Acousto-optic Q-switched cladding-pumped ytterbium-doped fiber laser

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Received February 26, 2007

A diode-pumped, acousto-optic Q-switched fiber laser is presented based on multimode ytterbium-doped fiber. The fiber with core diameter of 30 μm is used to increase the laser gain volume and the pulse energy efficiently. The average power in excess of 9 W is obtained at the repetition rate of 20 kHz with 66% slope efficiency. The pulse width is 198 ns with no evident amplified spontaneous emission between pulses, thus the pulse energy and peak power are 465 μJ and 2.36 kW, respectively.

OCIS codes: 060.2320, 140.0140, 140.3540.

Rare-earth-doped double-clad fiber lasers offer many advantages, and become the leading contenders for industry and military applications. Because of the large surface area-to-gain volume ratio of doped fibers, an excellent combination of high power and good spatial beam confinement can be achieved readily. The continuous-wave (CW) output power of a highly efficient cladding-pumped ytterbium-doped fiber laser operating at 1.1 μm was up to 1.36 kW, and with 83% slope efficiency[1]. On the other hand, since the first Q-switched fiber lasers was developed, great improvements have been achieved[2]. With the high doping concentration of double-clad fibers and the development of clad-pumping techniques, much higher energy output pulses can be obtained compared with conventional single-mode fiber lasers. Therefore, actively Q-switched ytterbium-doped fiber lasers supply a simple and robust method to generate high energy nanosecond pulses suitable for nonlinear frequency conversion, range finding and remote sensing[3]. In this paper, we present an actively Q-switched Yb-doped double-clad fiber laser. Pulse energy in excess of 400 μJ and average power more than 9 W were achieved at the repetition rate of 20 kHz.

Figure 1 shows the experimental setup of the Q-switched fiber laser. The laser resonator was of a simple Fabry-Perot (F-P) design, and the gain medium was an ytterbium-doped (2450 ppm/mol) step-index profile silica double-clad fiber with a 30-μm diameter core, and 340/400-μm D-shape inner cladding. The D-shape was chosen to eliminate helical trajectories for the pump radiation and increase the efficiency of pump absorption.

The length of the fiber used in the experiment was 6 m, and was optimized for the available pump sources in CW operation. The absorption efficiency of pump power can be calculated as[4]:

$$\alpha_{\text{eff}} = 1 - \exp[-(\Gamma_{\text{p}} N \sigma_{\text{a}} + \alpha_{\text{p}})L], \quad (1)$$

where Γ_{p} is power filling factor, N is dopant concentration (per unit volume), σ_{a} is the absorption cross section, L is the length of the fiber, α_{p} is scattering loss coefficient.

The absorption efficiency of the fiber can be up to 99.5% theoretically within 6-m length, as shown in Fig. 2. The left end (end A) of the fiber was fixed on an x-y-z differential micrometer translation stage, and pumped by a 975-nm fiber coupled diode laser (Apollo Inc.). To avoid instabilities of the pump wavelength and thermal problems during operation, the diode laser was cooled by circulating water at a temperature of 18—19 °C. A dichroic mirror was used to separate the pump light from the laser output. A convex lens focused the pump light into the fiber end A, which was simply perpendicularly cleaved; while the other end B had a slightly angled polished facet to prevent the fiber lasing from 4% Fresnel reflection, and the light from this end was collimated to an acousto-optic modulator (AOM) (NEOS Inc.), with about 70% diffraction efficiency. A high-reflectivity mirror reflected the zero-order diffracted light of the AOM back into fiber end B. Note that both ends of the fiber should be flat, otherwise, a bad cleave yielded a poor laser performance and dramatically reduced the output laser power and the facet damage threshold.

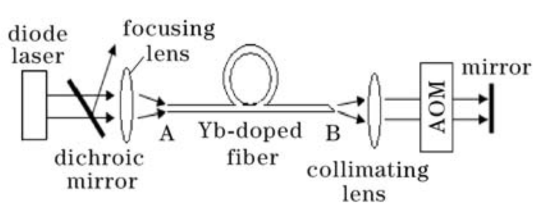

Fig. 1. Experimental configuration.

