Quantum Electronics **47** (4) 303–307 (2017)

LASERS

https://doi.org/10.1070/QEL16324

Repetitively pulsed Fe:ZnSe laser with an average output power of 20 W at room temperature of the polycrystalline active element

S.D. Velikanov, E.M. Gavrishchuk, N.A. Zaretsky, A.V. Zakhryapa, V.B. Ikonnikov, S.Yu. Kazantsev, I.G. Kononov, A.A. Maneshkin, D.A. Mashkovskii, E.V. Saltykov, K.N. Firsov, R.S. Chuvatkin, I.M. Yutkin

Abstract. **The energy and spectral-temporal characteristics of a Fe:ZnSe laser operating in pulsed and repetitively pulsed regimes are studied at room temperature of the polycrystalline active element. The crystal was pumped by a nonchain electric-discharge HF laser. The energy of the Fe:ZnSe laser in a single-pulse regime was 1.67 J at the slope efficiency with respect to the absorbed and incident energy of ~43% and ~27%, respectively. In a repetitively pulsed regime with a pulse repetition rate of 20 Hz and an efficiency with respect to the absorbed power of ~40%, the average laser power was ~20 W with an individual pulse energy of ~1 J. The possibility of increasing the average power of the repetitively pulsed Fe:ZnSe laser at room temperature is discussed.**

Keywords: *Fe:ZnSe laser, polycrystal, room temperature, repetitively pulsed regime, electric-discharge HF laser, average output power.*

1. Introduction

The lasers based on zinc selenide crystals doped with divalent iron ions (Fe:ZnSe) have been extensively studied for more than fifteen years [1–25]. The efforts of researchers are focused mainly on increasing the pulse and average output powers, which is explained by a wide field of possible applications of Fe:ZnSe lasers for molecular spectroscopy, physical experiments at high radiation flux densities, environment monitoring, medicine, etc. [6, 7, 17, 24]. The crystals are pumped by three-micron lasers. At present, the highest energies and average powers of Fe:ZnSe lasers are achieved at active element temperatures close to liquid nitrogen temperature. A pulse energy of 10.6 J was achieved in [22], and an average power of a repetitively pulsed laser reported in [21] was 35 W at a pulse repetition rate of 100 Hz. The crystals in [21, 22] were pumped by free-running Er:YAG lasers.

S.D. Velikanov, N.A. Zaretsky, A.V. Zakhryapa, A.A. Maneshkin, E.V. Saltykov, R.S. Chuvatkin, I.M. Yutkin Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics', prosp. Mira 37, 607188 Sarov, Nizhnii Novgorod region, Russia; e-mail: velikanov@otd13.vniief.ru;
E.M. Gavrishchuk, V.B. Ikonnikov G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul Tropinina 49, 603950 Nizhnii Novgorod, Russia; e-mail: gavr@ihps.nnov.ru;
S.Yu. Kazantsev, I.G. Kononov, D.A. Mashkovskii, K.N. Firsov A.M. Prokhorov General Physics Institute, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: k_firsov@rambler.ru

Received 16 February 2017
Kvantovaya Elektronika **47** (4) 303–307 (2017)
Translated by M.N. Basieva

Most attractive for practical applications is the possibility of laser operation at room temperature or at slight cooling of the laser element. Due to the relatively short lifetime of the upper laser level in the Fe:ZnSe crystal (~360 ns at room temperature [25]), these crystals must be pumped by short pulses [7, 25]. Ideal pump sources in this case, which, in the complete set of parameters, have no competitors in the three-micron wavelength region, are pulsed and repetitively pulsed electric discharge HF(DF) lasers [12, 26–29]. The excitation by HF lasers made it possible to obtain the highest known pulse energies and average powers of Fe:ZnSe lasers at room temperature. The laser energy was 1.43 J at an efficiency of 48% with respect to the energy absorbed in the crystal [23]. Operation of a Fe:ZnSe laser excited by a repetitively pulsed HF laser was demonstrated in [11, 12]. The average power achieved [12] was 2.4 W with an individual pulse energy of 14 mJ.

