

LASERS

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Fe^{2+}:ZnSe laser pumped by a nonchain electric-discharge HF laser at room temperature

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Abstract. **The characteristics of a Fe^{2+}:ZnSe laser in a scheme with transverse pumping by a nonchain electric-discharge HF laser at room temperature are studied. Doping of ZnSe crystals with Fe^{2+} ions was performed by diffusion simultaneously through two surfaces under the conditions of thermodynamic equilibrium. It is found that the Fe^{2+}:ZnSe laser pulses are modulated by short spikes (3–7 ns at half maximum at low pump energies), whose number decreases and modulation depth increases as the pump energy decreases to a threshold value. A laser pulse energy of 30.6 mJ is achieved at a pulse duration at half maximum of ~125 ns (at high pump energies); the possibility of a further increase in the energy of Fe^{2+}:ZnSe lasers pumped by nonchain HF lasers is discussed.**

Keywords: *Fe^{2+}:ZnSe laser, nonchain HF laser, transverse optical pumping.*

1. Introduction

High-power laser radiation in the spectral range 3–5 μm is of great interest for scientific investigations and some technical applications, which stimulates intense search and study of new promising materials for creating high-power and compact lasers emitting in this region. Special attention is paid to Fe^{2+}-doped ZnSe crystals, in which the authors of [1] observed for the first time lasing at the wavelength $\lambda = 4.0–4.5$ μm at temperatures from 15 to 180 K upon pumping by an Er:YAG laser. Subsequent investigations with short pump pulses (in the *Q*-switching mode of operation) [2] showed that lasing in this material in the wavelength range 3.9–4.8 μm can be obtained at room temperature as well. In a recent work [3], in which a Fe^{2+}:ZnSe crystal was pumped by an Er:YAG laser in the free-running regime (output energy up to 8 J, total pulse duration ~650 μs, modulation by short spikes with a duration of 0.3–0.5 μs at half maximum), lasing also was observed at room temperature, but its efficiency was low due to a short lifetime of the upper laser level (360 ns at a temperature of 292 K (see [3] and references therein). When the output energy of the Fe^{2+}:ZnSe laser was 42 mJ, the efficiency with respect to the absorbed pump energy was only 0.9% [3]. In [4], a superluminescent mode of operation of Fe^{2+}:ZnSe crystal emission at a wavelength of 4.6–4.7 μm was achieved at room temperature in a scheme with transverse laser pumping. The output energy in [4] was approximately 1 mJ at an incident pump energy of 15 mJ. The specific feature that allowed the authors to achieve these characteristics was that Fe^{2+} ions doped into the ZnSe crystals by the diffusion method were concentrated in a narrow subsurface layer. This distribution of active ions made it possible to efficiently use the pump radiation and simultaneously to obtain a very high gain. A review on lasers based on Fe^{2+}-doped crystals can be found in [5].

The energy of Fe^{2+}:ZnSe lasers at room temperature is limited to a great extent by a low energy of *Q*-switched solid-state pump lasers (Er:YAG and Er:Cr:YSGG lasers with wavelengths of 2.92 and 2.8 μm, respectively). For example, the highest energy of Fe^{2+}:ZnSe lasers (3.6 mJ) achieved to date at room temperature under pumping by a short laser pulse was obtained in [6] using a *Q*-switched Er:Cr:YSGG laser with an energy not exceeding 35 mJ.

Nonchain electric-discharge HF lasers, whose spectrum (2.6–3.1 μm) lies entirely in the absorption range of Fe^{2+} ions in ZnSe crystals, has almost unlimited (from the viewpoint of considered applications) output energy at a pulse duration of ~150 ns and can operate with a high pulse repetition rate (see [7–9] and references therein). Therefore, it is of obvious interest to study the characteristics of a Fe^{2+}:ZnSe laser pumped by a HF laser, which was the aim of the present work. Our main efforts were focused on the demonstration of the possibility of scaling up the energy of a laser described in [4], which was based on a crystal doped by the diffusion method.

