# Widely wavelength tunable gain-switched Er<sup>3+</sup>doped ZBLAN fiber laser around 2.8 μm

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Abstract: In this paper, we demonstrate a wavelength widely tunable gain-switched  $Er^{3+}$ -doped ZBLAN fiber laser around 2.8 µm. The laser can be tuned over 170 nm (2699 nm~2869.9 nm) for various pump power levels, while maintaining stable µs-level single-pulse gain-switched operation with controllable output pulse duration at a selectable repetition rate. To the best of our knowledge, this is the first wavelength tunable gain-switched fiber laser in the 3 µm spectral region with the broadest tuning range (doubling the record tuning range) of the pulsed fiber lasers around 3 µm. Influences of pump energy and power on the output gain-switched laser performances are investigated in detail. This robust, simple, and versatile mid-infrared pulsed fiber laser source is highly suitable for many applications including laser surgery, material processing, sensing, spectroscopy, as well as serving as a practical seed source in master oscillator power amplifiers.

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OCIS codes: (140.3510) Lasers, fiber; (140.3600) Lasers, tunable; (140.3538) Lasers, pulsed; (140.3070) Infrared and far-infrared lasers.

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#### 1. Introduction

Mid-infrared (Mid-IR) laser sources with emission wavelengths around 3 µm, which lie in one of the two main atmospheric windows and also well within the strong water absorption band, are of great scientific and technical interests as a result of their widespread applications in remote sensing, defense, highly precise biological tissue cutting, spectroscopy, chemical and biomolecular sensing, semiconductor micro-structuring, etc [1-4]. Compared with other kinds of lasers, fiber laser has distinct advantages of high conversion efficiency, excellent heat dissipation, good beam quality, compact and robust structure, and ease of integration. In the past decade, fiber lasers in the 3 µm spectral region were also fast developed with the availability of high-purity infrared fibers (e.g., fluoride especially ZBLAN, chalcogenide, etc.) [5–13]. The power has been scaled from ten-watt level in partly free-space arrangements to 30.5 W in an all-fiber scheme [5-8] while the output laser wavelength has been extended from near 3  $\mu$ m [5–8] to well beyond 3  $\mu$ m as well [9–13]. For some practical applications, such as selective excitation, spectroscopic sensors [14] and laser surgery [15], other than high output power, broad wavelength tuning range of the mid-IR sources are also of particular concerned. For example, theoretical study showed that a laser-based cutting and coagulation device could be developed with a laser source that tuned up-and-down the steep slope in the water absorption curve between 2.5 µm and 2.94 µm. Mid-IR solid-state lasers tunable over a wide range with parametric generation of light and a high radiation intensity have been developed and opened up new possibilities for less-invasive, high-precision, laser surgery, first and foremost, in ophthamology and neuro- and cardiosurgery [15]. Rare earth ion doped fluoride fiber lasers have been shown to offer broad tuning characteristics in the Mid-IR spectral region not easily covered with semiconductor sources [14,16–26]. In 2007, Xiushan Zhu et al. demonstrated a wavelength tunable  $Er^{3+}$ -doped ZBLAN fiber laser with a total wavelength tuning range of  $\sim$ 130 nm from 2.7 µm to 2.83 µm and maximum average power of  $\geq 2 \text{ W}$  [20]. However, with the increase in pump power, the continuous wavelength tuning range was fast shrank as a result of the narrowed gain bandwidth caused by enhanced reabsorption process and weakened population inversion associated with shorter-wavelength emissions. Although introducing  $Pr^{3+}$  ions into  $Er^{3+}$ -doped ZBLAN fiber eliminated the shrinkage of wavelength tuning range owing to the relatively small residual populations in the lower energy laser level  ${}^{4}I_{13/2}$ , the wavelength tuning range was still slightly narrowed to ~100 nm from 2700 nm to 2800 nm due to the absence of significant spectrum red-shifting [14]. In 2010, Shigeki Tokita et al. reported a ten-watt-level high power  $Er^{3+}$ -doped ZBLAN fiber laser with a continuous wavelength tuning range of 110 nm from 2770 nm to 2880 nm [21]. The total wavelength tuning range for various pump powers was extended to 170 nm from 2710 to 2880 nm [21]. Very recently, the continuous wavelength tuning range of  $Er^{+}$ -doped

