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Bandwidth modulation and pulse characterization of passively Q-switched erbium-doped fiber laser

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Abstract: We demonstrate the modulation of laser bandwidth by utilizing an ultranarrow tunable bandpass filter in a passively Q-switched erbium-doped fiber laser. The passive Q-switch mechanism is enabled by using carbon nanotubes as saturable absorber at a Q-switched threshold of 35.5 mW. Based on spectral filtering effect introduced by the ultranarrow tunable bandpass filter, the 3dB laser bandwidth can be tuned from 0.016 nm to 0.478 nm at a fixed pump power of 75.9 mW. The corresponding pulse behavior for each different bandwidth is characterized, and the results reveals that the pulse width can be as well tuned from 7.8 to 2.6 μs against the laser bandwidth, which agrees with the rule of time-bandwidth product (TBP). Correspondingly, the pulse repetition rate and the pulse energy vary from 16.23 kHz to 26.16 kHz and from 0.67 to 1.03 μJ respectively across the laser bandwidth. Further investigation of the pulse performance is performed against the pump power increment up to 107.2 mW. To the best of our knowledge, this is the first demonstration of spectrum bandwidth modulation in a passively Q-switched fiber laser, which can be useful for fully exploiting the possibilities of Q-switched pulse applications.

Keywords: Tunable laser bandwidth; Q-switching; carbon nanotubes; ultranarrow tunable bandpass filter, fiber laser.

1. Introduction

Extensive research has been conducted on Q-switched fiber laser owing to its reliable technique to generate high-energy pulses at kilohertz repetition rate range. Implemented within a compact system, the Q-switched fiber laser can find numerous potential applications such as in optical sensing [1], micromachining [2], signal processing [3] and optical communication [4]. Among the various methods employed to realize Q-switched fiber laser operation, utilizing a saturable absorber as a passive Q-switch element has proven to be a sophisticated approach, which enables the attainment of microsecond pulse durations in the mid-infrared region. Typically, the saturable absorption effect is induced by materials exhibiting a nonlinear dependence of their transmittance against the input optical intensity. Due to the distinct properties offered by different types of saturable absorber, the careful selection of a suitable saturable absorber material for a particular purpose is crucial.

Undeniably, the appeal of a saturable absorber lies predominantly in its saturable absorption performance, irrespective of its novelty or popularity. While recent research appraises the emergence of new materials as saturable absorbers from the group of metal organic frameworks [5-7], topological insulators [8,9], transition metal dichalcogenides [10-12], transition metal oxides [13,14] and MXenes [15], the compatibility of classic carbon nanotubes as saturable absorber remains noteworthy amidst this exploration. Numerous recent reports [16-20] underscore their significance, attributed to their ultrafast carrier dynamics, high third-order nonlinearity, sub-picosecond recovery time, broad operating wavelength range and high damage threshold. Alongside their outstanding saturable absorption properties, carbon nanotubes can be simply synthesised through electric arc discharge [21], chemical vapor deposition [22] and laser ablation [23]. It is also important to emphasize that the progress and evolution of real saturable absorber technologies were catalysed by the success of carbon nanotubes that serves as pioneers among all carbon-based saturable absorber materials since their first demonstration for pulse laser generation in 2003 [24].

To enhance the versatility of a Q-switched fiber laser, there has been considerable interest in tuning the laser wavelength. This is achieved using an air gap-based Fabry-Perot interferometer filter [25], tunable bandpass filter [26-29], tunable fiber Bragg grating [30] and tapered fiber variable attenuator [31]. In addition to wavelength tunability, the ability to modulate the spectral bandwidth is a valuable feature, providing flexibility in choosing the desired bandwidth. However, the conventional filtering effects commonly used for tuning output wavelength, lack the capability to alter spectrum bandwidth, thus limiting the potential applications. Tailoring the Q-switch laser parameters such as pulse repetition rate, pulse width and pulse energy synchronically at a consistent pump power is highly appealing. Yet, the interrelation between the mentioned pulse characteristics and spectral bandwidth in Q-switching has not been thoroughly investigated. While there have been efforts to analyze spectral bandwidth and pulse behaviour in mode-locking [32-35], there is still limited exploration of bandwidth modulation effect in Q-switching. Hence, there is a need to expand research efforts and enhance knowledge in introducing similar spectral bandwidth tuning effects in the Q-switching regime, to address existing gaps.

