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Abstract. We report a compact, 130-W single-stage master oscillator power amplifier with a high peak power of 51.3 kW and a narrow spectral linewidth of 0.1 nm. The seed source is a single-mode, passively mode-locked solid-state laser at 1064 nm with an average power of 2 W. At a repetition rate of 73.5 MHz, the pulse duration is 30 ps. After amplification, it stretches to 34.5 ps. The experiment enables the optical-to-optical conversion efficiency to reach 75%. To the best of our knowledge, this is the first report of such a high-power, narrow spectral linewidth, high peak power picosecond-pulse fiber amplifier based on a continuous-wave, mode-locked solid-state seeding laser. No amplified spontaneous emission and stimulated Raman scattering were observed when the pump was increased. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.54.9.096106]

1 Introduction

Today, one of the most challenging research topics in the field of laser application is laser projection technology.[1,2] Its brilliance and large depth of focus make a laser projection display an ideal projector in many ways. The red-green-blue fundamental laser output needed for a full-color laser image can be produced by frequency-converted near-infrared, diode-pumped solid-state lasers, as the narrow linewidth can effectively avoid the walk-off effect and the high peak power would improve conversion efficiency in the process of nonlinear frequency conversion. In addition, laser display technology demands high repetition rates and ultrashort pulses to prevent the appearance of beats and speckles on the screen; therefore, Yb-doped picoseconds fiber amplifiers with high average power, narrow linewidth, high peak power, and high repetition are currently in demand, especially considering the fiber laser possesses the advantages of high compactness, high-gain amplification, and high power efficiency. Also, some remarkable work has been achieved with such lasers in the wavelength ranges of ∼1 μm in the past few years. In 2009, Chen et al. generated 100 W, 13 ps pulses at 59.8 MHz by all-fiber master oscillator power amplifier (MOPA) but with a serious spectral broadening.[3] In 2011, Hu et al. constructed a 100 W picosecond pulsed fiber MOPA system at 1060 nm based on a figure-eight fiber laser operated in the all-normal-dispersion regime, while the full width at half maximum (FWHM) of the amplifier's spectrum was measured as broad as 0.7 nm.[4] In 2013, Teh et al. at University of Southampton reported a high-power, fully fiberized, single-polarization, gain-switched, diode-seeded fiber MOPA system with a 10 dB signal linewidth of 2.4 nm.[5] Common to all of the above-presented work, the available systems mainly started with all-fiber configuration based on gain-switched diode seeder with a narrow-band fiber Bragg grating (FBG) or passively mode-locked fiber laser to reduce the spectrum linewidth to a level of nanometer.

Thus far, the seeder with fiber pigtail based on a narrow-band FBG is a common way to achieve desirable narrow linewidth and then have the pulses amplified in an amplifier. However, the fiber seeder is not consistent with all fibers, and the seeder's power is so low that it requires more stages to be amplified, as it causes obvious spectral broadening to the nanometer level. Fortunately, the continuous-wave mode-locked (CWML) solid-state laser based on the semiconductor saturable absorber mirror (SESAM) has been well developed in the past decade,[6] and it can produce picometer-level narrow linewidth and W-level output easily. Furthermore, the combination of a solid-state seeding laser and a high-gain amplifier is an efficient way to realize ultranarrow linewidth and high peak power simultaneously. In addition, since it does not need the multistage fiber amplifier, it would reduce the complexity and improve the compactness of the whole system. In our earlier work, Sun et al. achieved 38.8 W average power output through a single-stage 2 m 30/250 μm Yb-doped fiber (YDF) amplifier with 80 MHz repetition and 35 ps pulse width.[7] In 2015, we also utilized this scheme to achieve 85 W burst mode picosecond pulses based on a Q-switched and mode-locked laser with output energy of 0.5 mJ per burst pulse.[8] Thus, the picosecond-pulse fiber amplifier based on the CWML solid-state laser can be a highly efficient and appropriate candidate for delivering high average power, high peak power, narrow-linewidth picosecond pulses.

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In this paper, we report a 130 W MOPA structured picosecond fiber amplifier with a high peak power and a narrow spectral linewidth, which employs a homemade CWML solid-state laser. At a repetition rate of 73.5 MHz, the pulse duration is 30 ps. A higher output power is expected if higher pump power becomes available. To the best of our knowledge, this is the first report of such a high average power, narrow spectral linewidth, high peak power picosecond-pulse fiber amplifier based on the CWML solid-state seeding laser. No amplified spontaneous emission and stimulated Raman scattering were observed when the pump was increased.

