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High pulse energy actively Q-switched dual-wavelength pumped Er:ZBLAN fiber laser at 3.5 μm

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A B S T R A C T

In order to further improve the single pulse energy of actively Q-switched fiber laser in deep mid-infrared region, a universal and simple mechanical switch (MS) was used to achieve the high pulse energy 3.5 μm Er:ZBLAN fiber laser in dual-wavelength pumping (DWP) system. The maximum pulse energy was 9.4 μJ at the repetition rate of 8.4 kHz and the corresponding pulse width and peak power was 578 ns and 16.3 W, respectively. However, the further improvement of the pulse energy was limited by the formation of multiple pulses as the pump power increasing. According to the results of the experiment and numerical calculation, the multiple pulses were caused by relaxation oscillation and it was influenced by the pump power, the modulation rate and duty cycle of MS. Meanwhile, the Q-switched 2.8 μm laser was also found in the system, and it would also reduce the pulse energy of 3.5 μm laser. Therefore, the pulse energy could be improved in the further.

1. Introduction

High pulse energy and high beam quality laser emitting in the mid-infrared wavelength range has many potential applications, in the field of free-space communication, chemical and biological sensing, remote sensing and earth atmosphere monitoring [1–3]. Lasers operating around 3.5 μm are particularly interesting due to their overlap with absorption lines of molecules containing C–H or N–O bands, and being in the middle of the transmission windows of earth atmosphere [4–5]. However, the development of fiber lasers operating at 3.5 μm has lagged considerably due to the low output power and the efficiency [6]. The laser efficiency has been improved by the method of dual-wavelength pumping (DWP) [7]. After that, the output characteristic parameters of the laser have been constantly refreshed through continuous optimization of laser design [8–11].

The pulse energy of 3.5 μm fiber laser as one of the important output parameters was also constantly being improved. In order to achieve high pulse energy, the methods of pulse modulation, such as gain switching [12–13], Q-switching [14–15] and passively mode locking [16–18] have been tried in DWP system. However, Q-switched fiber lasers have the capability of producing much higher pulse energy compared with mode-locked lasers. Qin et al. have achieved passively Q-switched operation at 3.5 μm using a black phosphorus saturable absorber mirror and the maximum pulse energy was 1.8 μJ [16]. Fang et al. have demonstrated a 3.46 μm passively Q-switched fiber laser by adopting a InAs based semiconductor saturable absorber mirror and the single pulse energy was 1.4 μJ [15]. Compared to passively Q-switched fiber lasers, actively Q-switched fiber lasers have the advantages including well controlled pulse repetition rate and high pulse energy [19]. In 2018, the actively Q-switched 3.5 μm fiber lasers based on acousto-optic modulators (AOMs) have been implemented by Bawden et al. and the maximum pulse energy of 7.8 μJ was achieved at a repetition rate of 15 kHz [14]. However, the mid-infrared AOMs have the disadvantages of large absorption loss, limited modulation effect. While the traditional mechanical switch (MS) is cheap, simple, high modulation depth and universal in all the wavelength region. It's very suitable to achieve high pulse energy fiber laser in deep mid-infrared region.

In this paper, the MS were used in DWP system to achieve actively Q-switched 3.5 μm fiber laser. The output pulse train, spectrum, and pulse width were measured. The curves of output power and pulse energy were also recorded. The multiple pulses were formed under the high pump power, which limited the further improvement of the pulse energy. The pulse envelope of the multiple pulses was compared under different pump power, repetition rate and duty of the MS.

2. Experimental set-up

The setup for experiment is shown in Fig. 1. The gain fiber is 3.6 m length and 1.5 mol. % concentration erbium doped fluoride (Er:ZBLAN) fiber. The diameter and numerical aperture of the fiber core are 16.5 μm

