Single-frequency terahertz source pumped by *Q*-switched fiber lasers based on difference-frequency generation in GaSe crystal

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We demonstrate a unique terahertz (THz) source that is compact, utilizes recently developed all-fiber *Q*-switched lasers, and is based on difference-frequency generation in a GaSe crystal. A single piezo simultaneously *Q* switched the two fiber lasers by using stress-induced birefringence, to achieve the temporal overlap of pulses from the two fiber lasers. These correlated pulses then combine in the GaSe crystal to produce coherent and highly monochromatic THz pulses. The peak power for this THz source can reach 0.53 mW, corresponding to an average power of 0.43 μW and a conversion efficiency of 4.75×10^{-7}. The estimated linewidth of this THz source can be as narrow as ~35 MHz or 1.17×10^{-3} cm^{-1}. © 2007 Optical Society of America

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Recently, terahertz (THz) technologies have attracted a great deal of attention due to applications in homeland security, space exploration, nondestructive testing, and scientific experimentation involving sensing, imaging, and spectroscopy.[1–3] THz sources are often the critical component for these applications. One of the most promising schemes for THz generation is based on optical parametric processes such as difference-frequency generation (DFG) in nonlinear optical (NLO) crystals.[4–8] These methods can produce tunable, narrow linewidth, high peak power THz pulses with the pulse durations in nanoseconds level and repetition rates that are widely tunable. These THz sources are able to be operated at room temperature and are not reliant upon cryogenic cooling. Recently a GaSe crystal was used to generate coherent THz waves tunable from 58.2 to 3540 μm pumped by using a Nd:YAG laser beam and the idler beam of an optical parametric oscillator (OPO) pumped by the third harmonic of the same Nd:YAG laser.[4] This THz source has an extremely wide tuning range, and its maximum output peak power can reach several hundred watts. However, much of the complexity, volume, and mass of this THz system is due to the pump laser and OPO system. High power fiber lasers have recently been developed, which have excellent mode quality, narrow linewidth, nanosecond pulses, and high peak power. These fiber lasers are also very attractive mainly due to their compactness, portability, and ease of maintenance, making them quite useful for nonlinear optical processes.

Previously, fiber laser pumps were used in optical-heterodyne mixing for THz generation.[9,10] In this Letter, we demonstrate the combination of all-fiber *Q*-switched lasers with an optical parametric process that promises a compact, single-frequency, high repetition rate and high power THz source. Figure 1 illustrates the schematic of this THz source. In this system, all fibers and fiber-based components are polarization maintaining (PM). Two fiber lasers were simultaneously *Q* switched by a single piezo to modulate the intracavity polarization-dependent loss. We believe this to be the first demonstration of the use of a single piezo element to *Q* switch multiple fiber-laser chains.

The wavelength of the fiber lasers was chosen to be in the range of 1550 nm for several reasons. First, there are many commercially available fiber-based components near this wavelength because this is a standard telecommunications industry wavelength region. Second, the GaSe crystal has a lower absorption coefficient at ~1550 nm (~0.16 cm^{-1}) than that at approximately the previously used wavelength of 1064 nm (~0.25 cm^{-1}).[4–6] Third, the longer wavelengths for the pumps have higher conversion efficiency in parametric THz generation due to the smaller refractive indices at 1550 nm than 1064 nm for GaSe. Finally, phase matching can be achieved in an extremely wide THz range when using the pump wavelengths in the area at ~1550 nm.

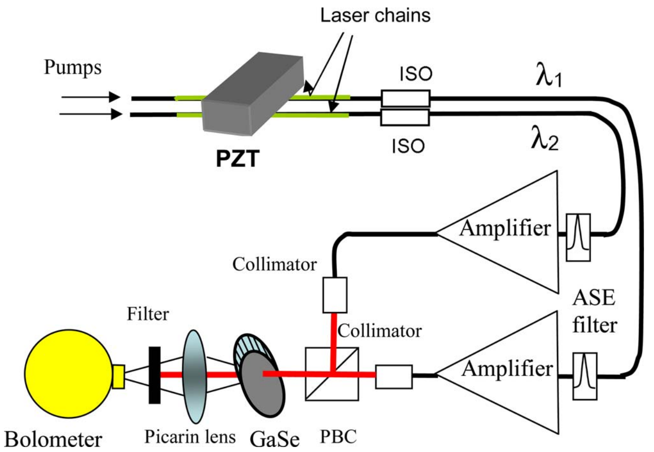

Fig. 1. (Color online) Schematic of the THz source pumped by all-fiber *Q*-switched lasers based on DFG in GaSe crystal: PZT, lead zirconate titanate; ISO, isolator; ASE, amplified stimulated emission; PBC, polarization beam combiner.