ZBLAN fiber laser was further extended to 157 nm from 2697 nm to 2854 nm reported by J. Liu et al [24]. Besides, wavelength tuning was also carried out in Ho<sup>3+</sup>/Pr<sup>3+</sup> co-doped and Ho<sup>3+</sup>-doped ZBLAN fiber with longer emission wavelengths than those in  $Er^{3+}$ -doped ZBLAN fiber [16,21–23]]. In 2015, Stephanie Crawford et al. reported a Ho<sup>3+</sup>/Pr<sup>3+</sup> co-doped ZBLAN fiber laser with continuously tuning range from 2825 nm to 2975 nm (150 nm) [23]. Recently, Ori. Henderson-Sapir et al. demonstrated a dual wavelength (980nm + 1973nm) cascaded pumped  $Er^{3+}$ -doped ZBLAN fiber laser [11] with 450 nm continuous wavelength tuning range (from 3.33 µm to 3.78 µm) [25] which was also the current broadest level in CW regime. Moreover, wavelength tunable Dy<sup>3+</sup>-doped ZBLAN fiber laser was also firstly presented very recently by Matthew R. Majewski et al. A total wavelength tuning range of 400 nm from 2.95 µm to 3.35 µm was obtained [26].

However, all the wavelength tunable fiber lasers in the 3 µm spectral region discussed above operated in CW regime. Compared with the CW ones, pulsed version of 3 µm fiber lasers could generate light with higher peak powers and shorter temporal durations that were much more preferred in industrial materials modification, infrared countermeasures, nonlinear frequency conversion, etc [27–30]. Recently, Yuxing Tang et al. realized 100 fs pulses with continuously wavelength tuning of  $2 \sim 4.3 \,\mu\text{m}$  through the soliton self-frequency shift in fluoride fibers [31]. Then Simon Duval et al. reported a watt-level femtosecond fiber source tunable from 2.8 µm to 3.6 µm in a more compact fluoride fiber laser system based on the same mechanism [32]. As an alternative, mode-locking can be utilized to realize fs- or pslong pulses [33]. In order to achieve wavelength tuning with ns and longer pulses for tunable 3 µm Mid-IR fiber laser, other techniques such as Q-switching have been utilized [24,34,35]. In 2013, Jianfeng Li et al. reported a wavelength tunable AOM actively Q-switched Ho<sup>3+</sup>doped ZBLAN fiber laser around 3 µm [34]. The continuous wavelength tuning range was 81 nm from 2.95  $\mu$ m to 3.031  $\mu$ m. Recently, they reported a Fe<sup>2+</sup>:ZnSe crystal passively Qswitched Ho<sup>3+</sup>-doped ZBALN fiber laser yielding light with a continuous wavelength tuning range of ~85 nm from 2919.1 nm to 3004.2 nm [35].

As another common technique, gain-switching, by periodically modulating laser gain via pulse pumping, is perhaps the simplest and most robust way to generate ns- and  $\mu$ s-level pulses while offering major practical advantages of compactness, since no external intracavity components are required. Unlike Q-switching, where the parameters of intra-cavity modulators (either actively or passively) play key roles in pulse generation and regulating, gain-switching exhibits higher temporal flexibility since its output pulse duration and repetition rate can be adjusted arbitrarily by the pump conditions (e.g., power, pulse duration, repetition rate). Besides, the simple and compact gain-switched laser is also the preference for the seeder of master oscillator power amplifier (MOPA). Therefore, gain-switching has drawn extensive interest and been employed in fiber lasers operating across the near-IR (845 nm) to Mid-IR (2.8  $\mu$ m) [36–46]. In 2001, B. C. Dickinson et al. reported a 2.7  $\mu$ m pulsed Er<sup>3+</sup>-doped ZBLAN fiber laser pumped transiently on the  ${}^{4}I_{15/2} \rightarrow {}^{4}I_{9/2}$  ground-state-absorption transition at 791 nm and achieved 1.9 mJ of output energy [43]. However, no stable single-pulse gainswitched operation was obtained. In 2011, Martin Gorjan et al. demonstrated a gain-switched laser in the 3  $\mu$ m spectral region with a piece of Er<sup>3+</sup>-doped ZBLAN fiber pumped by 976 nm laser pulses [45]. Stable single-pulse gain-switching with the maximum peak power of 68 W and average power of 2 W was obtained at a repetition rate of 100 kHz. Recently, Yanlong Shen et al. also reported their progress on gain-switching an  $Er^{3+}$ -doped ZBLAN fiber laser at 2.8  $\mu$ m [46], stable single-pulse gain-switching with the switchable repetition rate from 0.5 kHz to 10 kHz was achieved. However, until now, there are no investigations on wavelength tuning properties of the 3 µm Mid-IR gain-switched fiber lasers.

