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170 mW-level mode-locked Er-doped fiber laser oscillator based on nonlinear polarization rotation

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Abstract
In our work, by optimizing the length of the cavity and using high-power home-made pump source, based on the commonly-used nonlinear polarization rotation (NPR) technique, we designed a stable all-fiber high-power Er-doped mode-locked laser successfully. The maximum average output power was as high as 174 mW under the pump power of 2659 mW. To our knowledge, 174 mW was a new record average output power of NPR based all-fiber mode-locked Er-doped fiber laser, which was much higher than the results reported previously. Our work will provide a significant reference for future demonstrations of high-power mode-locked Er-doped fiber lasers and promote the applications of mode-locked Er-doped oscillators.

1 Introduction

Passively mode-locked Er-doped fiber lasers attract extensive attention and lead to a tremendous development due to their excellent properties of practicality, excellent beam quality, high average powers, long-term stability and so on [1–6]. Up to now, power scaling of mode-locked Er-doped fiber lasers have encountered several intractable and technical problems mostly arising from thermal effects, nonlinearity and high quantum defect [7]. Additionally, the power limitation of commercially-used 980 nm single-mode laser diodes also restricted the development of high power mode-locked Er-doped fiber lasers. In other words, the development of Er-doped mode-locked fiber lasers fell far behind Yb- and Tm-doped mode-locked fiber lasers.

In the past, two main constructions including oscillator and amplifier [7–11] were employed for achieving high-power Er-doped mode-locked fiber operations. In comparison with the single or multistage laser amplifier, laser oscillator exhibits the obvious advantages of low-cost, compact-structure, high-stability and so on, which has been investigated widely. Among which, based on the nonlinear polarization rotation (NPR) technique, in 2017, Li et al. achieved an all-fiber Er-doped mode-locked fiber laser with an output power of 88.5 mW, the pulse width and repetition rate were 317 ns and 630.2 kHz [12]. In addition, Luo et al. also reported a NPR based mode-locked Er-doped fiber laser, the maximum average output power of 80.5 mW at the pump power of 350 mW was obtained, the pulse width and pulse energy were 68.2 ns and 5.73 nJ, respectively [13]. Besides the commonly-used NPR technique, ultra-fast saturable absorbers (SAs) based passively mode-locked Er-doped fiber lasers also have been reported [14–28]. Based on Graphene as SA, Sun Young Choi et al. have demonstrated a 510 fs mode-locked Er-doped fiber laser with a maximum average output power of 80 mW, the corresponding pulse energy was 5.2 nJ [15]. Recently, a 83.2 mW mode-locked Er-doped fiber laser based on In_2Se_3 as SA was obtained by Yan et al. the pulse width was as short as 276 fs [19]. However, as is known, in comparison with NPR technique, SA will suffer from the heating effect, which will affect the long-time stability of the mode-locked operations. In addition, the

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low damage threshold and uncontrollable nonlinear absorption properties also limit its extensive industrial applications [24–28]. So far, to our knowledge, the maximum average output power of NPR or SA based Er-doped mode-locked fiber laser has not break through the 100 mW-level.

In this paper, based on NPR technique, by optimizing the length of the Er-doped fiber and the laser cavity, choosing the optimum ratio of the output coupler, and demonstrating high-power pump source, we designed an all-fiber structure stable high-power mode-locked Er-doped fiber laser successfully. The maximum output power was as high as 174 mW at the pump power of 2659 mW, in comparison with previous works, our experiment results exhibits obvious enhancement and 174 mW was an absolutely new record of an Er-doped mode-locked fiber lasers. The corresponding pulse energy and peak power were 7.7 nJ and 6.12 W, respectively.