2. Experimental setup

Similar to [4], Fe^{2+} ions were introduced into ZnSe crystals by diffusion under the conditions of thermodynamic equilibrium [10] simultaneously through two crystal faces. The thickness of the subsurface layer doped with Fe^{2+} ions was ~100 μm; the concentration of ions in the layer reached ~10^{20} cm^{-3} [4]. The faces through which doping occurred were polished to remove approximately identically thick layers from both surfaces. The transmission of the used crystals in the direction perpendicular to the faces was 6%–20% at the wavelengths of the HF laser. The transmission was determined by the absorption of the two doped layers and by the reflection from the two uncoated faces.

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In the experiments, we used four samples of Fe^{2+}:ZnSe crystals, which differed mainly by dimensions. The dimensions of faces through which the crystal was pumped and the dimensions of the irradiated zones are listed in Table 1. The thickness of the samples was ~1 mm (sample No. 4 was cut from sample No. 2, which was accidentally destroyed). The faces perpendicular to the long side of the irradiated zone (exit faces of the Fe^{2+}:ZnSe laser) were cleaved almost completely parallel to each other. These faces were not additionally treated. Most measurements were performed using sample No. 1. The other samples served mainly for demonstration of the possibility of achieving higher output energies E_{las} and efficiencies η of the Fe^{2+}:ZnSe laser pumped by an nonchain HF laser. Preliminarily, we measured the surface breakdown threshold of samples under action of the pump radiation (we used test samples similar to the samples listed in Table 1). The breakdown threshold corresponded to the pump energy density $E_p^{th} \approx 1$ J cm^{-2}, because of which the pump energy density E_p in our experiments did not exceed 0.9 J cm^{-2}. The experimental scheme is shown in Fig. 1.

Table 1.

Sample number	Sample dimensions/mm	Irradiated zone dimensions/mm
1	13×9	12×8
2	25×11	20×7
3	17×11	17×7
4	12×11	12×7, 12×2.5

The Fe^{2+}:ZnSe crystals were transversely pumped by a nonchain electric-discharge HF laser whose characteristics are described in detail in [11, 12]. The maximum laser energy was 5 J. The radiation was attenuated by calibrated filters F. To control the pump pulse shape and energy, a part of the laser beam was deflected by BaF_2 wedges W1 and W2 to a photodetector FD1 (Vigo-system Ltd) with a time resolution of ~ 1 ns and to a calorimeter C1 (Gentec-EO), respectively. The beam passed through the wedges was focused by a spherical lens L to a diameter of ~25 mm at a distance of 1 cm from the Fe^{2+}:ZnSe laser crystal surface and truncated by a rectangular aperture so that its dimensions on the sample surface corresponded to the irradiated zone dimensions listed in Table 1. The ratio of the HF laser energies in front of aperture A1 and on the sample surface was determined in a separate experiment. For this purpose, we placed a calorimeter instead of the sample. The shape and energy of the Fe^{2+}:ZnSe laser pulse were measured by a photodetector FD2 (Vigo-system Ltd) with a time resolution of ~1 ns and a calorimeter C2 (Molectron). Preliminary measurements showed that the pulses emitted from the two faces of the Fe^{2+}:ZnSe laser crystal have identical energies and similar temporal structures. This makes it possible to simultaneously record the pulse shape and energy without additional beam-splitting wedges (Fig. 1). Rectangular apertures A2 and A3 in Fig. 1 are placed to protect the photodetector and calorimeter from the scattered pump radiation. Signals from the photodetectors were sent to a digital oscilloscope with a transmission band of 500 MHz.

