Quantum Electronics **41** (1) 1 – 3 (2011)

LASERS

PACS numbers: 42.55.Rz; 42.62.Fi; 42.70.Hj
DOI: 10.1070/QE2011v041n01ABEH014451

Pulsed Fe^{2+} : ZnS laser continuously tunable in the wavelength range of 3.49 – 4.65 μm

V.I. Kozlovsky, Yu.V. Korostelin, A.I. Landman, V.V. Mislavskii,
Yu.P. Podmar'kov, Ya.K. Skasyrsky, M.P. Frolov

***Abstract*. A laser based on a Fe^{2+} : ZnS crystal is demonstrated for the first time. Lasing in this crystal is obtained at room temperature under pumping by 40-ns pulses of an Er : YAG laser at a wavelength of 2.94 nm. The slope efficiency of the Fe^{2+} : ZnS laser with respect to the absorbed pump energy was 32 %, and the output energy reached 3.4 mJ. Continuous tuning of the laser wavelength within the range of 3.49 – 4.65 nm was achieved using an intracavity dispersion prism.**

Keywords: *Fe^{2+} : ZnS laser, IR lasers, tunable lasers, solid-state lasers, A_2B_6 crystals.*

1. Introduction

Mid-IR lasers based on A_2B_6 crystals doped with divalent ions of transition metals have been extensively studied for the last decade. A characteristic feature of these crystals is a large ($\sim$ 1 μm) luminescence bandwidth, which allows one to achieve a continuous tuning of the laser wavelength in a wide spectral range. Previously, efficient lasing was demonstrated in a number of crystals doped with Cr^{2+} and Fe^{2+}. Lasers based on crystals with chromium ions (Cr^{2+} : ZnSe, Cr^{2+} : ZnS, Cr^{2+} : $Cd_{0.85}Mn_{0.15}Te$, Cr^{2+} : $Cd_{0.55}Mn_{0.45}Te$, Cr^{2+} : CdS, Cr^{2+} : CdSe) cover a spectral range of 1.88 – 3.61 μm [1 – 9], while lasers based on crystals with iron ions (Fe^{2+} : ZnSe, Fe^{2+} : CdSe) operate in the wavelength range of 3.77 – 6.1 μm [10 – 12]. In the range of 3.61 – 3.77 μm, lasing in crystals of this type has not been obtained until now.

The absorption spectrum of the Fe^{2+} : ZnS crystal (2.4 – 3.6 μm at half-maximum at room temperature) lies between the absorption spectra of the Cr^{2+} : CdSe and Fe^{2+} : ZnSe crystals. This gives grounds to suggest [13] that the luminescence spectrum of the Fe^{2+} : ZnS crystal will also lie between the luminescence spectra of the above two crystals. This consideration was the basis for experimental investigations of the Fe^{2+} : ZnS crystal performed in this work in order to obtain lasing in this crystal and study its tuning range.

2. Experiment

In this work, we studied a Fe^{2+} : ZnS single crystal grown from the vapour phase on a single-crystal seed by a method developed previously for growing single crystals of solid solutions with a perfect structure and a high optical homogeneity [15, 16]. The crystal was doped directly in the process of its growth. The high quality of laser elements made of the crystals produced by this method was repeatedly confirmed by our previous studies of the laser characteristics of Cr^{2+} : ZnSe [14], Fe^{2+} : ZnSe [11], Cr^{2+} : CdSe [9], Fe^{2+} : CdSe [12], and Cr^{2+} : CdS [17] crystals.

For experiments, we prepared from the grown boule a 17-mm-thick sample with faces polished to an optical finish. The polished faces were not antireflection coated, and the angle between them did not exceed $1'$.

Prior to laser experiments, we measured the luminescence decay time of the Fe^{2+} ion in the ZnS matrix at the $^5T_2 \rightarrow {}^5E$ transition (the band in the region of 4 μm) upon excitation by a pulsed Er : YAG laser ($\lambda = 2.94$ μm). The luminescence decay time at the level of 1/e was 1 μs at liquid nitrogen temperature (77 K) and $\sim$ 50 ns at room temperature, which was comparable with the exciting pulse duration.

All the experiments on the laser characteristics of the Fe^{2+} : ZnS crystal were performed at room temperature, because of which we used a *Q*-switched Er : YAG laser with $\lambda = 2.94$ μm as a pump source. The pump laser emitted single 40-ns pulses with an energy of 30 mJ. The optical scheme of the setup for laser experiments is shown in Fig. 1.

