Frequency doubling of narrow-linewidth pulsed fiber laser

Wendi Wu (吴闻迪)[1], Tingqi Ren (任廷琦)[1*], Jun Zhou (周 军)[2], Songtao Du (杜松涛)[2], and Xia Liu (刘 侠)[2]**

[1] *College of Physics and Engineering, Qufu Normal University, Qufu 273156, China*

[2] *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

[*] *Corresponding author: rtq@qfnu.edu.cn;* [**] *corresponding author: junzhousd@siom.ac.cn*

Received November 22, 2011; accepted January 10, 2012; posted online March 6, 2012

A pulsed master oscillator power amplifier system is constructed using a double-cladding polarized Yb-doped fiber and an all-fiber Q-switched narrow-linewidth pulsed laser used as seed laser. This system has a high repetition rate and provides a nanosecond pulsed laser with a narrow linewidth and linear polarization. Moreover, it generates amplified radiation with up to 14 W of average power, narrow linewidth (full-width at half-maximum is smaller than 0.12 nm), linear polarization at 1 080-nm wavelength, repetition rate of 51 kHz, and pulse duration of approximately 50 ns. Based on this pulsed amplified radiation, 3.5 W of green laser, with an optical-to-optical efficiency of 27.3%, is obtained via single-pass frequency doubling using a noncritical phase matching KTP crystal.

OCIS codes: 060.2320, 060.2420, 140.3515.

doi: 10.3788/COL201210.050604.

High-power green lasers are applied in material processing, medical treatments, laser projection, and pumping optical parametric amplifiers[1]. Green lasers with more than 100 W have been produced from solid-state lasers. However, these lasers have beam quality of M^2 >10[2]. Fiber lasers have drawn much attention because of their high beam quality, conversion efficiency, high stability, and high heat dissipation. High-powered, narrow-linewidth, and linearly polarized pulse lasers have been widely applied in laser radars, spectrography, and precision measurements[3−6]. Recently, with the emergence of the cladding pump, high-powered double-cladding fiber lasers and amplifiers have been rapidly developed. Therefore, because of the advantages in the volume, efficiency, and beam quality of Yb^{3+}-doped fiber lasers, researchers tend to adopt narrow-linewidth fiber lasers to obtain a second-harmonic generation (SHG) output and thus realize miniature and highly efficient short-wave lasers[7−10], particularly those from green sources. The application of narrow-linewidth fiber lasers, particularly those achieved via the frequency-doubling technique[11,12], often has high laser polarization requirements. Currently, many research groups have studied linearly polarized pulsed fiber lasers[13−16]. However, considering that the peak power of the pulsed laser is several orders of magnitude higher than the output power of the continuous-wave laser, the pulsed laser is much easily affected by the nonlinear efficiency of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), preventing the improvement of its output power[16,17]. Nevertheless, in fiber lasers, the frequency doubling of quasi-phase-matched ferroelectric materials is the most commonly used method. Aculight Company has employed a high-power 1 080-nm pulsed laser via using two LBO crystals to realize the average power of a green-source output of 60 W[18] with a conversion efficiency of 54.5%, the highest reported power achieved by green-source fiber lasers. As a frequency-doubling crystal, KTP has a higher nonlinear coefficient than LBO and a stronger damage threshold than PPKTP[19]. However, reports on green lasers produced from fiber laser using the KTP crystal are scarce[20].

In this letter, we employ all-fiber Q-switching methods for pulsed seed sources through single-stage amplification to obtain a 1 080-nm laser with narrow-linewidth pulse (full-width at half-maximum (FWHM) < 0.12 nm), linear polarization (PER≈13 dB), 51-kHz repetition rate, 50-ns pulsewidth, and 14-W highest average output power. Based on the above experiment, a noncritical phase matching (NCPM) KTP crystal is adopted in a narrow-linewidth pulse laser outer cavity single pass, obtaining a 540-nm frequency green-source output of 3.5 W and a relative optical-to-optical conversion efficiency of 27.3%.