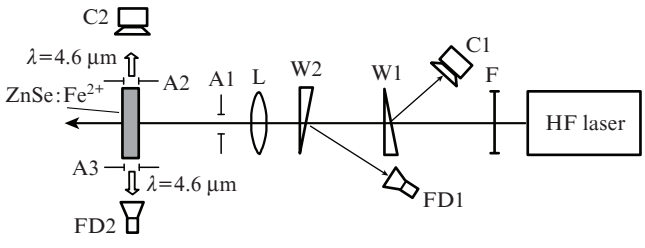

Figure 1. Experimental scheme: (W1, W2) BaF_2 wedges; (FD1, FD2) photodetectors; (A1–A3) rectangular apertures; (C1, C2) calorimeters; (F) calibrated filter; (L) spherical lens; (Fe^{2+}:ZnSe) pumped crystal.

3. Experimental results and discussion

Figure 2 shows the dependence of the Fe^{2+}:ZnSe laser energy E_{las} on the incident pump energy E_p for sample No. 1. One can see that the dependence exhibits a threshold behaviour typical of lasing. The maximum energy E_{las} is 11.7 mJ. Since the laser also emits a pulse with the same energy through the opposite face, the total laser energy is $2E_{las} = 23.4$ mJ.

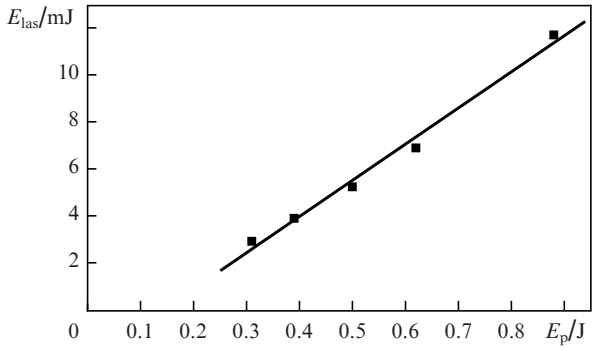

Figure 2. Dependence of the Fe^{2+}:ZnSe laser energy on the pump energy for sample No. 1.

Figure 3 presents the oscillograms of the Fe^{2+}:ZnSe and HF laser pulses (P_{las} and P_p, respectively) recorded at different pump energies. It is seen that the pulses are modulated by short spikes. The duration of individual spikes (at half maximum) in the case of near-threshold pumping is 3–7 ns. Under high-energy pumping (Fig. 3d), when the spike structure is less pronounced, the Fe^{2+}:ZnSe laser pulse duration at half maximum is ~125 ns. Analysis of the oscillograms shows no relation between spikes on the Fe^{2+}:ZnSe laser pulse and spikes on the pump pulse. The temporal structure of pump pulses chaotically varies from pulse to pulse, while the HF laser energy is stable with an accuracy no worse than 5%.

The nature of the spike structure of pump pulses relates to non-simultaneous development of lasing at different transitions of HF molecules, including cascade lasing [13]. The change in the spectral composition of the HF laser radiation during its pulse is not very important for pumping of Fe^{2+}:ZnSe lasers because the absorption coefficients of Fe^{2+} ions are similar for all the lines in the pump pulse [4]. Therefore, the reproducibility of the temporal structure of Fe^{2+}:ZnSe laser pulses is better than that of the pump laser pulses. As is seen from Fig. 3, the number of spikes in the Fe^{2+}:ZnSe laser pulse and its modulation depth depend on the pump energy. As the pump energy decreases closer to the lasing threshold, the number of spikes decreases and the modulation depth increases. A similar temporal shape of pulses (with much longer spikes) is observed for pulsed solid-state

