Narrowband Pulsed THz Source Using Eyesafe Region Fiber Lasers and a Nonlinear Crystal

Matthew A. Leigh, Wei Shi, Jie Zong, Zhidong Yao, Shibin Jiang, and Nasser Peyghambarian

***Abstract*—We report a high-power single-frequency fiber laser system in the eyesafe wavelength region that pumps a GaSe crystal through difference frequency generation, producing narrowband terahertz (THz). Two single-frequency continuous-wave fiber seed lasers are modulated, then amplified with a three-stage single-mode amplifier. The resulting pulses are transform-limited and high power, producing a peak THz power of 26.4 mW with narrow linewidth. This is significantly higher than earlier THz sources based on narrowband fiber lasers in the eyesafe region.**

***Index Terms*—Nonlinear optics, optical fiber amplifiers, optical fibers, single-frequency lasers, teraherz (THz) generation.**

I. INTRODUCTION

TERAHERTZ (THz) radiation is currently a very active research area due to the high potential of this technology and the relative lack of powerful and efficient sources in this frequency range. The ability of THz to penetrate packaging, similar to X-rays but without ionizing the contents, makes THz potentially useful for law enforcement applications such as detecting explosives and illegal drugs [1]–[3]. Many organic molecules have structural resonances in the THz region, creating great interest in possible biomedical applications, such as DNA analysis [4]. Recently developed THz imaging systems can obtain video-rate image acquisition [5], [6]. Narrowband THz has applications in high-precision spectroscopy, fingerprinting gas molecules, and exciting single molecular modes [7].

Currently, broadband THz sources, pumped by ultrafast lasers, are much more common than devices that generate narrowband THz [8], [9]. The short pulsewidths from ultrafast lasers can produce high peak power THz pulses, but their large bandwidths can limit effectiveness in imaging and free-space applications. Various narrowband THz sources with longer pulses are currently being developed by multiple research groups. Quantum cascade lasers (QCLs) have the advantage of a small size, though they require cooling to directly generate THz [10]. QCLs using intracavity difference frequency generation (DFG) have produced room-temperature THz [11]. DFG has also been used to generate THz using solid-state Q-switched lasers as a pump source, and have high-power and narrow linewidth THz [7], [12], [13]. However, solid-state lasers tend to be bulky, and require free space cavity alignment, compared to QCLs and fiber lasers.

Fiber lasers also have other advantages over solid state lasers, such as efficiency, packaging, and resistance to perturbations, which fuels interest in fiber pumped THz systems. Groups using fiber lasers in the 1-μm region have produced THz pulses using ultrafast fiber lasers, and diode-seeded fiber amplifier systems [14], [15].

While most high-powered fiber lasers are in the 1-μm region, there is considerable interest in developing high power fiber lasers with wavelengths longer than 1.4 μm. In this region, the human retina is reasonably protected due to absorption in the lens and cornea, significantly reducing the occupational hazard risk, and thus has become regarded as the eyesafe laser region. Groups have reported generating THz with fiber lasers around 1.5 and 2 μm using ultrafast pulses [16], [17]. Narrowband fiber laser pumped THz sources are rare, due in part to the competing requirements of high-power, single-frequency, and a single spatial mode [18]. In this letter, we report the highest power for narrowband THz pumped by a fiber laser in the eyesafe region.

II. EXPERIMENTAL SETUP

The master oscillator power amplifier system is seeded by two continuous-wave (CW) NP Photonics single-frequency fiber lasers, which have linewidths of less than 2 KHz, low noise, and high stability [19]. The fiber lasers have a complete monolithic fiber construction with a short phosphate glass gain region spliced to fiber gratings, unlike fiber-stabilized diode lasers in which the cavity includes the diode-fiber coupling. The all-fiber cavity design has also been used to produce monolithic single-frequency Q-switched fiber lasers at various wavelengths [20]. The two seed laser wavelengths were chosen to be 1538.63 and 1550.50 nm.

