CHIN. PHYS. LETT. Vol. 36, No. 7 (2019) 074201

A 1 kHz Fe:ZnSe Laser Gain-Switched by a $ZnGeP_2$ Optical Parametric Oscillator at 77 K *

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(Received 26 March 2019)

We demonstrate a Fe:ZnSe laser gain-switched by a 2.9 μm $ZnGeP_2$ optical parametric oscillator under pulse repetition frequency of 1 kHz at liquid nitrogen temperature of 77 K. The maximum output power is 63 mW with pulse duration of 34.4 ns. The wavelength covers 3686.6–4088.6 nm and centers at 3897.7 nm. The output power decreases with increasing the temperature of the crystal in 77–222 K.

PACS: 42.55.Rz, 42.60.Da, 42.60.Jf DOI: 10.1088/0256-307X/36/7/074201

Fe:ZnSe lasers have attracted much attention because they have a wide pump band and generate lasing in the spectrum range of 3–5 μm. The free-running, continuous wave, gain-switching and passively Q-switching regimes have been achieved since Adams *et al.*[1,2] demonstrated the first Fe:ZnSe lasing in 1999.

The passively Q-switching and gain-switching are the primary methods to obtain Fe:ZnSe lasers with short pulse duration.[1] Ewans *et al.* reported the only Q-switched Fe:ZnSe laser employed an SESAM as a passive shutter in 2014.[3] Compared with passively Q-switching, the gain-switching makes the inverted population deposit 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,[4–6] which is reported more in research of Fe:ZnSe lasers. In regard to low pulse repetition frequency (PRF) operation, the xenon flash-lamp pumped Q-switched Er:YAG, Er, Cr:YSGG, Er:YSGG lasers[7–14] and HF lasers[15–24] running at several hertz were employed as the pump to generate the Fe:ZnSe lasers with the pulse durations of tens of nanoseconds at room temperature. In regard to high PRF operation, Mirov *et al.* reported a 1 kHz gain-switched Fe:ZnSe laser at room temperature pumped by a gain-switched Cr:ZnSe laser in 2015.[1] We briefly reported another 1 kHz gain-switched Fe:ZnSe laser pumped by a $ZnGeP_2$-optical parametric oscillator (ZGP-OPO) at room temperature in 2015. However, the experimental process and results were not detailed, and the slope efficiency was only 4.8%.[25] For the lack of suitable high PRF pumps around 3 μm, which is located near the absorption peak of the Fe:ZnSe crystal, high PRF gain-switched Fe:ZnSe lasers were less studied compared with those with low PRF. Moreover, high PRF gain-switched Fe:ZnSe lasers running at low temperature have never been reported to date.

In this work, we demonstrate a gain-switched Fe:ZnSe laser pumped by a 2.9 μm ZGP-OPO under the PRF of 1 kHz at 77 K. Under the incident pump power of 250 mW, the maximum output power of 63 mW is obtained with the pulse duration of 34.4 ns, corresponding to an optical-to-optical efficiency of 25.2%. The laser has a broad wavelength range of 3686.6–4088.6 nm with the central wavelength at 3897.7 nm. Compared with the results in Ref. [25], the optical-to-optical efficiency is increased more than 5 times and the laser at this wavelength is more suitable for transmission in air than that with the wavelength of 4450 nm achieved at room temperature.[26]

The experimental setup is schematically shown in Fig. 1. A 2.1 μm electro-optical Q-switched Ho:YAG laser operating under the PRF of 1 kHz was employed as the pump for the ZGP-OPO. The ZGP-OPO had a rectangle cavity structure consisting of four flat mirrors. The signal light had a maximum output power of 250 mW with a pulse duration of 42 ns, used as the pump for the Fe:ZnSe laser.

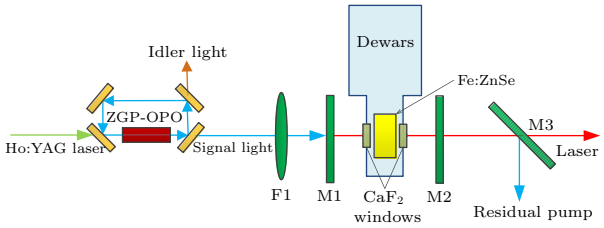

Fig. 1. Scheme of the gain-switched Fe:ZnSe laser.

