High-energy nanosecond all-fiber Yb-doped amplifier

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We demonstrate a high-energy, low-repetition-rate, all-fiber, 1 064-nm Yb-doped fiber laser based on the master oscillator power amplifier structure. Pulse-pumping technology is used to suppress amplified spontaneous emission. A maximum output pulse energy of 5.97 mJ is obtained at 16-ns pulses with an M^2 of 2.9.

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Fiber lasers and amplifiers have rapidly developed and attracted considerable research interest because of their high efficiency, robustness, and flexibility. Fiber lasers with high pulse energies and nanosecond-scale pulse durations are highly desirable in applications such as material processing, nonlinear frequency conversion, lidar, and free-space optical communications[1−5]. However, achieving high pulse energies and peak powers remains a technological challenge in fiber-based lasers[6−11], which are limited by phenomena such as fiber damage and nonlinear effects brought about by the very small fiber core sizes used in such lasers. Fiber lasers with high pulse energies and peak powers have been developed in recent years by significantly increasing fiber core sizes. In 2005, Cheng *et al.*[6] reported a 200-μm core diameter large mode area (LMA) Yb-doped fiber laser with an 82-mJ pulse energy and 500-ns pulse duration corresponding to an M^2 of 6.5. Thus far, this pulse energy is the highest ever reported for fiber lasers. In 2012, Wang *et al.*[7] reported an all-fiber laser based on the master oscillator power amplifier (MOPA) structure and obtained an output pulse energy of 36 mJ with a pulse width of 10 ns. An M_x^2 of 20.6 and an M_y^2 of 17.8 were measured as a result of using a 200-μm core fiber. Unfortunately, increasing the fiber core size of lasers leads to degradation of their output beam quality. Thus, devices with large core sizes cannot be applied in remote sensing, which requires as mall beam divergence angle[12] and a small beam size.

In this letter, a compact, high-energy, all-fiber pulsed laser is reported. A modulated 1 064-nm laser diode (LD) is used as a seed and injected into multistage,Yb-doped, all-fiber amplifiers. Pulse-pumping technology is used in the final amplification stage to suppress amplified spontaneous emission (ASE). An output pulse energy of 5.97 mJ is achieved at a repetition rate of 50 Hz with a 16-ns pulse duration. A LMA fiber with a small core diameter (50 μm) is used to achieve high beam quality, ultimately yielding an M^2 of 2.9. The beam quality is sufficient for the development of laser rangefinders.

The layout of the all-fiber laser is shown in Fig. 1. A single-mode, 1 064-nm LD is directly driven by a pulsed modulated current source as a seed with an output spectral width of 0.8 nm. The multistage amplifiers consist of three preamplifiers and one power amplifier. The preamplifiers are cascaded with a single-mode, core-pumped, Yb-doped fiber amplifier, a 6/125 double-clad Yb-doped fiber amplifier, and a 10/125 double-clad Yb-doped fiberamplifier. The first stage is pumped by a 976-nm single-mode LD. The second and third stages are pumped by 976-nm multi-mode LDs with a core diameter of 105 μm and a numerical aperture (NA) of 0.22. The output signal of the preamplifiers is coupled into the power amplifier stage by the signal input port of a (6+1)×1 beam combiner. Six multi-mode LDs with a core diameter of 105 μm and a NA of 0.22 are used to pump the power amplifier through the pump input ports of the combiner. Pulse-pumping technology is used in this stage to suppress ASE. The pumping pulse width is set to 1 ms, and the seed pulse is injected into the multistage amplifiers at the falling edge of the pumping pulse. A pumping wavelength of 915 nm is used because Yb ions have a broad absorption spectrum of approximately 915 nm and are less affected when the wavelength of the pumping LDs drifts because of pulse modulation. The output fiber of the combiner, which has a 20-μm core diameter and a 400-μm cladding diameter, is spliced to a 4.3-m long active fiber with the same cladding size but a larger core size of 50 μm. The estimated fusion loss is 0.7 dB. This active LMA double-clad Yb-doped fiber has a 0.14 core NA and a core absorption of 4.5 dB/m at 915 nm. A

