Optics and Laser Technology 129 (2020) 106285

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Pulse control in self-mode-locked 2.8 μm Er-doped fluoride fiber lasers

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HIGHLIGHTS

- The SML 2.8 μm fiber laser has been demonstrated in this work.
- The dark pulse has been obtained in the SML 2.8 μm fiber laser.
- The effect of feedback distance and pump power on the laser has been investigated.
- This laser is susceptible to the interaction between internal and external cavity.

ARTICLE INFO

Keywords:
Self-mode-locked fiber laser
Er-doped fluoride fiber
Dark pulse
Cavity interaction

ABSTRACT

In this work, it had been demonstrated that the Er doped fluoride fiber laser emitting at 2.8 μm could accomplish the dark pulse based on self-mode-locked (SML). And the different distances of external feedback were also investigated in experiment. It was found that signal-noise ratio (SNR) of fundamental cavity repetition rate was decreased with increasing the distance of feedback. It was not only caused by increasing the length of cavity, but also influenced by the interaction between inter-cavity and external cavity. The fundamental cavity repetition rate of SML 2.8 μm pulsed laser could be controlled by adjusting distance of external feedback.

1. Introduction

Recently, pulsed fiber lasers emitting at 2.8 μm waveband have attracted much interest owing to their inherent advantages of fiber lasers and important applications in laser medicine, spectroscopy, infrared counter-measures and mid-IR laser pumping, etc [1–6]. Q-switching and mode locking are two main approaches to achieve the pulsed 2.8 μm fiber laser, and the signal-noise ratio (SNR) of 43.5 dB and 60 dB have been demonstrated by using the multilayer graphene [7] and black phosphorus [8] as saturable absorber, respectively. And the using of acousto-optic modulator (AOM) [9] also achieved the pulsed 2.8 μm fiber laser. However, the simplicity, compactness and reliability of laser system are challenging for these methods due to the using of modulation elements in the cavity [10]. Meanwhile, the modulation elements would also introduce unnecessary losses in the cavity, which would seriously affect the stability and efficiency of the system. As for the mid-infrared laser, the modulation elements such as semiconductor saturable absorber mirror (SESAM) and AOM, are expensive and also not mature for the preparation.

Apart from active and passive modulation, self-mode-locking (SML) is an important and effective method to generate high power pulsed laser [11–16]. The SML laser doesn't need any additional active or passive modulation elements in the cavity, so the cavity losses are significantly decreased. The average output power and the optical conversion efficiency could be substantially enhanced [17]. Recently, Zhang et al reported the 1943 nm pulsed Tm:YAP laser based on SML with SNR of 60 dB, which reveals a pure mode locking with few continuous wave (CW) components. The phenomenon of pulse bundles was also found in SML Tm-doped fiber ring laser emitting at 1962 nm [18]. However, the SML lasers at longer wavelength were seldom reported. And the pulsed Er doped fluoride fiber laser emitting at 2.8 μm has only been realized by using active and passive modulation up to now.

In theory, the high concentrations of Er ion (6–7 mol.%) and longer natural lifetime of the upper laser level (~7 ms) in Er doped fluoride fiber makes it a promising candidate for SML operation [19–21]. However, because the effect of SML is easily affected by different cavity length and pump power, the SML is often overlooked and sometimes even considered to be noise in the system. So it is necessary to study the mechanism of SML in Er doped 2.8 μm fluoride fiber lasers.

In this paper, the SML of 2.8 μm Er-doped fluoride fiber laser was

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https://doi.org/10.1016/j.optlastec.2020.106285
Received 21 November 2019; Received in revised form 6 March 2020; Accepted 12 April 2020
Available online 20 April 2020

demonstrated without any modulation elements. And the SML with different distances of feedback were investigated. The interaction between inter-cavity and external cavity and its effect on the characteristics of SML was analyzed.