These seed lasers are modulated by fiber-coupled electrooptic modulators (EOMs), as shown in Fig. 1, and are similar to previous high-power single-frequency fiber laser systems [21]. Telecom EOMs with 10-GHz bandwidth, high extinction ratio, and polarization-maintaining (PM) outputs were used, permitting independent adjustment of pulsewidth and repetition rate. The first EOM chopped the CW optical signal from the seed laser into ~ns optical pulses, with the pulse shape and timing defined by the electrical system. These optical pulses are amplified by an erbium-doped fiber preamplifier, and filtered by a narrowband ~0.3-nm filter to remove amplified spontaneous emission (ASE). The trigger pulse for the second EOM is timed to coincide with the arrival of the pulse, eliminating in-band ASE.

Manuscript received August 16, 2008; revised October 11, 2008. First published October 31, 2008; current version published January 05, 2009.

M. A. Leigh was with NP Photonics, Tucson, AZ 85747 USA. He is now with Envisioneering, Inc, King George, VA 22485 USA.

W. Shi, J. Zong, and Z. Yao are with NP Photonics, Tucson, AZ 85747 USA (e-mail: wshi@npphotonics.com).

S. Jiang is with AdValue Photonics, Inc., Tucson, AZ 85714 USA.

N. Peyghambarian is with NP Photonics, Tucson, AZ 85747 USA. He is also with the College of Optical Sciences, University of Arizona, Tucson, AZ 85721 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2008195

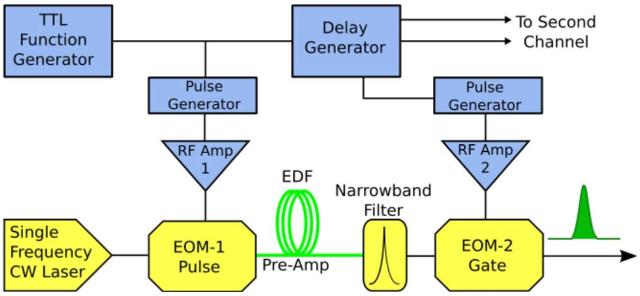

Fig. 1. EOM-1 forms the optical pulse, which is amplified, filtered, and gated by EOM-2. Second channel delay allows temporal overlap.

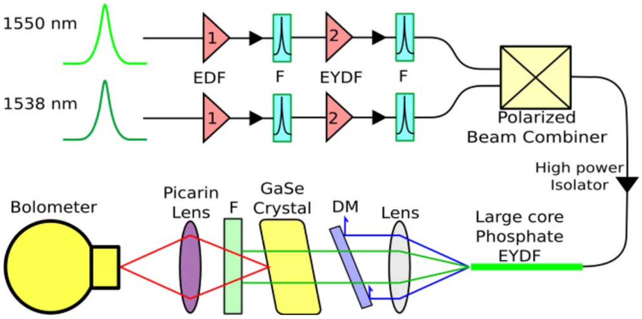

Fig. 2. Each amplifier channel contains an Er-doped amp (EDF), Er : Yb codoped amp (EYDF), and filters (F). Both wavelengths are combined and amplified in the final amp stage. The Dichroic mirror (DM) filters the diode laser. DFG in the GaSe crystal produces the THz.

Both of the pulses were amplified through separate two-stage amplifier channels, as shown in Fig. 2. Filters and isolators helped to maintain the spectral quality of the beam, and fiber-coupled taps were spliced between each stage to check both the spectra and temporal profile of the pulse. To suppress the nonlinearities common in fiber lasers, short lengths of 50 cm were used for the active fiber in each stage. Each wavelength was then combined into a single fiber using a fiber-spliced polarization beam combiner.

