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# All fibre Q-switched Thulium-doped fibre laser incorporating Thulium–Holmium co-doped fibre as a saturable absorber

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ABSTRACT

A novel all fibre Q-switched Thulium-doped fibre laser (TDFL) is reported which includes a short length of a Thulium–Holmium co-doped fibre (THDF) as a saturable absorber. A high repetition rate (27.26 kHz) coupled with a low pulse width (19.06 μs) is obtained for single wavelength Q-switched pulse operation at an output wavelength of 1911.5 nm using a pump power of 200 mW. Increasing the pump power from 200 mW to 700 mW results in the repetition rate increasing from 27.26 kHz to 99.67 kHz and the pulse width decreasing from 19.06 μs to 920 ns. The centre wavelength of the single Q-switched pulse was also red shifted from 1911.5 nm to 1932.5 nm with increasing the pump power. A 45 m length single-mode fibre (SMF-28) provided dispersion compensation, and effectively an SMF-THDF-SMF structure is inserted in the cavity which operates in a similar manner to an SMF-MMF-SMF structure, providing a strong multimode interference effect which supports dual-wavelength operation. A stable dual-wavelength Q-switched pulse was achieved at a threshold pump power of 213 mW. The dual-wavelength Q-switched pulse operation was generated at 1911.5 nm and 1914.5 nm with a repetition rate of 8.45 kHz and pulse width of 20.02 μs. The dual-wavelength spacing of this pulse operation was 3 nm, which was in good agreement with calculations based on the multimode interference effect induced by the THDF. The repetition rate increased from 8.45 kHz to 70.65 kHz and the pulse width decreased from 20.02 μs to 870 ns with increasing pump power. At the maximum pump power of 700 mW, the maximum output power was measured as 27.4 mW. The experimental results confirm that the THDF can be utilized as a SA to generate a stable and tunable single-wavelength Q-switched pulse output as well as dual-wavelength Q-switched pulse in the 2.0 μm wavelength region.

## 1. Introduction

During the past few decades, pulse fibre lasers have developed rapidly in numerous application fields including sensing, spectral ranging, optical communications, medical treatment and material processing etc. [1]. Q-switched fibre lasers have attracted significant attention particularly in applications where only a low repetition rate is required [2]. Furthermore, Q-switched fibre laser research has also expanded to cover multiple wavelength bands including those centred on 1.0 μm, 1.5 μm and 2.0 μm [3–5]. Among these lasing bands, fibre lasers in the 2.0 μm wavelength range have been successfully developed and are attractive for use in many applications including fibre sensing and optical communications due to their inherent advantages of being eye safe and being suitable for low loss atmospheric transmission applications [6–8].

Numerous approaches have been reported for the generation of Q-switched pulsed laser sources including the nonlinear optical loop mirror (NOLM) [9], nonlinear polarization rotation (NPR) [10] and through the use of saturable absorbers (SAs). The passive Q-switched technique based on SAs is considered one of the most efficient methods for pulse generation. Semiconductor saturable absorber mirrors (SESAMs) have proved to be a popular means of achieving passively Q-switched fibre lasers. However, they exhibit a low damage threshold, narrow bandwidth and high cost which have collectively hindered their

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development. To date, a series of nanomaterials have also been developed for Q-switched pulse generation including carbon nanotubes [11, 12], graphene [13,14], topological insulators [15], metal nanoparticles [3,16], transition metal dichalcogenides [4,17,18] and black phosphorus [19]. However, these nanomaterials still exhibit numerous drawbacks, including high cost, difficult fabrication, non-uniformity etc. Therefore, recent research efforts have largely concentrated around the use of SAs for Q-switched pulse generation. Gain medium fibres have also attracted strong interest due to their stable absorption profile. These doped fibres can play a similar role within the fibre laser cavity to SAs due to energy level transition of the rare earth ions. Given the wide range of possible doped fibre types, there exists a large number of different available processing techniques which in turn results in different absorption coefficient ranges. However, their absorption characteristics can be optimized by suitable predesign, where the simple and common method simply comprises adjustment of the doped fibre length.