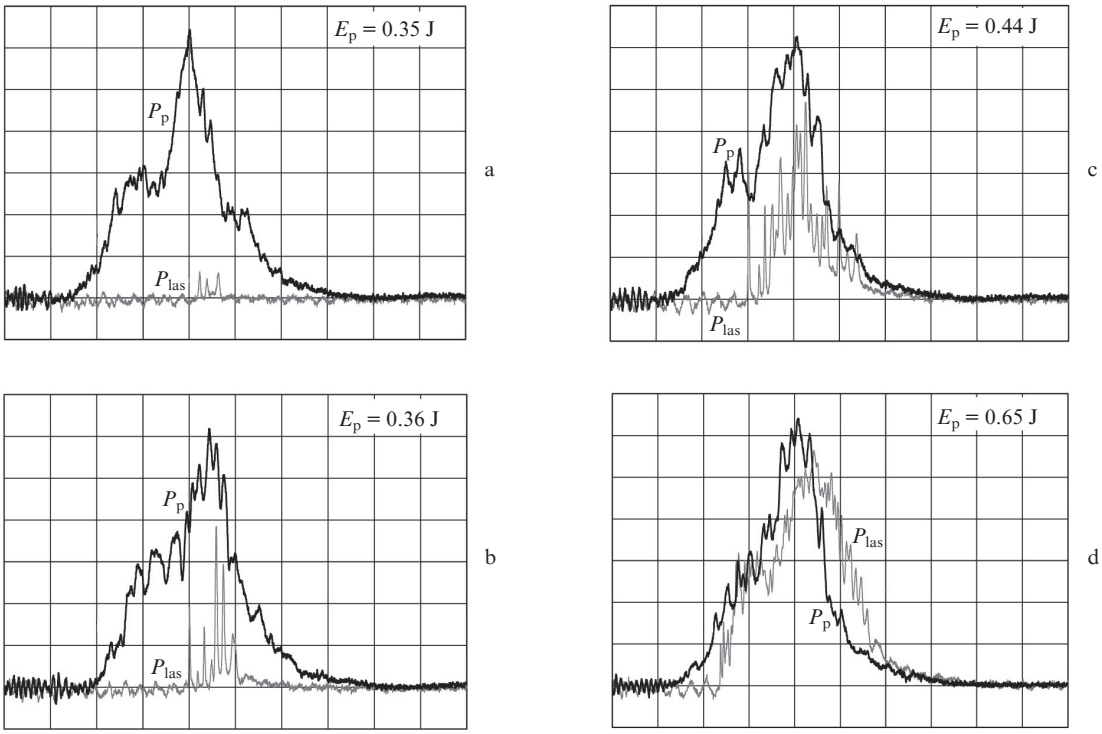

Figure 3. Oscillograms of the Fe^{2+}:ZnSe laser pulses P_{las} and pump laser pulses P_p at pump energies of (a) 0.35, (b) 0.36, (c) 0.44, and (d) 0.65 J. Scan rate 50 ns div^{-1}, sample No. 1.

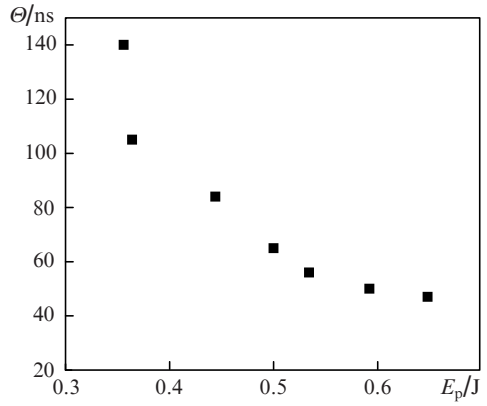

Figure 4. Dependence of the delay time Θ of Fe^{2+}:ZnSe laser pulses with respect to the pump pulse on the pump energy E_p for sample No. 1.

lasers operating in the free-running mode (see, for example, [3]). Form Fig. 3 one can also see that the Fe^{2+}:ZnSe laser pulse is delayed with respect to the pump pulse. The dependence of this delay Θ on the pump energy is given in Fig. 4. Naturally, the delay time decreases with increasing pump energy.

Table 2 presents the maximum output energies E_{las}^{max} and efficiencies $\eta^{max} = 2E_{las}^{max}/E_p^{max}$ [E_p^{max} is the maximum experimental pump energy at which we achieved a maximum efficiency in the case of linear (like in Fig. 2) dependence of the Fe^{2+}:ZnSe laser energy on the pump energy]. The highest E_{las}^{max} = 15.3 mJ was obtained with sample No. 2. Attention is drawn to the spread in the efficiencies for different samples. The highest efficiency (η^{max} = 4.7%) was achieved with the shortest sample No. 4 at an output laser energy comparable with the other samples. We can suggest that this to a great extent depends on the parallelism of the crystal faces, which

Table 2.

