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Z. Zhao, B. Sheehy, M. Minty

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Generation of 180 W average green power from a frequency-doubled picosecond rod fiber amplifier

ZHI ZHAO,* BRIAN SHEEHY, AND MICHIKO MINTY
Brookhaven National Laboratory, Upton, New York 11973, USA
*zzhao@bnl.gov

Abstract: We report on the generation of 180 W average green power from a frequency-doubled picosecond rod fiber amplifier. In an Yb-doped fiber master-oscillator-power-amplifier system, 2.3-ps 704 MHz pulses are first amplified in small-core fibers and then in large-mode-area rod fibers to produce 270 W average infrared power with high polarization extinction ratio and diffraction-limited beam quality. By carrying out frequency doubling in a lithium triborate (LBO) crystal, 180 W average green power is generated. To the best of our knowledge, this is the highest average green power achieved in fiber-based laser systems.

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1. Introduction

High-power green picosecond (ps) pulses have found important applications in material processing [1], optical parametric oscillators [2], optical parametric amplifiers [3], and accelerator photo-injectors [4]. A few laser concepts that include fiber [5, 6], cryogenically cooled Yb-YAG [7], Innoslab [8], and thin-disk amplifiers [9] have been developed to produce high-power infrared (IR) output. High average green power could be generated through efficient frequency doubling, and a ps green laser delivering 820 W at 515 nm has been realized in a thin-disk amplifier system [9].

The ytterbium (Yb)-doped fiber laser has been proven attractive because it has been demonstrated to achieve high average power with diffraction-limited beam quality and excellent beam pointing stability [5, 6]. Taking advantage of the chirped pulse amplification (CPA) technique, kilowatt class IR output [10,11] and 135 W average green power via frequency doubling [12] have been demonstrated in femtosecond fiber lasers. Although modest pulse chirping has also been used to reduce the peak power in a ps fiber amplifier [13], it is difficult to achieve a large stretching and compression ratio owing to the narrow spectral bandwidth of picosecond pulses. In scaling the power of picosecond fiber lasers, there is a tradeoff between the average power and the peak power. Double-clad fibers with a mode field area of 500-600 μm² exhibit excellent thermal conductivity and are preferably used to achieve higher average power. Experiments have been reported to achieve 13 ps, 96 W [14], 28 ps, 200 W [15], and 35 ps, 500 W [16] IR output through direct amplification and 10 ps, 97 W [17], 4.5 ps, 100 W [18] IR output through nonlinear amplification. On the other hand, rod fibers with a large mode field area of 4500 μm² can be easily used to mitigate the nonlinear effect and 2.5 ps, megawatt peak powers [19] have been demonstrated through direct amplification. But the maximum average power is limited to 130 W, owing to the thermally-induced mode instability.

Recently, rod fibers with a mode field area of about 3000 μm² have been reported to generate 292 W IR average power with diffraction-limited beam quality [20]. Direct amplification of 1-ps pulses at 1.3 GHz repetition rate using this type of rod fiber has been demonstrated to achieve 167 W IR average power and converted into 120 W green average power through frequency doubling [21]. In this paper, we demonstrate the direct amplification of 2.3-ps, 704 MHz pulses and extend IR average power to 270 W. Efficient frequency doubling has been carried out to generate 180 W average green power. To the best of our knowledge, this is the highest average green power in the fiber-based laser systems.

2. Experimental setup

A schematic of the Yb-doped fiber master oscillator power amplifier (MOPA) system is shown in Fig. 1. The MOPA consists of a fiber oscillator, preamp I (SC YDF), preamp II (DC...
YDF), preamp III (80-cm rod fiber), and the main fiber amplifier (100-cm rod fiber). Preamp I is a 40-cm single-mode Yb-doped fiber, and preamp II is a 2.5-meter Yb-doped double-clad (DC) polarization-maintaining (PM) fiber. Preamp III and the main amplifier are 80-cm and 100-cm rod fibers, respectively.

The seed source is a commercial Yb-doped fiber oscillator from Calmar Laser, Inc. The fundamental frequency of the cavity is 6.13 MHz, and the oscillator is actively mode-locked to its 115th harmonic. After the oscillator is locked to a low phase noise signal generator at 704 MHz, frequency sidebands are suppressed to less than 70 dB. The oscillator generates slightly chirped pulses with 28 pJ energy, 2.3 ps (FWHM) duration, and Fig. 2(b) shows a 1.1 nm (FWHM) spectral bandwidth at 1035.5 nm. The time-bandwidth-product is 0.71. The pulses from the oscillator are first amplified in preamp I. The pump light is coupled into the gain fiber (Yb 406, Coractive) through a wavelength division multiplexer (WDM), and 600 mW pump power yields 320 mW output, corresponding to a pulse energy of 450 pJ.

The output pulses from preamp I are then amplified in preamp II. The gain fiber is a photonic crystal fiber with a mode field area of 177 μm² and cladding absorption of 7 dB/m at 976 nm (DC-135/14-PM-Yb, NKT photonics). The fiber is coiled with a diameter of 20 cm, and is counter-pumped through a telescope, and the IR output is 5 W with 8 W pump power. The polarization extinction ratio (PER) is 15 dB, and the M² values of the laser beam are less than 1.1 in both directions. After an isolator, 4 W IR output is coupled into a rod amplifier with 1600 μm² mode field area (DC-aeroGAIN-ROD-PM55, NKT photonics). The rod fiber is counter-pumped and 55 W pump power yield 33 W output. The M² values of the laser beam behind preamp III are less than 1.1 in both directions. Finally, after another isolator, IR output from preamp III seeds the main rod fiber amplifier. The 100-cm Yb-doped rod fiber with 3300 μm² mode field area (aeroGAIN-ROD-PM85, NKT photonics), is counter-pumped with up to 400 W laser diode at 976 nm. In preamp III and the main amplifier, two telescopes are used to couple the pump power into two rod amplifiers, respectively and a chiller is used to cool down the two rod fibers to 15°C for heat dissipation.