The experimental setup is shown in Fig. 1. The seed source adopts all fiber acousto-optically modulated Q-switching lasers. The acousto-optic modulator improves the output pulse of the acousto-optic Q-switching pulsed laser via first-order diffraction because of the switched diffraction efficiency (approximately 75%) limitation. The reflection of the output coupled fiber Bragg grating is 10% at 1 080 nm, with a spectral bandwidth of

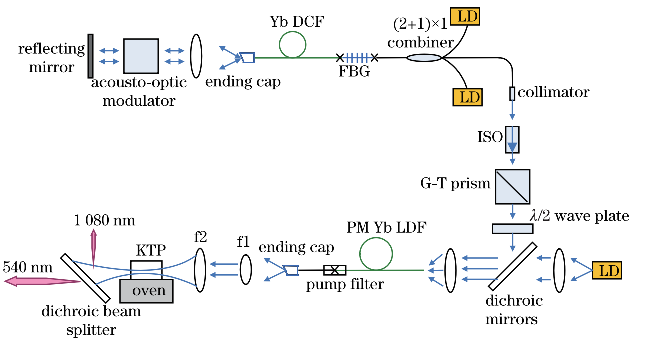

Fig. 1. Schematic diagram of the Yb-doped fiber MOPA.

0.1 nm, a single-mode fiber with a core diameter of 10 μm, and an numerical aperture (NA) of 0.08. The working-laser material is a 3-m Yb^{3+}-doped double-cladding fiber with core/cladding diameter of 10/128 μm and NA of 0.08/0.45. Its inner cladding has an octagon shape. The pump light produced via laser diode (LD) by (2+1)×1 coupling a backward pump enters the cavity of the fiber laser. Finally, the peak of the average power of the seed source reaches approximately 2.5 W at 51 kHz.

After the output is collimated, the seed laser first goes through a polarization-independent isolator to prevent the backward light of the amplifier. Then, it is linearly polarized at 1.4-W laser output using the Glan–Taylor prism polarizer. Finally, it enters the core of the fiber amplifier via aspheric lens coupling. The highest average power of the laser entering the fiber amplifier is higher than 1.2 W, whereas the power of the seed source entering the core is about 350 mW. The power amplifier is an 8-m-long polarization-maintaiming (PM) fiber with an inner-cladding diameter of 400 μm, n NA of 0.46, and a core diameter of 20 μm with a NA of 0.06. This fiber has an absorption value of 1.65 dB/m at 975 nm. With a cladding NA of 0.46, the Rayleigh focal spot is too small to damage the KTP crystal. Moreover, filtering pump light equipment is placed at the fusing point of the output end of the active fiber. A 1.8-mm-long pure silica end cap was polished at 8° to prevent the power from being reflected back into the fiber core and hence to avoid damage at the output end.

A $\lambda/2$ wave plate is added to keep the direction of the polarization orientation of the seed light and the fast- or slow-axis of the fiber amplifier consistent. The pump light of the amplifier enters the inner clad of fiber amplifier through a diachronic mirror and then through an aspheric lens couple.

The double-frequency system employs a 1 080-nm pulsed laser as the fundamental frequency light, which passes through the short focal lens with 12.56-mm focal distance and then through the lens with 87-mm focal distance. The laser focuses on the center of the KTP crystal. Using a temperature controller, KTP precisely controls its temperature to meet the phase matching requirement. A dichroic mirror is used to split the residual of the fundamental frequency light and the laser output of 540 nm.

Figure 2 shows the ultimate output power of the 1 080-nm laser changing with pump power. The above experimental system obtains the highest amplification laser

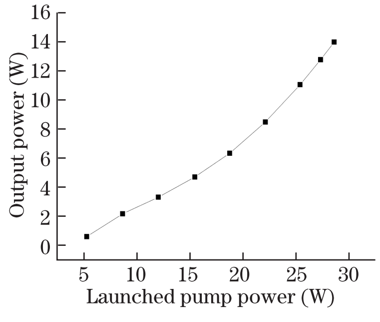

Fig. 2. Curve with the amplification output power changing according to the pump.

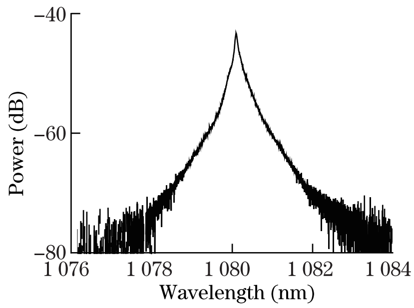

Fig. 3. Spectrum of laser amplification.