The ZGP type-Ⅱ phase matching is studied in theory. We solve the following phase-match equation, energy conservation equation, n_e expression and the Sellmeier equations,

$$\frac{n_p^o}{\lambda_p} = \frac{n_s^e(\theta)}{\lambda_s} + \frac{n_i^o}{\lambda_i}, \tag{1}$$

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \tag{2}$$

$$n_e^2(\theta) = \frac{n_o^2 n_e^2}{n_o^2 \sin^2\theta + n_e^2 \cos^2\theta}, \tag{3}$$

$$n_o^2 = 8.0409 + \frac{1.68625\lambda^2}{\lambda^2 - 0.40824} + \frac{1.288\lambda^2}{\lambda^2 - 611.05}, \tag{4}$$

$$n_e^2 = 8.0929 + \frac{1.8649\lambda^2}{\lambda^2 - 0.41468} + \frac{0.84052\lambda^2}{\lambda^2 - 452.05}, \tag{5}$$

*Supported by the National Natural Science Foundation of China under Grant No 51572053, and the Science Fund for Outstanding Youths of Heilongjiang Province under Grant No JQ201310.

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where n, λ and θ represent the refractive index, wavelength, and phase-matching angle, respectively, and the superscripts or subscripts p, s, i, o and e represent the pump, signal, idler, ordinary and extraordinary lights, respectively.[27] The angle tuning curve with $\lambda_p = 2.1\,\mu$m is shown in Fig. 2.

The ZGP crystal we employed is cut for type-Ⅱ phase matching with $\theta = 68.7°$, $\varphi = 90°$ relative to the optical axis. According to Fig. 2, the corresponding signal light wavelength is 2.9 μm.

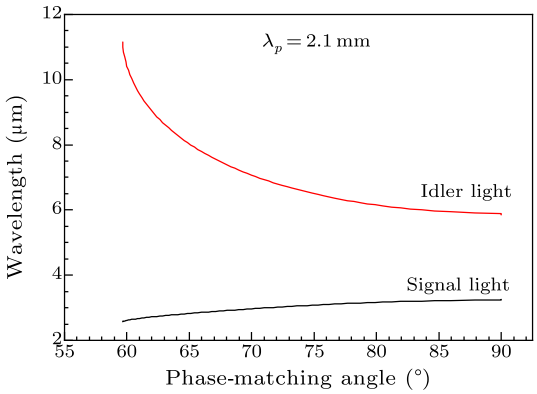

Fig. 2. The angle tuning curve of the ZGP type-Ⅱ phase matching.

The cavity of the Fe:ZnSe laser had a linear structure. The flat input mirror M1 was high-transmission coated at 2700–3100 nm and high-reflection coated at 3800–4700 nm. The flat output coupler M2 was coated with different transmittances at 3800–4700 nm. A 45° dichroic mirror M3 was laid behind M2 to filtrate the residual pump.

The Fe:ZnSe crystal has the dimensions of 10 × 10 mm^2(cross section)×4 mm(thickness), which was grown by high-pressure vertical zone melting with Fe^{2+} doping concentration of $5 \times 10^{18}/\text{cm}^3$. The cross sections were fine polished with a parallel degree within 30" and used as the working facets. The crystal was placed in a vacuum Dewars filled with liquid nitrogen. The Dewars had two parallel plane windows aligned parallel with the cross section of the crystal. The windows of the Dewars and the crystal were not coated. The temperature of the crystal was detected by a PT100 thermocouple, and the resistance value was displayed by a digital multimeter. The 2.9 μm pump was focused by F1 and injected into the crystal along the optical axis of the installation.

We calculate the thermal focal lengths of the Fe:ZnSe crystal at different incident pump powers. The theoretical values of the thermal focal lengths can be estimated by the expression[28]

$$f_{\text{th}} = \frac{\pi K_c \omega_p^2}{P_h (dn/dT)} \frac{1}{[1 - \exp(-\alpha l)]}. \tag{6}$$

The definitions and values of the parameters in the expression are listed in Table 1.

In Table 1, P_h is calculated to be 25.6% of the pump power for the 3.9 μm Fe:ZnSe laser pumped by the 2.9 μm ZGP-OPO, and a is 6.0 cm^{-1} according to our measurement.