The pulse repetition rate in [11, 12] reached 200 Hz. For some applications, it is also of interest to have Fe:ZnSe lasers operating at lower (10–20 Hz) pulse repetition rates but with an individual pulse energy of ~1 J. These pulse energies at room temperature are achieved in single-crystalline and polycrystalline active elements with large transverse dimensions [16, 23], and the needed pump parameters in the repetitively pulsed regime can be easily provided by high-power HF lasers described in [27, 28]. Therefore, the aim of the present work is to study the possibility of achieving a high average output power of a Fe:ZnSe laser with a high individual pulse energy under excitation by a repetitively pulsed HF laser at room temperature.

2. Experimental setup

The polycrystalline Fe:ZnSe active element had the form of a disk 64 mm in diameter and 4 mm thick. The technology of its fabrication did not differ from the technology of fabrication of active elements with large transverse dimensions which was considered in detail in [23]. From a polycrystalline ZnSe plate preliminarily grown by the chemical vapour deposition method described in [30], we cut a disk and coated its plane polished faces with thin (~1 μm) iron films by electron-beam evaporation. Doping of the crystal with iron ions was performed in the process of its high-temperature gas-static treatment in an argon atmosphere at a pressure of 100 MPa and a temperature of 1270 °C for 126 h. To decrease pollution with the equipment material and reduce the sublimation mass transfer rate, the gas-static treatment was performed in a high-purity carbon container. The processes occurring upon the high-temperature gas-static treatment of zinc chalcogenide crystals were analysed in detail in [31]. After doping, the