Doped fibre based SA has excellent stability and this, coupled with optimized absorption means that they have been widely investigated in recent literature. In 2010, Tsai et al. demonstrated a 2 kHz repetition rate Q-switched EDFL incorporating a Thulium-doped fibre (TDF) for the first time [20]. In 2012, Tao et al. demonstrated a thulium-holmium-doped fibre (THDF) based EDFL which was Q-switched and mode-locked [21], which further confirmed the possibility of use of a doped fibre as an SA in fibre lasers. Recently, Latiff et al. have successfully demonstrated an all-fibre dual-wavelength Q-switched and mode-locked EDFL including a short length of THDF in the laser cavity [22]. However, reported investigations of doped-fibre in the 2.0 μm laser range remains rare. There therefore exists a clear need for and strong motivation to investigate alternative wavelength regions based on the use of a doped-fibre saturable absorber.

In this paper, an 18 cm long THDF was fusion spliced with single-mode fibre (SMF-28) to form a SMF-THDF-SMF structure. The SMF-THDF-SMF structure works in a similar fashion to a multi-mode fibre (MMF) based SMF-MMF-SMF structure placed within the lasing cavity [22]. A stable tunable single wavelength Q-switched pulse laser output was obtained using the doped fibre structure in the lasing cavity. Furthermore, a 45 m long SMF (SMF-28) was inserted into the lasing cavity to optimize the in-cavity dispersion. A stable dual-wavelength Q-switched pulse was thus obtained, whose peak spacing agrees well with the theoretically predicted value owing to the multimode interference effect induced by the SMF-THDF-SMF structure. To the best of our knowledge, this is the first time that a tunable single Q-switched and dual-wavelength pulse operation laser has been experimentally demonstrated where a length of THDF is used as the SA in a Thulium-doped fibre laser (TDFL).

## 2. Experimental installation and processing

The THDF was fusion spliced with two standard SMFs to form the SMF-THDF-SMF structure. The single-clad THDF was 18 cm in length with core and cladding diameters of 11.5 μm and 125 μm respectively. The refractive index difference and cutoff wavelength were 0.0068 and 2545 nm respectively. The SMF-THDF-SMF structure is shown schematically in Fig. 1(a). The cutoff wavelength values of the THDF and SMF fibres are 2545 nm and 1260 nm, respectively. It functions as a SA device due to the energy level transition of the ions in the THDF, which is similar to the Pauli blocking principle which occurs in a two-dimensional material SA [23]. The operation of the THDF SA provides the basis upon which pulse operation is achieved in the designed fibre laser cavity. The THDF plays the same role as the length of multimode fibre within an SMF-MMF-SMF structure as the THDF in the SMF-THDF-SMF structure in this investigation, in that multimode interference occurs within the THDF section. According to the multimode interference effect theory within a fibre heterostructure, a series

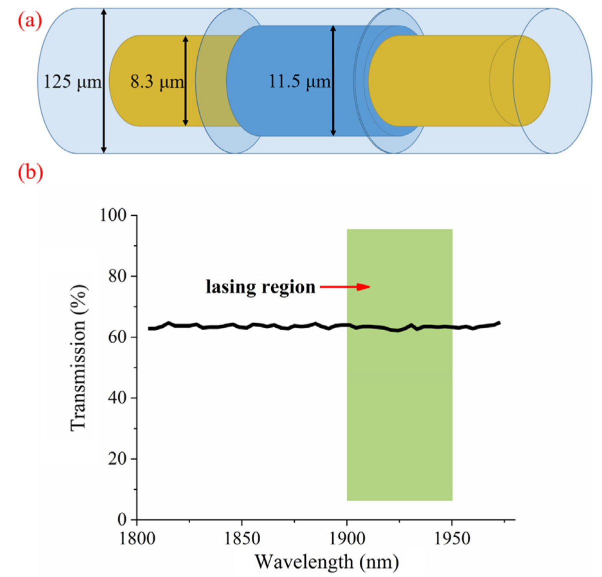


**Fig. 1.** SMF-THDF-SMF structure. (a) Schematic diagram of the structure with and 18 cm length of THDF (b) The spectral absorption characteristic of the THDF in the range 1800 to 1950 nm.

