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Laser parameters of a Fe : ZnSe crystal in the 85 – 255-K temperature range

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Abstract. **The temperature dependence of the efficiency of a laser based on a Fe : ZnSe crystal grown from the vapour phase by the free-growth method is studied in the 85 – 255-K temperature range. As the temperature was increased, the slope efficiency of the laser with respect to absorbed energy decreased from 43 % (at 85 K) down to 9 % (at 255 K) and its emission spectrum shifted from 4.0 to 4.17 µm. Lasing was obtained in a Fe^{2+} : ZnSe crystal cooled with a thermoelectric module down to ~ 220 K. In this case, the slope efficiency of the laser with respect to absorbed energy was 30 %. The output energy of the thermoelectrically cooled laser was 142 mJ for the slope efficiency with respect to the incident pump energy equal to 21 %.**

Keywords: *IR lasers, tunable solid-state lasers, Fe^{2+} : ZnSe laser.*

1. Introduction

A ZnSe crystal doped with Fe^{2+} ions is a promising laser medium for the mid-IR spectral region. The generation of a Fe^{2+} : ZnSe laser was first demonstrated in the spectral region 3.98 – 4.54 µm [1]. In this paper, a Fe : ZnSe crystal grown by the Bridgman method was used. Pulsed lasing was observed in the crystal cooled in the 15 – 180 K temperature range. The maximum slope efficiency (SE) of the laser with respect to absorbed energy was achieved at 150 K to be 8.2 % and the maximum output energy was 12 µJ. The laser spectrum was tuned by varying the crystal temperature.

We obtained [2, 3] much better parameters of a Fe^{2+} : ZnSe laser. In particular, the SE of the laser based on a Fe : ZnSe crystal grown from the vapour phase was 40 % and the maximum output energy was 130 mJ [3]. The laser spectrum was continuously tuned in the 3.77 – 4.40-µm range using a dispersion prism resonator. These results were obtained by cooling the Fe : ZnSe crystal by liquid nitrogen.

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It is obvious that the necessity of using liquid nitrogen is a substantial disadvantage of the laser because this presents considerable inconveniences in the laser operation. In this paper, we studied the parameters of a Fe^{2+} : ZnSe laser in a broad temperature range and analysed the possibility of its operation by cooling the crystal with a thermoelectric module.

2. Fabrication of the active element

The active element of the Fe : ZnSe laser of transverse dimensions 17 × 10 mm and length 10 mm was cut from a Fe : ZnSe single crystal grown from the vapour phase by the free-growth method on a single-crystal seed by using chemical transport in hydrogen. The crystal was doped with Fe^{2+} ions directly during its growth. The growth technology was close to the technology developed for growing the II – VI compound single crystals [4]. The growth was performed from separate sources containing polycrystalline ZnSe and FeSe. The concentration of Fe^{2+} ions measured from the absorption spectrum taking into account the absorption cross section presented in [1] was $\sim 1 \times 10^{18}$ cm^{-3}.

3. Experimental setup

The lasing and spectral characteristics of the Fe^{2+} : ZnSe laser at different temperatures of the active element were studied using a setup shown schematically in Fig. 1. The Fe : ZnSe crystal was mounted at the Brewster angle to the resonator axis on a copper heat conductor inside a vacuum cryogenic chamber with plane – parallel CaF_2 windows also oriented at the Brewster angle. The chamber was made of a stainless steel. The heat conductor was fastened to the bottom of a thin-wall vessel with a liquid cooler. The

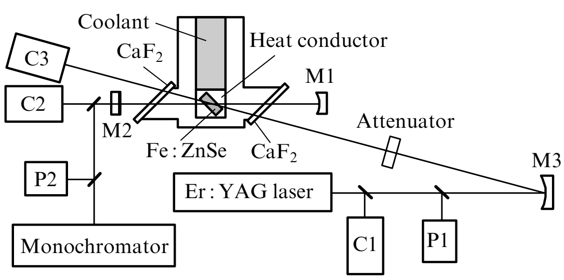

Figure 1. Scheme of the experimental setup: (M1, M2) resonator mirrors; (M3) focusing mirror; (C1, C2, C3) calorimeters; (P1, P2) photodetectors.

resonator of the Fe^{2+} : ZnSe laser was formed by spherical mirror M1 (with the radius of curvature 50 cm) with the reflectivity close to 100 % and plane output mirror M2 with the reflectivity 70 % in the vicinity of $\lambda \sim 4$ μm. The resonator length was 32 cm.