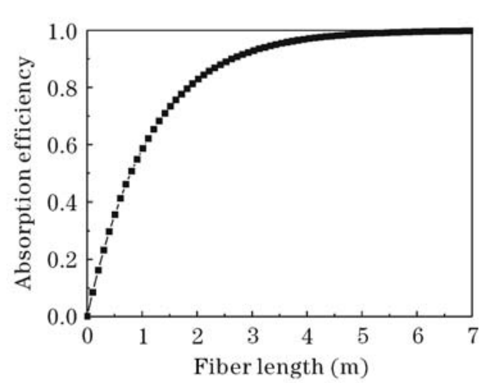

Fig. 2. Absorption efficiency versus fiber length.

1671-7694/2007/070415-03

The laser output was monitored with a power meter (Molectron EPM2000) to measure the average power simultaneously. It provided 9.3-W average power output with 15.9-W absorbed pump power at 20-kHz repetition rate. The pulse width was 198 ns without significant amplified spontaneous emission (ASE) between pulses, thus the pulse energy and peak power were 465 μJ and 2.36 kW, respectively. With lower pump power, the pulse energy decreased, and the pulse width increased to 308 ns at 10.0-W absorbed power. The pump threshold was about 2.03 W, and the slope efficiency was up to 66%. Figure 3 shows the more comprehensive data which can be used to describe the dependence of the pulse peak power and the pulse duration on pump power. Higher pump power produces shorter duration pulses, with a consequent increase in peak power.

The pulse shape under 15.9-W absorbed pump powers is shown in Fig. 4, detected with a 1.5-GHz digital oscilloscope (Agilent Inc. Infiniium). The pulse was smooth with no evident self-mode-locking phenomena reported by Feng[5]. A typical pulse train on a large time scale at 20-kHz repetition rate was shown in Fig. 5. The measured pulse stability (root-mean-square, RMS) was better than 10%.

The variation of pulse energy and pulse width with repetition rate is shown in Fig. 6 when pumping at 13.9 W. At a certain pump power, the pulse width decreased with the falling of the repetition rate while the peak power increased with it. The laser could operate stably under Q-switching regime when the repetition rates varied from 50 to 15 kHz; meanwhile, the pulse duration decreased from 549 to 170 ns with corresponding pulse energy of 0.507 mJ. The highest repetition rate was limited by the AOM driver and the lowest one was limited by the facet damage of the fiber. This variation was typical in Q-switched ytterbium laser. The falling of pulse energy with higher repetition rates is caused by the finite recovery time of the population inversion, which is directly related to the lifetime of the metastable level for the Yb-doped fibers.

The optical spectrum is presented in Fig. 7, which was calibrated with an optical spectrum analyzer (Agilent Inc.). The strong lasing spectrum was centered around 1082 nm, with a bandwidth of 1.6 nm (3 dB). Note that, the high gain, which built up between successive pulses, limited the possible stored energy because of the appearance of ASE. $T_{\rm ase}$ was used to represent ASE build-up time, and dependent on the pump power, the cavity design, and the fiber structure. Therefore, at operating pulse repetition rates lower than $1/T_{\rm ase}$, the ASE loss will become significant and reduce the laser device efficiency markedly. But in the experiment with higher repetition rates of Q-switched laser, it was proved that there was no evident ASE between pulses with the spectrum analyzer. Therefore, the average power of Q-switched laser was close to that of CW operation.

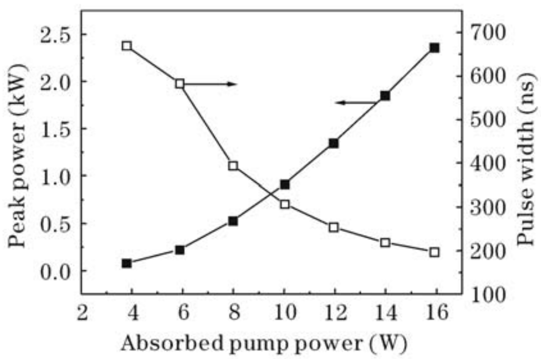

Fig. 3. Pulse duration (open rectangle) and peak power (rectangle) as a function of absorbed pump power at 20-kHz repetition rate.