of peak wavelengths are generated due to the multimode interference effect, which are given as [24]:

$$\lambda_0 = \frac{p n_{MMF} D_{MMF}^2}{L}, \; p = 0, 1, 2, 3..., \tag{1}$$

where $n_{MMF}$ is the refractive index, $D_{MMF}$ is the diameter of the MMF core, and $L$ is the MMF length, respectively. $p$ is the self-imaging number. The SMF-THDF-SMF structure inherently generates a multimode interference effect, which in turn results in more than one peak wavelengths which provides the possibility of dual-wavelength output lasing operation [22]. The dual-wavelength lasing spacing can be calculated according to the following equation:

$$\Delta\lambda = \frac{\lambda_1 \lambda_2}{\Delta n L} \tag{2}$$

where $\Delta\lambda$ is the dual-wavelength lasing spacing, $\lambda_1$ and $\lambda_2$ are the dual-wavelength values, $\Delta n$ is the refractive index difference and $L$ is the length of the THDF.

In the SMF-THDF-SMF structure, the THDF length was chosen as 18 cm to ensure good absorption in the lasing region. The spectral absorption of the THDF was measured using a supercontinuum source (YSL SC-series) and an optical spectral analyzer (YOKOGAWA, AQ-6370C). The absorption characteristic is shown in Fig. 1(b). Fig. 1(b) shows that the fibre has a transmission of 62.7% in the lasing region.

The balanced twin-detector method was used to measure the nonlinear transmission characteristic of the THDF [25]. The schematic diagram of the nonlinear transmission measurement is shown in Fig. 2(a). A home-made watt-level CW Tm-doped fibre laser and a acoustic optical modulator (AOM, 100 ns, 10 kHz) were used as the pump source. The nonlinear transmission of the film was measured by comparing the input power and output power values using a two-channel power meter (PM320E). As illustrated in Fig. 2(b), the THDF exhibits a classical saturable absorption characteristic in that the transmission initially increases with the pumping power and then levels out. The modulation depth of the THDF were measured as 36.2%, respectively and the former is shown in Fig. 2(b). The nonsaturable loss is about 27.2% and the peak power intensity of the saturable point is about 60 W. However, when the pumping power was set at low power level (below 60 mW), a subtle drift of wavelength is generated when the pumping light propagate through the THDF [26]. The throughput instability is caused by the subtle drift of wavelength, which results in an unstable and hence

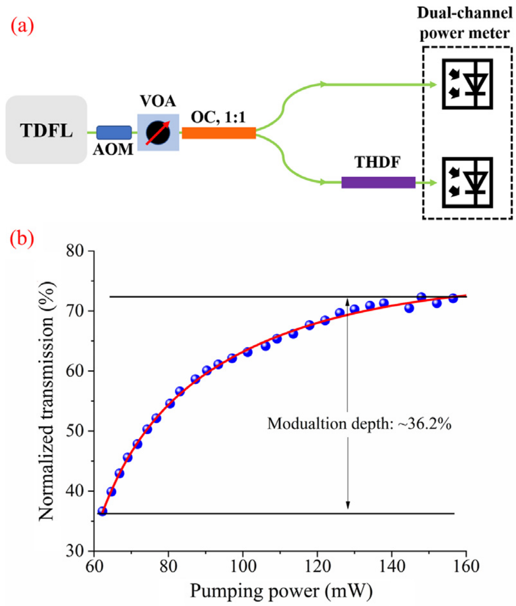


**Fig. 2.** (a) Schematic diagram of the nonlinear transmission measurement (balanced twin-detector method) (b) Nonlinear transmission of the THDF as a function of the pump power at wavelength of 1923 nm.

unreliable measurement state when the pump power is low (below 60 mW). Therefore, to avoid measurement error, the experimental results of the nonlinear transmission characteristic were measured only when the pump power was greater than 60 mW. The experimental results are shown in Fig. 2(b).

