High power passively Q-switched ytterbium fiber laser with Cr^{4+}:YAG as a saturable absorber

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Abstract: We report an efficient high-peak-power and high-average-power passively Q-switched ytterbium fiber laser with a Cr^{4+}:YAG crystal as a saturable absorber in an external-resonator configuration. At an incident pump power of 17.5 W, the passively Q-switched fiber laser produces an average power greater than 6.2 W with a pulse repetition rate of 48 kHz. The output pulses noticeably display a mode-locking phenomenon that leads to the maximum peak power to be higher than 20 kW.

OCIS codes: (140.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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1. Introduction

High-power diode-pumped rare-earth-doped double-clad fiber lasers have been promised as efficient and compact light sources with excellent beam quality, high efficiency, and a broad tuning range [1, 2]. Compared to cw fiber lasers, high-peak-power Q-switched fiber lasers are practically useful in numerous applications, such as range finding, remote sensing, industrial processing, and medicine [3-6]. Active Q-switching is typically achieved by inserting an acoustic-optic or an electro-optic modulator into the cavity. On the other hand, passive Q-switching by means of saturable absorbers is a convenient technique to simplify the cavity design and eliminate the need for external Q-switching electronics. So far, Cr^{4+}-doped [7], Sm-doped [8], and Tm^{3+}-Yb^{3+} co-doped [9] fibers have been developed as fiber saturable absorbers in fiber laser systems in the range of 1.0-1.1 μm. Another effective approach for passive Q-switching of fiber lasers is to use crystals [10-12] or semiconductor materials [13] as saturable absorbers. Recently, giant pulses with a duration of 2.7 ns and a peak power of 9 kW have been achieved in a Yb-doped fiber by a Cr^{4+}:YAG saturable absorber [14]. However, the average power and the conversion efficiency have been limited by 0.3 W and 17.6%, respectively. In view of that, it is of practical interest and value to develop high-average-power and high-peak-power fiber laser sources.

Here we report on an efficient high-peak-power and high-average-power passively Q-switched Yb-doped fiber laser with a Cr^{4+}:YAG saturable absorber. The high conversion efficiency is achieved by using a highly doped doubly clad fiber which combines a large core with excellent beam quality and high cladding absorption. With an incident pump power of 17.5 W, the fiber laser, operating at 48 kHz, produces an average output power up to 6.2 W with a pulse energy of 110~130 μJ. The mode-locking phenomenon leads to the maximum peak power to be higher than 20 kW.

2. Experimental setup

Figure 1 displays the schematic of the experimental setup for the passively Q-switched Yb-doped fiber laser that consists of a 3-m Yb-doped fiber and an external feedback cavity including a saturable absorber. The fiber has an absorption coefficient of 10.8 dB/m at 976 nm and a double-clad structure with a diameter of 350 μm octagonal outer cladding, diameter of 250 μm octagonal inner cladding with a numerical aperture (NA) of 0.46, and 25 μm circular core with a NA of 0.07. Note that the use of larger diameter cores is vital for storing higher pulse energies. Here the fiber possesses a low NA core to sustain the excellent beam quality. The end facets of the fiber were cut to be normal incident. Therefore, the lasing by end facets usually occurred for the free-running operation. The external cavity consists of a collimating

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lens of 50-mm focal length, a focusing lens of 25-mm focal length to focus the fiber output into a Cr^{4+}:YAG saturable absorber, a re-imaging lens to re-image the beam on a highly reflective mirror for feedback. The Cr^{4+}:YAG crystal has a thickness of 1.5 mm with 40% initial transmission at 1075 nm. Both sides of the Cr^{4+}:YAG crystal were coated for antireflection at 1075 nm (R<0.2%). The focal lengths of the collimating and focusing lenses were chosen to have a beam waist of 12.5 μm inside the saturable absorber. The saturable absorber was wrapped with indium foil and mounted in a copper block without active cooling. A translation stage was used to adjust the longitudinal position of the Cr^{4+}:YAG saturable absorber for minimizing the beam volume inside the crystal and achieving the lowest Q-switching threshold.

