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L-band Q-switched fiber laser with gallium/thulium-doped silica fiber saturable absorber

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HIGHLIGHTS

- Fabrication of Ga/Tm-doped silica fiber as the saturable absorber to generate Q-switched fiber laser.
- Generation of Q-switched fiber laser with short Ga/Tm-doped silica fiber saturable absorber length of only 10 cm.
- Acquisition of Q-switched laser pulses from 39.6 to 53.3 mW pump power.

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ABSTRACT

An L-band Q-switched fiber laser was demonstrated using gallium/thulium-doped silica fiber saturable absorber. At 10 cm in length, the saturable absorber generated Q-switched fiber laser at a pump power threshold of 39.6 mW and a central wavelength of 1601.93 nm. Beyond 53.3 mW, a spectrum with a central wavelength at 1602.00 nm was generated. On the other hand, the pulse repetition rate was obtained from 3.44 to 7.47 kHz whereas the pulse width reduces from 100.2 to 58.6 µs for pump power ranges from 39.6 to 53.3 mW. Within this range, the pulse energy is attained between 0.2600 and 0.2843 µJ, at a laser power slope efficiency of 6.94%. The constantly operated Q-switched fiber laser over 50 min observation time at 53.3 mW pump power ensures the feasibility of this pulse laser source as a practical device.

1. Introduction

Q-switched lasers have been extensively studied for its ability to generate higher pulse energy than short-cavity mode-locked lasers. This laser characteristic is attractive for a series of applications such as material processing, optical communication, laser marking, laser machining, laser surgery, and pigment removal [1–3]. A simple yet effective way to generate Q-switched laser is through the integration of saturable absorber (SA) in a laser cavity. Rare-earth material such as thulium (Tm) doped in silica fiber possesses the elementary absorption properties suitable for SA. The thulium-doped fiber (TDF) has been demonstrated as passive Q-switcher in C-band operating wavelength with erbium-doped fiber (EDF) as the active gain medium [4].

Apart from C-band wavelength, TDF has potential in operating within the L-band as well; from 1.57 to 1.62 µm. Using a 980 nm pump and an erbium-doped fiber amplifier (EDFA), an emission band ranging from 1.5 to 1.9 µm can be generated and absorbed by the TDF to cause the transition of energy states $^3H_4$ to $^3F_4$ and $^3H_6$ (ground state). This phenomenon releases photons with high emission cross section in wavelength bands from 1.45 to 1.50 µm and a parabolic-type emission cross section from 1.57 to 2.20 µm, which makes TDF feasible for L-band wavelength operation [5]. However, the investigation of Q-switched fiber laser (QSFL) incorporating TDF-SA in L-band wavelength still falls short.

TDF-SA has been employed in the demonstration of C-band QSFLs with ring cavity configuration. A study reported the employment of TDF-SA in a C-band QSFL with pump power from 1.6 to 9.8 W, which generated a pulse repetition rate from 27.5 to 135.8 kHz [6]. In addition to that, the pulse width, output power and pulse energy were measured as 430 ns, 2.2 W, and 16.4 µJ at the maximum pump power of 9.8 W. In another study, a 2 m long TDF-SA was demonstrated to generate QSFL with low pump power threshold of 20 mW [4]. From 20 to

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33.7 mW pump power, the pulse repetition rate was acquired from 3.9 to 12.7 kHz, whereas the pulse width reduces from 20.6 to 7.4 μs. A 40 cm thulium/holmium co-doped single clad fiber was also studied to generate the QSFL with pump power from 30 to 110 mW which acquired a pulse repetition rate from 9 to 39 kHz, whilst the pulse width reduces from 10.6 to 3.5 μs [7]. A similar study to [7] but with shorter length of 34 cm was also demonstrated with a 20 mW maximum subsidiary pump power to increase the pulse repetition rate of the QSFL [8]. From 30 to 110 mW pump power, the pulse repetition rate increased from 7.5 to 28.2 kHz, whilst the narrowest pulse width was recorded as 2.5 μs at the maximum pump power of 110 mW. Last but not least, a 1.3 m TDF was pumped by a 3.6 to 7.3 W pump source to generate Q-switched pulses with repetition rate from 42 to 76 kHz [9]. Simultaneous Q-switched and gain-switched lasers were observed at ~1550 nm and 1862 nm with 4.9 W pump power.

In this work, we demonstrate an L-band QSFL with 10 cm gallium/thulium-doped silica fiber (GTSF) as a SA for the first time to the best of authors' knowledge. The QSFL was achieved at a pump power of 39.6 mW and the Q-switched operation was maintained when the pump power was increased to 53.3 mW. The success of this work will contribute to the advancement of Q-switched laser application incorporating a rather low threshold power seed laser source integrated with only 10 cm GTSF-SA in the L-band region.