2 Experimental Setup

Our experimental system consists of a picosecond seed oscillator and a single-stage, double-clad fiber amplifier, which is depicted in Fig. 1. Experimentally, the seeding laser is a
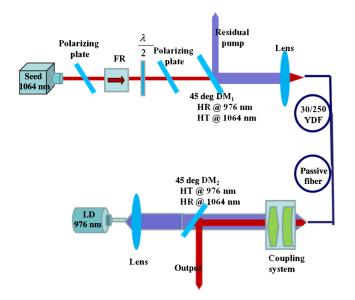

Fig. 1 Schematic diagram of the high-power picosecond fiber amplifier based on a dual-cladding fiber.

CWML solid-state laser based on the SESAM with the wavelength centered at 1064 nm. As shown in Fig. 1, the output of the seeder was injected into the amplifier. In order to avoid disturbance from the amplifier and to increase the stability of the seed source, an optical isolator consisting of two thin-film polarizers, a Faraday rotator (FR), and a half-wave plate was inserted between the picosecond seed oscillator and the fiber power amplifier. The seed laser was coupled into the fiber core with an aspheric lens with a focal length of 11 mm and coupling efficiency of ∼80%, which is high enough to satisfy the required seeding level for the 130-W amplifier and to make sure that the amplified spontaneous emission (ASE) is well controlled. We employed a 5-m-long dual-cladding fiber with diameter parameter of $30/250~\mu$m (NA = 0.06/0.46), which is composed of a high-doped segment and a passive segment with much lower splicing loss. The high-doped segment is 4 m long with 6.3 dB/m absorption at 980 nm, and the Yb^{3+} concentration is evaluated to be ∼6500 ppm, while the passive segment is 1 m long. The fiber is coiled into a kidney in the air without a cooling facility to filter higher-order transverse modes. The introduced bending losses allow only the fundamental mode to be guided and amplified.[9] The fiber port adjacent to the laser diode (LD) pump launched side is cleaved at an angle of 8 deg to suppress the broadband ASE feedback of the high-power fiber amplifier and hence parasitic lasing between the fiber-end facets. The 2-W seeder from the oscillator was amplified in a simple single-stage fiber amplifier, which was pumped backward by a 976-nm LD with a 220-μm core diameter and 0.22 NA using free-space coupling. The amplified output was selected by a dichroic mirror DM_1 [high transmission (HT) at 976 nm and high reflectivity (HR) at 1064 nm], while the residual pump power rejected by the dichroic mirror DM_2 (HR at 976 nm and HT at 1064 nm).

In the MOPA system, a stable, mode-locked seed source is significant to our amplifier. The seed oscillator produced W-level stable CWML pulses with the linewidth of 0.04 nm and an FWHM pulse width of 30 ps measured with an autocorrelator (APE SM-1200) under a repetition rate of 73.5 MHz, as seen in Fig. 2(a).
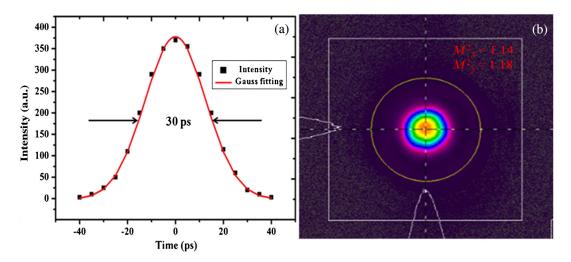

Fig. 2 (a) The pulse width of the continuous wave mode locked (CWML) laser and (b) the beam quality profile at an output power of 2 W.
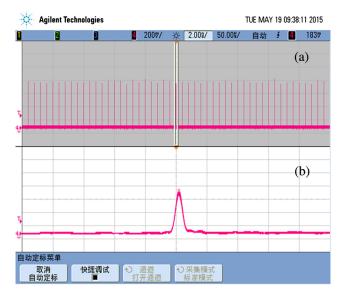
Fig. 3 Typical CWML pulse trains at the repetition rate of 73.5 MHz in different time scales: (a) 50 ns/div and (b) 2 ns/div.

The beam quality profile was measured both horizontally and vertically, with $M^2_x = 1.14$ and $M^2_y = 1.18$, respectively, as shown in Fig. 2(b). At an output power of 2 W, stable CWML pulse stream at 73.5 MHz is illustrated in Fig. 3 with time scales of 50 and 2 ns/div, respectively. It is shown that the peaks of the pulses have the same height, indicating that the cavity was in stable, continuous mode-locked operation. During the operation of the CWML laser, the SESAM was in the normal operation condition without any visible damage from the high pulse energy.

