High Power SESAM Mode-Locked Laser Based on $Yb^{3+}:YAlO_3$ Bulk Crystal

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Abstract

Yttrium aluminium perovskite $YAlO_3$ (YAP) crystal, doped with rare-earth ions, has been extensively studied as a diode-pumped laser host material. The wide interest to rare-earth ions doped YAP crystals is explained by its good thermal and mechanical properties, high natural birefringence, widely used Czochralski growth method. The aim of this work was to study the $Yb^{3+}:YAlO_3$ crystal as an active medium for high power mode-locked laser.

Yb^{3+}-doped perovskite-like aluminate crystals have unique spectroscopic and thermooptical properties that allowed using these crystals as an active medium of high power continuous wave (CW) and mode-locked (ML) bulk lasers with diode pumping.

In our work spectroscopic properties of Yb:YAP crystal and laser characteristics in CW and ML regimes are investigated. Maximum output power of 4 W with optical-to-optical efficiency of 16.3 % and 140 fs pulse duration have been obtained for Yb:YAP *E*//*c*-polarization with 10 % output coupler transmittance. Tunability range as wide as 67 nm confirms high promise of using Yb:YAP crystal for lasers working in wide spectral range.

Keywords: mode-locked laser, ytterbium ions, diode pumping, yttrium aluminate crystals.

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Высокомощный лазер на кристалле Yb^{3+}:$YAlO_3$, работающий в режиме синхронизации мод на основе полупроводниковых зеркал с насыщающимся поглотителем

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Кристаллы иттрий-алюминиевого перовскита $YAlO_3$ (YAP), легированные ионами редкоземельных элементов интенсивно изучались в качестве активных сред лазеров с диодной накачкой. Интерес к данным кристаллам обусловлен их высокими теплофизическими и механическими свойствами, высоким двулучепреломлением, возможностью роста по широко распространённому методу Чохральского. Целью данной работы было изучение кристалла Yb^{3+}:$YAlO_3$ в качестве активной среды лазера с высокой средней выходной мощностью, работающего в режиме синхронизации мод.

Кристаллы $YAlO_3$, легированные трёхвалентными ионами иттербия имеют уникальные спектроскопические и теплофизические свойства, что позволяет использовать данные кристаллы в качестве активных сред лазеров с высокой средней выходной мощностью и диодной накачкой, работающих в режимах непрерывной генерации и пассивной синхронизации мод.

В работе исследованы спектроскопические характеристики кристалла Yb:YAP, а также выходные характеристики лазеров на основе данного кристалла, работающих в режимах непрерывной генерации и пассивной синхронизации мод. Средняя выходная мощность 4 Вт с оптической эффективностью 16.3 % и длительностью импульса 140 фс получена для *E*//*c*-поляризации при пропускании выходного зеркала 10 %. Диапазон перестройки 67 нм подтверждает высокие перспективы использования кристалла Yb:YAP в качестве активной среды лазеров, работающих в широком спектральном диапазоне.

Ключевые слова: лазер с синхронизацией мод, ионы иттербия, диодная накачка, кристаллы иттриевого алюмината.

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Introduction

Yttrium aluminium perovskite (YAP) crystal, $YAlO_3$, doped with rare-earth ions, has been extensively studied as a diode-pumped laser host material. Numerous impressive results were reported for Nd^{3+}-doped YAP crystal. Among them 100 W output power at 1079 nm and 18.3 W at 1341 nm were obtained in diode-side-pump module [1]. 6.2 W laser output with a slope efficiency as high as 27.2 % at 1341.4 nm were demonstrated in a compact plane-concave cavity [2]. Laser emitting at 1378 and 1385 nm with power of 800 mW was reported in a folded cavity with prism inserted [3] and second harmonic generation at 536 nm was obtained with an LBO crystal inside the cavity [4]. Intensive studies were also made with Tm^{3+} and Ho^{3+}-doping. 730 mW of laser output power with 40.3 % slope efficiency were obtained over the range 1965–2020 nm with singly Tm-doped aluminate [5] and as high as 8.36 W at 2120 nm [6] and 9.3 W at 2044 nm [7] with slope efficiencies 35.7 % and 42.5 %, correspondingly, were demonstrated in Tm and Ho co-doped YAP crystal. Furthermore efficient Pr-doped $YAlO_3$ laser operation under diode pumping was recently reported emitting in the near-infrared spectral range [8].