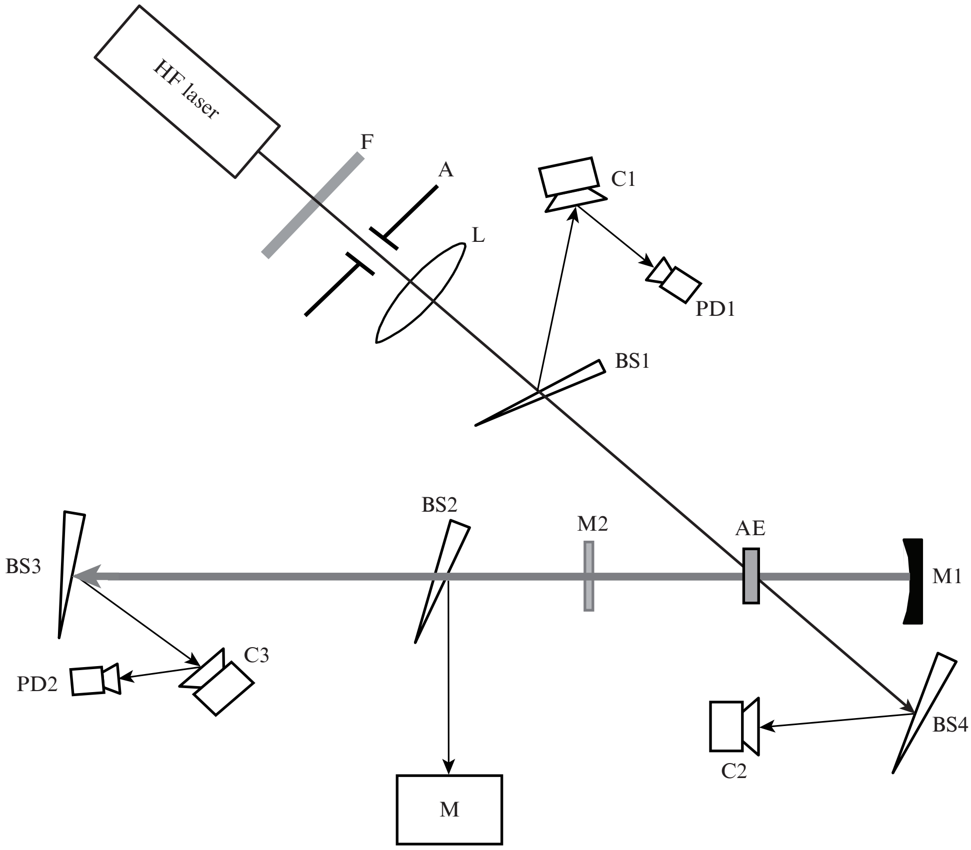

Figure 1. Experimental scheme: (F) set of light filters; (A) aperture 80 mm in diameter; (L) lens; (BS1 – BS4) CaF_2 beam splitting wedges; (C1 – C3) calorimeters; (AE) active element (Fe : ZnSe crystal); (M1, M2) mirrors of the Fe : ZnSe laser cavity; (M) monochromator with a pyroelectric array at the exit.

crystal was polished so that the angle between the polished surfaces did not exceed 30″. According to the results of [23], in which two-size doping of samples with a large transverse size was also performed in the process of hot isostatic pressing, the concentration of iron ions on the surface of the crystal used in the present paper can be estimated to be (7 – 9)× 10^{18} cm^{-3} at a doping depth of ~1.5 mm (at a level of 0.1). This estimate takes into account the time for which the sample was exposed to the gas-static treatment. The diameter of the active element allows it to operate with large pump beam spots on the surface (i.e., at high pump energies) without risk of parasitic generation [23, 32]. It was found in preliminary experiments that parasitic generation does not develop in the above-described sample used as an active element if the pump spot size on the surface does not exceed 16 mm.

The scheme of the experimental setup is shown in Fig. 1. The Fe : ZnSe laser cavity 120 mm in length was formed by a copper concave mirror M1 with a curvature radius of 1 m and a plane output mirror M2 with a reflection coefficient of 60 % within the wavelength range λ = 3.9 – 4.8 μm. The active element was excited by a nonchain electric discharge HF laser described in [28]. A beam of this laser was attenuated by a set of light filters, confined by an aperture 80 mm in diameter, and focused on the active element surface by a spherical lens L with a focal length of 1 m into an elliptical spot with axes $a \times b$ = 14×16 mm (90 % of the energy incident on the surface). The angle of incidence of the pump beam on the crystal surface was ~20°. The crystal was placed so that one of its polished faces was perpendicular to the optical axis of the cavity. The energies of the HF laser radiation incident on the sample and passed through it, as well as the Fe : ZnSe laser energy, were measured by calorimeters C1 – C3 with J-50MB-HE pyroelectric sensors (COHERENT). The shapes of the Fe : ZnSe and HF laser pulses were controlled by photodetectors PD1 and PD2 (Vigo-system Ltd.) with a time resolution of ~1 ns. The photodetectors recorded the radiation scattered by the receiving plates of corresponding calorimeters. The Fe : ZnSe laser spectra were measured using an MS 2004 (SOLAR TII) monochromator . At the exit from the monochromator, we placed an HPL-256-500 pyroelectric array (Heimann Sensor) consisting of 256 elements at the receiving part length of 12.8 mm.

3. Experimental results and discussion

3.1. Single-pulse regime

Figure 2 presents the dependence of the Fe : ZnSe laser energy on the pump energy incident on the crystal, which was measured in the single-pulse regime of the HF laser. The transmission coefficient of the crystal at pump wavelengths under the conditions of the Fe : ZnSe operation at the HF laser energy exceeding 1.8 J (the energy density incident on the crystal exceeding 1 J cm^{-2}) was ~19 %. One can see that the maximum laser energy reaches 1.67 J. The efficiencies with respect to the incident and absorbed pump energies were 27 and 43 %, respectively. The achieved laser energy (1.67 J) is higher than the maximum energy (1.43 J) achieved previously in [23] at room temperature for active elements with large transverse dimensions. However, the experiments reported in the present paper showed the appearance of noticeable damages on the output surface of the crystal after several (five and more) pump pulses with an energy exceeding 4.5 J. The surface breakdown occurred only in the presence of the Fe : ZnSe laser generation. When the cavity was blocked by a nontransparent screen, the surface showed no damages even at the maximum used pump energy of 6.2 J (pump energy density $\sim$3.5 J cm^{-2}).