In this work, a Q-switched erbium-doped fiber laser (EDFL) with tunable spectral bandwidth is proposed and demonstrated. The system incorporates a single-wall carbon nanotubes (SWCNT) saturable absorber as the passive Q-switching element and an ultranarrow tunable bandpass filter (UNTBF) as the bandwidth modulation device. With the pump power increasing from the Q-switched threshold of 35.5 mW, the pulse repetition rate rises from 7.5 kHz to 22.5 kHz, while the pulse duration decreases from 13.4 μs to 4.1 μs. Through precise tuning of the UNTBF, we have obtained, for the first time, a tunable spectral bandwidth with a minimum interval of 0.012 nm, covering approximately a 0.462 nm spectral range at the 3dB power level. As the spectral bandwidth is increased from 0.016 nm to 0.478 nm, the pulse repetition rate can be tuned from 16.23 kHz to 26.16 kHz, with the pulse width changing from 7.8 to 2.6 μs. Analysis of the pulse energy reveals a decreasing trend from 1.03 to 0.67 μJ across the bandwidth. To the best of our knowledge, this marks the first demonstration of spectrum bandwidth modulation in a passively Q-switched fiber laser, adding significant value to its functionality and application.

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2. Experimental Setup

The experimental setup for the SWCNT-based Q-switched EDFL with tunable bandwidth is depicted in Figure 1. A 980 nm laser diode with a maximum power of ~107 mW is used as the pump source to provide excitation in a ~3.0 m long MetroGain-12-type erbium-doped fiber (EDF) with an erbium ion concentration of 960 ppm. This concentration results in an absorption coefficient of approximately 12 dB/m at 980 nm and 18 dB/m at 1550 nm. The laser diode is coupled to the EDF through a 980/1550 nm wavelength-division multiplexer (WDM). An isolator is connected to the output of the EDF to ensure unidirectional laser propagation. The SWCNT saturable absorber, assembled in a sandwich structure, is placed after the isolator as the Q-switching element. The SWCNT is initially in solution form, which is mixed with a polyethylene oxide (PEO) solution to create a thin film. Subsequently, this SWCNT thin film is incorporated onto the tip of a fiber ferrule to be connected to a pristine fiber ferrule through a fiber adaptor, resulting in the assembly of a sandwich-type saturable absorber device. Ref. [36] describes in detail the fabrication process and the properties of the SWCNT thin film used in this work.

For providing bandwidth tuning of the laser output, an XTM-50 Yenista ultra-narrow tunable bandpass filter (UNTBF) is integrated into the laser cavity. This is made possible by the high selectivity of the constituent diffraction gratings in the UNTBF. The signal from the UNTBF is extracted from the cavity through the 10% port of a 90:10 output coupler for performance analysis. The ring laser cavity is completed by connecting the 90% port of the output coupler to the 1550 nm port of the WDM. For spectral analysis, the output signal is channelled to an optical spectrum analyzer (OSA Yokogawa AQ63703) with a resolution of 0.02 nm. On the other hand, the output pulse in time domain is analysed by using an oscilloscope (LeCroy 352A) via an InGas photodetector (Thorlabs D400 FC) with a bandwidth of 1 GHz.

