VI Serbian-Belarusian Symp. on Phys. and Diagn. of Lab. &
Astrophys. Plasma, Belgrade, Serbia, 22 - 25 August 2006
eds. M. Ćuk, M.S. Dimitrijević, J. Purić, N. Milovanović
Publ. Astron. Obs. Belgrade No. 82 (2007), 149-156 *Invited lecture*

DIODE-PUMPED SOLID-STATE LASERS WITH CONTROLLED PARAMETERS FOR SPECTROSCOPIC APPLICATIONS

V. V. Mashko[1], G. I. Ryabtsev[2], M. V. Bogdanovich[2], A. S. Drakov[1], A. I. Enzhyieuski[2], O. E. Kostik[1], A. V. Pozhidaev[3] , A. G. Ryabtsev[3], M. A. Shemelev[3], L. L. Teplyashin[1]

[1] *Institute of Molecular and Atomic Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[2] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[3] *Belarussian State University, Minsk, Belarus*

Abstract. This work is devoted to analysis of possibility of control of frequency, polarization and spatial radiation attributes of diode-pumped solid-state lasers (DPSSLs) fabricated on the base of modern active elements (AEs). Crystals of yttrium aluminum garnet and yttrium vanadate activated by neodymium ions (Nd:YAG и Nd:YVO_4) lasing at the wavelength λ = 1.06 μm and the boro-silico-phosphate glass co-activated by erbium and ytterbium ions lasing in the 1.5 μm spectral region are considered. The schemes of longitudinal and transversal laser diode (or laser diode array) pump are compared.

Compact diode-pumped solid-state lasers (DPSSLs) are perspective sources of coherent light for range finding, metrology, spectral analysis as well as for investigations of impact of the radiation on a substance. The predetermined parameters of laser beam are needed for many of these applications. Because of specific properties of DPSSLs (small dimensions, peculiar pump unit and so on) the well known approaches for control of the laser beam characteristics are not always convenient for utilization in practice. As a result, the task of elaboration of the new methods of the DPSSL control and adaptation of the earlier one is posed.

The tuned single- and double-frequency lasing modes were realized for the Nd:YAG longitudinally pumped radiation source with a composite resonator [1]. The laser scheme is shown in Fig. 1. In spite of monolithic construction [2], it allows quick changing and tuning the lasing frequency in a wide spectral interval. The AE length and diameter were 1.3 mm and 5 mm respectively. Dielectric mirror M1 with the reflection coefficient R = 99.8% for λ = 1.06 μm and transmission coefficient 90% for λ = 0.809 μm (pump radiation wavelength) was deposited on one AE facet. The second facet of the AE crystal was covered with antireflecting coating (λ = 1.06 μm, residual reflection is as high as 1.2%). Output mirror M2 deposited on outer spherical surface (r = 50 mm) of the substrate had R = 98% at λ = 1.06 μm. The second substrate surface was covered with antireflecting coating (λ = 1.06 μm).

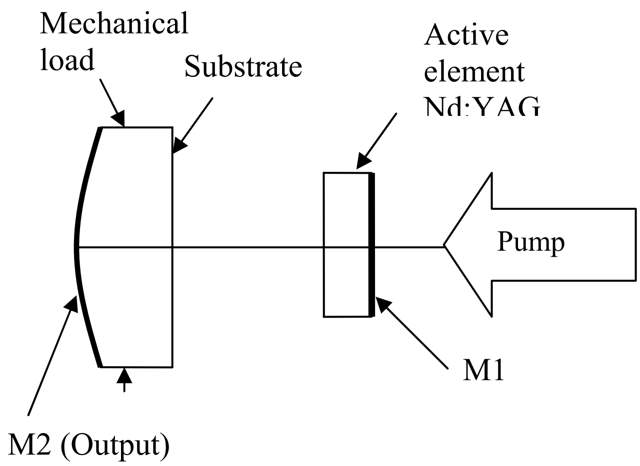


Fig. 1. Optical scheme of the Nd:YAG laser with coupled resonators and longitudinal diode pump unit

Adjustable mechanical load was applied to the output mirror substrate using the piezoelectric cell. This allowed us to achieve lasing at splitted orthogonally polarized modes due to linear phase anisotropy of the resonator.