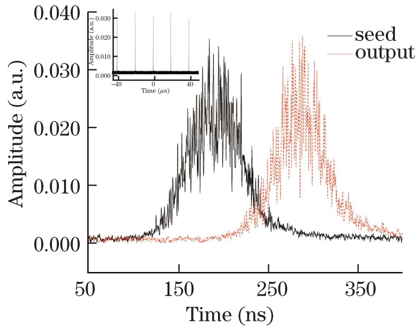

Fig. 4. Comparison between the pulsed shape of seed source and the amplified laser.

output power of 14 W with a repetition frequency of 51 kHz. When the pump power is 28.6 W, the optical-to-optical conversion efficiency reaches nearly 50%.

Figure 3 illustrates the laser amplification spectrum with 0.02-nm resolution. The FWHM is less than 0.12 nm and still maintains a narrow linewidth. Evidently, the amplification process effectively prohibits the effects of amplified spontaneous emission (ASE) and SBS.

Figure 4 shows the comparison between the pulse shapes of the seed source and the amplified laser with a repetition frequency of 51 kHz. The amplified pulse is slightly narrower than that of the seed pulse, whereas the FWHM of the pulse envelope is 50 ns. The split pulses in a Q-switched envelope are caused by the self-mode locking effect of the seed laser that is usually found in Q-switched fiber lasers[21−23], and the amplified pulse is the same as the seed pulse whose shape has many sentuses. The amplification pulse train has a repetition frequency of 51 kHz. The inset in Fig. 4 shows that the pulse train is stable and the jitter is within 10%.

Moreover, rotating the $\lambda/2$ wave plate makes the seed output polarization orientation and fast-axis (or slow-axis) of the amplified fiber consistent, maintaining the good polarization characteristics of the amplified light. The polarization extinction ratio of the amplified pulse laser is measured as over 13 dB.

Among traditional nonlinear crystals and compared with other potential crystal choices, the KTP crystal has features of highly effective nonlinearity, huge acceptance angle, no deliquescence, high thermal conductivity, and stable mechanical property. In particular, at room temperature, when the light beam is at the incidence of θ=90°, φ=0°, the correspondent wavelength of the second-harmonic generation should be about 1077 nm. When the KTP crystal (θ=90°, φ=0°) cut by α is heated to a certain

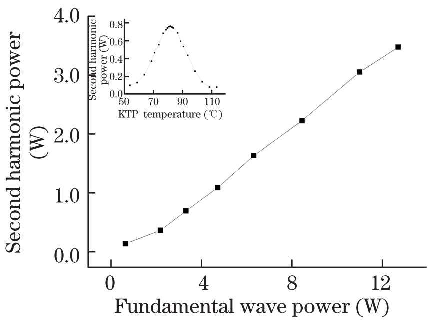

Fig. 5. Changing relation curve of fundamental frequency light power against a 540-nm laser power.

temperature, a 1 079.6-nm light wave can realize type II NCPM. Thus, the beam walk-off effect is completely resolved. Therefore, using the KTP crystal (θ=90°, φ=0°) cut by α, the experiment allows a 1 080-nm laser to realize the second-harmonic generation in type II NCPM by adjusting the temperature.

Figure 5 shows that the relationship curve of the fundamental frequency light power varies with the 540-nm laser power. According to the chart, when the incident fundamental frequency light power is 12.8 W, the highest 3.5-W green light output can be obtained with a corresponding optical-to-optical conversion efficiency of 27.3%. In the experiment, the SHG outputs exist in the wider temperature scope (~30 °C). However, at approximately 83 °C, the highest frequency transfer efficiency is achieved (see inset of Fig. 5). Therefore, the crystal temperature is controlled within 83 °C by controlling the oven temperature in the experiment.

