Photonic Narrow Linewidth GHz Source Based on Highly Codoped Phosphate Glass Fiber Lasers in a Single MOPA Chain

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***Abstract*—We present the first demonstration of a fiber pumped source of coherent gigahertz (GHz) radiation based on parametric processes. The GHz source is compact, and pumped by two Q-switched highly codoped phosphate all-fiber lasers in a fusion-spliced master oscillator power amplifier chain at eye safe C-band wavelengths, with a GaSe crystal used for difference-frequency generation. The final stage used a novel highly codoped phosphate glass fiber that was only 12 cm long, and scaled the peak power of the narrow linewidth fiber laser to more than 4 kW. The generated GHz radiation at 270 GHz has a peak power of 48.1 μW, corresponding to a peak power spectral density of $\sim$1.2 W/THz with an estimated linewidth of 40 MHz.**

***Index Terms*—Fiber-optics amplifiers and oscillators, frequency conversion, gigahertz (GHz) source, infrared and far-infrared lasers, lasers and laser optics, nonlinear optics.**

I. INTRODUCTION

AMONG the photonic solid-state technologies that have been used to generate coherent gigahertz (GHz) sources, mainly two types of photomixers have used to generate coherent GHz radiation: one is low-temperature-grown GaAs pumped by fiber and microchip lasers [1], [2]; another is a uni-travelling-carrier photodiode pumped by fiber lasers, which has been developed to be used for the local oscillator for the large millimeter telescope array [3], [4]. In addition, subpicosecond GHz or terahertz (THz) pulses with a broad bandwidth can be generated by using ultrafast laser pulses based on photoconduction and optical rectification [5]. Also, coherent GHz waves tunable from 84 GHz to 5 THz were generated based on difference-frequency generation (DFG) in a GaSe crystal pumped by a free-space Nd:YAG laser and a related optical parametric oscillator [6]. Compared with electronic THz sources that mainly include solid-state GHz devices based on semiconductor technologies and vacuum electronic beam tubes, a photonic approach can generate narrow linewidth GHz waves by using ultralinewidth laser pumps [1]–[6], and the generated GHz beam can be laser-like and diffraction-limited due to the laser pumps, especially the diffraction-limited fiber laser pumps [7].

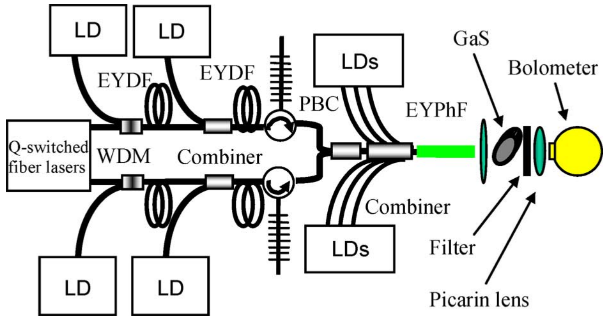

Fig. 1. Schematics of Q-switched fiber lasers in fusion-spliced MOPA chains and scheme for parametric GHz generation and detection. LD: laser diode.

Recently, fiber-based THz generation based on phase-matched DFG was reported [7], which promises compact, coherent, tunable THz and GHz sources due to the unique advantages of fiber lasers. In this letter, narrow linewidth coherent GHz generation was demonstrated based on forward and backward parametric processes, respectively, pumped by Q-switched highly codoped phosphate all-fiber lasers in a single master oscillator power amplifier (MOPA) chain at eye safe wavelength of 1550 nm by using GaSe crystal. This is the first report of this type of system that we know. Previously, the highly codoped phosphate fibers were successfully used to implement the low-noise narrow-linewidth fiber lasers and single-frequency Q-switched fiber lasers [7], [8]. What we also demonstrated in this letter is a specialized highly codoped polarization-maintaining (PM) large mode area phosphate fiber only 12 cm long that successfully amplified high peak power pulses with narrow linewidth and single-mode (SM) output, owing to its high optical gain per unit of length [9].

II. Q-SWITCHED FIBER LASERS

Similar to previous experiments [7], [10], two single-frequency fiber laser chains with wavelengths of 1550.10 and 1552.27 nm were simultaneously Q-switched by one piezo actuator. The pulse duration can be tuned from 8.23 to 74 ns with the repetition rate in the range of 50 Hz–630 KHz.

The two simultaneously Q-switched fiber lasers were first amplified by two identical two-stage preamplifiers as shown in Fig. 1. Then, two preamplified lasers were orthogonally combined together by using a PM beam combiner after amplified spontaneous emission filters by combining a PM circulator and a related PM grating, and amplified in the same active fiber at

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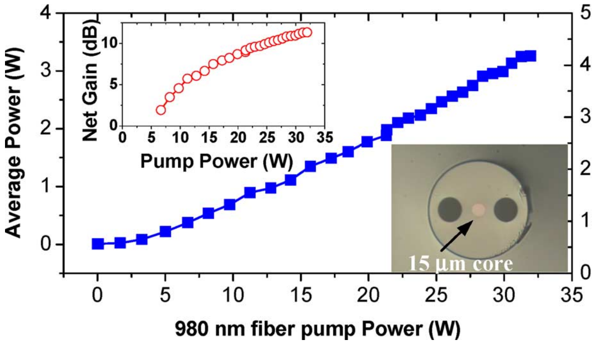

Fig. 2. Average/peak power versus 980-nm fiber pump power for power amplifier when input power is 200 mW at 1550.1 nm. Top inset, net gain versus 980-nm fiber pump power for power amplifier; bottom inset, cross section of the large core SM PM EYPhF.