2 Experimental setup

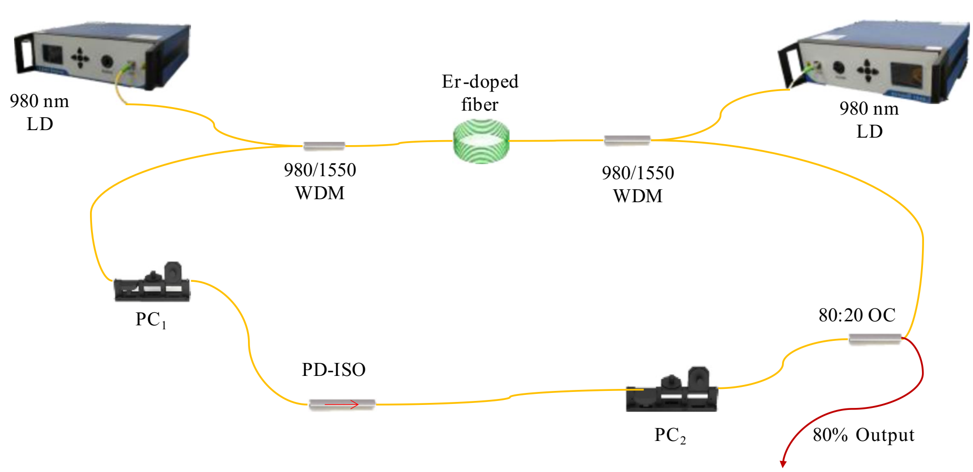
The experimental setup is schematically presented in Fig. 1. As is shown, a commonly-used ring laser cavity configuration is demonstrated. For obtaining high-power mode-locked pulse operation, Er-doped fiber (Liekki, Er-80) with a relative large core diameter of 8 μm is used as laser gain medium for reducing the effect of nonlinearity under high peak power. In our experiment, the length of the Er-doped fiber was optimized to be about 80 cm. Two home-made 976 nm single-mode fiber lasers with maximum pump power of 1.35 W were employed as pump source for delivering enough energy. The pump source was injected into the laser cavity via two 980/1550 nm wavelength division multiplexers (WDMs), respectively. Two polarization controllers (PCs) were used to adjust the polarization state for stabilizing the mode-locking operation. It should be noted that in order to study the performance of the high power mode-locked laser, a customized polarization-dependent isolator (PD-ISO) with an optical damage threshold of 500 mW was used for ensuring unidirectional operation within the laser cavity. In addition, a 20/80 output coupler (OC) is employed to extract 80% of the power from the cavity for analysis and another 20% is connected back to the 1550 nm end of WDM. An optical spectrum analyzer (OSA) (AQ6317B, Yokogawa), a radio frequency analyzer (R&S FPC1000), and a 500 MHz oscilloscope (Tektronix DPO 4054) together with a 3 GHz photodetector were utilized to simultaneously monitor the laser output.

3 Experimental results and discussions

In our experiment, firstly, we focused our attention in optimizing the length of the Er-doped fiber and the laser cavity. Finally, when the length of the Er-doped fiber and the laser cavity were about 80 cm and 9–10 m, stable mode-locked operation with a optimum average output power was obtained. In the experiment, by adjusting the state of the PCs, stable mode-locked operation can be achieved when the pump power arranged from 220 to 2659 mW. During the experiment, the degrees of the PC1and PC2 are adjusted about between 0° and 180° for maintaining the stable mode-locked state constantly, in addition, the adjustment of the PCs also caused the formations of other kinds of solitons, however, the states were unstable, which mainly due to the short cavity length designed for obtaining traditional soliton operation.

Output characteristics of the stable mode-locked operation under the maximum pump power are depicted in Fig. 2. The emission optical spectrum recorded by the OSA with a resolution of 0.05 nm is shown in Fig. 2a, the central wavelength and the 3 dB bandwidth are 1557.63 and 3.925 nm. As is shown, typical soliton-like spectrum shape with characteristic Kelly sideband peaks was obtained. The relationship between the average output powers and pump powers