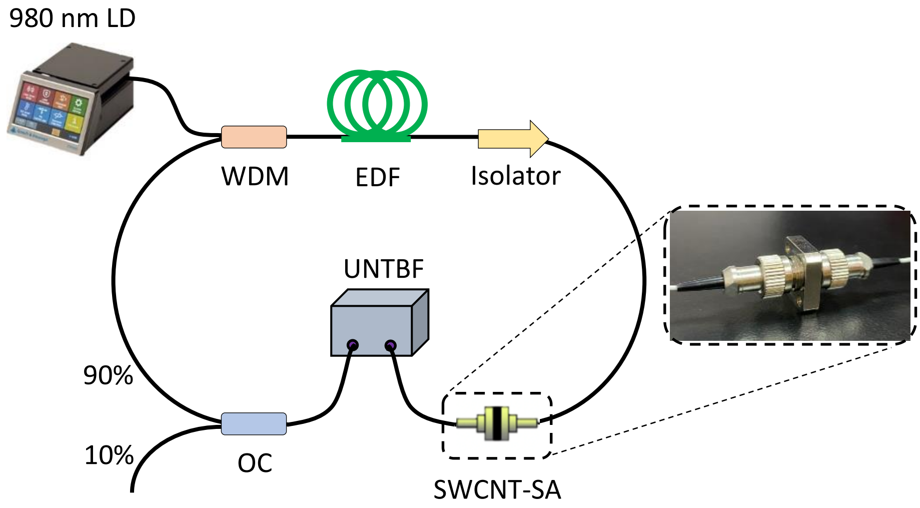

Figure 1. Experimental setup of SWCNT-based Q-switched EDFL with tunable bandwidth

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3. Results and Discussions

The continuous wave (CW) laser threshold of the proposed system is reached at a pump power 15.5 mW. Beyond the pump power of 35.5 mW, Q-switching behavior is observed until the maximum pump power of 107.2 mW. By adjusting the bandwidth knob of the UNTBF, different bandwidth of the Q-switched output spectrum can be generated. Figure 2 shows the output spectra of the Q-switched EDFL as measured from the OSA for 10 tuned bandwidths, taken at a fixed pump power of 75.9 mW. Considerably, stable Q-switched operation is maintained throughout the entire measurement. With a minimum bandwidth interval of 0.012 nm, the bandwidth of the output spectrum can be tuned over 0.462 nm, ranging from the narrowest value of 0.016 nm to the widest value of 0.478 nm at the 3dB power level. The central wavelength for all the output spectra with different bandwidths is kept constant at ~1558.85 nm. It is worth mentioning that when the pump power is varied at a specific setting of the UNTBF, no obvious change in bandwidth is observed. The modification capability of the spectrum bandwidth is determined by the passive bandwidth of the built-in grating embedded in the UNTBF, which can be expressed mathematically as [37]:

$$\Delta\lambda = (d\lambda/\pi\omega m)\cos\alpha \qquad \text{Equation 1}$$

where d is the groove spacing of the grating, λ is the laser wavelength, ω is the beam radius, m is the diffraction order and α is the incident angle. The minimum bandwidth shift of 0.012 nm in this study stands out as the narrowest bandwidth change reported to date. Furthermore, the manually tunable UNTBF employed in this work affords flexible control over bandwidth adjustments.