2. Fabrication of Tm/Ga-doped fiber

The SA deployed in this work utilized the same GTSF fabricated in our previous work [10]. The fiber was fabricated using the modified chemical vapour deposition technique. The incorporation of the Tm and Ga ions inside the fiber core was aided by using solution-doping technique. The main element of the fiber contains ~2000 ppm Tm ions based on the absorption peak that was obtained at 800 nm wavelength (i.e., 24 dB/m) from an ultraviolet-visible spectrometer, and 2.9 mol% of gallium oxide based on energy-dispersive X-ray (EDX) measurement [10]. The detection of gallium oxide is attributed to the presence of oxygen in the ambient environment when the EDX measurement is taken. Table 1 shows the optical properties of GTSF used in this research work. The background loss of the fiber was measured using the conventional cut-back method at 1300 nm wavelength [11]. The loss of the fiber is affected by the phase separation effect that occurs in the core at the preform stage, even though it was suppressed during fiber drawing. The fiber numerical aperture and fiber core size were measured as 0.113 and 12.1 μm, respectively. which were obtained using similar measurement method as [11]. The decay lifetime $^3F_4$ manifold of Tm ions in the tested SA was 0.53 ms which is longer than other Tm-doped fiber that was fabricated using the same amount of aluminium (Al) in the fiber core. A long upper state lifetime is favorable in maintaining the population inversion by pumping process with a relatively low pump power. Therefore, a large amount of stored energy is available in which the accumulation of population inversion bleaches the SA to generate Q-switched laser pulses.

3. Characterization of GTSF as a SA

A section of 10 cm GTSF was investigated with the transmission loss against wavelength and the saturable absorption properties as a function of peak power intensity. The transmission profile of the GTSF was characterized with a spontaneous emission source [model: Amonics model ALS-CL-17-B-SC]. Based on Fig. 1(a), the transmission loss of the GTSF is between 1.2 and 1.8 dB in L-band wavelength spanning from 1573 to 1618 nm. A similar twin detector experimental setup with an M-Fiber Menlosystems seed pulsed laser with pulse repetition rate of 250 MHz and pulse duration of 120 fs at 1550 nm central wavelength was employed to characterize the nonlinear saturable absorption properties of the fabricated fiber [12]. The GTSF possesses a saturation intensity (I_{sat}) of 114.73 MW/cm^2, modulation depth (MD) of 1.74%, and non-saturable loss of 20.3%, as shown in Fig. 1(b). These parameters are significant in determining the characteristics of pulsed laser in terms of pump power threshold and pulse width. Compared with nanomaterial-based SA, the MD of the GTSF-SA is lower than tungsten disulfide (WS_2) SA with 5.10% [13] and iron trioxide (Fe_2O_3) nanoparticles SA with 2.58% [14].

Table 1
Optical parameters for the GTSF.

Parameters	Measurement
Background loss	3.09 dB/m
Absorption	1.25 dB/m
Lifetime	0.53 ms
Numerical aperture	0.113
Diameter core size	12.1 μm

4. QSFL experimental setup

Fig. 2 depicts the laser cavity in ring configuration. The 5 m long EDF (Liekki Er80-8/125) with peak core absorption of 80 dB/m at 1530 nm was pumped by a 1480 nm laser diode (LD) through a wavelength division multiplexer (WDM). A polarization insensitive isolator (ISO) was spliced next to the EDF to ensure the unidirectional signal propagation in anti-clockwise direction. Then, 10 cm of GTSF-SA was employed as the passive Q-switching component in the laser cavity. A fiber paddle polarization controller (PC) was incorporated to provide stress-induced birefringence that creates independent wave plates which alters the polarization state of the laser cavity. Next, a 70/30 optical coupler (OC) was utilized for laser output (OP) measurement through the 30% optical port, whereas the remaining 70% optical signal reverts into the WDM to complete the ring laser cavity.

5. Result and discussion

Fig. 3(a) presents the optical spectrum for the proposed laser scheme in free-running laser regime without inserting the GTSF-SA inside the laser cavity. An additional 50/50 OC was attached at the 30% port of the 70/30 OC to observe the output traces through optical spectrum analyzer and oscilloscope simultaneously. Based on the experimental investigation, the continuous wave laser is generated at the pump power threshold of 33.5 mW. As the pump power increases from 33.5 to 81.2 mW, monotonous continuous wave laser was observed with central wavelength of approximately 1605.12 nm. The optical pulse characteristic of the free-running laser regime was examined by an oscilloscope through an L-band photodetector. The oscilloscope traces are illustrated in Fig. 3(b). The absence of Q-switching pulses from 30.3 to 81.2 mW pump power indicates all passive components inside the laser cavity do not contribute to the pulse formation.

