Stable nanosecond passively Q-switched all-fiber Erbium-doped laser with a 45° tilted fiber grating

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Nanosecond passive Q-switching generation from an all-fiber Erbium-doped laser with a UV inscribed 45° tilted fiber grating (TFG) is systematically demonstrated. The 45° TFG is employed as a polarizer together with two polarization controllers (PCs) to realize the nonlinear polarization rotation (NPR). Because of the NPR effect, stable Q-switched pulses with an average output power of 17.5 mW, a single pulse energy of 72.7 nJ, a repetition rate of 241 kHz, a pulse width of 466 ns and a signal to noise ratio (SNR) of 58.8 dB are obtained with 600 mW pump power. To the best of our knowledge, the SNR is the highest among all-fiber passively Q-switched Erbium-doped laser. The stability of this Erbium-doped fiber laser (EDFL) is also examined by monitoring the laser consecutively for 5 hours at the laboratory conditions.

OCIS codes: *(140.3510) Lasers, fiber; (060.3735) Fiber Bragg gratings; (140.3540) Lasers, Q-switched; (140.3500) Lasers, erbium*

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1. INTRODUCTION

Nowadays, with the rapid development of pulsed fiber lasers, practical applications which include telecommunications [1], optical coherence tomography [2], optical oscillators [3], remote sensing [4] and nonlinear frequency conversion [5] need to use the Q-switching technique owing to the fact it can achieve high single pulse energy. Generally speaking, Q-switched fiber lasers are mainly divided into two categories using either active or passive system. In opposition to the conventional actively Q-switched fiber lasers which are characterized by easy controlling of pulse repletion rate and high modulation efficiency [6,7], passively Q-switched fiber lasers possess some notable merits, such as compact setups and superior performance of heat dissipation. There are several kinds of methods to realize passive Q-switching in fiber lasers. One of these methods which is used most early is employing the semiconductor saturable absorber mirrors (SESAMs) as the mature Q-switchers, but their operating wavelength range is narrow and expensive [8,9]. Using the transition metal-doped crystals as saturable absorbers (SAs) is another way to obtain stable Q-switched pulses, but the involvement of free space optics would induce extra loss [10,11]. Recently, sandwiched SAs based on nanomaterials (carbon nanotubes, graphene, WS_2, *etc*) are popular in achieving Q-switchers, however at high pump power the laser will either damage the materials or cause the Q-switching turning into mode locking regime [12-14]. To improve the properties of such SAs, the fiber devices which combine both novel materials and optical fiber itself are under a wide range of explorations. Depositing the novel materials onto the D-shaped fibers or fiber tapers, and wrapping a microfiber on a nanomaterial-coated rod have been successively realized by the researchers [15-17]. Nevertheless, the improved damage threshold of such SAs significantly relies on the specialty fiber devices which would surely elevate the cost and complexity of the system. Moreover, these novel materials are expensive and difficult to control. Compared with the before-mentioned methods, nonlinear polarization rotation (NPR) can be employed as an effective SA to achieve Q-switching [18]. The laser cavity based on the NPR technique normally utilizes the inherent nonlinearity from the optical fiber thus can undertake higher damage threshold and features a low cost and compact design. The polarizer which plays an important role in NPR is generally classified as bulk polarizer, and fiber polarizer. Although the bulk polarizer can provide high polarization extinction ratio, the free space optics inevitably break the all-fiber laser concept [19]. The application of fiber based polarizers can be a neat solution to obtain practical NPR in fiber laser. So far, a few types of fiber polarizers have been developed including microstructured fiber based polarizer [21], D-shaped fiber based polarizer [20], and high birefringence polarization fiber [22]. All these types of fiber polarizers require complicated fabrication procedure and manifest high cost devices. Furthermore, the low compatibility of microstructured fiber and polarizing fiber with standard fiber geometry would induce extra loss. D-shaped fiber is more fragile due to the modified fiber structure. In addition, the polarizing fiber would only work in a certain length which would not be an ideal option for compact laser system design.