The Fe^{2+} : ZnS laser cavity was formed by a highly reflecting aluminum-coated spherical mirror ($R = 200$ mm) and a plane output coupler. We used two output couplers whose spectral characteristics are given below. The cavity length was 150 mm. The Fe^{2+} : ZnS crystal was placed at a distance of 3 mm from the output coupler so that its face directed toward this mirror was oriented perpendicular to the optical axis of the cavity.

The pump radiation was focused by a spherical mirror ($R = 1500$ mm) to the sample centre into a spot 1.7 mm in diameter. The pump beam propagated at angle of 2° to the cavity axis. If necessary, the pump beam was attenuated by

V.I. Kozlovsky, Yu.V. Korostelin, A.I. Landman, Ya.K. Skasyrsky P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia;
V.V. Mislavskii, Yu.P. Podmar'kov, M.P. Frolov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia; e-mail: frolovmp@x4u.lebedev.ru

Received 29 September 2010
Kvantovaya Elektronika **41** (1) 1 – 3 (2011)
Translated by M.N. Basieva

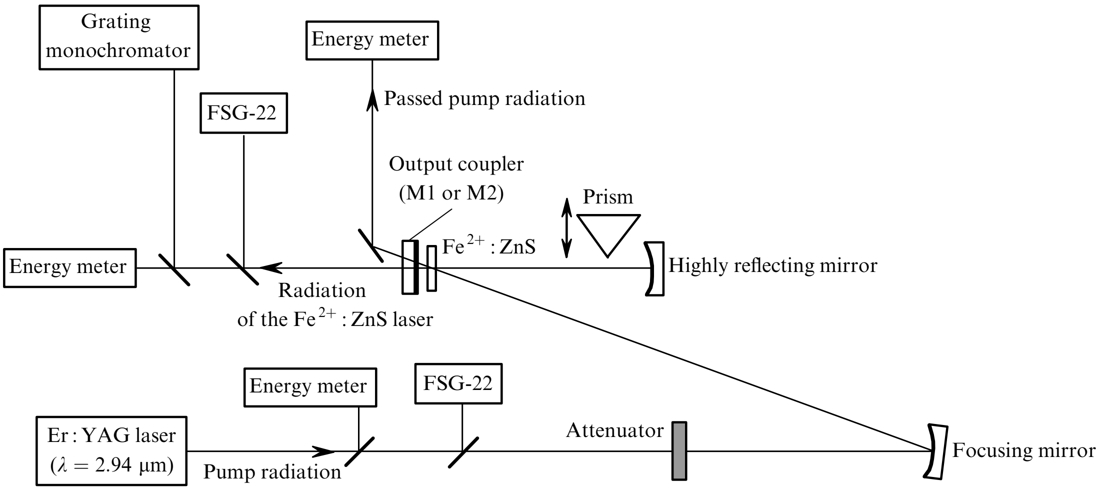

Figure 1. Scheme of the setup for laser experiments.

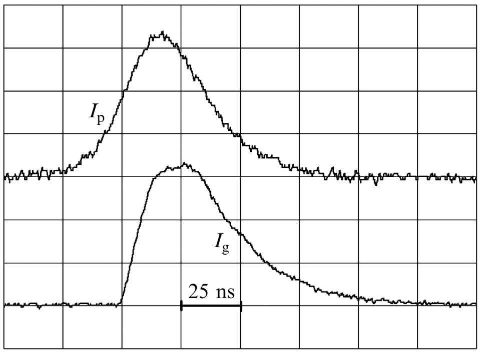

Figure 2. Shapes of the pump (I_p) and $Fe^{2+}:ZnS$ laser (I_g) pulses. Scan rate is 25 ns div^{-1}.

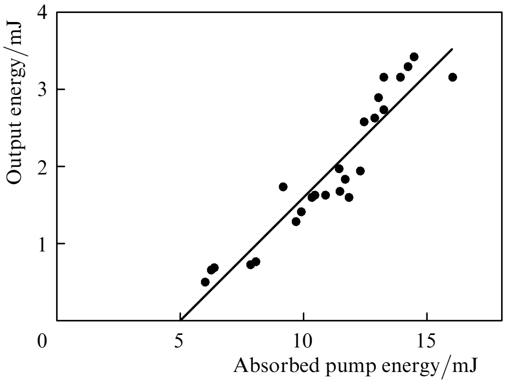

Figure 3. Dependence of the $Fe^{2+}:ZnS$ laser output energy on the absorbed pump energy.

calibrated filters The laser crystal absorption at the pump wavelength was 0.7 cm^{-1}.

