*Quantum Electronics* **40** (1) 7 – 10 (2010) 

*LASERS*

PACS numbers: 42.55.Rz; 42.60.Lh; 42.70.Hj
DOI: 10.1070/QE2010v040n01ABEH014189

# Continuous-wave $Cr^{2+}$ : CdS laser

V.I. Kozlovskii, Yu.V. Korostelin, A.I. Landman, Yu.P. Podmar'kov, Ya.K. Skasyrskii, M.P. Frolov

***Abstract*. Continuous-wave lasing is obtained for the first time in a $Cr^{2+}$ : CdS crystal pumped by a thulium fibre laser at 1908 nm. The output power of the laser at 2534 nm achieved 0.81 W with the slope efficiency with respect to the absorbed pump power equal to 52.3 %. The parameters of $Cr^{2+}$ : CdS and $Cr^{2+}$ : CdSe lasers are compared. A $Cr^{2+}$ : CdSe crystal generated 1.7 W of cw radiation at 2638 nm with the slope efficiency with respect to the absorbed power equal to 53.4 %.**

***Keywords***: *$Cr^{2+}$ : CdS laser, $Cr^{2+}$ : CdSe laser, IR lasers, solid-state lasers, tunable lasers, II – VI crystals.*

## 1. Introduction

The II – VI crystals doped with bivalent transition-metal ions are being extensively studied for the development of tunable IR lasers emitting in the range from 2 to 5 μm [1 – 6]. Interest in lasers based on such crystals is related to a broad scope of their applications in science and technology, for example, in spectroscopy, photochemistry, medicine, in devices for the environmental monitoring, etc. These lasers have a high efficiency, broad continuous tuning ranges and can operate in pulsed and cw regimes at room temperature by using convenient pump sources, including semiconductor lasers. By now tunable lasing has been obtained in a number of crystals such as $Cr^{2+}$ : ZnS (the tuning range is from 1.94 to 2.84 μm [7, 8]), $Cr^{2+}$ : ZnSe (1.88 – 3.10 μm [9]), $Cr^{2+}$ : CdSe (2.26 – 3.61 μm [10]), $Cr^{2+}$ : CdMnTe (2.17 – 3.01 μm [11, 12]), $Cr^{2+}$ : CdTe (2.54 μm [13]), and $Fe^{2+}$ : ZnSe (3.77 – 5.05 μm [14 – 16]). Recently a $Cr^{2+}$ : CdS laser has been demonstrated (2.18 – 3.32 μm) [17, 18].

A $Cr^{2+}$ : CdS crystal has considerably better mechanical and thermooptical parameters than a $Cr^{2+}$ : CdSe crystal with a similar luminescence band. The lifetime of the upper laser level in these materials strongly depends on temperature, decreasing from 6 μs at liquid nitrogen temperature down to 4 μs at room temperature in $Cr^{2+}$ : CdSe and from 7.3 μs to 0.93 μs, respectively, in $Cr^{2+}$ : CdS. Although the upper-level lifetime of the $Cr^{2+}$ : CdS crystal at room temperature is lower, this crystal can be preferable for a number of applications, especially upon high-power cw pumping, because it has a higher heat conductivity and therefore will be heated weaker, and a decrease in the upper-level lifetime will be less considerable than that in the $Cr^{2+}$ : CdSe. In addition, the radiation parameters of lasers based on II – VI crystals doped with transition-metal ions are considerably affected by a thermal lens produced upon high-power pumping [19]. The thermal lens effect in the $Cr^{2+}$ : CdS crystal should be weaker than that in the $Cr^{2+}$ : CdSe crystal. The $Cr^{2+}$ : CdS crystal was studied earlier only upon pulsed pumping [17, 18]. The operation of the $Cr^{2+}$ : CdS laser in the cw regime obtained in our work considerably extends the scope of its applications.

In this paper, we obtained for the first time cw lasing in a $Cr^{2+}$ : CdS crystal and studied parameters of this laser. For comparison, we also investigated a cw $Cr^{2+}$ : CdSe laser on the same experimental setup and managed to obtain the higher output power and slope efficiency than those reported in [20].