This paper adopts the narrow-linewidth pulsed seed source and the Yb^{3+}-doped polarized double-cladding fiber obtained using the single-stage master oscillator power amplifier configuration. Its average power is 14 W, the repetition frequency is 51 kHz, and the narrow linewidth (FWHM $<$ 0.12 nm) has a 50-ns pulsed width. Moreover, a 1 080-nm linearly polarized (PER≈13 dB) pulsed laser output is obtained. Consequently, a NCPM KTP crystal is employed for the narrow-linewidth pulsed laser frequency doubling using an external cavity single pass. A 3.5-W high-average-power green light output is obtained, with the corresponding light–light transfer efficiency reaching 27.3%. In the experiment, the polarization extinction ratio of the fundamental frequency light is only 13 dB. Therefore, an all-fiber seed source with better polarization characteristics and a multilevel polarization amplification process obtain an all-fiber, narrow-linewidth, and linearly polarized laser source with better polarization characteristics and higher power. Moreover, considering that the experiment uses a NCPM KTP crystal, the crystal length is not limited by the walk-off effect. Therefore, regardless of whether the aim is to improve the polarization characteristic of the fundamental frequency light, to improve the fundamental frequency light power, or to increase the length of the KTP crystal, the transfer efficiency of the SHG and a double-frequency laser output with high power are obtained.

This work was supported by the Natural Science Foundation of Shanghai (No.10ZR1433600) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20103705110001).

References

1. Y. Nabekawa, K. Kuramoto, T. Togashi, T. Sekikawa, and S. Watanabe, Opt. Lett. **23,** 1384 (1998).
2. S. Konno, T. Kojima, S. Fujikawa, and K. Yasui, Opt. Lett. **25,** 105 (2000).
3. S. A. Babin, D. V. Churkin, A. E. Ismagulov, S. I. Kablukov, and M. A. Nikulin, Laser Phys. Lett. **4,** 428 (2007).
4. V. M. Paramonov, A. S. Kurkov, O. I. Medvedkov, and V. B. Tsvetkov, Laser Phys. Lett. **4,** 740 (2007).
5. M. W. Wright and G. C. Valley, J. Lightwave Technol. **23,** 1369 (2005).
6. V. Philippov, C. Codemard, and Y. Jeong, Opt. Lett. **29,** 2590 (2004).
7. F. J. Kontur, I. Dajani, and Y. Lu, Opt. Express **15,** 12882 (2007).
8. M. G. Pullen, J. J. Chapman, and D. Kielpinski, Appl. Opt. **47,** 1397 (2004).
9. C. D. Brooks and F. D. Teodoro, Opt. Commum. **280,** 424 (2007)
10. R. Horiuchi, K. Saiki, K. Adachi, K. Tei, and S. Yamaguchi, Opt. Rev. **15,** 136 (2008).
11. A. Kuznetsov and S. Babin, Laser Phys. **20,** 1266 (2010).
12. A. Denisov, A. Kuznetsov, D. Kharenko, S. Kablukov, and S. Babin, Laser Phys. **21,** 277 (2011).
13. P. Jiang, D. Yang, Y. Wang, T. Chen, B. Wu, and Y. Shen, Laser Phys. Lett. **6,** 384 (2009).
14. C. Ye, M. Gong, P. Yan, Q. Liu, and G. Chen, Opt. Express **14,** 7604 (2006).
15. C. Liu, Y. Qi, Y. Ding, J. Zhou, J. Dong, Y. Wei, and Q. Lou, Chin. Opt. Lett. **9,** 031402 (2011).
16. J. Limpert, S. Höfer, A. Liem, H. Zellmer, A. Tünnermann, S. Knoke, and H. Voelckel, Appl. Phys. B **75,** 477 (2002).
17. C. Ye, P. Yan, L. Huang, Q. Liu, and M. Gong, Laser Phys. Lett. **4,** 376 (2007).
18. A. Liu, M. A. Norsen, and R. D. Mead, Opt. Lett. **30,** 67 (2005).
19. C. H. Tu, Z. C. Huang, K. Lou, H. J. Liu, Y. S. Wang, Y. N. Li, F. Y. Lu, and H. T. Wang, Opt. Express **18,** 25183 (2010).
20. H. Sunaga, R. Horiuchi, K. Jyosui, K. Tei, S. Yamaguchi, K. Nanri, and T. Fujioka, Chin. Opt. Lett. **5,** (Suppl.) S111 (2007).
21. V. Philippov, A. Kir'yanov, and S. Unger, IEEE Photon Technol. Lett. **16,** 57 (2004).
22. P. Grelu, F. Belhache, F. Gutty, and J. M. Soto-Crespo, JOSA B **20,** 863 (2003).
23. P. Myslinski, J. Chrostowski, J. Koningstein, and J. R. Simpson, Appl. Opt. **32,** 286 (1993).