The wide interest to rare-earth ions doped YAP crystals is explained by its good thermal and mechanical properties similar to those of YAG, but growing faster and anisotropic [9]. Previously thermal conductivity of undoped YAP crystal was reported to be close to 11 W/[m·K] [9, 10]. Lately more modest values of 7–8 W/[m·K] were published [11]. Nevertheless they remain two times higher then those of tungstate crystals [12]. $YAlO_3$ is a biaxial crystal and belongs to orthorhombic space group [9]. Its high natural birefringence dominates thermally induced one in lasers and leads to overcoming depolarization losses at high average powers [13]. It results in a very high polarization degree of the laser emission under different levels of pump power which is advantageous for non-linear frequency conversion [14], efficient modulation loss in Q-switch lasers [6] and other applications where linearly polarized light is necessary.

In this work we present the experimental study results of high power passively mode-locked laser based on yttrium aluminium perovskite crystal doped with Yb^{3+} ions.

Crystal growth

Single crystals of Yb:YAP can be grown by several growth techniques [15–20] among which Czochralski is the most usable for practical applications.

For this study Yb:YAP crystals were grown by Czochralski method using Y_2O_3, Yb_2O_3 and crystalline sapphire as starting oxides of at least 99.99 % purity and seeds oriented along the b axis. The melts were corresponding to stoichiometric compositions $Y_{1-x}Yb_xAlO_3$ (x = 0–0.03). The growth melts (x = 0–0.03) were held in iridium crucibles ($40\times5\times40$ mm^3) and inductively heated under a pure Ar atmosphere. The pulling and rotation rates were 2.5 mm/h and 35 rpm. The grown boules are 15 mm in diameter and 30–40 mm long, transparent but some of them of a yellow-brown shade.

Spectroscopy

Polarized absorption spectra of Yb^{3+}(2 at.%):YAP (corresponding ytterbium concentration was 4.02×10^{20} cm^{-3}) at room temperature were registered by a Varian CARY-5000 spectrophotometer. Absor-ption cross-section spectra for three light polarizations parallel to the a, b and c crystallographic axes are shown in Figure 1.

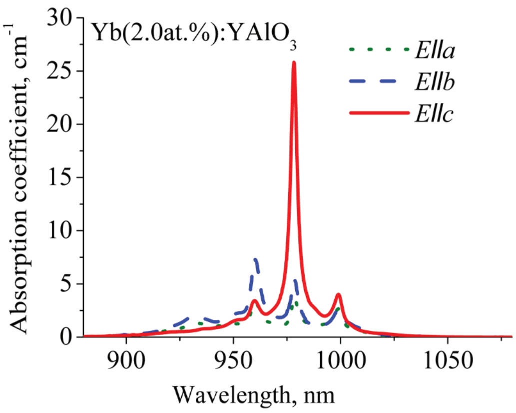

Figure 1 – Polarized absorption spectra of Yb^{3+}:$YAlO_3$ crystal (the spectra were obtained for Yb^{3+}(2 at.%):$YAlO_3$)

Strong absorption is found for $E//c$ light polarization with the peak absorption at 978.2 nm of about 25 cm^{-1} and spectral bandwidth FWHM of 4 nm.

It is well known that radiation trapping strongly affects the measured lifetime of Yb-doped materials because of significant overlap of the absorption and emission bands [21, 22]. The comparatively high index of refraction of YAP (n_c = 1.914 for λ = 1040 nm) also increases the probability of reabsorption even in optically thin samples because of the total internal reflection. Thus the special methods discussed in the literature [21, 22] should be used to determine the luminescence lifetime accurately. In our experiments we used a fine powder of Yb:YAP crystal immersed in glycerin. The diameter of the powder particles was measured to be approximately 30–40 µm, several times lower than absorption length of the most heavily doped Yb^{3+}(8 at.%):YAP crystal (97 µm at 978.2 nm). The Yb ions contents in the samples were 1.5, 2, 3 and 8 at.%. The samples were excited by 20 ns pulses at wavelength of about 978 nm and luminescence kinetics were registered with the use of a 0.3-m monochromator, fast Ge-photodiode with a rise time of < 20 ns and a 500 MHz digital storage oscilloscope. All the samples exhibited single exponential decays (see Figure 2).