## 2. Experimental

Figure 1 presents the optical scheme of the setup. A nearly semi-concentric $Cr^{2+}$ : CdS laser resonator is formed by plane mirror M1, transmitting 96 % of the 1.908-μm pump radiation and reflecting almost 100 % of radiation in the spectral range from 2.4 to 3.4 μm, and by output spherical mirror M2 ($R = 50$ mm). We used in experiments two

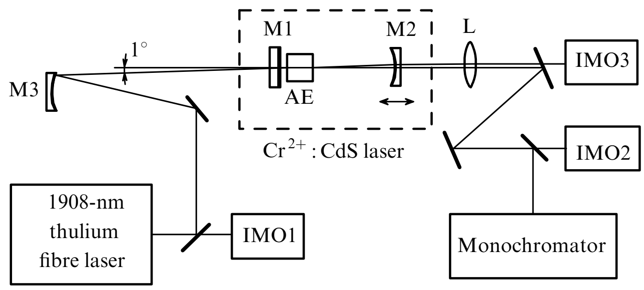


**Figure 1.** Optical scheme of the experimental setup: (AE) active element; (M1, M2) laser resonator mirrors; (M3) spherical ($R = 50$ cm) focusing mirror; (L) collimating lens; (IMO1-3) power meters.

**V.I. Kozlovskii, Yu.V. Korostelin, A.I. Landman, Ya.K. Skasyrskii** P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: frolovmp@x4u.lebedev.ru, yans@sci.lebedev.ru;
**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

Received 20 July 2009; revision received 25 September 2009
*Kvantovaya Elektronika* **40** (1) 7 – 10 (2010)
Translated by M.N. Sapozhnikov

output mirrors M2(I) and M2(II) with transmission spectra in the region of the maximum gain in the $Cr^{2+}:CdS$ crystal shown in Fig. 2. The transmission of both output mirrors at the pump wavelength was 90 %. Mirror M2 was moved along the laser resonator axis during alignment, thereby varying the resonator length to obtain the best matching between a resonator mode and the pump region.

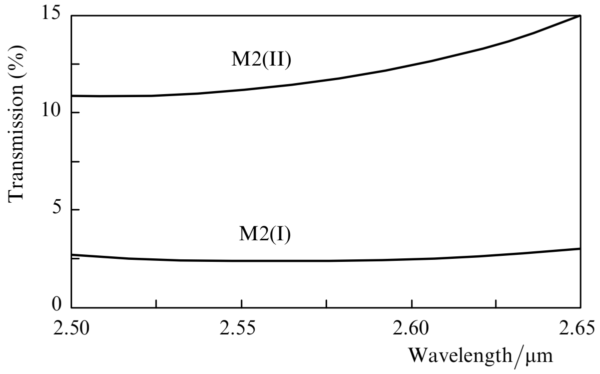


**Figure 2.** Transmission spectra of output mirrors.

The active element (AE) of the laser was made of a $Cr^{2+}:CdS$ single crystal grown from a vapour phase on a single-crystal seed by using the physical transport in helium. Doping was performed during the growth process by using the technology developed for growing solid-solution single crystals [21, 22]. The concentration of $Cr^{2+}$ ions measured by the atomic emission analysis was $1.1 \times 10^{18}$ $cm^{-3}$. The spectral and lasing parameters of this crystal were studied earlier upon pulsed pumping [17, 18].

The working length of the AE was $l_a = 5.1$ mm, its transverse dimensions were $1.5 \times 5$ mm, and it was placed at a distance of 0.3 – 0.6 mm from mirror M1. The working surfaces of the AE had no antireflection coatings, but they were carefully polished and parallel to each other with good accuracy (the wedge was less than 30″). The angle between the crystal axis and normal to the polished working surfaces of the AE was $\sim 4°$. To provide the efficient heat removal, the AE was clamped via indium interlayers between two copper plates cooled by running water at a temperature of 14 °C. To minimise losses caused by the Fresnel reflection of radiation from crystal faces, the AE working surfaces were oriented perpendicular to the resonator optical axis.

The $Cr^{2+}:CdS$ laser was pumped by a 5.8-W, 1.908-μm modified cw TLM-05LP thulium fibre laser (IRE-Polyus Research and Technology Association). The pump radiation beam was focused through M1 by a spherical mirror ($R = 50$ cm) to a spot of diameter 0.24 mm on the nearer face of the AE and was directed at a small angle (to $\sim 1°$) to the optical axis of the $Cr^{2+}:CdS$ laser resonator. This prevented the incidence of pump radiation reflected from resonator elements on the focusing mirror, thereby excluding the influence of the latter on the pump laser operation. In this case, the angle between the pump beam and resonator axis inside the crystal did not exceed 25′, which provided good matching between the volumes of the pumped region and the fundamental transverse mode of the resonator. The unsaturated absorption coefficient of the $Cr^{2+}:CdS$ crystal at the pump wavelength was 1.47 $cm^{-1}$.

