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Intensity noise and pulse repetition frequency stability measurements of a passive mode-locked Cr:ZnSe laser

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The results on intensity noise and repetition frequency stability measurements for a passively mode-locked Cr : ZnSe laser pumped by a thulium-doped fiber laser at a wavelength of 1.94 μm are presented. The stability parameters and intensity noise are compared for three different generation regimes of the Cr:ZnSe laser. The laser operated at a repetition rate of 129.5 MHz and a central wavelength of 2.45 μm.

Keywords: optical frequency comb, mode-locking, relative intensity noise, repetition frequency stability.

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Introduction

Compact stable radio frequency synthesizers based on the optical frequency standard (OFS) have proved their relevance for the tasks of time and frequency metrology, navigation [1]. In addition, such OFS-based RF synthesizers can be used as simple laboratory instruments that provide a stable frequency in the radio range. Several implementations of radio frequency synthesis systems based on an optical standard have already been demonstrated, the essence of which is the use of a mode-locked laser and an superstable cw laser with relative frequency instability in the range from 10^{-14} to 10^{-18} [2,3]. Depending on the design method, both key elements of stable RF synthesizer systems (stable cw laser and mode-locked laser) will have advantages and disadvantages [4].

One of the concepts for development of a cw laser with stabilized frequency is based on linking the laser frequency to narrow absorption lines of gases [5], but in this case the system generates a stable frequency signal in the range 10^{14} Hz. To obtain the stable frequency in the range 10^6-10^9 Hz, the femtosecond laser is optically linked to stabilized cw laser, which makes it possible to stabilize the pulse repetition rate at the output of the femtosecond laser f_{rep} by the reference frequency of a cw laser [6]. It should be noted that the main factor limiting the final repetition rate stability is the stability of the optical frequency standard, which depends on the parameters of the gas absorption line. One of the methods to improve the stability of OSF used in [6] can be the usage of other methane absorption lines. For example, several potential methane lines are located at wavelength of 2.36 μm, and the advantage of using these lines is demonstrated in the work [7], where the width of the methane line was measured using a two-mode cw laser based on chromium-doped zinc selenide crystal. On the other hand, the same active crystal can be effectively used to create mode-locked lasers [8], which can be easily optically linked to a stable cw Cr:ZnSe laser due to overlapping of their generation spectra. For a number of applications, the femtosecond laser is used as a separate element without reference to the optical frequency standard, and the main attention is paid to such parameters as intensity noises and repetition rate stability. At the moment, studies of such parameters for femtosecond lasers based on a Cr:ZnSe solid-state crystal have been carried out only partially. The work [9] presents intensity noises measurements for femtosecond laser based on a Cr:ZnSe crystal with pumping by an fiber Er-laser at wavelength of 1.55 μm. The laser operated with pulse repetition rate of 300 MHz, pulse duration of 47 fs, an output power of 250 mW, and integrated intensity noise of the order of 1 mrad in the frequency range from 100 Hz to 10 MHz, which corresponds to the absolute time jitter 530 fs. One of the disadvantages of this laser is the presence of residual relaxation noise from the pumping source. The authors of the work [10] used laser diodes at wavelength of 1.65 μm as pumping source, which made it possible to eliminate the effect of fiber-pumping relaxation noise, although the integrated intensity noise was 6.8 mrad (in the range from 10 Hz to 1 MHz).

In this work, the intensity noise and repetition rate stability for passively mode-locked Cr:ZnSe laser and pumping by the thulium fiber laser at wavelength of 1.94 μm for three operating modes, are measured.

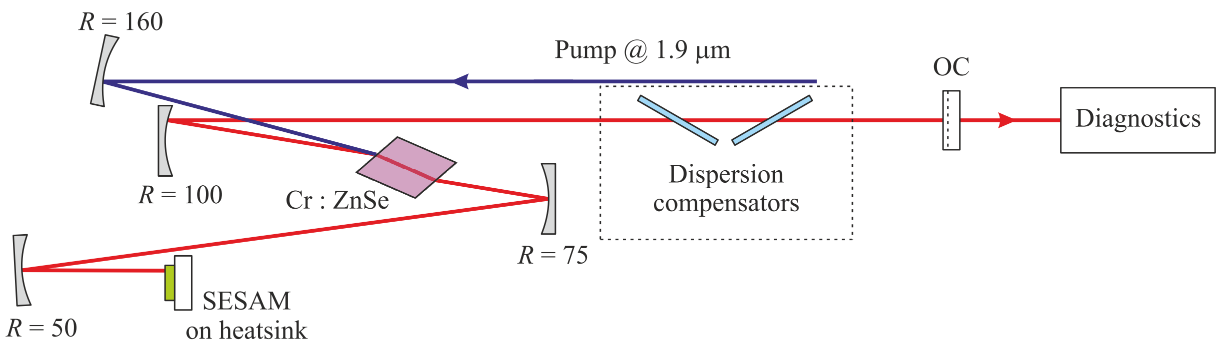

Figure 1. Scheme of passively mode-locked Cr:ZnSe laser.

