09

Pulsed 2.77 μm Cr^{2+}:CdSe laser with output energy of 1.2 J

© V.I. Kozlovsky, Yu.V. Korostelin, Ya.K. Skasyrsky, M.P. Frolov

Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
E-mail: kozlovskiyvi@lebedev.ru

Received June 24, 2024
Revised August 30, 2024
Accepted September 8, 2024

Due to a high value of the CdSe crystal thermo-optical coefficient, energy characteristics of Cr^{2+}:CdSe lasers are limited by the thermal lens development. To reduce the effect of the thermal lens, a large-volume crystal was grown, which made it possible to increase the diameter to ~ 5 mm and excitation region length to ~ 9 mm. As a result, the mode of linear growth of the Cr^{2+}:CdSe laser output energy to the record value of 1.2 J at the differential laser efficiency of 51% in terms of absorbed pump energy was implemented.

Keywords: Cr^{2+}:CdSe laser, thermal lens, Er:YAG laser, Cr:Tm:Ho:YAG laser.

DOI: 10.61011/TPL.2025.01.60144.20032

The II−VI compounds doped with divalent transition metal ions, which were first proposed as a laser media for the mid-infrared range [1,2], later attracted serious attention from researchers [3]. Due to their wide gain bandwidth, these materials are of great interest for developing both tunable lasers and femtosecond lasers which find applications in medicine, environmental monitoring, spectroscopy and metrology.

In this class of lasers, the best studied are the Cr^{2+}:ZnSe and Fe^{2+}:ZnSe lasers covering spectral ranges of 1.880−3.349 [4.5] and 3.76−5.29 μm [6], respectively. The Cr^{2+}:CdSe-based laser proposed for the first time in [7] provides access to the spectral range of 2.22−3.61 μm [8,9] whose long-wavelength part complements emission ranges of the Cr^{2+}:ZnSe and Fe^{2+}:ZnSe lasers.

The vast majority of research devoted to the Cr^{2+}:CdSe laser is aimed at increasing its average power. For a continuous-wave laser with moving active medium, output power of 22.5 W was achieved [10], while for the pulse-periodic mode at the pulse repetition rate of 8 kHz there was demonstrated average power of 6 W at the efficiency of 67% [11]. So far, the maximum single-pulse energy has been 17 mJ [8]. Meanwhile, in a number of practical applications, e. g. biomaterial processing [12], of great interest are high-energy laser pulses whose spectrum coincides with the water absorption band. The goal of this study was scaling the single-pulse output energy of the Cr^{2+}:CdSe laser.

The experimental setup diagram is given in Fig. 1. The laser active element (AE) was an uncoated plane-parallel wafer of the Cr^{2+}:CdSe single crystal 8.8 mm in thickness and 27 mm in diameter with the optical axis aligned with the cavity axis; the wafer was grown by using the technique of physical transport in helium [9]. Concentration of the Cr^{2+} ions was $1.8 \cdot 10^{18}\,\mathrm{cm}^{-3}$. Highly reproducible crystal growth was carried out at the temperature of 1150°C for 200 h. The Cr^{2+}:CdSe laser cavity 110 mm long was formed by the totally reflecting spherical mirror 300 mm in radius and planar outcoupling mirror. Active element AE was mounted close to the outcoupling mirror and was not intentionally cooled. Transmittances of the used outcoupling mirrors were 19, 45 and 63% near the wavelength of 2.75 μm.

In tentative experiments, the pump source was a pulsed 1.78 μm Er:YAG laser with the maximum energy of 350 mJ and pulse duration of 250 μs. When focusing was done with lens L with the focal length of 100 mm, the pump spot 1.4 mm in diameter on the AE input surface contained 80% of the pump energy. The pump beam was directed at the angle of 0.06 rad to the cavity axis. To increase the efficiency of the pump energy utilization, the pump beam reflected from the AE face (Fresnel reflection of 18%) was returned to AE by spherical mirror M 100 mm in radius. The pump energy was controlled by the attenuator (a set of calibrated light filters). Three energy meters (Ophir Optronics) were used to record both the pump energy entering AE and passing through it and laser Cr^{2+}:CdSe output energy; this allowed determining the laser efficiency in terms of absorbed pump energy. The time dependence of pump and lasing pulses was measured with photodiodes PD36 („AIBI"LLC); the lasing spectrum was measured with a homemade diffraction-grating spectrograph.