The following is the stability criterion of the laser cavity with an internal thin lens caused by heat,[29]

$$0 < g_1 \cdot g_2 < 1, \tag{7}$$

$$g_1 = \left(1 - \frac{L_2}{f_{\text{th}}} - \frac{L_0}{R_1}\right), \tag{8}$$

$$g_2 = \left(1 - \frac{L_1}{f_{\text{th}}} - \frac{L_0}{R_2}\right), \tag{9}$$

where $L_0 = L_1 + L_2 - (L_1 L_2 / f_{\text{th}})$, L_1 and L_2 are the distances of mirrors M1 and M2 from the lens. Because the thickness of the thin lens could be ignored, the values of L_1 and L_2 equal the distances of mirrors M1 and M2 from the center of the Fe:ZnSe crystal.

In our simulation, M1 and M2 are flat mirrors ($R_1 = R_2 = \infty$), L_1 and L_2 are 27.5 and 37.5 mm, respectively, and the cavity length is $L_1 + L_2 = 65$ mm. The results are shown in Fig. 3, where the black dots are the theoretical values of f_{th} determined by Eq. (6), and the red dots are the calculated values of $g_1 \times g_2$. It can be seen that the cavity is stabilized with a thermal lens in the Fe:ZnSe crystal. We analyze the conditions of the cavity lengths equal to 55 and 60 mm in the following experiment, and the cavities are also stabilized.

Table 1. Definitions of the parameters and values of the Fe:ZnSe laser.

Definition, unit	Parameter	Value
Thermal conductivity at 77 K (W·mm^{-1}K^{-1})	K_c	0.1[30]
Pump radius (mm)	ω_p	0.3
Fraction of pump power results in heat (%)	P_h	25.6
Thermo-optic coefficient (10^{-6}/K)	dn/dT	60[31]
Crystal length (cm)	l	0.4
Pump absorption coefficient (cm^{-1})	a	6.0

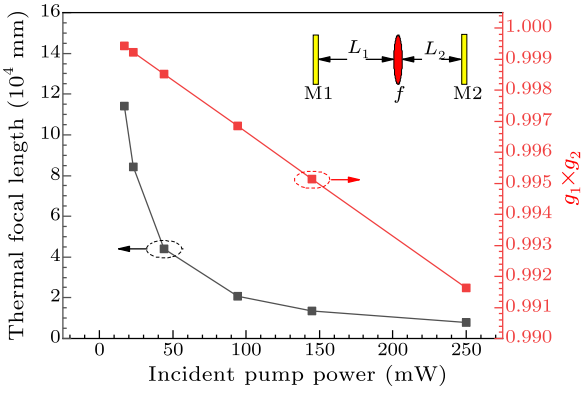

Fig. 3. Theoretical values of f_{th} and $g_1 \times g_2$ at different incident pump powers for the Fe:ZnSe crystal. Inset: geometry of a cavity containing a thin positive lens.

Figure 4 shows the dependences of the output power on the incident pump power at different transmittances of the output couplers (T) and the cavity lengths (L) at the PRF of 1 kHz. The power was measured by an Ophir power meter (power range: 0.1 mW–10 W).

When different flat output couplers were used with $L = 55$ mm, the output power of the Fe:ZnSe laser reduced as the transmittance increases. Compared with $T = 2.5\%$, the output powers with $T = 30\%$ and $T = 50\%$ are lower due to the transmission loss of the

cavity. When the cavity length with the output coupler of $T = 30\%$ is set to be $L = 55$, 60 and 65 mm, the output power decreases in proper sequence, which is attributed to the increasing diffraction loss.

The maximum output power of 63 mW is obtained when the output coupler of $T = 2.5\%$ is used with $L = 55$ mm, corresponding to an optical-to-optical efficiency of 25.2%.

The pulse shape of the Fe:ZnSe laser was detected by a HgCdTe detector (spectral range: 2000–10600 nm, response time: 2 ns), and recorded by a LeCroy Wavesurfer 64Xs digital oscilloscope (bandwidth: 600 MHz, sampling rate: 2.5 GS/s). The pulse duration is 34.4 ns at the maximum output power of 63 mW, as shown in Fig. 5.