Sample number	E_{las}^{max}/mJ	η^{max} (%)
1	11.7	2.9
2	15.3	3.1
3	14.8	3.9
4	14.0	4.7

may serve as cavity mirrors (the parallelism is difficult to control upon manual cleavage of crystal faces).

This suggestion was tested the following way. The irradiated zone width of sample No. 4 was decreased to 2.5 mm. The energy E_{las} was measured at identical pump energies in the ordinary position of the sample (Fig. 5a) and after its rotation around the pump beam axis by approximately 45° (Fig. 5b). This rotation led to a more than twofold decrease in E_{las}. Figure 6 shows the dependence of the Fe^{2+}:ZnSe laser energy (sample No. 4) on the irradiated zone length l at a pump energy density of 0.62 J cm^{-2} and an irradiated zone width of 2.5 mm. This dependence is linear, and the lasing threshold is achieved at $l \approx 3.8$ mm.

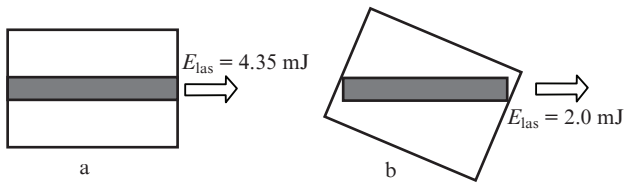

Figure 5. Fe^{2+}:ZnSe crystal (a) in the normal position with respect to the pump beam and (b) rotated by 45° around the pump beam axis. Sample No. 4, irradiated zone width 2.5 mm, pump energy density 0.62 J cm^{-2}.

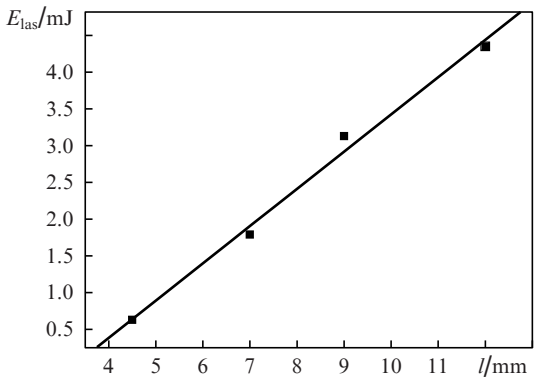

Figure 6. Dependence of the Fe^{2+}:ZnSe laser energy E_{las} on the irradiated zone length l for sample No. 4; irradiated zone width 2.5 mm, pump energy density 0.62 J cm^{-2}.

4. Conclusions

The characteristics of a Fe^{2+}:ZnSe laser in the scheme with transverse pumping by a nonchain electric-discharge HF laser are studied at room temperature. Fe^{2+} ions were introduced into ZnSe crystals by the diffusion method under the conditions of thermodynamic equilibrium simultaneously through two faces of the crystal; the concentration of Fe^{2+} ions in the subsurface layers 100 μm thick was ~ 10^{20} cm^{-3}. It is found that the Fe^{2+}:ZnSe laser pulses have a pronounced spike structure. The number of spikes in a pulse decreases and the modulation depth increases with decreasing pump power. The achieved total output energy of the Fe^{2+}:ZnSe laser is 30.6 mJ, which is almost an order of magnitude higher than the maximum energy obtained at room temperature in [6] under pumping by a *Q*-switched solid-state laser.

It should also be noted that the energy of lasers based on Fe^{2+}:ZnSe crystals with bulk doping (see, for example, [3, 5, 6, 14, 15]) operating in the wavelength range 4.6–4.7 μm under pumping by nonchain HF lasers is determined only by the size of the crystal. In the case of samples doped by the diffusion method, in which dopant occupies only a thin subsurface layer, high energies can also be achieved simply by increasing the crystal surface through which the diffusion of dopant occurs and then the crystal is optically pumped.

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