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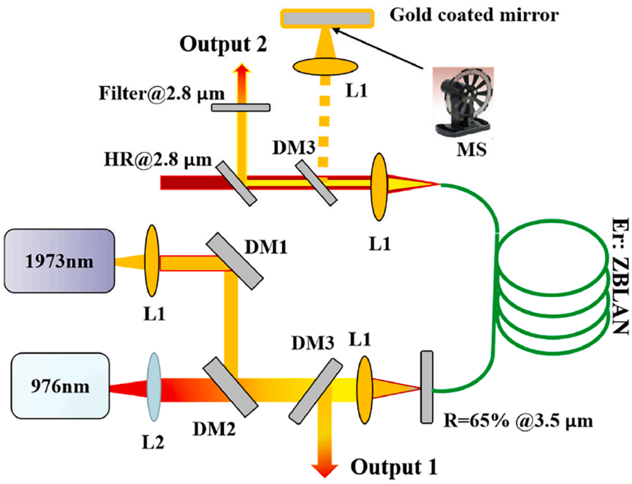

Fig. 1. Schematic of the actively Q-switched DWP fiber laser system using a MS. L1, L2, Aspherical lens; HR, high reflection; DM, dichroic mirror (DM1, HT@793 nm & HR@1973 nm, DM2, HT@976 nm &HR@1973 nm, DM3, HT@976 nm, 1973 nm & HR@ 3500 nm); MS, Mechanical switch.

and 0.12, respectively. Its 260 μm cladding have a circular shape with two parallel flats separated by 240 μm. The 976 nm fiber coupled diode laser and 1973 nm homemade fiber laser are used as pump sources. Double pump sources are combined by a dichroic mirror (DM2) and then coupled into the Er:ZBLAN fiber. The focus length of lens L1, L2 are 12.7 mm and 8 mm, respectively. The reflection of output coupling mirror is about 65 % at 3.5 μm. The MS is comprised of a controller and a steel wheel, which has 100 slots, corresponding to repetition rate from 0.8 kHz to 8 kHz. The diameter of the steel wheel is 100 mm, the duty cycle of the wheel is 50 %, and the slot width at the edge of steel wheel is about 1.5 mm. The wheel is located closely to the gold coated mirror, and the spot diameter on the gold coated mirror is about 17 μm. A 45 angles dichroic mirror (HR@2.8 μm) and the filter are used for 2.8 μm laser output. The pulse train is captured by a HgCdTe detector (PVI-4TE-5, VIGO System) and the rise time of the detector is about 2 ns. The captured results are showed on a digital oscilloscope (MOD 3104, Tektronix) with 1 GHz bandwidth. The spectrum is measured by a Fourier spectrometer analyzer (Thorlab OSA207C).

3. Results and discussion

3.1. High pulse energy 3.5 μm fiber laser

The actively Q-switched 3.5 μm fiber laser was achieved based on the above setup. The output pulse train was captured under the pump power of 2 W for 976 nm and 3.4 W for 1973 nm, as shown in Fig. 2(a). There were 17 pulses in the time region of 2 ms and the standard deviation of the amplitude peak is about 0.19 %. The repetition rate of the pulse train was about 8.4 kHz. The spectrum was also measured and plotted in Fig. 2(b), and the center wavelength was about 3536 nm. The average pulse width (collected 20 pulse widths and then calculated the average value) under different pump power of 1973 nm was plotted in Fig. 2(c). Increasing the pump power of 1973 nm from 2.5 W to 3.4 W, the pulse width was decreased from 2.9 μs to 578 ns. And the insert illustration of the Fig. 2(c) was the pulse envelope corresponding to the 578 ns pulse width. The curves of the output power and pulse energy of the actively Q-switched 3.5 μm fiber laser were also displayed in Fig. 2(d). In experiment, it was also found that the multiple pulses occurred under the high pump power, as shown in the dark area. The maximum output

