Passively Q-switched Erbium doped fiber laser by incorporating a segment of Thulium doped fiber saturable absorber

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Abstract. We propose a segment of 1 cm long Thulium-doped fiber (TDF) as a passive saturable absorber (SA) in generating a stable Q-switched Erbium-doped fiber laser (EDFL). The obtained pulsed laser has a central wavelength of 1560 nm and emerges stably within a repetition rate range of 54.1-106.7 kHz over a pump power range of 35-136 mW. At the maximum pump power of 136 mW, the EDFL produces a maximum output power of 14.3 mW, a maximum pulse energy of 134.7 nJ and a maximum peak power of 41 mW as well as the narrowest pulse width of 3.28 µs. The fundamental frequency of the pulsed laser has a signal to noise ratio (SNR) of approximately 63 dB. The proposed laser would have a good prospect for material processing and medicine.

Keywords: 1.5 µm fiber laser, Q-switched laser, fiber saturable absorber

1. Introduction
Q-switched fiber lasers have attracted a lot of attention recently, as they provide simple configuration, compactness, high flexibility as well as excellent beam quality, which favoured various applications including material processing, medicine and remote sensing. The Q-switched laser could be realized through an active or a passive technique. However, the passive technique is more preferred over the active Q-switching, as it offers various advantages, including robust in an environment, simpler in preparation, smaller in size as well as not needing complicated electronic circuits, which makes the passive method more cost-efficient. Various saturable absorbers (SAs) have been demonstrated so far, including semiconductor saturable absorption mirrors (SESAMs)[1], carbon nanotubes (CNTs) [2, 3], graphene[4, 5], Transition metal dichalcogenides (TMDs) [6, 7], Topological insulators (TIs) [8, 9], Antimony film [10-12] as well as element oxides[13, 14]. Originally, SESAMs were the favourite choice for generating pulsed lasers for some years, however, due to bulky in geometry, relatively cost-expensive and complex in handling, the interests have been diverted into other types of passive SAs. While, graphene, CNTs and other SAs (mentioned earlier) provide simplicity and cost-effective in fabrication and preparation, they have low thermal damage threshold, which limits their ability in obtaining high pulse energy. Several reports demonstrated that the Q-factor modulation could also be realized by utilizing a segment of doped fiber, where these fiber SAs hold enormous gain excited in the gain fiber lasing, despite offering high damage...
threshold for high power operation. However, up to-date, only a few fiber SAs have been reported in the literature [15-18]. It is reported that the absorption cross section of Tm$^{3+}$: $^3\text{H}_6 - ^3\text{F}_4$ which extends from 1.5 to 1.9 μm covers some areas of the EDF emission cross section in the 1.5 μm vicinity, suggesting a viability of using TDF as an alternative passive Q-switcher. Previously, Tiu et al. reported that a 2 m long TDF SA was feasible in promoting a stable Q-switched EDFL with a repetition rate ranged from 3.9 kHz to 12.7 kHz, by utilizing 3 meters long EDF gain medium in a ring cavity scheme [17]. However, the TDF SA and the EDF gain medium used, were too long, and not economic; while the shortest attainable pulse width was reported to be around 7.4 μs.

In this paper, we demonstrated a stable passively Q-switched EDFL, utilizing a shorter length of TDF SA of 11 cm and EDF gain medium of 2.4 meters in a ring cavity scheme. The pulse repetition rate was obtained in the range of 54.1–106.7 kHz. Meanwhile the shortest attainable pulse width at the maximum pump power was measured to be around 3.28 μs, which is relatively narrower than the report [17] and comparable to [15, 18].

2. TDF SA preparation and characterization

In this work, 11 cm long TDF was used as the SA, with both ends of the TDF were coupled with 10 cm long standard single mode (SMF28) fibers via fusion splicing, to make a 10 cm SMF28 – 11 cm TDF SA – 10 cm SMF28 fiber SA configuration, as depicted in Figure 1. However, for simplicity, the whole fiber SA configuration is regarded as 11 cm TDF SA. The TDF (Nufern, SM-TSF-9/125) has a core diameter of 9 μm, a cladding diameter of 125 μm, a numerical aperture (NA) of 0.15. Meanwhile, the SMF28 from Corning has a core diameter of 8.2 μm, a cladding diameter of 125 μm and an NA of 0.14. The linear absorption profile of the TDF SA is provided in Figure 2, and as shown, there is 2 dB absorption measured at the Q-switched operating region of 1560 nm. The inset of Figure 2, shows the experimental set-up, used to measure the TDF SA linear absorption.

