Q-switched Erbium-doped fiber laser with solid state saturable absorber fiber

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A simple Q-switched Erbium-doped fiber laser (EDFL) operating at 1556 nm is demonstrated based on a solid state saturable absorber fiber. The laser employs a newly developed Erbium-doped fiber with a high Erbium concentration as a gain medium and a 1 m long commercial Thulium-doped fiber as a Q-switcher. The EDFL generates Q-switching pulse train within 980 nm pump power tuning range from 77.2 to 97.5 mW. The repetition rate of the Q-switched pulses monotonically grows from 7.7 to 15.4 kHz while the pulse duration reduces from 21.4 to 14.1 µs as the pump power increases from 77.2 to 97.5 mW. The maximum pulse energy of 11.7 nJ is obtained at pump power of 97.5 mW.

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1. Introduction

Q-switched fiber lasers have great potential applications in many fields including spectroscopy, biomedical diagnoses, fiber communication and others [1,2]. Q-switching in all-fiber lasers has been achieved by using active techniques such as acousto-optics modulators [3], piezoelectric actuators [4], or magnetostrictive transducers [5] to modulate the Q-factor of the cavity. Q-switched fiber lasers can also be realized using passive approaches where saturable absorber (SA) is a key component. Several types of materials and construction techniques have been proposed to develop SA for passive Q-switching such as semiconductor SA mirror (SESAM), graphene and carbon nanotubes (CNTs) [6-8]. SESAM is the type that is widely used. However, there are still some disadvantages associated with SESAM, such as limited operation bandwidth, low damage threshold and complex fabrication/packaging. As a promising SAs candidate, graphene and CNTs have advantages of easy fabrication, wideband operation and low cost. However, both SAs also have a low damage threshold and thus limits the attainable pulse energy.

Modulation of the Q-factor can also be realized using solid-state SA fibers [9-11]. The advantages of the solid-state SA fibers are their ability to hold enormous gain excited in the gain fiber from lasing and their high damage threshold for high-power Q-switched pulses. Only a few SA fibers have been demonstrated in the literature, and most are for Ytterbium-doped fiber lasers [9-10]. The energy transition $^3H_6$ - $^3F_4$ of Tm^{3+} has a very broad emission wavelength range, from 1.6 to 2.1 µm, and an absorption band from 1.5 to 1.9 µm. It is reported that the absorption cross section of Tm^{3+} doped fibers (TDFs) are larger than the emission cross sections of Erbium-doped fiber (EDF) at 1.6 µm region, suggesting a possible realization of a passively Q-switched EDFL using a TDF as a passive SA. In this paper, a Q-switched fiber laser operating at 1556 nm is demonstrated using a solid state SA fiber based on ring laser cavity. In this work, a 2 m long newly developed EDF and 1 m long a commercial TDF are used as a gain medium and a Q-switcher, respectively.

2. Experimental arrangement

Fig. 1 shows the schematic diagram of a passively Q-switched all-fiber EDFL using a solid state SA fiber. The laser cavity consists of a 2 m long EDF as the gain medium, a wavelength division multiplexer (WDM), a polarisation controller (PC), a 10 dB coupler and 1 m long TDF as a SA and an optical isolator. The EDF used is obtained from a fiber preform, which is fabricated in a ternary glass host, zirconia–yttria–aluminum codoped silica fiber using a modified chemical vapor deposition (MCVD). Doping of Er_2O_3 into zirconia–yttria–aluminosilicate-based glass is done through a solution doping process. Small amounts of Y_2O_3 and P_2O_5 were added, where both Y_2O_3 and P_2O_5 serve as a nucleating agent to increase the phase separation with generation of Er_2O_3-doped microcrystallites into the core matrix of optical fiber preform.With a combination of both Zr and Al, we could achieve the high erbium doping concentration in the glass host without any phase separations of rare earths. Only a minor amount of Y_2O_3 is used in the preform to prevent a cracking problem. A fiber of 126.83 µm in cladding diameter is drawn from the fabricated preform at a temperature of around 2000 °C using the conventional fiber drawing technique. The fabricated EDF has an NA of 0.17, a core diameter of 10.04 µm, and the peak absorption of 80 dB/m at 980 nm.