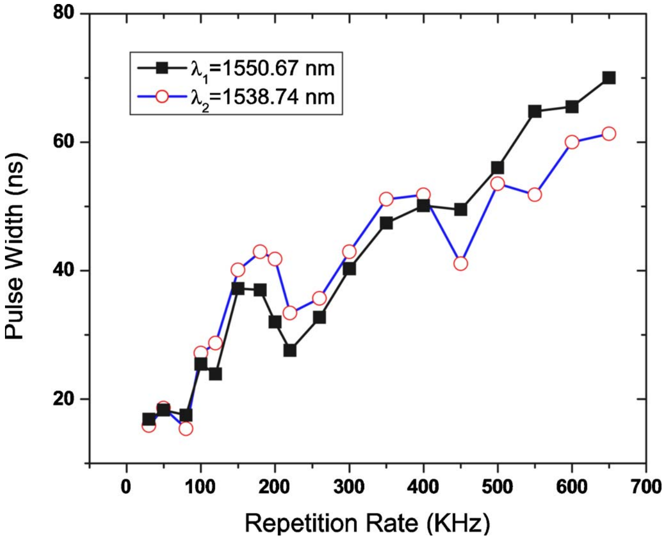

Fig. 2. (Color online) Pulse width versus the repetition rate for two simultaneously Q-switched fiber lasers: $\lambda_1 = 1550.67$ nm; $\lambda_2 = 1538.74$ nm.

Each of the laser chains in Fig. 1 consists of a 2 cm long Er/Yb codoped phosphate glass fiber spliced between a pair of silica-based fiber Bragg gratings (FBGs). The phosphate glass allows high doping concentration of active ions due to the high solubility of the glass, enabling efficient lasers with active fibers only a few centimeters long. One FBG has a high reflectivity (HR) grating imprinted on a non-PM silica fiber. The other FBG, the output coupler, has a low reflectivity grating made on a PM fiber, creating a different reflection wavelength for each polarization, with each grating having only approximately 10 GHz of bandwidth. The reflection band of the high reflector is matched to only one of the reflection bands of the output coupler, making the laser cavity polarization dependent.

The HR-FBG on a silica fiber is cleaved and spliced a few millimeters away from the FBG, leaving room for the non-PM fiber to be stressed, producing birefringence.[11] The longitudinal mode spacing is 2.5–3 GHz; therefore there are only a few longitudinal modes supported in the reflection band of the output coupling FBG. By adjusting the temperature of the FBGs and the laser cavity single-frequency operation can be maintained, and the wavelength can be tuned.[12] To modulate the loss internal to the resonator, we clamped a lead zirconate titanate (PZT) piezo on the fiber in the section between the splice and the HR-FBG. This allowed us to apply stress from the side of the fiber, introducing birefringence in the fiber that depended on the electrical driving of the PZT. Because of the polarization dependence of the resonator, the loss of the resonator can be modulated. The orientation of the stress was keyed at an angle of 45° with respect to the slow and fast axes of the PM fiber to obtain a high modulation contrast. Two laser chains were each pumped by two commercial fiber-pigtailed, single-mode, 976 nm diodes.

Figure 2 shows the pulse width versus the repetition rate for two simultaneously Q-switched fiber lasers with wavelengths of $\lambda_1 = 1550.67$ nm and $\lambda_2 = 1538.74$ nm. We can see the two Q-switched lasers have very similar pulse widths at different repetition rates, which can produce a large fraction of energy overlap for DFG. The repetition rate for two Q-switched lasers can be varied from 50 Hz to 650 KHz, pulse width from 15 to 70 ns, average power from 3 to 56 mW, and peak power from 1 to 12 W without any external amplifier. Figure 3 shows typical pulse shapes and pulse overlaps of two Q-switched lasers that have the pulse widths of 18.5 and 20.1 ns, respectively. The pulse shape for both fiber lasers is Gaussian, and the temporal overlap is necessary for optical parametric processes or DFG to generate THz radiation. The laser spectra of two Q-switched lasers were measured by a scanning Fabry–Perot interferometer with a free spectral range (FSR) of 1 GHz. The observed spectrum shows bursts of pulses under transmission peaks of the Fabry–Perot, which are separated in time by the repetition rate of the laser. This observation confirms that the Q-switched laser operates at a single frequency. From the envelope of the pulse train in the scanning Fabry–Perot spectrum, the linewidth of the Q-switched lasers is ~35 MHz. Considering the pulse width in Fig. 3, this linewidth of two Q-switched lasers is very close to transform limited.

The two Q-switched lasers were amplified by two identical three-stage cascade amplifiers as in Fig. 1. Before the amplifiers, two amplified stimulated emission (ASE) filters were used to avoid cascade amplifying the ASE, and isolators were used to block feedback. Two three-stage cascade amplifiers were built by using PM components and active fibers to maintain a pure polarization state for the DFG. We used the single-mode PM Er-doped fibers pumped by the single-mode 980 nm diodes for the first stages and the single-mode PM Er/Yb-doped double-clad fibers pumped by multimode diodes for second stages. Pulsed fiber amplifiers are limited by the nonlinear effects of the fiber, such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) due to the high peak power and tight confinement in the fiber core. To decrease the nonlinearities we

