All-fiber single-mode actively Q-switched laser at 1120 nm

Jianhua Wang,[1, 2] Shuzhen Cui,[2] Lei Si, [1] Jinbao Chen, [1] and Yan Feng[2,*]

[1]*College of Optoelectric Science and Engineering, National University of Defense Technology, Changsha 410073, China*

[2]*Shanghai Key Laboratory of Solid State Laser and Application, and Shanghai Institute of Optics and fine Mechanics, Chinese Academy of Sciences, Qinghe Road 390, Jiading, Shanghai 201800, China*

**feng@siom.ac.cn*

Abstract: An all-fiber single-mode actively Q-switched laser at 1120 nm is demonstrated. The laser cavity consists of a 5 m long Yb-doped polarization maintaining gain fiber, an acousto-optical modulator and a pair of FBGs. At a pump power of 2.5 W, a peak power of 0.8 kW is achieved with a pulse duration of 140 ns at a repetition rate of 1 kHz. A slope efficiency of 16.9% with respect to launched pump power is obtained at 10 kHz. The low achievable gain at 1120 nm, imposed by the parasitic lasing limit at conventional Yb lasing wavelength, has a major role in laser performance.

OCIS codes: (140.3510) Lasers, fiber; (140.3540) Lasers, Q-switched; (140.3615) Lasers, ytterbium.

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1. Introduction

Pulsed Yb-doped fiber lasers and amplifiers are taken as promising candidates for replacing bulk solid-state lasers in many scientific and industrial applications. At conventional wavelength between 1030 nm and 1090 nm for Yb-doped fiber, pulsed lasers have drawn a great deal of attentions, such as compact single-frequency Q-switched fiber laser [1] and high energy fiber lasers [2–8]. Thanks to the progress in large mode area (LMA) fiber, the limit of nonlinear optical effects in the fiber have been pushed back and higher average power and higher energy Yb-doped pulse laser have been realized in recent years. With a rod-type photonic crystal fiber of 100 μm core, 1 ns long pulses of energy in excess of 4.3 mJ was obtained [2]. Recently, 26 mJ pulse energy with 60 ns pulse duration was realized by Stutzki *et al.* employing a 2 stage rod-type photonic crystal amplifier [4]. At shorter wavelength, pulsed Yb-doped fiber laser at 977 nm is interesting for frequency doubling to blue light. A linearly-polarized pulsed laser with a peak power of 1 kW and pulse energy of 15 μJ was obtained by Khitrov *et al*. using polarization maintaining (PM) LMA 10/125 fiber [9]. With rod-type photonic crystal fiber, millijoule class pulse with a duration of 12 ns was obtained by Boullet *et al*. at a low repetition rate [10]. At longer wavelength beyond 1100 nm where gain is low and competition from central gain wavelength around 1060 nm is a severe problem. There are some reports of CW laser [11–14]. However, very few pulsed Yb fiber lasers were reported. Based on the use of a combination of free-space acousto-optical modulator (AOM) and distributed stimulated Brillouin scattering in the gain fiber as the Q-switching mechanism, millijoule class pulse tunable fiber laser from 1080.8 nm to 1142.7 nm was realized by Fan *et al.* [15].

High power fiber laser at 1120 nm has a variety of applications, such as pumping Raman fiber amplifier at 1178 nm for laser guide star [16, 17] and Tm-doped fiber laser [18]. A high peak power fiber laser at 1120 nm is therefore useful for studying the physical processes in these lasers, such as stimulated Raman scattering and stimulated Brillouin scattering. In this paper, we report a single-mode all-fiber actively Q-switched Ytterbium fiber laser at 1120 nm. With a pump power of 2.5 W, output power of 291 mW is obtained at a repetition rate of 10 kHz. A peak power of 0.8 kW with a pulse duration of 140 ns is realized at a repetition rate of 1 kHz. To the best of our knowledge, this is the first report of single-mode all-fiber Q-switched Ytterbium fiber laser at the longer wing of emission spectrum.