Minimal optical length of the main resonator formed by the mirrors M1 and M2 was equal to 10.8 mm. This value is related to a frequency difference between the main resonator characteristic modes $\Delta\nu$ = 13,9 GHz. Intermode difference for the complementary resonator formed by the AE facets was approximately equal to 64 GHz. During experiments the output mirror was moved along the resonator optical axes with help of piezoelectric cell. Output laser radiation frequency spectrum was controlled by means of scan Fabry-Perot interferometer (the free dispersion interval of 1.5 GHz, the resolution at the level of 50 GHz), high-speed photodiode and spectrum analyzer.

CW laser diode (LD) emitted polarized radiation at λ = 0.809 μm with maximum power of 450 mW was used as a pump light source. The LD beam was focused by the microscope objective on the AE facet (through the M1 mirror).

DPSSL lasing frequency structure was defined by a relative position of the modes of two coupled resonators and power-level overshoot over the threshold value. By varying of these parameters in the absence of the resonator phase anisotropy the following lasing regimes were realized: 1) lasing of single longitudinal mode with a possibility of its tuning within the gain spectrum, and 2) lasing of two adjacent modes with the frequency difference of 7.5 – 13.9 GHz (depending on the optical length of the main resonator). Induction of linear phase anisotropy during pressing of the output mirror substrate allowed lasing of two orthogonally polarized modes with a gradual tuning of the frequency difference within the interval of 50 MHz – 2.4 GHz in the regime 1) and up to 8.4 GHz in the regime 2). Thus, one can conclude that the proposed method allows two modes lasing both with small and large intermode intervals at relatively small-scale elastic strains induced in the output mirror substrate.

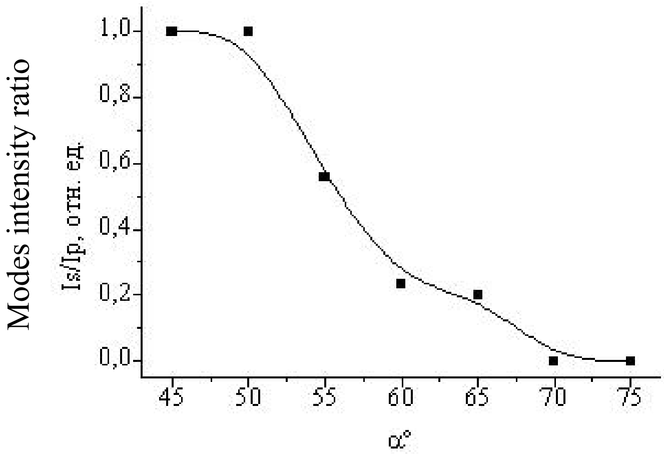


Fig. 2. The dependence of the orthogonally polarized modes intensity ratio on the angle α .

As is well known [3], the polarization of radiation of the Nd:YAG laser with isotropic resonator is coupled with the polarization of the LD beam used in the longitudinal pump unit. Similar phenomenon was investigated in our experiments for the case when the resonator has the linear phase anisotropy being responsible for two orthogonally polarized mode lasing. If the LD polarization azimuth was directed at the angle $\alpha = 45°$ relative to the axis along which the mirror substrate is pressed, the identical conditions were created for lasing of two orthogonally polarized modes. If the frequency of the initial mode was close to the central frequency ν_0 of the coupled resonator transmission line, the intensities of these modes were equal. In other cases the higher intensity was achieved for the mode which polarization vector is closer to the pump radiation polarization one. Only one mode with the corresponding polarization vector was selected when the pump radiation polarization vector was directed along or perpendicularly to the resonator anisotropy axis ($\alpha = 0°, 90°$). The lasing frequency was gradually tuned during changing of the anisotropy value (mechanical load).