3 Performance of the Single-Stage Fiber Amplifier

In our experiments, we selected backward, 976-nm LD pumping for high conversion efficiency and absorption. To avoid optical damage to fiber,[10] we constructed the gradiently Yb-doped, single-stage fiber amplifier as described earlier[11]; namely, the coupling fiber is composed of two different parts. At certain locations, the doping level suddenly turns to zero along the direction of signal propagation for backward pumping. Initially, the signal power is lowest and the dopant concentration is highest; as the pump power and signal power increase, the passive fiber was adapted to increase thermal damage threshold of the fiber, where its impact is greatest. This thermal management mechanism will govern the high-power CW mode-locking pulse and high-energy pulse experimentally.

The characteristic of amplified output power is shown in Fig. 4(a), which is rather smooth without obvious trailing or jitter. When the coupling pumping power of the end-pumped module is at ~176 W, the output power was amplified to 130 W. Figure 4(b) shows the measured optical spectra at output power of 130 W. The pulse width after amplification is shown in Fig. 4(c).

With 176 W pump power coupled into fiber cladding, we obtained 130 W stable average output power, and it could continuously work for long time with a power fluctuation of <3%, which would increase the usage of this amplifier system. The light–light conversion efficiency was as high as 75%, while the residual pump power is 3 W at the highest output power. The corresponding peak power is 51.3 kW and
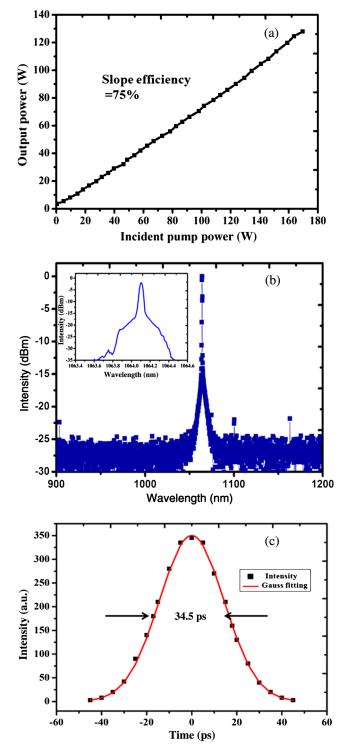

Fig. 4 (a) Power scaling characteristics of the fiber amplifier, (b) optical spectrum obtained from amplifier at output power of 130 W (Inset shows the enlarged spectrum around the central wavelength), and (c) the pulse width at output power of 130 W.

the pulse energy is 1.77 μJ; neither obvious ASE nor stimulated Raman scattering (SRS) can be observed at this high average power output as demonstrated in Fig. 4(b), measured by Anritsu MS9710B spectrometer.

As shown in Fig. 4(b), the central wavelength is 1064.01 nm at output power of 130 W, while inset shows the spectrum linewidth of the output beam is 0.1 nm after

amplification. No obvious ASE was induced in the spectrum ranging from 900 to 1200 nm. This could be attributed to the optimization of the characteristic of the fiber due to Yb-doped density management, sufficient seed source, and suitable pump power. Stimulated Brillouin scattering effect is barely observed in picosecond lasers.[12] Using a short fiber in a high-power amplifier is an effective way to avoid non-linear effects such as SRS. With a 4-m-long YDF used in our work, it can efficiently suppress self-phase modulation, SRS, etc. For a pure silica fiber, the thermal damage threshold of pulse laser is generally <100 W/μm^2; therefore, the 30-μm fiber core could bear 70.6 kW peak power output at most in theory. The fiber core's thermal damage threshold is largely reduced due to the concentration of Yb^{3+}, so that utilizing passive fiber in the pump side of the fiber instead of the end cap would help to achieve higher power output. Therefore, with a higher pump power, further power scaling is possible with the current system because the maximum output power was merely limited by the available pump power rather than thermal distortions due to exceeding damage threshold and heating accumulation in the pump side of the fiber.

4 Conclusions

In conclusion, we have demonstrated a 130-W narrow-line-width, high peak power picosecond-pulse amplifier operated in CW mode-locking using gradiently Yb-doped, single-stage 30/250 μm fiber amplifier system, which is, to the best of our knowledge, the highest output reported in such laser systems. The amplified pulses, without ASE and other nonlinear effects, showed a stable 130 W output under the thermal damage threshold, thanks to the thermal management method. Furthermore, it has also been shown that this MOPA system, based on the CWML all-solid-state laser under the thermal management method, can achieve high power and narrow linewidth output. The advantages of the structure-optimized system of high-power picosecond MOPA fiber laser and the thermal-managed gain fiber design are valuable, and further development may lead to remarkable improvements in nonlinear frequency conversion. Further research work will be focused on applying polarization-maintaining double-clad fibers to conserve the linear polarization of the seed source and improve output power of the visible laser source in efficient frequency conversion using such a mini MOPA system.

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