2. Experiment

The experimental setup for SML of Er-doped fluoride fiber laser was schematically depicted in Fig. 1. As shown in Fig. 1, a fiber coupled 975 nm diode laser was used as pump source and coupled into Er-doped fluoride fiber by an aspheric collimation lens and a CaF_2 plano-convex lens. A highly reflecting mirror (> 96% reflection at the wavelength of 2.8 μm) coated with gold was put at the other end of fluoride fiber as end mirror with a variable distance of L and a CaF_2 lens was used for collimating. The gold coated mirror was used as an end mirror of the resonator to provide high reflection at laser wavelength. A specially designed dichroic mirror was used for laser output with a 45° angle formed with the pump laser beam. The dichroic mirror had a transmission of > 99% at the pump wavelength and a reflection > 99% at 2.8 μm. The active fiber was a heavily Er-doped (7 mol.%) fluoride double-clad fiber with a length of 2.5 m. Its core diameter and number aperture (NA) were 15.6 μm and 0.12, respectively. The truncated circular (double-D-shaped) cladding of the fluoride fiber had short/long diameters of 240/260 μm and NA of 0.4. Both end facets of fiber were perpendicularly cleaved and the natured reflectivity was about 4% due to the Fresnel reflection. The pulse train and RF spectrum were captured by a HgCdTe detector (PVI-4TE-5, VIGO System) and showed on a 1-GHz bandwidth digital oscilloscope (MOD 3104, Tektronix).

3. Results and discussion

3.1. Dark pulse generation in 2.8 μm SML fiber laser

Fig. 2 showed the pulse train of SML fiber laser at different pump power. It was self-starting without any operation above the threshold of laser. The mechanism of SML for high concentrated Er-doped fiber had been demonstrated that ion pairs and clusters, which formed by high ion concentration, acted as saturable absorbers to achieve mode locking [19]. It was observed that the temporal traces of SML fiber laser were similar to dark pulse. It had been proven that the dark pulse was formed by one of the polarization modes in laser cavity [22]. When change the state of polarization, the bright pulse could be switched to dark pulse. As for the D-shaped double cladding fluoride fiber, the asymmetry of the fiber made the refractive index different in two orthogonal directions (n_x, n_y). The linear cavity phase delay could be calculated by the formula $\Delta\phi = 2\pi l(n_y - n_x)/\lambda$ and the state of polarization would be changed at different phase delay [23]. The polarization corresponding to dark pulse may be first emitted due to the asymmetry of the fiber. Although the shape of pulse varied with pump power. However, the time interval between neighboring pulses was 25 ns, which corresponded to the pulse repetition rate of 40 MHz. According to F. Fontana's theory [20], the laser signal modulations at a period corresponding to the cavity round-trip time were usually referred to SML at any pulse width. The cavity round-trip time can be calculated by formula $t = 2\ nl/c$, where l was the cavity length, n was the effective refractive index. The length of laser cavity selected in experiment was about 2.5 m. So the mode locking repetition rate should be near 40 MHz. The theoretical values were consistent with the experimental results.

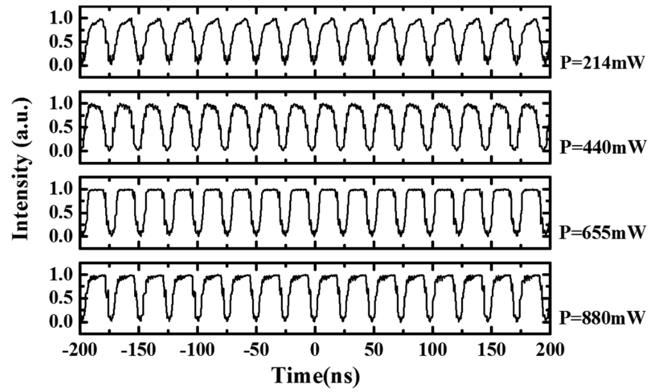

Fig. 2. The pulse traces of SML fiber laser at the different pump powers.

In order to better observe the stability of SML fiber laser, the long time span of pulse train was measured and shown in Fig. 3(a). The tiny variation of the pulse peak indicated the stable operation of SML fiber laser. In addition to the time domain, the frequency domain was also eventful. The RF spectrum was also shown in Fig. 3(c) and the fundamental cavity repetition rate was 40.7 MHz.