The experimental scheme allowed us to measure the output energy of the $Fe^{2+}:ZnS$ crystal, as well as the energy of the pump beam incident to and passed through the crystal. Knowing these energies and taking into account the Fresnel reflection from the surfaces of optical units and the transmittance of the output coupler at the pump wavelength, we determined the pump energy absorbed by the $Fe^{2+}:ZnS$ sample in the process of lasing. We used energy meters from Gentec and Ophir, as well as IMO-2N and VChD-2.

The pump and output laser pulses were recorded using liquid-nitrogen-cooled FSG-22 photoresistors based on gold-doped germanium and a Tektronix TDS 2022B digital oscilloscope.

The wavelength tuning range of the $Fe^{2+}:ZnS$ laser was studied using a selective cavity with a CaF_2 dispersion prism placed near the highly reflecting mirror. The prism refraction angle was 70.3°. The spectral characteristics of the $Fe^{2+}:ZnS$ laser radiation were studied using a diffraction monochromator with a slit spectral width of 50 nm.

3. Experimental results

Using the presented setup, we obtained lasing in the $Fe^{2+}:ZnS$ crystal. As far as we know, it is the first demonstration of a $Fe^{2+}:ZnS$ laser. Figure 2 shows typical shapes of the pump and laser pulses.

The dependence of the output energy of the $Fe^{2+}:ZnS$ laser with a nonselective cavity on the absorbed pump energy is shown in Fig. 3. These data were obtained with the output coupler M1, whose transmission spectrum is shown in Fig. 4b. At the maximum pump energy, the laser linewidth at half maximum in the nonselective cavity was 200 nm with the centre at 3.85 μm. The threshold absorbed pump energy was 5 mJ. The laser slope efficiency determined from the slope of the straight line drawn through experimental points was 32 %. The maximum output energy of 3.4 mJ was achieved at an absorbed pump energy of 16 mJ.

In the cavity with the prism, we achieved continuous tuning of the $Fe^{2+}:ZnS$ laser wavelength. The tuning curves shown in Fig. 4a were obtained using output couplers M1 and M2, whose transmission spectra are shown in Fig. 4b. Both curves were plotted for a fixed absorbed pump energy of 13 mJ. With the more transparent output coupler M1, we obtained the continuous tuning range of 3.52 – 4.21 μm. In this case, the laser linewidth was 180 nm in the tuning curve maximum and did not exceed 80 nm at its edges. Note that, with the intracavity prism, the laser output energy in the tuning curve centre in this case reached 70 % of the output energy achieved with the same pumping without the prism.

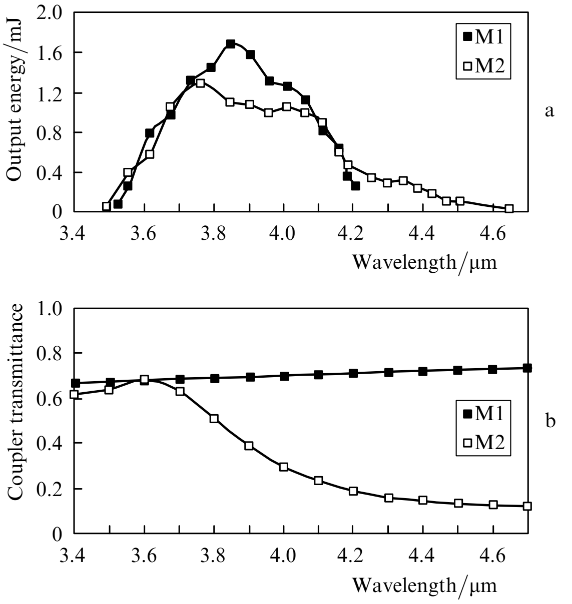

Figure 4. Tuning curves of the Fe^{2+} : ZnS laser obtained with an intracavity dispersion prism and output couplers M1 and M2 at an absorbed pump energy of 13 mJ (a) and transmission spectra of the output couplers (b).

The use of the M2 coupler, which has a lower transmittance in the long-wavelength spectral region, allowed us to extend the tuning range to 3.49 – 4.65 μm. The short-wavelength tuning region was obviously limited due to the long-wavelength absorption wing of the Fe^{2+} ion in the ZnS single crystal.