2. Experimental configuration

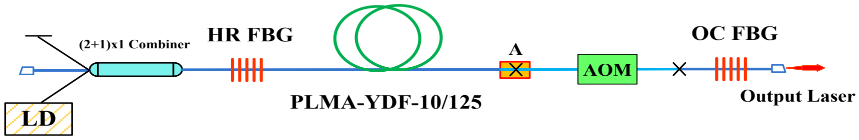

Fig. 1. Experimental configuration of Q-switched fiber laser at 1120 nm.

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The experimental configuration of the actively Q-switched fiber laser at 1120 nm is shown in Fig. 1. The laser cavity is constructed by a pair of FBGs, 5 m of Yb-doped fiber and a fiber-pigtailed AOM. The cavity is about 9 m long in total. The gain fiber (PLMA-YDF-10/125, Nufern Inc.), whose nominal cladding absorption is 4.8 dB/m at 975 nm, has a core and inner cladding diameter of 10 μm and 125 μm, respectively. The FBGs are written in matched passive fibers (PM085-LNA-FA, Nufern Inc.). The FBG with high reflectivity of 99% (HR-FBG) at 1120 nm is spliced to one end of the gain fiber. The other FBG with a reflectivity of 20% (OC-FBG) is used as the output coupler. An AOM with pigtail fiber (Gooch & Housego Inc.) is inserted between the gain fiber and OC-FBG. The AOM is operated on the first-order diffraction with an insert loss of 2.3 dB at 1120 nm. The pigtail fiber is single cladding and polarization maintaining with a core and cladding diameter of 6 μm and 125 μm, respectively. The fiber ends in the AOM were anti-reflection-coated at 1120 nm in order to avoid spurious oscillation. The mismatch in core diameter between the AOM pigtail and other fibers introduces extra cavity loss, which should be avoided in future experiments. The pump source is a laser diode (LD) with an output power of 10 W at 975 nm, whose output fiber has a core diameter of 105 μm and a NA of 0.15. The pump laser is injected to the laser cavity by a (2 + 1) × 1 combiner. The pump input fibers of the combiner are same with those of laser diodes. The residual pump laser in the cladding is removed at the splice point A between the gain fiber and the single cladding fiber of AOM as shown in Fig. 1. All the fiber ends are cleaved with an angle of 8° to suppress parasitic oscillation.

3. Results and discussion

The output power as a function of launched pump power is shown in Fig. 2. With an input pump power of 2.5 W, the maximum output power of 111 mW at 1120 nm is achieved with a slope efficiency of 6.1% at a repetition rate of 1 kHz. Correspondingly, a maximum output power of 291 mW is obtained at a repetition rate of 10 kHz. A slope efficiency of 16.9% is observed, which is lower compared to CW fiber lasers at 1120 nm. Further power scaling is limited by the break of the gain laser, which we believe is due to giant pulses generated by parasitic lasing at higher-gain wavelength around 1060 nm. This sets the up-limit of laser gain [19], which can be given as

$$G_{Max} = \frac{\sigma_{e,S}\Gamma_S}{\sigma_{e,ASE}\Gamma_{ASE}} G_{th} \tag{1}$$

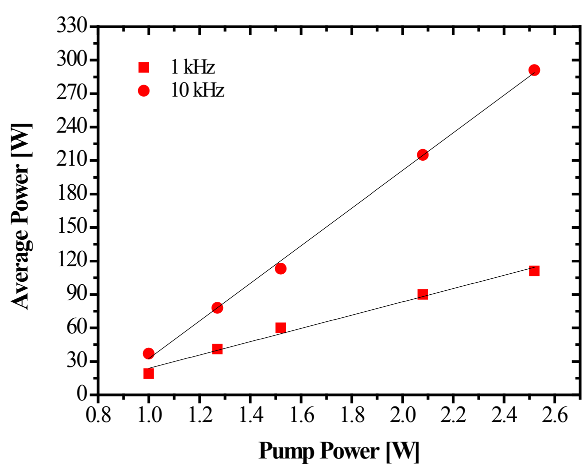

Fig. 2. Average output power versus launched pump at different repetition rates.

