Cr^{2+}: ZnSe Crystal Based High Power Passively Q-switched Tm-doped Fiber Laser

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Abstract— We presented a passively Q-switched Tm^{3+}-doped fiber laser using Cr^{2+} : ZnSe crystal as saturable absorber. By employing a crystal with 70% initial transmission, stable Q-switched pulses with a repetition rate of 150.7 kHz and pulse duration of 160 ns were achieved at the maximum pump power of 7.13 W. The obtained maximum output power of 1.32 W was also the reported highest level from the Cr^{2+} : ZnSe crystal based passively Q-switched Tm^{3+}-doped fiber lasers. Moreover, an 80% initial transmission Cr^{2+} : ZnSe crystal was also employed to compare. Stable Q-switched pulses with maximum output power of 0.96 W at a repetition rate of 138.1 kHz and pulse duration of 352 ns were obtained at the launched pump power of 4.19 W. Further increasing of the pump power will lead to the unstable Q-switching regime.

1. INTRODUCTION

Pulsed lasers operating at 2 μm eye safe wavelength region have attracted substantial attention owing to their widespread applications in metrology, remote sensing, free-space communication, time-resolved molecular spectroscopy, and mid-IR supercontinuum generation. Comparing to mode-locking, Q-switching provided the potential of delivering high power and high energy pulses, and more compact and flexible scheme would also be obtained if combining the preferred passively Q-switching and the fiber laser. Until now, a variety of passively Q-switched fiber lasers around 2 μm have been reported employing various saturable absorbers (SAs), e.g., semiconductor saturable absorber (SESAM) [2], graphene [3–5] and Cr^{2+} : ZnSe crystal [6–8]. In contrast to the other SAs, Cr^{2+} : ZnSe crystal was more favored in high power and high energy pulsed fiber lasers because of its large damage threshold of $2.8\,J/cm^2$ [9]. J. K. Sahu et al. demonstrated a passively Q-switched Tm^{3+}-doped fiber laser with pulse energy and duration of 12 μJ and 16 ns at 1822 nm, respectively [6]. F. Z. Qamar et al. realized a 1.9 μm single-clad passively Q-switched Tm^{3+}-doped fiber laser producing pulse duration of 330 ns and peak power of 15 W [7]. Y. Tang et al. achieved stable 2 μm passively Q-switching using a short double-clad Tm^{3+}-doped fiber, pulse energy of over 14 μJ and pulse duration of 120 ns at a repetition rate of 53 kHz were obtained.

In this paper, we demonstrated a passively Q-switched Tm^{3+}-doped fiber laser with Cr^{2+} : ZnSe crystals as the SA. Stable Q-switching regimes were both achieved using 70% and 80% initial transmission Cr^{2+} : ZnSe crystals, respectively. In the former case, maximum Q-switched pulse power of 1.32 W with pulse energy and duration of 8.74 μJ and 160 ns at a repetition of 150.7 kHz were achieved. In the latter case, the stable Q-switching was finally terminated at the launched pump power of 4.19 W yielding maximum output power of 0.96 W but free from crystal damage.

2. EXPERIMENTAL SYSTEM

The schematic diagram of Cr^{2+} : ZnSe crystal passively Q-switched Tm^{3+}-doped fiber laser was shown in Figure 1. Two 793 nm diode lasers were used to pump the active fiber through a $(2+1)\times 1$ pump combiner (ITF Canada). One signal port of the pump combiner was perpendicularly cleaved to provide 4% feedback by Fresnel reflection and act as the output coupler. The other signal port was spliced to a 3 m double-clad Tm^{3+}-doped active fiber (Coractive, DCF-TM-6/125) which had a hexagonal shaped inner cladding with a diameter of 125 μm and a numerical aperture (NA) of > 0.45. The core diameter and NA were 6 μm and 0.23, respectively. The pump absorption coefficient at 790 nm was $1.4 \pm 0.3\,dB/m$. In order to avoid the parasitic lasing, the other end of the Tm^{3+}-doped fiber was cleaved at an angle of 8^0. The laser beam from angle cleaved end was collimated via an anti-reflection coated ZnSe objective lens and finally terminated by a broadband Au-coated mirror. A confocal scheme including two same anti-reflection coated plano-covex CaF_2 lens with focal length of 40 mm was inserted between the objective lens and the Au-coated mirror along the light path. Then 70% and 80% initial transmission Cr^{2+} : ZnSe crystals fabricated by

