A Gain-Switched Fe:ZnSe Laser Pumped by a Pulsed Ho,Pr:LLF Laser *

Ying-Yi Li(李英一), You-Lun Ju(鞠有伦), Tong-Yu Dai(戴通宇)**, Xiao-Ming Duan(段小明), Chun-Fa Guo(郭春发), Li-Wei Xu(徐丽伟)

National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001

(Received 14 January 2019)

We demonstrate a gain-switched Fe:ZnSe laser pumped by a 2958 nm pulsed Ho,Pr:LLF laser. The maximum single pulse energy is 16.4 μJ with a minimum pulse duration of 13.9 ns at the pulse repetition frequency of 1 Hz when the Fe:ZnSe crystal is cooled to 77 K by liquid nitrogen, corresponding to a slope efficiency of 22.9%. The central wavelength and FWHM linewidth are 3957.4 nm and 23.2 nm, respectively. The output energy monotonically decreases as the crystal temperature increases in the range 77–293 K.

PACS: 42.55.Rz, 42.60.Da, 42.60.Jf DOI: 10.1088/0256-307X/36/4/044201

The all-solid-state 3–5 μm lasers which locate in the atmospheric transmission window have played an important role in many fields, such as atmospheric monitoring, laser radar, high resolution spectroscopy and medical care.[1–3] In the last two decades, the divalent Fe-doped Ⅱ–Ⅵ materials have been actively studied as promising active media for this spectral range.[4] Among them, the Fe:ZnSe crystal has received most attention due to its large emission cross section, broad emission spectroscopy and high thermal conductivity. The Fe:ZnSe crystal has a broad absorption band with the peak around 3 μm, and thus Er^{3+} lasers operating from 2.7 to 2.9 μm,[5–13] Cr^{2+} lasers operating from 2.6 to 2.9 μm,[14–16] HF lasers operating at 3.0 μm,[17–26] and D_2 Raman shifted Nd:YAG laser operating at 2.92 μm[27] were used as the pump. However, the available pumps near 3 μm are very limited, which is one of the challenges in the development of Fe:ZnSe lasers. Furthermore, the lifetime of the upper laser state $^5T_2$ of Fe^{2+} reduces quickly with temperature increment due to non-radiative losses, which leads to a strong requirement for sharp pump pulses.[28,29]

In 2012, the Ho,Pr:LLF crystal became a promising material for generating 3 μm lasers[30] and the first Ho,Pr:LLF bulk laser was reported in 2017.[31] Thus it is possible to employ the Ho,Pr:LLF laser as a pump for the Fe:ZnSe laser. In this work, we demonstrate a gain-switched Fe:ZnSe laser pumped by a 2958 nm pulsed Ho,Pr:LLF laser at the pulse repetition frequency (PRF) of 1 Hz. The gain-switching makes the inverted population be deposited very quickly in the upper state such that the gain reaches a level considerably above the threshold before the laser has the time to build up in the resonator,[32–34] and is especially suitable for the Fe:ZnSe crystal. Under the incident pump energy of 98 μJ, the maximum output energy of 16.4 μJ is obtained with the minimum pulse duration of 13.9 ns at 77 K, corresponding to a slope efficiency of 22.9%. The central wavelength and FWHM linewidth are 3957.4 nm and 23.2 nm, respectively.

An optical schematic diagram of the experiment is shown in Fig. 1. In the experiment, a 532 nm frequency-doubled Nd:YAG pulsed laser operating at the PRF of 1 Hz was focused into the KTP crystal as the pump for the KTP-OPO. The KTP-OPO cavity consisted of four flat mirrors laid out as a rectangle. The KTP crystal cut for type Ⅱ phase-matching was adjusted to make the output wavelength 1150 nm, which was located at the absorption peak of the Ho,Pr:LLF crystal. The Ho,Pr:LLF laser had a straight cavity structure, and the 2958 nm output laser and the 1150 nm residual pump were separated with a 45° dichroic mirror.