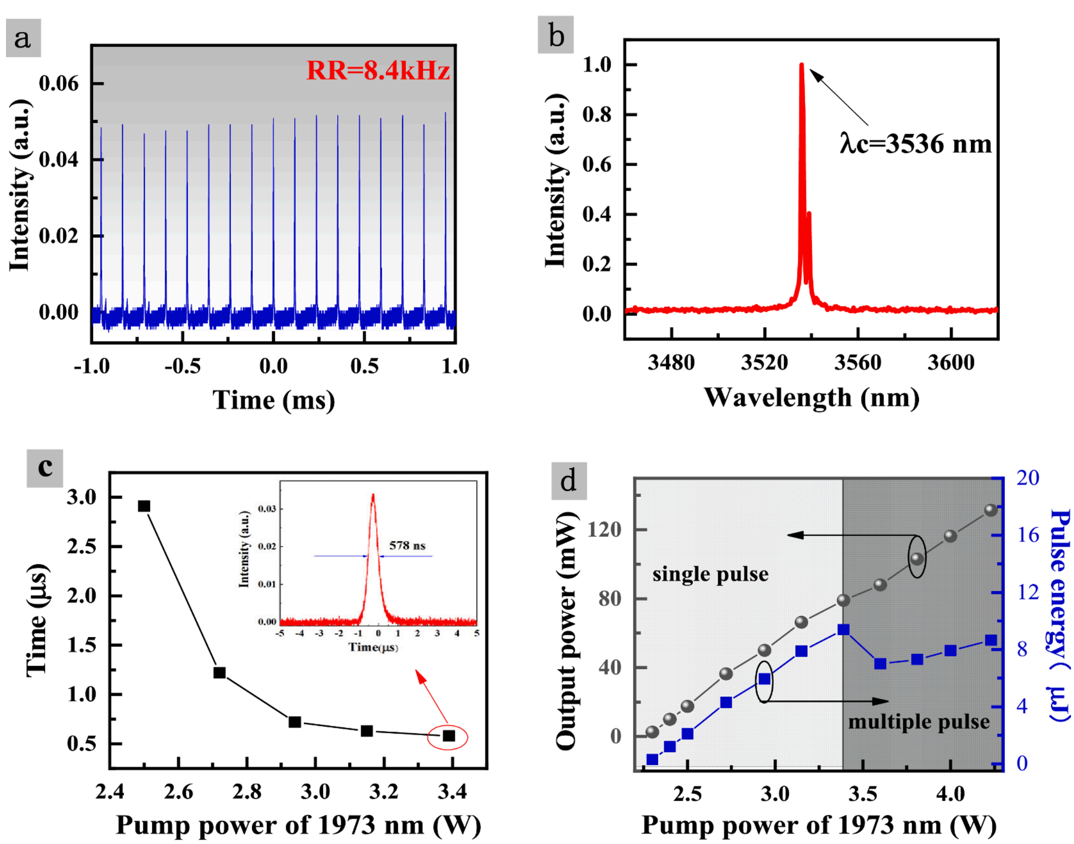

Fig. 2. The output characteristics of 3.5 μm actively Q-switched fiber laser. (a) the pulse train of the stable actively Q-switched laser, RR, repetition rate, (b) the output spectrum, (c) the average pulse width of the single pulse under different pump power, (d) the average output power and pulse energy as a function of pump power.

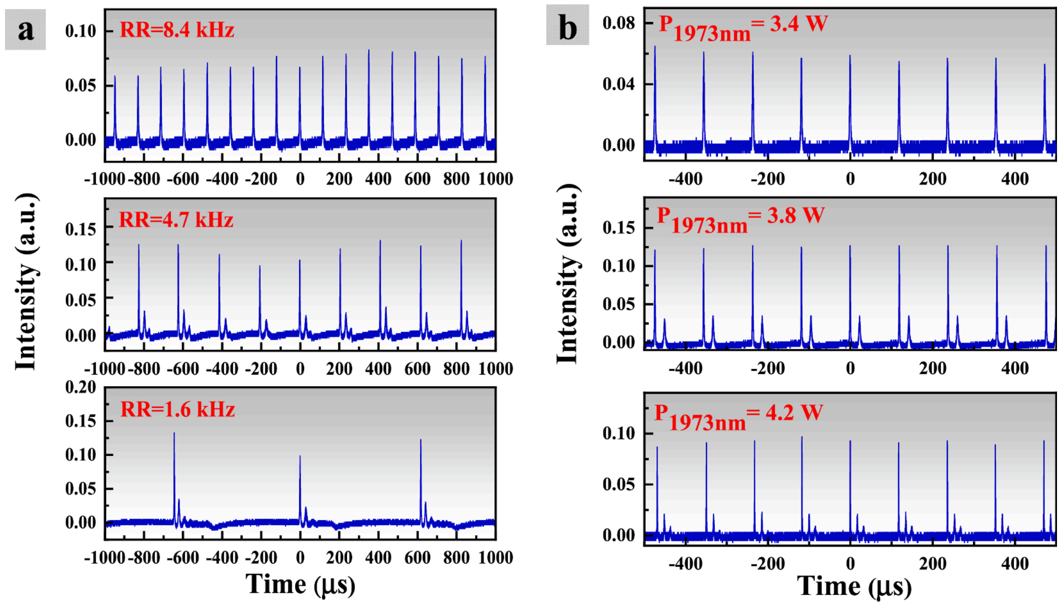

Fig. 3. The pulse train of 3.5 μm actively Q-switched fiber laser under (a) different repetition rate (RR) and (b) different pump power of 1973 nm.