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**Figure 1.** TDF SA configuration

**Figure 2.** TDF SA linear absorption profile
3. Q-switched EDFL experimental set-up

The proposed Q-switched EDFL ring cavity set-up is illustrated in Figure 3. The laser utilizes a 2.4 m long EDF (Fibercore, I-25) with a GVD of 27.6 ps/km$^2$, a numerical aperture of 0.23, a core diameter of 4 μm, a cladding diameter of 125 μm as well as Erbium ions absorption of 23 dB/m at 980 nm. The laser diode pump provides a 980 nm single wavelength input pump power into the EDF gain medium, propagating through the 980 WDM port of a 980/1550 nm WDM. An optical isolator (ISO) was employed between the gain medium and the 80/20 coupler, to preserve unidirectional light propagation in the cavity while suppressing back reflections. The 80/20 coupler splits the laser into 80:20 ratio, where 80% of the light is propagated into the fiber SA and then, back into the ring cavity via the 1550 WDM port. Meanwhile, the rest, 20% is directed out, into another coupler (3 dB coupler). The 3 dB coupler provides dual outputs with 50:50 light separations, allowing parallel signals observations via two different optical devices. A 350-MHz oscilloscope and a radio frequency (RF) spectrum analyzer, both coupled with a 1.2 GHz photodetector, were used to observe the Q-switched laser in the time domain and in the frequency domain, respectively. Meanwhile, an optical power meter and an optical spectrum analyzer (OSA) with a spectral resolution of 0.07 nm were used to record the Q-switched laser output power and the optical spectrum, separately.

4. Result and discussion

The proposed EDFL set-up began to generate a stable Q-switched laser with an initial repetition rate of 54.1 kHz at a threshold pump power of 35 mW and remained stable up to a repetition rate of 106.7 kHz, at a maximum available pump power of 136 mW. No pulsed laser could be detected, after removal of the fiber SA from the cavity, even with an increasing pump power to the maximum, verifying the function of the fiber SA in constructing a stable Q-switched EDFL. The optical spectrum of the Q-switched laser is demonstrated in Figure 4, showing a central wavelength of 1560 nm with an intensity of around -12.7 dBm. Figure 5 provides the enlarged scale of the Q-switched pulsed laser in the time domain at the maximum pump power of 136 mW, illustrating a peak to another peak duration of 9.37 μs (that equivalents to a pulse period), which also corresponds to a pulse repetition rate of 106.7 kHz. The pulse signal has an FWHM of 3.28 μs. Meanwhile, the pulses train observed in a larger period of 1000 μs is depicted in the inset of Figure 5, demonstrating almost levelled pulses amplitude within the entire time-span, suggesting the stability of the generated Q-switched laser. The frequency domain of the pulsed signal is provided in Figure 6, depicting several frequency harmonics without severe spectral modulation. The pulsed laser has a fundamental frequency of 106.7 kHz, which is in a good agreement with the pulse repetition rate obtained in the time domain (Figure 5). The enlarged scale of the fundamental frequency is shown in the inset of Figure 6, which illustrates a considerably high SNR of 63 dB, suggesting that the Q-switched laser is relatively stable. We
obtained a maximum pulse energy of 134.7 nJ and a maximum peak power of 41 mW at the maximum available pump power of 136 mW.

Figure 4. Q-switched EDFL optical spectrum

Figure 5. Q-switched EDFL pulses train in the time domain
5. Conclusion
We have suggested and demonstrated a compact, stable and reliable Q-switched EDFL working at a central wavelength of 1560 nm by employing a short length of TDF SA (11 cm). The EDFL produces a Q-switching pulse with an operating frequency of 54.1-106.7 kHz against an increasing pump power of 35-136 mW. The Q-switched laser has a maximum output power of 14.3 mW, a maximum pulse energy of 134.7 nJ and a maximum peak power of 41 mW as well as the shortest pulse width of 3.28 μs, all were obtained at the maximum available pump power of 136 mW. The laser fundamental frequency has a signal to noise ratio (SNR) of approximately 63 dB, denoting strong pulsed laser signal. The viability of the TDF SA in generating a stable Q-switched EDFL offers simplicity, flexibility as well as high damage threshold to the pulsed unit system, which entirely would benefit the material processing and medical applications.

Acknowledgment
The authors would like to acknowledge University of Malaya, Universiti Teknikal Malaysia Melaka (Grant No.: PJP/2018/FKEKK(1B)/S01613) and Ministry of Education, Malaysia for their financial support via SLAB scholarship.

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