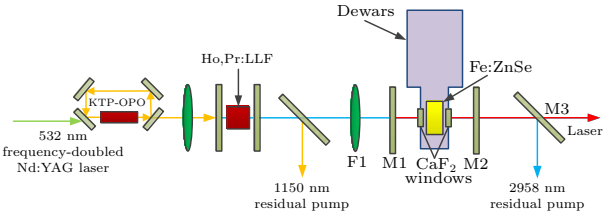

Fig. 1. Scheme of the gain-switched Fe:ZnSe laser.

The straight cavity of the Fe:ZnSe laser was composed of a flat input mirror M1 and an output coupler (OC) M2 with different curvature radii (R). M1 was high-transmission (HT) coated at 2700–3100 nm and high-reflection (HR) coated at 3800–4700 nm, and M2 was coated with different transmittances (T) at 3800–4700 nm. The cavity length (L) was set to be 50, 60 and 70 mm. A 45° dichroic mirror M3 was placed behind the OC to filtrate the residual pump.

The Fe:ZnSe crystal grown by high-pressure vertical zone melting was 4 mm in thickness and $10 \times 10\ mm^2$ in cross section with a Fe^{2+} doping concentration of $5 \times 10^{18}/cm^3$. The uncoated working facets were high-quality polished and parallel to each other within 30″. The crystal was wrapped in indium foil and mounted in a copper heat sink. The temper-

*Supported by the National Natural Science Foundation of China under Grant No 61405047.
**Corresponding author. Email: daitongyu2006@126.com
© 2019 Chinese Physical Society and IOP Publishing Ltd

ature of the crystal was controlled by a cryogenic vacuum Dewars, which had two parallel plane uncoated CaF_2 windows aligned perpendicularly to the optical axis of the cavity, and detected by a thermocouple of PT100. The Ho,Pr:LLF laser was focused via F1 and injected into the center of the Fe:ZnSe crystal along the optical axis.

We performed a study on the output energy by changing the transmittance and curvature of the OC, and the length of the cavity. The Dewars were filled with liquid nitrogen to keep the temperature of the Fe:ZnSe crystal at 77 K. The Ho,Pr:LLF laser had a PRF of 1 Hz, and the maximum single pulse energy was 98 μJ with the minimum pulse duration of 22 ns.

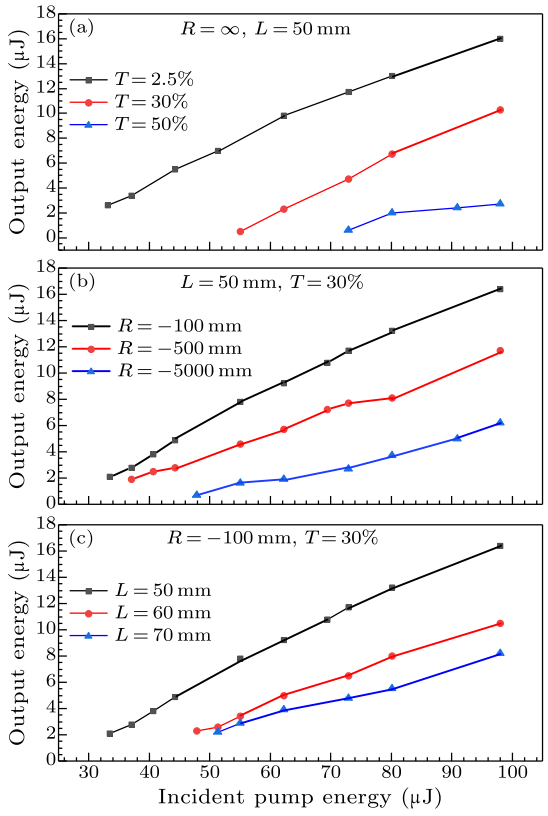

Fig. 2. Dependence of the output energy on the pump energy at different transmittances (a), curvature radii (b) of the output couplers, and cavity lengths (c).

Figure 2 shows the dependence of the output energy on the incident pump energy at different transmittances, curvature radii of the output couplers and cavity lengths at the PRF of 1 Hz. The energy was measured by a Coherent LabMax energy meter with J-10MB-LE sensor (energy range 300 nJ–600 μJ).