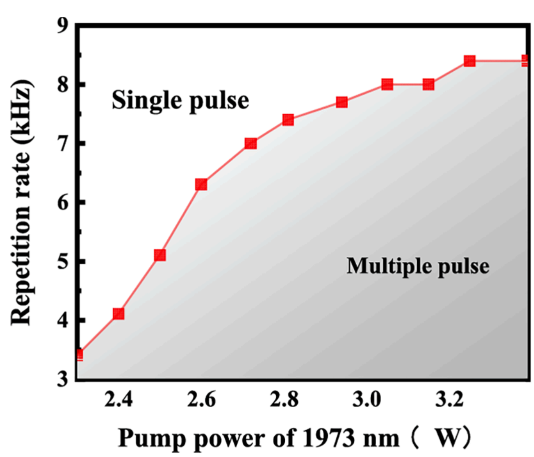

Fig. 4. The region of the single pulse and the multiple pulses for 3.5 μm actively Q-switched fiber laser.

power and pulse energy for single pulse was 79 mW and 9.4 μJ, respectively. And the corresponding peak power was about 16.3 W. While the further improvement of the single pulse energy was hindered by multiple pulses. And the maximum output power of the multiple pulses was up to 131 mW, but the main pulse energy for the multiple pulses was less then the energy of the single pulse.

In order to better understand the process of single pulse to multiple pulses, the pulse train under different repetition rate and pump power were compared, as shown in Fig. 3. Reducing the repetition rate of the Q-switched fiber laser, the single pulse was gradually changed to multiple pulses under the same pump power, as shown in Fig. 3(a). At the same repetition rate, the single pulse would be changed to multiple pulses by increasing the pump power of 1973 nm, as shown in Fig. 3(b). Therefore, the repetition rate and pump power were two influence facts to multiple pulses. In order to intuitively show their effect on multiple pulses, the region of the single pulse and multiple pulses was plotted in Fig. 4. At high pump power, high repetition rate is required to achieve the single pulse. The main reason for the multiple pulses is the mismatch between the modulation rate of the MS and the number of photons in the cavity.

The Q-switched pulse could be simply characterized by solving the rate equations to optimize the modulation design and avoid the multiple pluses, as shown in Appendix. The calculated Q-switched pulse variation rule was the same with the experiment. The multiple pulses were gradually generated with the pump power increasing, but disappeared by improving the repetition rate. However, it is very difficult to further improve the modulation rate (repetition rate) of MS. Therefore, the duty cycle of the MS was considered to prevent the formation of the multiple pulses. Fig. 5 was the calculated pulse profile under different duty cycle. With the duty cycle increasing, the multiple pluses were gradually formed. Although the designed duty cycle of the MS used in the experiment was 50 %. In fact, it was not accurate 50 % due to the influenced of the modulation rate and the cavity loss. In summary, it would be helpful for the high pulse energy of the 3.5 μm fiber laser by optimizing the duty of the MS.

3.2. The influence of 2.8 μm laser

In experiment, it was also found a weak 2.8 μm laser from *output 2* in Fig. 1. The reason of the 2.8 μm laser could be understand according to the energy level of DWP 3.5 μm fiber laser, as shown in Fig. 6(a). The spectrum was measured and showed in Fig. 6(b), the center wavelength was 2793 nm. The state of the 2.8 μm laser was also the Q-switching pulse and the repetition rate was the same with 3.5 μm laser under the action of the MS modulation. Similarly, the multiple pulses gradually changed to single pulse by increasing the repetition rate, as shown in Fig. 7(a). But the multiple pulses gradually changed to single pulse under high pump power of 1973 nm, as shown in Fig. 7(b). Because the multiple pulses were formed under high pump power of 976 nm, more particles were pumped to the upper energy level of 2.8 μm, but the 1973 nm pump source consume the population in the upper energy level. However, the 2.8 μm laser would still have a great impact on the improvement of the pulse energy of the 3.5 μm laser. Therefore, the methods should be taken to avoid the generation of 2.8 μm laser, such as anti-reflection coating or 8 degrees angle of fiber end.