Fig. 1. Schematic of the fiber MOPA system: SC YDF, single-clad Yb-doped fiber; DC YDF, double-clad Yb-doped fiber; ISO, optical isolator; WDM, wavelength division multiplexer; DM, dichroic mirror; SHG, second harmonic generation.

3. Characterization of amplified IR pulses

Figure 2 shows the characteristics of the fiber MOPA system. In Fig. 2(a), the maximum average power of 272 W and pulse energy of 386 nJ is achieved with 395 W pump power. The optical-to-optical slope efficiency from the pump to IR output in the amplifier is 61%. The autocorrelation width is measured to be 3.3 ps (full-width at half-maximum, FWHM) at
the low output and 3.7 ps (FWHM) at 250 W, as shown in Fig. 2(b). The pulse durations are thus 2.3 and 2.6 ps, respectively if a Gaussian pulse shape is assumed. The maximum peak power is 148 kW, and the nonlinear phase shift during the pulse amplification is calculated to be 1.8 radians. As shown in Fig. 2(c), the spectral bandwidth of the seed is 1.1 nm (FWHM), but it is broadened to 1.9 nm at 150 W and 250 W. The time-bandwidth product is 1.38, and the optical pulses are chirped.

The polarization extinction ratio is more than 15 dB and there is no degradation going from low to high IR output. Frequency sidebands are still less than 70 dB at any output power. The laser beam exhibits a nearly symmetric profile, as shown in Fig. 2(d), and the $M^2$ values in both directions are measured to be 1.09 at 250 W, based on $D4\sigma$ method. So, diffraction-limited beam quality has been delivered from this high-power laser system.

The maximum IR output is limited by the potential mode instability [20]. At the maximum output, the peak power is far below the threshold for stimulated Raman scattering, and the nonlinear phase shift would be less than $\pi$ radians. Potentially, it could be used to linearly amplify pulses of as short as 1.6 ps and obtain a peak power of 220 kW. However, in the present amplifier, continuum components from the seed grow faster in the amplification and leads to the complex spectrum in the output pulses. So, it is necessary to improve the pulse quality of the seed in order to scale the peak power of the amplifier.

4. Green light generation and characterization

Second harmonic generation (SHG) is conducted to generate high-power green light. IR output from the fiber amplifier is frequency doubled through a type I noncritically phase matched lithium triborate (LBO) crystal. The $5\times5\times20$-mm$^3$ LBO crystal is put in an oven at 181 °C and its phase matching bandwidth is 1.5 nm. The IR laser beam is focused to a spot of 40 μm diameter with an $f = 10$ cm lens. As the incident power is increased, the small shifts in the beam direction and polarization are compensated using a pair of mirrors and a pair of wave plates (half- and quarter-wave) in front of the doubling crystal. Behind the SHG crystal, a lens and two dichroic mirrors are used to collimate and separate the green light from the
unconverted IR laser beam. The focus and collimation lenses are water-cooled to avoid potential damage. Also, water-cooled apertures with a diameter of 10 mm are used before and after the SHG crystal in order to eliminate cladding light from the rod fiber as well as any back reflection from green light.

![Fig. 3. Green output versus IR input (a); SHG efficiency versus IR input (b); autocorrelation signal of the green pulses at 150 W (c); and M² values at 140 W green average power (d).](image)

The green power versus IR input is shown in Fig. 3(a). A maximum average power of the 704 MHz picosecond pulse train obtained is 182 W, using 272 W IR input. To the best of our knowledge, this is the highest average green power in a fiber-laser based system. As shown in Fig. 2(b), the conversion efficiency increases to 70%, before dropping to about 67% in the high-power regime. The spectral bandwidth of the optical pulses is gradually becoming broader than the phase matching bandwidth, leading to the decrease in frequency-doubling efficiency. The measurement of intensity autocorrelation at 150 W green power is shown in Fig. 3(c). The FWHM duration is measured to be 2.9 ps, corresponding to 2.1 ps duration if a Gaussian pulse shape is assumed. So, a maximum green pulse energy of 258 nJ and peak power of 123 kW are obtained through the frequency doubling of IR pulses from this ps rod amplifier. The spatial profile of the ps green laser was characterized by measuring M² values at high output power. The M² values in the horizontal and vertical directions are measured to be about 1.1 at 140 W, as shown in Fig. 3(d), and thus the ps green laser exhibits diffraction-limited beam quality. However, it is obvious that the temporal walk-off is an issue with a choice of 20 mm LBO SHG crystal [22] and a 15 mm crystal would be recommended for the future development to minimize this unwanted effect [21, 22].

5. Summary

We have reported on the direct amplification of 2.3 ps, 704 MHz pulses and generated 270 W IR average power. Efficient frequency doubling has been carried out to generate 180 W average green power. To the best of our knowledge, this is the highest average green power in fiber-based laser systems. Such a high-power ps green laser could benefit many scientific and industrial applications.
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