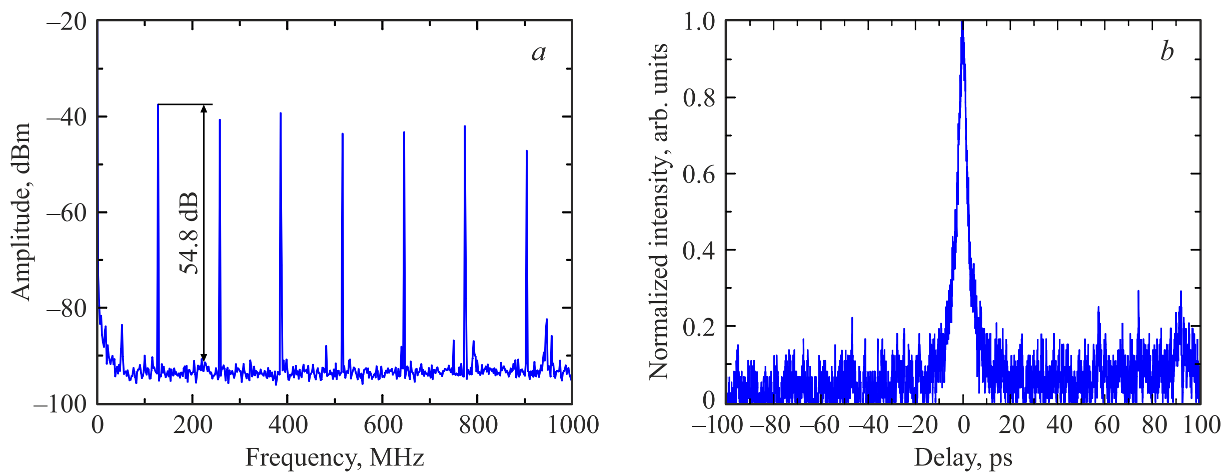

Figure 2. RF spectrum (*a*) and intensity autocorrelation (*b*) for the single-pulse mode (transmission of the resonator output mirror 2%).

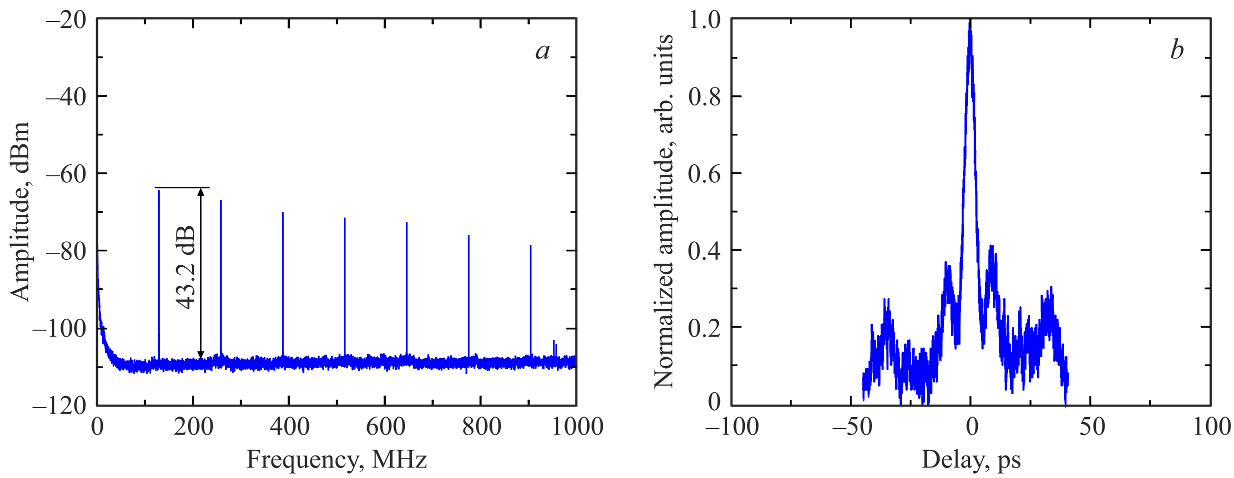

Figure 3. RF spectrum (*a*) and intensity autocorrelation (*b*) for the single-pulse mode (transmission of the resonator output mirror 5%).