Fig. 1 The schematic diagram of the mode-locked fiber laser



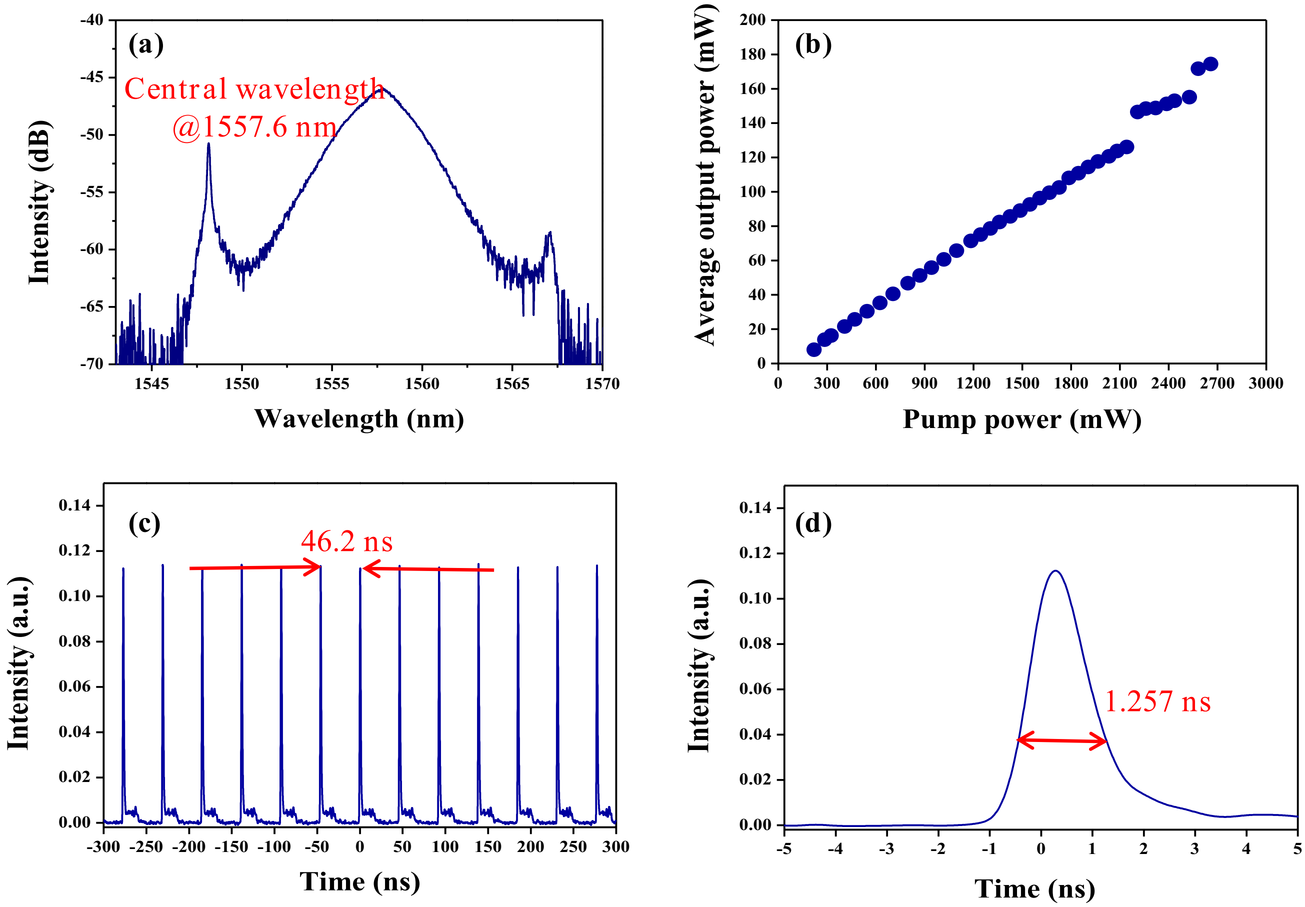


Fig. 2 **a** The emission spectrum of the fiber laser. **b** The relationships between the average output power and pump power. **c** Pulse train of the mode-locked operation. **d** A single pulse sharp with a pulse width of 1.257 ns

is shown in Fig. 2b. As is shown, the output power and the pump power have a linear correlation. Under the maximum pump power of 2659 mW, the maximum average output power is as high as 174 mW, corresponding to an optical conversion efficiency of 6.54%. Figure 2c shows the pulse train of the mode-locked operation, the pulse-to-pulse time is 46.2 ns, corresponding to a cavity-length matched fundamental repetition rate to be 21.65 MHz. The profile of the single pulse shape is presented in Fig. 2d, and the full width at half-maximum (FWHM) is about 1.257 ns, thus, the time-bandwidth product (TBP) is about 610, which is much higher than the theoretical limit value (0.315). Due to the lack of the necessary commercial autocorrelator, it is difficult for us to study the real characteristics of pulse width. However, form the informations of the optical spectra, the pulse width was calculated to be ps-level, in addition, the influence of the dispersion to the pulse width should not be neglected. Thus, in our future works, we will do our best to investigate the real characteristics of the pulse widths.