Fig. 3 shows the schematic diagram of the Q-switched TDFL with THDF based SA. It consists of a tunable laser (Santec TSI-710) with a centre wavelength of 1562 nm, an Erbium-doped fibre amplifier (EDFA, MC-EDFA-230), a wavelength division multiplexer (WDM, MCWDM-15/19), a polarization independent isolator (PI-ISO, MCI-1980), a Thulium-doped fibre (Nufern SM-TSF-9/125) of 5 m length and a 1:9 optical coupler (OC, 1980-FBT-C). The pump source with a centre wavelength of 1562 nm was optically coupled into the EDFA which produced an amplified light output signal. The EDFA provides a maximum output power of 700 mW, which was used to pump the gain medium, the 5 m long TDF via the WDM. The generated photons then propagate into the polarization independent isolator (PI-ISO) pigtailed with the THDF. The SMF has an 8.3 μm core diameter. The THDF was used as the SA device, which generates a Q-switched pulse train. In the designed laser cavity, the PI-ISO not only kept the lasing unidirectional in operation, but also reduced Brillouin back-scattering, which otherwise could potentially disturb the stability of the pulsed operation. The 90% port of the optical coupler was spliced with the WDM to complete the ring cavity. The 10% port was connected to the optical spectral analyzer (OSA, YOKOGAWA, AQ-6370C) to measure the laser's output spectrum. The time resolved pulsed laser output signal was also measured using a digital storage Oscilloscope (Tektronix MDO4054-6, 6 GHz) and a photodetector (Kemai, PDA, 10 GHz). An optical power meter (Newport 1918-R) was used to measure the output power. The total cavity length of the fibre laser was about 23 m.

## 3. Results and discussion

A wide range of experimental measurements were performed to fully characterize the optical source of this investigation. They are described in the following sub sections:

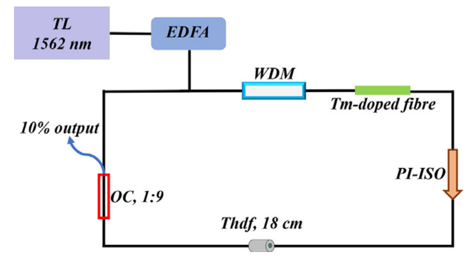


**Fig. 3.** Schematic diagram of the experimental setup.

### *3.1. Wavelength and time domain (pulse) characteristics of the single wavelength Q-switched device with a fixed (200 mW) pump power*

The characteristic of the single-wavelength Q-switched pulse operation is shown in Fig. 4. The Q-switched pulse was obtained by simply incorporating the 18 cm THDF into the standard cavity. The pump power was increased gradually from 0 and Continuous Wave (CW) lasing was observed when the pump power reached circa 100 mW. There was no evidence of any pulse-like behaviour in the time-based waveforms observed on the oscilloscope. As the power was further increased to 200 mW, Q-switching operation was initiated and recorded. The output spectrum and typical pulse train waveform are shown in Fig. 4(a) and (b) respectively. The centre wavelength of the Q-switched laser output was 1911.5 nm. The repetition rate and the pulse width were 27.26 kHz and 19.06 μs respectively. In the lasing cavity, the $Tm^{3+}$ ion in the THDF was excited from the ground state $^3H_6$ to the excited state $^3F_4$ when the photons have sufficient energy to reach the bonding energy of the $Tm^{3+}$. Once sufficient energy is reached at the $^3F_4$ energy level of $Tm^{3+}$, energy was transferred to the $^5I_7$ energy state of $Ho^{3+}$ [23,27]. According to the previously reported work, the lifetime of the $Tm^{3+}$ is about 200 μs at the energy state of $^3F_4$ [23]. The energy transition between the $Tm^{3+}$ and $Ho^{3+}$ in the THDF is very important as it underpins the generation of pulses and increases the repetition rate of the pulse operation. The interaction of the two ions in the THDF is similar to the Pauli blocking principle, which occurs in a two-dimensional SA material. In order to confirm the long-term stability of the Q-switched pulse operation, the emission spectra of the Q-switched lasing were recorded every 1 h for 4 h. The spectra recorded over the 4 h duration are shown in Fig. 4(c), and it was observed that neither the central wavelength nor output power values varied. These results clearly indicate that the Q-switched lasing operation was very stable.

