 

*LASERS*

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# Room-temperature $Fe^{2+}$:ZnS single crystal laser pumped by an electric-discharge HF laser

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***Abstract.*** **A room-temperature laser based on a $Fe^{2+}$:ZnS single crystal has been studied. The crystal was pumped by a nonchain electric-discharge HF laser with a light pulse FWHM of ~140 ns. The pump spot diameter on the crystal surface ($d$) varied from 3.9 to 11.6 mm. The slope efficiency at these values of $d$ was 37%–39%, respectively. The maximum laser energy was 380 mJ (at $d$ = 11.6 mm) with the total efficiency with respect to the absorbed pump energy of ~19%. A further increase in the laser energy was not achieved because the crystal was destroyed at an incident pump energy and power of 3.4 J and ~24 MW, respectively. The damaged region has a form of a long narrow channel shifted from the entrance surface inside the active element.**

***Keywords:*** *$Fe^{2+}$:ZnS laser, single crystal, electric-discharge HF laser, optical pumping, room temperature.*

## 1. Introduction

Sources of high-power coherent radiation in the spectral range 3.5–5 μm are of great interest for scientific research and some practical applications. This stimulates investigations of $Fe^{2+}$:ZnSe and $Fe^{2+}$:ZnS lasers aimed at improvement of their output characteristics (pulse energy and power, as well as average power) [1–25].

The highest pulse energies achieved to date from $Fe^{2+}$:ZnSe and $Fe^{2+}$:ZnS lasers at liquid nitrogen temperature are 4.9 [14] and 3.25 J [18], respectively. The active elements of these lasers were $Fe^{2+}$:ZnSe and $Fe^{2+}$:ZnS single crystals excited by a free-running Er:YAG laser. The maximum average power of a laser with a polycrystalline $Fe^{2+}$:ZnSe active element at liquid nitrogen temperature was 35 W [23] under pumping by a free-running Er:YAG laser with a pulse repetition rate of 100 Hz.

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At room temperature, these crystals must be pumped by short radiation pulses due to relatively short lifetimes of the upper laser levels in $Fe^{2+}$:ZnSe and $Fe^{2+}$:ZnS crystals (~360 [8, 19] and ~50 ns [17, 19], respectively). Convenient and efficient sources under these conditions are high-power electric-discharge HF lasers, which can operate both in pulsed (pulse duration 100–200 ns) and repetitively pulsed regimes [26–29]. The use of these sources made it possible to obtain the highest to date energy and average power of the $Fe^{2+}$:ZnSe laser and the highest pulse energy of the $Fe^{2+}$:ZnS laser at room temperature. The maximum pulse energies of the $Fe^{2+}$:ZnSe laser were achieved in [24] (253 mJ, polycrystals) and [21, 25] (~1.2 J, single crystal). An average power of a repetitively pulsed $Fe^{2+}$:ZnSe laser pumped by a HF laser in [14] was 2.4 W.

Pumping of a $Fe^{2+}$:ZnS crystal by a HF laser also resulted in an increase in the laser energy at room temperature by more than seven times (to 25.5 mJ [20] versus 3.4 mJ obtained in [17] with pumping by a $Q$-switched Er:YAG laser). The authors of [20] used a polycrystalline $Fe^{2+}$:ZnS sample doped with iron ions from both sides by thermal diffusion. The doping depth at a level of 0.1 from each of the sample surfaces did not exceed 500 μm at the iron concentration of $\sim 5\times10^{18}$ cm$^{-3}$ in the surface layer. The combination of the low doping depth (which is equivalent to a short length of the active medium) with a high dopant concentration in the surface layer at a relatively small transverse size of the sample (10 mm in diameter) did not allow one to completely realise the energy capacity of the HF laser due to spurious oscillations at large pump beam spots on the active element surface. Similar restriction also took place when the authors of [24] tried to increase the energy of a laser based on a $Fe^{2+}$:ZnSe polycrystal (diffusion-doped from two sides, 20 mm in diameter) by increasing the pump spot size at a pump energy density limited by the surface breakdown threshold. A natural way out of this situation is to decrease the concentration of iron ions in the sample and simultaneously to increase the active medium length. This can be achieved either by developing polycrystalline samples with several doped layers [24] or by using single crystals [17, 18] with a large length of the active medium with a lower concentration of iron ions.

The use of a $Fe^{2+}$:ZnSe single crystal as an active element excited by a HF laser in [21, 25] made it possible to considerably increase the pump spot size and, therefore, the laser energy at room temperature compared to the corresponding parameters achieved for polycrystalline samples. It is of natural interest to study the possibility of increasing the output energy of a room-temperature $Fe^{2+}$:ZnS laser excited by a HF laser by using a single-crystal active element with a large gain length. This study is the aim of the present work.

## 2. Experimental setup

We performed experiments with a $Fe^{2+}$:ZnS crystal grown by vapour-phase chemical transport in hydrogen on a single-crystal seed [30]. Doping with iron was performed in the process of growth; the $Fe^{2+}$ concentration in the sample was $\sim 0.7\times10^{18}$ cm$^{-3}$. The shape of the sample was close to cylindrical. The cylinder diameter and length (active medium length) were 16 and 17 mm, respectively. The crystal was placed in a cavity so that one of its polished faces was perpendicular to the optical axis of the cavity. The angle between the polished faces was ~45″. It is this sample that previously operated at room temperature with a pulse energy of 3.25 J [18].