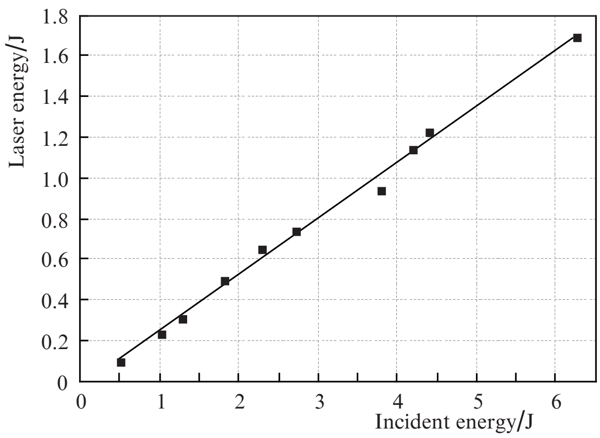

Figure 2. Dependence of the Fe : ZnSe laser energy on the pump energy incident on the crystal.

Figure 3 shows the Fe : ZnSe and HF laser pulses recorded in the case of single-pulse pumping at an incident energy of $\sim$4 J. One can see that the FWHM of the HF laser pulse is $\sim$210 nm. The Fe : ZnSe laser pulse has a short high-power front peak typical for the conditions of high pump energy densities [18]. The shapes of pulses were well reproduced in the repetitively pulsed regime.

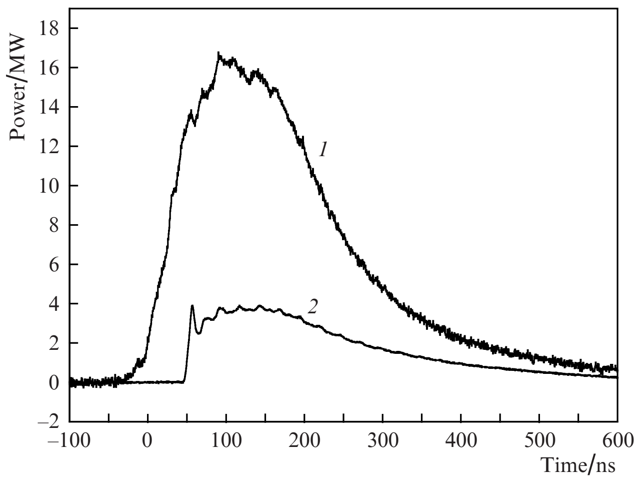

Figure 3. (*1*) HF and (*2*) Fe : ZnSe laser pulses. The pump energy incident on the crystal is 4 J.

Figure 4 shows the Fe : ZnSe laser spectrum averaged over 10 pulses. It is seen that the laser emits at wavelengths $\lambda >$ 4300 nm. At wavelengths $\lambda <$ 4200 nm, lasing is almost indistinguishable (on the figure scale). To study the spectral-temporal characteristics of the laser in this region, we had to use a highly sensitive photodetector behind the exit slit of the monochromator. The same situation was observed previously in [11], in which the Fe : ZnSe laser spectra were recorded by a pyroelectric array. The oscillograms of laser pulses recorded using a photodetector at different wavelengths (by a photodetector PD2 placed behind the exit slit of the monochromator) also confirmed the wavelength dependence of the pulse shape revealed previously in [11]. The pulse in the region of $\lambda <$ 4200 nm has a shape of a sharp peak with an FWHM of $\sim$7 ns and a low total energy, because of which it is difficult to observe by pyroelectric detectors. At wavelengths $\lambda \geqslant$ 4350 nm, the peak is accompanied by a tail, whose duration and amplitude increase with increasing wavelength with respect to the peak.