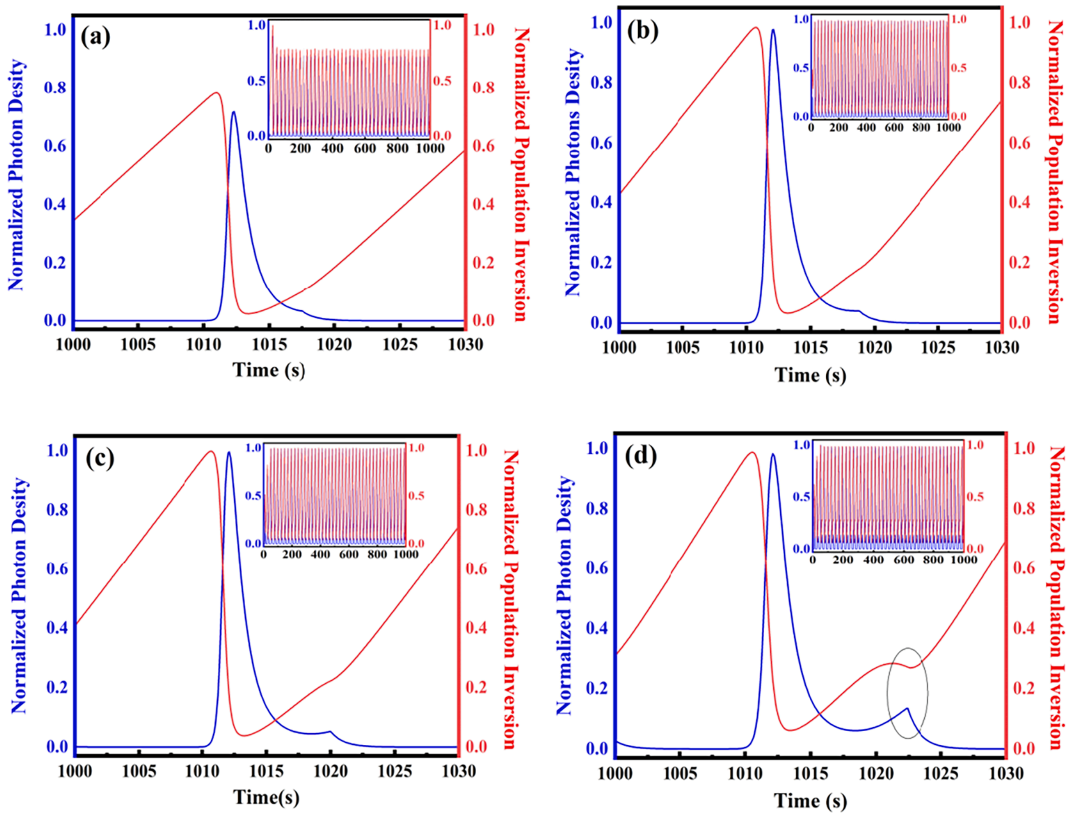

Fig. 5. The variation in the number of photons and carriers in the Q-switched fiber laser under the same repetition rate of 6 kHz and the pump power of 3 W with different duty (a) 40 %, (b) 45 %,(c) 50 %,(d) 60 %. The insert graph was the variation in the number of photons and carriers in Q-switched pulse train over the long time region.

