All-fiber cascaded ytterbium-doped nanosecond pulsed amplifier

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Received September 3, 2009

A cascaded ytterbium-doped all-fiber master oscillator power amplifier (MOPA) with 1064-nm pulsed laser is demonstrated, and it can produce up to 20-W average power and 0.1-mJ pulse energy at tunable repetition rates from 10 to 200 kHz. Two main difficulties of the all-fiber configuration are overcome: all fiber isolator and mode field adapter between single mode fiber (SMF) and double cladding fiber (DCF). Gain saturation and nonlinear effect are analyzed theoretically, and the possibility of further power-scaling of this cascade scheme is predicted.

OCIS codes: 060.2320, 060.3510.
doi: *10.3788/COL20100805.0457.*

Ytterbium-doped pulsed fiber laser systems are widely used in commercial industries in recent years, replacing conventional bulk solid-state lasers. All-fiber configuration makes the system compact and robust which is easier for commercialization.

Recently, up to 44-kW peak power has been achieved in 30-ns pulses at 40-kHz from a 30-μm core polarization maintaining fiber using a one-stage amplifier of discrete components, seeded by a Q-switched solid state laser[1]. Compared with non-fiber Q-switched seed, direct modulated diode source provides compactness and robustness, as well as flexibility in terms of pulse parameters such as repetition rate, pulse duration, and shape. As modulated diode source generally has average power lower than 1 mW, cascaded amplifiers are commonly required to get high gain. Direct modulated diode master oscillator power amplifier (MOPA) cascade has been used to realize high peak power output with the pulse duration from picoseconds to nanoseconds[2,3]. The typical amplifier cascade consists of a seed diode, one or more pre-amplifiers, and a final power amplification stage. A core-pumped all-fiber single mode fiber (SMF) amplifier with milliwatts output has been common in commercial use. However, few works use all-fiber configuration as the power amplification stage. It is mainly limited by isolation and different fiber cores of SMF and doublecladding fiber (DCF). As high power laser of several watts will cause damage to all-fiber in-line isolator, bulk isolator would be inserted and all-fiber scheme would be broken. Splicing between fibers with the same core ensures the signal transmission efficiency, avoiding the great loss from lens coupling. However, transmission loss from splicing between SMF and DCF with different numerical apertures (NAs) and core diameters still exists.

In this letter, we present our work of high power multistage all-fiber amplifiers using modulated diode seed. We illuminate theoretically and experimentally that all-fiber scheme is suitable for pulsed amplification with output power of dozens of watts. In addition, we further discuss the limitations including simulated Brillouin scattering (SBS), self pulsing, and amplified spontaneous emission (ASE)[4,5], which eventually lead to instability or damage of the all-fiber configuration. In order to predict the possibility of further power-scaling of this cascade scheme, we analyze the required average power and linewidth from pre-amplifier stage by theoretical calculations.

The experimental setup is shown in Fig. 1. A 1064-nm laser diode in a fiber-pigtailed package is driven directly with current, resulting in the generation of 10–900 ns duration, 10–200 kHz repetition rate pulses with square shape. The average power is about 3 mW from the pigtail fiber. These pulses are first amplified to about 60 mW of average power with two stages of pre-amplifier. For each stage, a 2-m-long single mode (SM) ytterbium-doped-fiber (YDF) is core-pumped by a 975-nm SM diode. An isolator between two stages prevents backreflected light such as ASE and SBS. Suppression of ASE injection between pre- and final-amplifier stage has been ensured by using 10-nm band-pass filters centered at 1064 nm. A 94/6 coupler is required to monitor the backreflected light. For all-fiber high power pulsed fiber amplifier, the coupler is necessary to ensure SBS-free running. Then the signal is coupled into the final power amplifier stage by a combiner. The combiner also acts as a mode-field-adapter (MFA) with signal transmission of 90%, avoiding the signal loss from direct splicing between the SMF and the DCF. The DCF of the final power amplifier is 12 m long with a 20-μm diameter, NA0.05 core. The inner cladding is octagon with 400-μm diameters. Up to 40 W of pump power is launched into the fiber. The fiber is polished at output end at an angle of $\sim 8°$ to avoid signal feedback. The pump absorption in the inner cladding is $\sim$1.7 dB/m.

In order to compare the results, another discrete DCF configuration is arranged in Fig. 2. The seed source and pre-amplifier stages are the same as that mentioned above.