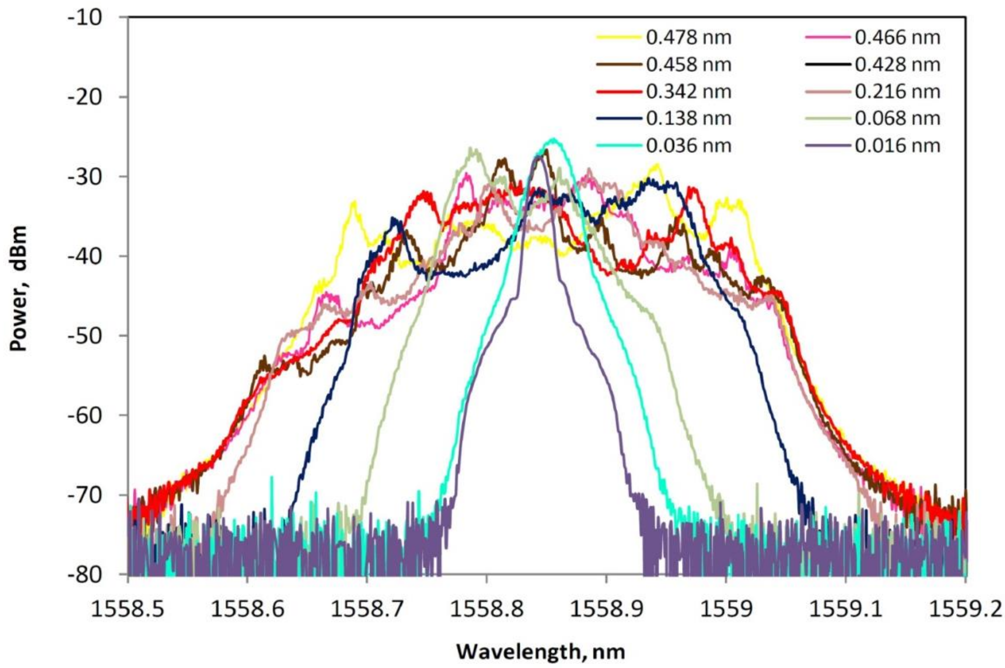

Figure 2. Output spectra of bandwidth tunable Q-switched EDFL at 75.9 mW

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Figure 3 illustrates the variation in repetition rate and average output power across different bandwidths ranging from 0.016 nm to 0.478 nm, while maintaining a constant pump power of 75.9 mW. The graph shows a gradual increase in both repetition rate and average output power as the bandwidth expands from 0.016 nm to 0.478 nm. The narrowest bandwidth, 0.016 nm, yields the lowest repetition rate of 16.23 kHz and the lowest average output power of 16.6 μW. Conversely, the widest bandwidth, 0.478 nm, results in the highest repetition rate of 26.16 kHz and the maximum average output power of 17.6 μW. In each bandwidth interval, the graph anticipates an increase in repetition rate ranging from approximately 0.46 to 2.32 kHz, accompanied by a corresponding rise in average output power ranging from approximately 0.2 to 0.5 μW.

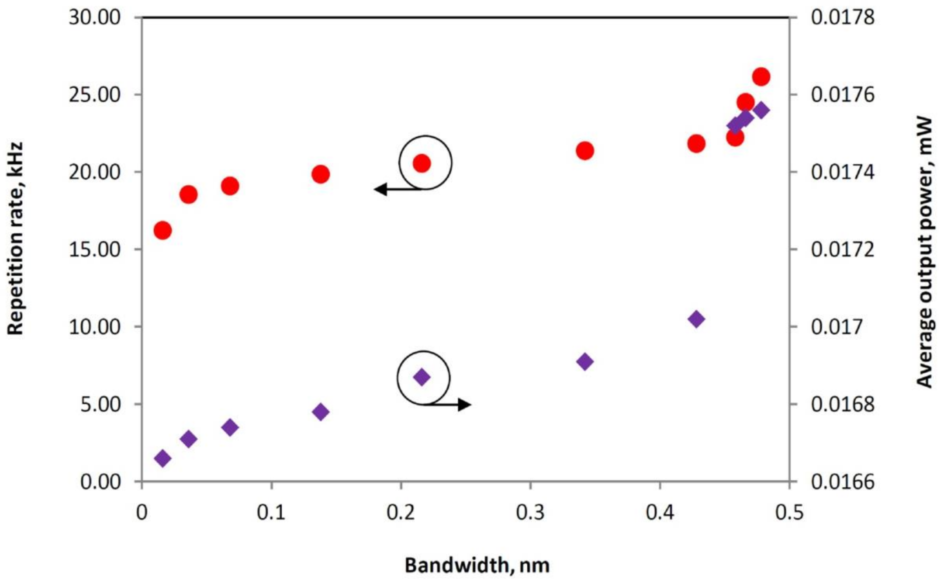

Figure 3. Pulse repetition rate and average output power against bandwidth

On the other hand, the pulse width exhibits an opposite trend to the repetition rate against the bandwidth, as shown in Figure 4. At the narrowest bandwidth of 0.016 nm, the largest pulse width is obtained, with a value of 5.4 µs. As the Q-switched spectrum's bandwidth widens, the pulse width gradually decreases, reaching its smallest value of 2.6 µs at the maximum bandwidth of 0.478 nm. This observation aligns with the inverse correlation between spectrum bandwidth and pulse width in a pulsed laser, as described by the time-bandwidth product (TBP) in Equation 2.