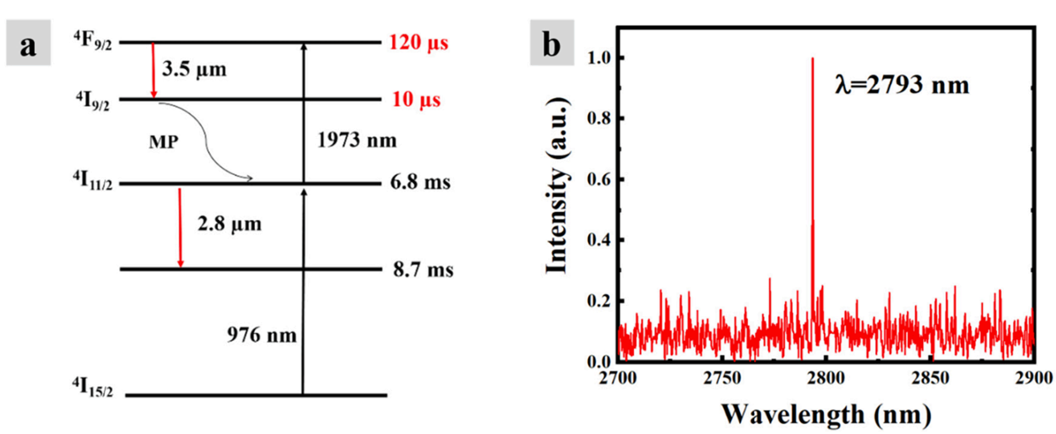

Fig. 6. (a) The energy structure of the DWP 3.5 μm fiber laser, (b) the output spectrum for 2.8 μm laser.

4. Conclusions

In conclusion, it has been demonstrated that the high pulse energy of actively Q-switched fiber laser operating at 3.5 μm was achieved by MS in DWP system. The maximum output pulse energy was 9.4 μJ at the repetition rate of 8.4 kHz. It was also found that the single pulse would be changed to multiple pulses under low repetition rate and high pump power. The maximum output power for the multiple pulses was 131 mW, but the pulse energy of the main pulse was lower than the energy of the single pulse. Therefor, it is significant to avoid the generation of multiple pulses for improving the pulse energy. The numerical model was also built to optimize the MS modulation design. It was found that the multiple pulses could be eliminated by decreasing the modulation duty cycle. Simultaneously, the 2.8 μm laser was also found in the system, which would also affect the improvement of 3.5 μm pulse energy. Therefore, anti-reflection coating and 8 degree angle of fiber end should be used to avoid 2.8 μm laser and the modulation rate and duty cycle of the MS also need to be optimized for high pulse energy of 3.5 μm fiber laser. The pulse energy is expected to further double by optimizing the design of MS and the optical components in the cavity. In addition, the controllable multiple pulses in deep mid-infrared region could see the beginning of the use of these lasers in pulse encoding, pulse train laser detection technology and other fields.

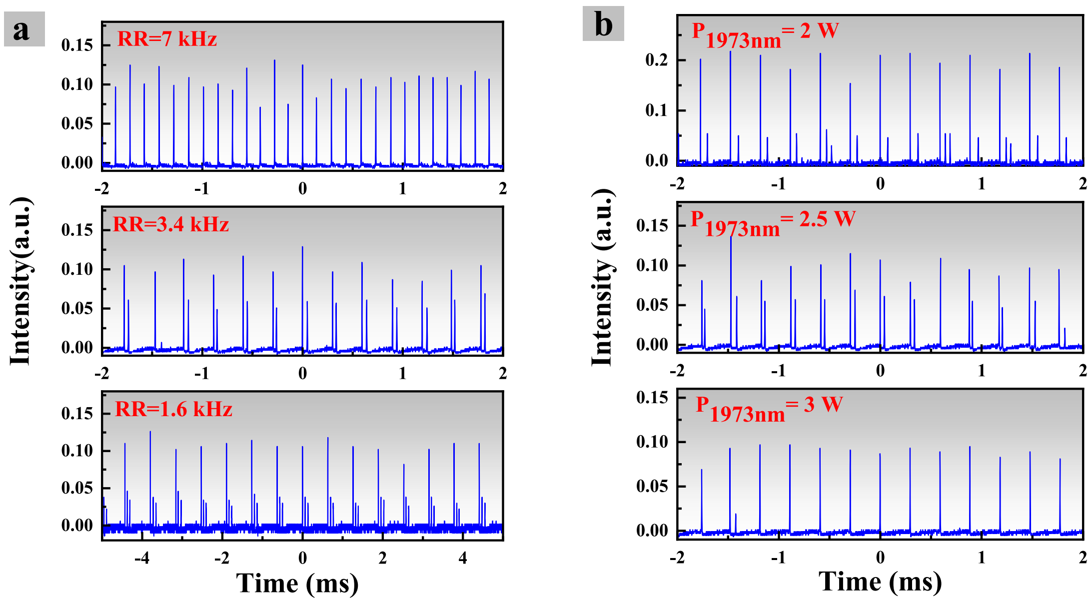

Fig. 7. The pulse train of actively Q-switched 2.8 μm fiber laser under (a) different repetition rate (RR), and (b) pump power of 1973 nm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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Appendix: Evolution of the multiple pulses