Next, GTSF-SA was positioned inside the laser cavity [refer Fig. 2]. Simultaneous measurement was performed on both optical spectrum and oscilloscope with the aforementioned 50/50 OC. Fig. 4(a) and (b) show the perspective and top views of the optical spectrum generated with the GTSF-SA incorporated in the laser cavity. Based on the optical spectrum, the first and second laser peaks are observed at the central wavelengths of approximately 1601.9 and 1602.9 nm, respectively. In contrast to Fig. 3(a), higher continuous wave laser pump power threshold is observed at 36.4 mW which is due to the insertion loss of the GTSF-SA. Additionally, a region of spectral broadening was observed from 39.6 to 53.3 mW pump power. The same observation was also reported in [15] that corresponds to the operation of Q-switched pulsed laser. Beyond 53.3 mW pump power, the pulse phenomenon was diminished from the fiber laser scheme with gradually increased second laser peaks in optical output power centered at 1602.84 nm wavelength.

The optical spectrum with the incorporation of GTSF-SA inside the

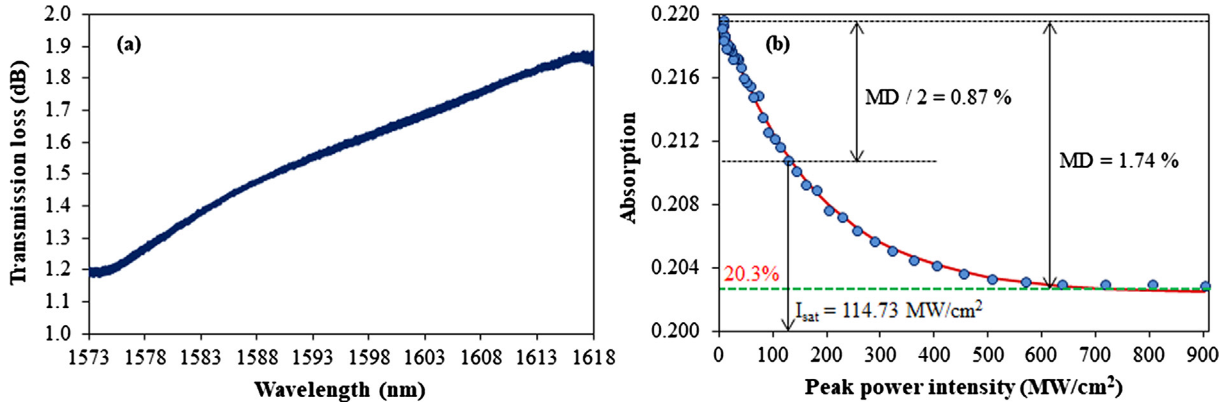

Fig. 1. (a) Transmission loss and (b) nonlinear saturable absorption properties of the Tm/Ga fiber as a SA.

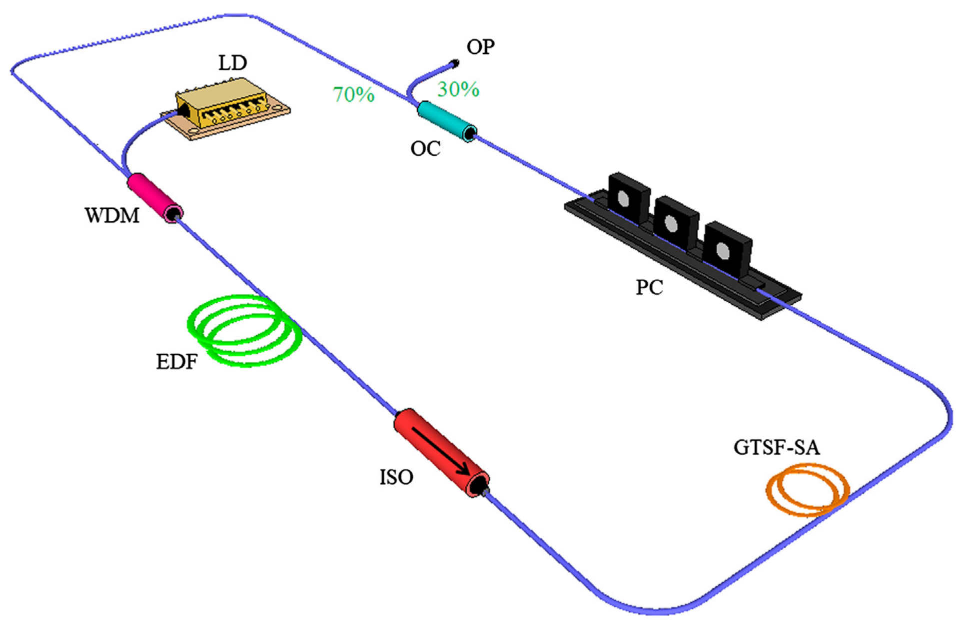

Fig. 2. Schematic diagram of the QSFL cavity.