The UV inscribed 45° tilted fiber grating (45°TFG) in a standard commercial single mode fiber (Corning SMF28e) possesses significant advantages over the above mentioned polarizers including all-fiber structure, environmental robustness and low fabrication cost. Strong polarization dependent loss (PDL) and low insertion loss are two characteristic features of the 45° TFG. While the light propagates through this kind polarizer based on the Brewster's Law, the light will become linear polarized [23]. At applied level, the 45° TFGs are promising for numerous applications, including the PDL equalizer [24,25], polarimeter [26], in-fiber Lyot filter [27], mode locked fiber laser [28], spectrometer [29] and so on. Generally speaking, the 45° TFG is an ideal in-fiber polarization element for NPR facilitated Q-switching implementation.

In this report, we experimentally demonstrate nanosecond passive Q-switched pulses generation from an all-fiber Erbium doped laser based on a 45° TFG, which obtains stable Q-switched output working at 1558.8 nm with a pulse duration of 466 ns, repetition rate of 241.1 kHz, a signal to noise ratio (SNR) of 58.8 dB, a single pulse energy of 72.7 nJ and an average output power of 17.5 mW pumped via a 980 nm hybrid pump module for a maximum pump power of 600 mW. In addition, the laser stability has been examined by monitoring the Q-switched EDFL for 5 hours under maximum available pump power of 600 mW. The demonstrated laser features a genuine all-fiber laser structure. To the best of our knowledge, the SNR of the proposed laser is the highest among all-fiber based passively Q-switched Erbium-doped lasers. Such nanosecond Q-switched fiber laser has potential applications in optical time domain reflectometry (OTDR) and photoacoustic microscopy [30,31].

2. FABRICATION AND PROPERTIES OF A 45° TFG

A CW frequency doubled argon ion 244 nm laser is used for grating inscription in a SMF with the typical phase mask scanning technique to produce the required 45° TFGs. Detailed procedure of the grating fabrication can be found in reference [32]. The effective length of fiber grating is determined by the length of the phase mask which is about 23.8 mm. In the former reports, strong polarization dependent characteristics of these 45° TFGs have been demonstrated. When the light passes through this device, unpolarized light will become linear polarization output [23]. The PDL response and insertion loss of this 45° TFG are measured by a commercial examination kit (LUNA system) together with a tunable laser (Agilent 8164A, 1pm resolution). The examined spectral coverage of such polarizing element is relatively wide ranging between 1525 nm and 1608 nm. Actually, the theoretical spectral coverage could be much wider than the measured coverage owing to the limitation of the tunable laser used in the experiment.

Typical transmission spectrum of a 45° TFG is presented in Fig. 1(a). An average insertion loss of ~4.5 dB can be observed directly from this figure. This total insertion loss consists of 3 dB loss to *s*-light and splicing loss which is caused by the average effect from the two orthogonal polarization mode. Due to the environmental perturbation during the measurement, the insertion loss spectrum does not look flat. There is also an obvious dip in Fig. 1(a) mainly caused by the high-order Bragg reflection which does not have noticeable influence on the polarization functionality of the grating in our experiment. Compared with the non-tilted fiber grating, 45° TFG has a noticeable PDL property as illustrated in Fig. 1(b). It can be seen that the PDL of this 45° TFG is examined over a broad wavelength range in full compliance with the before-mentioned range of the tunable laser. Obviously, the maximum value of PDL at 1560 nm is larger than 30 dB. The PDL response in the examined wavelength region also resembles part of a Gaussian fitting which corresponds well to the theoretical prediction [32]. Nevertheless, > 25 dB average PDL covering total range of the tunable laser manifests the component to be an efficient wideband in-fiber polarizing device operating at ~1550 nm. It is not difficult to take notice of the spectral ripples in Fig. 1(b). This phenomenon can be explained in the following. When the light transmits through the 45° TFG, *s*-light will be coupled out from the fiber core in the form of radiation whose direction is orthogonal to the fiber axis. However, the cladding of traditional optical fiber is limited, then part of the radiated modes are reflected back to the core/cladding boundary from the border between cladding and air to form the oscillation [33]. In addition, with 1pm measurement resolution, due to the high PDL of the device and non-polarization – maintaining measurement facility, 1~2 dB fluctuation would appear across the PDL spectrum. Currently, we have two ways to remove these ripples. One is immersing the 45° TFG in refractive index gel, the other is using a thermal shrinking polymer tube with refractive index matched to the fiber cladding to package the grating. In our experiment, the oscillation in PDL does not have a noticeable influence in the laser performance.