The stability of the laser is important to its practical application. Thus, the stability of the mode-locking operation was further recorded by the RF spectrum analyzer and shown in Fig. 3. As is shown in Fig. 3a, the peak of the fundamental frequency locates at 21.65 MHz with a signal-to-noise ratio of 53 dB, which proves that the mode-locked state is stable. In addition, wide-span RF spectrum also exhibits significance in testing the stability of mode-locked lasers. RF spectrum within a 500 MHz bandwidth is recorded and depicted in Fig. 3b. Obviously, the wide-band RF spectrum also exhibit high signal-to-noise ratios. Therefore, the RF characteristics indicate that mode-locked pulses with high stability are obtained in our work.

Figure 4a shows that the pulse width broadens with the increase of pump power and the amplitude of pulse keeps invariable. Typical pulses under different pump powers are shown in the Fig. 4b, under the pump powers of 325 mW, 942 mW, 1360 mW, 1906 mW, 2320 mW and 2659 mW, the recorded pulse width are 806.1 ps, 891.9 ps, 1.025 ns, 1.133 ns, 1.140 ns and 1.257 ns, respectively. The evolution of the corresponding optical spectra of pulses is shown in Fig. 4c, d. It is obvious that the 3 dB bandwidth increases with the increase of pump power.

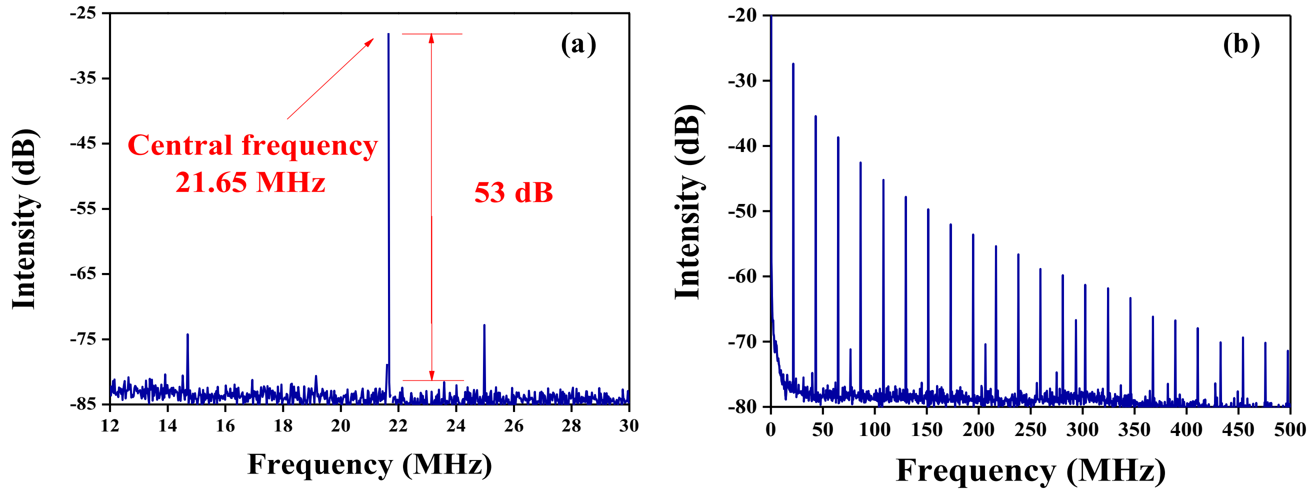


Fig. 3 **a** The radio-frequency optical spectrum at the fundamental frequency of 21.65 MHz. **b** The RF spectrum within a bandwidth of 500 MHz