The pump and laser powers were measured by IMO1 and IMO2 power meters. Because the absorption coefficient decreases during lasing, the pump-power absorption in the AE was determined by measuring (with an IMO3 power meter) the pump power transmitted thorough the crystal during lasing. We took into account the Fresnel losses of pump radiation at the AE input and the contribution of pump radiation transmitted through the AE and reflected backward from the AE end facing the output mirror. The lasing spectrum was measured with a grating monochromator.

## 3. Experimental results and discussion

We obtained for the first time cw lasing in a $Cr^{2+}:Cds$ crystal in our setup. In most experiments the laser spectrum was centred at 2534 nm. We observed small line shifts (no more than by 10 nm) depending on the resonator mirror and resonator alignment. The laser linewidth did not exceed 6 nm (the spectral resolution of the monochromator was 3 nm).

Figure 3 presents the dependences of the output power of the $Cr^{2+}:CdS$ laser on the absorbed pump power $P_{abs}$ for two output mirrors. The maximum value $P_{out} = 0.81$ W was obtained with output mirror M2(II) for $P_{abs} = 2$ W. In this case, the threshold absorbed pump power $P_{th}$ was 0.538 W and the slope efficiency $\eta_{abs}$ was 52.3 %. When output mirror M2(I) with a smaller transmission was used, the threshold power $P_{th}$ decreased down to 0.433 W and $\eta_{abs}$ decreased to 30.9 %. Note that due to losses in external optical elements and the input face of the crystal (the Fresnel reflection coefficient is 15.2 %) and due to weak absorption of pump radiation by the crystal (less than 50 % during lasing), the pump power was used incompletely. As a result, the total optical efficiency of the $Cr^{2+}:CdS$ laser was 14 %.

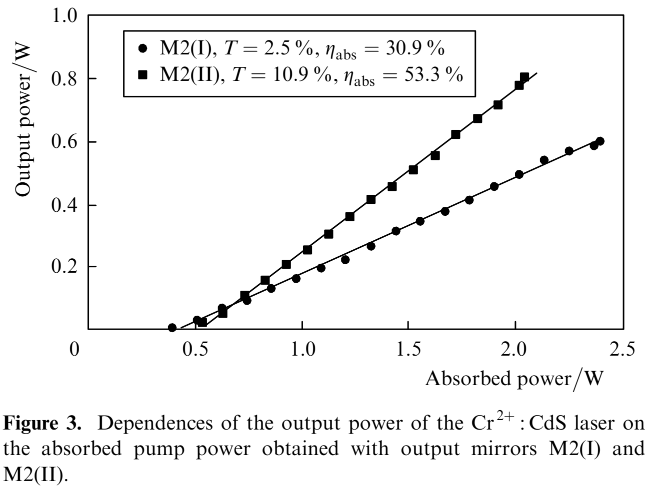


**Figure 3.** Dependences of the output power of the $Cr^{2+}:CdS$ laser on the absorbed pump power obtained with output mirrors M2(I) and M2(II).

The dependence of $\eta_{abs}$ on the transmission $T$ of the output mirror was used to estimate passive losses $L$ in the $Cr^{2+}:CdS$ laser resonator from the expression [23]

$$\frac{1}{\eta_{abs}} = \frac{1}{\eta'_0} + \frac{L}{\eta'_0}\frac{1}{T}, \tag{1}$$

where $\eta'_0 = \eta_p(\lambda_p/\lambda_{las})(1 - \sigma_{ESA}/\sigma)$ is the limiting efficiency; $\eta_p$ is the pump radiation use efficiency; $\lambda_{las}$ is the laser wavelength; $\lambda_p$ is the pump wavelength; $\sigma_{ESA}$ is the excited-state absorption cross section; and $\sigma$ is the laser transition cross section. We obtained from experiments the value $L = 2.7\,\%$. By assuming that these losses are internal losses in the AE, the upper estimate of the loss factor in the $Cr^{2+}$ : CdS crystal at the laser wavelength is 0.026 $cm^{-1}$.