The pump source was a 20-W 976-nm fiber-coupled laser diode with a core diameter of 400 μm and a NA of 0.22. A focusing lens with 25 mm focal length and 92% coupling efficiency was used to re-image the pump beam into the fiber through a dichroic mirror with high transmission (>90%) at 976 nm and high reflectivity (>99.8%) at 1075 nm. The pump spot radius was approximately 200 μm. The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10G samples/sec; 1 GHz bandwidth) with a fast InGaAs photodiode.

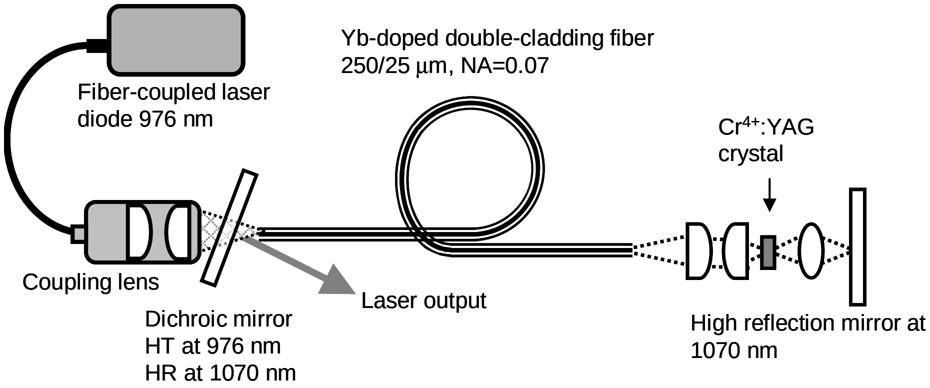

Fig. 1. Schematic of a diode-pumped passively Q-switched Yb-doped double-clad fiber laser. HR, high reflection; HT, high transmission.

3. Results and discussions

The cw performance of the present fiber laser was studied first. For this investigation, the external cavity only comprised a focusing lens and a high reflector (R>99.8% at 1075 nm). The cw performance provides the baseline for evaluating the passively Q-switched efficiency. Figure 2 shows the average output powers with respect to the incident pump power in cw and passively Q-switching operations. In the cw regime the laser had a slope efficiency of 61.6%; the output power reached 10.1 W at an incident pump power of 17.5 W. In the passively Q-switching regime an average output power of 6.2 W was obtained at an incident pump power of 17.5 W. The Q-switching efficiency (ratio of the Q-switched output power to the CW one at the maximum pump power) was found to be up to 61.3%. This Q-switching efficiency is generally superior to those of Yb-doped crystal lasers with Cr^{4+}:YAG crystals as saturable absorbers [15-20]. The M^2 beam-quality factor was measured to be <1.5 over the complete output power range. On the other hand, no damage to the fiber was observed over several hours of operation, and the laser performance was reproducible on a day-to-day basis.

Figure 3 shows the pulse repetition rate and the pulse energy versus the incident pump power. The pulse repetition rate initially increases with pump power, and is approximately up

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to 50 kHz at an incident pump power of 17.5 W. Like typically passively Q-switched lasers, the pulse energies weakly depend on the pump power and their values are found to be in the range of 110~130 μJ.

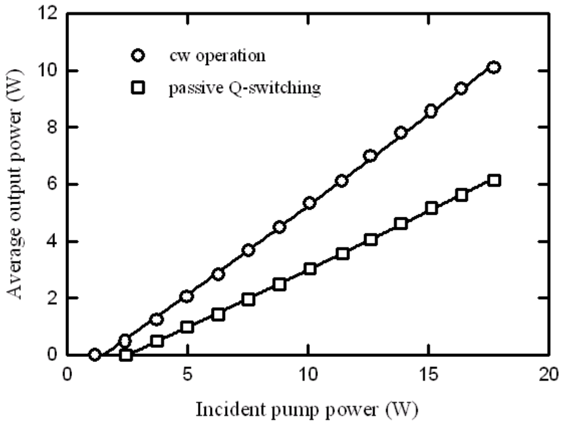

Fig. 2. Dependence of the average output power on the incident pump power for the cw and passive Q-switching operations.