laser cavity is presented from the pump power of 39.6 to 81.2 mW in Fig. 5(a)–(d). The central wavelengths are measured as 1601.93, 1601.92, 1602.00, and 1602.84 nm with peak power of −19.55, −18.44, −21.81, and −18.18 dBm, respectively from Fig. 5(a)–(d). It can be observed that the spectral bandwidth evolved from 0.012 to 0.032 nm from 39.6 to 53.3 mW pump power within the QSFL range, whereas the spectral bandwidth of 0.276 nm was attained at the maximum pump power of 81.2 mW.

Simultaneous pulse measurement was conducted with an oscilloscope and the output traces are presented in Fig. 6. Within the spectral

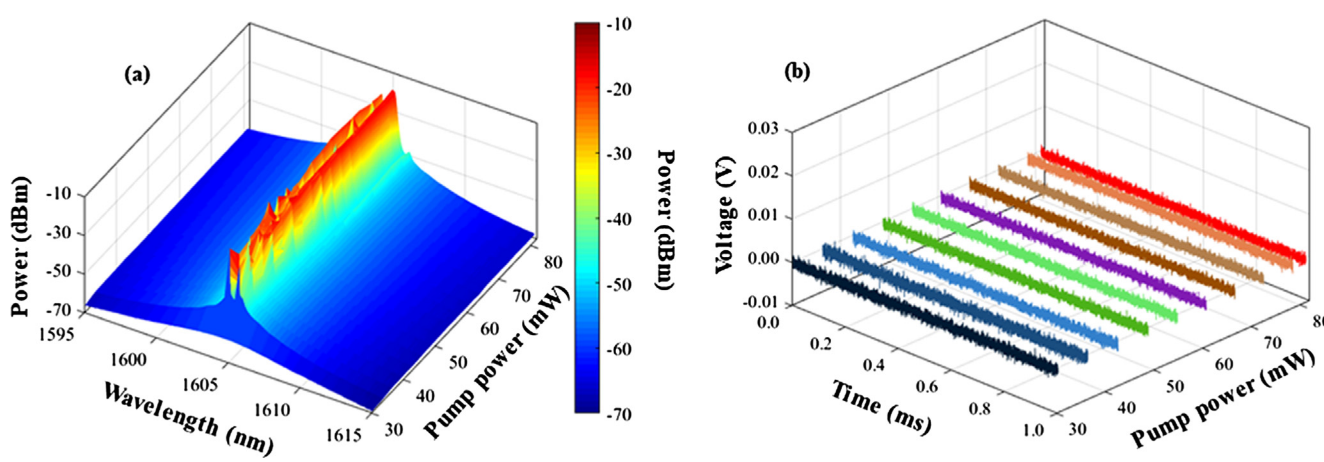

Fig. 3. (a) Optical spectrum and (b) oscilloscope traces for free-running laser regime without GTSF-SA inside the laser cavity.

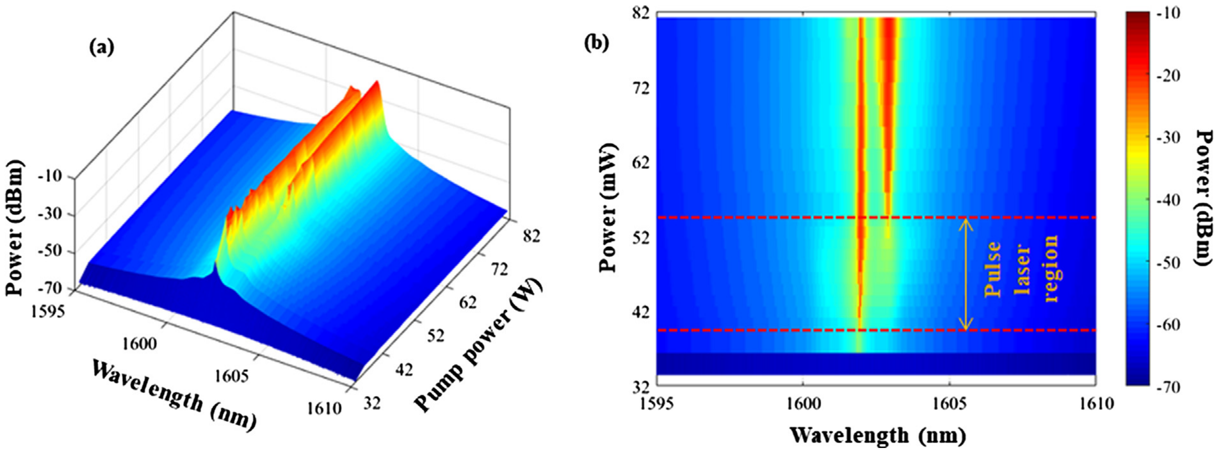

Fig. 4. (a) Perspective and (b) top view of the optical spectrum with the integration of GTSF-SA inside the laser cavity.