In this paper, we reported a wavelength widely tunable gain-switched  $\text{Er}^{3+}$ -doped ZBLAN fiber laser for the first time. By rotating the plane ruled grating which acted as the cavity end mirror, we achieved an ultra-wide range of wavelength tuning from 2699 nm to 2869.9 nm for various pump power levels, while keeping stable µs-level single-pulse gain-switching with

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controllable duration at a selectable repetition rate. The ~170 nm total wavelength tuning range, to the best of our knowledge, presents the broadest wavelength tuning range of a pulsed fiber laser around 3  $\mu$ m. The reliability of this pulsed operation is characterized by the high optical signal-to-noise ratio (OSNR) of >50 dB and great long-term stability (during 24 hours) (power fluctuation < 4.8%). Influences of pump energy and power on laser output performances were also studied in detail. The results suggested that this laser source was a reliable and cost-effective solution for laser surgery, sensing, spectroscopy and other industrial applications of pulsed lasers in the 3  $\mu$ m spectral region.

## 2. Experimental setup



Fig. 1. Schematic diagram of gain-switched Er<sup>3+</sup>-doped ZBLAN fiber laser.

Figure 1 shows the schematic diagram of the experimental setup of the gain-switched  $Er^{3+}$ doped ZBLAN fiber laser. The pump is a domestic commercial 976 nm laser diode system, operating in either CW or pulse mode in which the pulse duration and repetition rate can be separately adjusted in the range of 13 µs~999 ms and 1 Hz~20 kHz, respectively. The radiation is delivered via a piece of multimode silica fiber with a core diameter of 105 µm and a numerical aperture (NA) of 0.22. The 976 nm pump light was collimated using an aspheric condenser lens with a focal length of 16 mm (labeled as Lens1). Pump injection and laser beam collimation were provided by a CaF<sub>2</sub> plano-convex lens with a focal length of 20 mm (labeled as Lens2). It has a transmittance of ~95% around 2.8 µm (provided by manufacturer). A specially designed dichroic mirror (labeled as DM2) placed at an angle of 45° with respect to the pump laser that has a transmission >90% at the pump wavelength and a reflection >95% for the output Mid-IR laser was used to direct the laser signal output. A dichroic mirror (labeled as DM1) with a splitting ratio of 20:80 at 976 nm was placed between the pump fiber pigtail and DM2 at an angle of  $45^{\circ}$  with respect to the pump laser to direct ~20% pump light onto an InGaAs detector (Thorlabs, DET10C/M) (labeled as Dectector1) connected with a 500MHz digital oscilloscope (RIGOL DS4054) to capture the temporal shapes of the pump pulses. The ZBLAN fiber (FiberLabs, Japan) is doped with 8 mol.%  $Er^{3+}$  ions and has a core diameter of 15 µm with a numerical aperture (NA) of 0.1. The circular inner cladding has a diameter of 250 µm with a NA of 0.4. The cladding launching efficiency and absorption coefficient were measured to be 80% and 2.9 dB/m at 976 nm, respectively, using cutback method. Thus the selected fiber length of 4.1 m provided a total pump absorption efficiency of  $\sim$ 94%. The fiber end close to the pump was perpendicularly cleaved to serve as the cavity feedback and output coupler with the aid of 4% Fresnel reflection. The other end of the fiber, which faced the approximately 95-cm-long free-space cavity, was cleaved at an angle of 10° to prevent parasitic lasing owing to the back reflections into the fiber. The distance of 95 cm was optimized to obtain narrow spectrum bandwidth and broad wavelength tuning range. An un-coated ZnSe objective lens (Innovation Photonics) with a focal length of 6 mm was used to collimate the light from the angle-cleaved fiber end. It has a transmittance of 95% at the wavelength range of  $2.7 \sim 2.9 \,\mu$ m. A plane ruled grating which is blazed at  $3.1 \,\mu$ m with 450 grooves per millimeter and provides an average reflectivity of 86% at 2.7~3 µm was acted as