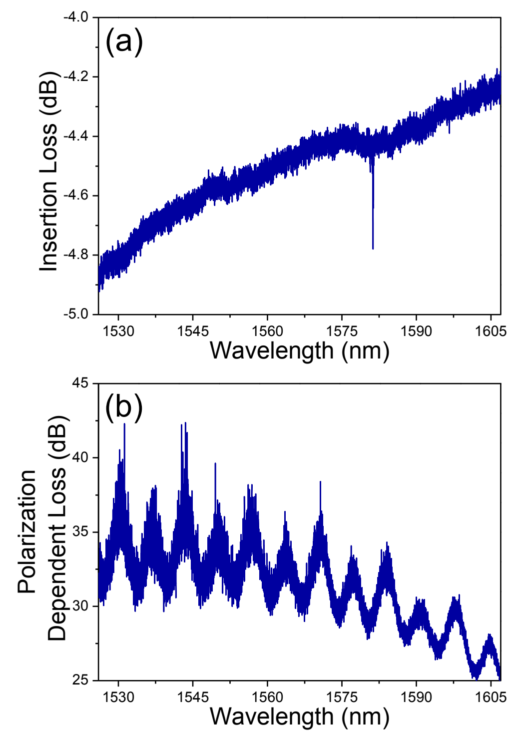

Fig. 1. Measured (a) insertion loss, and (b) PDL response of the 45° TFG from 1525 nm to 1608 nm.

3. LASER SETUP

The schematic setup of this all-fiber passively Q-switched Erbium-doped laser based on a 45° TFG is presented in Fig. 2. This laser cavity mainly consists of a ~100 cm length of heavily doped Erbium-doped laser (EDF) which has a nominal absorption coefficient of ~80 dB/m at 1530 nm and group velocity dispersion β_2 of +66.1 ps^2/km, a segment of ~30 cm OFS 980 with dispersion β_2 of +4.5 ps^2/km and a section of ~241 cm SMF with dispersion β_2 of -22.8 ps^2/km. So, the overall cavity β_2 is estimated to be ~+0.012 ps^2 indicating slightly normal dispersion. If the net dispersion is greatly larger or smaller than zero, mode locking pulse trains would be relatively easy to be obtained so that we could not do a systematic research about Q-switched operation.

This EDF is pumped via a commercial 980 nm benchtop laser (from Ymlasers) which consists of driver and controller with the pump power up to 600 mW. A wavelength division multiplexer (WDM) is used to combine 980 nm and 1550 nm laser transmitting in the EDFL cavity. The unidirectional operation in the cavity is maintained by a fiber pigtailed optical polarization-independent isolator (OIS). A 45° TFG is located between two in-line PCs (PC1 & PC2) to achieve NPR effect for Q-switching operation. 10% of the intracavity laser power is coupled out of total cavity by a 90:10 fiber coupler. The output optical spectrum and pulse trains are monitored by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) and a 1 GHz mixed signal oscilloscope (OSC, Tektronix MSO4104) with a 10 GHz photodetector (PD, Conquer KG-PD-10G-FP), respectively. The radio frequency (RF) spectrum of the Q-switched pulses is analyzed by a 26.5 GHz signal source analyzer (SSA, Rohde & Schwarz FSUP) with a 12.5 GHz photodetector (PD, Newport 818-BB-51F). The output power is monitored by a digital optical power meter (PM, Thorlabs PM100D) with a 100 μW to 2 W stabilized thermal absorber (Thorlabs S302C).

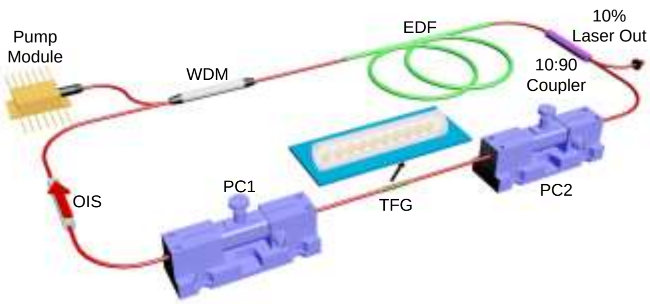

Fig. 2. Schematic diagram of the proposed Q-switched all-fiber Erbium-doped laser using a 45° TFG.