Fig. 2, a presents the dependences of the Cr^{2+}:CdSe laser output energy on the absorbed pump energy, which were measured at the pump spot diameter of 1.4 mm for three outcoupling mirrors. The lasing spectrum center was located near the wavelength of 2.77 μm in all the three cases, while its width at half maximum at the pump energy of 300 mJ was $\sim 0.2\,\mu$m.

The best result was obtained by using the outcoupling mirror with transmittance of 45%. In this case, the differential laser efficiency measured in the initial experimental curve region (absorbed pump energy below 100 mJ) was 43%. However, as shown in Fig. 2, a, at higher energies saturation of the output energy is observed in all the cases, which may be associated with the AE heating resulting in a decrease in the upper-laser-level lifetime and formation

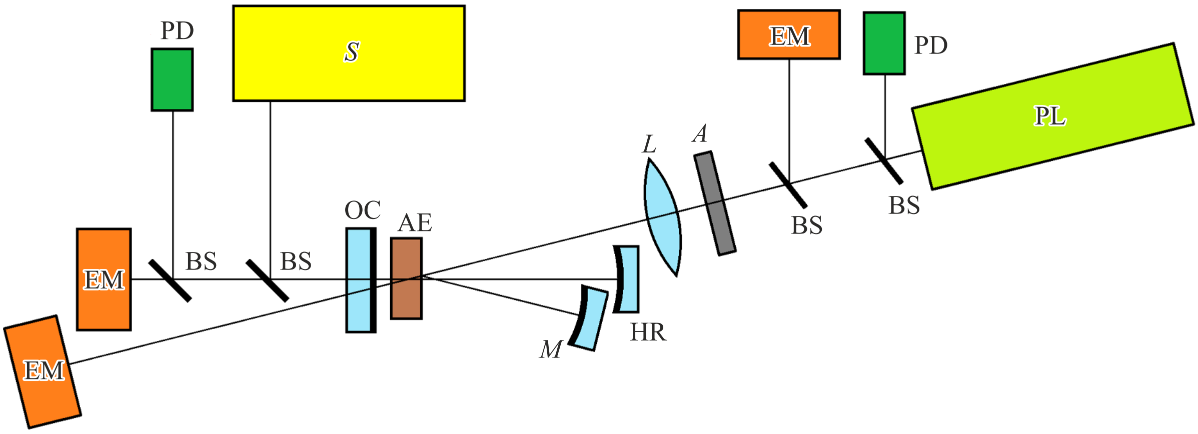

Figure 1. Experimental details. PL — pump laser, BS — beam splitter, PD — photodiode, EM — energy meter, L — focusing lens, A — beam attenuator, HR and OC — totally reflecting and outcoupling mirrors of the Cr^{2+}:CdSe laser cavity, AE — Cr^{2+}:CdSe crystal, M — spherical Al mirror, S — diffraction-grating spectrograph.

