Ytterbium doped fiber saturable absorber for a stable passively Q-switched fiber laser in the 1-micron region

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Abstract. In this paper, we experimentally demonstrate a stable passively Q-switched fiber laser in the 1-micron regime by incorporating a segment of Ytterbium-doped fiber (YDF, 12 cm) as a saturable absorber (SA) in a ring cavity scheme. The fiber SA exhibits a linear absorption of about 2.44 dB at the Q-switched oscillating regime (1068 nm). The Q-switched pulses started to self-occur as the pump power elevated to its threshold of 151 mW and steadily existed up to the maximum pump power of 233 mW. At the maximum pump power, we obtained a maximum repetition rate of 74.2 kHz, a maximum output power of 3.7 mW, a maximum pulse energy of 49 nJ and a pulse width as short as 1.97 μs. Our results denote that a segment of YDF is possible of generating a reliable Q-switched fiber laser in the 1-micron regime, revealing its potential as another fiber SA candidate.

Keywords: 1 μm fiber laser, Q-switched laser, fiber saturable absorber

1. Introduction
Passively Q-switched fiber lasers have received a growing interest in modern research and industrial needs, owing to their great features of compactness, flexibility, reliability and cost efficiency. They have been successfully integrated into many applications including gas sensing, medical treatment, material marking and engraving. In the last two decades, various SAs have been discovered, such as semiconductor saturable absorbers mirrors (SESAMs) [1], a single walled-carbon nanotube (SWNT) [2, 3] and a graphene [4, 5]. The SESAMs, however, has a narrow wavelength tunable range and its packaging is relatively complex and expensive. On the other hand, the graphene has an ultra-fast recovery time which is preferable for SA; however, it has low saturable absorption co-efficiency of 2.3 %/layer, which requires considerably strong light-medium interaction for a stable Q-switched operation [6]. Besides above SAs, various alternative SAs have been revealed as successful Q-switchers, such as material oxides [7, 8], Transition metal dichalcogenides (TMDs [9, 10]; MoS2, MoSe2, and WS2, and WSe2), Topological insulators (TIs [11, 12]; Bi2Te3, and Bi2Se3), Antimony [13-15], Black phosphorus (BP) [16] and fiber SAs [17-20].

Various SA prepared nowadays, are in the forms of mechanical exfoliation, tapered fiber and polymer film. However, these conventional fabrication techniques suffer from a few drawbacks. For instances in
mechanical exfoliation (e.g. graphene, BP), it is difficult to deposit the same amount of exfoliated material and the same number of layers onto the fiber ferrule in every exfoliation trial. The exfoliated BP for example, requires an external case to protect it from a humid environment. On the other hand, the tapered fiber SA has a very narrow waist, therefore, is fragile and suffers a considerably high-power loss. In addition to that, the polymer film SAs have low thermal damage threshold and tends to deform when used for a long run. In order to overcome these drawbacks, fiber SAs which are known for their great flexibility, ruggedness, high efficiency and excellence thermal handling have been suggested and proposed in the literature [17-19].

In this paper, we report for the first time, to the best of our knowledge, the integration of YDF SA (12 cm) in the Ytterbium-doped fiber laser (YDFL) ring cavity for a stable Q-switched operation at 1068 nm. The YDF SA consists of a 12 cm long YDF fusion spliced with 10 cm long single-mode fiber SMF28 at both of its’ ends. The YDF is reported to have an absorption curve which is overlapped with its emission curve near the 1-micron vicinity, suggesting a feasibility of incorporating a segment of YDF as an optical loss modulator and the Q factor in the YDFL.

