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Design and Optimal Parameters of a Small-sized Diode-Pumped Nd:YAG Laser Setup

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This paper is dedicated to the modeling, design, and consequent construction of the practical setup of the small-size solid-state laser with Nd:YAG gain medium and the diode pumping. Solid-state lasers have been in existence for around 50 years and have experienced both positive and negative aspects during their evolution. Nevertheless, they have always held an essential position in numerous industries, scientific endeavors, and everyday activities. Nowadays, such devices are widely used and developed in location, manufacturing, medicine, and of course in military. Hence, the development and optimization of their structure remain a pertinent and important issue. The research reveals the basic component parameters for a compact Nd:YAG laser with diode pump, which can be implemented in the construction of range-finder. The main results of the work. Nd:YAG laser with overall dimensions of 350 × 25 × 25 mm was developed and modeled; the dimensions of the laser active head are 110 ×25 × 25 mm. Diode pumping is a matrix of six diodes with a power of 90 W each, which operate in a pulse mode with a duration of 250 ns. The resonator consists of two mirrors, with an output reflectance from 0.66 to 0.74. The active element is 72 mm long. With these laser parameters, the first giant pulse after the start of pumping was achieved at 59 μs, an output energy of 25 mJ, and a laser system efficiency of 22 %. Additionally, the following radiation pulses were generated with a time interval of 4 μs. The results obtained in this work make it possible to create a diode-pumped solid-state laser with an output radiation energy of up to 25 mJ and have compact cavity dimensions of about 80 × 25 × 25 mm.

Keywords: Laser diode, Radiation power, Pumping, Solid-state laser, Active zone, Reflective mirror, Wavelength, Laboratory setup.

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1. INTRODUTION

Lasers on solid active medium have already got a long history as well as a huge number of applications in people's life. Solid-state lasers (SSL) are considered the ancestors and vital members of the laser family. The initial type of laser discovered was the SSL, which had ruby as an active zone [1]. The ability to produce stimulated emission of optical radiation led to the creation of various other types of solid-state emitters. Newman was the first to publish a record of utilizing a semiconductor source for pumping, where fluorescence at wavelength 1060 nm in Nd:CaWO4 was excited by the pumping radiation of GaAs diodes at $\lambda = 880$ nm [2]. Such diodes allowed directed in-band pump of the emittance levels [3]. By direct pumping to the upper level of the laser's active region, the system experienced reduced heat dissipation, resulting in higher optical efficiency [4]. Afterward, there was extensive research into the diode pump, which attracted the attention of many researchers in various fields of science, even in medicine [5]. Diode pumping enables the achievement of high efficiency of generation, simplicity of implementation, radiation quality, and smaller sizes. One of the major benefits of diode-pumped lasers is that the spectral consistency of laser diode radiation aligns with the bands of absorption of the active ions in the gain crystal.

SSL early investigations indicate that Nd:YAG crystals garnered significant interest, but the deeper investigation began after some stagnation of this laser physics branch [6]. Consequently, the SSL continued their development just in the 1980s, A variety of lasers that use diode pumps were studied, and their active regions were doped with various rare earth ions, including the following: Er^{3+}, Yb^{3+}, Tm^{3+} and Ho^{3+} [7-11]. Next, lasers based on Ti and Ti^{3+}– doped crystals and Cr^{4+} and Cr^{2+} – doped active elements were examined [12-14]. Currently, among the active elements used in SSL, Nd:YAG crystal is a commonly favored choice. The primary benefits of Nd:YAG crystal are its low threshold, high gain, excellent efficiency, remarkable optical quality, strong mechanical properties, and efficient thermal conductivity. These crystals are usually manufactured allying Czochralski technique. While it is possible to grow Nd:YAG crystal using other methods, the Czochralski technique offers significant advantages, including the ability to produce a large diameter crystal with high optical quality.

The advancement of the industry necessitates reducing the size of laser devices while preserving high radiation energy [15-21]. This would open up further possibilities for applications in areas such as space exploration, laser-based instrument manufacturing for range-finding and location detection, information systems, and more. In recent decades, the progress made in semiconductor lasers has enabled efficient diode laser pumping of gain materials and the compact and reliable production of SSL [22-24].

The objective of this work is to conduct theoretical calculations through computational simulation in order to design an experimental laser setup. The paper is based on our conference papers [25-26]. The results obtained are implemented to select the optimal laser design that can be used in the further development of a range finder.

2. LASER SETUP SCHEME

A laser is a type of optical quantum generator that emits a highly directional beam of monochromatic coherent light [22]. The primary physical mechanism governing the functioning of a laser is the stimulated emission of photons from a gain medium via an external pumping source, leading to the accumulation of energy within the laser cavity [23-24].

One can see the laser scheme in the Fig. 1, which consist of a Fabry-Perot resonator defined as 1, 2, a gain medium - 3, pump diodes 4, an aluminum base 5, a cylindrical lens 6, and a reflector 7. Laser active region is a crystal of yttrium aluminum garnet doped with neodymium ions (Nd: YAG) which has a four-level energy scheme [27]. The crystal has following parameters: a length of 72 mm, a diameter of 3 mm, and a neodymium concentration of 1.0 %. The laser stable resonator is built on the well-known Fabry-Perot scheme which includes two flat mirrors.