Description of the experimental setup

Single crystal of zinc selenide doped with chromium ions was used as an active element. The crystal was grown from the gas phase on a substrate, with simultaneous doping with chromium ions, at the Troitsk Separate Division of the Lebedev Physical Institute of RAS [11]. Scheme of passively mode-locked Cr:ZnSe laser is shown in Fig. 1.

Active element 2.2 mm thick was fixed in a water-cooled copper holder and placed in a Z-folded resonator between two spherical mirrors with radii of 100 and 75 mm. Semiconductor Saturable Absorber Mirror (SESAM) was

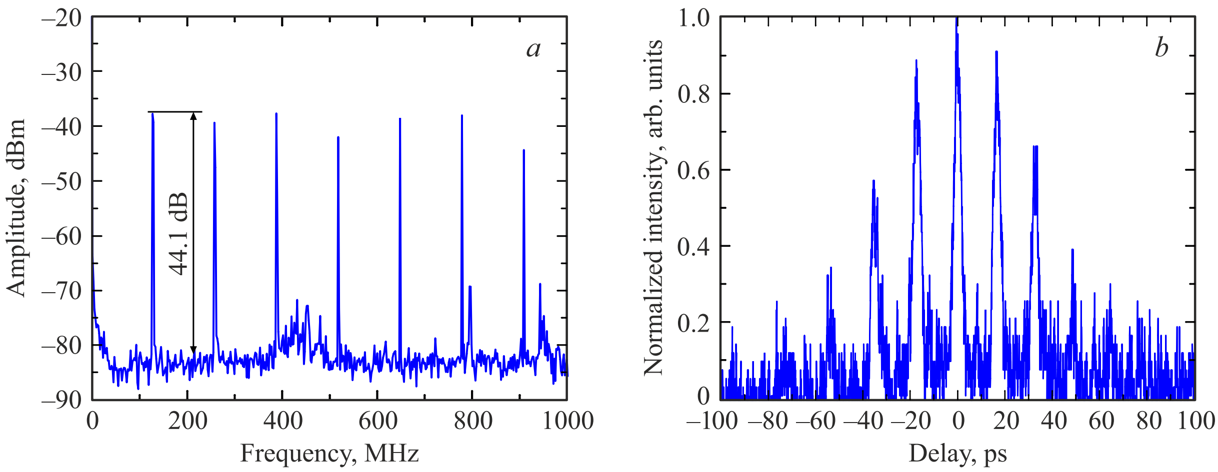

Figure 4. RF spectrum (a) and intensity autocorrelation (b) for the bound pulses regime (transmission of the resonator output mirror 2%).

used for mode-locking. A CW thulium fiber laser operating at a wavelength of 1940 nm was used as pumping source. Plane-parallel plates of magnesium fluoride and sapphire were used to compensate for the total dispersion in the resonator. With magnesium fluoride plates, the laser operated in the single-pulse mode, and with sapphire plates, the operation mode was changed to the generation of bound pulses. A detailed description of the laser and its operating modes can be found in the work [12].

Measurement results

Studies of the intensity noise and repetition rate stability for the Cr:ZnSe laser were carried out for several configurations and operating modes. The first mode of operation was implemented with compensating plates made of magnesium fluoride and the output mirror of a laser resonator with a transmission of 2%. In this configuration, the laser operated in the single-pulses regime with an output power of 15 mW, repetition rate of 129.5 MHz, signal-to-noise ratio for the mode locking of 54.8 dB at the first harmonic of the radio frequency spectrum, and pulse duration of 3 ps. The central wavelength of laser generation was 2.453 μm, and the spectral width was 4 nm. The measured ntensity autocorrelation at the output of the laser and the radio frequency spectrum at the output of the photodetector are shown in Fig. 2.