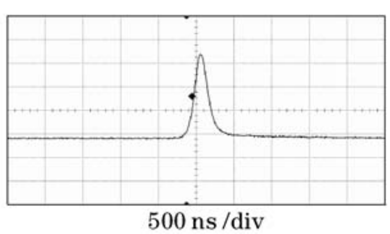

Fig. 4. Q-switched pulse shape at 20-kHz repetition rate under 15.9-W absorbed pump power.

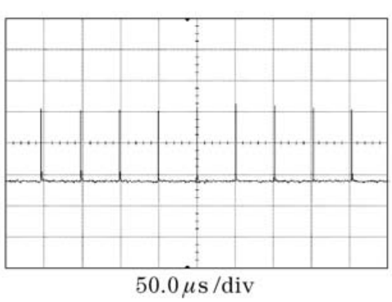

Fig. 5. Typical Q-switched output pulse train.

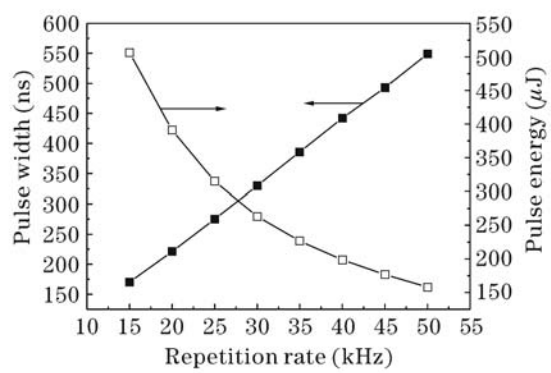

Fig. 6. Pulse energy (open rectangle) and width (rectangle) as functions of repetition rate.

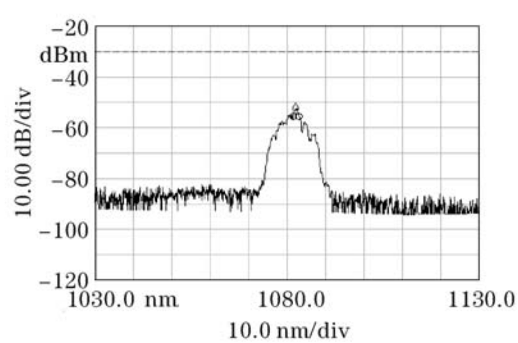

Fig. 7. Optical spectrum.

In this paper, we have experimentally studied actively Q-switched fiber lasers, and obtained high energy pulses with 465 μJ and 2.36 kW of peak power at a repetition rate of 20 kHz. The average power output can reach 9.3 W when pumping at 15.9 W. We believe that increasing the pump power can produce much higher output power, and the facet damage of fibers can be avoided with the use of endless caps. These improvements will lead to lower repetition rate, higher peak power, and shorter pulse duration.

This work was supported by the State Key Lab of All Optical Network & Advanced Telecommunication Network under Grant No. 0501. B. Peng's e-mail address is pengb04@mails.tsinghua.edu.cn.

References

1. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, Opt. Express **12,** 6088 (2004).
2. J. A. Alvarez-Chavez, H. L. Offerhaus, J. Nilsson, P. W. Turner, W. A. Clarkson, and D. J. Richardson, Opt. Lett. **25,** 37 (2000).
3. C. C. Renaud, R. J. Selvas-Aguilar, J. Nilsson, P. W. Turner, and A. B. Grudinin, IEEE Photon. Technol. Lett. **11,** 976 (1999).
4. I. Kelson and A. A. Hardy, IEEE J. Quantum Electron. **34,** 1570 (1998).
5. X. Feng, B. Chen, Y. Zhu, J. Chen, L. Liang, and Z. Lin, Chin. J. Lasers (in Chinese) **32,** 873 (2005).