### *3.2. Wavelength and time domain (pulse) characteristics of the single wavelength q-switched device with a varying the pump power*

The performance of the single wavelength Q-switched TDFL was further investigated where a series of spectra were recorded (shown in Fig. 5(a)) where the pump power was increased from 200 mW to the maximum value of 700 mW. It is worth noting that the centre wavelength of the Q-switched lasing was significantly red shifted when the pump power was increased. The observed red shifted wavelength value was approximately 4 nm for every 100 mW increase in the pump power. The THDF is a multi-mode fibre in the laser cavity, therefore the lasing modes of $LP_{01}$ and $LP_{11}$ may be excited at the SM-MM splicing point. There may be two modes, $n_{ef01}$ and $n_{ef11}$, propagating in the THDF fibre. The light may be coupled back into the single-mode fibre following transmission through the second SM-MM splicing point. At this point, the electric field is the sum of these two fields, which can be expressed by the following equation:

$$E = k_{01}exp(i\varphi_{01}) + k_{11}\gamma exp(i\varphi_{11}) \tag{3}$$

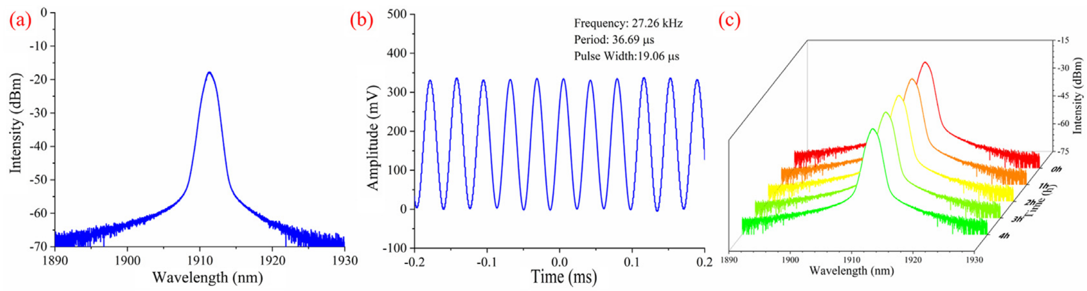


**Fig. 4.** Characteristic of the single Q-switched pulse with 200 mW pump power. (a) Optical spectrum (b) Typical oscilloscope pulse waveform (c) Long term spectral variation.

$k_{01}$ and $k_{11}$ are the fractions of the two electric fields coupled into the single-mode fibre, and is the excitation coefficient of the high-order mode. Accordingly, the intensity of the electric field is

$$T(\lambda) = {k_{01}}^2 + \gamma^2 {k_{11}}^2 + 2\gamma k_{01} k_{11} cos[\frac{2\pi L_s(n_{ef01} - n_{ef11})}{\lambda}] \tag{4}$$

$L_s$ is the length of the THDF and $\lambda$ is the laser wavelength.

In this laser cavity, the gain $G(\lambda)$ of the light signal is determined by two main sections: the emission of the active fibre, Tm-doped fibre and the absorption of the THDF, according to the equation below [26]:

$$G(\lambda) = 4.343[L_a N_a M_a[n_a(\sigma_a(\lambda) + \sigma_e(\lambda)) - \sigma_a(\lambda)] - L_s N_s M_s n_s \sigma_{at}(\lambda)] \tag{5}$$

where $L_a$ and $L_s$ are the length of the active fibre and THDF, $N_a$ and $N_s$ are the doping concentrations of the active fibre and the THDF. $M_a$ and $M_s$ are the overlap factors of the active fibre and THDF and $\sigma_a$ and $\sigma_e$ are the absorption and emission cross sections of the active fibre respectively. $\sigma_{at}$ is the absorption cross section of the THDF at the wavelength of $\lambda$. $n_a$ is the fraction of the excited population at the ${}^3F_4$ energy level of $Tm$ ions, while $n_s$ is the fraction of the ground state population at the ${}^5I_7$ energy level of $Ho$ ions. $n_a$ is determined by the pump power, which shows a monotonic decreasing relationship with the pump power [27].