4. Conclusions

Thus, in this work we obtained lasing in the Fe^{2+} : ZnS crystal for the first time. The laser operated at room temperature. The output laser energy was 3.4 mJ at a slope efficiency of 32 % with respect to the absorbed pump energy. In the case of a dispersive cavity, the spectral tuning range was 3.49 – 4.65 μm. This means that, using A_2B_6 crystals doped with divalent ions of transition metals, one can obtain laser radiation at any wavelength in the range of 1.88 – 6.1 μm.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant Nos 09-02-00864-a, 09-02-00877-a), the program 'Development of the Scientific Potential of the Higher School' of the Ministry of Education and Science of the Russian Federation, and the program 'Physical and Technological Studies of Semiconductor Lasers Aimed at Achieving Limiting Parameters' of the Department of Physical Sciences of RAS.

References

1. Page R.H., Schaffers K.I., DeLoach L.D., Wilke G.D., Patel F.D., Tassano J.B., Payne S.A., Krupke W.F., Chen K.-T., Burger A. *IEEE J. Quantum Electron.*, **33**, 609 (1997).
2. Demirbas U., Sennaroglu A. *Opt. Lett.*, **31**, 2293 (2006).
3. Sorokina I.T., Sorokin E., Mirov S., Fedorov V., Badikov V.V. Panyutin V., Schaffers K.I. *Opt. Lett.*, **27**, 1040 (2002).
4. Seo J.T., Hömmerich U., Trivedi S.B., Chen R.J., Kutcher S. *Opt. Commun.*, **153**, 267 (1998).
5. Trivedi S.B., Kutcher S.W., Wang C.C., Jagannathan D.V., Hömmerich U., Bluiett A., Turner M., Seo J.T., Schepler K.L., Schumm B., Boyd P. R., Green G. *J. Electronic Mater.*, **30**, 728 (2001).
6. Akimov V.A., Kozlovsky V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Skasyrsky Ya.K., Frolov M.P. *Kvantovaya Elektron.*, **38** (9), 803 (2008) [*Quantum Electron.*, **38** (9), 803 (2008)].
7. Akimov V.A., Frolov M.P., Korostelin Y.V., Kozlovsky V.I., Landman A.I., Podmar'kov Y.P., Skasyrsky Y.K., Voronov A.A. *Appl. Phys. B*, **97**, 793 (2009); DOI 10.1007/s00340-009-3617-6.
8. McKay J., Schepler K.L., Catella G.C. *Opt. Lett.*, **24**, 1575 (1999).
9. Akimov V.A., Kozlovsky V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Skasyrsky Ya.K., Frolov M.P. *Kvantovaya Elektron.*, **38** (3), 205 (2008) [*Quantum Electron.*, **38** (3), 205 (2008)].
10. Adams J.J., Bibeau C., Page R.H., Krol D.M., Furu L.H., Payne S.A. *Opt. Lett.*, **24**, 1720 (1999).
11. Fedorov V.V., Mirov S.B., Gallian A., Badikov V. V., Frolov M.P., Korostelin Yu.V., Kozlovsky V.I., Landman A.I., Podmar'kov Yu.P., Akimov V.A., Voronov A.A. *IEEE J. Quantum Electron.*, **42**, 907 (2006).
12. Mislavskii V.V., Frolov M.P., Korostelin Yu.V., Kozlovsky V.I., Landman A.I., Podmar'kov Yu.P., Skasyrsky Ya.K. *Techn. Program 14th Intern. Conf. on Laser Optics 'LO-2010'* (St. Petersburg, Russia, 2010) p. 60, WeR1-p18.
13. Payne S.A., Chase L.L., Smith L.K., Kway W.L., Krupke W.F. *IEEE J. Quantum Electron.*, **28**, 2619 (1992).
14. Kozlovsky V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Frolov M.P. *Kvantovaya Elektron.*, **33** (5), 408 (2003) [*Quantum Electron.*, **33** (5), 408 (2003)].
15. Korostelin Yu.V., Kozlovsky V.I., Nasibov A.S., Shapkin P.V. *J. Crystal Growth*, **159**, 181 (1996).
16. Korostelin Yu.V., Kozlovsky V.I. *J. Alloys Compounds*, **371**, 25 (2004).
17. Akimov V.A., Frolov M.P., Korostelin Yu.V., Kozlovsky V.I., Landman A.I., Podmar'kov Yu.P., Skasyrsky Ya.K., Voronov A.A. *Appl. Phys. B*, **97**, 793 (2009).