When different flat output couplers were employed with $L = 50$ mm, the single pulse energy of the Fe:ZnSe laser reduced as the transmittance increased. Compared with $T = 2.5\%$, the single pulse energies with $T = 30\%$ and $T = 50\%$ are lower, which is attributed to the transmission loss of the resonance.

As the curvature radius of the output coupler increases, the single pulse energy decreases at the same cavity length and transmittance of the output coupler, due to the increasing diffraction loss.

When the cavity length with the output coupler of $R = -100$ mm and $T = 30\%$ is changed, the single pulse energy with $L = 50$, 60 and 70 mm decreases in proper sequence, also due to the increasing diffraction loss.

The maximum output energy of 16.4 μJ is acquired when the output coupler of $T = 30\%$ and $R = -100$ mm is employed with $L = 50$ mm, corresponding to a threshold of 23.1 μJ and a slope efficiency of 22.9%.

The temporal characteristics of the Fe:ZnSe laser and pump were detected simultaneously by a HgCdTe detector (spectral range: 2000–10600 nm, response time: 2 ns), and recorded by a Tektronix MSO 3034 digital oscilloscope (sampling rate: 2.5 GS/s, bandwidth: 300 MHz). A typical temporal profile is shown in Fig. 3, and the minimum pulse duration of the Fe:ZnSe laser was 13.9 ns at the maximum single pulse energy of 16.4 μJ.

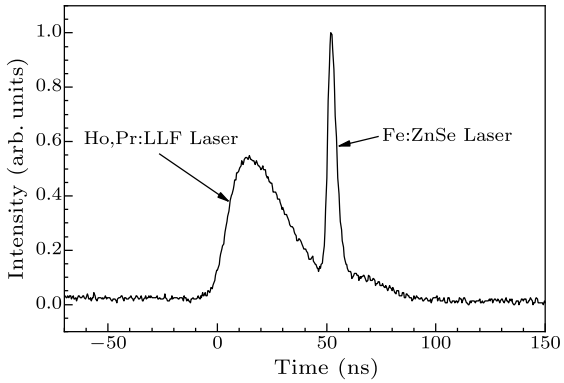

Fig. 3. Temporal profile of the Fe:ZnSe laser (right) and pump (left).

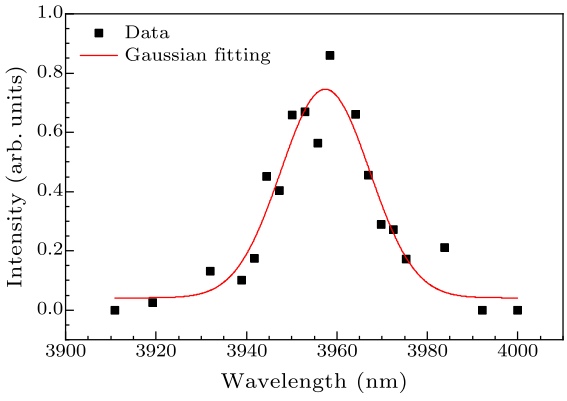

Fig. 4. Output spectrum of the Fe:ZnSe laser.

The wavelength of the Fe:ZnSe laser was recorded with the help of a WDG-30 monochromator (resolution: 0.3 nm). At the maximum single pulse energy of 16.4 μJ, the central wavelength was located at 3957.4 nm with an FWHM linewidth of 23.2 nm, as shown in Fig. 4.

The output energy dependence on the crystal temperature at the maximum pump energy of 98 μJ is shown in Fig. 5. The output energy monotonically decreases with the increase of temperature in the range 77–293 K, which is probably explained by the lifetime of $^5T_2$ decrement caused by the non-radiative losses.