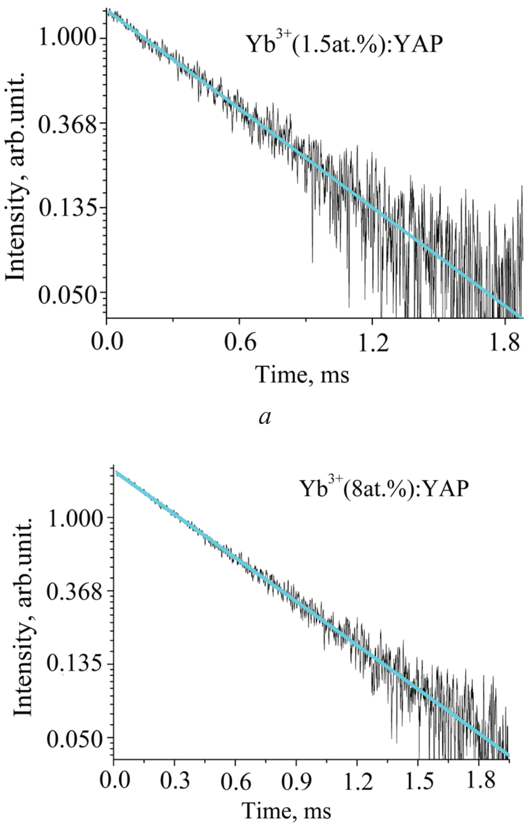

Figure 2 – Kinetics of luminescence decay for Yb(1.5 at.%):YAP (*a*) and Yb(8 at.%):YAP (*b*)

Starting from certain powder content, the lifetime remained constant despite further dilution (Figure 3), thus indicating that reabsorption effects became negligible. Emission lifetime for 8, 3, 2 and 1.5 at.% Yb-doped crystals was measured to be about 510 ± 20 µs that indicates a weak influence of the luminescence concentration quenching. Presented values are in good agreement with the previously obtained data [23].

The stimulated-emission (SE) cross sections were calculated by use of the modified reciprocity method in which it is not necessary to know the Stark level structure of the Yb^{3+} manifolds ($^2F_{5/2}$ and $^2F_{7/2}$) [24]:

$$\sigma_{SE}^{\alpha}(\lambda)=\frac{3\cdot\exp(-hc/(kT\lambda))}{8\pi n^2\tau_{rad}\cdot c\cdot\sum_{\beta}\int\lambda^{-4}\sigma_{ABS}^{\beta}(\lambda)\exp(-hc/(kT\lambda))d\lambda}\sigma_{ABS}^{\alpha}(\lambda), \quad (1)$$

where τ_{rad} is the radiation lifetime of an active center; c is the light velocity; h and k are Planck and Boltzmann constants, respectively; T is the crystal temperature; n is the refractive index of a crystal; α and β denote the polarization state; and σ_{ABS} is the ground-state absorption cross section.

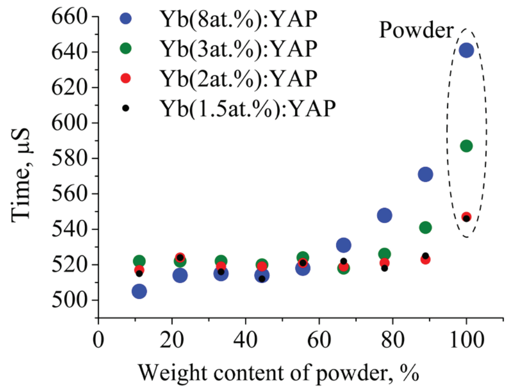

Figure 3 – Measured lifetime for different weight content of Yb:YAP crystalline powder in glycerin suspension for YAP with different Yb^{3+} concentrations

The SE cross section spectra calculated with this method are presented in Figure 4.

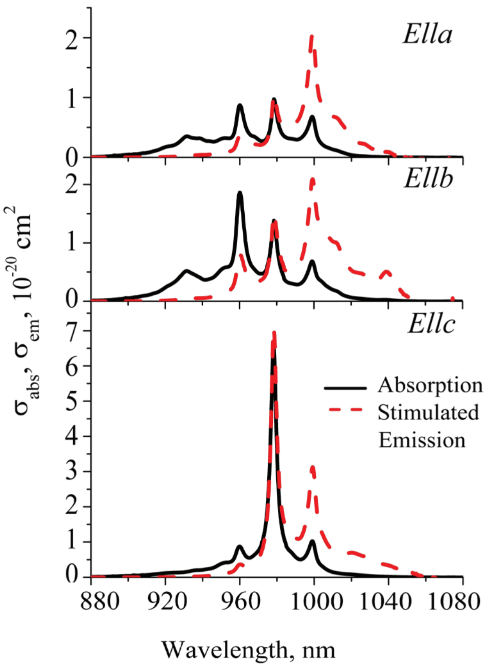

Figure 4 – Polarized absorption and stimulated emission cross-section spectra of $Yb^{3+}:YAlO_3$ crystal

The most intensive SE cross-section band at 999.2 nm has peak value of about 3.13×10^{-20} cm^2 for *E*//*c*-polarization. Such a high value is very suitable for mode-locked and actively Q-switched laser operation.

Moderate SE cross-section values (0.4–1.1×10^{-20} cm^2) are observed for *E*//*b*- and *E*//*c*-polarizations in wavelength range 1005–1030 nm where the spectra are smooth.