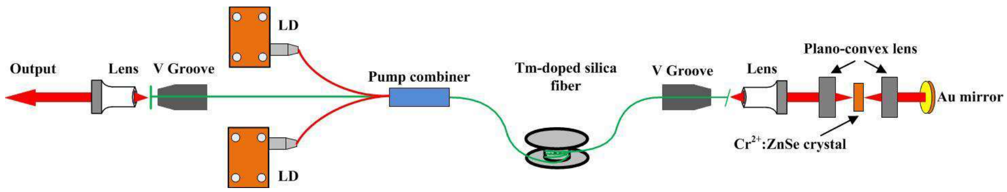

Figure 1: Experimental setup of Cr^{2+} : ZnSe crystal passively Q-switched Tm^{3+}-doped fiber laser.

post-growth thermal diffusion of iron in polycrystalline ZnSe were introduced into the confocal scheme, respectively. At the output end, another objective lens was employed to collimate the output laser and a 2 µm bandpass filter was used to block the residual pump. An InGaAs detector (Photonic Solution ET-5000F) with response time of approximately 28 ps connected with a 500 MHz bandwidth digital oscilloscope was used to monitor the pulse train. An RF spectrum analyzer (Advantest R3267) with resolution bandwidth of 10 Hz to 100 MHz was used to measure the signal-to-noise ratio (SNR) of the pulses. A monochromator with scanning resolution of 0.005 nm (Princeton instrument Acton SP2300) was used to measure the laser spectrum.

3. RESULTS AND DISCUSSION

Firstly, the Cr^{2+} : ZnSe crystal with 70% initial transmission was employed. The oscillator started to operate at continuous wave (CW) regime after reaching the launched pump power of 0.81 W. As the pump power was increased to 1.5 W, stable Q-switched pulses were achieved with corresponding pulse train and envelope shown in Figures 2(a) and (c), respectively. In this case, the obtained pulse width and repetition rate were 198 ns and 21.4 kHz, respectively. The stable Q-switching regime can be maintained to the maximum pump power of 7.13 W as shown in Figures 2(b) and (c), with an increasing repetition rate of 150.7 kHz and decreasing pulse duration of 160 ns. Figure 3(a) shows the measured spectrum of Q-switched pulses at the maximum launched pump power of 7.13 W. The center wavelength and FWHM bandwidth were 1985 nm and 15.3 nm, respectively. Figure 3(b) shows the measured radio frequency (RF) spectrum of the pulse train at a scanning span of 140 kHz and a resolution of 100 Hz. Such high SNR of 56 dB indicated the stable Q-switched operation of this laser.

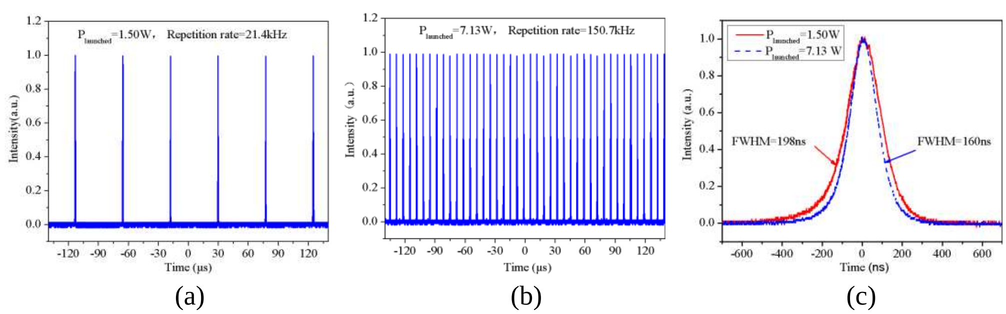

Figure 2: Q-switched pulse train at the launched pump power of (a) 1.5 W, (b) 7.13 W, and (c) their single pulse envelopes.

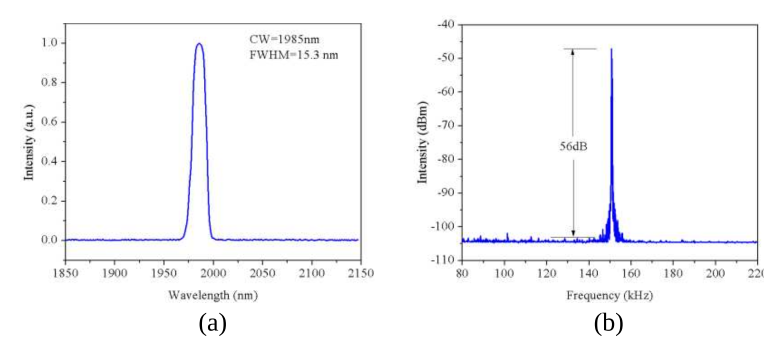

Figure 3: (a) Measured optical spectrum and (b) RF spectrum at the launched pump power of 7.13 W.