$$\text{TBP} = \Delta\lambda \times \Delta t \qquad \text{Equation 2}$$

where $\Delta\lambda$ is the spectrum bandwidth in frequency domain and Δt is the pulse width. Given a constant value for the TBP, this relationship elucidates how the pulse width of a pulsed laser is influenced by the spectrum bandwidth. To calculate pulse energy, the average output power is divided by the pulse repetition rate, and the resulting values are depicted in Figure 4. Similar to pulse width, the pulse energy experiences a gradual decrease across the bandwidth. The highest pulse energy attained is 1.026 µJ at the bandwidth of 0.016 nm, while the lowest pulse energy measured is 0.617 µJ at the bandwidth 0.478 nm.

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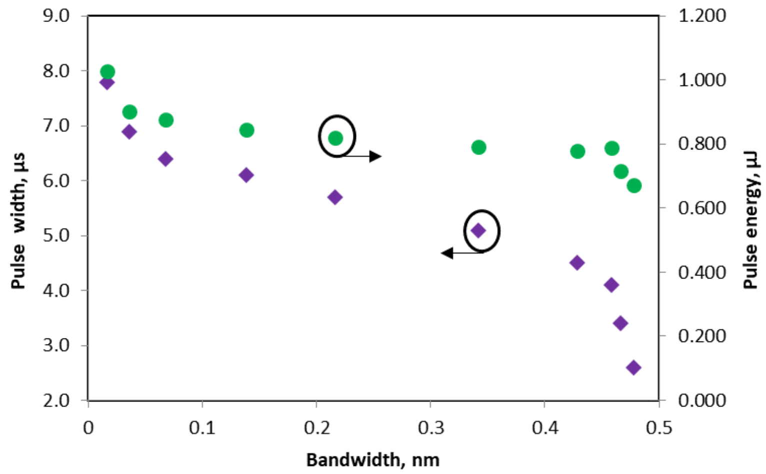

Figure 4. Pulse width and pulse energy against bandwidth

Figure 5(a) and (b) show the output pulse train of this proposed system at the lowest and highest pulse repetition rates, respectively, corresponding to Figure 3. These pulse trains are measured from the oscilloscope. In Figure 5(a), the time interval between pulses is 61.6 µs, giving a repetition rate of 16.23 kHz. In Figure 5(b), a repetition rate of 26.16 kHz is computed from the time interval between pulses of 38.2 µs. Both pulse trains exhibit slight fluctuations in intensity, indicating stable pulse operation.

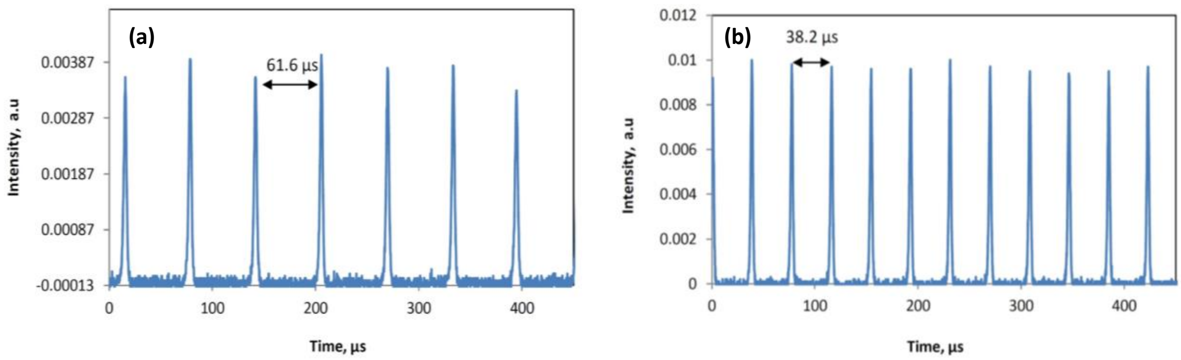

Figure 5. Output pulse train of (a) 16.23 kHz and (b) 26.16 kHz at pump power of 75.9 mW