As power increases, it becomes increasingly important to use short fiber lengths and large cores to suppress nonlinearities. For the final stage amplifier, we used a large core codoped phosphate glass fiber that was doped with 3% Er and 15% Yb by weight. This allowed us to realize high gain while keeping the fiber length to only 12 cm, which was computed to be the optimal length using the “effective beam propagation method” [22]. This fiber is one to two orders of magnitude shorter than amplifiers using silica fiber, limiting nonlinearities and realizing a compact system. The core size was 15 μm, which is currently the largest core for single-mode PM phosphate fibers. The fiber was end polished to help reduce feedback and decrease the chance of end damage.

The light from the fiber laser system is collimated by a lens and directed to the nonlinear crystal. The dichroic mirror eliminates residual 980-nm diode light, reducing the possibility of thermal damage to the crystal.

We chose z-cut 15-mm-thick GaSe as our nonlinear crystal because it has low absorption in the C-band, has a relatively high nonlinear coefficient of $d_{22} = 54$ pm/V, and has been used to generate THz power up to 389 W [7]. GaSe is negative uniaxial, requiring type II phase matching with crossed polarizations. In this configuration, the 1538 nm was the pump with o-polarization, while both the 1550-nm pump and the THz had e-polarization. We set the crystal at a phase matching angle of 15°, which agreed well with the theoretical value of 14.8°, and set the azimuthal angle to satisfy $|\cos 3\varphi| = 1$ to maximize the emission.

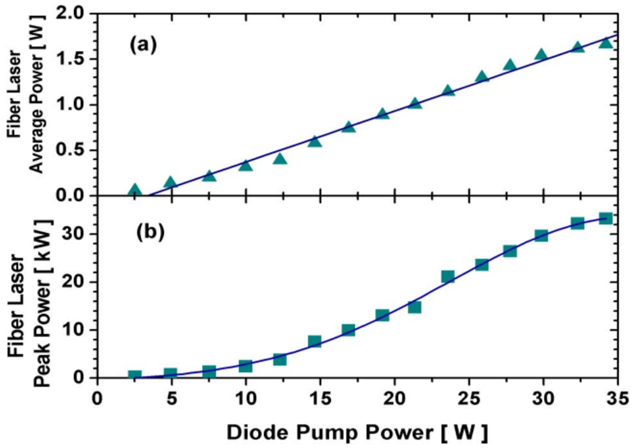

Fig. 3. Narrowband fiber laser. (a) Measured average power (points) and linear fit. (b) Measured peak power (points) and Gaussian fit (line).

To separate the THz output from the residual 1538- and 1550-nm laser light we used a black polyethylene filter. A picarin lens focused the generated THz into a liquid He cooled bolometer made by IR Labs, Inc. The output was measured by using a lock-in detector and optical chopper.

III. Results

For the fiber laser system we used a pulse repetition rate of 20 KHz, which provided a good balance of high peak power and sufficient average power. Narrow linewidth operation of the fiber laser was measured with a fiber Fabry–Pérot interferometer, similar to previous experiments [20], [21]. We measured a linewidth of less than 400 MHz at high pump powers with a 2-ns pulsewidth, demonstrating transform-limited operation. As shown in Fig. 3, the average power of the fiber laser system increased linearly with pump power, reaching 1.66 W at maximum pumping. The peak power increased in a roughly Gaussian manner with pump power, reaching a 33.2-KW maximum. While the onset of rollover for peak power was observed, it was incomplete, indicating that increasing the pump power will likely lead to higher peak fiber laser power.

The difference in pump wavelengths was 1.49 THz, which agreed well with the frequency of 1.5 THz measured with a metal grating Fabry–Pérot, and the measured phase-matching angle. The linewidth of pulsed narrowband THz is currently difficult to measure directly. However, since the THz is generated through DFG, it is reasonable to estimate the resulting linewidth as less than or equal to the linewidth of the pump wavelengths, as has been measured previously [7]. Thus, we infer that the linewidth of the THz is <400 MHz, corresponding to the linewidth of the fiber lasers. This compares favorably with linewidths on the order of THz or hundreds of gigahertz (GHz) [11], [15].