In the experiments, the seed source and the preamplifiers were operated at their maximum power, while the

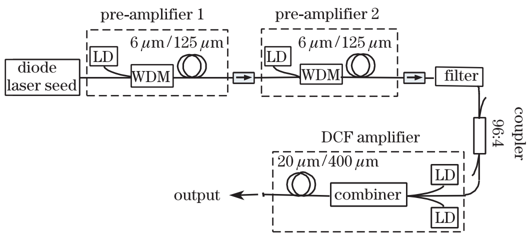

Fig. 1. Experimental setup. LD: laser diode; WDM: wavelength division multiplexing.

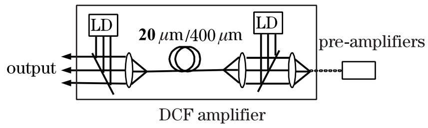

Fig. 2. Experimental setup of the final amplifier with discrete configuration.

pump power of the final-stage amplifier was varied. The characteristics of the MOPA output power are shown in Fig. 3. The measured optical spectra at maximum powers are shown in Fig. 4. All the data points were measured at 200-kHz repetition rate and 100-ns pulse duration. At the maximum pump power, 21.07 and 22.3 W of average powers were respectively achieved from two different configurations, with slope efficiencies of 71% and 65% with respect to launched pump power. In the all-fiber amplifier, no ASE is observed. The 3, 10, and 20 dB linewidth before and after the amplifier cascades are 2, 4.3, 7.6 nm and 3, 6.2, 11.1 nm. The spectrum linewidth broadening is due to nonlinear effect such as self-phase modulation (SPM) and cross-phase modulation (XPM). In the discrete configuration, the 1064-nm signal peak is 18 dB above the peak of background ASE. By integrating the spectrum, about 15% of out-band ASE power is calculated. Therefore only ~19 W out of the total 22.3 W is in-band 1064-nm pulses at the maximum pump power, and we can deduce that the slope efficiency of the discrete configuration after ASE filtering will be lower than 65%. As mentioned above, the output power from pre-amplifiers are both ~60 mW for the two coupling configurations. Lower lens coupling efficiency leads to lower incident signal power coupling into the DCF amplifier. The small signal is not strong enough for gain saturation and leads to background noises. Lens coupling efficiency is not measured exactly, however, it is estimated to be ~50–60% by experience. We analyzed the gain saturation effect of the final amplifier by theoretical calculations. As shown in Fig. 5, about 50-mW signal will saturate the amplifier when pumping at 30 W. The stars represent the experimental results of two different configurations. For further power scale, about 200-mW signal is enough to ensure 70-W output power when pumping at 100 W (shown in Fig. 5). 200 mW signal power could be achieved with more pre-amplifier stages and limited by damage threshold of SM in-line component.

We also observed the SBS pulses in the experiment. At first a fiber grating is written into the fiber pigtail of the seed diode, resulting in narrow linewidth of 0.1 nm. Then the fiber grating is removed and ~3-nm linewidth is obtained from the free-running diode. Under the former condition, the output-peak power is limited below 1 kW by SBS pulses (at 200 kHz). Measured SBS threshold at different repetition rates are shown in Fig. 6. When the linewidth is broadened, more than 1.1-kW peak power is achieved at 200 kHz with SBS-free stable operation. Available output power is limited by the thermal load caused by pump power leakage from splicing joint between the combiner and the DCF. We calculated the available average output power of the final amplifier under SBS threshold[6], as shown in Fig. 7. The results are obtained at 200-kHz repetition rate, 10-, 50- and 100-ns pulse durations. It can be deduced from Figs. 5 and 7

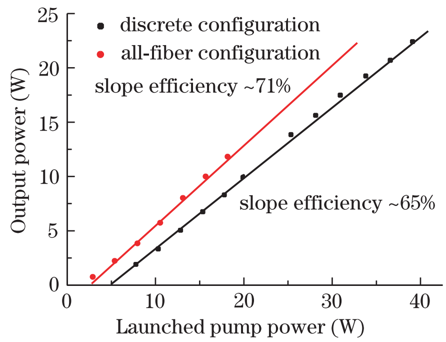

Fig. 3. Output power from the MOPA source versus launched pump power.

