High conversion efficiency, high power density Q-switched fiber laser*

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An acoustic–optic Q-switched all-fiber laser with a high-repetition-rate, a short pulse width, a wide spectrum, and a high conversion efficiency is experimentally demonstrated. In the laser configuration, a (1+1)×1 side-pumping coupler is introduced to perform backward pumping, and a 10/130-μm Yb fiber is adopted. The acoustic–optic component operates in the first direction, achieving a Q-switched pulse with a repetition rate adjustable in the range of 20 kHz–80 kHz. Under a repetition rate of 20 kHz and a pump power of 6.76 W, the fiber laser obtains a highly efficient and stable pulse output, with an average power of 4.3 W, a pulse width of 56 ns, a peak power of 3.83 kW, and a power density of 1.39×10^{10} W/cm^2. Particularly, the optic–optic conversion efficiency of the laser reaches as high as 64%. Another feature of the pulsed laser is that the high reflection mirror reflects the pump light as well, which brings the secondary absorption of the pump power into the gain fiber.

Keywords: Q-switching, wide spectrum, fiber lasers, laser diode-pumped, peak power

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1. Introduction

With the rapid development of fiber lasers, nowadays they are used in many fields such as precision machining, material processing, medical treatment, satellite communication, etc.[1–4] A fiber laser can be classified into a pulsed fiber laser and a continuous one, depending on the mode of the power output. In the continuous wave operation, the output power of the fiber laser has exceeded 10 kW by using the large-mode-area (LMA) double clad fiber technology and high power laser diode (LD) technology.[5–8] In the pulsed operation, the peak power of the fiber laser has reached 17.33 kW. Compared with a continuous fiber laser, the pulsed fiber laser has a high peak power while maintaining good beam quality, which receives more attention in actual applications. Therefore, the pulsed fiber laser has always been a research subject of interest. In most pulsed fiber lasers, photonic crystal fiber (PCF) is adopted as a gain material. A highly ytterbium (Yb)-doped PCF can produce a pulsed laser output with a single pulse energy of 1.2 mJ and a pulse width of 10 ns, under a repetition frequency of 20 kHz. Its optical conversion efficiency is 55% and the power density is 0.5×10^{10} W/cm^2.[9] A Q-switched fiber laser system emitting a sub-60-ns pulse with a 26-mJ pulse energy and near-diffraction-limited beam quality ($M^2 < 1.3$) has also been reported.[10] However, a crucial problem brought by PCF is the bending loss. A direct and effective means to cope with this challenge is to increase the diameter of the fiber core. Thus many people adopt LMA fiber as the gain medium, but at the expense of reducing laser power density. For LMA fiber, a duration of 40 ns and an energy of as high as 1.2 mJ at a repetition rate of 10 kHz has been reported. The 1-mJ pulse propagating in the fundamental mode has a peak power density of 0.675×10^{10} W/cm^2, and an optical conversion efficiency of 41%.[11] Another study is based on a Tm:LMA fiber with a length of 3.3 m, a core of 25 μm and a clad of 400 μm. At a 10-kHz repetition rate, the LMA fiber reaches a maximal average power of less than 5 W, with a peak power of 6.5 kW, an M2 factor of smaller than 1.3, a power density of 0.13×10^{10} W/cm^2, and an optical conversion efficiency of 30.3%.[12] But the disadvantage of the LMA fiber is that it is of the multi-mode operation, which would deteriorate the laser beam quality.[13,14] Therefore, how to build a pulsed fiber laser while suppressing nonlinearity and maintaining good beam quality and stability, is a harsh and complicated job.

In this paper, a new acousto–optic (AO) Q-switched fiber laser is presented to solve the problems mentioned above. The laser is based on conventional fiber and has obtained high power density and high optical conversion efficiency. In the laser configuration, a reflector with high reflectivity in a wide spectrum range and a fiber Brag grating (FBG) with low reflec-

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tivity are adopted to realize a wide spectrum-range laser output. One feature of the pulsed laser is that the high reflection mirror reflects the pump light as well, which brings the secondary absorption of pump coupled into the gain fiber. In the experiment, wide spectrum-range pulsed laser output is realized through Q-switched device with the repetition frequency adjustable from 20 kHz to 100 kHz. Stable pulsed laser output with an average power of 4.3 W, a pulse width of 56 ns and a peak power of 3830 W is obtained with a repetition frequency of 20 kHz and a pump power of 6.76 W. The laser power density is 1.39×10^{10} W/cm^2, and the optic–optic conversion efficiency of the pulsed laser is 64%. The laser configuration improves pump utilization and reduces the gain fiber length in experiment. Besides, the wide-spectrum-range laser output reduces the power density within the unit spectrum width, thus indirectly raising the nonlinear threshold and effectively inhibiting the nonlinear effect in the laser. The influence of the nonlinear effect is effectively mitigated in the laser presented here, compared with that in the narrow spectrum-range output, which helps to improve the peak power of the pulsed laser significantly.