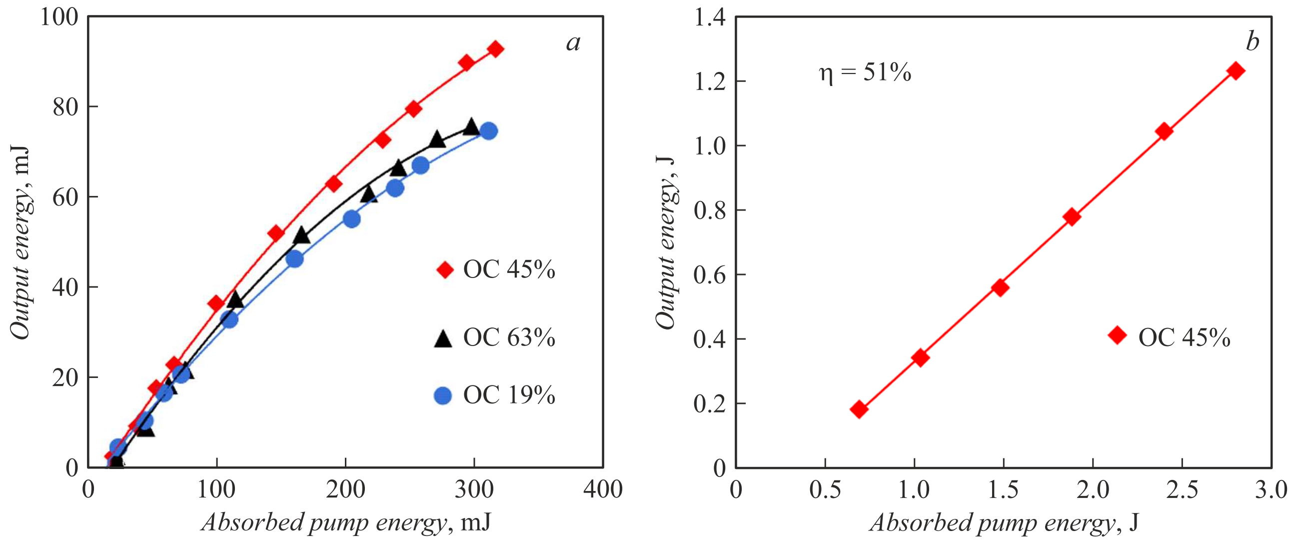

Figure 2. Dependences of the Cr^{2+}:CdSe laser output energy on absorbed pump energy, which were obtained using different outcoupling mirrors at the pump spot diameters of 1.4 (a) and 4.7 mm (b).

in AE of a positive dynamic thermal lens. The first factor cannot affect the laser efficiency, since the estimated AE heating by up to 3 K results only in a slight lifetime decrease from 3.8 μs by no more than 0.25 μs [13].

In our opinion, the main role is played by the thermal lens arising in AE. Based on the analysis performed in [14], it is easy to show that, in the case of a parabolic pump energy distribution over the beam cross section, the focal length may be estimated as

$$F = \pi r_0^4 C/(4Q \cdot dn/dT), \tag{1}$$

where $r_0 = 0.95$ mm is the radius of the pump beam containing 100% of energy, heat capacity is $C = 2.85\,\mathrm{J \cdot cm^{-3} \cdot K^{-1}}$ [15], $dn/dT = 98 \cdot 10^{-6}\,\mathrm{K^{-1}}$ [16] (thermoelastic deformations were ignored because of a low thermal expansion coefficient), Q is the pump energy spent on AE heating. At the maximum absorbed pump energy of 315 mJ, the output laser energy was 93 mJ; therefore, energy $Q = 222$ mJ what was converted into heat. In this case, the calculated focal length of the lens is $F \approx 84$ mm. Since AE is located near the planar outcoupling mirror, this mirror, jointly with the thermal lens, serves as a spherical mirror with the curvature radius of F; this brings the cavity beyond the stability region defined by condition $0 < (1 - S/R_1)(1 - S/R_2) < 1$ [17], where $S = 110$ mm is the cavity length, $R_1 \approx F \approx 84$ mm is the effective radius of the outcoupling mirror, $R_2 = 300$ mm is the curvature radius of the totally-reflecting mirror. In our case of non-coaxial pumping, the thermal lens effect on the beam gets weaker and results only in the energy saturation.

Fig. 3 presents the oscillograms of pump pulse P_{abs} and lasing pulse P_{out}, and also the time dependence of the ratio between the laser output power and absorbed pump power. Oscillograms presented in Fig. 3, a show that, when the