The THz generation system showed a strong quadratic dependence on the fiber laser pump power, as shown in Fig. 4, in

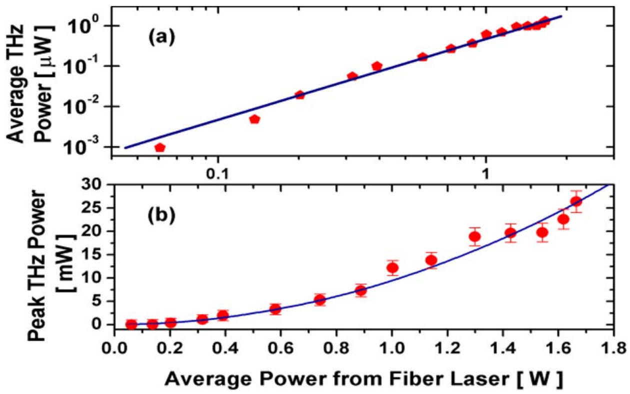

Fig. 4. THz generation versus average fiber laser power: (a) Measured average power (points) and quadratic fit (line). (b) Measured peak power (points) and fit (line).

agreement with a second-order nonlinear process. We also selectively blocked a single pump wavelength to verify the DFG process. We achieved a peak power of 26.4 mW, corresponding to an average power of 1.32 μW. This is a factor of over 49 times more than previous results for narrowband THz sources pumped by eyesafe Q-switched fiber lasers [18], [21].

The power conversion efficiency for the THz generation was 8×10^{-7}, and the photon conversion efficiency was at least 1×10^{-4}. The GaSe crystal used for the DFG was uncooled, and the fiber amplifier cooled only using forced air, indicating the efficiency of the system.

IV. SUMMARY

We developed the highest power THz source pumped by an eyesafe, narrowband fiber laser system, with an output of 26.4 mW. Further improvements could be realized through the development of phosphate fibers with larger cores for the final amplifier stage, and higher pumping, leading to the powers necessary for practical imaging and detection. This system shows the potential of developing narrowband fiber-laser pumped THz systems that would be more portable and robust than solid-state pumped THz generation systems.

REFERENCES

[1] M. J. Fitch, M. R. Leahy-Hoppaa, E. W. Otta, and R. Osiander, "Molecular absorption cross-section and absolute absorptivity in the THz frequency range for the explosives TNT, RDX, HMX, and PETN," *Chem. Phys. Lett.*, vol. 443, pp. 284–288, 2007.

[2] P. Taday, I. Bradley, D. Arone, and M. Pepper, "Using terahertz pulse spectroscopy to study the crystalline structure of a drug: A case study of the polymorphs of ranitidine hydrochloride," *J. Pharm. Sci.*, vol. 92, no. 4, pp. 831–838, 2003.

[3] J.-Y. Lu *et al.*, "Terahertz microchip for illicit drug detection," *IEEE Phtoton. Technol. Lett.*, vol. 18, no. 21, pp. 2254–2256, Nov. 1, 2006.

[4] S. W. Smye, J. M. Chamberlain, A. J. Fitzgerald, and E. Berry, "The interaction between Terahertz radiation and biological tissue," *Phys. Med. Biol.*, vol. 46, pp. R101–R112, 2001.

[5] B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," *Opt. Lett.*, vol. 20, no. 16, pp. 1716–1718, 1995.

[6] A. W. M. Lee, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Real-Time imaging using a 4.3-Thz quantum cascade laser and a 320 × 240 microbolometer focal-plane array," *IEEE Photon. Technol. Lett.*, vol. 18, no. 13, pp. 1415–1417, Jul. 1, 2006.