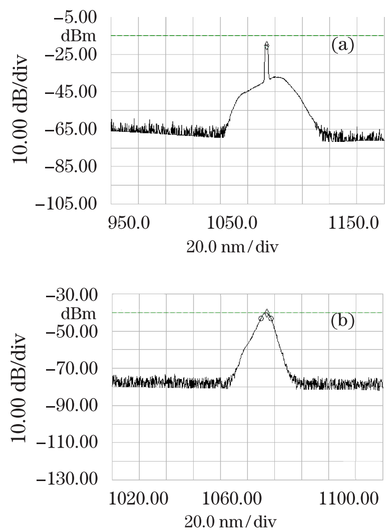

Fig. 4. Optical spectra at maximum average output powers (both at 200 kHz repetition rate and 100-ns pulse duration). (a) Discrete configuration; (b) all-fiber configuration.

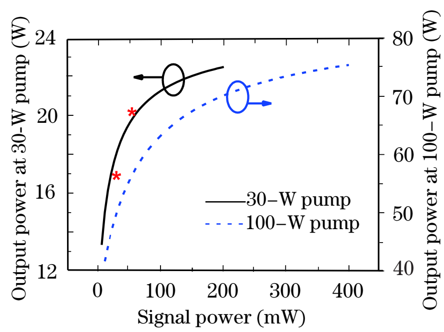

Fig. 5. Calculated output power from the MOPA versus signal power at different pump power.

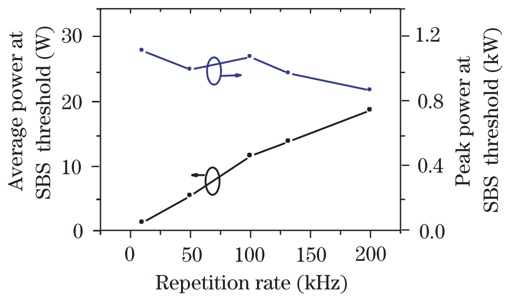

Fig. 6. Measured SBS threshold at different repetition rates.

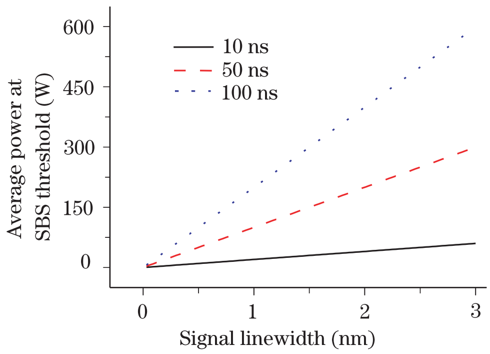

Fig. 7. Calculated SBS threshold versus signal linewidth at different pulse duration.

that average power of dozens of watts can be achieved in this all-fiber cascade at tens of nanoseconds pulse duration and line-width around several nanometers.

Pulse deformation is also observed. As shown in Fig. 8, the pulse shape of the seed is square. The spike at the leading edge is due to the driven current relaxation of the seed diode laser and could be suppressed through more stable driven current. After amplification, a pulse deformation occurs. As well known, the leading edge is offered more gain than the trailing edge, which makes the pulse peak shift forward during the propagation.

In conclusion, we demonstrate a 21.07-W pulse source based on an ytterbium-doped all-fiber amplifier cascade seeded by a direct modulated laser diode at 1064 nm. Our results show that high power nanosecond pulse amplification is available in an all-fiber amplifier cascade based on commercial in-line components. Owing to the high gain of fiber, only hundreds or dozens

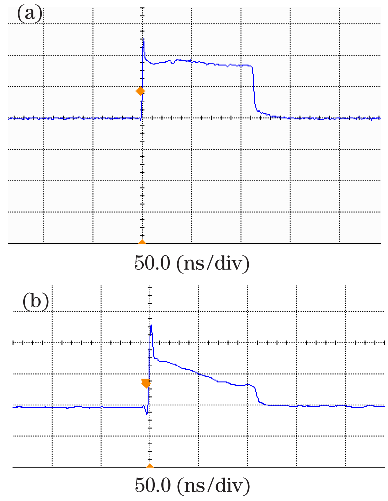

Fig. 8. Pulse shape (a) of the seed and (b) at maximum average output power.

of milliwatts signal power generated from all-fiber core-pumped system is able to saturate the power amplifier. Therefore, commercial SM in-line isolator and filter are available to replace the bulky free-space components. Gain saturation and nonlinear effects are observed and analyzed in experiment. Owing to our theoretical work, we believe that further power scaling is possible under current configuration with higher power from SM amplifier and broadened seed source linewidth. The limitation will be nonlinear effect (such as SBS) and damage threshold of SM components (such as in-line isolator).

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