and (b) sample B3 with QPM period of 759 μm.

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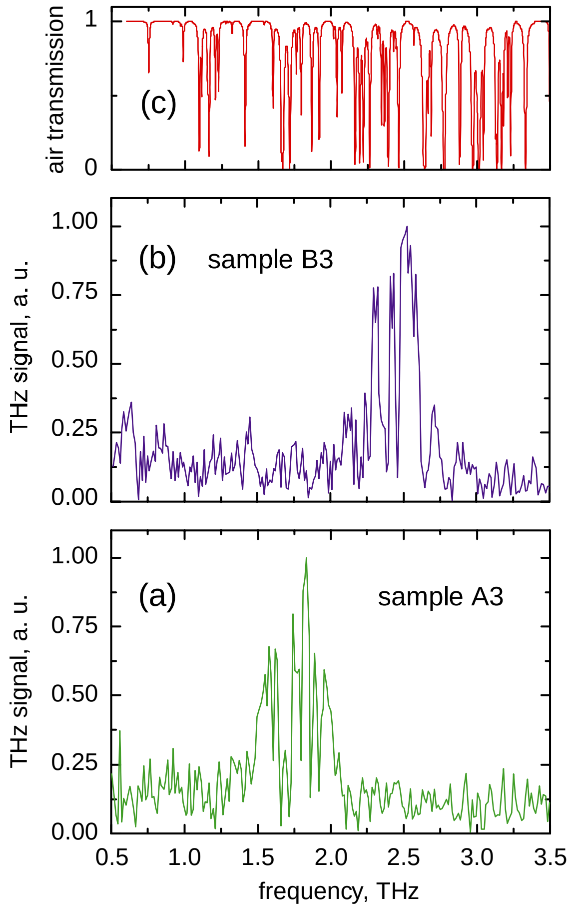

Fig. 3. Generated THz wave spectra obtained from (a) sample A3 and (b) sample B3. Also shown (c) is the transmission spectrum of 20 cm of standard air as calculated from the HITRAN database.

The focusing of the pump beam was optimized to produce the maximum THz power. The resulting spot size was w_0 = 65 μm, thus the generated THz radiation spot size was $w_{THz} = w_0/\sqrt{2}$ = 46 μm which is about 3 times smaller than the spot size that would give the THz confocal parameter kw_{THz}^2 equal to the crystal length of 3 mm (here k is a terahertz wave-vector inside the crystal, and we assumed the terahertz frequency to be near 2 THz). This observation is in agreement with theoretical predictions for optimal focusing [19]. The generated THz beam was collimated with a Picarin plastic lens that had a focal length of 50 mm. THz power was measured with a Si bolometer operating at liquid helium temperature.

In order to measure spectral properties of the generated THz radiation we used a Michelson interferometer as shown in Fig. 1. We utilized a 25-μm-thick mylar film as a beam splitter and two gold mirrors as end reflectors. One of the mirrors was mounted on a computer-controlled motorized stage. The acquired interferograms are shown in Fig. 2. The interferograms are asymmetric due a slight imbalance of the interferometer. By computing the amplitude of the Fourier transform of the interferograms we extracted the power spectra of the generated THz radiation as shown in Fig. 3. For the sample A3 the spectrum is centered at 1.78 THz and has a width of 0.3 THz, while for the sample B3 the spectrum is centered at 2.49 THz and has a width of 0.25 THz, in agreement with predicted QPM peak position and width. Strong spectral modulation was observed due to water vapor absorption in the air.

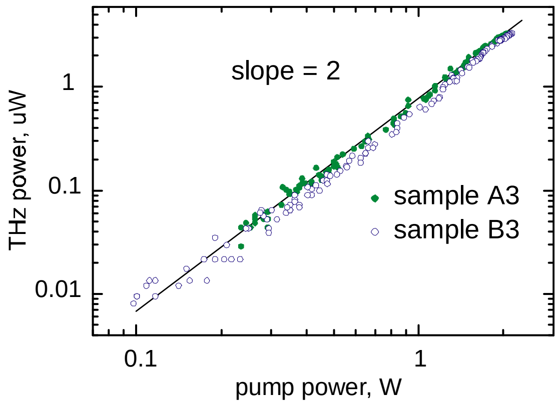

Fig. 4. THz average power versus average pump power for the OP-GaAs samples A3 (filled circles) and B3 (open circles). Straight line is the best fit to the sample A3 data.

Figure 3(c) shows transmission of a 20 cm path (comparable to the air-paths in the experiment) of standard air taken from the HITRAN database.

Figure 4 shows the measured THz power versus the incident optical power at 1980 nm. Both samples show very similar power-curve behavior: at the highest optical power of 2.1 W available at the samples we obtained ~ 3.3 μW of THz average power. The THz output power is quadratic with respect to the incident pump power and does not show any saturation effects, up to the maximum pump power of 2.1 W at the samples (peak intensity inside the samples of 1.85 GW/cm^2). Thus further power scaling should be possible with increased pumping.

The maximum optical-to-THz efficiency achieved was 1.6×10^{-6}. Here we note that the OP-GaAs samples were not antireflection-coated and the Fresnel losses at optical and terahertz frequencies exceeded 30% per surface. Thus, the internal THz efficiency was calculated as 4.7×10^{-6}, corresponding to the internal normalized efficiency of 2.24×10^{-4} μJ^{-1}. The conversion efficiencies achieved in these experiments are about 25% of the ideal calculated values [19]. The discrepancy can be accounted for by several factors, namely, clipping of the generated THz beam because the wavelength of the THz wavelength is comparable to the sample thickness (0.4 mm); attenuation of THz radiation in air due to water vapor absorption; the pump pulses being about twice the transform limit and not having the ideal Gaussian shape as was used in the theoretical calculations of Ref. [19].

In this work, we have used two separate OP-GaAs samples to produce different THz frequencies, however the lithographic nature of fabrication readily allows for a sample with multiple QPM grating segments or even a fan-out QPM grating design [20] so that THz frequency tuning can be achieved by transverse translation of the sample.

3. Conclusions

We demonstrated a tunable, 3.3-μW average power, 100-MHz repetition rate source in the range of 1.78 - 2.49 THz, based on parametric down-conversion in OP-GaAs pumped a compact all-fiber femtosecond laser at the wavelength of 2 μm. Further THz power scaling should be possible with increased pumping and improved OP-GaAs samples (larger thickness, larger length, antireflection coating). The demonstrated source should be suitable for many THz applications. Such combination of fiber laser and OP-GaAs technologies promises a truly practical source of THz radiation.

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