the cavity end mirror and wavelength tuning component. The output laser from the perpendicularly cleaved fiber end was split into two beams by a dichroic mirror (labeled as DM3) that placed at an angle of  $45^{\circ}$  with respect to the output laser with a measured splitting ratio of 46:54 around 2.8 µm. The average power of the reflected output laser beam was measured with a power meter (Laserpoint) after passing through a bandpass filter (Thorlabs, FB2750-500) with a transmittance of  $71\% \sim 79\%$  at the wavelength range of  $2.7 \sim 2.9$  µm (provided by manufacturer). The transmitted beam was split into two beams again by another dichroic mirror (labeled as DM4) placed at an angle of  $45^{\circ}$  with respect to the output laser with a measured splitting ratio of 49:51. The output laser beam was guided onto an InAs detector (Judson, J12-18C-R01M) (labeled as Dectector2) connected with another channel of the digital oscilloscope to capture the temporal signal pulses. The RF spectrum of signal pulses was measured by a RF spectrum analyzer (YIAI, AV4033A). The optical spectrum was measured using a monochromator using nitrogen cooled photodiode (Princeton instrument Acton SP2300).

#### 3. Results



3.1 Performance of the gain-switching at a fixed wavelength

Fig. 2. Temporal pump and gain-switched pulse trains at the pump power (launched average pump power) of (a) 333.4 mW,(b) 705.6 mW, (c) 707.7 mW, (d) 720.3 mW, (e) 1.84 W, (f) 1.92W. (Pump pulse duration:13 µs, pump repetition rate: 20 kHz).

We firstly studied the temporal evolution of the fiber laser at a fixed wavelength of ~2800 nm corresponding to its free-running wavelength by locking the angle of the plane ruled grating. The repetition rate and pulse duration of the pump laser were fixed at the available maximum and minimum values of 20 kHz and 13  $\mu$ s, respectively. In this case, when the pump power

was increased to 164.2 mW, gain-switching signal was observed but with serious timing jitter and amplitudes fluctuation. Each output pulse was induced by two or three pump pulses due to the low energy of one pump pulse. Note that all the pump powers mentioned in this paper refer to the average pump powers that were launched into the  $Er^{3+}$ -doped ZBLAN fiber. Further increasing the pump power to 333.4 mW leads to stable single-pulse gain-switching, as shown in Fig. 2(a). At this pump level, the populations on the  ${}^{4}I_{11/2}$  level given by one pump pulse was exactly enough for one gain-switched pulse to deplete. The gain-switched build-up time and pulse duration were 17.3 µs and 3.06 µs, respectively, as shown in the inset of Fig. 2(a). Here, the build-up time refers to the time delay of gain-switched pulse relative to pump pulse, reflecting the time needed for the photon density buildup. It is calculated from the front edge of the pump pulse envelope to that of the induced gain-switched pulse envelope and has been utilized in the previous reports [39,41]. This stable single-pulse gain-switched operation can be maintained until the pump power was increased to 705.6 mW. Figure 2(b) shows the temporal pump and gain-switched pulse trains at the pump power of 705.6 mW. The reduced pulse build-up time of 10.9  $\mu$ s and pulse duration of 1.55  $\mu$ s were mainly owing to the faster population accumulation rate on the  ${}^{4}I_{11/2}$  level that directly led to more populations storage. Slightly increased the pump power to 707.7 mW, we observed that the output immediately switched to the chaotic oscillation state showing unstable relaxation spike pulses with serious amplitudes fluctuation as shown in Fig. 2(c). The quite chaotic temporal characteristics of the output are related to mode-hopping and mode competition [47]. When the pump power was increased to 720.3 mW, stable triple-pulse gain-switching was observed as shown in Fig. 2(d) because the pump energy became too large for the first pulse to extract fully the energy stored in the gain medium, thus the second and third pulses were generated. It should be noted that double-pulse gain-switching was not observed during this process but can be obtained by wavelength tuning, indicating that the temporal output waveform was also closely related to the operation wavelength. With the further increase of the pump power, the first and third sub-pulse of each triple-pulse unit got stronger and stronger. Figure 2(e) shows the temporal pulse waveforms at the pump power of 1.84 W, which was the highest pump power for stable triple-pulse gain-switching. Once beyond this pump level, the stable triplepulse gain-switching became unstable relaxation spike pulses again as shown in Fig. 2(f) which was captured at the pump power of 1.92 W. Actually, the output pulses would switch between stable multi-pulse gain-switching and unstable relaxation spike pulses involving more sub-pulses with the increased pump power before the laser reaching CW regime.



