Fibre-based Saturable Absorbers for Pulsed Generations in the 1-micron Region

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Abstract. In this paper, we demonstrated and compared several fibre-based saturable absorbers (SAs) used in the generation of stable Q-switched fibre lasers in the 1-micron region, using 1.5 m long Ytterbium-doped fibre (YDF) as the gain medium. The tested fibre SAs consist of four segments; (1) 8 cm long Hafnium bismuth erbium-doped fibre (HBEDF), (2) 12 cm long Ytterbium-doped fibre (YDF), (3) 20 cm long Titanium dioxide-doped fibre (TDDF) and (4) 11 cm long Thulium-doped fibre (TDF). The fibre segments were joint with a single-mode fibre (SMF28) of approximately 10 cm at both of their ends via fusion splicing to become useful fibre-based SAs. The Q-switched fibre lasers stably operated at ∼1060 nm wavelength. Among these fibre SAs, the highest pulse energy (191 nJ) was achieved through the TDDF SA, while the shortest pulse width (1.97 μs) and the highest pulse frequency (74.2 kHz) were obtained via the YDF SA. These fibre SAs provide simple operation, high stability and high thermal damage threshold which are desirable for high power laser operations.

Keyword: Fibre-based SA, passive Q-switching, Ytterbium-doped fibre laser

1. Introduction

Q-switched fibre lasers have many benefits, such as compactness, possesses high temperature and vibrational stability, high-quality beam, and low maintenance cost, which suits many applications, including material processing, medicine and remote sensing. The Q-switched fibre lasers can be generated via an active or a passive method. The passive method is much simple in preparation and handling, and is much cheaper and reliable in comparison to the active method. It uses saturable absorber (SA), such as graphene [1-3], carbon nanotubes (CNTs) [4, 5], topological insulators (TIs) [6, 7], transition metal dichalcogenides (TMDs) [8-11], and metal oxides [12-15] to modulate intra-cavity losses and Q-factor in the cavity.

Many of these SAs present in the form of exfoliated bulk materials or thin films and are integrated in the cavity by attaching them between two fibre ferrules tightened with fibre adapters. Bulk material SA, such as graphene, tends to be oxidised when contacted with the air and thus is not so reliable. In contrary, the thin film SAs, have low melting points of ∼230°C, and may deform when subjected to high pump power. Another technique is by using a side-polished fibre deposited with SA materials. The side-polished fibres deposited SA, however, are fragile (particularly at the polishing area), and produce high power losses. Thus, to overcome this problem,
fibre-based SAs, which doped with certain materials (that have sufficient linear absorption at the specified operating bandwidth) are proposed for alternative solutions. The present of the linear absorption attribute enables losses modulation occurs in the cavity, particularly at the Q-switching operating wavelength. These fibre SAs are renowned for excellent thermal handling with a softening temperature of around 1200ºC, besides, are suitable for applications that requires high flexibility, maintenance-free and simple operation. Several fibre-based SAs with stable pulse performances have also been demonstrated in literature in the past few fears [16-18].

In this paper, we demonstrated and proposed several fibre-based SAs, consisting of newly developed fibres and commercial fibres; (1) 8 cm of Hafnium bismuth erbium-doped fibre (HBEDF), (2) 12 cm of Ytterbium-doped fibre (YDF), (3) 20 cm of Titanium dioxide-doped fibre (TDDF) and (4) 11 cm of Thulium-doped fibre (TDF) for the Q-switching in the 1-micron region. Theses fibre SAs were integrated in the YDFL ring cavity, with the help of fibre connectors and adapters. Several important Q-switched laser characteristics were investigated and reported such as the pulse width, pulse period, pulse frequency, and pulse energy. These parameters are summarised in the chapters to follow.

2. Method

2.1. Fibre SA preparation and characterisation

The selected fibre was cut into segment and then connected with a single-mode fibre (SMF28, length ~10 cm) at both of its ends through fusion splicing. The simplified structure of the fibre SA is shown in Figure 1. However, in this paper, the additional length of SMF28 will not be addressed, and only the fibre SA’s length will be reported for simplicity. The fibre SAs’ characterisation details could also be found in the previous reports [19-23]. The appropriate length for the fibre segment was determined from the linear absorption profile, measured at the respective Q-switched operating wavelength. The linear absorption profile was investigated by propagating low density and wideband white light source into one end of the fibre-based SAs. The output was then collected from another end of the fibre SA, and then channelled into an Optical spectrum analyser (OSA). The fibres segment length with their respective measured linear absorption value are summarized in Table 1.