The measured repetition rate and pulse duration as a function of launched pump power were shown in Figure 4(a). It is observed that the repetition rate increased almost linearly from 21.4 kHz to 150.7 kHz as the launched pump power increased from 1.5 W to the maximum of 7.13 W. On contrary, the pulse duration decreased as the increased pump power as a result of strengthened cavity net gain which matched well with the typical Q-switched pulses evolution [10–12]. However, the speed of pulse narrowing was dramatically slowed down after arriving at the pump power of ∼4 W due mainly to the fully saturable Cr^{2+} : ZnSe crystal hence the dependence of the duration on the pump was weakened. Figure 4(b) shows the pulse power and energy as a function of the launched pump power. It was observed that the pulse power increased near linearly as the pump power and maximum output power of 1.32 W was achieved at a slope efficiency of 20.1%. The pulse energy also increased near linearly with pump power at the beginning, and then tended to saturate once the pump power was larger than ∼4 W as a result of full saturation of the Cr^{2+} : ZnSe crystal. During the available pump range, the pulse energy increased from 7.58 µJ to 8.74 µJ as the launched pump power was increased from 1.5 W to 7.13 W. Note that the saturation energy of the active fiber was calculated to be 15.7 µJ according to the saturable energy formula which was far beyond the measured value in this case. It indicated that the pulse energy was only limited by the Cr^{2+} : ZnSe crystal and further energy improvement was also expected if Cr^{2+} : ZnSe crystal of higher concentration was employed.

Then, an 80% initial transmission Cr^{2+} : ZnSe crystal was employed to replace the previous one in order to further increase the pulse power as a result of lower cavity insertion loss. The similar pulse evolution as the pump power as before was observed. However, after the pump exceeding the launched pump power of 4.19 W, the stable Q-switched pulses in this case tended to become unstable as shown in Figure 5 until the maximum launched pump power of 7.13 W. If re-adjusting the pump power down to 4.19 W, stable Q-switching re-appeared indicating the Cr^{2+} : ZnSe crystal was free from damage. At this launched pump power, broader pulse duration of 352 ns, higher repetition rate of 138.1 kHz, lower pulse energy of 6.92 µJ with respect to that employing 70% initial transmission Cr^{2+} : ZnSe crystal at the same pump level were achieved with maximum pulse power of 0.96 W at a slope efficiency of 25.8%.

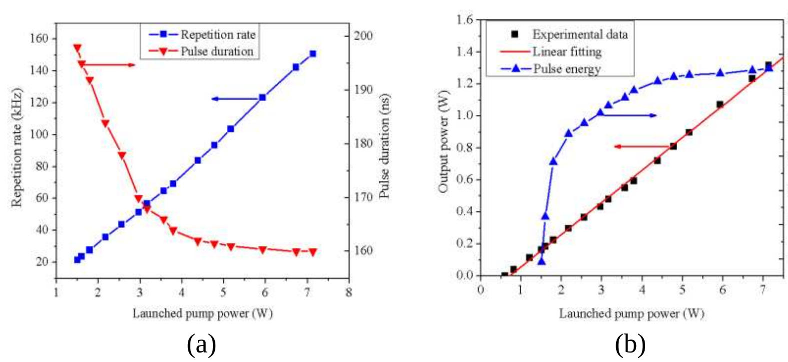

Figure 4: (a) The repetition rate and pulse duration, and (b) the output power and pulse energy of the Q-switched Tm^{3+}-doped fiber laser as a function of the launched pump power.

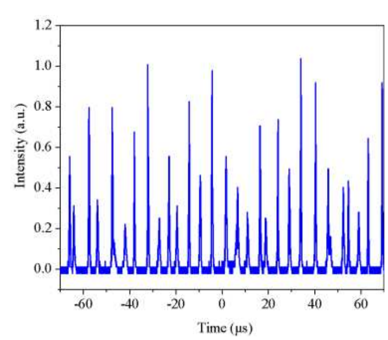

Figure 5: The unstable Q-switched pulse train after the launched pump power of 4.19 W.