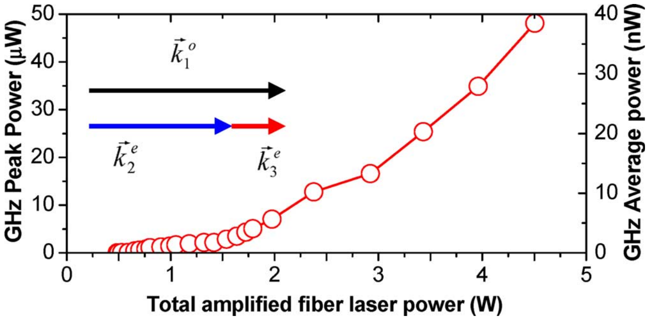

Fig. 3. Generated GHz average/peak power at different total pump power of amplified fiber lasers 1550.10 and 1552.27 nm based on forward phase-matched DFG. Inset, scheme of forward collinear parametric DFG.

the same time in order to achieve excellent spatial and temporal overlap of pulses from the two fiber chains and maintain their orthogonal polarization state. A commercial 7 : 1 PM pump power combiner was fusion-spliced between the polarization beam combiner and the large-mode area Er–Yb phosphate fiber (EYPhF) with an angle-polished output end. Six single-emitter diodes were combined and used to cladding pump the EYPhF. From Fig. 1, one can see that the whole two-wavelength Q-switched fiber laser system was fusion-spliced in a single MOPA chain.

Due to the low absorption of Er at the current diode pump wavelength, the recent scaling of fiber laser peak power at ~1550 nm has been much slower than that at ~1064 nm, where Yb-doped fibers perform very well. Even when cladding-pumped Er–Yb codoped fibers were demonstrated in order to increase the pump absorption as early as the 1990s [11], the highest peak power for narrow-linewidth pulses at 1550 nm is still in the kilowatt-level, and remains challenging for silica fiber [12]. An active phosphate glass fiber can have higher doping, leading to shorter lengths while still maintaining single-frequency operation.

In the power amplifier, the large core (~15 μm) SM PM highly codoped EYPhF has a core numerical aperture of about 0.053. The typical cross section with two circular regions is illustrated as the bottom inset in Fig. 2. This is the largest core size for an SM PM EYPhF to the best of our knowledge. For this high doping (~3%Er–15%Yb) EYPhF, the optimum fiber length for the maximum gain at ~1550 nm was calculated to be from 10 to 15 cm with the input power of 10–1000 mW and fixed pump power of ~30 W according to our simulation based on the transcendental power equation model by using the intrinsic parameters of the highly doped fiber [13], [14]. So in the power amplifier, the length of EYPhF active fiber we used is only 12 cm, which is one to two orders of magnitude shorter than commercial silica fibers to achieve a similar gain level. Nonlinear effects scale with the intensity-length product, making this short length of active fiber very important for significantly suppressing the nonlinear effects in the pulse amplification, especially for our narrow-linewidth pulses that is critical when driving parametric processes.

Fig. 2 depicts the output average/peak powers of the power amplifier at different pump powers for one of the preamplified fiber lasers that has an average power of ~200 mW and a pulse repetition rate of 40 KHz. In this experiment, the amplification performances for 1550.10 and 1552.27 nm that coupled into power amplifier along fast and slow axes, respectively, are nearly the same under the same pump conditions. Their final pulse durations after power amplification were measured to be about 20 ns, ~5 ns wider than that of original Q-switched pulses at repetition rate of 40 KHz. From Fig. 2, one can see the highest average/peak power for these eye-safe pulses can reach 3.26 W/4.08 kW when the pump power is about 32 W, which corresponds to a optical gain per unit length of 0.94 dB/cm as shown in the top inset of Fig. 2. This highest amplified power was limited by the pump power and not by damage threshold or nonlinearities, and can be further scaled up when using higher pump power. While achieving the above performance, the EYPhF and the fusion-splicing joint between EYPhF and power combiner were just put on a metal sink, and no forced water sink was needed for the whole fiber laser MOPA chain.

The amplified laser spectra of two Q-switched lasers were measured by a scanning Fabry–Pérot interferometer with a free-spectral range (FSR) of 1 GHz at the highest output power. From the envelope of the pulse train in the scanning Fabry–Pérot spectrum, the linewidths for two amplified Q-switched lasers are all about 40 MHz. According to our experiments and measurements, the diffraction-limited beam was achieved for the final amplified pulses.