The second regime was realized with compensating magnesium fluoride plates and a 5% resonator output mirror. In this configuration, the laser operated in the single-pulse mode with an output power of 45 mW, repetition rate of 129.5 MHz, signal-to-noise ratio of 43.2 dB, and pulse duration of 3.6 ps. The central wavelength of laser generation was 2.45 μm, and the spectral width was 3 nm. The measured intensity autocorrelation at the output of the laser and the radio frequency spectrum at the output of the photodetector are shown in Fig. 3.

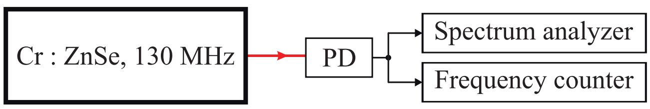

Figure 5. Scheme for measuring noise intensity and repetition rate stability of the Cr:ZnSe laser.

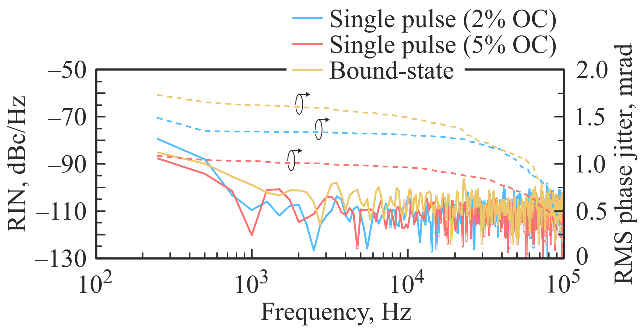

Figure 6. Intensity noise measurements for a Cr:ZnSe laser.

The third mode was realized with compensation plates made of sapphire and the output mirror of the resonator 2%. In this configuration, the laser operated in the bound pulses mode with an output power of 18 mW, repetition rate of 129.5 MHz, a signal-to-noise ratio of 44.1 dB, single pulse duration of 2.3 ps, and time interval between adjacent pulses in a train of 16.7 ps. The central wavelength of laser generation was 2.457 μm, and the spectral width was 5 nm. The measured intensity autocorrelation and the radio frequency electrical spectrum at the output of the laser are shown in Fig. 4.

Scheme for measuring noises and repetition frequency stability is shown in Fig. 5. The laser radiation was launched

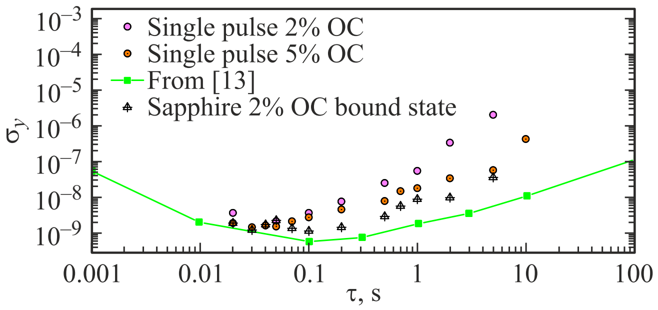

Figure 7. Relative Allan deviation.

to a high-speed high-frequency radiation receiver (PD24-01-HS, IBSG Co., Ltd.), and the signal from the radiation receiver was recorded by a 100 kHz radio-frequency spectrum analyzer (SR760, Stanford Research) and a universal 350 MHz- frequency counter (53230A, Keysight).

The results of intensity noise measurements for the three implemented generation modes are shown in Fig. 6.

Relative Allan deviation was measured at various averaging times, and the results obtained are presented in Fig. 7. In addition, the same figure shows the stability curve of an erbium fiber laser presented in the work [13].

Discussion

All three modes of generation have a sufficiently high signal-to-noise ratio, which indicates the quality of mode locking, while the largest value of 54.8 dB is realized for the single-pulse mode, when magnesium fluoride plates and an output mirror with a transmission of 2% are installed in the resonator. This mode has the maximum value of Allan's relative deviation $\sigma_y = 5.64 \cdot 10^{-8}$ for the averaging time of 1 s, in comparison with the operating modes when bound pulses are generated. It should be noted that changing (from 2 to 5%) the transmission of the cavity output mirror allows not only to increase the output power of the Cr:ZnSe laser from 15 to 45 mW (with a fixed pumping power and a slight increase in the pulse duration), as well as to improve the repetition rate stability up to $\sigma_y = 1.83 \cdot 10^{-8}$ for the averaging time of 1 s. The obtained results on the repetition rate stability of a Cr:ZnSe solid-state laser show comparability with the results for a fiber laser presented in the work [13] However, it should be noted that when performing measurements in the laboratory, such parameters as temperature and humidity were not controlled, the laser resonator was not isolated by a special covering, and nitrogen purge was not implemented to reduce the effect of absorption by water vapor contained in the laboratory air. Thus, this work demonstrates the possibility of implementing a Cr:ZnSe laser with passive mode locking in natural conditions, which is a significant advantage that makes it possible to widely use this technology.