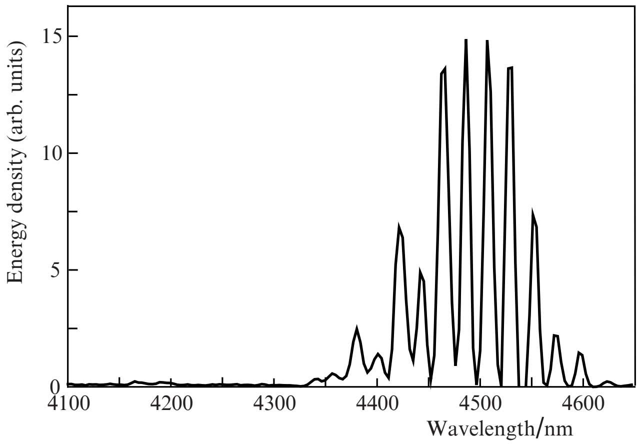

Figure 4. Spectrum of the Fe : ZnSe laser (averaged over 10 pulses). The pump energy incident on the crystal is 4 J.

Figure 5 presents a photograph of the Fe : ZnSe laser beam spot obtained on thermal paper placed at a distance of 30 cm from the output cavity mirror. Like the pump beam, the laser beam has an elliptical cross section. One can see a noticeable inhomogeneity in the laser energy density distribu-

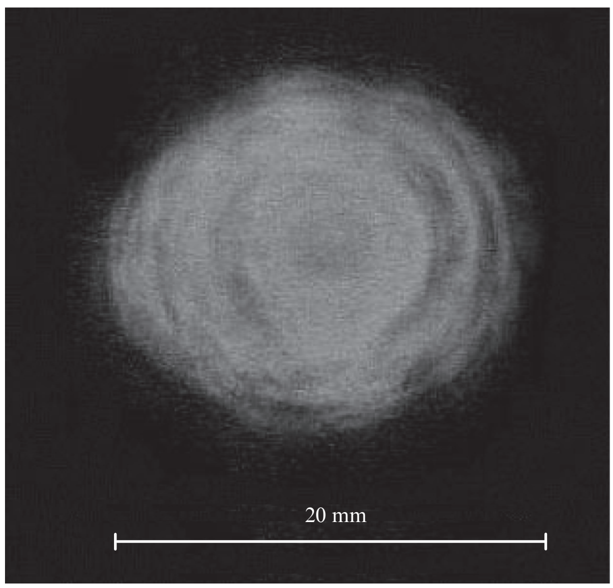

Figure 5. Spot of the Fe : ZnSe laser on thermal paper.

tion over the spot. It is obvious that, to achieve beams with a higher quality at large pump spots (disk laser geometry), one should develop special unstable cavities.

3.2. Repetitively pulsed regime of the Fe:ZnSe laser

The characteristics of the Fe:ZnSe laser in the repetitively pulsed regime were studied at a pulse pump energy no higher than 4.2 J in order to prevent breakdown of the active element surface. The HF laser operated in short series (1–2 s) at a pulse repetition rate of 10–20 Hz. Figure 6 shows the time dependences of the HF laser energy incident on the crystal, the energy passed through the crystal, and the Fe:ZnSe laser energy at a pulse repetition rate of 20 Hz (series duration 1 s). Figure 7 presents the time dependence of the Fe:ZnSe lase efficiency with respect to the energy absorbed in the crystal under the same conditions. As is seen from Figs 6 and 7, the Fe:ZnSe laser pulse energy is close to 1 J during the entire series, the average Fe:ZnSe laser power in a series is ~20 W at efficiencies with respect to the incident and absorbed power of ~25% and ~40%, respectively.