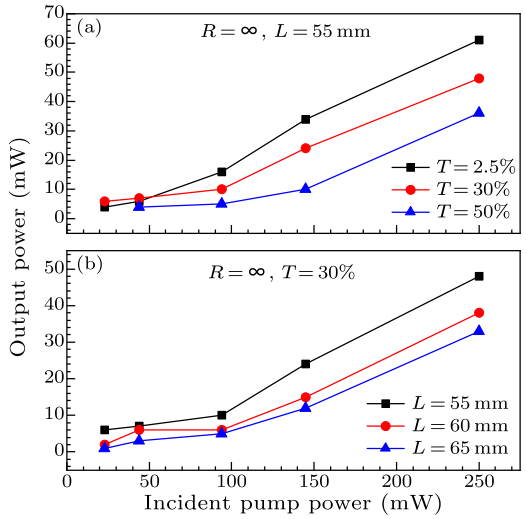

Fig. 4. Dependences of the output power on the incident pump power at different transmittances of the output couplers (a), and the cavity lengths (b).

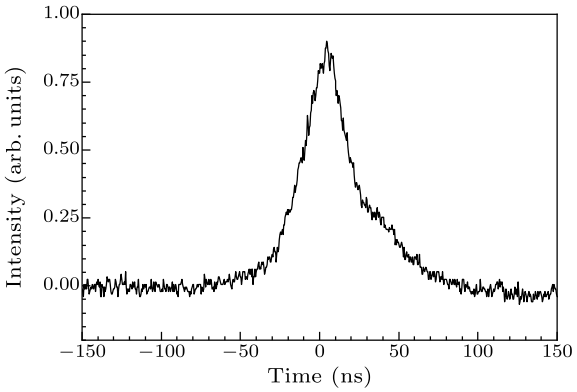

Fig. 5. Temporal profile of the Fe:ZnSe laser.

The wavelength of the Fe:ZnSe laser was measured, taking advantage of an auto-scan monochromator (resolution: 0.3 nm). About 1600 points were collected between 3000 nm and 5000 nm. At the maximum output power of 63 mW, the wavelength is in 3686.6–4088.6 nm and centers at 3897.7 nm, as shown in Fig. 6. The spectrum width is 402 nm due to the board emission spectrum of the Fe:ZnSe crystal.[32]

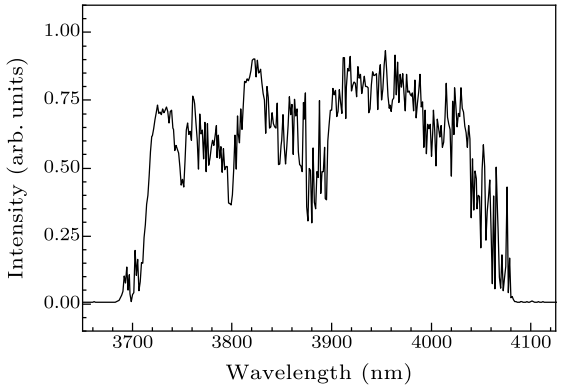

Fig. 6. Output spectrum of the Fe:ZnSe laser.

The output power dependence on the crystal temperature is shown in Fig. 7. The output power decreases with increasing the temperature of the crystal in 77–222 K, due to the lifetime of $^5T_2$ decrement caused by the multiphonon quenching.[32]

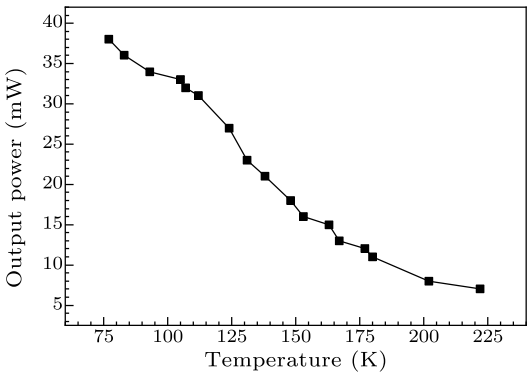

Fig. 7. Output power dependence on the crystal temperature.

In conclusion, we have reported a Fe:ZnSe laser gain-switched by a 2.9 μm ZGP-OPO. The maximum output power is 63 mW with a pulse duration of 34.4 ns under the PRF of 1 kHz at 77 K, corresponding to an optical-to-optical efficiency of 25.2%. The wavelength covers 3686.6–4088.6 nm and centers at 3897.7 nm. It is the first reported Fe:ZnSe laser with such a high PRF at low temperature to date.

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