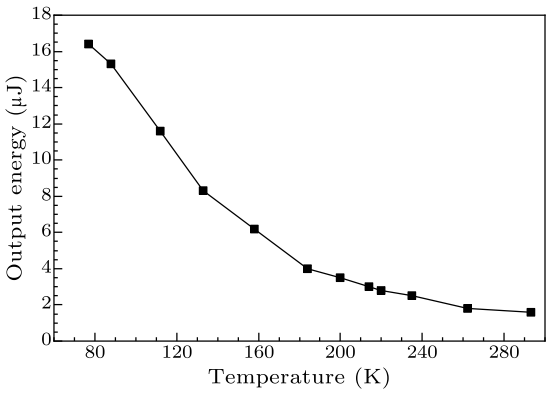

Fig. 5. Output energy dependence on the crystal temperature.

In conclusion, we have reported a gain-switched Fe:ZnSe laser pumped by a pulsed 2958 nm Ho,Pr:LLF laser. The maximum single pulse energy is 16.4 μJ with the pulse duration as short as 13.9 ns, with a PRF of 1 Hz at a temperature of 77 K, corresponding to a slope efficiency of 22.9%. The central wavelength is 3957.4 nm with a linewidth of 23.2 nm. This work demonstrates that the pulsed Ho,Pr:LLF laser is an effective pump for the Fe:ZnSe crystal to generate mid-IR lasers.