Continuous wave laser experiment

For laser operation the most interesting polarization states in the crystal are *E*//*c* and *E*//*b* (*c* and *b* are crystallographic axes) due to high stimulated-emission cross sections values.

For a continuous wave laser experiments a set up with X-folded cavity design was used (see Figure 5). It consisted of two curved mirrors M1 and M2 and two plane mirrors: OC and HR.

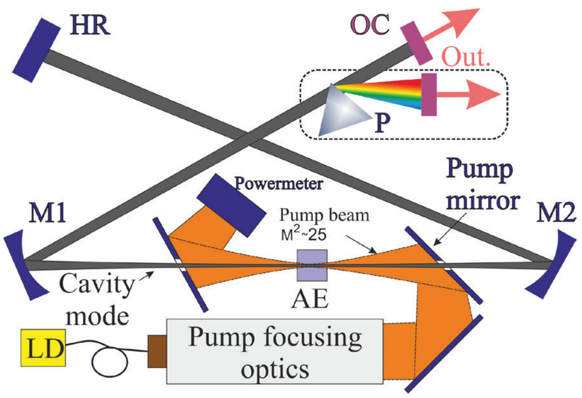

Figure 5 – Experimental setup of continuous wave diode-pumped Yb:YAP laser: HR – highly reflective mirror; OC – output coupler; P – prism; M1, M2 – concave mirrors; AE – active element; LD – laser diode

The calculated TEM_{00} mode diameter in the crystal was about 100 µm. As a pump source, a multiple single emitter InGaAs fiber-coupled laser diode (Ø105 µm, NA = 0.15) with a maximum output power of about 25 W was used. An "off-axis" pump layout was used for longitudinal pumping of the active element (see Figure 5). This pump arrangement was successfully tested in our previous work [25–26] and the main advantage of such a pump scheme is that all the cavity mirrors have highly reflecting coating at 900–1100 nm. The pump light was formed by a set of lenses into the spot with a diameter of about 100 µm ($1/e^2$). A 2 mm long Yb^{3+}(2 at.%):$YAlO_3$ crystal was used as a gain medium. The crystal was a-cut to provide *E*//*b* and *E*//*c* polarized laser output. It was a slab with dimensions $2(a)\times5(b)\times1.5(c)$ mm^3; both 5×2 mm^2 lateral faces were maintained at 15 °C by means of copper plates (indium foil was used to improve thermal contact) and thermo-electrical cooling elements with water-cooled heat sink, while 1.5×5 mm^2 working faces were antireflection coated for pump and laser radiation.

The dependencies of the laser output power on the absorbed pump power for *E*//*b*– and *E*//*c*–polarized outputs and different OCs are shown in Figure 6. Absorbed pump power was real-time measured during the laser action.

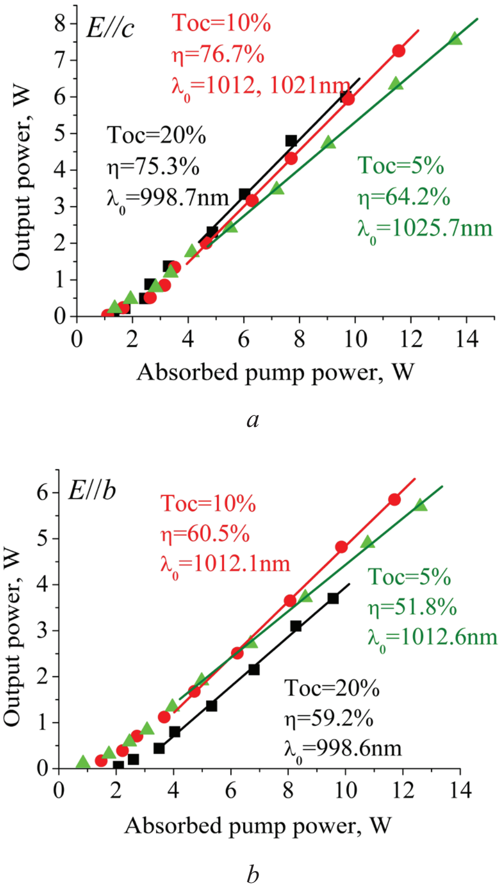

Figure 6 – CW laser performance of Yb:YAP crystal for different polarizations and output coupler transmittances

The maximum CW output power of 7.6 W at absorbed pump power of 13.6 W with slope efficiency of 64.2 % was demonstrated for *E*//*c* polarization with 5 % OC transmittance (Figure 6*a*). With output coupler transmission of 10 % and 20 % the laser output power slightly decreased to 7.3 W and 6.0 W, respectively, while the corresponding slope efficiencies increased to 76.7 % and 75.3 %. Similar output powers were demonstrated for *E*//*b* laser output (Figure 6*b*). With 10 % output coupler transmittance 5.9 W of output power was obtained at 11.7 W of absorbed pump power with 60.5 %

slope efficiency. Output powers of 5.7 W and 3.7 W with slope efficiencies of 51.8 % and 59.2 % were obtained for 5 % and 20 % OCs, respectively.