To compare the parameters of $Cr^{2+}$ : CdS and $Cr^{2+}$ : CdSe lasers under identical experimental conditions, the $Cr^{2+}$ : CdS crystal was replaced by the $Cr^{2+}$ : CdSe crystal of almost the same size (with slightly different $l_a$). We used two $Cr^{2+}$ : CdSe crystals: crystal No. 1 ($l_a$ = 4.9 mm) with the same $Cr^{2+}$ ion concentration ($1.1\times 10^{18}$ $cm^{-3}$) as in the $Cr^{2+}$ : CdS crystal, and crystal No. 2 ($l_a$ = 5.2 mm) with a lower $Cr^{2+}$ concentration ($0.81\times 10^{18}$ $cm^{-3}$). The $Cr^{2+}$ concentration in $Cr^{2+}$ : CdSe crystals was determined from absorption spectra by using the absorption cross section taken from [3]. The unsaturated absorption coefficient at the pump wavelength was 3.3 and 2.43 $cm^{-1}$ for crystals No. 1 and 2, respectively.

We obtained cw lasing in both $Cr^{2+}$ : CdSe crystals. The maxima of the lasing spectra of these crystals (at 2638 and 2598 nm for crystals No. 1 and 2, respectively) were shifted to the red with respect to the maximum of the lasing spectrum of the $Cr^{2+}$ : CdS laser. The width of these spectra did not exceed 6 nm.

Figure 4 presents the dependences of the output power of $Cr^{2+}$ : CdSe (No. 1), $Cr^{2+}$ : CdSe (No. 2), and $Cr^{2+}$ : CdS lasers on the absorbed power, which were obtained by using output mirror M2(II). A considerable difference in the maximum absorbed pump power for these three crystals is caused by the difference in their absorptions during cw lasing.

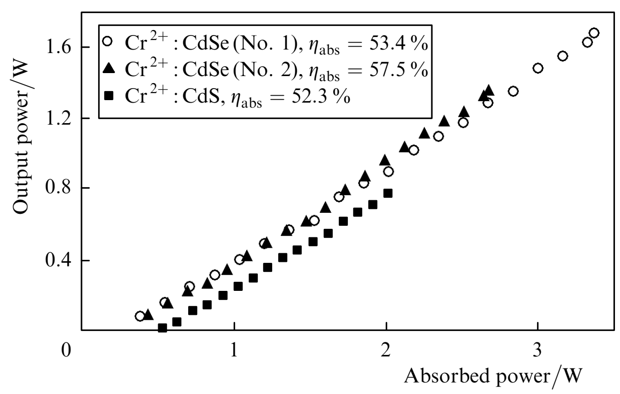


**Figure 4.** Dependences of the output power $Cr^{2+}$ : CdS, $Cr^{2+}$ : CdSe (No. 1) and $Cr^{2+}$ : CdSe (No. 2) crystals on the absorbed pump power obtained with mirror M2(II).

The maximum value $P_{out} = 1.7$ W was obtained in the laser based on crystal No. 1 for $P_{abs} = 3.37$ W and $P_{th} = 0.274$ W. The achieved output power exceeds 1.1 W obtained earlier in the cw $Cr^{2+}$ : CdSe laser [20]. This can be explained by the more efficient use of pump radiation due to a smaller angle between the pump beam direction and laser resonator axis and by the better matching between the pump and lasing volumes in the crystal. In addition, the working faces of the crystal were well polished, which reduced scattering losses. The achieved slope efficiency $\eta_{abs} = 53.4\,\%$ also exceeded the efficiency $\eta_{abs} = 44\,\%$ obtained in [20]. Even the higher value $\eta_{abs} = 57.5\,\%$, which is the highest for the $Cr^{2+}$ : CdSe laser, was obtained in the laser based on crystal No. 2.

We measured the parameters of the $Cr^{2+}$ : CdSe laser with output mirror M2(I) as well. As in the case of the $Cr^{2+}$ : CdS laser, we estimated passive losses in the $Cr^{2+}$ : CdSe laser resonator as 3.5 % and 2.9 % in crystals No. 1 and 2, which corresponds to absorption coefficients equal to 0.036 and 0.028 $cm^{-1}$, respectively. The main lasing parameters of $Cr^{2+}$ : CdS and $Cr^{2+}$ : CdSe crystals are presented in Table 1.