![Figure 1. Fibre-based SA structure, consisting of single-mode fibre, SMF28 (~ 10 cm) fusion spliced at both of the fibre segment’ ends.](image1)

![Figure 2. Fibre-based SA linear absorption measurement set-up](image2)
Table 1. Fibre SA’s segment length and its linear absorption profile

| fibre SA  | Length (cm) | Linear absorption profile (dB) |
|-----------|-------------|-------------------------------|
| HBEDF     | 8           | 3                             |
| YDF       | 12          | 2.44                          |
| TDDF      | 20          | 3.24                          |
| TDF       | 11          | 1.35                          |

2.2. **YDFL cavity configuration**

The experimental design used for the YDFL Q-switching operation is illustrated in Figure 3. The cavity is pumped by 980 nm LUMICS laser diode (LD) through a wavelength division multiplexer (980/1060 WDM). The light is then propagated into YDF gain medium (1.5 m), 3 dB coupler 1, fibre-based SA (8 cm HBEDF/ 12 cm YDF/ 20 cm TDDF/ 11 cm TDF) and finally into an isolator, before reaching back to the WDM through a 1060 nm port, for a complete light propagation. The YDF gain medium (LIEKKI, YB 1200-4125 from the THORLABS) used in the set-up has a core and cladding diameter of around 4.4 μm and 125 μm, respectively. It has a core absorption of 1200 dB/m at 975 nm wavelength. The 3 dB coupler 1 splits the light into 50:50 separations. 50% of the output is channelled into 3 dB coupler 2, while half of the quantity is left circulated in the cavity. The extended 3 dB coupler 2 further splits the output into halves, to ease the process of monitoring dual optical quantities, using optical equipment (OSA, radio frequency spectrum analyser (RFSA), oscilloscope) simultaneously. The fibre SA is integrated in the cavity to modulate losses, as well as Q-factor in the cavity. The isolator ensures unidirectional light propagation. The OSA measures the optical spectrum of the laser, while the RFSA and the oscilloscope displays the Q-switching characteristic in the frequency domain and time domain, respectively.

![Figure 3. YDFL cavity design for the Q-switching operation](image-url)
3. Result and Discussion

3.1. Q-switching performance via HBEDF SA
The Q-switched YDFL using HBEDF SA stably emerged at a threshold pump power of 106 mW and steadily appeared until 175 mW. The pulse frequency could be varied from 41 kHz to 67 kHz. Figure 4(a) shows the YDFL Q-switched output spectrum, which is centred at 1069 nm. Figure 4(b) shows the temporal performance of the Q-switched YDFL at the maximum pump power of 175 mW. As illustrated, the peak to peak separation time (pulse period, T) is measured as 14.9 μs (67 kHz), while the pulse width, τ is obtained as 3.48 μs. The fundamental frequency has a signal to noise ratio (SNR) of 48 dB, and the maximum pulse energy was around 70.2 nJ.

![Figure 4. YDFL via HBEDF SA Q-switching performance (a) optical spectrum, and (b) time domain](image)

3.2. Q-switching performance via YDF SA
The Q-switched YDFL also could be obtained by using a short length of YDF (12 cm). With the YDF SA in the cavity, a stable Q-switched laser with a peak wavelength of 1068 nm was observed. The related optical spectrum is shown in Figure 5(a). The Q-switched YDFL stably arose at a threshold pump power 151 mW and diminished into a continuous wave, CW beyond the 233 mW. The pulse frequency has an initial value of 63.2 kHz which could be further lifted up to 74.2 kHz, with the increase of pump power. Figure 5(b) shows the Q-switching temporal performance at the maximum pump power (233 mW). As illustrated, the pulse period is measured as 13.4 μs (74.2 kHz), while the pulse width is recorded as 1.97 μs. The fundamental frequency had an SNR of 45 dB, while the maximum pulse was obtained as 49.9 nJ.

![Figure 5. YDFL via YDF SA, Q-switching performance (a) optical spectrum, and (b) time domain](image)
3.3. Q-switching performance via TDDF SA
The TDDF SA was integrated in the same YDFL cavity configuration (Figure 2). The Q-switched laser stably emerged within a pump power range of 109-233 mW. The initial frequency was recorded as 35 kHz. Figure 6(a) shows the optical spectrum of the Q-switched laser, with an output spectrum centred at 1062 nm wavelength. Meanwhile, Figure 6(b) illustrates the Q-switching in the time domain, observed at the maximum pump power of 233 mW. As shown, the pulse train is quite uniform in shape, suggesting excellent pulsing stability. The pulse has a peak to peak separation of 18 μs, that corresponds to a pulse frequency of 53 kHz, and a pulse width of 2.55 μs. The first harmonic has an SNR of 47 dB, while the most attainable pulse energy was measured to be around 191 nJ.