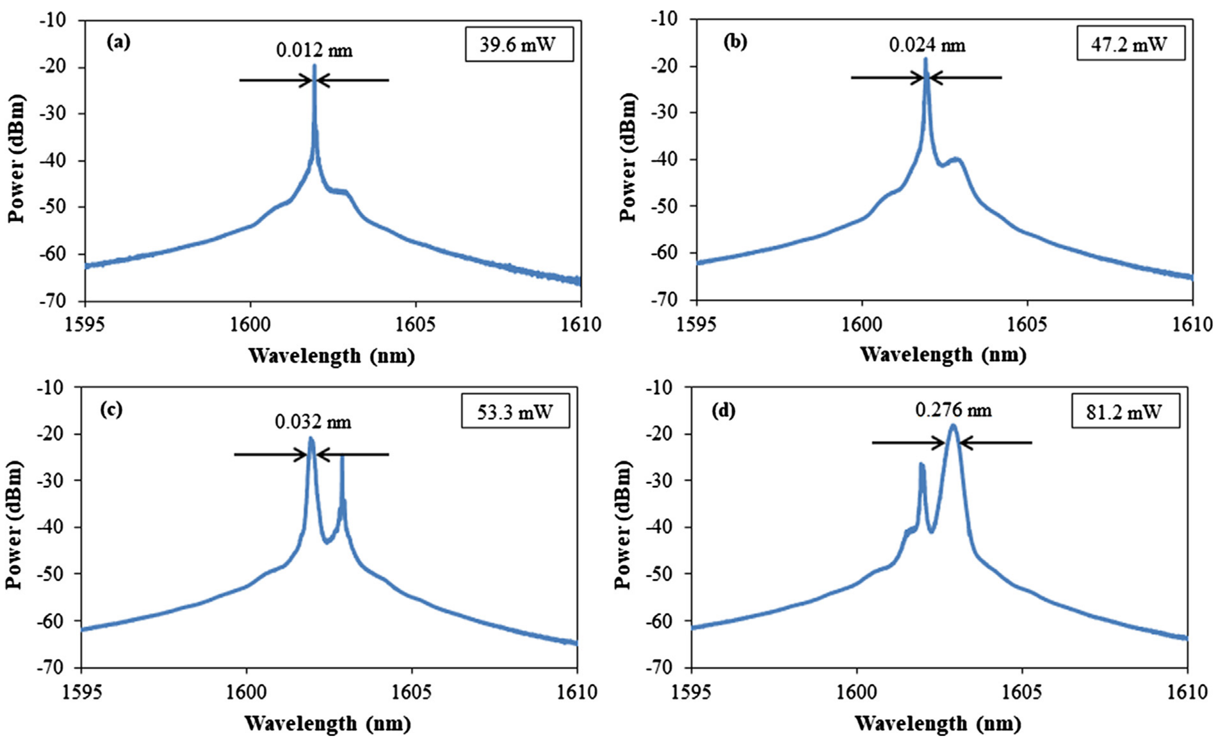

Fig. 5. Optical spectrum with the integration of GTSF-SA inside the laser cavity at the pump powers of (a) 39.6, (b) 47.2, (c) 53.3, and (d) 81.2 mW.

broadening region, Q-switched pulses were attained from 39.6 mW to 53.3 mW. The lowest pulse intensity was obtained with 39.6 mW of pump power, which increased until an optimum point of 47.2 mW [refer Fig. 6(a)–(d)]. Beyond this pump power until 53.3 mW, the pulse intensity decreased as shown in Fig. 6(e)–(f). Subsequently, the pulse laser transitioned back to the continuous wave laser operation when higher pump power than 53.3 mW was employed. This is due to the reduced saturable absorption when the gain uniformity along GTSF-SA is increased by higher pump power, which leads to a limitation whereby the continuous wave laser is attained [16]. Therefore, the relaxation time to maintain the Q-switched laser operation is 0.1338 ms as illustrated in Fig. 6(f). This experimental result tallies with the decay lifetime $^3F_4$ manifold of thulium ions of the tested SA, which should be equal or lower than 0.53 ms. As a result, the generation of the Q-switched pulse laser is validated with the integration of the GTSF-SA inside the laser cavity.