Wavelength tunability of the Yb:YAP laser was investigated during CW laser experiments. For this purpose prism was inserted into the cavity. The dependency of average output power (in normalized units) from the central wavelength of the Yb:YAP laser is shown in the Figure 7.

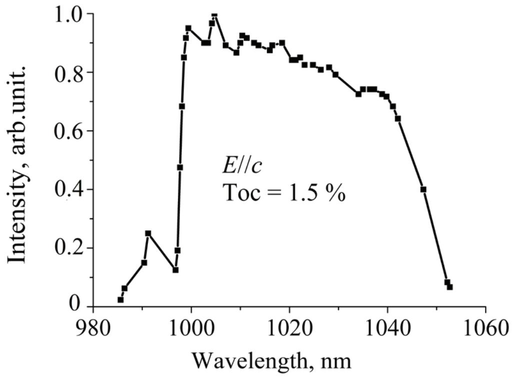

Figure 7 – Tunability curve of Yb:YAP laser with output coupler transmittance 1.5 % for *E*//*c*-polarization

Tunability range as wide as 67 nm (985.6–1052.7 nm) was demonstrated with output coupler transmittance of 1.5 %.

Mode-locked laser experiment

For the mode-locked laser experiment the same crystal was used as for CW one. Schematic of the experimental setup is shown in Figure 8.

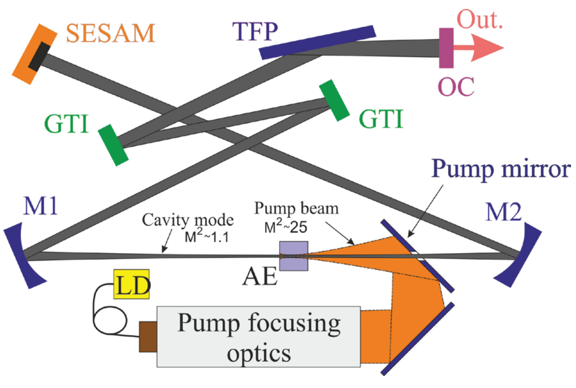

Figure 8 – Schematic of the Yb:YAP mode-locked laser: SESAM – semiconductor saturable absorber mirror; TFP – thin film polarizer; OC – output coupler; GTI – chirped mirrors; M1, M2 – concave mirrors; AE – active element; LD – laser diode

InGaAs-based SESAM with modulation depth of about 4.0 % was used in the experiments. The SESAM based on quantum wells separated by nano-structured barriers was grown by molecular beam epitaxy (MBE) technique over the semi-insulating GaAs substrate of (001) orientation. The crystallinity of each layer was controlled via reflection of high energy electrons diffraction (RHEED technique). The number of quantum wells, their thickness and the concentration of the ternary alloy were chosen to match the requirement on the saturable absorption modulation depth. The recovery time shortening was performed by the barriers separation into the thinner layers via the insertion narrow band gap material. The design of the SESAM described in [27]. The measured reflectivity spectrum of the SESAM is presented in Figure 9. Used SESAM enabled to support mode-locking in the spectral range from 1000 nm to about 1050 nm. The result of the pump-probe testing of the SESAM with modulation depth of 4 % is shown in Figure 10. The saturation energy fluence of the SESAM was measured to be about 70–120 μJ/cm^2.