The Fe^{2+} : ZnSe laser was pumped by a flashlamp-pumped free-running 2.9364-μm Er : YAG laser. The Er : YAG laser emitted the 200-μs, 0.75-J pulses. The pump radiation was linearly polarised, with the electric field vector lying in the plane of incidence of the pump beam on the laser crystal and chamber windows. This minimised the losses of pump radiation caused by the Fresnel reflection from the active element and windows of the cryogenic chamber. The pump radiation was incident on the crystal at a small angle ($\sim 2°$) to the resonator axis. The pump beam was focused by spherical mirror M3 with the focal distance 75 cm so that its cross section in front of the crystal had the shape of an ellipse with axes 3 and 3.5 mm. The pump energy was varied by using a set of calibrated optical filters.

The incident pump energy, the output energy of the Fe^{2+} : ZnSe laser, and the pump energy transmitted through the crystal were measured with calorimeters C1, C2, and C3, respectively (IMO-2N average power and energy meters). The simultaneous detection of the incident and transmitted pump energy provided the reliable measurement of the energy absorbed in the crystal. The emission wavelength of the Fe^{2+} : ZnSe laser was measured with a diffraction grating monochromator.

The shape of the pump and output pulses was recorded with photodetectors P1 and P2, respectively (FSG-22-3A2 photoresistors) whose signals were fed to a Tektronix TDS 1012 oscilloscope. The pump pulse had an irregular spike structure, which is typical for multimode pulsed solid-state lasers. The output pulse also consisted of spikes, which at the sufficiently high pump energy followed the pump spikes after the 0.2 – 0.5-μs delay depending on the excess over the threshold.

The temperature dependence of the Fe^{2+} : ZnSe laser efficiency was studied by using liquid nitrogen or ethanol cooled by liquid nitrogen to the required temperature. The temperature of the active element was monitored with a copper-constantan thermocouple whose measuring junction was located inside a hole drilled in a copper heat conductor. The measurement error of the crystal temperature did not exceed 3 K.

4. Results and discussion

We studied the laser characteristics of the Fe : ZnSe crystal at the active element temperature $T = 85 - 255$ K. Figure 2 shows the dependences of the output energy of the laser on the absorbed pump energy obtained at different temperatures. The SE and threshold absorbed pump energy were determined from the straight lines drawn through experimental points by the method of least squares.

Figures 3 and 4 present the combined results demonstrating the temperature dependences of the SE of the laser with respect to the absorbed energy and threshold absorbed pump energy. The maximum SE of the laser amounting to 43 % (the quantum efficiency was 59 %) was obtained at $T = 85$ K. For the pump energy 733 mJ, we obtained (at the same temperature) the maximum output energy of 187 mJ (the absorbed pump energy was 470 mJ).

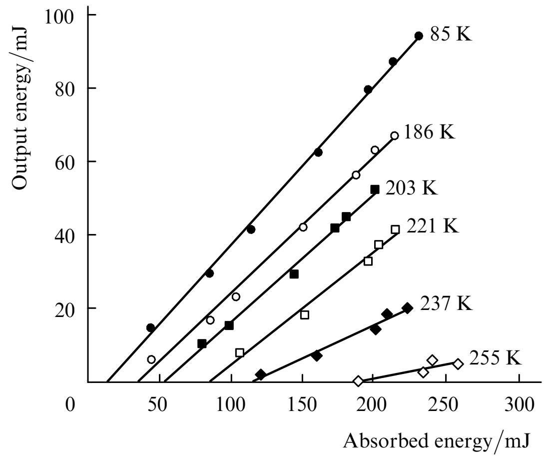

Figure 2. Dependences of the output energy of the Fe^{2+} : ZnSe laser on the absorbed pump energy obtained at different temperatures.