2. Experiment

In the experimental system, an LD with the output at 976 nm is employed as the pump source. A (1+1) ×1 side-pumping coupler is introduced to couple the pump light into the gain fiber in the backward direction. The gain fiber used in the experiment is a Yb-doped 10/130 μm one, with a length of 5 m. The core numerical aperture (NA) and clad NA of the fiber are 0.08 and 0.46, respectively. After the one-way absorption of the pump light by the gain fiber, the unabsorbed pump is reflected by the reflection mirror back into the gain fiber. Here, when the A–O Q-switched device is working at primary diffraction order, the change of the angle is relatively small, which makes the signal light unable to couple and return to the fiber core. However, due to the relatively large numerical aperture of the fiber cladding, the pump light could be easily coupled back into the cladding. The transmission angle is changed very little by the A–O Q-switched device. Therefore, its influence on the inverse coupling of pumping light is relatively minimal to reach the objective of secondary absorption of the pumping light. Because of the more sufficient utilization of the pump light, a fiber laser with this structure has a great advantage in optic–optic efficiency.

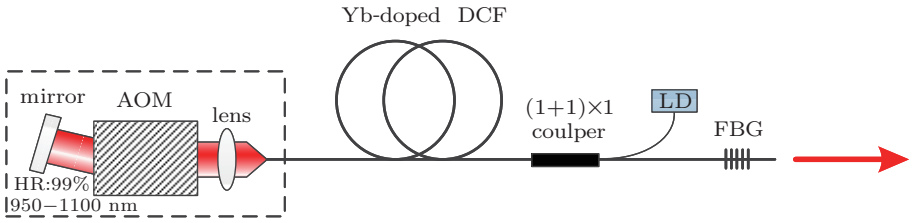


Fig. 1. (color online) Scheme of the A–O Q-switched fiber laser.

Besides, the stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) threshold equations are shown as follows:

$$P_{\mathrm{SRS}} = \frac{G_{\mathrm{th}} \cdot A_{\mathrm{eff}}}{g_{\mathrm{B}} \cdot L_{\mathrm{eff}}}, \tag{1}$$

$$P_{\mathrm{SRS}} = \frac{G_{\mathrm{th}} \cdot A_{\mathrm{eff}}}{g_{\mathrm{B}} \cdot L_{\mathrm{eff}}} \cdot \frac{\Delta V_{\mathrm{B}} + \Delta V_{\mathrm{P}}}{\Delta V_{\mathrm{B}}}, \tag{2}$$

where P_{SRS} and P_{SBS} are the thresholds of SRS and SBS respectively, A_{eff} refers to the net sectional area of the fiber, g_{R} the Raman gain coefficient, ΔV_{B} the Brillouin gain coefficient, ΔV_{p} the effective length of the fiber, ΔV_{B} the Brillouin gain spectrum width, and ΔV_{p} the laser spectrum width. According to Eqs. (1) and (2), the fiber laser with this structure can effectively reduce the length of the gain fiber L_{eff} to increase the values of thresholds P_{SRS} and P_{SBS}, which could avoid nonlinearity under high peak power. Meanwhile, the threshold of SBS is also related to the width of spectra. When ΔV_{p} of the fiber laser increases, P_{SBS} also increases and the onset of SBS is effectively postponed. Therefore, the pulsed fiber laser with this structure could effectively inhibit the nonlinear effect and efficiently avoid the nonlinear-effect-caused fiber damage.

3. Results

In the experiment, by controlling the repetition frequency of the A–O Q-switch, we study the relationships of pump power with laser peak power, pulse width, and average output power. The results under different repetition frequencies are plotted in Figs. 2 and 3, respectively.