4. CONCLUSIONS

In conclusion, we have realized passively Q-switched Tm^{3+}-doped fiber lasers employing 70% and 80% initial transmission Cr^{2+} : ZnSe crystals as the saturable absorber, respectively. In the former case, the pulse duration of 160 ns, pulse energy of 8.74 μJ, repetition rate of 150.7 kHz were achieved at the maximum launched pump power of 7.13 W. The obtained slope efficiency and largest output power were 20.1 % and 1.32 W which was also the highest level generating from the Cr^{2+} : ZnSe crystal based passively Q-switched Tm^{3+}-doped fiber lasers. In the latter case, though stable Q-switching was terminated at the launched pump power of 4.19 W, broader pulse duration, lower pulse energy, higher repetition rate, higher output power and slope efficiency were gained compared to that using the 70% initial transmission Cr^{2+} : ZnSe crystal at the same pump level. Thus if Q-switched pulses of higher output power and slope efficiency were expected, higher initial transmission Cr^{2+} : ZnSe crystal though not benefitting the initiation of Q-switching was preferred. On contrary, lower initial transmission Cr^{2+} : ZnSe crystal was recommended in order to obtain narrower and higher energy Q-switched pulses. Moreover, further pulse narrowing was also possible if shorter cavity was selected, and improved ion concentration of the active fiber was necessary in order to provide enough total cavity gain. The above conclusions can be shifted to crystal-based passively Q-switched fiber lasers operating at other wavelength regions as well, e.g., Co^{2+} : ZnSe crystal based Er^{3+}-doped silica fiber lasers, Fe^{2+} : ZnSe crystal based Ho^{3+}- or Er^{3+}-doped ZBLAN fiber lasers, etc..

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REFERENCES

1. Svelto, O., *Principles of Lasers*, Springer, New York, 2010.
2. Kivistö, S., R. Koskinen, J. Paajaste, S. D. Jackson, M. Guina, and O. G. Okhotnikov, "Passively Q-switched Tm^{3+}, Ho^{3+}-doped silica fiber laser using a highly nonlinear saturable absorber and dynamic gain pulse compression," *Opt. Commun.*, Vol. 16, No. 26, 22058–22063, 2008.
3. Liu, J., J. Xu, and P. Wang, "Graphene-based passively Q-switched 2 μm thulium-doped fiber laser," *Opt. Commun.*, Vol. 284, No. 24, 5319–5322, 2012.
4. Wang, F., F. Torrisi, Z. Jiang, D. Popa, T. Hasan, Z. Sun, W. Cho, and A. C. Ferrari, "Graphene passively Q-switched two-micron fiber lasers," *CLEO Technical Digest*, JW2A.72, San Jose, USA, May 2012.
5. Tang, Y. L., X. C. Yu, X. H. Li, Z. Y. Yan, and Q. J. Wang, "High-power thulium fiber laser Q switched with single-layer grapheme," *Opt. Lett.*, Vol. 39, No. 3, 614–617, 2014.
6. Sahu, J., V. Philippov, J. Kim, C. Codemard, P. Dupriez, J. Nilsson, A. Abdolvand, and N. V. Kuleshov, "Passively Q-switched thulium-doped silica fiber laser," *Conference on Lasers and Electro-Optics*, CThGG7, San Francisco, USA, May 2004.
7. Fadi, Q. Z. and K. A. Terence, "Passive Q-switching of the Tm-silica fibre laser near 2 μm by a Cr^{2+} : ZnSe saturable absorber crystal," *Opt. Commun.*, Vol. 248, No. 4, 501–508, 2005.
8. Tang, Y., Y. Yang, J. Xu, and Y. Hang, "Passive Q-switching of short-length Tm^{3+}-doped silica fiber lasers by polycrystalline Cr^{2+} : ZnSe microchips," *Opt. Commun.*, Vol. 281, No. 22, 5588–5591, 2008.
9. Fedorov, V. V., I. S. Moskalev, S. B. Mirov, T. J. Wagner, M. J. Bohn, P. A. Berry, and K. L. Schepler, "Energy scaling of nanosecond gain-switched Cr^{2+} : ZnSe lasers," *SPIE LASE*, 79121E–79121E-7, San Francisco, USA, Jan. 2011.
10. Li, J. F., H. Y. Luo, Y. L. He, et al., "Semiconductor saturable absorber mirror passively Q-switched 2.97 μm fluoride fiber laser," *Laser Phys. Lett.*, Vol. 11, No. 6, 065102, 2014.
11. Liu, C., C. Ye, Z. Luo, H. Cheng, D. Wu, Y. Zheng, Z. Liu, and B. Qu, "High-energy passively Q-switched 2 μm Tm^{3+}-doped double-clad fiber laser using grapheme-oxide-deposited fiber taper," *Opt. Express*, Vol. 21, No. 1, 204–209, 2013.
12. Laroche, M., A. M. Chardon, J. Nilsson, D. P. Shepherd, W. A. Clarkson, S. Girard, and R. Moncorge, "Compact diode-pumped passively Q-switched tunable Er-Yb double-clad fiber laser," *Opt. Lett.*, Vol. 27, No. 22, 1980–1982, 2002.