The EDF is pumped by a commercial 980 nm laser diode via a 980/1550 WDM. The TDF was a 1.0 meter long with an initial absorption loss of 6 dB at 1570 nm, numerical aperture of 0.16 and core diameter of 2.9 µm. An optical isolator is used to avoid the backward reflection and ensure unidirectional operation. The PC is used to control the polarization of the oscillating light and optimize the Q-switching and laser operations. The laser light is extracted from the cavity by a 10 dB fiber coupler which retains 90 % of the light in the cavity for further oscillation. An optical spectrum analyzer (OSA) with wavelength resolution of 0.05 nm is used to capture the output laser spectrum while a 350 MHz oscilloscope in conjunction with 1.2 GHz bandwidth photo-detector is used to detect the pulse train. The total length of the cavity is around 6 m.

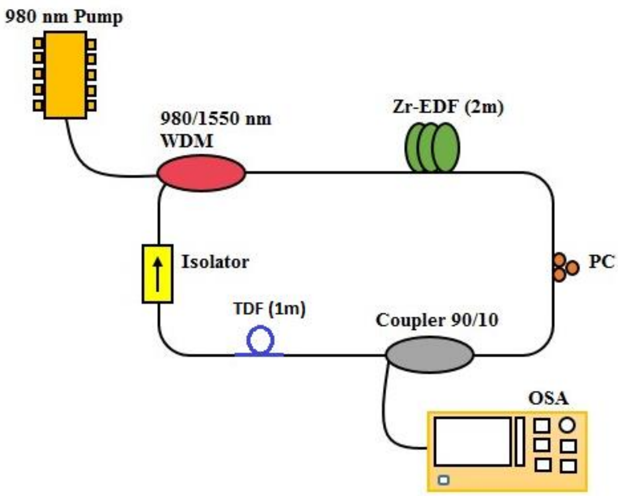

Fig. 1. Schematic configuration of the proposed Q-switched EDFL.

3. Results and discussion

Fig. 2 shows the output spectra of the EDFL with and without the TDF SA when the 980 nm pump is fixed at 92.4 mW. Without Tm-doped fiber absorber we observed the stable CW operation of EDFL at 1571.2 nm. After installation of 1 m long TDF inside the cavity, a Q-switching pulse train is generated as the pump power is increased above 77.2 mW. The operating wavelength of the Q-switched laser shifts to a shorter wavelength (1556.0 nm) due to the cavity loss which increases with the incorporation of TDF. The compensate for the loss, the laser operates at a shorter wavelength which has a higher gain. Fig. 3 shows the typical observed pulse train at pump power of 92.4 mW. As shown in the figure, the peak to peak pulse separation is measured to be around 80.9 µs, which translated to repetition rate of 12.36 kHz. The pulse width was 15.3 µs from the oscilloscope. The Q-switching pulse generation is due to gain-switching action provided by the Thulium ions interaction with the oscillating Erbium laser.

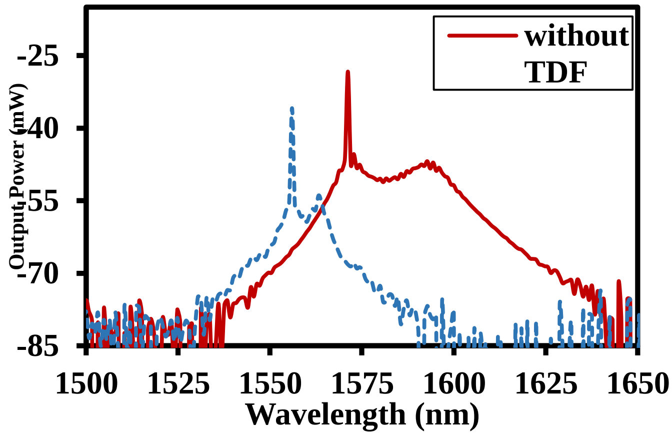

Fig. 2. Output spectra from the EDFL with and without the solid state TDF SA.

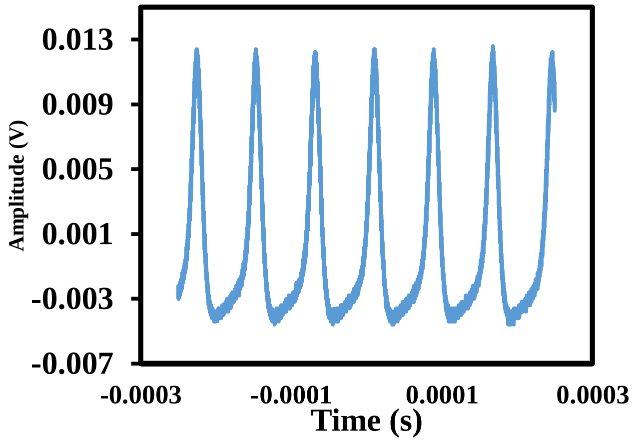

Fig. 3. Typical pulse train of the Q-switched EDFL at pump power of 92.4 mW.