The spectrum of SML fiber laser at different pump power was shown in Fig. 4. It was measured by a Fourier spectrometer analyzer (Thorlab OSA207C). As the pump power increased, the emitting wavelength shifted to longer wavelength. However, side modes with low intensity may appear occasionally, which might be due to the incidental instability of the pulse operation [22].

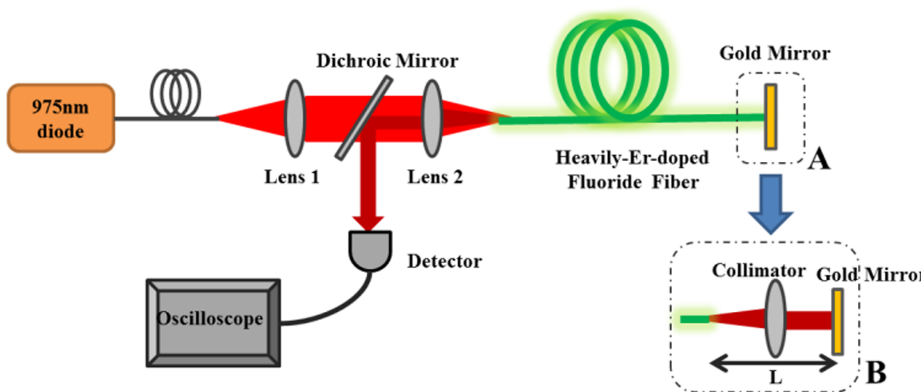

Fig. 1. Experimental setup of SML Er-doped fluoride fiber laser.

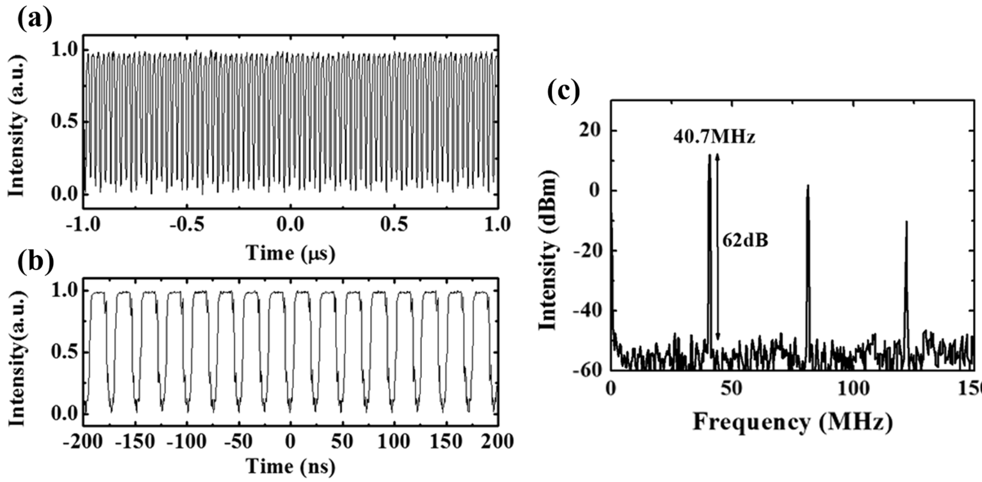

Fig. 3. (a) long time span (2 μs) and (b) short time span (400 ns) of pulse trains. (c) RF spectrum of SML fiber laser at the pump power of 655 mW.

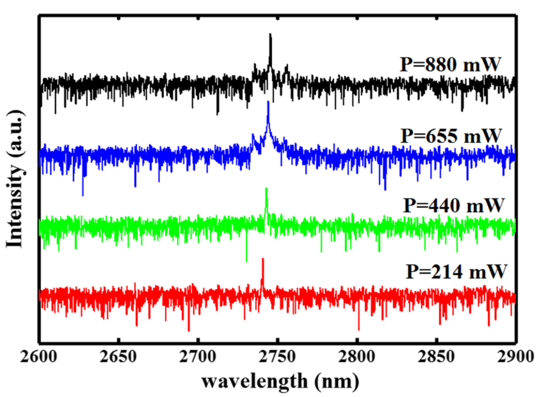

Fig. 4. The spectrums of SML fiber laser at the different pump power.