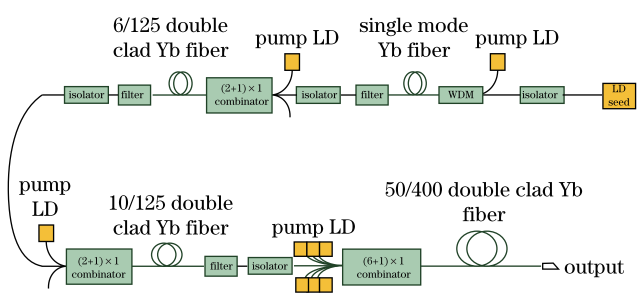

Fig. 1. Experimental setup of the proposed all-fiber MOPA-structured laser.

1.5-mm-long, 400-μm coreless end cap with an 8° face angle is spliced onto the output end of the active fiber to prevent fiber damage at the glass-air interface. The output beam is collimated using a 30-mm focal length lens. Throughout the MOPA architecture, interstage isolators and bandpass filters are used to prevent feedback and reject ~1 030 nm ASE.

The measured pulse energy from the 10/125 double-clad,Yb-doped fiber is higher than 30 μJ, which corresponds to a high peak power (>1 kW). Stimulated Raman scattering (SRS)[13] readily occurs at the kilowatt levelin the size-limited fiber core and results in pulse distortion[14,15]. To increase the SRS threshold, the passive fibers of the all-fiber filter and isolator used in this stage must be as short as possible.

To distinguish the output pulse energy clearly from continuous wave (CW) ASE, the output pulse energy is measured by an energy meter that is insensitive to CW radiation. A 1 064±5-nm filter is inserted in front of the energy meter to filter out residual pump light as well as ASE. The final output pulse energy versus the launched pump energy obtained at a repetition rate of 50 Hz is shown in Fig. 2. A maximum output pulse energy of 5.97 mJ is achieved under a launched pumping pulse energy of 42.8 mJ. Even at this pulse energy, we do not observe any fiber face damage. An M^2 of 2.9 is measured at the highest output power when the active fiber of the power amplification stage is coiled at a diameter of 20 cm (Fig. 3). The beam quality sufficiently meets the requirements for laser rangefinder application.

A spectrometer (Ocean Optics HR4000) is used to measure the output spectrum (Fig. 4). The central lasing wavelength is approximately 1 064 nm, and the spectral width is 3.2 nm. The observed spectrum broadening is mainly attributed to self-phase modulation[11,13] in the high-power laser.

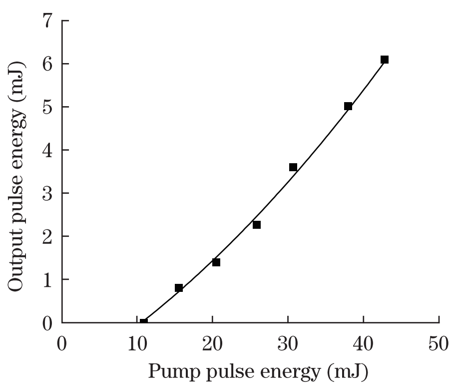

Fig. 2. Output pulse energy of the power amplifier versus the launched pump pulse energy.

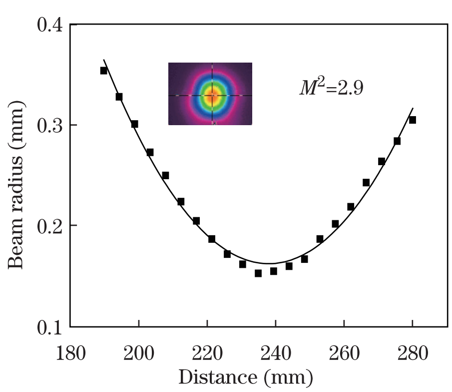

Fig. 3. Output beam quality and beam pattern.