4. RESULTS AND DISCUSSIONS

First of all, the continuous wave (CW) laser state can be easily observed under the pump power of 70 mW in this experiment by properly adjusting the PCs. As the pump power continues to increase, we can obtain a self-started Q-switching with a ~100 mW pump power which belongs to a rather high threshold due to the relatively high loss in the cavity. By using the NPR technique, the light propagated through the 45° TFG will become intensity dependent. Owing to the states of two PCs, the net loss of the total cavity can be high so that laser pulsation enjoys a small nonlinearity; hence, lasing radiation cannot propagate through the polarizer. Therefore, the upper energy level of the Erbium ion will accumulate a large quantity of populations, which is possibly due to the fact that ~10 ms life time of the upper level is much longer than the ~18 ns interval between two adjacent pulses. While both accumulation level and intensity of laser radiation are under a proper situation, the large inverted populations of this cavity will exhaust immediately [34]. Ultimately, passive Q-switching output is formed. By raising the pump power to 600 mW, stable Q-switching pulse can still be obtained. The optical spectrum which possesses a 3 dB bandwidth of 1.3 nm at the central wavelength of 1558.8 nm is recorded, as shown in Fig. 3(a). The corresponding Q-switched pulse trains with a repetition rate of 241 kHz is then shown in Fig. 3(b). The measured average output power is 17.5 mW, corresponding to the single pulse energy of ~72.7 nJ. The profile of Q-switched pulse whose pulse duration is ~466 ns is shown in Fig. 3(c). The measured RF spectrum of this passively Q-switched EDFL is depicted in Fig. 3(d). Furthermore, we can see from the Fig. 3(d) that Q-switching is stable with a SNR of ~58.8 dB.

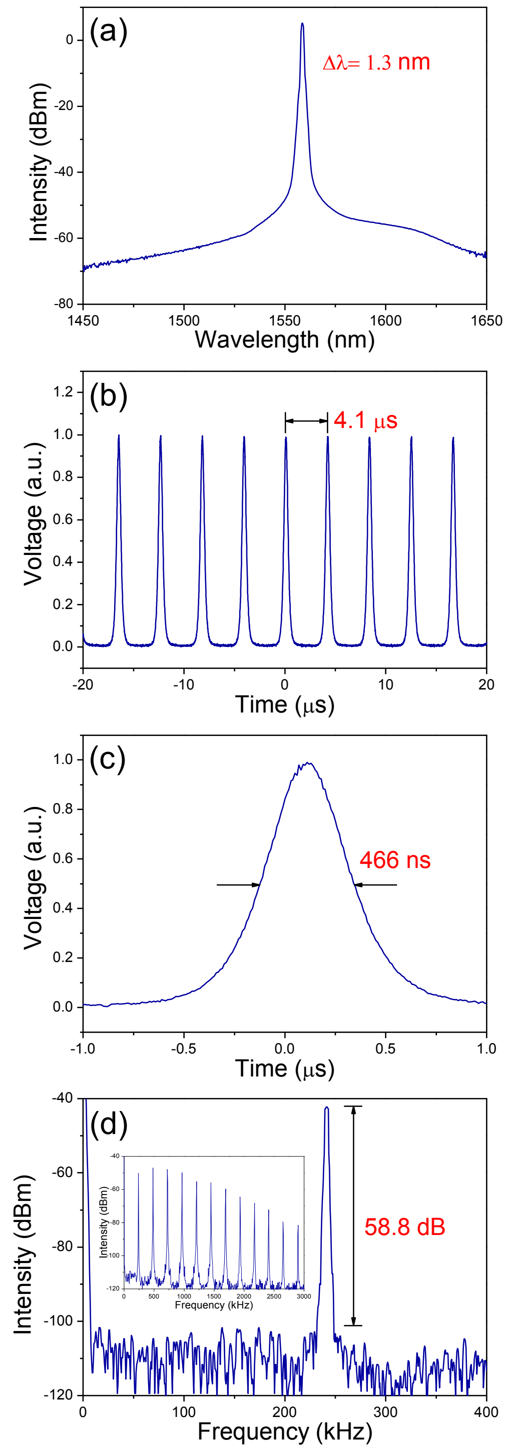

Fig. 3. Measured characteristics of laser under the pump power of 600 mW, (a) Optical spectrum, (b) pulse trains, (c) profile, and (d) RF spectrum with a 400 kHz span and 10 Hz resolution bandwidth. Inset presents the RF spectrum with a 3 MHz span and 500 Hz resolution bandwidth.