3.2. External cavity feedback

The characteristics of SML fiber laser were directly depended on the cavity round-trip time, so the performance can be modulated by changing the cavity length. Fig. 5 showed the RF spectrum of SML fiber laser with different feedback distances at the pump power of 880 mW. It was found that the repetition rate was decreased from 40.7 MHz to 39.6 MHz as the feedback distance increasing from 0 to 15 cm. In order to confirm the changing of frequency was due to feedback distance and not the instability of frequency, it was measured multiple times at different feedback distances and the repeat rate was quite stable. And the SNR of the fundamental cavity repetition rate was reduced from 61 dB to 23.1 dB as the feedback distance increasing from 0 to 15 cm. The pulse train of SML fiber laser at different feedback distances was also recorded and shown in Fig. 6. The pulse width τ was measured based on full width at half maximum. However, it didn't show obvious dependent on the feedback distance and the small changes of pulse width may be caused by fluctuations.

In addition to the feedback distance, the pump power would also affect the characteristics of SML fiber laser. Fig. 7 plotted the measured SNR of repetition rate with different feedback distances as a function of pump power. The SNR curves showed a trend of increase with the power and the maximum SNR of repetition rate could reach up to 62 dB with 0 cm feedback distance at pump power of 655 mW. It was also found that the SNR of repetition rate decreased with the increase of feedback distance in all range of power. However, it was decreased more obviously for the feedback distance of 15 cm compared with other distances. So it was considered this was not only the effects of feedback distance and pump power, but the influence of inter-cavity.

3.3. The effect of inter-cavity

In theory, there was an internal cavity in the SML fiber laser system. Because the perpendicularly cleaved end of active fiber could also provide nearly 4% reflections, which regarded as inter-cavity. In order to clearly understand the relationship between the inter-cavity and external cavity, the simple model of cavity was described in Fig. 8. When feedback distance was zero, only one cavity existed with 100% reflections. As the feedback distance increased, there were two cavities with the reflections of 4% and 100% respectively.

In order to investigate the effect of inter-cavity on SML fiber laser, the end face of fiber used as feedback (4% reflections) was tested in experiment. The curve lines of output power were plotted in three cases, 100% reflections under 0 cm feedback distance, 100% reflections under 15 cm feedback distance (external cavity) and 4% reflections under 0 cm feedback distance (inter-cavity), as shown in Fig. 9. When pump power reached 214 mW, the external cavity fiber lasers started emitting. But for inter-cavity, the pump power needed to be 440 mW. The SNR of fundamental cavity repetition rate for these three cases were also compared in Fig. 10. The phenomenon of SML for inter-cavity was started at the pump power of 440 mW and the repetition rate locked at 40.7 MHz was the same as 100% reflections under 0 cm feedback distance. The SNR of repetition rate for inter-cavity was lower than external cavity and presenting a rising trend with the pump power increased. However, there was only one repetition rate corresponding to the length of cavity for external cavity. That mean the SML of inter-cavity was suppressed. So there was an interaction between the inter-cavity and external cavity, which would suppress the SML of inter-cavity and caused the SNR of external cavity repetition rate decrease.

The interaction of inter-cavity and external cavity was affected by the feedback distance. Because the loss of external cavity was enhanced with feedback distance increased, especially for 2.8 μm, which would be strongly absorbed by water vapor. And the loss of external cavity would affect the intensity of feedback. When the feedback distance L was small, the external cavity loss was less. And the external cavity feedback of the SML fiber laser was obviously stronger than that of inter-cavity. So the external cavity frequency of SML fiber laser was not disturbed. When L was gradually increased, the external cavity loss was