To further investigate the output performance of the bandwidth-tunable Q-switched fiber laser system, analysis of the pulse output is conducted by varying the pump power from the Q-switching threshold of 35.5 mW to the maximum pump power of 107.2 mW, while keeping the spectrum bandwidth fixed. Figure 6 elucidates the evolution of the pulse repetition rate and pulse width versus the pump power at a spectrum bandwidth of 0.342 nm. As for the case of pulse repetition rate, the value rises almost linearly from 7.5 kHz to 22.5 kHz with the increase of pump power from 35.5 mW to 107.2 mW. In contrast, the recorded pulse width decreases from 13.4 µs to 4.1 µs across the same range of pump power. Upon exceeding the pump power of 107.2 mW, the Q-switched pulses became unstable and eventually disappears. This probably

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arises from the over-saturation effect within the gain medium, compounded by the system's high average loss resulting from various other nonlinear effects [38-40]. Remarkably, the Q-switched pulses could be restored when the pump power is reduced below 107.2 mW, indicating the resilience of the SWCNT-based saturable absorber and the reversibility of the Q-switched laser operation.

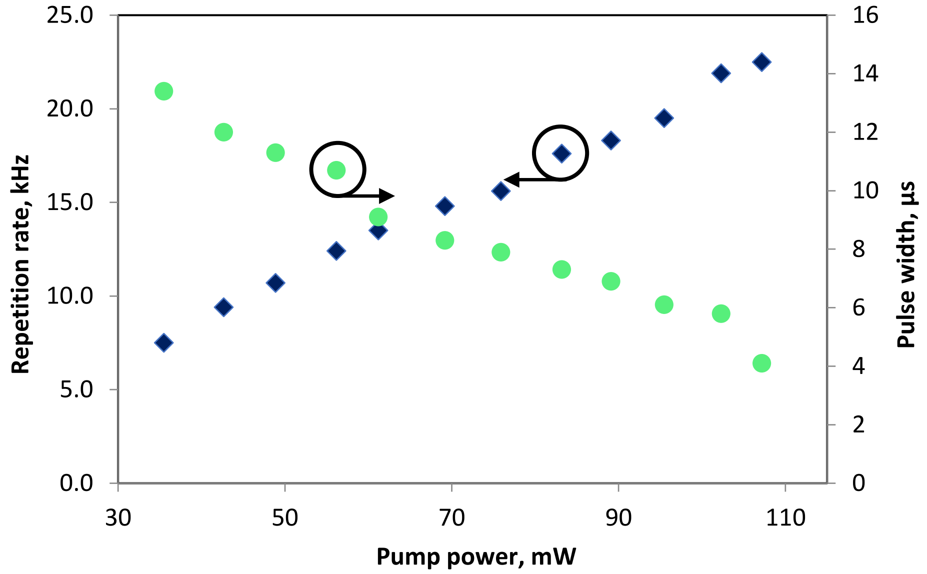

Figure 6. Evolution of pulse repetition rate and pulse width against pump power

In Figure 7, the progression of pulse energy and average output power is plotted in relation to pump power. Both parameters demonstrate an increase as the pumping power rises, aligning with the typical Q-switching laser behavior. The pulse energy escalates from 0.112 µJ to 2.05 µJ whereas the average output power expands from 1.5 µW to 8.4 µW. This corresponds to an increase of approximately 0.2 µJ in pulse energy and 0.6 µW in average output power for every pump power interval of ~5 to 8 mW.