III. GHz GENERATION

In GHz generation, forward type-oee (o and e denote beam polarization directions in crystal) and backward type-eoe optical parametric configurations were used, which have the same effective nonlinear optical coefficient expression, $d_{\text{eff}} = d_{22} \cos^2 \theta \cos 3\varphi$, where θ is the phase-matching angle, and φ the azimuthal angle was chosen such that $|\cos 3\varphi| = 1$ in our experiment. The collimated pump beam diameter of the fiber lasers in GaSe crystal is about 500 μm that corresponds to a pump intensity of $\sim 2 \times 10^6$ W/cm^2. For forward collinear phase-matched DFG, the momentum conservation is schematically illustrated as the inset of Fig. 3, where subscripts 1 and 2 denote the two pump beams, and subscript 3 the generated GHz beam. The phase-matching angle was measured to be 5.84°, very close to the calculated value of 5.96° according to the phase-matching conditions [6], [7]. The typical phase-matching

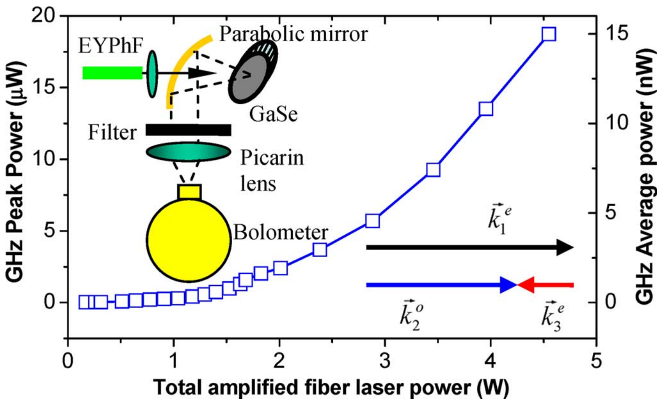

Fig. 4. Generated GHz average/peak power at different total pump power of amplified fiber lasers 1550.10 and 1552.27 nm based on backward phase-matched DFG. Top inset, schematic setup of backward GHz generation. Bottom inset, scheme of backward collinear parametric DFG.

curve was observed by probing the generated GHz signal while tuning the incident angle of pumps. Fig. 3 shows generated GHz average/peak power at different total amplified fiber laser power for 1550.10 and 1552.27 nm. The wavelength of the generated GHz signal is 1109 μm (i.e., 270.6 GHz) according to the frequency difference of two pumps, which was calibrated by using a homemade Fabry–Pérot. The maximum average/peak power for this GHz source can reach 38.5 nW/48.1 μW, which corresponds to a power conversion efficiency of 1.71×10^{-8}. One can see the maximum total output average power for both orthogonal fiber lasers is more than 4.5 W when the power amplifier is pumped by $\sim$30 W. The fiber lasers used feature high mode stability of less than $+/-10$ MHz over hours with a frequency noise of $\sim$ 12.2 Hz/$\sqrt{\text{Hz}}$ and a relative intensity noise peak of $\sim$ -130 dB/Hz at 1 MHz [8]. The linewidth of the generated GHz can be estimated as $\sim$40 MHz after a parametric process of two pump beams as above, so the peak power spectral density of the generated GHz waves is about 1.2 W/THz.

For backward type-eoe collinear phase-matching DFG, the momentum conservation is schematically illustrated as the bottom inset of Fig. 4. In order to collect the generated GHz radiation, we employed the GHz generation setup shown at the top inset of Fig. 4. In this experiment, one parabolic mirror with a tiny hole ($\sim$0.5 mm) was used to collect and collimate the backward GHz generation, and the two pump beams were collimated into the GaSe crystal through the tiny hole in the collection mirror. The measured phase-matching angle of this backward parametric process is 8.22°, which is in very good agreement with the calculated value of 8.34°. The typical phase-matching curve was observed by monitoring the generated GHz signal through tuning the incident angle of pumps. In calculating d_{eff}, backward d_{eff} for type-eoe DFG is a little bit smaller than the forward d_{eff} for type-oee DFG in GaSe pumped by two wavelengths of 1550.10 and 1552.27 nm. Fig. 4 illustrates that the maximum average/peak power for this backward GHz source can reach 15.0 nW/18.7 μW, which are in the same order with those for forward GHz shown in Fig. 3.

IV. CONCLUSION

We demonstrated the first photonic narrow linewidth GHz generation based on collinear forward and backward phase-matching DFG configurations pumped by eye-safe Q-switched all-fiber lasers in a single MOPA chain. This GHz source is tunable by changing the wavelength of fiber lasers. In addition to narrow-linewidth low-noise Q-switched fiber lasers, the highly codoped phosphate fiber was successfully used to amplify fiber laser pulses in a very short fiber length and a high gain per unit, where 4-kW peak power is among the highest ever reported for all-fiber-based narrow-linewidth pulses at $\sim$1550 nm.

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