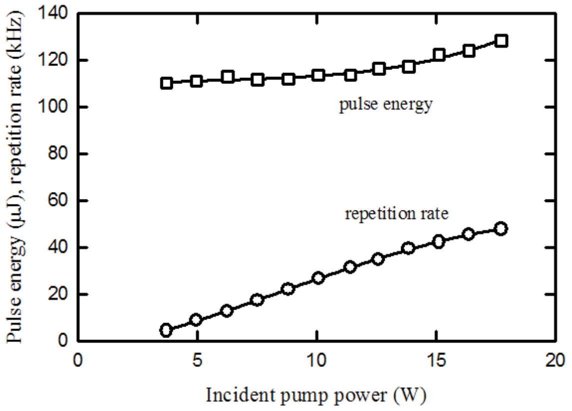

Fig. 3. Pulse repetition rate and the pulse energy versus the incident pump power

With the model of the coupled rate equations, the expression for the pulse energy of the passively Q-switched has been derived to be given by [21, 22]

$$E=\frac{h\nu A}{2\sigma\gamma}\ln(1/R)x \quad , \tag{1}$$

where $h\nu$ is the laser photon energy, A is the mode area in the gain medium, σ is the stimulated emission cross section of the gain medium, γ=2 is the inversion reduction factor, R is the reflectivity of the output mirror, and the parameter x represents the extraction efficiency of the energy stored in the gain medium through the lasing process. The equation for the parameter x is given by

$$1-e^{-x}-\frac{(1-\beta)\ln(1/T_o^2)}{\ln(1/T_o^2)+\ln(1/R)+L}\,\frac{1-e^{-\alpha x}}{\alpha}-\frac{\beta\ln(1/T_o^2)+\ln(1/R)+L}{\ln(1/T_o^2)+\ln(1/R)+L}x=0\,, \tag{2}$$

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where

$$\alpha = \frac{1}{\gamma}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s} \quad , \quad \beta = \frac{\sigma_{es}}{\sigma_{gs}} \quad , \tag{3}$$

L is the intracavity round-trip dissipative optical loss, T_o is the initial transmission of the saturable absorber, A_s is the effective mode area in the saturable absorber, σ_{gs} and σ_{es} are the ground-state and excited-state absorption cross sections of the saturable absorber, respectively. With Eqs. (1)-(3) and the values of the parameters: $\sigma = 3\times10^{-21}$ cm^2 [23], $\sigma_{gs} = 8.7\times10^{-19}$ cm^2 [24], $\sigma_{es} = 2.2\times10^{-19}$ cm^2 [24], $T_o = 0.4$, $R = 0.04$, $L = 0.04$, $A = 4.9\times10^{-6}$ cm^2, and $A_s = 6.3\times10^{-6}$ cm^2, the calculated result of the parameter x was found to be approximately 0.65. With this calculated value and Eq. (1), the pulse energy could be found to be 155 μJ. This value agrees very well with the experimental result. Furthermore, the present pulse energy is comparable with the maximum energy storage capacity of the laser given by the saturation energy $E_{sat} = h\nu A/\sigma = 303$ μJ. To confirm the theoretical analysis, we changed the mode area in the absorber by moving the absorber away from the focal plane. It was found that the output pulse energy decreased from 130 μJ to 90 μJ as the mode area A_s was changed to be 1.1×10^{-5} cm^2. This experimental result is close to the theoretical value of 97 μJ. The good agreement validates the present analysis.

A typical oscilloscope trace of Q-switched pulse train is shown in Fig. 4(a). With the optimum alignment, the pulse-to-pulse stability was found to be approximately ±15%. The pulse-to-pulse stability may be improved by the angle-cleaved end facets of the fiber. The stable self-mode-locking pulse output could be usually observed as the pump power is higher than 10 W. Figure 4 (b) shows the temporal shape of a single Q-switched pulse envelope, which was recorded at the maximum pump power. It can be seen that the self-mode-locking effect [25, 26] leads to the formation of the mode-locked pulses inside the Q-switched pulse envelope. The separation of the mode-locked pulses was found to be 33 ns, which matched exactly with the cavity roundtrip time and corresponded to a repetition rate of 30 MHz. The estimated energy of the highest pulse inside envelope was found to be close to 50 μJ. As shown in Fig. 4(c), the expanded oscilloscope traces reveal that the mode-locked pulse width is approximately 2.1 ns. As a consequence, the peak power can be found to be more than 20 kW. This is to our knowledge by far the highest mode-locked peak power reported for diode-pumped Yb-doped fiber lasers with simultaneous Q-switching. The present result indicates that the output peak power can be significantly enhanced by using a fiber with a larger core size and a saturable absorber with a lower initial transmission.