Along with the increasing pump powers, the varied repetition rates and pulse widths of output Q-switched pulses are shown in Fig. 4(a). It can be seen clearly that the threshold of Q-switching is ~100 mW. Under the same state of two PCs, with increasing pump power from 100 mW to 600 mW in 50 mW step, stable output pulse width varies from 1598 ns to 466 ns while the repetition rate increases from 113.2 kHz to 241.1 kHz monotonically. A more intuitive change process of the repetition rate and pulse duration with varying pump power from

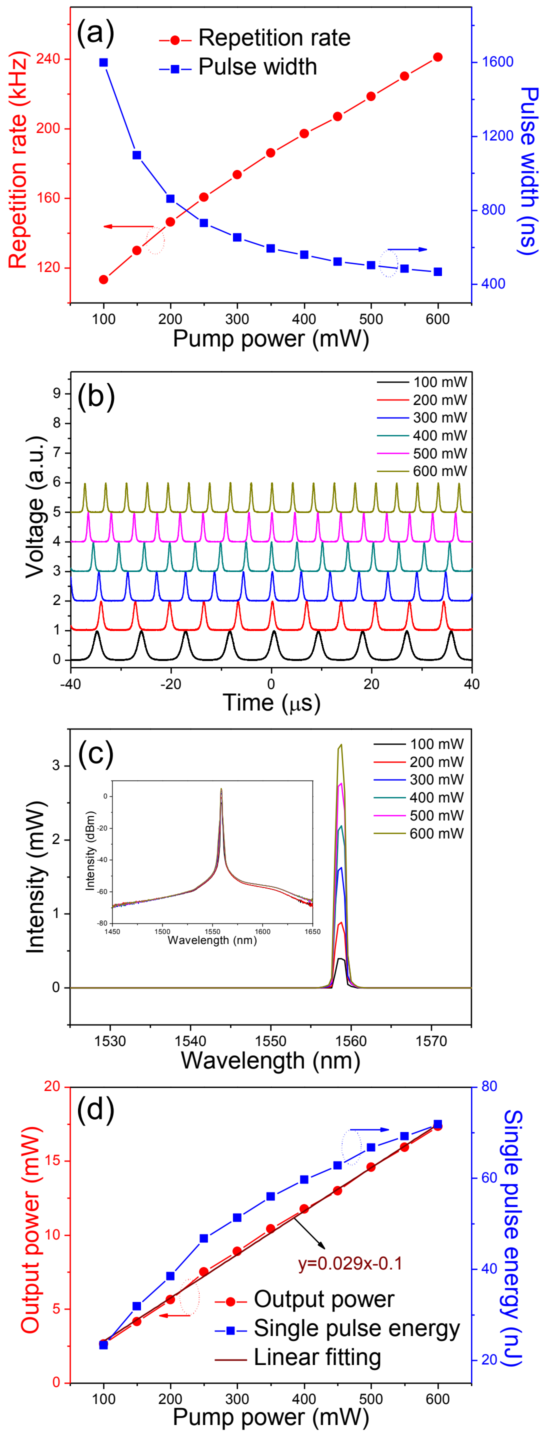

Fig. 4. (a) The pulse duration and repetition rate variations along with increasing pump power, (b) the Q-switched pulse trains under different pump power, (c) the Q-switched optical spectrum under different pump power with linear (mW) and log units (dBm,inset), and (d) the laser output power and pulse energy variations along with elevating pump power.