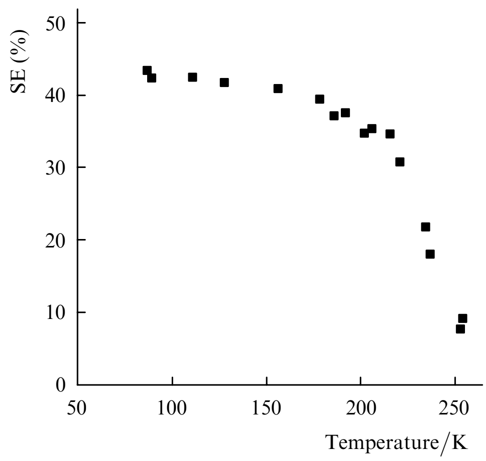

Figure 3. Temperature dependence of the SE of the Fe^{2+} : ZnSe laser with respect to absorbed energy.

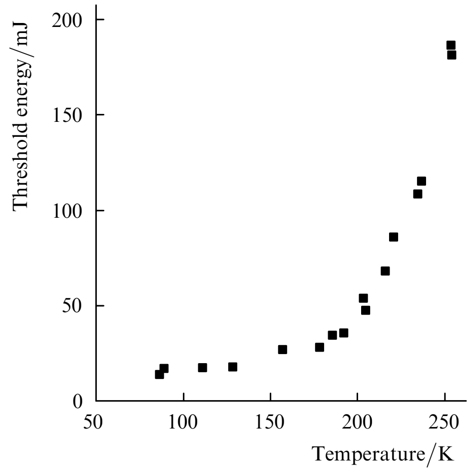

Figure 4. Temperature dependence of the threshold absorbed pump energy.

One can see from Fig. 3 that the SE of the Fe^{2+} : ZnSe laser monotonically decreases with temperature in the entire temperature range 85 – 255 K. This contradicts to the results obtained in [1], where lasing was observed only for $T <$ 180 K and the maximum efficiency was obtained at $T =$

150 K. One can see from Fig. 4 that the threshold pump energy of the laser equal to 15 mJ at $T = 85$ K drastically increases at temperatures above 200 K, which is probably explained by the decrease in the lifetime of the upper laser level due to relaxation [1].

The red temperature shift of the emission spectrum of the laser (Fig. 5) is caused by the red temperature shift of the long-wavelength edge of the absorption spectrum of the Fe : ZnSe crystal [1]. The laser wavelength increased from 4 μm at 85 K to 4.17 μm at 255 K, which differs from the spectral shift from 3.98 to 4.54 μm observed in [1]. This can be explained by the spectral dependence of the reflectivity of our output mirror, which decreased from 70 % at 4 μm down to 59 % at 4.5 μm.

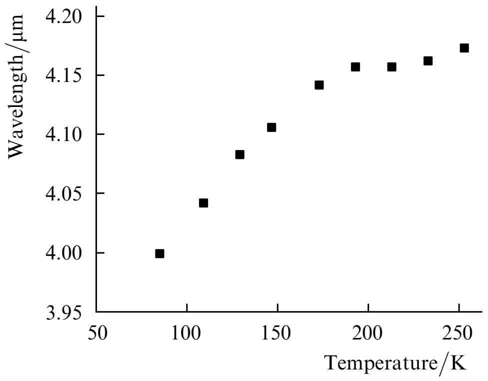

Figure 5. Temperature tuning of the Fe^{2+} : ZnSe laser wavelength.

The data presented above showed (Fig. 3) that the SE of the laser with respect to the absorbed pump energy exceeded 30 % at the crystal temperature below 220 K. Because the temperature 220 K can be easily achieved using a two-stage thermoelectric cooler, we studied in this paper the characteristics of the laser with a thermoelectric cooler.

To work with a thermoelectric cooler, we constructed a cryogenic chamber made of duralumin. The heat-releasing surface of the thermal module was in thermal contact with a massive bottom of the chamber at temperature close to room temperature. A two-stage thermal module was used whose surface under our experimental conditions had, according to the certificate, the temperature ~ 220 K. The crystal temperature was not measured in this case. The optical scheme of the setup remained the same.