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where $\sigma_{e,ASE}$ and $\sigma_{e,S}$ are the emission cross sections at the amplified spontaneous emission (ASE) peak wavelength and laser wavelength, respectively. Γ_{ASE} and Γ_S are the overlap factors at the two wavelengths. G_{th} is the threshold gain of the parasitic lasing, which is around 40–50 dB for a fiber laser with angle-cleaved fiber ends. With the values given in reference [19], the maximum gain at 1120 nm is only ~12 dB. On the other hand, the intra-cavity loss of the laser setup is high and estimated to be ~3 dB, counting the 2.3 dB inserting loss of the AOM and the extra loss induced by the unmatched fibers. The gain-to-loss ratio is calculated to be only ~4, which can explain the low efficiency.

Figure 3 shows the changes of pulse duration as a function of launched pump power at different repetition rate. The pulse is recorded by a digitally sampled oscilloscope (600 MHz bandwidth, LeCroy Corp.) together with a 2.3 ns rising time photodiode (PDA 10CF, Thorlabs Inc.). The pulse duration decreases with the increase of pump power. At lower repetition, the pulse duration is much shorter due to the higher stored energy. However, at high pump power, the pulse starts to split into two peaks. With a pump power of 2.5 W, a pulse duration of 140 ns is obtained at 1 kHz as compared to 181 ns at the repetition rate of 10 kHz. The pulse profile at repetition rate of 1 kHz is shown in Fig. 4, where the inset shows the pulse train. The pulse splits to two peaks with a separation of about 90 ns, which corresponds to the cavity round trip

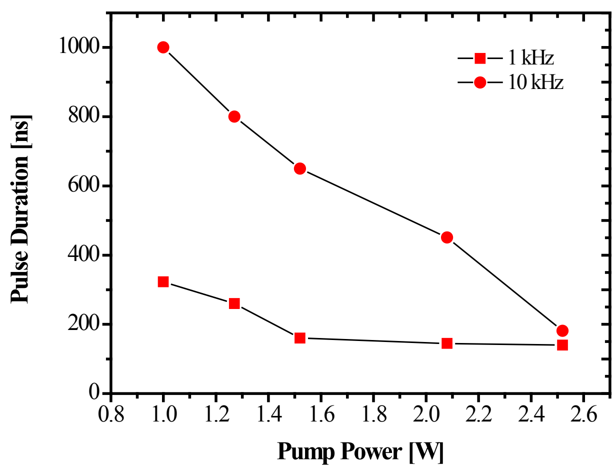

Fig. 3. Pulse duration versus launched pump power at different repetition rate.

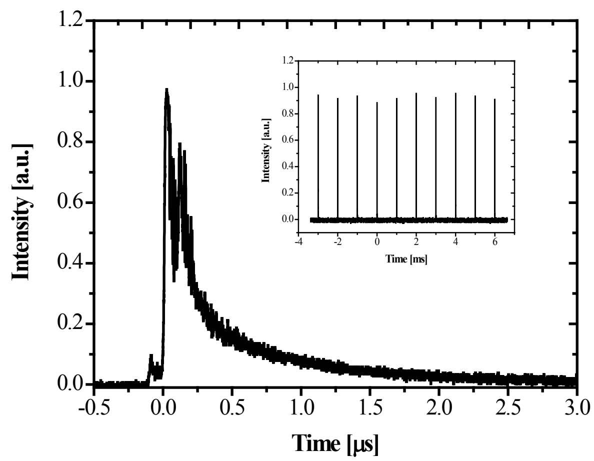

Fig. 4. Single pulse profile at repetition rate of 1 kHz. Inset, measured pulse train.

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time well. Therefore, the pulse splitting is likely due to self-mode-locking effect as commonly seen in actively Q-switched fiber laser [20]. No interpulse ASE was observed. The pulse is obtained at a time interval of 20 μs when the AOM is in transmission. The rise/fall time of AOM is 10 ns.

Figure 5 demonstrates the spectral characteristics of the Q-switched 1120 nm fiber laser, which is measured with a spectral analyzer (AQ 6370, Yakogawa Corp.). ASE is more than 40 dB lower than the laser signal at the repetition rate of 1 kHz with the pump power of 2.5 W. The inset shows the zoom-in view of the laser emission. The FWHM linewidth is 0.47 nm measured with a resolution of 0.02 nm. The amount of ASE is estimated by spectral integration [4]. The ratio of ASE to laser power is below 0.2% at the maximum output power. Although little ASE is measured from the laser output, much stronger ASE is observed from the backward direction, which emits even when the AOM is closed. A Raman scattering signal at 1180 nm is also observed, which is by far rather small but would limit the power scaling at higher power.