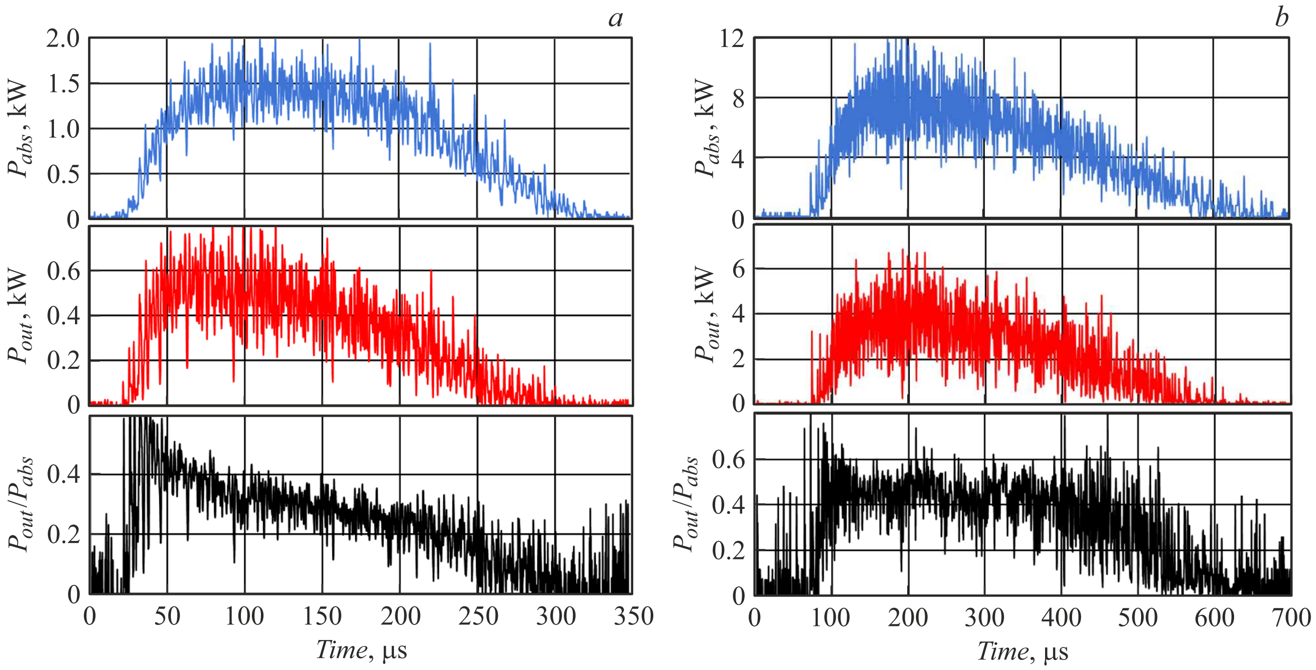

Figure 3. Shapes of the pump pulse (top oscillogram) and lasing pulse (middle oscillogram), and the lasing power to pump power ratio (bottom oscillogram). *a* — pump beam diameter is 1.4 mm, absorbed pump energy is 300 mJ; *b* — pump beam diameter is 4.7 mm, absorbed pump energy is 2.6 J.

pump beam diameter is 1.4 mm, the lasing pulse decreases faster than the pump pulse, which confirms the assumption about the dynamic thermal lens development in AE.

The obvious solution is to increase the active area transverse size, which would allow reducing the thermal lens negative role by increasing its focal length. However, enlargement of the pump spot results in an increase in the lasing threshold, which requires an increase in the pump pulse energy. Therefore, in further experiments a single-pulse 2.11 μm Cr:Tm:Ho:YAG laser with the maximum energy of 3.3 J and pulse duration of 500 μs was selected as a pump source. When focusing with a lens with the focal length of 320 mm, the pump spot on the AE input surface had a diameter of 4.7 mm (80% of the energy). Under these conditions, at the maximum pumping, the energy consumed by heating (the difference between the absorbed and output energies) was $Q = 1.6$ J, while $r_0 = 3.2$ mm; thus, the focal length obtained via (1) was $F \approx 1500$ mm, i.e. the laser cavity remained stable even at maximum pumping.

Fig. 2, *b* demonstrates the output energy dependence on absorbed pump energy, which was obtained in this case with the optimal outcoupling mirror having transmittance of 45%. Over the entire range of pump energies, a linear increase in the output energy is observed, and the maximum output energy exceeds 1.2 J at the differential efficiency of 51% in terms of absorbed pump energy. The oscillograms presented in Fig. 3, *b* show that the ratio of lasing power to pump power remains constant during almost the entire pump pulse. The laser operating regime was multimode, divergence angle of the Cr^{2+}:CdSe laser beam was approximately 15 mrad at the energy of 1 J.

Thus, the Cr^{2+}:CdSe laser output energy obtained in this work was 1.2 J, which exceeds the previously published results by almost two orders of magnitude. The laser differential efficiency appeared to be 51%. The advantage of this laser over the well-known Er:YAG (2.94 μm) and Cr:Er:YSGG (2.79 μm) lasers is wide wavelength tunability in the range of 2.22–3.61 μm.