![Figure 6. YDFL via TDDF SA, Q-switching performance (a) optical spectrum, and (b) time domain](image)

3.4. Q-switching performance via TDF SA
A reliable YDFL Q-switched operation with a starting frequency of 40 kHz until 60.2 kHz emerged stably as the pump power rose from 109 mW to 206 mW. The Q-switched laser has an output spectrum centred at 1069 nm wavelength, as illustrated in Figure 7(a). Figure 7(b) shows the Q-switched pulse train, traced by the oscilloscope at the maximum pump power (206 mW). As shown, the pulse signal has a pulse width of 2.87 μs and a pulse period of 16.6 μs (60.2 kHz). The maximum pulse energy was 80.7 nJ, and the Q-switched output has a fundamental frequency with an SNR of 47 dB.

![Figure 7. YDFL via TDF SA, Q-switching performance (a) optical spectrum, and (b) time domain](image)

3.5. Q-switching overall performance
The overall performance of the Q-switched lasers using the proposed fibre-based SAs are summarized in Table 1. Within these fibre-based SAs, the highest pulse energy of 191 nJ was obtained from the TDDF SA, while the narrowest pulse width of 1.97 μs was attained via the YDF SA. These fibre SAs
shows quite good maximum pulse energy, minimum pulse width and the tunable range of pulse frequency, which are comparable to other SAs demonstrated in the literature.

To test the Q-switching stability, the fibre SAs were integrated in the laser cavity for few hours, at the maximum Q-switching pump power. Based on the experimental results, the Q-switching pulse remained almost unchanged (during the test period), indicating that the fibre SAs were in still excellent condition and performed under their thermal damage threshold.

### Table 2. YDFL Q-switching performance using fibre-based SAs (our work) in comparison with other SAs in the literature.

| Saturable absorber (SA) | Maximum pulse energy (nJ) | Minimum pulse width, τ (μs) | Pulse frequency, f (kHz) | Central wavelength, λc (nm) | Reference |
|-------------------------|---------------------------|-----------------------------|--------------------------|-----------------------------|-----------|
| HBEDF (8 cm)            | 70.2                      | 3.48                        | 41-67                    | 1069                        | This work |
| YDF (12 cm)             | 49.9                      | 1.97                        | 63.2-74.2                | 1068                        | This work |
| TDDF (20 cm)            | 191                       | 2.55                        | 35-53                    | 1062                        | This work |
| TDF (11 cm)             | 80.7                      | 2.87                        | 40-60.2                  | 1069                        | This work |
| CNTs                    | 143.5                     | 12.18                       | 7.9-24.2                 | 1060.2                      | [4]       |
| CNTs                    | 18.4                      | 1                          | 30-50                    | 1061                        | [5]       |
| Graphene                | 141.8                     | 1.3                         | 28.9-110                 | 1027                        | [3]       |
| MoS₂                    | 32.6                      | 5.8                         | 6.4-28.9                 | 1066.5                      | [10]      |
| MoSe₂                   | 116                       | 2.85                        | 60-74.9                  | 1060                        | [11]      |
| BP                      | 2.09                      | 1.16                        | 52.52-58.73              | 1038.8 & 1042.1             | [24]      |
| BP                      | 7.1                       | 4                           | 6-44.8                   | 1056.6-1083.3               | [25]      |
| Bi₂Se₃                  | 6.2                       | 2.1                         | 14.9-62.5                | 1050.4                      | [26]      |
| Bi₂Te₃                  | 38.3                      | 1                           | 35-77                    | 1056                        | [7]       |

4. Conclusion
We have demonstrated and compared several fibre-based SAs; (1) 8 cm of HBEDF, (2) 12 cm of YDF (3) 20 cm of TDDF and (4) 11 cm of TDF in the 1-micron region, using 1.5 m long YDF as the gain medium. All these fibres showed quite excellent Q-switching stability as well as comparable laser performances to several of other SAs in the literature. The Q-switched fibre lasers operated near the 1060 nm wavelength. The highest pulse energy (191 nJ) was achieved via the TDDF SA, while the shortest pulse width (1.97 μs) and the highest pulse frequency (74.2 kHz) were obtained via the YDF SA. Incorporating of these fibre-based SAs, provide better flexibility and high thermal damage threshold, which significantly desired for applications such as in medical and material processing.

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