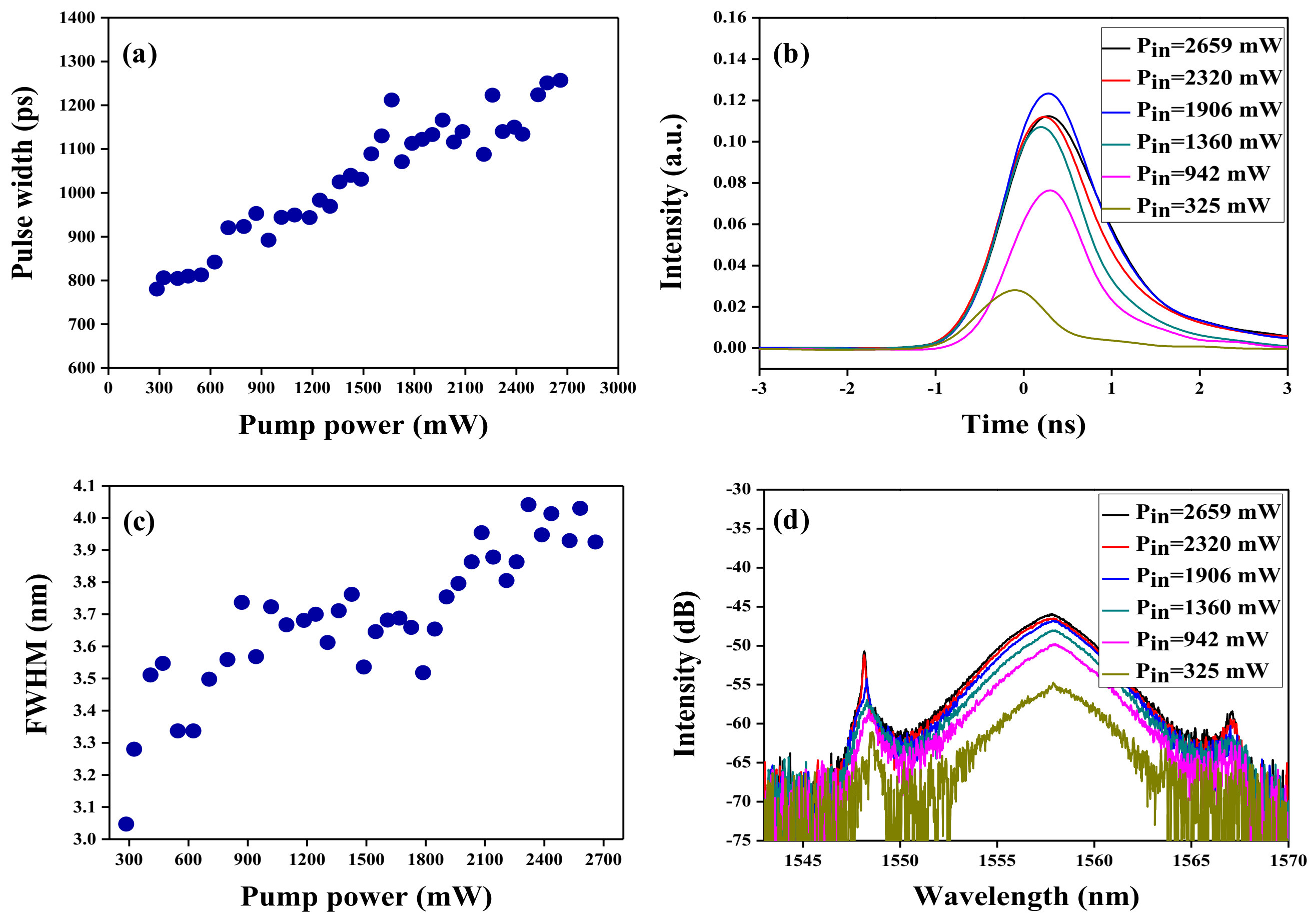


Fig. 4 **a** The relationships between the pulse width and pump power. **b** Few typical single pulse. **c** The relationships between the FWTH and pump power. **d** Few typical optical spectra

The corresponding pulse energies and peak powers under different pump power were shown in Fig. 5, as is shown, the pulse energy and peak power all increased with the growth of the pump power. As is shown, the pump power increased

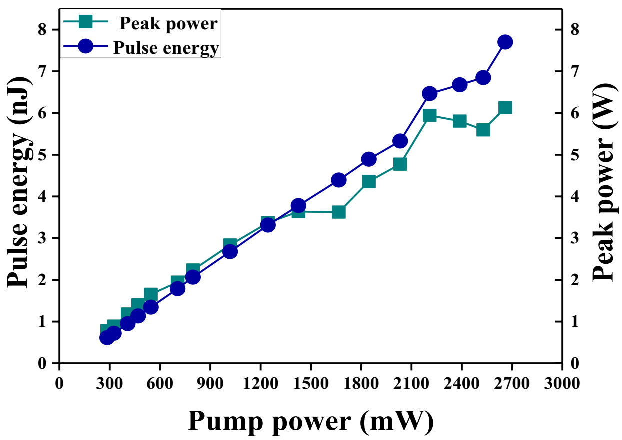


Fig. 5 Peak power and pulse energy as functions of pump power

from 285 to 2659 mW, and the pulse energy increased from 0.61 to 7.70 nJ, the reason is that the repetition rate is constant but the output power is increasing when the laser is in mode-locked state.