The scheme of the experimental setup is shown in Fig. 1. The $Fe^{2+}$:ZnS laser cavity 155 mm long was formed by a concave mirror M1 (gold coating on a quartz substrate) with a curvature radius of 1 m and a plane output mirror M2. As an output mirror, we used a $CaF_2$ substrate with an interface coating having a reflection coefficient of 80% at wavelengths $\lambda$ = 3.6–4.1 μm. The pump beam spot diameter $d$ (90% of energy) on the crystal surface varied in the experiment from 3.9 to 11.6 mm. The radiation of a nonchain electric discharge HF laser with a pulse FWHM of ~140 ns was attenuated by a set of calibrated filters F and focused on the sample surface by a lens L with a focal length of 45 cm. The HF laser operated in a single-pulse regime; the laser characteristics are described in detail in [31, 32]. The angle of incidence of the pump beam on the crystal surface was ~20°. The energy of the HF laser radiation passed through the sample and the $Fe^{2+}$:ZnS laser energy were measured by C1, C3 (Molectron), and C2 (Gentec-EO) calorimeters, respectively.

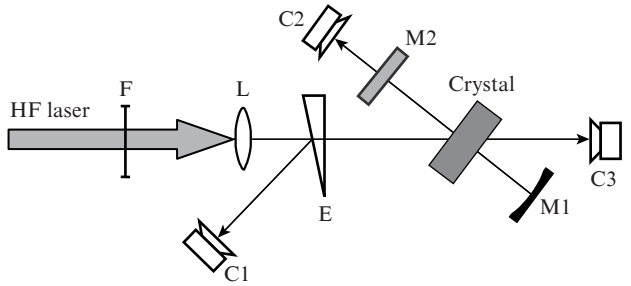


**Figure 1.** Experimental scheme: (M1, M2) cavity mirrors; (F) set of calibrated filters; (L) spherical lens; (E) optical edge; (C1, C2, C3) calorimeters.

## 3. Experimental results and discussion

Figure 2 presents the dependence of the studied single crystal transmittance on the incident HF laser energy density measured under conditions of $Fe^{2+}$:ZnS lasing at the pump spot diameter on the sample surface $d$ = 3.9 mm. In experiments, pumping of the crystal occurred on multiple lines within the spectral range 2.7–3.1 μm [13, 31] generated in one pulse. The crystal transmittance nonlinearly depends on the incident energy density [21, 24]. Because of this, the plot shown in Fig. 2 seems to be more informative than ordinary transmittance spectra measured at low energy density. As is seen from Fig. 2, the crystal transmittance changes from 27% to 30% as the pump energy density changes from 0.8 to 3.2 J cm$^{-2}$.

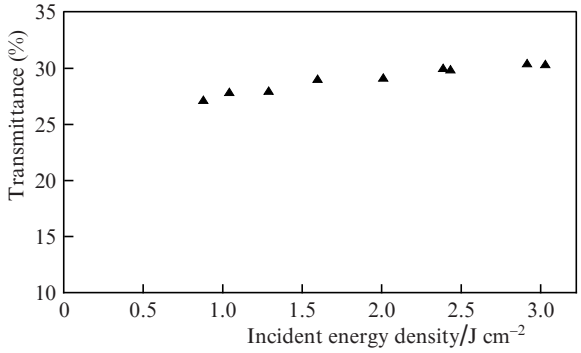


**Figure 2.** Dependence of the $Fe^{2+}$:ZnS crystal transmittance on the incident energy density under lasing conditions.

Figure 3 shows the dependences of the $Fe^{2+}$:ZnS laser energy on the absorbed energy measured at different diameters of the HF laser beam on the crystal surface. One can see that the slope efficiencies achieved at $d$ = 3.9–9.6 mm are rather high, i.e., $\eta_{slope}$ = 37%–39%. The maximum output energy at $d$ = 9.6 mm is ~250 mJ with the total efficiency with respect to the absorbed energy $\eta$ = 24%. An increase in the spot diameter to 11.6 mm leads to a decrease in $\eta_{slope}$ to 28%, but the maximum laser energy in this case is 380 mJ at $\eta$ = 19%.

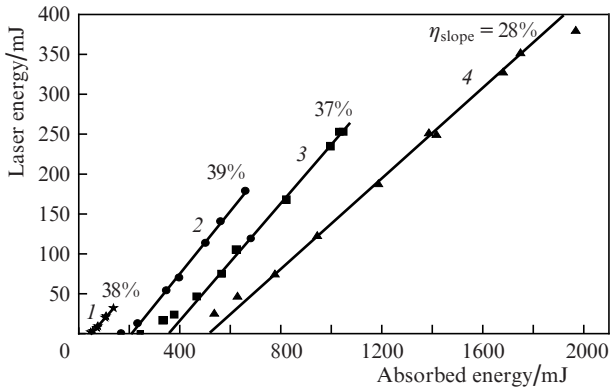


**Figure 3.** Dependence of the $Fe^{2+}$:ZnS laser energy on the absorbed HF laser energy at pump spot diameters $d$ = (*1*) 3.9, (*2*) 8.1, (*3*) 9.6 and (*4*) 11.6 mm.

Figure 3 also shows that the point corresponding to the maximum absorbed energy (2000 mJ) is noticeably shifted from the linear dependence because the crystal was damaged during the measurement of this point. In this case, the HF laser energy and peak power on the crystal surface were 3.4 J and 24 MW. The destroyed region had the shape of a long narrow channel shifted from the entrance surface inside the sample. Such damages are usually observed in crystals upon filamentation and self-focusing of high-power beams, but to date we have no enough experimental material to identify the breakdown mechanism.

Thus, in this work we achieved 380 mJ energy from a laser based on a $Fe^{2+}$:ZnS single crystal at room temperature. To further increase the laser energy, one must find a way to avoid breakdown of crystals at large spots and, correspondingly, high powers of pump radiation. It is also reasonable to fur-

ther improve the doping technique of polycrystalline ZnS samples in the process of hot isostatic pressing, which allows one to produce active elements with a high optical quality [20, 33].

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