For the laser cavity described in this paper, the output lasing spectrum $O(\lambda)$ is determined by the combined interaction of the transmission spectrum of the filter, the emission spectrum of the gain fibre at different pump powers and the absorption spectrum of the THDF at different lasing intensities. Therefore, the $O(\lambda)$ can be written as follows:

$$O(\lambda) = G(\lambda)T(\lambda) \tag{6}$$

In (6), the centre wavelength location is determined by $G(\lambda)$, to be precise, mainly determined by $n_a$. $n_a$ shows a typical monotonic decreasing relationship with the pump power, it can explain that the centre lasing wavelength presents a significant shift to the long wavelength region.

The repetition rate, pulse width and output power were also recorded. It can be seen from Fig. 5(b) that when the pump power increased from the Q-switched threshold 200 mW to the maximum 700 mW, the repetition rate increased from 27.26 kHz to 99.67 kHz and the pulse width decreased from 19.06 μs to 920 ns, and thus exhibits the characteristic features of passive Q-switching [28,29]. These experimental results confirmed that the THDF used as a SA material in a fibre laser has the ability to generate a tunable Q-switched pulse operation. The output power was measured using the same optical power meter as referred to above and is shown in Fig. 5(c). The maximum output power is about 31.2 mW.

### 3.3. *Wavelength and time domain (pulse) characteristics of the two wavelength q-switched device*

A 45 m length SMF was inserted into the laser cavity between the 18 cm length of THDF and the 1:9 optical coupler, increasing the total laser cavity length to 68 m. The pump power was increased gradually, and CW lasing was obtained when the pumping power reached 105 mW. The slightly higher threshold value was due to the added insertion loss caused by inclusion of the SMF. As the pump power was increased further to 213 mW, a dual-wavelength Q-switched output was observed. The typical spectrum and oscilloscope pulse waveform recorded using the OSA and OSC are shown in Fig. 5(a) and (b), respectively. The two peaks of the dual-wavelength are located at 1911.5 nm and 1914.5 nm. The repetition rate and pulse width were measured as 8.45 kHz and 20.02 μs respectively. It is worth noting that the spacing of the two lasing peaks is about 3 nm, which is in good agreement with the multimode interference effect of the THDF, based on (2). By increasing the pump power, it was observed that the repetition rate and pulse width of the dual-wavelength Q-switched pulse also changed. This agrees well with the characteristic features of passive Q-switching [28,29]. The repetition rate increased from 8.45 kHz to 70.65 kHz while the pulse width decreased from 20.02 μs to 870 ns when the pump power was increased from the Q-switched threshold of 213 mW to the maximum of 700 mW. The output power was measured using the same optical power meter (Newport 1918-R), and the output power versus pump power is shown in Fig. 6(d). The maximum output power is about 27.4 mW.

## 4. Conclusion

Typical tunable single-wavelength Q-switched operation was successfully obtained using the standard all-fibre laser cavity incorporating an 18 cm length of THDF as a SA, fabricated as part of this investigation. The energy level transition of the $Tm^{3+}$ and $Ho^{3+}$ in the THDF provides the saturable absorption to achieve Q-switched pulse operation. The typical tunable Q-switched laser action was generated with a single lasing peak at 1911.5 nm when a pump threshold power of 200 mW was reached. A red shift of 4 nm was observed with each subsequent 100 mW increase in the pump power. The repetition rate increased and the pulse width decreased with increasing pump power, which is in agreement with the typical characteristics of passive Q-switching. Dual-wavelength Q-switched pulse operation was also achieved by inserting a 45 m length of standard SMF into the same ring cavity. Dual-wavelength Q-switched lasing was obtained at the pump power of 213 mW. The dual-wavelength Q-switched pulse operation was generated at 1911.5 nm and 1914.5 nm with a repetition rate of 8.45 kHz and pulse width of 20.02 μs at a pump power of 213 mW. The SMF-THDF-SMF structure operates in a similar manner to an SMF-MMF-SMF structure, which provides a strong multimode interference effect to support dual-wavelength operation. The experimental results obtained in this investigation confirm the potential of the THDF for use in many fibre laser applications. Furthermore, they also provide confirmation that the gain medium fibre can be usefully deployed in other application areas.