From Figs. 2 and 3, it is seen that when the repetition frequency increases, the laser peak power decreases while the pulse width increases. Figure 4 shows that under the same repetition frequency, the average output power increases as the pump power increases. It is found in Fig. 3 that some curves fluctuate significantly, just because of the half-frequency data measured. In Fig. 3, at the repetition frequencies under 60 kHz (from 20 kHz to 50 kHz), the laser pulse width decreases while the pump power increases, so these curves fluctuate slightly;

when the repetition frequencies exceed 60 kHz (from 60 kHz to 80 kHz), these curves fluctuate significantly. It is seen that for a low repetition frequency laser, due to the decrease of pulse repetition frequency, each cycle of initial inversion of particle number density is subjected to enough gain pumping to approach or reach the saturation values. So for each cycle for its initial inversion of particle number density in the same saturation values, obviously from 20 kHz to 50 kHz the curves fluctuate slightly. In the meantime, under the same pump power, if we increase the repetition frequency and make the pulse repetition frequency higher, each cycle of the initial inversion of particle number density will not obtain enough pump gain. There will be a positive feedback, in which the pump width will show a sharp decline in process, and obviously from 60 kHz to 80 kHz in low pump power these curves fluctuate significantly. For example, under a repetition frequency of 60 kHz and a pump power of 3.21 W, the pulse width is 327 ns, and if the pump power is reduced to 2.19 W, the pulse width drops off to 269 ns. In the experiment, by controlling the repetition frequency of the A–O Q-switch below 20 kHz, an average output power of 4.3 W (in the experiment we place a 976 nm/1064 nm beam splitter between the end of the system output fiber and the power meter) is achieved from the pulsed fiber laser, under a pump power of 6.76 W. The peak power of the fiber laser is 3830 W, with a pulse width of 56 ns and an optic–optic conversion efficiency up to 64%.

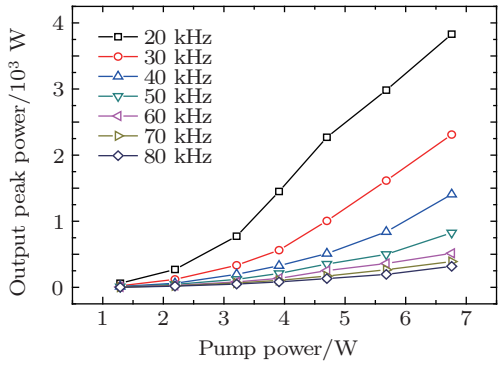


Fig. 2. (color online) Relationships between pump power and laser peak power (Y) under different repetition frequencies.

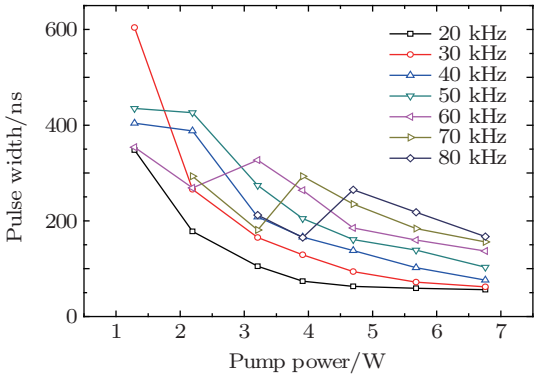


Fig. 3. (color online) Relationships between pump power and pulse width under different repetition frequencies.

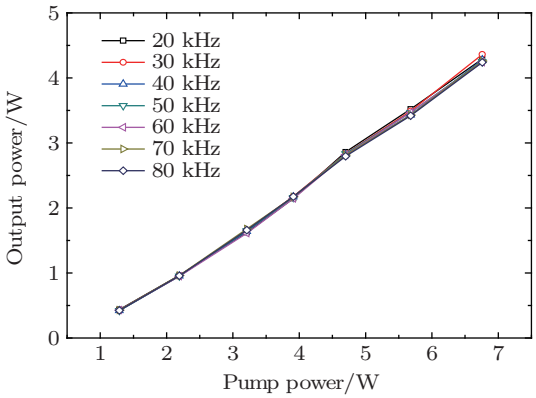


Fig. 4. (color online) Relationships between pump power and average output power under different repetition frequencies.

Figure 5 shows a single pulse waveform when the pump power is 6.76 W and the repetition frequency is 20 kHz. As shown in the figure, the pulse width is 56 ns and the pulse waveform is smooth with no sub-pulse, which means a steady output wave.

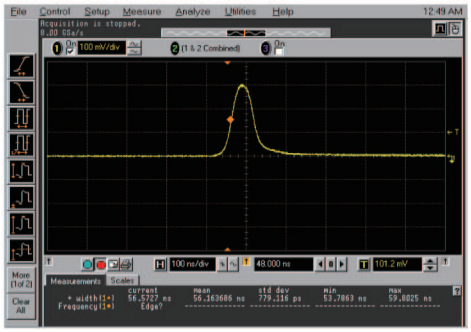


Fig. 5. (color online) Single pulse waveform under a repetition frequency of 20 kHz.