Fig. 7(a) shows the evolution of pulse repetition rate and pulse width in conjunction to Fig. 6. As similar to any Q-switched lasers, the pulse repetition rate is increased and pulse width is decreased with respect to pump power. This is because the relaxation oscillations are amplified to a faster rate when high pump power is employed to achieve faster pulse repetition rate [16]. The reduction of the pulse width on the other hand is due to the gain population excitation process which causes the generation of more pulses with a narrower pulse width within the same period of time. In this work, the pulse repetition rate increased linearly from 3.44 to 7.47 kHz whereas the pulse width reduces from 100.2 to 58.6 µs as the pump power is increased from 39.6 to 53.3 mW. Fig. 7(b) illustrates the single pulse width extracted from the pulse train at the pump power of 53.3 mW. Based on the measurement, the single pulse width for the maximum pump power within the QSFL region [refer Fig. 4(b)] is measured as 58.6 µs.

The power development curve of output power and pulse energy as a function of pump power is portrayed in Fig. 8. Region W denotes the spontaneous emission region from 8.05 to 33.45 mW pump power with the lowest slope efficiency of only 2.44%. Region X indicates the continuous wave laser region with laser pump power threshold of

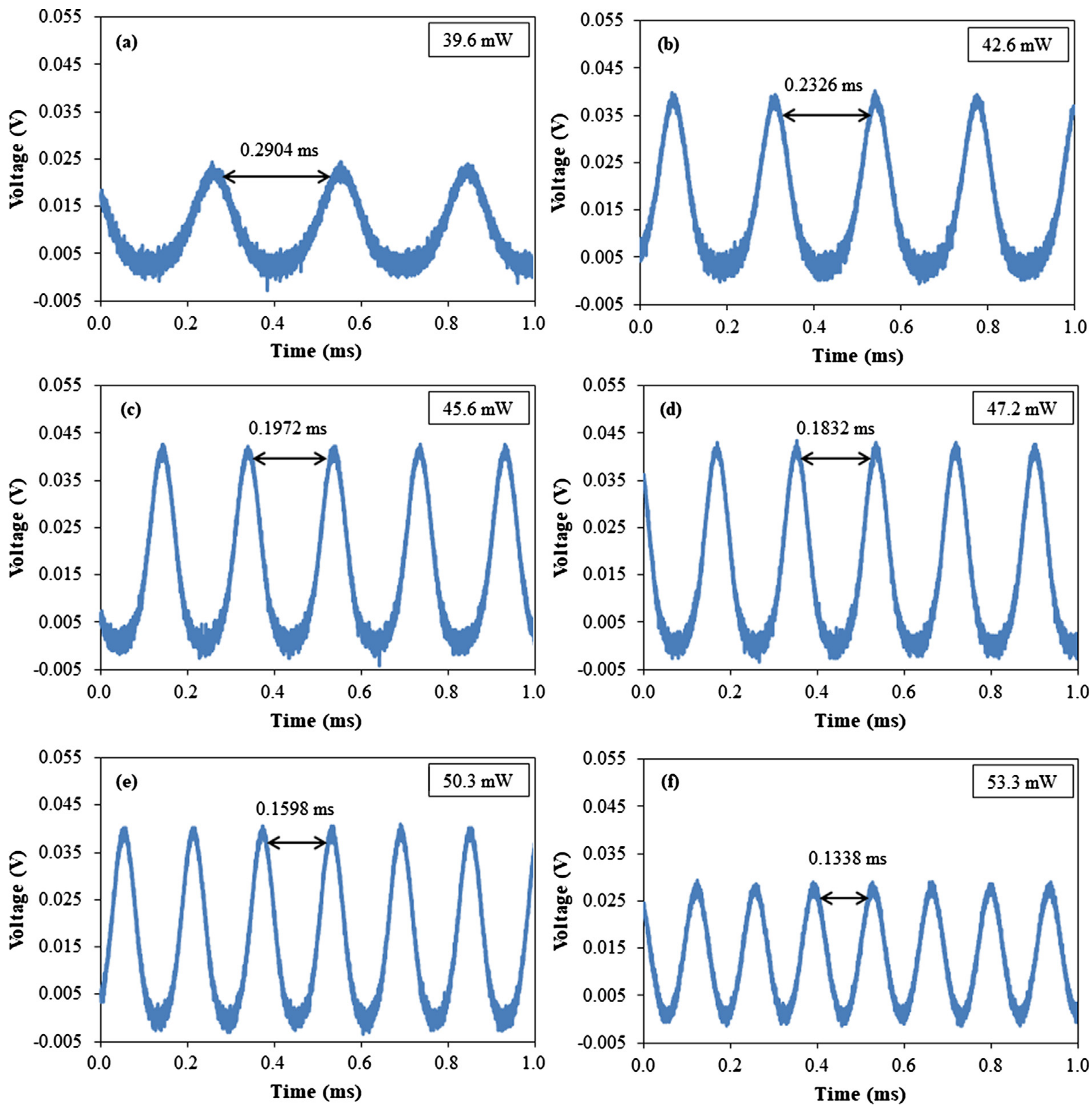

Fig. 6. Oscilloscope traces for QSFL incorporate GTSF-SA at the pump power of (a) 39.6 mW, (b) 41.1 mW, (c) 45.6 mW, (d) 47.2 mW, (e) 50.3 mW, and (f) 53.3 mW.

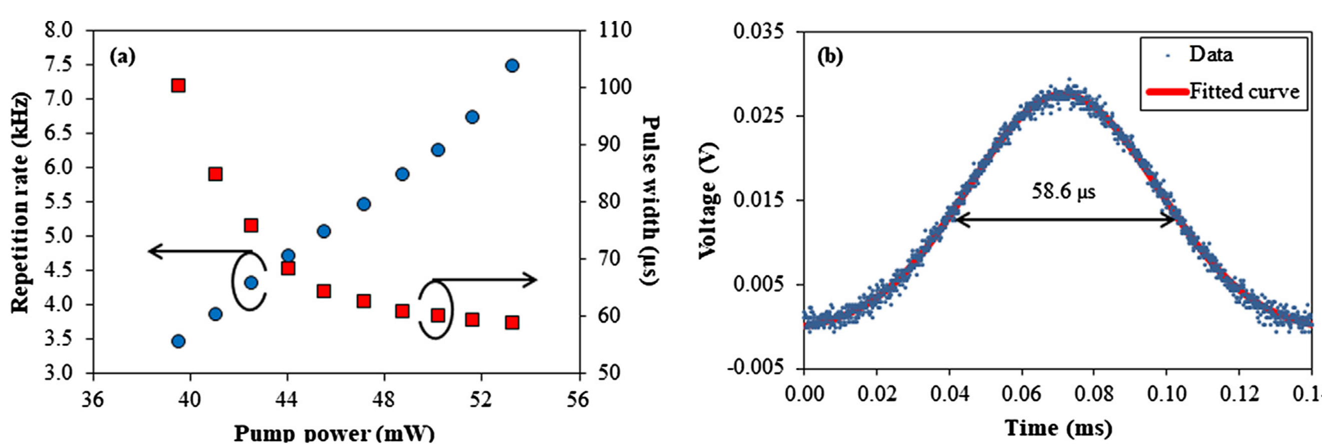

Fig. 7. (a) Evolution of repetition rate and pulse width, (b) pulse width for QSFL at 53.3 mW pump power.

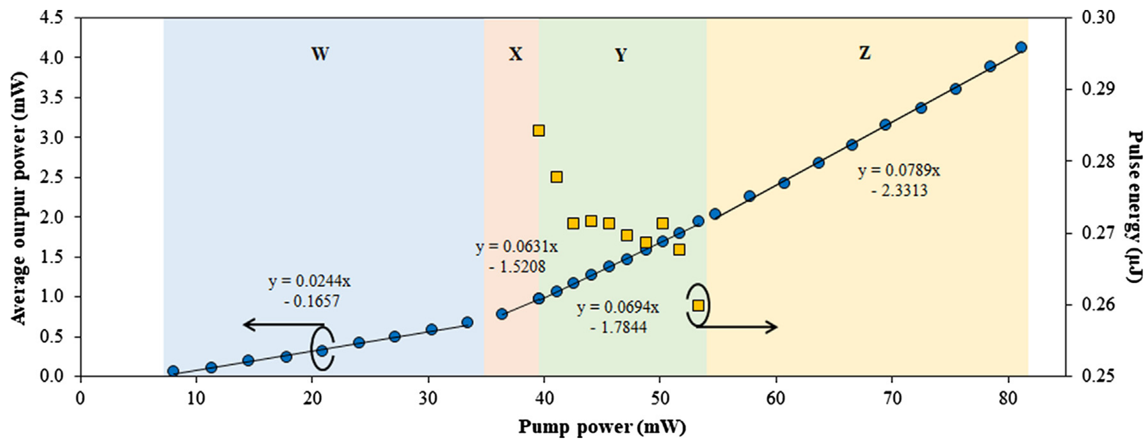

Fig. 8. Power development curve and pulse energy evolution as a function of pump power.