**Table 1.** Main radiation parameters of $Cr^{2+}$ : CdS and $Cr^{2+}$ : CdSe lasers.

| Crystal | $\lambda_{las}$/nm | Output mirror M2(I) | | Output mirror M2(II) | |
|---|---|---|---|---|---|
| | | $P_{th}$/W | $\eta_{abs}$ (%) | $P_{th}$/W | $\eta_{abs}$ (%) |
| $Cr^{2+}$ : CdS | 2534 | 0.433 | 30.9 | 0.538 | 52.3 |
| $Cr^{2+}$ : CdSe (No. 1) | 2638 | 0.194 | 29.7 | 0.273 | 53.4 |
| $Cr^{2+}$ : CdSe (No. 2) | 2598 | 0.137 | 33.1 | 0.310 | 57.5 |

These data show that $Cr^{2+}$ : Cd and $Cr^{2+}$ : CdSe lasers have close values of $\eta_{abs}$. As expected, the threshold pump power for the $Cr^{2+}$ : CdS crystal is higher than that for the $Cr^{2+}$ : CdSe laser. It can be estimated from the expression [24]

$$P_{th} = (E_{ph}/\sigma\tau)(S_p + S_{las})(L + T), \quad (2)$$

where $E_{ph}$ is the pump photon energy; $\sigma$ is the gain cross section ($\sigma_{CdS} = 1.1 \times 10^{-18}$ $cm^2$ [18], $\sigma_{CdSe} = 1.1\times 10^{-18}$ $cm^2$ [25]); $\tau$ is the upper laser-level lifetime; and $S_p$ and $S_{las}$ is the pump and laser mode area, respectively. It follows from expression (2) that the difference between threshold pump powers observed in [24] is manly determined by the difference in the values of $\tau$, which is 0.93 and 4.05 μs for $Cr^{2+}$ : CdS and $Cr^{2+}$ : CdSe, respectively, according to our measurements at room temperature. Therefore, according to (2), the threshold powers for these two crystals at 300 K should differ by more than four times. However, the data presented in Table 1 show that the difference in the values of $P_{th}$ is smaller. In our opinion, this can be explained by the difference in thermooptical parameters of these crystals.

We demonstrated qualitatively the advantage of the $Cr^{2+}$ : CdS crystal over the $Cr^{2+}$ : CdSe crystal at high pump powers in additional experiments in which the pump beam diameter on a crystal was reduced down to 0.15 mm. In this case, the growth rate of the output power of the $Cr^{2+}$ : CdSe (No. 1) crystal decreased when the absorbed pump power exceeded 1.6 W. As a result, the maximum output power did not exceed 1.2 W, unlike $P_{out} = 1.7$ W obtained for the pump spot of diameter 0.24 mm. In the $Cr^{2+}$ : CdS laser, such a decreases in the growth rate of the output power was not observed, and the output power at the maximum absorbed pump power of 2 W was 0.785 W, which is close to 0.81 W obtained with a large pump spot. This gives promise that higher output powers can be achieved by using higher-power pumping of the $Cr^{2+}$ : CdS laser.

At present the highest output power among cw lasers based on II – VI crystals was achieved in $Cr^{2+}$ : ZnS (10 W) and $Cr^{2+}$ : ZnSe (13 W) lasers pumped by a 30-W fibre laser [8]. We can assume that the optimisation of pumping conditions and the use of higher-power pumping will provide the increase in the output power of $Cr^{2+}$ : CdSe and $Cr^{2+}$ : CdS lasers.

The homogeneous nature of the amplification band of II–VI crystals doped with transition-metal ions allows in principle a considerable narrowing of the laser line without significant power losses, while the results that we obtained earlier upon pulsed pumping [17, 18] give promise that continuous tuning of cw $Cr^{2+}$ : CdS laser can be achieved in the range from 2.2 to 3.3 μm. Narrowband and tunable lasers of this type can find applications in high-resolution spectroscopy, in particular, in the development of compact optical frequency standards.

## 4. Conclusions

We have obtained for the first time cw lasing in a $Cr^{2+}$ : CdS crystal emitting 0.81 W of output power with the slope efficiency with respect to the absorbed pump power equal to 52.3 %. In our opinion, the laser efficiency can be increased by further optimising the transmission of the output mirror and matching the pump and lasing regions in the active element. To increase the total laser efficiency, it is necessary to use the active element with AR coated surfaces having a stronger absorption at the pump wavelength.