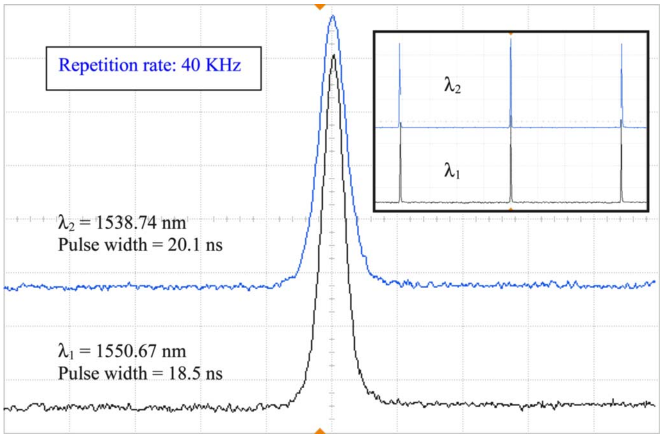

Fig. 3. (Color online) Typical pulse shapes and pulse overlaps of two simultaneously Q-switched lasers. Inset, pulse overlaps each other for two simultaneously Q-switched lasers.

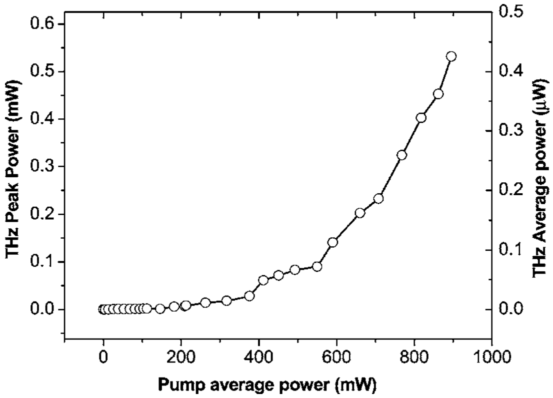

Fig. 4. Generated THz output power versus the pump average power.

used the large core (~15 μm) single-mode PM Er/Yb-codoped double-clad fibers pumped by multimode diodes for third stages. The peak power of the final amplified pulses by the three-stage amplifiers can be more than 1 KW without noticeable nonlinear effects when the repetition rate is 40 KHz for the Q-switched lasers. The pulse width of the amplified pulses was slightly decreased, and the linewidth was approximately the same as those before amplification. The peak-ASE ratio was more than 10 dB, and the polarization extinction ratio (PER) was ~10 dB.

Then, two amplified beams were collimated into a commercial GaSe crystal with a thickness of 15 mm through a polarization beam combiner (PBC). After the crystal, the generated THz waves were focused into a liquid-helium cooled bolometer by a picarin lens, and the residual pumps were blocked by using a black polyethylene filter. The detected THz signal was recorded by using a lock-in amplifier as in Fig. 1. The THz output power can be determined by the calibrated bolometer and verified by using the responsivity of the bolometer. According to the phase-matching conditions, type-oee collinear phase matching can be achieved for two pump wavelengths ($\lambda_1=1550.67$ nm and $\lambda_2=1538.74$ nm) in the GaSe crystal,[13] where e and o indicate the polarization directions of beams inside the crystal. The experimental external phase-matching angle (θ) of 15.0° has very good agreement with the calculated $\theta=14.8°$ in our experiments. The azimuthal (φ) angles were chosen such that $|\cos 3\varphi|=1$ according to the effective nonlinear optical coefficient as $d_{\mathrm{eff}}=d_{22}\cos^2\theta\cos 3\varphi$. In this experiment, we observed the typical phase-matching curve of the THz output power versus the incident angle of pumps.

Figure 4 shows the THz output power versus the pump average power. One can see that the average power for the generated THz radiation can reach 0.43 μW when the pump average power is 895 mW and the peak power is 1.12 KW, corresponding to a peak power of 0.53 mW and a conversion efficiency of 4.75×10^{-7}. The normalized conversion efficiency of this parametric process is $5.31\times 10^{-7}\ \mathrm{W}^{-1}$. The THz wavelength of 200 μm can be easily obtained by the difference frequency of two pump beams, which was verified by using a metal-mesh etalon. The estimated linewidth of this THz source is 35 MHz, or $1.17\times 10^{-3}\ \mathrm{cm}^{-1}$, according to the optical parametric theory and the linewidth of the amplified Q-switched lasers. This narrow linewidth is very useful to fingerprint molecular gases, especially for low-pressure gases, because the linewidth of their rotational transitions can be smaller than 50 MHz. Additionally, this single-frequency THz source can be tuned by tuning the wavelength of fiber lasers and by changing fiber laser chains with different wavelengths. We have already observed 0.27 THz radiations by using another pair of fiber-laser chains with wavelengths of 1550.10 and 1552.27 nm.

In conclusion, we have implemented a novel compact single-frequency THz source that has an average power of 0.43 μW and a peak power of 0.53 mW based on DFG by using all-fiber Q-switched lasers. In this Letter, we used one piezo to Q switch two fiber lasers simultaneously for what we believe to be the first time. Two identical three-stage cascade amplifiers were used to amplify two Q-switched lasers, producing a promising THz source.

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