Funding

The study was performed under State Assignment FFMR-2024-0017).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] L.D. DeLoach, R.H. Page, G.D. Wilke, S.A. Payne, W.P. Krupke, IEEE J. Quantum Electron., **32** (6), 885 (1996). DOI: 10.1109/3.502365

[2] R.H. Page, K.I. Schaffers, L.D. Deloach, G.D. Wilke, F.D. Patel, J.B. Tassano, Jr, S.A. Payne, W.F. Krupke, K.T. Chen, A. Burger, IEEE J. Quantum Electron., **33** (4), 609 (1997). DOI: 10.1109/3.563390

[3] S. Mirov, I. Moskalev, S. Vasilyev, V. Smolski, V. Fedorov, D. Martyshkin, J. Peppers, M. Mirov, A. Dergachev, V. Gapontsev, IEEE J. Sel. Top. Quantum Electron., **24** (5), 1601829 (2018). DOI: 10.1109/JSTQE.2018.2808284

[4] U. Demirbas, A. Sennaroglu, Opt. Lett., **31** (15), 2293 (2006). DOI: 10.1364/OL.31.002293

[5] E. Sorokin, I.T. Sorokina, M.S. Mirov, V.V. Fedorov, I.S. Moskalev, S.B. Mirov, in *Advanced solid-state photonics 2010* (San Diego, USA, 2010), paper AMC2. DOI: 10.1364/ASSP.2010.AMC2

[6] P. Fjodorow, M.P. Frolov, Yu.V. Korostelin, V.I. Kozlovsky, C. Schulz, S.O. Leonov, Ya.K. Skasyrsky, Opt. Express, **29** (8), 12033 (2021). DOI: 10.1364/OE.422926

[7] J. McKay, K.L. Schepler, G.C. Catella, Opt. Lett., **24** (22), 1575 (1999). DOI: 10.1364/OL.24.001575

[8] T.T. Fernandez, M.K. Tarabrin, Y. Wang, V.A. Lazarev, S.O. Leonov, V.E. Karasik, Yu.V. Korostelin, M.P. Frolov, Yu.P. Podmarkov, Ya.K. Skasyrsky, V.I. Kozlovsky, C. Svelto, P. Maddaloni, N. Coluccelli, P. Laporta, G. Galzerano, Opt. Mater. Express, **7** (11), 3815 (2017). DOI: 10.1364/OME.7.003815

[9] V.A. Akimov, V.I. Kozlovskii, Yu.V. Korostelin, A.I. Landman, Yu.P. Podmar'kov, Ya.K. Skasyrskii, M.P. Frolov, Quantum Electron., **38** (3), 205 (2008). DOI: 10.1070/QE2008v038n03ABEH013707.

[10] N.G. Zakharov, R.A. Zorin, V.I. Lazarenko, E.V. Saltykov, A.A. Lobanova, A.V. Marugin, V.A. Garyutkin, G.M. Mishchenko, M.V. Volkov, F.A. Starikov, Tech. Phys. Lett., **48**, 150 (2022). DOI: 10.1134/S1063785022040150.

[11] O.L. Antipov, I.D. Eranov, M.P. Frolov, Yu.V. Korostelin, V.I. Kozlovsky, Ya.K. Skasyrsky, Opt. Lett., **44** (5), 1285 (2019). DOI: 10.1364/OL.44.001285

[12] M. Yumoto, N. Saito, T. Lin, R. Kawamura, A. Aoki, Y. Izumi, S. Wada, Biomed. Opt. Express, **9** (11), 5645 (2018). DOI: 10.1364/BOE.9.005645

[13] M.K. Tarabrin, D.V. Ustinov, S.M. Tomilov, V.A. Lazarev, V.E. Karasik, V.I. Kozlovsky, Yu.V. Korostelin, Ya.K. Skasyrsky, M.P. Frolov, Opt. Express, **27** (9), 12090 (2019). DOI: 10.1364/OE.27.012090

[14] L.V. Tarasov, *Fizika protsessov v generatorakh kogerentnogo opticheskogo izlucheniya* (Radio i svyaz; M., 1981), s. 231–238. (in Russian)

[15] S. Mirov, V. Fedorov, I. Moskalev, M. Mirov, D. Martyshkin, J. Lumin., **133**, 268 (2013). DOI: 10.1016/j.jlumin.2011.09.040

[16] I.T. Sorokina, Opt. Mater., **26**, 395 (2004). DOI: 10/1016/j.optmat.2003.12.025

[17] *Spravochnik po lazeram*, pod red. A.M. Prokhorova (Sov. radio, M., 1978), t. II, s. 16. (in Russian)

Translated by EgoTranslating