***Acknowledgements.*** This work was partially supported by the program 'Development of the Scientific Potential of the Higher School' of the Ministry of Education and Science of the Russian Federation and by the Russian Foundation for Basic Research (Grant Nos 09-02-00864-a and 09-02-00877-a).

## References

1. DeLoach L.D., Page R.H., Wilke G.D., Payne S.A., Krupke W.F. *IEEE J. Quantum Electron.*, **32**, 885 (1996).
2. 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).
3. McKay J., Schepler K.L., Catella G.C. *Opt. Lett.*, **24**, 1575 (1999).
4. Adams J.J., Bibeau C., Page R.H., Krol D.M., Furu L.H., Payne S.A. *Opt. Lett.*, **24**, 1720 (1999).
5. Kuck S. *J. Alloys Compounds*, **341**, 28 (2002).
6. Sorokina I.T. *Opt. Mater.*, **26**, 395 (2004).
7. Sorokina I.T., Sorokin E., Mirov S., Fedorov V., Badikov V.V., Panyutin V., Schaffers K.I. *Opt. Lett.*, **27**, 1040 (2002).
8. Moskalev I.S., Mirov S.B., Fedorov V.V. *Opt. Express*, **17**, 2048 (2009).
9. Demirbas U., Sennaroglu A. *Opt. Lett.*, **31**, 2293 (2006).
10. Akimov V.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Skasyrskii Ya.K., Frolov M.P. *Kvantovaya Elektron.*, **38**, 205 (2008) [*Quantum Electron.*, **38**, 205 (2008)].
11. Seo J.T., Hömmerich U., Trivedi S.B., Chen R.J., Kutcher S. *Opt. Commun.*, **153**, 267 (1998).
12. Trivedi S.B., Kutcher S.W., Wang C.C., Jagannathan G.V., Hömmerich U., Bluiett A., Turner M., Seo J.T., Schepler K.L., Schumm B., Boyd P.R., Green G. *J. Electron. Mater.*, **30**, 728 (2001).
13. Bluiett A., Hömmerich U., Shah R.T., Trivedi S.B., Kutcher S.W., Wang C.C. *J. Electron. Mater.*, **31**, 806 (2002).
14. Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Frolov M.P. *Kvantovaya Elektron.*, **35**, 809 (2005) [*Quantum Electron.*, **35**, 809 (2005)**.**
15. Akimov V.A., Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Frolov M.P. *Kvantovaya Elektron.*, **36**, 299 (2006) [*Quantum Electron.*, **36**, 299 (2006)].
16. 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).
17. Akimov V.A., Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Skasyrskii Ya.K., Frolov M.P. *Kvantovaya Elektron.*, **36**, 299 (2006) [*Quantum Electron.*, **36**, 299 (2006)].
18. Akimov V.A, Frolov M.P., Korostelin Yu.V., Kozlovsky V.I., Landman A.I., Podmar'kov Yu.P., Skasyrsky Yu.K., Voronov A.A. *Appl. Phys. B*, **97**, 793 (2009).
19. Schepler K.L., Peterson R.D., Berry P.A., McKay J.B. *IEEE J. Selected Topics Quantum Electron.*, **11**, 713 (2005).
20. 20. Akimov V.A., Voronov A.A., Kozlovskii V.I., Korostelin Yu.V., Landman A.I., Podmar'kov Yu.P., Skasyrskii Ya.K., Frolov M.P. *Kvantovaya Elektron.*, **37**, 991 (2007) [*Quantum Electron.*, **37**, 991 (2007)].
21. Korostelin Yu.V., Kozlovsky V.I., Nasibov A.S., Shapkin P.V. *J. Crystal Growth*, **159**, 181 (1996).
22. Korostelin Yu.V., Kozlovsky V.I. *J. Alloys Compounds*, **371**, 25 (2004).
23. Caird J.A., Pane S.A., Staver P.R., Ramponi A.J., Chase L.L., Krupke W.F. *IEEE J. Quantum Electron.*, **24**, 1077 (1988).
24. Moulton P.F. *IEEE J. Quantum Electron.*, **21**, 1582 (1985).
25. McKay J.B. *PhD Dissertation* (Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 2003).