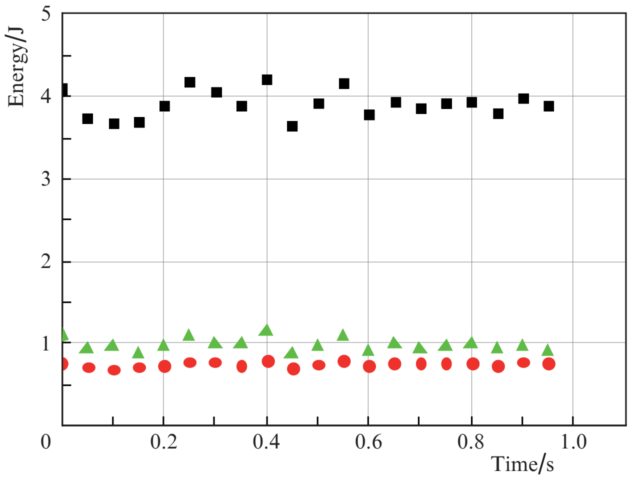

Figure 6. Time dependences of (■) the HF laser energy incident on the crystal, (▲) the Fe:ZnSe laser energy, and (●) the pump energy passed through the crystal at a pulse repetition rate of 20 Hz.

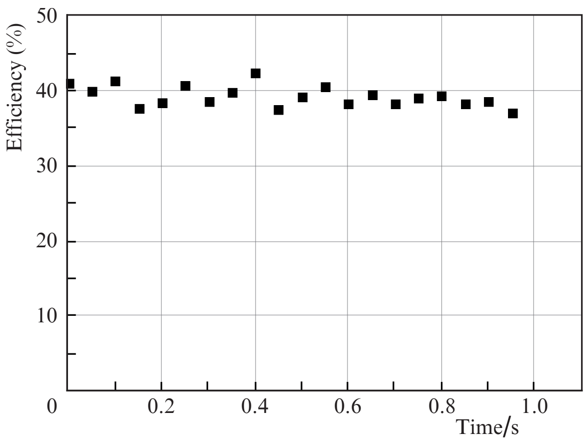

Figure 7. Time dependence of the Fe:ZnSe laser efficiency with respect to the absorbed energy in a pulse series with a duration of 1 s; pulse repetition rate is 20 Hz.

The average laser power at a pulse repetition rate of 10 Hz was ~10 W with the same efficiencies. Further increase in the average power of the Fe:ZnSe laser can be achieved by increasing the pulse repetition rate. The large transverse dimensions of the polycrystals doped with iron ions by the technology described in [23] allow one to use the method of rotating active disk element (see, for example, [21] and references therein) in order to decrease the influence of the crystal overheating on the laser characteristics in the case of an increased pulse repetition rate. Using this method, the authors of [21] achieved a record average power of a Cr:ZnSe laser at room temperature. The same method can obviously be used in the case of a Fe:ZnSe laser based on polycrystals with large diameters.

4. Conclusions

Thus, we have demonstrated the possibility of achieving a high average power of a Fe:ZnSe laser with a high individual pulse energy at room temperature of the active element. As far as we know, the obtained average power of 20 W is the highest achieved to date for lasers operating in the spectral range λ = 4–5 μm at room temperature. Further increase in the average power can be achieved by increasing the pulse repetition rate and using the method of rotating active disk element.

Acknowledgements. This work was supported by the Russian Science Foundation [Grant No. 15-13-10028 (development of technology and fabrication of Fe:ZnSe samples)], as well as by the Russian Foundation for Basic Research [Grant Nos 15-02-06005 and 15-08-02562 (development of experimental methods and laser experiments)].