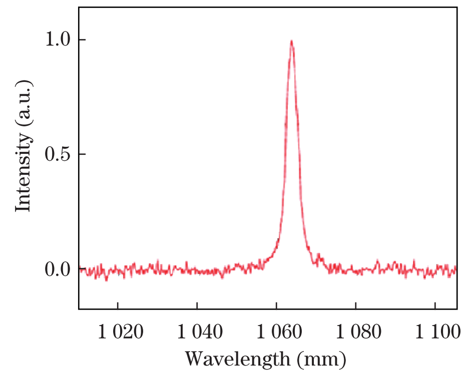

Fig. 4. Output spectrum (linear scale).

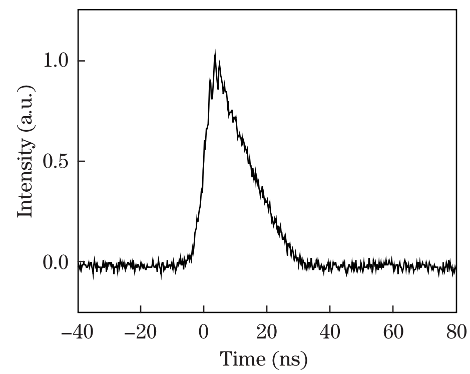

Fig. 5. Output pulse temporal profile obtained at the maximum output pulse energy.

Figure 5 shows the output pulse temporal profile obtained at the maximum output pulse energy as measured by a Thorlabs DETAFC silicon detector. The pulse duration is 16 ns, and the pulse peak power is calculated as 408 kW. Three distinct peaks appear near the pulse peak. This slight pulse distortion is caused by interstage bandpass filters, which filter the outside-band spectrum of the pulse and leave dips on the pulse.

In conclusion, we demonstrate a MOPA-structured, Yb-doped fiber laser operating at 1 064 nm. This device can produce 5.97-mJ pulse energies with a pulse duration of 16 ns, which corresponds to a peak power of 408 kW. An M^2 of 2.9 is obtained from a 50/400 active fiber. The laser has a monolithic, all-fiber design and is robust in nature. Thus, the proposed device has potential applications in miniature laser range finders.

References

1. W. Shi, E. B. Petersen, N. Moor, A. Chavez-Pirson, and N. Peyghambarian, Proc. SPIE **8164,** 81640M (2011).
2. Y. Liu, J. Liu, and W. Chen, Chin. Opt. Lett. **9,** 090604 (2011).
3. B. Liu, M. Hu, X. Fang, Y. Wu, Y. Song, L. Chai, C. Wang, and A. M. Zheltikov, Laser Phys. Lett. **6,** 44 (2009).
4. Y. Feng, J. Zhou, S. Du, and W. Chen, in *Proceedings of 2009 CLEO/Pacific Rim* 633 (2009).

5. J. Yun, C. Gao, S. Zhu, C. Sun, H. He, L. Feng, L. Dong, and L. Niu, Chin. Opt. Lett. **10,** 121402 (2012).
6. M. Cheng, Y. Chang, A. Galvanauskas, P. Mamidipudi, R. Changkakoti, and P. Gatchell, Opt. Lett. **3,** 358 (2005).
7. J. Wang, H. Lin, Y. Deng, D. Xu, R. Zhang, and M. Li, in *Proceedings of SOF 2012* STu4F.2 (2012).
8. S. Desmoulins and F. Di Teodoro, Opt. Express **16,** 2431 (2008).
9. J. Nilsson, in *Proceedings of 2010 CLEO/QELS* CTuC1 (2010).
10. P. Wan, J. Liu, L. Yang, and F. Amzajerdian, Opt. Express **19,** 18067 (2011).
11. L. Lago, D. Bigourd, A. Mussot, M. Douay, and E. Hugonnot, Opt. Lett. **36,** 734 (2011).
12. Y. Dai, *The Principle of Lidar* (in Chinese)(National Defence Industry Press, Beijing, 2002).
13. G. P. Agrawal, *Nonlinear Fiber Optics,* 4th ed. (Academic, Oxford, 2006).
14. Y. Wang, IEEE J. Quantum Electron. **41,** 779 (2005).
15. K. T. Vu, "High power nanosecond pulsed fiber laser amplifiers" Master Thesis (University of Southampton, 2008).