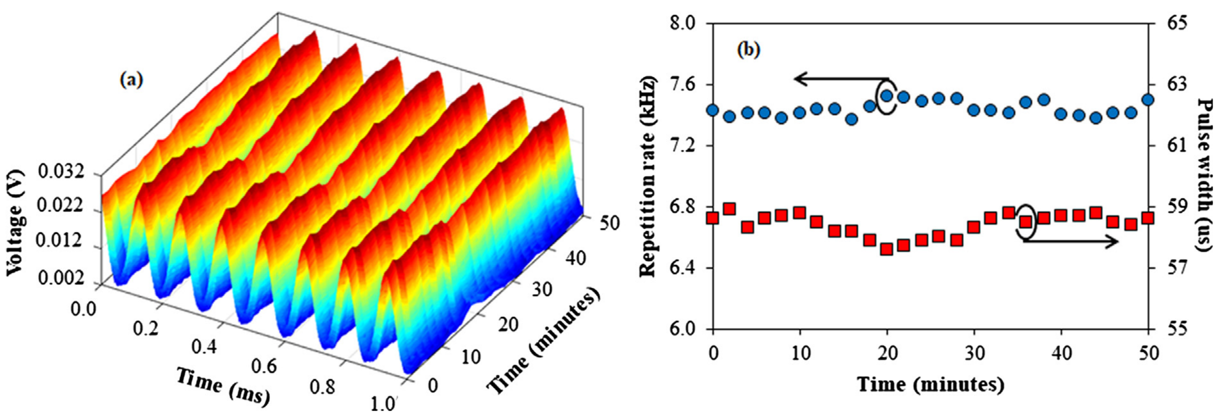

Fig. 9. (a) Pulse laser stability evaluation at 53.3 mW pump power and (b) deviation in repetition rate and pulse width within 50 min.

36.45 mW and laser slope gradient of 6.31%. The Q-switched laser is shown in Region Y with average output power developed from 0.98 to 1.94 mW at a laser slope efficiency of 6.94%. The higher slope efficiency in Region Y than Region X is predicted with the transition from low intensity continuous wave laser [refer Fig. 4(b)] to the Q-switched laser. This laser output power is similar to [16], in which low output power was obtained before approaching to the Q-switching operation. Therefore, the low output power contributes to low laser slope efficiency. The pulse energy was calculated by dividing the average output power by the pulse repetition rate in Region Y. The range of the pulse energy is within 0.2600–0.2843 μJ. After the Q-switched laser was transitioned back to the continuous wave laser, the average output power evolved from 2.03 to 4.12 mW when the pump powers were increased from 54.8 to 81.2 mW at a laser slope efficiency of 7.89% (Region Z). The minor difference in slope efficiency when the Q-switched laser reverts into the continuous wave laser is due to the strong intensity continuous wave laser in Fig. 4(b), which is in agreement with the results in [16].

Fig. 9(a) depicts the evaluation of pulsed laser stability with the pulse train measurement of 53.3 mW pump power over observation time of 50 min. The maximum pump power for the Q-switched laser was chosen since this cut-off value determines the barrier between the Q-switching and continuous wave lasers. Therefore, the ability of 53.3 mW pump power to preserve the Q-switching operation is important to design a stable laser system. Based on the measurement, the Q-switching laser operation was maintained throughout the experimental observation. For instance, the voltages of the pulse train were maintained between approximately 0.002–0.030 V within the observation period. Moreover, the pulses were constantly separated with the pulse repetition time of approximately 0.1338 ms, which matches to the pulse repetition rate of 7.47 kHz. Fig. 9(b) shows the deviation of repetition rate and pulse width as a function of observation time. The standard deviations for the repetition rate and pulse width were deduced as 0.04638 kHz and 0.3609 μs, respectively. The rather small deviation of both parameters presents an overall stable Q-switched laser system.

6. Conclusion

In conclusion, an L-band QSFL was successfully demonstrated by employing a 10 cm gallium/thulium-doped silica fiber as SA. The Q-switched pump power threshold was attained as 39.6 mW with a central wavelength of 1601.93 nm and was observed until 53.3 mW at 1602.00 nm. Within this range, the pulse repetition rate evolved from 3.44 to 7.47 kHz while the pulse width decreased from 100.2 to 58.6 μs with pulse energy ranging between 0.2600 and 0.2843 μJ. The QSFL showed continuous operation within 50 min with the standard deviation in repetition rate and pulse width of 0.04638 kHz and 0.3609 μs, respectively. This success of this work shows the feasibility of developing a low threshold Q-switched seed laser source using gallium/thulium-doped silica fiber as SA that will be useful in many practical applications.

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