2. Experimental setup
At first, the YDF was cut into a segment of 12 cm long. Then, two pieces of 10 cm long SMF28 were fusion spliced at both YDF ends, yielding a YDF SA configuration of 10 cm SMF28 – 12 cm YDF – 10 cm SMF28 as provided in Figure 1. For simplicity, the YDF SA is being regarded as 12 cm YDF in this paper. The YDF is a single mode fiber, and has a core diameter of 4.4 μm, a cladding diameter of 125 μm, a numerical aperture (NA) of 0.2 and a peak core absorption of 1200 dBm⁻¹ at 975 nm. Meanwhile, the SMF28 has a core diameter of 8.2 μm, a cladding diameter of 125 μm and an NA of 0.14. Experimentally, the fiber SA shows a linear absorption of 2.44 dB at the Q-switched YDFL regime, when tested with a broadband white light source.

![Figure 1. YDF SA configuration](image1)

![Figure 2. The proposed Q-switched YDFL experimental layout](image2)
Figure 2, shows the experimental layout of the proposed Q-switched YDFL. As shown, the gain medium (YDF, 1.5 m) is pumped by a 975 nm single mode laser diode (LD) through a wavelength division multiplexer (WDM, 975/1060). A 3 dB optical coupler divides the laser into 50/50 separations, where half of the laser output is forced to circulate inside the cavity, while the other half is propagated out for various data collections. A second 3 dB coupler is incorporated to further splits the laser output into 50/50 separations for simultaneous and data observations. An optical isolator ensures that light propagates in one-direction. A digital oscilloscope (GWINSTEK, GDS-3352) and a radio frequency spectrum analyzer (RFSA, Anritsu MS2683) measures the optical signal in the time domain and frequency domain, respectively. In addition to that, an optical spectrum analyzer (OSA, Anritsu MS9710C) displays the laser output spectrum, while, an optical power meter measures the laser output power.

3. Result and discussion

With the fiber SA placed inside the cavity, a stable Q-switched YDFL began to appear when the pump power elevated to the threshold source of 151 mW. At this pump power, we obtained an output power of 2.4 mW, a pulse energy 38 nJ, a repetition rate of 63.2 kHz and a pulse width of 2.7 μs. As we further increased the pump power to its maximum available pump power of 233 mW, the pulse repetition rate grew faster, while the pulse width became shorter. The trend shown by the pulse repetition rate against the pump power, is in good agreement with a typical behavior of a Q-switched fiber laser. At this pump power, we obtained a maximum output power of 3.7 mW, and a maximum pulse energy of around 49 nJ. Figure 3 illustrates the Q-switched YDFL pulses train observed at the maximum pump power (233 mW). As shown, the pulses train has a peak to peak separation of 13.4 μs (pulse period), that is corresponding to a maximum pulse repetition rate of 74.2 kHz. Meanwhile, the shortest pulse width of 1.97 μs is obtained. The inset of Figure 3, provides the oscilloscope trace of the obtained Q-switched pulses seen in enlarged scale. As shown, the pulses train is quite stable, depicting almost similar pulse shape, pulse height and pulse pattern between one another, over a long period of 1000 μs. Figure 4, shows the spectral trace of the Q-switched laser output. As illustrated, the Q-switched YDFL has a quite broad laser spectrum centered at the 1068 nm wavelength. To analyze the fiber SA performance under a moderate usage, the fiber SA was kept inside the cavity and left operating for about 1 hour at the maximum pump power. As expected, the quality of the Q-switched YDFL did not degrade, suggesting that the YDF SA was still in a good condition.

Figure 3. Q-switched YDFL oscilloscope trace
4. Conclusion

We have successfully demonstrated a flexible and stable Q-switched YDFL by integrating a segment of YDF (11 cm long) in a ring cavity. The Q-switched YDFL began to steadily self-start as the pump power tuned to 151 mW (threshold) and remained steady with further increasing of the pump power to its maximum available pump of 233 mW. At the maximum pump power, a maximum output power of 3.7 mW and a maximum pulse energy of 49 nJ were obtained. The highest repetition rate was achieved at around 74 kHz, while the shortest pulse width was attained at 1.97 μs. This work implies that a short YDF is feasible for generating quite stable Q-switched fiber laser in the 1-micron region with a low threshold pump.

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