In order to better understand the formation process of multiple pulses in the actively Q-switched DWP 3.5 μm fiber laser and take the effective method to suppress it, the Q-switched pulses were simulated based on simple rate equations. Since the first pump mainly provides particles to the intermediate energy level, and the main influence of multi-pulse is the energy level of the second pumping action, we simplify the theoretical model to a three-level system with only 1973 nm pumping. The variation of the photon density Φ and population inversion N are described by the equation [20–21]:

$$\frac{d\Phi}{dt} = (\frac{\alpha l}{t_1}F(\omega t) - \frac{1}{T})\Phi \tag{1}$$

$$\frac{d\mathrm{N}}{dt} = -\frac{2\alpha l}{t_1}\Phi + W_p \tag{2}$$

Where the $F(\omega t)$ is periodic step function with the repetition rate of ω, $W_P = P_{abs}/(h\nu_{pump}V)$ is the contribution of pumping in the volume element, $T = t_1/\gamma$ is the life time of the photon, α is the coefficient of amplification. γ is the loss coefficient and it may be subdivided into $\gamma = \gamma_1 + \gamma_2$, where γ_1 represents the fraction of photons emitted as useful output of the device and γ_2 represents incidental losses.

Then we introduce the normalized variables,

$$n = \frac{N}{N_0}, \varphi = \frac{\Phi}{N_0}, \alpha = \alpha_0 N/N_0 \tag{3}$$

$$\frac{d\varphi}{dt} = (\frac{\alpha_0 l}{t_1}nF(\omega t) - \frac{1}{T})\varphi \tag{4}$$

$$\frac{dn}{dt} = -\frac{2\alpha_0 l}{t_1}n\varphi + W_p/(N_0) \tag{5}$$

Now we change the timescale to make T the unit of time, $t' = t/T$. In this manner we obtain:

$$\frac{d\varphi}{dt} = (\frac{\alpha_0 l}{\gamma}nF(\omega t' T) - \frac{1}{T})\varphi \tag{6}$$

$$\frac{dn}{dt} = -\frac{2\alpha_0 l}{\gamma} n\varphi + W_p T/(N_0) \quad (7)$$

We further introduce the constant n_p, which is the population inversion which corresponds to threshold for the given laser. The final form of the equation is:

$$\frac{d\varphi}{dt} = ((\frac{n}{n_p})F(\omega t' T) - 1)\varphi \quad (8)$$

$$\frac{dn}{dt} = -2(n/n_p)\varphi + TW_p/N_0 \quad (9)$$

According to the previously reported dual wavelength pumping numerical calculation model [22–24], the population density on the energy level $^4I_{11/2}$, which is also the ground state level for the simplified three-level system, has been calculated $N_0 = 3 \times 10^{24}(m^{-3})$ when the pump power of 976 nm is 2 W. When the pump power of 976 nm and 1973 nm are both 2 W, the laser is near the threshold. The population inversion which corresponds to threshold for the lasing energy level has been calculated $N_{th} = 6 \times 10^{23}(m^{-3})$, and $n_p = N_{th}/N_0 = 0.2$. The length and the diameter of the fiber core are 3.5 m and 16 μm, respectively. The variation in the number of photons and carries under different pump power and repetition rate were compared, as shown in Fig. 8. Under the repetition rate of 6 kHz, the multiple pulses are gradually generated with the pump power increased, as shown in the Fig. 8 (a) (b) (c). Under the power of 3 W, the multiple pulses are gradually disappear with the repetition rate increased, as shown in the Fig. 8(d) (e) (f).This is consistent with the rule of the Q-switched pulse variation in our experiment. However, there are some differences in the envelope of multiple pulses between the simulation and experiment. This is mainly due to some facts (such as spontaneous radiation, etc.) are not taken into account, and the simulation model would be optimized in the future.