References

1. Adams J.J., Bibeau C., Page R.H., Krol D.M., Furu L.H., Payne S.A. *Opt. Lett.*, **24** (23), 1720 (1999).
2. Kernal J., Fedorov V.V., Gallian A., Mirov S.B., Badikov V.V. *Opt. Express*, **13** (26), 10608 (2005).
3. Akimov V.A., Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Frolov M.P. *Quantum Electron.*, **36** (4), 299 (2006) [*Kvantovaya Elektron.*, **36** (4), 299 (2006)].
4. Il'ichev N.N., Danilov V.P., Kalinushkin V.P., Studenikin M.I., Shapkin P.V., Nasibov A.S. *Quantum Electron.*, **38** (2), 95 (2008) [*Kvantovaya Elektron.*, **38** (2), 95 (2008)].
5. Doroshenko M.E., Jelinkova H., Koranda P., Sulc J., Basiev T.T., Osiko V.V., Komar V.K., Gerasimenko A.S., Puzikov V.M., Badikov V.V., Badikov D.V. *Laser Phys. Lett.*, **7** (1), **39** (2010).
6. Myoung NoSoung, Martyshkin D.V., Fedorov V.V., Mirov S.B. *Opt. Lett.*, **36** (1), 94 (2011).
7. Mirov S.B., Fedorov V.V., Martyshkin D.V., Moskalev I.S., Mirov M.S., Vasilyev S.V. *IEEE J. Select. Topics Quantum Electron.*, **21** (1), 1601719 (2015).
8. Velikanov S.D., Danilov V.P., Zakharov N.G., Il'ichev N.N., Kazantsev S.Yu., Kalinushkin V.P., Kononov I.G., Nasibov A.S., Studenikin M.I., Pashinin P.P., Firsov K.N., Shapkin P.V., Shchurov V.V. *Quantum Electron.*, **44** (2), 141 (2014) [*Kvantovaya Elektron.*, **44** (2), 141 (2014)].
9. Gavrishchuk E.M., Kazantsev S.Yu., Kononov I.G., Rodin S.A., Firsov K.N. *Quantum Electron.*, **44** (6), 505 (2014) [*Kvantovaya Elektron.*, **44** (6), 505 (2014)].
10. Firsov K.N., Gavrishchuk E.M., Kazantsev S.Yu., Kononov I.G., Rodin S.A. *Laser Phys. Lett.*, **11** (8), 085001 (2014).
11. Firsov K.N., Gavrishchuk E.M., Kazantsev S.Yu., Kononov I.G., Maneshkin A.A., Mishchenko G.M., Nefedov S.M., Rodin S.A., Velikanov S.D., Yutkin I.M., Zaretsky N.A., Zotov E.A. *Laser Phys. Lett.*, **11**, 125004 (2014).