Fig. 3. (a) RF spectrum in a narrow scanning range, Inset: RF spectrum at a broad scanning range and (b) optical spectrum of the laser pulses at the pump power of 705.6 mW (launched average pump power). (Pump pulse duration: 13  $\mu$ s, pump repetition rate: 20 kHz)

By quickly switching off the pump after the laser pulse reached some pre-adjusted threshold, further oscillations can be suppressed typical for the transient effect. In this way, only a single laser pulse with short duration and high peak power is obtained consistently from a single pump pulse. Here we focused on the laser output characteristics at the stable single-pulse gain-switched operation state. The RF spectrum, optical spectrum, and long-term

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stability were all measured. Figure 3(a) and its inset show the RF spectra at the pump power of 705.6 mW scanning in a narrow range from 10 kHz to 30 kHz and a broad range from 0 kHz to 800 kHz, respectively. The high OSNR of the fundamental harmonic frequency of ~65 dB (64.3 dB) suggested the high ratio of pulsed components which was even comparable to mode-locking [48–51]. The corresponding optical spectrum is shown in Fig. 3(b) showing a center wavelength (cw) of ~2800 nm and FWHM of ~1 nm. Both output power and temporal waveforms were monitored within 24 hours, excellent stability (power fluctuation<4.8%) and great repeatability proved its high reliability.



Fig. 4. (a) Pulse duration and build-up time, (b) average power, peak power, and pulse energy as a function of pump energy (launched pump energy). (Pump pulse duration:13  $\mu$ s, pump repetition rate: 20 kHz)

Then the influence of pump energy on gain-switched output performances (including pulse duration, build-up time, average power, peak power, and pulse energy) was investigated and the results are shown in Figs. 4(a) and 4(b). In this case, the pump repetition rate and pulse duration were fixed at 20 kHz and 13  $\mu$ s, respectively. It is observed that the pulse duration and build-up time monotonically decreased from 3.06 µs to 1.55 µs and 17.3 µs to 10.9 µs, respectively, while the average power, pulse energy, and peak power increase almost linearly as the pump energy increased from 16.67 µJ to 35.28 µJ. Note that all the average powers mentioned in this paper refer to the deduced values at the perpendicularly cleaved fiber output end based on the measured values. They were estimated by dividing the measured values by a factor of  $(95\% \times (71\% - 79\%) \times 95\% \times 54\%)$  considering the transmittances of Lens2 and the bandpass filter as well as the reflections of DM2 and DM3. The pulse energies and peak powers were estimated according to the measured pulse durations and repetition rates. For the case of increasing the pump energy, the pump range of stable single-pulse gain-switching was 16.67  $\mu$ J~35.28  $\mu$ J. The highest average power of 119.4 mW, pulse energy of 5.97 µJ and peak power of 3.85 W were obtained. For the case of decreasing the pump energy, the pump pulse energy range was slightly blue-shifted to 16.17  $\mu$ J~33.7  $\mu$ J. Similar phenomena were also observed at other tuned wavelengths in our experiment. We supposed that it should be related to the formation mechanism of gainswitched pulses. Further investigation on the mechanism underlying this phenomenon is undergoing.