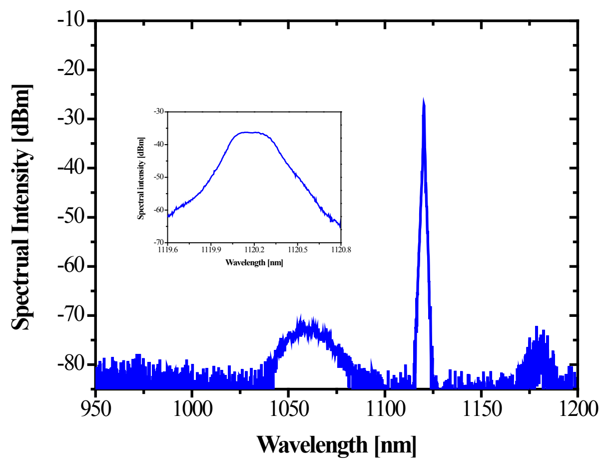

Fig. 5. Spectral characteristic of the 1120 nm Q-switched fiber laser. Inset, detailed spectrum at 1120 nm.

For a given pump power, there is a range of AOM switching rates that can produce a regular pulse train [21, 22]. Outside the range, the laser may operate at certain subharmonics of the repetition rate [22]. In our experiment, regular pulsed fiber laser can be obtained from 1 kHz to

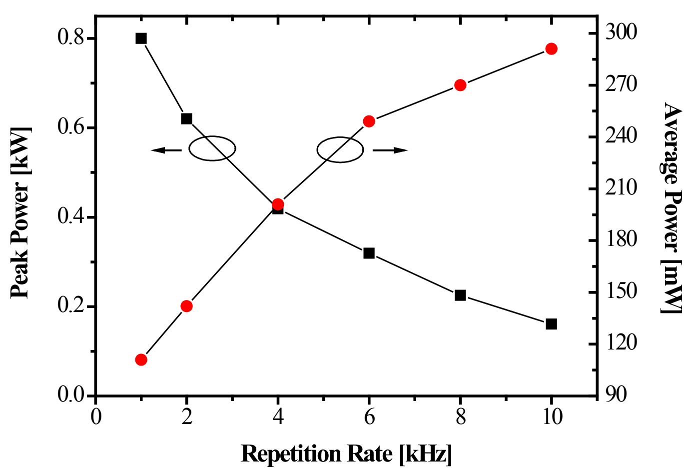

Fig. 6. The peak power and average power versus different repetition rate at pump power of 2.5 W.

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10 kHz. The pulse peak power and average output power of the actively Q-switched 1120 nm fiber laser versus repetition rate at pump power of 2.5 W is shown in Fig. 6. The average output power increase with the increase of repetition rate. The maximum output power of 291 mW is produced at repetition rate of 10 kHz as compared to 111 mW at 1 kHz. The maximum peak power of 0.8 kW is obtained at repetition rate of 1 kHz with a pulse duration of 140 ns.

4. Conclusion

In conclusion, we demonstrate a single-mode all-fiber actively Q-switched fiber laser at 1120 nm. The pulse repetition rates are tunable from 1 kHz to 10 kHz by varying the frequency of AOM. A peak power of 0.8 kW was obtained with a pulse duration of 140 ns at a repetition rate of 1 kHz with a pump power of 2.5 W. As far as we know, this is the first report of single-mode all-fiber Q-switched Yb-doped fiber laser at wavelength longer than 1100 nm. The parasitic lasing at the conventional high gain wavelength around 1060 nm imposes a low achievable gain at 1120 nm, which makes higher power operation difficult. Much shorter pulse and higher efficiency can be expected with a shorter cavity and low inserting-loss AOM. The single-mode 1120 nm Q-switched fiber laser is useful for studying Raman fiber amplifier at 1178 nm for laser guide star.

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