References

[1] Zhou Y X, Yu X Y, Xu X C and Dai S X 2012 *Acta Phys. Sin.* **61** 157701 (in Chinese)
[2] Yuan J H, Duan X M, Yao B Q, Li J, Shen Y J, Cui Z, Dai T Y and Pan Y B 2015 *Chin. Phys. Lett.* **32** 084204
[3] Wang S Q, Deng Y, Zhang Y L, Li C, Wang F, Kang M Q, Luo Y, Xue H T, Hu D X, Su J Q, Zheng K X and Zhu Q H 2016 *Acta Phys. Sin.* **65** 044206 (in Chinese)
[4] DeLoach L D, Page R H, Wilke G D, Payne S A and Krupke W F 1996 *IEEE J. Quantum Electron.* **32** 885
[5] Adams J J, Bibeau C, Page R H, Krol D M, Furu L H and Payne S A 1999 *Opt. Lett.* **24** 1720
[6] Fedorov V V, Mirov S B, Gallian A, Badikov D V, Frolov M P, Korostelin Y V, Kozlovsky V I, Landman A I, Podmar'kov Y P, Akimov V A and Voronov A A 2006 *IEEE J. Quantum Electron.* **42** 907
[7] Voronov A A, Kozlovskii V I, Korostelin Y V, Landman A I, Podmar'kov Y P and Frolov M P 2005 *Quantum Electron.* **35** 809
[8] Evans J W, Berry P A and Schepler K L 2012 *Opt. Lett.* **37** 5021
[9] Frolov M P, Korostelin Y V, Kozlovsky V I, Mislavskii V V, Podmar'kov Y P, Savinova S A and Skasyrsky Y K 2013 *Laser Phys. Lett.* **10** 125001
[10] Evans J W, Berry P A and Schepler K L 2014 *IEEE J. Quantum Electron.* **50** 204
[11] Evans J W, Stites R W and Harris T R 2017 *Opt. Mater. Express* **7** 4296
[12] Myoung N, Martyshkin D V, Fedorov V V and Mirov S B 2011 *Opt. Lett.* **36** 94
[13] Kozlovsky V I, Frolov M P, Korostelin Y V and Skasyrsky Y K 2018 *Opt. Express* **26** 24497
[14] Mirov S B, Fedorov V V, Martyshkin D, Moskalev I S, Mirov M and Vasilyev S 2015 *IEEE J. Sel. Top. Quantum Electron.* **21** 1601719
[15] Voronov A A, Kozlovsky V I, Korostelin Y V, Landman A I, Podmar'kov Y P, Skasyrsky Y K and Frolov M P 2008 *Quantum Electron.* **38** 1113
[16] Vasilyev S, Moskalev I, Mirov M, Smolski V, Martyshkin D, Fedorov V, Mirov S and Gapontsev V 2017 *Proc. SPIE. Ultrafast Bandgap Photon. II* (California United States 9–13 April 2017) p 101930U
[17] Velikanov S D, Danilov V P, Zakharov N G, Il'ichev N N, Kazantsev S Y, Kalinushkin V P, Kononov I G, Nasibov A S, Studenikin M I, Pashinin P P, Firsov K N, Shapkin P V and Shchurov V V 2014 *Quantum Electron.* **44** 141
[18] Gavrishchuk E M, Kazantsev S Y, Kononov I G, Rodin S A and Firsov K N 2014 *Quantum Electron.* **44** 505
[19] Firsov K N, Gavrishchuk E M, Kazantsev S Y, Kononov I G and Rodin S A 2014 *Laser Phys. Lett.* **11** 085001
[20] Firsov K N, Gavrishchuk E M, Kazantsev S Y, Kononov I G, Maneshkin A A, Mishchenko G M, Nefedov S M, Rodin S A, Velikanov S D, Yutkin I M, Zaretsky N A and Zotov E A 2014 *Laser Phys. Lett.* **11** 125004
[21] Velikanov S D, Zaretskiy N A, Zotov E A, Kozlovsky V I, Korostelin Y V, Krokhin O N, Maneshkin A A, Podmar'kov Y P, Savinova S A, Skasyrsky Y K, Frolov M P, Chuvatkin R S and Yutkin I M 2015 *Quantum Electron.* **45** 1
[22] Gavrishchuk E M, Ikonnikov V B, Kazantsev S Y, Kononov I G, Rodin S A, Savin D V, Timofeeva N A and Firsov K N 2015 *Quantum Electron.* **45** 823
[23] Firsov K N, Frolov M P, Gavrishchuk E M, Kazantsev S Y, Kononov I G, Korostelin Y V, Maneshkin A A, Velikanov S D, Yutkin I M, Zaretsky N A and Zotov E A 2016 *Laser Phys. Lett.* **13** 015002
[24] Firsov K N, Gavrishchuk E M, Ikonnikov V B, Kazantsev S Y, Kononov I G, Kotereva T V, Savin D V and Timofeeva N A 2016 *Laser Phys. Lett.* **13** 055002
[25] Dormidonov A E, Firsov K N, Gavrishchuk E M, Ikonnikov V B, Kazantsev S Y, Kononov I G, Kotereva T V, Savin D V and Timofeeva N A 2016 *Appl. Phys. B* **122** 211
[26] Velikanov S D, Zaretsky N A, Zotov E A, Kazantsev S Y, Kononov I G, Korostelin Y V, Maneshkin A A, Firsov K N, Frolov M P and Yutkin I M 2016 *Quantum Electron.* **46** 11
[27] Kernal J, Fedorov V V, Gallian A and Mirov S B 2005 *Opt. Express* **13** 10608
[28] Kulyuk L L, Laiho R, Lashkul A V, Lahderanta E, Nedeoglo D D, Nedeoglo N D, Radevici I V, Siminel A V, Sirkeli V P and Sushkevich K D 2010 *Physica B* **405** 4330
[29] Pan Q K, Chen F, Xie J J, Wang C R, He Y, Yu D Y and Zhang K 2018 *Laser Phys.* **28** 035002
[30] Zhang P X, Hang Y and Zhang L H 2012 *Opt. Lett.* **37** 5241
[31] Guo L, Li T, Zhang S Y, Wang M J, Zhao S Z, Yang K J, Li D C and Yan Z Y 2017 *Opt. Mater. Express* **7** 2090
[32] Ding X, Li X, Sheng Q, Shi C P, Yin S J, Li B, Yu X Y, Wen W Q and Yao J Q 2011 *Chin. Phys. Lett.* **28** 094205
[33] Ding X, Zhang H, Wang R, Yu X Y, Wen W Q, Zhang B G, Wang P and Yao J Q 2008 *Chin. Phys. B* **17** 3759
[34] Zhou R L, Ju Y L, Zhao J, Yang C and Wang Y Z 2013 *Chin. Phys. B* **22** 064208