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Fig. 5. Average power, peak power, pulse energy, and pulse duration as a function of pump power (launched average pump power) by varying repetition rate. (Pump energy: 35.28 µJ)

Moreover, the effect of pump power on laser output performances was also investigated by varying pump repetition rate while keeping the pump energy at 35.28  $\mu$ J. Figure 5 shows the average power, pulse duration, pulse energy, and peak power of the stable single-pulse gain-switched pulses as a function of pump power. It is observed that the average power increases linearly from 17.1 mW to 119.4 mW at a slope efficiency of 25.6% with increasing the pump power from 306.9 mW to 705.6 mW. On the contrary, the pulse duration decreased slower and slower from 2.61  $\mu$ s to 1.55  $\mu$ s. The phenomenon that the pulse duration became independent on the further increased pump power was reasonably expected. The corresponding pulse energy and peak power increased from 1.97  $\mu$ J to 5.97  $\mu$ J and 0.75 W to 3.85 W, respectively. Further pump power improvement was limited by the maximum repetition rate of 20 kHz. Once the pump power was less than 306.9 mW corresponding to the pump repetition rate of 8.7 kHz, stable single-pulse gain-switching disappeared because that the decreased pump repetition rate led to less residual populations on the <sup>4</sup>I<sub>11/2</sub> level before the arrival of next pump pulse, thus the population inversion provided by one pump pulse became insufficient to form a stable gain-switched pulse.

#### (b)<sub>3.5</sub> $(a)^{500}$ 1.0 Average power (mW) (a.u. 0.8 Pulse duration (µs) 400 0.6 3.0 0.4 300 02 2.5 0.0 2730 2760 2790 2820 200 2700 enath (nm)2.0 100 1.5 2730 2765 2800 2835 2870 2730 2765 2800 2835 2695 2695 2870 Wavelength (nm) Wavelength (nm) 264.6 mW - 372.8 mW --- 488.3 mW 538.7 mW --- 573.3 mW



--- 609.0 mW --- 761.3 mW --- 1.14 W



2.46 W

-3.86 W

The wavelength tunability of the stable single-pulse gain-switching was also investigated at the pump repetition rate of 20 kHz and pulse duration of 13  $\mu$ s. Figure 6(a) shows the average powers of stable single-pulse gain-switching at different tuned wavelengths and various pump powers. It is observed that the left tuning edge is red-shifted while the right tuning edge is blue-shifted as the pump power increased from 264.6 mW to 1.14 W. Once the pump power

exceeded 1.14 W, however, both the left and right tuning edges were red-shifted with the increased pump power. Note that at some pump power levels, the stable single-pulse gainswitched operation could not be obtained in some tuned wavelengths which attributed to the either too small or too large intra-cavity gain. Such wavelength ranges corresponded to the gaps between two points with the same color but with no line connected. Moreover, it is also found that with the increased pump power, the total continuous wavelength tuning range becomes broader at first and then narrower. At the pump power of 488.3 mW, the broadest continuous wavelength tuning range of 107.6 nm from 2706.2 nm to 2813.8 nm was obtained. The corresponding optical spectra are shown in the inset of Fig. 6(a) with FWHMs of  $\sim 1$  nm. When the pump power exceeded 1.14 W, the continuous wavelength tuning range only located at the long wavelength region and became narrower and narrower as the pump power further increased. At the pump power of 3.86 W, the continuous wavelength tuning range of the stable single-pulse gain-switched pulses was narrowed to only 1.9 nm from 2868 nm to 2869.9 nm. The maximum average power of 473.3 mW was achieved at 2868 nm. Once the pump power was increased beyond 3.86 W, however, it is difficult to achieve stable singlepulse gain-switching in a continuous wavelength range any more. Accordingly, the broadest total wavelength tuning range of 170.9 nm from 2699 nm to 2869.9 nm for various pump power levels was obtained. Such wavelength tuning range was also the broadest level of  $\sim$ 3 um pulsed fiber lasers. Across the entire wavelength tuning range even at the edges, the gainswitching was always operated at a high OSNR of >50 dB. Figure 6(b) shows the pulse duration of stable single-pulse gain-switching at various pump powers. It is seen that the pulse duration keeps decreasing with the increased pump power for a fixed wavelength. But for a fixed pump power level, the pulse duration decreased at first and then increased roughly with the increased wavelength, corresponding to the gain spectrum of  $Er^{3+}$ -doped ZBLAN fiber. Similar phenomena have been also observed in wavelength tunable gain-switched  $Tm^{3+}$ -doped fiber lasers around 2  $\mu m$  [33,52]. The shortest pulse duration of 1.36  $\mu s$  was obtained at the tuned wavelength of 2714.2 nm at the pump power of 488.3 mW.