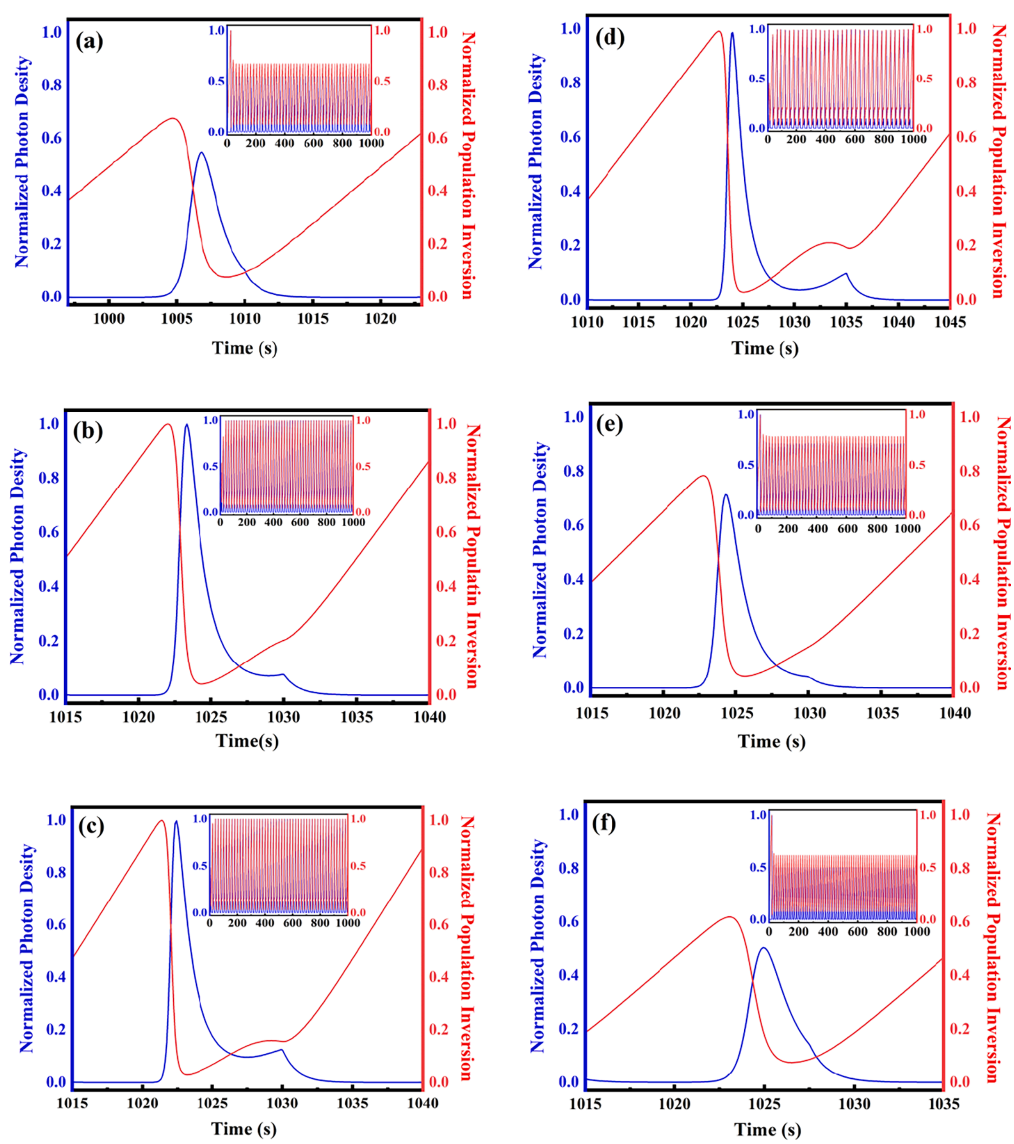

Fig. 8. The variation in the number of photons and carriers in the Q-switched fiber laser over the time. (a),(b),(c) are the pump power of 2 W, 4 W and 6 W under the same repetition rate of 6 kHz and 50 % duty, (d),(e),(f) are the repetition rate of 4 kHz, 6 kHz and 8 kHz under the same pump power of 3 W and 50 % duty.

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