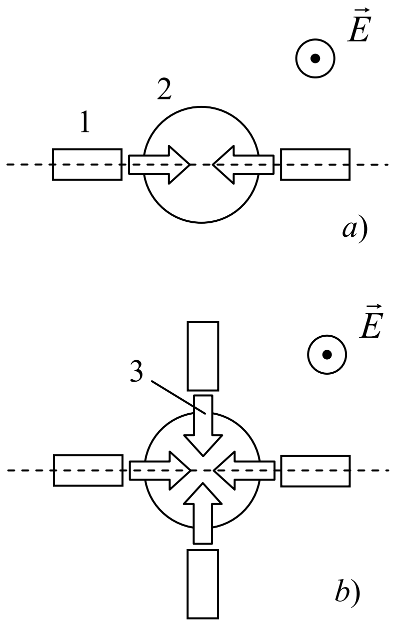


Fig. 3. Scheme of transversal pumping of erbium laser AE using two (a) and four (b) LDAs: LDA (1), AE (2), pump radiation (3)

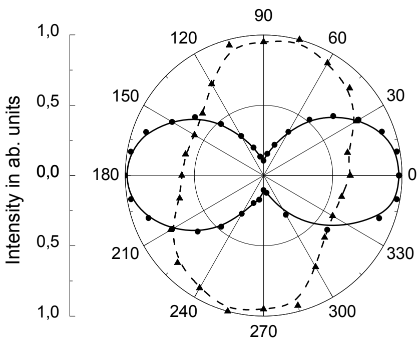


Fig. 4. Intensity azimuth dependence for the Er^{3+} laser beam after its passing through the polarizer: pumping by two (solid) and four LDAs (dashed lines)

The dependence of the orthogonally polarized modes intensity ratio on orientation of the pump radiation polarization vector relative to the selected anisotropy axis is given in Fig. 2 for the case of tuning of the lasing frequencies to the composite resonator transmission line center. Deviation of the pump radiation polarization azimuth from a medium position between the resonator anisotropy directions leads to the change in the intensity ratio for the orthogonally polarized mode components similar to theirs changing during the scan of the modes relative to central frequency of the resonator transmission line, i.e. to theirs spectral selection.

An increase of the output radiation power is a key problem for many application areas of DPSSLs. A rather high level of the power can be reached in the case of the transversal pumping of AE by the laser diode arrays (LDAs) [4]. In the frame of our experiments the spatial-polarization properties of radiation of the solid-state erbium laser (λ = 1.54 μm) with transversal LDA pump unit have been studied. AE based on the boro-silico-phosphate glass co-activated by Er and Yb ions was fabricated in the form of rod with the diameter of 3 mm and the length of 11 mm. The erbium laser AE facets were covered with the antireflection coatings for the 1.50-1.58 μm spectral region. The erbium laser pump unit had two or four LDAs fabricated from the *InGaAs/AlGaAs* heterostructures. The LDA active layers are placed parallel to the AE axis (Fig. 3). LDA output radiation was linear polarized with the light wave electrical vector $\vec{E}$ parallel to the laser optical axis. Duration of the LDA current pulses was equal to 5 ms at the repetition rate of 1 Hz. The laser output radiation pulse energy was varied within the range of 10-30 (two LDAs) or 10-60 mJ (four LDAs).

It has been determined that output radiation of the erbium laser is polarized with a degree of the polarization $P \approx 0.8$ (pumping by two LDAs) and $P \approx 0.3$ (pumping by four LDAs), where $P = (I_{max} - I_{min})/(I_{max} + I_{min})$, I_{max} and I_{min} are the maximum and minimum values of the signal after passing of the DPSSL beam through the polarizer. Indicatrixes of the laser radiation intensity for these two pumping variants are shown in Fig. 4.

Since the vector $\vec{E}$ of the LDAs is directed parallel to the resonator optical axis the pump radiation can not be the source of the anisotropy of induced optical parameters for the laser active medium. The investigated resonator had no any anisotropic elements. No traces of the dichroism were revealed both the *Er-Yb* glass absorption or transmission measurements. So, polarization of the erbium laser output radiation can be attributed to the anisotropy induced in AE by mechanical and/or thermal strains. The reason for the conclusion is the fact that the polarization degree of the erbium laser is distinctly different in the cases of pumping with help of two and four LDAs.

If the problems concerned with focusing and/or delivering of laser radiation are arisen the beam quality begins to play an important role. The beam quality is usually described with the propagation parameter M^2 [5] reflecting an excess of the product of the real beam divergence and waist diameter over that for the gaussian beam.