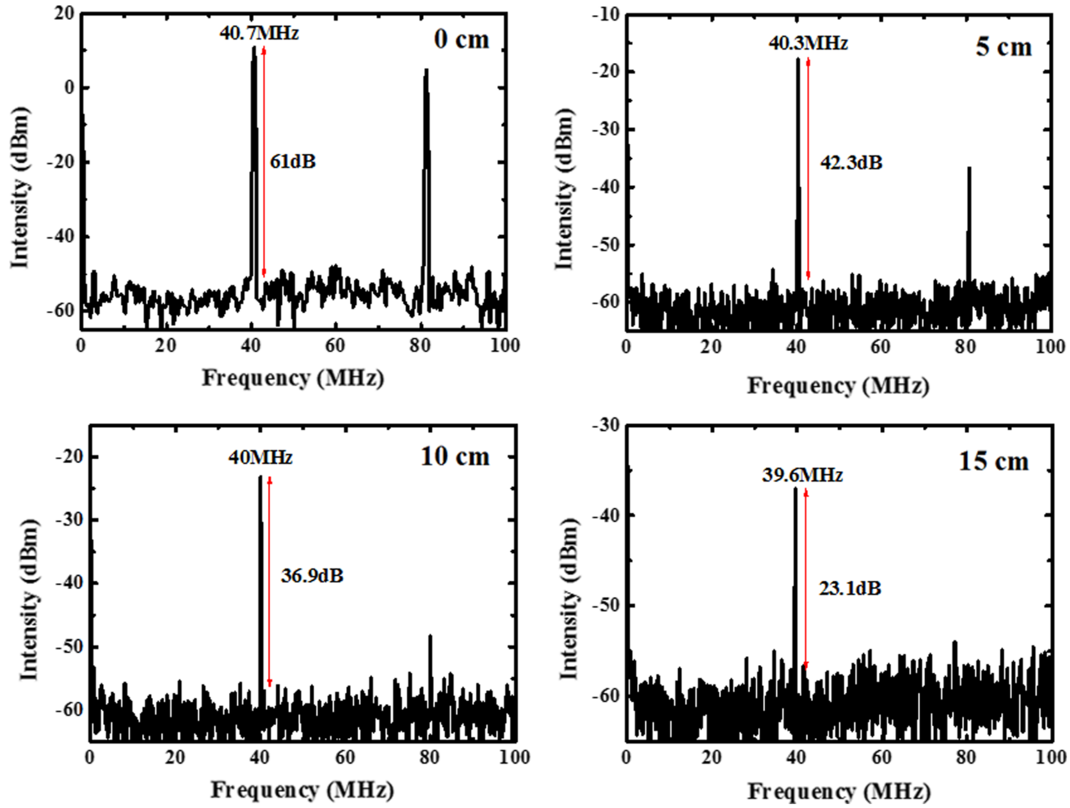

Fig. 5. Measured RF spectrum of SML fiber laser with different feedback distances at the pump powers of 880 mW.

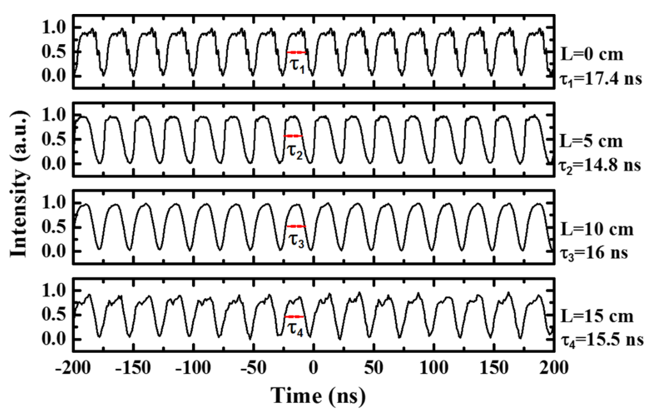

Fig. 6. Measured pulse traces of SML fiber laser with different feedback distances at the pump powers of 880 mW.

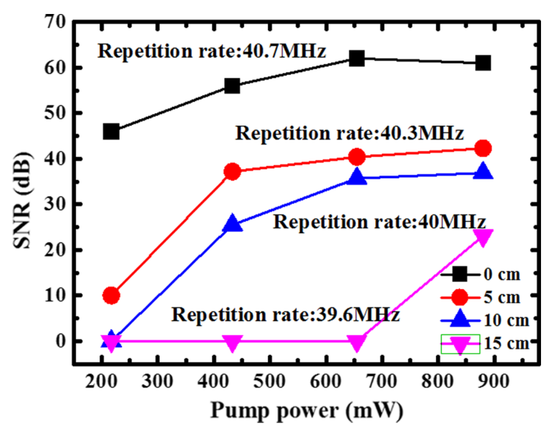

Fig. 7. The SNR curves of different feedback distances as a function of pump powers.

also gradually increased. In the case of low power, the SML fiber laser based on external cavity was weakened, the interaction of the inter-cavity and external cavity occurred, which suppress the effect of SML. As the pump power continued to increase, the phenomenon of SML based on the external cavity was gradually enhanced. So the external fundamental cavity repetition rate began to appear and the SNR of the repletion rate was gradually increased.