#### 4. Discussion

In our case, further scaling the average power of stable single-pulse gain-switching was limited because that higher power would lead to the appearance of unstable relaxation spikes which was a common feature of gain-switching with the increased pump power. Accordingly, the key point to achieve higher average power is to increase the threshold of unstable relaxation spike pulses. The most direct approach is to increase the pump power by increasing its repetition rate at a constant pump energy level. Besides, MOPA structure can be also used to further improve the average power in virtue of its high OSNR and stability.

In addition, pulse narrowing is expected as well. Considering the similarities between Q-switching and gain-switching, it is possible to apply the theories and formulas developed for Q-switching in gain-switching [53]. Specifically, the gain-switched pulse duration can be also expressed as single dimensionless variable  $z = 2g_0 l/\delta$ , where  $2g_0 l$  is the logarithmic small-signal gain and  $\delta$  is the round-trip loss [54]. The cavity round trip time influences the pulse duration directly. Although decreasing the free-space length can efficiently shorten the cavity round trip time, the shortened distance between the plane ruled grating and the objective lens in our system would undoubtedly weaken the wavelength selection capability of the plane ruled grating. Thus decreasing the gain fiber length while improving the rare earth ions dopant concentration in the fiber to ensure enough intra-cavity gain is much more feasible. The second factor that has effect on the pulse duration is the gain-loss contrast which depends on a series of parameters (e.g., output coupling ratio, pump power, component insertion loss). Generally speaking, with higher pump power and smaller component insertion losses, shorter pulse duration is expected.

In terms of wavelength tuning, though slightly extending the continuous wavelength tuning range was available by reducing the residual reflections from the objective lens, much

broader wavelength tuning range should resort to new broadband gain media with flat gain spectra or cascading multi gain media.

#### 5. Conclusion

In conclusion, we have presented a wavelength widely tunable gain-switched  $Er^{3+}$ -doped ZBLAN fiber laser in the 3 µm spectral region for the first time. Broadly tunable single-pulse gain-switched operation over a broad tuning range of 107.6 nm (2706.2 nm~2813.8 nm) at a moderate pump power of 488.3 mW was achieved. The 107.6 nm continuous wavelength tuning range is the broadest wavelength tuning range for the ~3 µm pulsed fiber lasers to our knowledge. By varying the pump power, we achieved an ultra-broad total wavelength tuning range of 170.9 nm from 2699 nm to 2869.9 nm, twice the wavelength tuning range record of the ~3 µm pulsed fiber lasers and comparable to that of the CW fiber lasers. The relative reports are listed in Table 1 as a contrast. The high OSNR of >50 dB and long-term stability (power fluctuation<4.8%) of single-pulse gain-switching across the entire wavelength tuning range were also characterized. In the next step, the MOPA would be exploited to significantly improve its average/peak power and pulse energy at a wavelength tunable regime. This simple, reliable, robust, and versatile Mid-IR pulsed fiber laser source with broad wavelength tuning range and flexibly controllable temporal characteristics provided a new selection for a number of applications such as laser surgery, material processing, sensing, spectroscopy, etc.