The spectral information was measured by an optical spectrum analyzer (Advantest Q8381A) that utilizes a grating monochromator for the high speed measurement of pulse light with the resolution of 0.1 nm. Figure 5 shows the output spectrum of the passively Q-switched fiber laser at an average output power of 5 W. The experimental FWHM line width was approximately 0.2 nm. Note that the mode-locked pulse width of 2.1 ns is consistent with the measured bandwidth of 0.2 nm and the pulses are near transform-limited.

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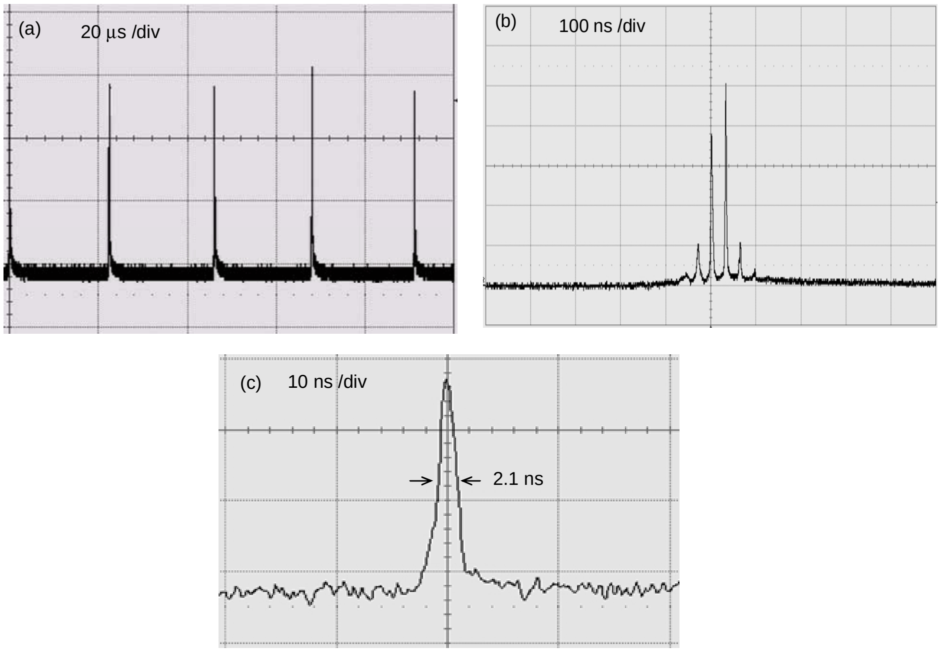

Fig. 4. (a). Oscilloscope traces of a train of Q-switched pulses, (b) Oscilloscope traces of a typical Q-switched envelope, (c) Oscilloscope traces of a mode-locked pulse inside the Q-switched envelope.

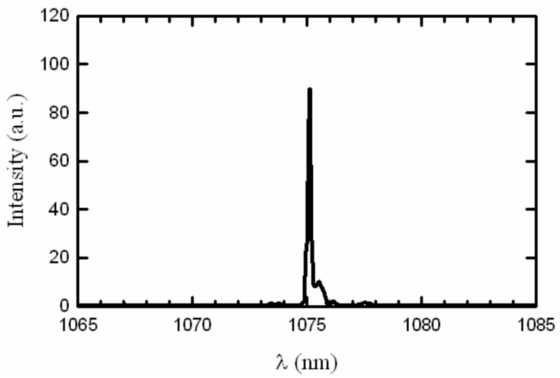

Fig. 5. Output spectrum of the Q-switched laser at an output power of 5 W.

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4. Conclusion

In conclusion, we have demonstrated an efficient high-peak-power and high-average-power passively Q-switched Yb-doped fiber laser with a Cr^{4+}:YAG crystal as a saturable absorber in an external-resonator configuration. Greater than 6.2 W of an average output power at a repetition rate of 48 kHz was generated with a 17.5-W diode pump power. Moreover, the mode-locking phenomenon enhances the peak power higher than 20 kW. It is believed that this efficient Q-switched fiber laser should be a useful light source for technical applications because of its high average power as well as high peak power.

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