[7] J. Ding, "Tunable coherent radiation from terahertz to microwave by mixing two infrared frequencies in a 47-mm-long GaSe crystal," *Int. J. High Speed Electronics & Systems*, vol. 16, no. 2, pp. 589–604, 2006.

[8] K. Reimann, "Table-top sources of ultrashort THz pulses," *Rep. Prog. Phys.*, vol. 70, pp. 1597–1632, 2007.

[9] M. D. Thomson, M. Kreß, T. L̈ffler, and H. G. Roskos, "Broadband THz emission from gas plasmas induced by femtosecond optical pulses: From fundamentals to applications," *Las. Photon. Rev.*, vol. 1, no. 4, pp. 349–368, 2007.

[10] B. Williams, S. Kumar, Q. Hu, and J. Reno, "Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode," *Opt. Express*, vol. 13, no. 9, pp. 3331–3339, 2005.

[11] M. A. Belkin *et al.*, "Room temperature terahertz quantum cascade laser source based on intracavity difference-frequency generation," *Appl. Phys. Lett.*, vol. 92, p. 201101, 2008.

[12] J. Nishizawa, T. Tanabe, K. Suto, Y. Watanabe, T. Sasaki, and Y. Oyama, "Continuous-wave frequency-tunable THz-wave generation from GaP," *IEEE Photon. Technol. Lett.*, vol. 18, no. 19, pp. 2008–2010, Oct. 1, 2006.

[13] J. E. Schaar, K. L. Vodopyanov, and M. M. Fejer, "Intracavity terahertz-wave generation in a synchronously pumped optical parametric oscillator using quasi-phase-matched gaas," *Opt. Lett.*, vol. 32, no. 10, pp. 1284–1286, 2007.

[14] G. Chang, C. Divin, C. Liu, S. Williamson, A. Galvanauskas, and T. Norris, "GaP waveguide emitters for high power broadband THz generation pumped by Yb-doped fiber lasers," *Opt. Express*, vol. 15, no. 25, pp. 16308–16315, 2007.

[15] D. Creeden *et al.*, "Compact fiber pumped terahertz source," in *Terahertz for Military and Security Applications V*, 2007, vol. 6549, Proc. SPIE, p. 65490P.

[16] M. Nagai *et al.*, "Generation and detection of terahertz radiation by electro-optical process in gaas using 1.56 μm fiber laser pulses," *Appl. Phys. Lett.*, vol. 85, no. 18, pp. 3974–3976, 2004.

[17] G. Imeshev *et al.*, "High-power source of THz radiation based on orientation-patterned gaas pumped by a fiber laser," *Opt. Express*, vol. 14, no. 14, pp. 4439–4444, 2006.

[18] W. Shi, M. Leigh, J. Zong, and S. Jiang, "Single-frequency terahertz source pumped by Q-switched fiber lasers based on difference-frequency generation in GaSe crystal," *Opt. Lett.*, vol. 32, no. 8, pp. 949–951, 2007.

[19] C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, "Low-noise narrow-linewidth fiber laser at 1550 nm," *J. Lightw. Technol.*, vol. 22, no. 1, pp. 57–62, 2004.

[20] M. Leigh *et al.*, "Compact, single-frequency all-fiber Q-switched laser at 1 μm," *Opt. Lett.*, vol. 32, no. 8, pp. 897–899, 2007.

[21] M. Leigh, W. Shi, J. Zong, Z. Yao, S. Jiang, and N. Peyghambarian, "High peak power single frequency pulses using a short polarization maintaining phosphate glass fiber with a large core," *Appl. Phys. Lett.*, vol. 92, pp. 181108–181108, 2008.

[22] D. T. Nguyen, A. Chavez-Pirson, S. Jiang, and N. Peyghambarian, "A novel approach of modeling cladding-pumped highly Er-Yb Co-doped fiber amplifiers," *IEEE J. Quantum Electron.*, vol. 43, no. 11, pp. 1018–1027, Nov. 2007.