Gain	Continuous wavelength tuning range	Total wavelength tuning range	Operation Mode	Year[Ref.]
Ho <sup>3+</sup> ( ${}^{5}I_{6} \rightarrow {}^{5}I_{7}$ )	120 nm (2.83 μm~2.95 μm)	N/A	CW	1990 [16]
$Er^{3+}$ ( ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ )	160 nm (2.67 μm~2.83 μm)	N/A	CW	1992 [17]
$Er^{3+}$ ( ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ )	110 nm (2.7 μm~2.81 μm)	130 nm (2.7 μm~2.83 μm)	CW	2000 [18]
$Er^{3+}$ ( ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ )	100 nm (2.705 μm~2.805 μm)	130 nm (2.7 μm~2.83 μm)	CW	2007 [19]
${\rm Er^{3^+}/Pr^{3^+}} $ ( ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ )	100 nm (2.7 μm~2.81 μm)	100 nm (2.7 μm~2.8 μm)	CW	2008 [14]
${\rm Er}^{3^+}$ ( <sup>4</sup> I <sub>11/2</sub> $\rightarrow$ <sup>4</sup> I <sub>13/2</sub> )	130 nm (2710 nm~2840 nm)	170 nm (2710 nm~2880 nm)	CW	2010 [20]
$\begin{array}{c} \text{Ho}^{3+}/\text{Pr}^{3+} \\ ({}^{5}\text{I}_{6} \rightarrow {}^{5}\text{I}_{7}) \end{array}$	75 nm (2825 nm~2900 nm	N/A	CW	2011 [21]
$Ho^{3+}$ $({}^{5}I_{6} \rightarrow {}^{5}I_{7})$	66 nm (2955 nm~3021 nm)	73 nm (2948 nm~3021 nm)	CW	2012 [22]
$\begin{array}{c} \text{Ho}^{3+}/\text{Pr}^{3+} \\ ({}^{5}\text{I}_{6} \rightarrow {}^{5}\text{I}_{7}) \end{array}$	150 nm (2825 nm~2975 nm)	N/A	CW	2015 [23]
$Er^{3+}$ ( ${}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2}$ )	157 nm (2697 nm~2854 nm)	N/A	CW	2016 [24]
${\rm Er}^{3+}$ ( ${}^{4}{\rm F}_{9/2} \rightarrow {}^{4}{\rm I}_{9/2}$ )	450 nm (3.33 μm~3.78 μm)	N/A	CW	2016 [25]
$\begin{array}{c} Dy^{3+} \\ (^{6}H_{13/2} \rightarrow ^{6}H_{15/2}) \end{array}$	400 nm (2.95 μm~3.35 μm)	N/A	CW	2016 [26]
$\begin{array}{c} \text{Ho}^{3+} \\ ({}^{5}\text{I}_{6} \rightarrow {}^{5}\text{I}_{7}) \end{array}$	81 nm (2.95 μm~3.031 μm)	N/A	Q-switching (AOM)	2013 [34]
$\frac{\text{Ho}^{3+}}{({}^{5}\text{I}_{6}^{5}\text{I}_{7})}$	85 nm (2919.1 nm~3004.2 nm)	N/A	Q-switching (Fe <sup>2+</sup> :ZnSe)	2015 [35]
$\begin{array}{c} \mathrm{Er}^{3^{+}}\\ (^{4}\mathrm{I}_{11/2} \rightarrow ^{4}\mathrm{I}_{13/2})\end{array}$	62 nm (2762 nm~2824 nm)	N/A	Q-switching (TI)	2016 [24]
$Er^{3+} ({}^{4}I_{11/2} \rightarrow {}^{4}I_{13/2})$	107.6 nm (2706.2 nm~2813.8 nm)	170.9 nm (2699 nm~2869.9 nm)	Gain- switching	2017 This work

Table 1. The reports on wavelength tunable fiber lasers in the 3 µm spectral region

# Funding

National Nature Science Foundation of China (NSFC) (61505024, 61435003, 61421002); Fundamental Research Funds for the Central Universities (ZYGX2015KYQD015); Science and Technology Project of Sichuan Province (2016JY0102); Science and Technology Innovation Young Talent Project of Sichuan Province (2016RZ0073).