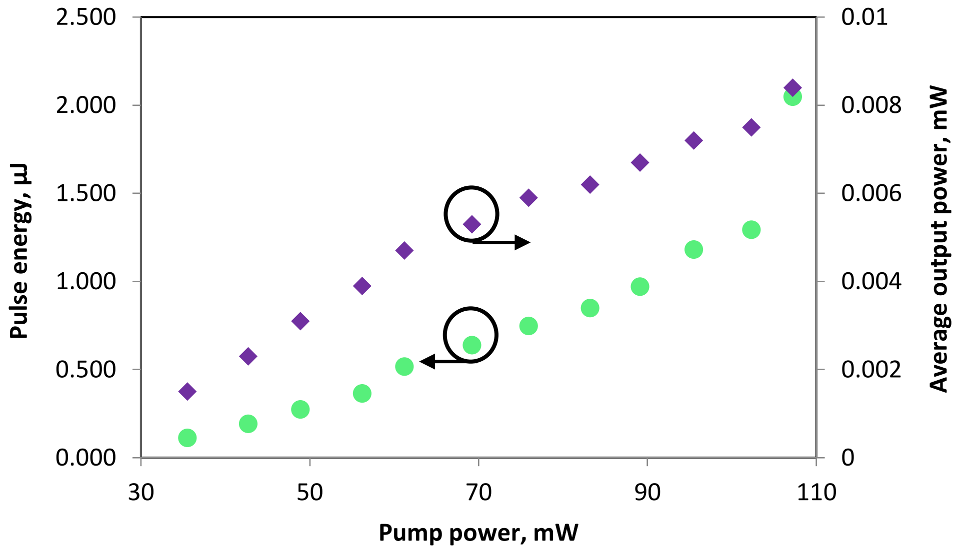

Figure 7. Evolution of pulse energy and average output power against pump power

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Figure 8(a) and (b) display the output pulse train of the proposed system at the lowest and highest pump power of 35.5 mW and 107.2 mW, respectively, corresponding to Figure 6. As the time interval between consecutive pulses decreases from 132.8 μs to 44.4 μs at the respective pump powers, the resulting repetition rates are recorded to be 7.5 kHz and 22.5 kHz, respectively. The slight fluctuation in the intensity of the pulse train is potentially attributed to the timing jitter of the Q-switched pulse.

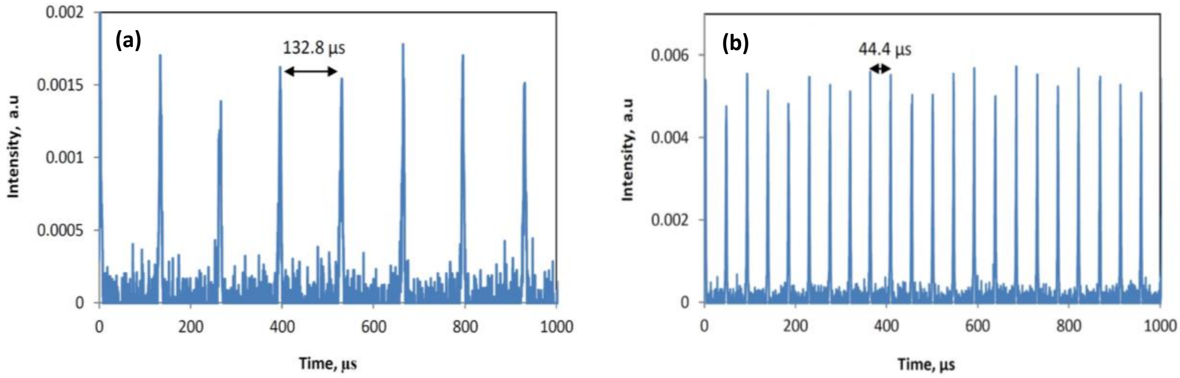

Figure 8. Output pulse train of (a) 7.5 kHz at 35.5 mW and (b) 22.5 kHz at 107.2 mW

While the measurement of the saturable absorption properties of the SWCNT thin film device would typically be ideal, it is not conducted in this study. To justify this omission, we draw upon our review of the influence of the modulation depth of a saturable absorber on Q-switched pulse performance, leading us to conclude the non-dependence of Q-switched pulse properties on the modulation depth from a few perspectives.