Relatively complete results of the passively mode-locked Er-doped fiber lasers based on different 2D materials as SAs and NPR technique are described in Tables 1 and 2, respectively. As is shown in Table 1, various 2D materials have been employed as SAs for demonstrating high-power passively mode-locked Er-doped fiber lasers [14–22], maximum average output powers of 80 and 83.2 mW were obtained based on graphene and In_2Se_3 as SAs [15, 19], however, mainly due to the low-intensity pump source and damage threshold of the SAs, the output powers of 2D materials-based mode-locked Er-doped fiber lasers are less than 100 mW level without obvious breakthrough. In addition, based on NPR technique, the maximum average output power is limited to be about 80 mW. However, due to the combination of high-power pump source and optimization of the cavity length and the radio of the OC, the maximum average output power of our work is as high as 174 mW, which is a tremendous enhancement in comparison with previous works. Meanwhile, the great breakthrough also proves the superiority of our experiment design. Besides the mentioned works, based on NPR and intra-cavity polarizing beam splitter structure, mode-locked all-fiber oscillator producing fs-level pulse width and watt-level average output power have been widely demonstrated by Ruehl et al. [34–36]. Among which, they reported an 64 fs self-similar Er-doped oscillator with a 675 mW output power and 6.2 nJ pulse energy. Their works exhibit high significance in proving that Er-doped mode-locked oscillators have the capacity of producing watt-level pulsed generations with fs-level pulse width. Thus, inspired by those works, demonstrating compact all-fiber structure Er-doped oscillators with high output power and ultra-short pulse width will attract much attention due to its wide applications and compact low-cost designed structure.

Table 1 Performance summary of mode-locked fiber lasers based on different SAs

SA	λ (nm)	τ (fs)	P_{ave} (mW)	f (MHz)	E_{pulse} (nJ)	References
Graphene	1568	844	30	16.34	1.84	[14]
Graphene	1555	510	80	15.36	5.21	[15]
Bi_2Te_3	1564.1	920	45.3	2.95 GHz	15.36 pJ	[16]
BP	1559.5	670	~53	8.77	6.04	[17]
WSe_2	1557.4	163.5	28.5	63.133	0.45	[18]
In_2Se_3	1565	276	83.2	40.9	2.03	[19]
WSe_2	1562	185	30	58.8	0.51	[20]
WS_2	1568.3	1.49 ps	62.5	0.487	128.3	[21]
Bi_2Te_3	1560	12.8 ns	32.9	1.7	22.4	[22]

Table 2 A comparison of passively mode-locked Er-doped lasers based on NPR

Cavity type	λ (nm)	τ (ns)	P_{ave} (mW)	f (MHz)	E_{pulse} (nJ)	References
Ring	1567	15–306	11.5	195 kHz	58.97	[29]
Ring	1570	55 fs	56.4	37.8	1.5	[30]
Ring	1563	30.5 ps	39.8	3.3	12	[31]
Ring	1563	155.4	22.16	278 kHz	79.5	[32]
Figure-8	1561	1.5	20.55	3.2	6.4	[33]
Ring	1557.63	1.257	**174**	21.65	7.70	Our

Bold value 174 mW is the maximum average output power obtained within all-fiber single-mode Er-doped mode-locked fiber lasers

λ wavelength, τ pulse width, P_{ave} average output power, f pulse repetition rate, E_{pulse} pulse energy

4 Conclusion

In conclusion, we have demonstrated a compact all-fiber high-power mode-locked fiber laser based on two home-made high-power 976 nm pump sources. The recorded maximum average output power was as high as 174 mW with a pulse energy of 7.7 nJ. In comparison with previous works, our experiment results show significant enhancement and have wide potential applications due to its obvious advantages of high output power, large pulse energy compact construction and so on. Especially, our work will provide a meaning reference for future demonstrations of high-power large-energy mode-locked Er-doped fiber laser oscillators.

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