Conclusion

In the present work, we measured the noise intensity and repetition rate stability for three configurations of a solid-state laser based on a Cr:ZnSe crystal with passive mode-locking. The lowest value of the integral temporal jitter (1.5 mrad) was obtained for the single-pulse mode, when two plates of magnesium fluoride are used as a dispersion compensators and an output mirror of 2% transmission The best repetition frequency stability at the level of $9.1 \cdot 10^{-9}$ for the averaging time of 1 s is realized for the bound pulses mode, when two sapphire plates are used as a dispersion compensator. The results show that solid-state and fiber lasers can be comparable in stability parameters. Thus, a solid-state laser is promising for use as an optical frequency divider.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] F. Riehle, P. Gill, F. Arias, L. Robertsson. Metrologia, **55** (2), 188–200 (2018). DOI: 10.1088/1681-7575/aaa302

[2] X. Xie, R. Bouchand, D. Nicolodi, M. Giunta, W. Hänsel, M. Lezius, A. Joshi, S. Datta, C. Alexandre, M. Lours, P.-A. Tremblin, G. Santarelli, R. Holzwarth, Y.L. Coq. Nature Photon, **11**, 44–47 (2017). DOI: 10.1038/nphoton.2016.215

[3] A.S. Shelkovnikov, A.I. Boiko, A.N. Kireev, A.V. Tausenev, D.A. Tyurikov, D.V. Shepelev, A.V. Konyashchenko, M.A. Gubin. Quantum Electronics, **49** (3), 272–277 (2020). DOI: 10.1070/QEL16909.

[4] F. Riehle. *Frequency standards: basics and applications* (John Wiley & Sons, 2006).

[5] V.L. Velichansky, M.A. Gubin. Physics-Uspekhi, **52** (11), 11531158 (2009). DOI: 10.3367/UFNe.0179.200911h.1219

[6] M.A. Gubin, A.N. Kireev, A.V. Konyashchenko, P.G. Kryukov, A.V. Tausenev, D.A. Tyurikov, A.S. Shelkovnikov. Kvantovaya elektronika, **38** (7), 613–614 (2008). DOI: 10.1070/QE2008v038n07ABEH013914 [M.A. Gubin, A.M. Kireev, A.V. Konyashchenko, P.G. Kryukov, A.V. Tausenev, D.A. Tyurikov, A.S. Shelkovnikov. Quantum Electronics, **38** (7), 613–614 (2008). DOI: 10.1070/QE2008v038n07ABEH013914].

[7] M. Gubin et al. *2012 European Frequency and Time Forum*, (IEEE 2012), pp. 459–461. DOI: 10.1109/EFTF.2012.6502425

[8] I.T. Sorokina, E. Sorokin. In: *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, no. 1, pp. 273–291 (2015), Art no. 1601519. DOI: 10.1109/JSTQE.2014.2341589

[9] Y. Wang, T.T. Fernandez, N. Coluccelli, A. Gambetta, P. Laporta, G. Galzerano. Opt. Express, **25**, 25193–25200 (2017). DOI: 10.1364/OE.25.025193

[10] N. Nagl, S. Gröbmeyer, V. Pervak, F. Krausz, O. Pronin, K.F. Mak. Opt. Express, **27**, 24445–24454 (2019). DOI: 10.1364/OE.27.024445
[11] V.A. Akimov, M.P. Frolov, Y.V. Korostelin, V.I. Kozlovsky, A.I. Landman, Y.P. Podmar'kov, A.A. Voronov. Phys. Stat. Sol. C, **3** (4), 1213–1216 (2006). DOI: 10.1002/pssc.200564723
[12] S.O. Leonov, M.P. Frolov, Y.V. Korostelin, et al. Appl. Phys. B, **127**, 56 (2021). DOI: 10.1007/s00340-021-07604-x
[13] M.A. Gubin, A.N. Kireev, A.V. Tausenev, A.V. Konyashchenko, P.G. Kryukov, D.A. Tyurikov, A.S. Shelkovikov. Laser Phys., **17** (11), 1286–1291 (2007). DOI: 10.1134/S1054660X07110023