The dependence of the output energy of the laser on the absorbed pump energy obtained by cooling the crystal with the two-stage thermal module is shown in Fig. 6. For the absorbed pump power 370 mJ, the maximum output energy was 91 mJ (the incident pump power was 718 mJ). The SE of the laser with respect to absorbed energy was 30%. The data presented in Fig. 6 are in good agreement with the data obtained at 221 K by cooling the crystal with ethanol (Fig. 2).

The laser element used in the study had considerable transmission at the pump wavelength, whose value depended on temperature. Our measurements showed that the crystal cooled by the thermal module transmitted in the lasing regime 48 % of the incident pump energy. This considerably restricted the SE of the laser with respect to the incident pump energy, which was 14.5 %. To increase the SE, we mounted two additional aluminium mirrors, which

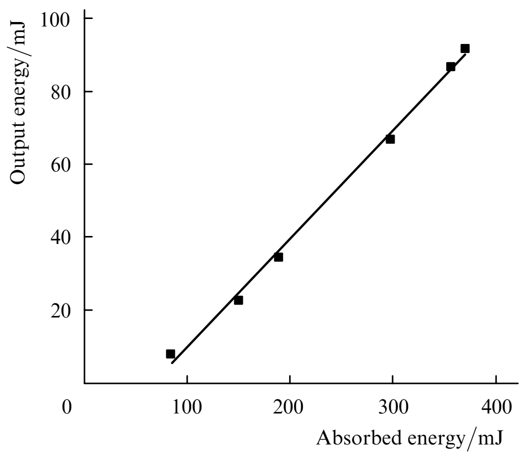

Figure 6. Dependence of the output energy of the Fe^{2+} : ZnSe laser on the absorbed pump energy upon thermoelectric cooling of the laser crystal.

returned the transmitted pump radiation to the crystal so that it intersected the optical axis of the resonator at an angle of $\sim 4^\circ$ at the crystal centre. The dependence of the output energy of the Fe^{2+} : ZnSe laser on the total pump energy after the round-trip transit of the pump radiation in the active element is presented in Fig. 7. The most efficient use of the pump radiation resulted in the increase in the output energy of the laser with thermoelectric cooling to 142 mJ for the incident pump energy 746 mJ. The SE of the laser with thermoelectric cooling with respect to the incident pump energy was 21 %.

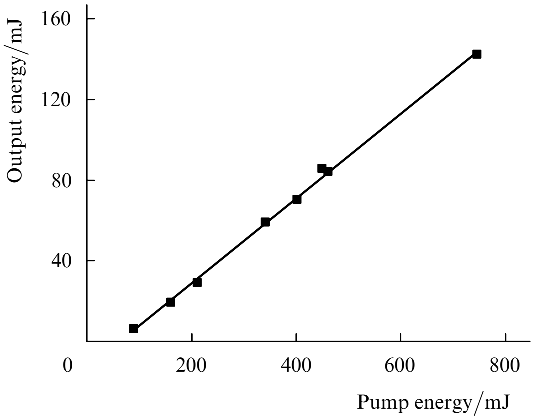

Figure 7. Dependence of the output energy of the Fe^{2+} : ZnSe laser on the incident pump energy upon the round-trip transit of the pump radiation in the active element.

Therefore, the optimisation of the laser resonator (selection of the optimal reflectivity of the output mirror, elimination of intracavity losses at chamber windows, better matching of the pump and lasing regions) will possibly provide even higher parameters of the Fe^{2+} : ZnSe laser.

5. Conclusions

We have studied the generation of the Fe^{2+} : ZnSe laser in the 85–255-K temperature range. The SE of the laser with respect to absorbed energy decreased with temperature from 43 % (at 85 K) down to 9 % (at 255 K), and its emission spectrum shifted from 4.0 to 4.17 μm. We have observed for the first time the generation of the $Fe^{2+}:ZnSe$ laser by cooling the laser crystal with a thermoelectric element. In this case, the SE of the laser with respect to absorbed energy was 30 %. We have shown that the SE of the thermoelectrically cooled laser with respect to the incident pump energy can exceed 20 %.

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