In the first perspective, it is acknowledged that a high modulation depth is a favourable property of a saturable absorber. However, this alone does not guarantee optimal pulse performance in Q-switching operations. Some examples of Q-switched EDFL reported in Refs. [41-45], as outlined in Table 1, clearly indicate that a high modulation depth saturable absorber does not necessarily result in better output performance compared to those with low modulation depth, as presented in Table 2. On the contrary, a high modulation depth saturable absorber is a crucial parameter for mode-locking operations, significantly impacting output pulse performance.

Table 1. Cluster of high modulation depth saturable absorber

SA material	Modulation depth (%)	Repetition rate (kHz)	Max. output power (mW)	Max. pulse energy (nJ)	Reference
TiS_2	8.3	25.2 – 50.7	0.48	9.46	41
Bi_2Se_3	11.1	26.1 – 36.6	0.22	6.1	42
BP	18.55	6.98 – 15.8	1.5	94.3	43
Ti_2AlC	6.3	16.1 – 27.5	0.62	22.6	44
MAX-phase	21	25.6 – 46.3	0.49	10.54	45

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Table 2. Cluster of low modulation depth saturable absorber

SA material	Modulation depth (%)	Repetition rate (kHz)	Max. output power (mW)	Max. pulse energy (nJ)	Reference
ZIF-67	4.2	13.6 – 32.6	7.22	221.5	46
Bi_2Te_3	4.1	26.6 – 47.1	0.83	17.8	47
$Ti_3C_2T_x$	3.8	29.5 – 47.8	1.85	38.6	48
WSe_2	3.5	4.5 – 49.6	1.23	33.2	49
Ti_2AlN	3.2	37.0 – 41.5	0.29	7.0	50
WS_2	2.9	90 – 125	5.7	46.3	51
MoS_2	2.0	8.8 – 43.5	5.9	160	52
Graphene	1.5	10.4 – 41.8	1.1	28.7	53
Fe_3O_4	0.8	8.5 – 28.0	1.7	71.0	54
BP	0.47	5.7 – 31.1	4.2	142.6	55
ReS_2	0.12	12.6 – 19	1.2	62.8	56
Fe_2O_3	3.63	9.9 – 22.5	0.83	36.9	38

In the second perspective, it is indisputable that a saturable absorber with low modulation depth remains functional in generating stable Q-switched pulses, presenting itself as not a limiting factor for achieving commendable Q-switched pulse performance. This assertion finds support in references listed in Table 2, which highlight favourable performance of Q-switched pulses based on saturable absorbers with relatively low modulation depth. Moreover, certain pulse characteristics showcased in Table 2 surpass those in Table 1, underscoring that a low modulation depth of a saturable absorber does not inhibit good Q-switched pulse performance. Consequently, it can be inferred that the pulse performance in Q-switching is not significantly contingent on the modulation depth, unlike the case of mode-locking where modulation depth plays a crucial role in shaping the pulse output.

Conclusion

A Q-switched EDFL based on SWCNT saturable absorber has been proposed and demonstrated, featuring tunable spectral bandwidth. The tuning mechanism relies on the UNTBF, providing a minimum tuning interval of 0.012 nm. The spectrum bandwidth can be tuned from 0.016 nm to 0.478 nm, covering a cumulative change of 0.462 nm at the 3dB power level. Correspondingly, the pulse repetition rate can be adjusted from 16.23 kHz to 26.16 kHz, while the pulse width varies from 7.8 to 2.6 µs across the bandwidth. Contrary to the increasing trend in the repetition rate, the pulse energy decreases from 1.03 to 0.67 µJ across the tunable bandwidth. Taking a specific bandwidth of 0.342 nm, an analysis of the pulse output while increasing the pump power from 35.5 mW to 107.2 mW reveals a common increasing trend of pulse repetition rate from 7.5 kHz to 22.5 kHz, accompanied by a simultaneous decrease in pulse duration from 13.4 µs to 4.1 µs. This study marks the inaugural demonstration of spectrum bandwidth modulation in a passively Q-switched fiber laser, offering additional advantages beyond those of ordinary Q-switched fiber lasers.

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