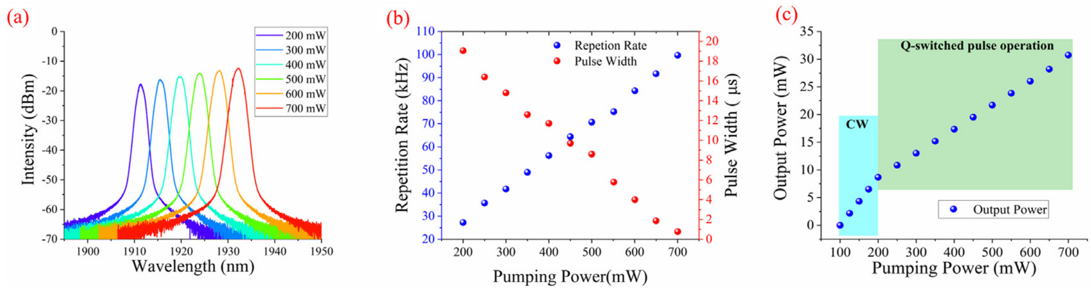


**Fig. 5.** Characteristic of the THDF Q-switched fibre laser versus the pump power. (a) Tunable spectra. (b) Repetition rate and pulse width. (c) Output power.

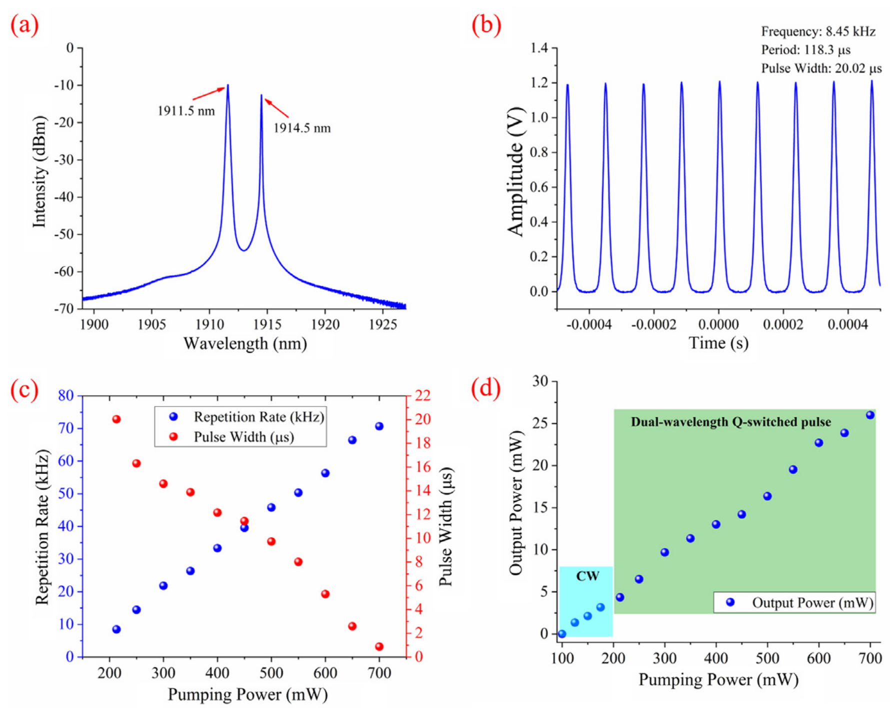


**Fig. 6.** Characteristic of the dual-wavelength Q-switched pulse operation (a) Optical spectrum at 213 mW pump power. (b) Typical oscilloscope pulse waveform at 213 mW pump power. (c) Repetition rate and pulse width. Versus pump power (d) Output power versus pump power.

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