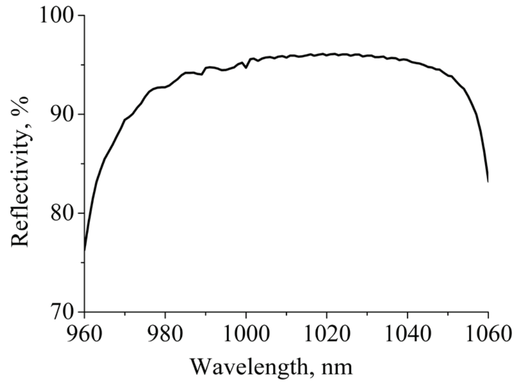

Figure 9 – SESAM reflectivity spectrum with modulation depth 4 %

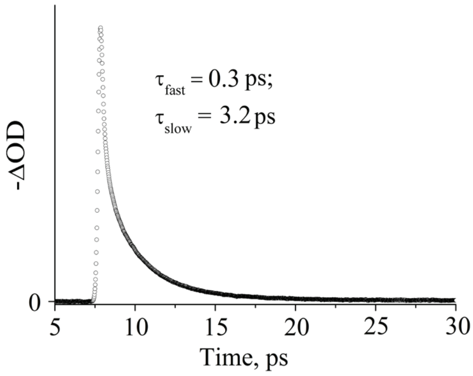

Figure 10 – "Fast" (0.3 ps) and "slow" (3.2 ps) recovery times of the SESAM

Stable mode-locked operation of Yb^{3+}(2 at.%):YAP laser was obtained only for OCs with 5 % and 10 % transmittance. The maximum output power of 4 W with optical-to-optical efficiency of 16.3 % was obtained with 10 % OC for *E*//*c*-polarization.

Pulses with 8 nm (see Figure 11) full width at half maximum (FWHM) obtained at 1009.7 nm central wavelength resulting in 140 fs pulse duration (see Figure 12) with time-bandwidth product of about 0.32 assuming $Sech^2$ pulse shape.

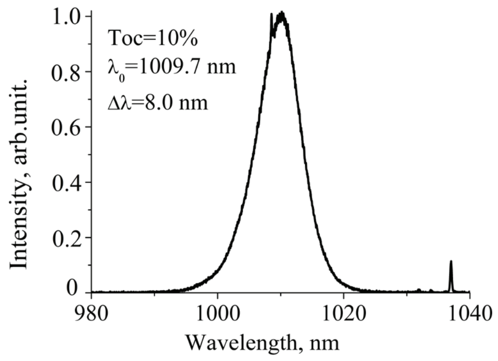

Figure 11 – Spectrum of the Yb:YAP (*E*//*c*) mode-locked laser for 10 % OC

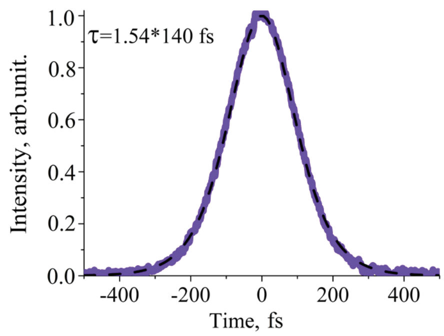

Figure 12 – Autocorrelation trace of the Yb:YAP (*E*//*c*) mode-locked laser pulses for 10 % OC

Output power of 2.4 W with optical-to-optical efficiency of 10.7 % obtained with 5 % OC transmittance. Spectral width of 7.6 nm at 1021.9 nm central wavelength (Figure 13) was demonstrated resulting in about 150 fs pulse duration (Figure 14) with time-bandwidth product of about 0.33 assuming $Sech^2$ pulse shape. The pulse repetition frequency was around 70 MHz.

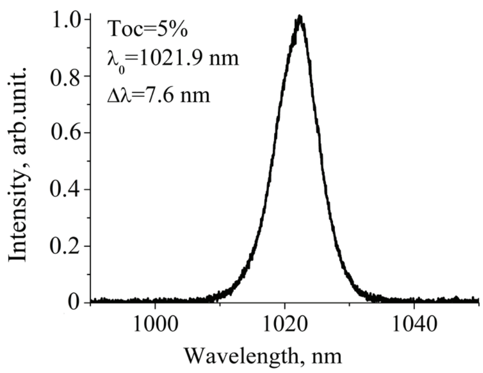

Figure 13 – Spectrum of the Yb:YAP (*E*//*c*) mode-locked laser for 5 % OC

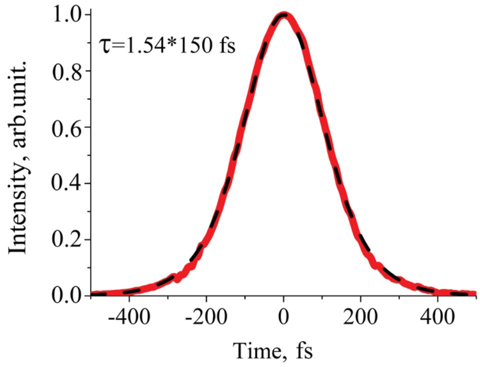

Figure 14 – Autocorrelation trace of the Yb:YAP (*E*//*c*) mode-locked laser pulses for 5 % OC

Conclusion

In conclusion, Yb:YAP bulk crystal as a gain medium for high power mode-locked lasers was investigated in our work. Maximum output power of 4 W with optical-to-optical efficiency of 16.3 % and 140 fs pulse duration have been obtained for Yb:YAP *E*//*c*-polarization with 10 % output coupler transmittance. Tunability range as wide as 67 nm confirms high promise of using Yb:YAP crystal for lasers working in wide spectral range.