Moreover, the output spectra of the pulsed fiber laser are investigated in experiments, including a narrow one and a wide one. Firstly, a fiber grating with a narrow reflectance spectrum and a reflector with high reflectivity in a wide spectrum are used as a pair of cavity mirrors. The output spectrum from the laser with such a structure is shown in Fig. 6. Then a fiber grating with a wide reflectance spectrum is adopted instead of the former one, and an output spectrum is obtained as shown in Fig. 7.

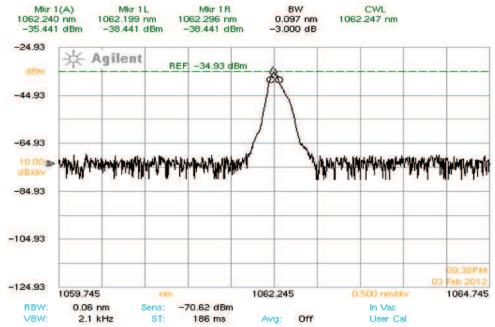


Fig. 6. (color online) Narrow output spectrum of the pulsed fiber laser.

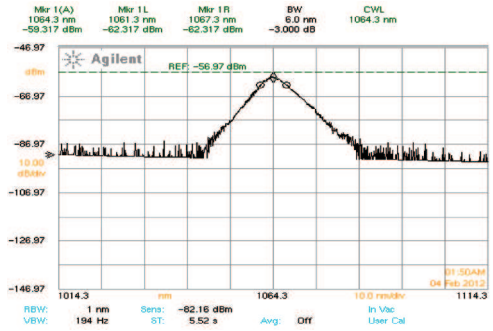


Fig. 7. (color online) Wide output spectrum of the pulsed fiber laser.

A comparison of the laser spectrum between Fig. 6 and Fig. 7 shows that the narrow spectrum has a width of 0.097 nm, while the wide one has a width of 6 nm. It is rather remarkable in Fig. 6 that the resolution of the optical spectrum analyzer (OSA) used in the present experiment is 0.06 nm. Figure 7 shows that the OSA is 1 nm. Comparing the differences in resolution of the laser spectrum between Fig. 6 and Fig. 7, considering the result accuracy of the experiment, we need to make trade-offs between the wavelength range and the wavelength resolution. If we only use the resolution to obtain the laser spectrum, it must influence the authenticity of the experiment. Therefore, we check the wavelength of the sampling interval (the coordinate data intervals) to obtain accurate data. According to experiments, it is known that with a narrow output spectrum, when the average laser power is 2.25 W and the pulse width is 62 ns, the output spectrum is greatly influenced by the nonlinearity and thus it is harmful to the gain fiber. By calculation, we know that the peak power of the narrow spectrum is 1815 W, while the peak power of the wide spectrum is 3830 W. In the experiment with a narrow spectrum output, the gain fiber is significantly influenced, or even damaged by the nonlinear effect. While in the experiment with a wide spectrum output, under the same average output power, the gain fiber is not influenced, and the spectrum is smoother with no sign of the nonlinear effect. Experiments show that a wide-spectrum laser output could obtain a higher peak power than the narrow-spectrum one. When the laser spectrum is wider, the output power density in the unit spectrum width is smaller, thus the nonlinearity threshold is higher and the direct influence of the nonlinear effect on the gain fiber is reduced, which turns into an increased average output power and peak power in a pulsed fiber laser.

4. Conclusion

A pulsed fiber laser based on A–O Q-switch is presented in this paper. With secondary use of pumping and wide spectrum laser oscillation, a wide-line, high repetition frequency adjustable and high optical–optical transfer efficient pulsed fiber laser output is obtained. Under a repetition frequency of 20 kHz and a pump power of 6.76 W, an average output power of 4.3 W and a peak power of 3830 W are obtained from the A–O Q-switched pulsed fiber laser, with a pulse width of 56 ns and an optic–optic conversion efficiency up to 64%. The laser is centered at 1064 nm, with a spectrum width of 6 nm, In this experiment, the variations of laser peak power, pulse width, and average output power with pump power are studied under different repetition frequencies, and their variation tendency and influence factors are analyzed. Based on a comparison of the laser output between the narrow-spectrum laser and the wide-spectrum one, it is found that for an output laser in a wide spectrum, the direct influence of the nonlinear effect on the gain fiber can be effectively reduced, as well as the fiber damage brought by the effect. Meanwhile, the average output power and peak power of the pulsed fiber laser are greatly increased under a wide-spectrum laser output. The laser structure presented and the laser spectrum characteristics demonstrated in this paper could be used in further research and development of pulsed fiber lasers.

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