100 mW to 600 mW in 100mW step is presented in Fig. 4(b). When the pump power increases, higher nonlinearity of the intra cavity makes the saturable absorption effect of pulse become stronger, thus leading to the narrower pulse width. Due to the limitation of pump module, the narrowest pulse duration in this experiment is 466 ns. If the pump power can be further increased, we will get a narrower pulse width. In addition, we can see from Fig. 4(c) distinctly, with the pump power changing from 100 mW to 600 mW, the central wavelength actually keeps fixed with the increase of spectral peak intensity. It indicates the excellent balance between spectral center, bandwidth and peak intensity. During the experiment, single pulse energy is found to elevate with pump power levitation. Moreover, when the pump power is raising, the average output power increases monotonically as illustrated in Fig. 4(d). The slope efficiency of the proposed Q-switched EDFL is ~2.9%. The obtained maximum output single pulse energy is 72.7 nJ under 600 mW pump power. From our perspective, the intra cavity single pulse energy can be promoted further. There are two alternative methods to solve this problem which is caused by low cavity nonlinearity. One is using another 980 nm pump laser whose maximum pump power is higher than 600 mW, the other is employing a high output coupling ratio coupler in the EDFL cavity.

Furthermore, the stability of this EDFL is experimentally verified. Firstly, the optical spectrum of the Q-switched EDFL is successively recorded with the time interval of 30 minutes during 5 hours. As shown in Fig. 5(a), the spectral shape remained almost the same over the evaluation time, manifesting an excellent spectral stability. Besides, the time stability of the single pulse energy and the SNR is also estimated. As presented in Fig. 5(b), 0.5% and 2.5% fluctuations of the single pulse energy and the SNR are obtained, respectively. One needs to notice that due to the NPR effect the laser will not be stable under environmentally under environmental perturbation. This is simply because the mechanical perturbation will either degrade the NPE induced saturable absorption effect or change the intracavity birefringence filtering resulting a central wavelength fluctuation. A polarization maintaining (PM) all-fiber setup can be designed to enhance the stability [35]. This will be for future work.

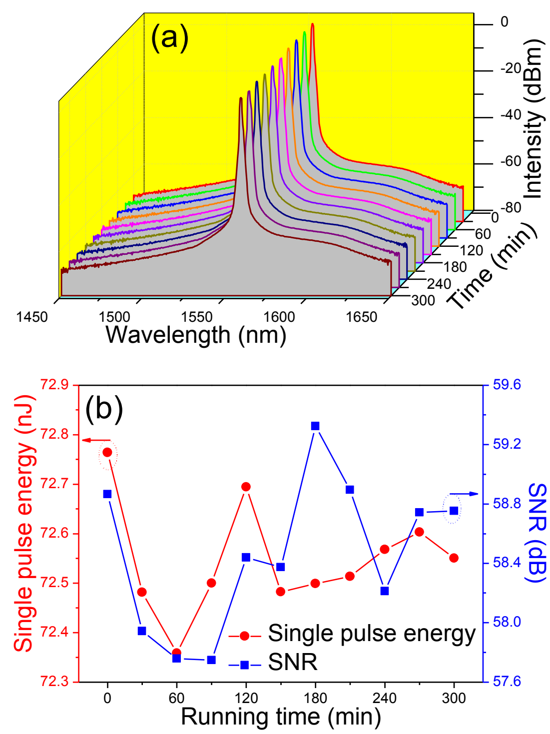

Fig. 5. (a) Optical spectrum evolution and (b) single pulse energy and SNR variations of EDFL within 5 hours running time.

5. CONCLUSIONS

In summary, we have done systematical investigation in nanosecond passive Q-switching generation from an all-fiber Erbium-doped laser with a UV inscribed 45° TFG. Repetition rates variation from 113.2 kHz to 241.1 kHz has been achieved under the pump power variation from 100 mW to 600 mW. In particular, 241.1 kHz Q-switched pulses with a pulse width of 466 ns, an average output power of 17.5 mW, a SNR of 58.8 dB, and the single pulse energy of 72.7 nJ at central wavelength of 1558.8 nm are observed in the experiment. In addition, we also proved that the proposed Q-switched EDFL is able to work for 5 hours to manifest the stability. Moreover, the environmental stability of this EDFL can be further optimized by employing a PM all-fiber laser cavity. This nanosecond Q-switched laser also has potential applications in OTDR and photoacoustic microscopy. The successful demonstration of the application of 45° TFG as the key element of Q-switcher imprints future technological development of efficient all-fiber Q-switched lasers in other wavelength region from which fiber polarizing elements are either expensive or not available.

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