References

1. Ruifen Wu, Poh Boon Phua, Kin Seng Lai. Linearly Polarized 100-W Output From a Diode-Pumped Nd:YAlO Laser. *Applied Optics*, 2000, vol. 39, iss. 3, pp. 431–434.
DOI: 10.1364/AO.39.000431

2. Zhu H.Y., Zhang G., Huang C.H., Wei Y., Duan Y.M., Chen W.D., Zhuang F.J. 6.2 W laser-diode end-pumped continuous-wave Nd:$YAlO_3$ laser at 1.34 µm. *Optics Communications*, 2011, vol. 284, pp. 2985–2987.
DOI: 10.1016/j.optcom.2011.01.080

3. Yiou S., Balembois F., Georges P., Brun A. High-power continuous-wave diode-pumped Nd:$YAlO_3$ laser that emits on low-gain 1378- and 1385-nm transitions. *Appled Optics*, 2001, vol. 20, iss. 18, pp. 3019–3022.
DOI: 10.1364/AO.40.003019

4. Fu X.H., Li Y.L., Tao Z.H., Zeng Y.H. Diode pumped CW Nd^{3+}:$YAlO_3$ laser at 1339 nm. *Laser Physics*, 2011, vol. 21, no. 5, pp. 877–879.
DOI: 10.1134/S1054660X1109009X

5. Elder I.F., Payne M.J. YAP versus YAG as a diode-pumped host for thulium. *Optics Communications*, 1998, vol. 148, iss. 4–6, pp. 265–269.
DOI: 10.1016/S0030-4018(97)00714-1

6. Li L.J., Yao B.Q., Wu D.Y., Wang J., Gang L., Wang Y.Z., Zhang Z.G. High Efficient Double End-Pumped b-cut Tm,Ho:$YAlO_3$ Laser. *Laser Physics*, 2011,

vol. 21, no. 3, pp. 446–449.
DOI:10.1134/S1054660X11050148

7. Li L.J., Yao B.Q., Qin J.P., Wu D.Y., Wang Y.M., Wang J., He Z.L., Liu W.Y., Chen J.J., Wang Y.Z., Zhang Z.G., Li A.H. High Power and Efficiency of a 2044-nm c-cut Tm, Ho:$YAlO_3$ Laser. *Laser Physics*, 2011, vol. 21, no. 3, pp. 489–492.
DOI: 10.1134/S1054660X11050173

8. Fibrich M., Jelínková H., Šulc J., Nejezchleb K., Škoda V. Diode-pumped Pr:YAP lasers. *Laser physics letters*, 2011, vol. 8, p. 559–568.
DOI: 10.1134/S1054660X11050173

9. Weber M.J., Bass M., Andringa K., Monchamp R.R., Comperchio E. Czochralski growth and properties of $YAlO_3$ laser crystals. *Applied Physics Letters*, 1969, vol. 15, no. 10, p. 342.
DOI: 10.1063/1.1652851

10. Aggarwal R.L., Ripin D.J., Ochoa J.R., Fan T.Y. Measurement of thermo-optic properties of $Y_3Al_5O1_2$, $Lu_3Al_5O1_2$, $YAIO_3$, $LiYF_4$, $LiLuF_4$, BaY_2F_8, $KGd(WO_4)_2$, and $KY(WO_4)_2$ laser crystals in the 80–300 K temperature range. *J. Appl. Phys.*, 2005, vol. 98, p. 103514.
DOI: 10.1063/1.2128696

11. Petit Johan, Viana Bruno, Goldner Philippe, Roger Jean-Paul, Fournier Danièle. Thermomechanical properties of Yb^{3+} doped laser crystals: Experiments and modeling. *J. Appl. Phys.*, 2010, vol. 108, p. 123108.
DOI:10.1063/1.3520216

12. Lagatsky A.A., Abdolvand A., Kuleshov N.V. Passively Q switched and self-frequency Raman conversion in a diode-pumped Yb:$KGd(WO_4)_2$ laser. *Optics Letters*, 2000, vol. 25, no. 9, p. 616.
DOI: 10.1364/OL.25.000616

13. Massey G.A. Criterion for selection of CW laser host materials to increase available power in the fundamental mode. *Applied Physics Letters*, 1970, vol. 17, no. 5, p. 213. **DOI:** 10.1063/1.1653370