It has been revealed that output beam cross-section of the investigated laser has an elliptic form. It can be characterized by two propagation parameters M^2_x and M^2_y (axes *Ox, Oy* are directed along major and minor axes of the ellipse). Appling the relation establishing the correlation among the laser beam diameters D_x, D_y along *Ox, Oy* axes, the distance z from the principal plane of the focusing lens placed for obtaining the beam waist at a plane *A-A* and the beam examination plane $D_{x,y}(z) = D_{0x,y}(1 + 4\, M^2_{x,y}\, \lambda\, (z - z_{0x,y})/\pi\, D_{0x,y}{}^2))^{1/2}$ [6] the parameters M^2_x and M^2_y were determined. Numerical values of the beam waist diameters D_{0x}, D_{0y} at the *A-A* plane, the distance $z_{0x,y}$ from the *A-A* plane as well as the M^2_x and M^2_y were treated as the adjustable parameters. They have been found by the least-squares technique in the course of making the match between the above given function $D_{x,y}(z)$ with a set of the $D_x(z)$,$D_y(z)$ data calculated based on the experimental beam cross-section profiles [5].

The M^2_x,M^2_y measurements were performed for different resonator lengths and configurations using two or four LDAs in the pump unit. The best results (M^2_x =

1.9 and M^2_y = 1.2) were obtained for the 85 mm-length parallel-plane resonator of the *Er-Yb* laser pumped by four LDAs.

The beam propagation parameter M^2 was also investigated for the high-power Nd^{3+}:YVO_4 laser with longitudinal pumping through the fiber depending on the AE exciting power P_{pump}, degree of overlapping of the AE pump and lasing volumes, uniformity of the Nd^{3+} ion distribution within AE. It has been shown that in the case of considerable excess of the lasing mode cross-section over that for the pump radiation the limiting dimension of the beam spot is rose when a sharp focusing is carried out. The regularly varying intervals of an abrupt increase of the beam propagation parameter were obtained on the background of the M^2 (P_{pump}) monotonous dependence. This phenomenon can be explained by action of the AE nonlinear lenses originated both from the lasing radiation and the pump one.

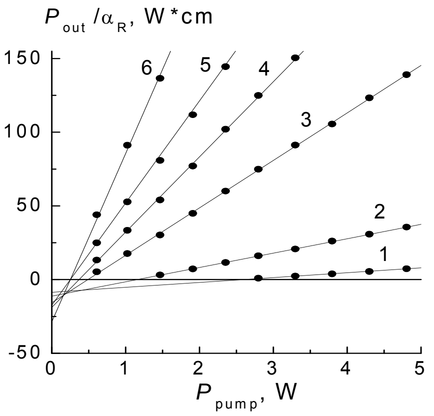
The active elements with uniform (Nd^{3+}:YVO_4) and nonuniform (YVO_4/Nd^{3+}:YVO_4) distributions of the activator ions within the AE volume were studied with the aim of search of the most effective lasing medium for DPSSLs. In the first case the Nd^{3+} concentration was at the level of 0.4 at. %, and the AE crystal was a parallelepiped 4x4x8 mm. In the second case the 3x3x10 mm crystal was used. From its length of 10 mm the main part of 8 mm was the uniform activated section, whereas the rest 2 mm-section was the passive one. It has been ascertained that the AE with the passive section allows us to improve noticeably the output beam quality: the M^2 parameter takes on the value of 1.4 – 1.8. Probably, this is a consequence of diminishing the thermoelastic strains developing at the AE active region border.

For the purpose of quantitative comparative analysis the internal loss coefficient ρ was determined for the laser active elements with uniform and nonuniform distributions of the activator ions. A method based on the measurements of the lasing output power P_{out} as a function of the output cavity losses $\alpha_R = (1/L)\ln(1/\sqrt{R_1 R_2})$, where R_1 and R_2 are the reflection coefficients for cavity mirrors was used [7]. With this object in view the $P_{out} = F(\alpha_R)$ dependence was presented in the following form:

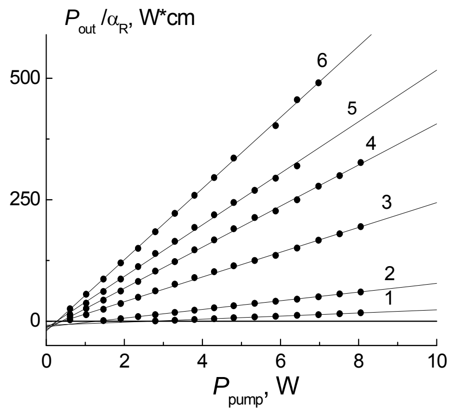
$$\frac{P_{out}}{\alpha_R} = Ls \cdot n \cdot h\nu_l \left[\frac{\eta\beta P_{pump}}{\rho + \alpha_R} - \frac{\eta\beta P_{pump} + (p_{31} + p_{32})}{\chi} \right],$$

where Ls is the lasing volume of the active element, n is the concentration of the active particles, $h\nu_l$ is the lasing photon energy, $\eta\beta P_{pump}$ is the pump rate, p_{31} and p_{32} are the optical transition probabilities for the lasing energy levels, χ is the maximum gain value.

Typical dependences of normalized output power on the pump level are shown in Fig. 5. The results of measurement of the internal loss coefficient for DPSSLs on the base of the Nd^{3+}:YVO_4 and YVO_4/Nd^{3+}:YVO_4 active elements are summarized in Table 1 It should be noted that in the case of the YVO_4/Nd^{3+}:YVO_4 DPSSL two different variants of the AE orientation were studied: 1) YVO_4 passive region is directed towards income of the pump beam, 2) YVO_4 passive region is directed in the opposite direction.



a)



b)

Fig. 5. Watt-Watt characteristics normalized to the α_R coefficient for DPSSLs on the base of the Nd^{3+}:YVO_4 (a) and YVO_4/Nd^{3+}:YVO_4 (b) active elements with uniform and nonuniform distributions of activator ions respectively. In the (b) case the YVO_4 passive region of the active element was orientated towards income of the pump beam. The output laser mirror reflection coefficient R_2 = 20 (1), 53 (2), 83 (3), 90 (4), 95 (5), 98 (6) %.

Table 1. Magnitudes of the internal loss coefficient ρ for DPSSLs with different types of AE.

Type of active element	Internal loss coefficient, cm^{-1}
AE with uniform (Nd^{3+}:YVO_4) distribution of activator ions	0,0091
AE with nonuniform (YVO_4/Nd^{3+}:YVO_4) distribution of activator ions, passive region is directed towards the pump beam	0,0089
AE with nonuniform (YVO_4/Nd^{3+}:YVO_4) distribution of activator ions, passive region is directed away from the pump beam	0,0093

As may be seen from Table 1, obtained results show that the DPSSL emitter with nonuniform distribution of activator ions and orientation of the passive region directed towards the pump beam has the minimum optical losses, all things being equal. In other words, this type of the DPSSL emitter is the best suited for powerful applications.

The obtained data demonstrate new possibilities for control of the frequency, polarization and spatial characteristics of the DPSSLs radiation. One perspective application is the development and fabrication of the narrowband laser sources with tuning of the lasing frequency within the range approximately 10 GHz for the purpose of spectroscopy. Another possible application is dealt with the development of the relatively powerful compact lasers with the output radiation pulse energy of several tens of mJ and a very high beam quality which are sufficient for a precise focusing manipulation. Such laser installations can be used as the atomizer suitable for portable spectrometers, just as the intensive light sources adjusted to the investigation of interaction of radiation and solids as well as to obtaining the plasma technology.

REFERENCES

1. V.G. Gudelev et al., Appl. Phys. B, **76**, 249 (2003)
2. A. Owyoung, P. Esherick, Optics Letters, **12**, 999 (1987)
3. N.V. Kravtsov, et al., Quantum. Electron. (in Russian), **34**, 839 (2004)
4. G.I. Ryabtsev, et. al., J. Optical Technology (in Russian), **73**, 10 (2006)
5. B.J. Neubert, et. al., Journal of Physics D: Applied Physics, **34**, 2414 (2001)
6. N. Reng, B. Eppich, Optical and Quantum Electronics, **24**, 973 (1992)
7. B.I. Stepanov, editor, Method of calculations of optical quantum generators (in Russian), Nauka i Technika, Minsk, **1**, 403 (1966)