12. Velikanov S.D., Zaretsky N.A., Zotov E.A., Kozlovskii V.I., Korostelin Yu.V., Krokhin O.N., Maneshkin A.A., Podmar'kov Yu.P., Savinova S.A., Skasyrskii Ya.K., Frolov M.P., Chuvatkin R.S., Yutkin I.M. *Quantum Electron.*, **45** (1), 1 (2015) [*Kvantovaya Elektron.*, **45** (1), 1 (2015)].
13. Kozlovsky V.I., Akimov V.A., Frolov M.P., Korostelin Yu.V., Landman A.I., Martovitsky V.P., Mislavskii V.V., Podmar'kov Yu.P., Skasyrsky Ya.K., Voronov A.A. *Phys. Status Sol. B*, **247** (6), 1553 (2010).
14. Evans J.W., Berry P.A., Schepler K.L. *Opt. Lett.*, **37** (23), 5021 (2012).
15. Myoung NoSoung, Fedorov V.V., Mirov S.B., Wenger L.E. *J. Luminescence*, **132** (3), 600 (2012).
16. Firsov K.N., Frolov M.P., Gavrishchuk E.M., Kazantsev S.Yu., Kononov I.G., Korostelin Yu.V., Maneshkin A.A., Velikanov S.D., Yutkin I.M., Zaretsky N.A., Zotov E.A. *Laser Phys. Lett.*, **13** (1), 015002 (2016).
17. Akimov V.A., Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Frolov M.P. *Quantum Electron.*, **37** (11), 1071 (2007) [*Kvantovaya Elektron.*, **37** (11), 1071 (2007)].
18. Gavrishchuk E.M., Ikonnikov V.B., Kazantsev S.Yu., Kononov I.G., Rodin S.A., Savin D.V., Timofeeva N.A., Firsov K.N. *Quantum Electron.*, **45** (9), 823 (2015) [*Kvantovaya Elektron.*, **45** (9), 823 (2015)].
19. Velikanov S.D., Zaretsky N.A., Zotov E.A., Kazantsev S.Yu., Kononov I.G., Korostelin Yu.V., Maneshkin A.A., Firsov K.N., Frolov M.P., Yutkin I.M. *Quantum Electron.*, **46** (1), 11 (2016) [*Kvantovaya Elektron.*, **46** (1), 11 (2016)].
20. Firsov K.N., Gavrishchuk E.M., Ikonnikov V.B., Kazantsev S.Yu., Kononov I.G., Kotereva T.V., Savin D.V., Timofeeva N.A. *Laser Phys. Lett.*, **13** (5), 055002 (2016).
21. Mirov S.B., Fedorov V., Martyshkin D., Moskalev I., Mirov M., Vasilyev S. *Advanced Solid State Lasers Conf.* (Berlin, Germany, 2015) AW4A.1.
22. Kozlovsky V.I., Korostelin Y.V., Podmar'kov Y.P., Skasyrsky Y.K., Frolov M.P. *J. Phys. Conf. Ser.*, **740**, 012006 (2016).
23. Dormidonov A.E., Firsov K.N., Gavrishchuk E.M., Ikonnikov V.B., Kazantsev S.Yu., Kononov I.G., Kotereva T.V., Savin D.V., Timofeeva N.A. *Appl. Phys. B*, **122** (8), 211 (2016).
24. Potemkin F.V., Migal E.A., Pushkin A.V., Sirotkin A.A., Kozlovsky V.I., Korostelin Yu.V., Podmar'kov Yu.P., Firsov V.V., Frolov M.P., Gordienko V.M. *Laser Phys. Lett.*, **13** (12), 125403 (2016).
25. Frolov M.P., Korostelin Yu.V., Kozlovsky V.I., Mislavskii V.V., Podmar'kov Yu.P., Savinova S.A., Skasyrsky Ya.K. *Laser Phys. Lett.*, **10**, 125001 (2013).
26. Velikanov S.D., Garanin S.G., Domazhirov A.P., Efanov V.M., Efanov M.V., Kazantsev S.Yu., Kodola B.E., Komarov Yu.N., Kononov I.G., Podlesnykh S.V., Sivachev A.A., Firsov K.N., Shchurov V.V., Yarin P.M. *Quantum Electron.*, **40** (5), 393 (2010) [*Kvantovaya Elektron.*, **40** (5), 393 (2010)].
27. Bulaev V.D., Gusev V.S., Kazantsev S.Yu., Kononov I.G., Lysenko S.L., Morozov Yu.B., Poznyshev A.N., Firsov K.N. *Quantum Electron.*, **40** (7), 615 (2010) [*Kvantovaya Elektron.*, **40** (7), 615 (2010)].
28. Velikanov S.D., Domazhirov A.P., Zaretsky N.A., Kazantsev S.Yu., Kononov I.G., Kromin A.A., Podlesnykh S.V., Sivachev A.A., Firsov K.N., Kharitonov S.V., Tsykin V.S., Shchurov V.V., Yutkin I.M. *Quantum Electron.*, **45** (11), 989 (2015) [*Kvantovaya Elektron.*, **45** (11), 989 (2015)].
29. Andreev S.N., Firsov K.N., Kazantsev S.Yu., Kononov I.G., Samokhin A.A. *Laser Phys.*, **17** (6), 834 (2007).
30. Gavrishchuk E.M. *Inorganic Mater.*, **39** (9), 883 (2003).
31. Gavrishchuk E.M., Ikonnikov V.B., Savin D.V. *Inorganic Mater.*, **50** (3), 222 (2014).
32. Firsov K.N., Gavrishchuk E.M., Ikonnikov V.B., Kazantsev S.Yu., Kononov I.G., Kotereva T.V., Savin D.V., Timofeeva N.A. *Laser Phys. Lett.*, **13** (6), 065003 (2016).