4. Conclusion

In summary, the SML fiber laser based on Er-doped fluoride fiber emitting at 2.8 μm was achieved. The max SNR of fundamental cavity repetition rate could reach up to 62 dB. As changing the feedback distance, not only the cavity length but also the interaction of inter-

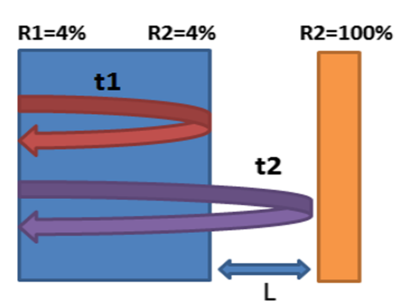

Fig. 8. Schematic diagram of inter-cavity and external cavity. t1: the round-trip time of inter-cavity; t2: the round-trip time of external cavity; L: feedback distance.

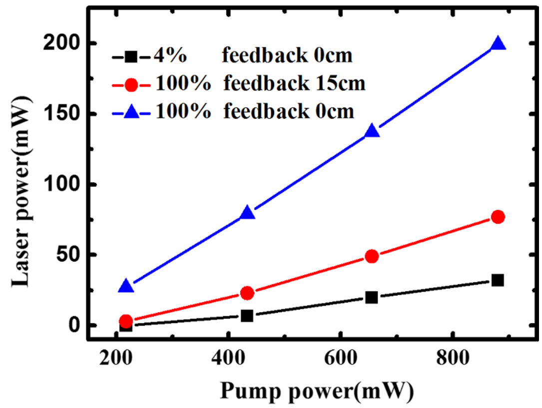

Fig. 9. The curve lines of output laser power at the circumstances of 100% reflections under 0 cm feedback distance, 100% reflections under 15 cm feedback distance and 4% reflections under 0 cm feedback distance.

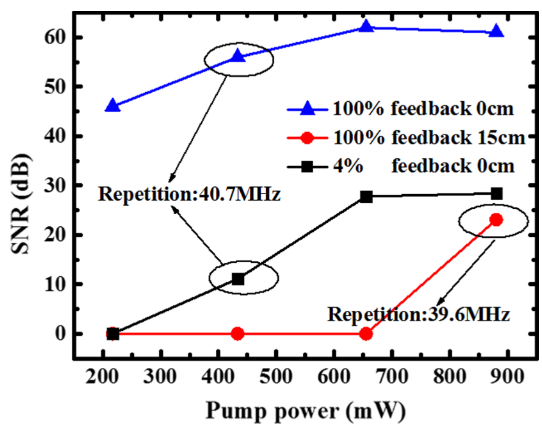

Fig. 10. The SNR of fundamental cavity repetition rate at the circumstances of 100% reflections under 0 cm feedback distance, 100% reflections under 15 cm feedback distance and 4% reflections under 0 cm feedback distance.

cavity and external cavity would affect the SML fiber laser. Increasing the length of the cavity would suppress the phenomenon of SML and the interaction of Internal and external cavity would also influence the SNR of fundamental cavity repetition rate. Our result will be useful to better understand the influence of cavity to SML Er-doped fluoride fiber laser emitting at 2.8 μm.

CRediT authorship contribution statement

Xin Zhang: Data curation, Writing - original draft. **Shili Shu:** Conceptualization, Methodology, Supervision. **Kaidi Cai:** Investigation, Software. **Yanjing Wang:** Investigation, Software. **Cunzhu Tong:** Writing - review & editing, Funding acquisition.

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.

Acknowledgment

This work is supported by National Natural Science Foundation of China (NSF) (61790584, 61774153)

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