Fig. 4 shows the pulse repetition rate and pulse width as a function of the pump power. As the pump power increases from 77.2 to 97.5 mW, the repetition rate of the Q-switched pulses monotonically grows from 7.7 to 15.4 kHz. At the same time, the pulse duration reduces from 21.4 to 14.1 µs as expected. We also measured the average output power and calculated the corresponding single-pulse energy. Fig. 5 shows the output power and pulse energy against the 980 nm pump power. As shown in Fig. 5, the average output power almost linearly increases with the input pump power from 77.2 to 97.5 mW. On the other hand, the pulse energy shows the similar trend as the pump power is increased within 77.2 to 92.4 mW. As the pump power further increases to 97.5 mW, pulse energy becomes saturated, which is most probably due to the timing jitter noise in the laser cavity. It is worth noting that the Q-switching pulse train becomes unstable and disappears as the pump power is increased above 97.5 mW. This is due to the TDF SA could not fully recover in time after a pulse and less gain population was excited before the next pulsing. It indicates that the relaxation lifetime ($^3F_4$) of the thulium fiber should be near and less than 0.065 µs that was the inversion of the largest repetition rate before the disappearing. At the pump power of 97.5 W, the maximum output power of 0.18 mW is obtained which corresponds to the maximum pulse energy of 11.7 nJ.

It is expected that the pulse duration could be further narrowed by optimizing the parameters, including shortening the cavity length and optimizing the solid-state TDF Q-switcher. For future work, the optimisations of gain medium, cavity design and SA will be carried out to improve the pulse energy. Since it has a higher thermal stability, the attainable pulse energy is expected to be higher than that of the conventional SWCNTs and graphene based SAs. The saturable absorber is also robust and has a high damage threshold.

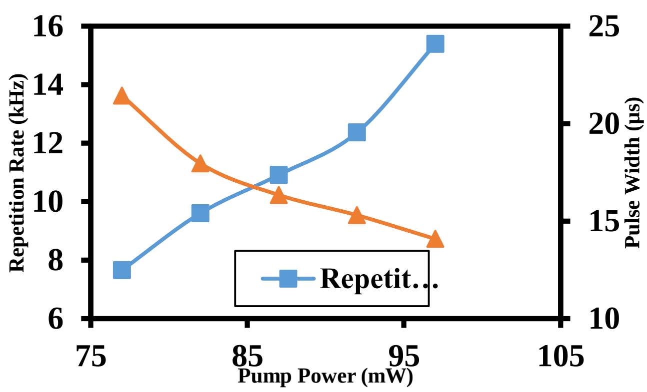

Fig. 4. Repetition rate and pulse width of the proposed Q-switched EDFL against the pump power.

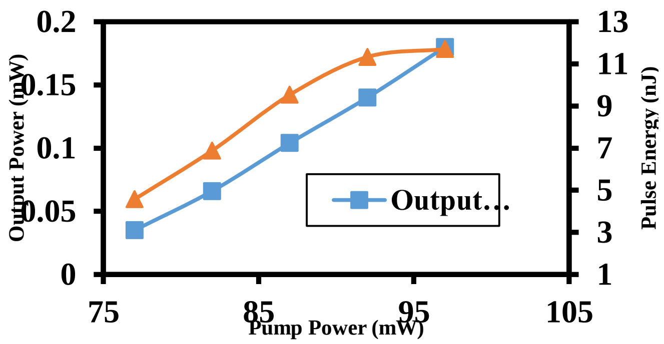

Fig. 5. Output power and pulse energy of the proposed Q-switched EDFL against the pump power.

4. Conclusion

A simple Q-switched EDFL is proposed and demonstrated based on 1 m long TDF SA. The laser employs a newly developed EDF with a high Erbium concentration as a gain medium to operate at 1556 nm. The EDFL generates Q-switching pulse at a threshold pump power of 77.2 mW. By varying the pump power from threshold power to 97.5 mW, pulse repetition rates can be increased from 7.7 to 15.4 kHz, whereas the pulse width reduces from 21.4 to 14.1 µs. The Q-switching operation is maintained before disappears as the pump power is above 97.5 mW. This is due to the TDF SA could not fully recover in time after a pulse and less gain population was excited before the next pulsing. The maximum pulse energy of 11.7 nJ is obtained at pump power of 97.5 mW.

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