14. Shen H.Y., Zhou Y.P., Lin W.X., Zeng Z.D., Zeng R.R., Yu G.F., Huang C.H., Jiang A.D., Jia S.Q., Shen D.Z. Second harmonic generation and sum frequency mixing of dual wavelength Nd:$YAlO_3$ laser in flux grown $KTiOPO_4$ crystal. *IEEE Journal of Quantum Electronics*, 1992, vol. 28, iss. 1, p. 48–51. **DOI:** 10.1109/3.119494

15. Sugak D., Matkovskii A., Savitskii D., Durygin A., Suchocki A., Zhydachevskii Y., Solskii I., Stefaniuk I., Wallrafen F. Growth and Induced Color Centers in $YAlO_3$–Nd Single Crystals. *Phys. Status Solidi A*, 2001, vol. 184, p. 239.
DOI: 10.1002/1521-396X(200103)184:1<239::AID-PSSA239>3.0.CO;2-I

16. Kvapil J., Perner B., Manek B., Blazek K., Hendrich Z. Nonstoichiometric Defects in YAG and YAP. *Cryst. Res. Technol.*, 1985, vol. 20, p. 473.
DOI: 10.1002/crat.2170200410

17. Petit P.O., Petit J., Goldner Ph., Viana B. Colour centre-free perovskite single crystals. *J. Lumin.*, 2009, vol. 129, p. 1586. **DOI:** 10.1016/j.jlumin.2009.04.056

18. Antonov V.A, Arsenev P.A., Linda I.G., Farshtendiker V.L. Studies of Some Point Defects in $YA1O_3$ and GdAlO Single Crystals. *Phys. Status Solidi A*, 1973, vol. 15, p. K63. **DOI:** 10.1002/pssa.2210150158

19. Kovaleva N.S., Mochalov I.V. Formation of color centers in yttrium orthoaluminate crystals. *J. Quantum Electron.*, 1978, vol. 8, no. 12, p. 1427.
DOI: 10.1070/QE1978v008n12ABEH011380

20. Kvapil J., Kvapil, J., Kubelka, J., and Autrata, R. The Role of Iron Ions in YAG and YAP. *Cryst. Res. Technol.*, 1983, vol. 18, pp. 127−131.
DOI: 10.1002/crat.2170180120

21. Kühn Henning, Fredrich-Thornton Susanne T., Kränkel Christian, Peters Rigo, Petermann Klaus. Model for the calculation of radiation trapping and description of the pinhole method. *Opt. Lett.*, 2007, vol. 32, pp. 1908−1910. **DOI:** 10.1364/OL.32.001908

22. Sumida D.S., Fan T.Y. Effect of radiation trapping on fluorescence lifetime and emission cross section measurements in solid-state laser media. *Opt. Lett.*, 1994, vol. 19, pp. 1343−1345. **DOI:** 10.1364/OL.19.001343

23. Kisel V.E., Kurilchik S.V., Yasukevich A.S., Grigoriev S.V., Smirnova S.A., Kuleshov N.V. Spectroscopy and femtosecond laser performance of Yb^{3+}:$YAlO_3$ crystal. *Opt. Lett.*, 2008, vol. 33, p. 2194.
DOI: 10.1364/OL.33.002194

24. Yasyukevich A.S., Shcherbitskii V.G., Kisel V.E., Mandrik A.V., Kuleshov N.V. Integral method of reciprocity in the spectroscopy of laser crystals with impurity centers. *Journal of Applied Spectroscopy*, 2004, vol. 71, no. 2, pp. 202−208.
DOI: 10.1023/B:JAPS.0000032875.04400.a0

25. Alexander Rudenkov, Viktor Kisel, Anatol Yasukevich, Karine Hovhannesyan, Ashot Petrosyan, Nikolay Kuleshov. Spectroscopy and continuous wave laser performance of Yb^{3+}:$LuAlO_3$ crystal. *Opt. Lett.*, 2016, vol. 41, pp. 5805−5808.
DOI: 10.1364/OL.41.005805

26. Alexander Rudenkov, Viktor Kisel, Anatol Yasukevich, Karine Hovhannesyan, Ashot Petrosyan, Nikolay Kuleshov. Yb^{3+}:$LuAlO_3$ crystal as a gain medium for efficient broadband chirped pulse regenerative amplification, *Opt. Lett.*, 2017, vol. 42, pp. 2415−2418.
DOI: 10.1364/OL.42.002415

27. Rubtsova N.N., Borisov G.M., Ledovskikh D.V., Kovalyov A.A., Preobrazhenskii V.V., Putyato M.A., Semyagin B.R., Kisel’ V.E., Rudenkov A.S., Kuleshov N.V., Pavlyuk A.A. Fast mirrors for femtosecond passive mode-locked near-infrared lasers. *Laser Phys.*, 2016, vol. 26, p. 125001.
DOI: 10.1088/1054-660X/26/12/125001