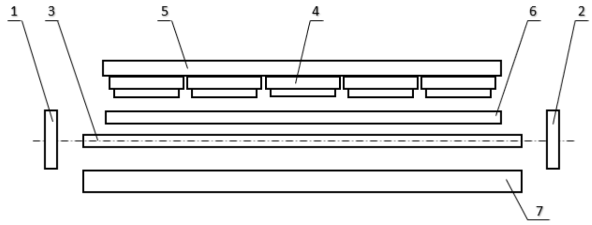

Fig. 1 – The Nd:YAG laser with diode pump setup scheme

To simplify the design, laser diodes were placed in line for the transverse pump of the active region from single direction. The chosen diodes are made by Focuslight and have following characteristics: emittance wavelength is 808 nm, maximum consumption of current is 220 A, efficiency of diode is 45 % that corresponds to radiation power per diode around 90 W.

Laser semiconductor radiation exhibits a high diffraction difference, making its primary advantages applicable in lasers with a short active element length. Optimizing the resonator to match sources of light can improve the efficiency of SSL with laser diodes.

Fig. 2 shows the path of the pumping beams through the laser elements. Incorporating a lens 2 (which has cylindrical form) between laser diode 1 and gain crystal 3 in the system can reduce losses and increase the efficiency. The cylindrical lens is positioned in such a way that its focus lies in the radiation source plane, which allows for the collection of the full pumping flux in the gain material. The scattered radiation is then reflected backward to the active element by reflector 4. Laser diodes offer a significant advantage over phosphor plates or LEDs of the same area due to their much smaller length. Thus, it is feasible to employ laser diode multiplexing for producing a high-intensity white light source with improved emittance.

SSLs have become reliable laser tools due to the long laser diodes service life, which can reach up to 20,000 hours. The low heat dissipation in the gain material of the semiconductor-pumped laser eliminates the need for water cooling, resulting in a reduction in the overall size and mass of the laser. Reduced heat dissipation in the semiconductor-pumped laser active material results in lower thermal stresses in the active medium, enabling the formation of a laser beam with high spatial-angular brightness [28-30].

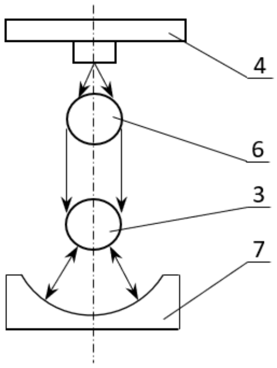

Fig.2 – The geometrical optics image of the pumping beams' path

3. CALCULATION OF SETUP PARAMETERS

To simplify the computational modeling, we used the Laskin 5.0 program. This software enables a straightforward, precise, and dependable simulation of solid-state laser properties, making it an efficient instrument for laser design.

In Fig. 3. presents the diagram of Nd:YAG energy levels, where following denotes can be explained as the working ions population on *i*- level is N*i* , the sensitizer ions population on *i*- level is N`*i*, the intracavity photons lifetime is τ_c, the absorption cross-section in exited pump state is σ_p, the lasing transition emission cross section is σ_e, and the absorption cross section in exited lasing state is σ_L. The energy equation that balances the transfer, relaxation and absorption processes depicted in the diagram can be expressed as follows:

$$\frac{\partial N`2}{\partial t} = \frac{a\cdot(N`1-N`2)}{N_{Sion}}\cdot W_p\eta_c\frac{\left(-\left(R_p\cdot e^{(\alpha\cdot L_p)}+1\right)\cdot\left(e^{(\alpha\cdot L_p)}-1\right)\right)}{V\cdot E_{pph}} - k\cdot N`2\cdot N1 - g_{2`-1`}\cdot N`2 + A0\cdot k\cdot N4\cdot N`1, \quad (1)$$

$$\frac{\partial N2}{\partial t} = N3\cdot g_{3-2} + I\cdot\sigma_e\cdot(N3-m_0\cdot N2) - g_{2-1}\cdot N2, \quad (2)$$

$$\frac{\partial N3}{\partial t} = N4\cdot g_{4-3} - N3\cdot(g_{3-2}+g_{3-1}) - I\cdot\left(\sigma_e\cdot(N3-m_0\cdot N2)+\sigma_{L1}\cdot(N3-N5)\right), \quad (3)$$

$$\frac{\partial N4}{\partial t} = k\cdot N`2\cdot N1 - A0\cdot k\cdot N4\cdot N`1 - N4\cdot g_{4-3} + N5\cdot g_{5-4} + \frac{\sigma_p\cdot(N1-N4)}{\alpha}\cdot\frac{W_p\cdot\eta_c\cdot\left(-R_p\cdot e^{\alpha}+1\right)\cdot(e^{\alpha}-1)}{V\cdot E_{pph}}, \quad (4)$$

$$\frac{\partial N5}{\partial t} = I\cdot\sigma_e\cdot(N3-m_0\cdot N2) - N5\cdot(g_{5-4}+g_{5-1}), \quad (5)$$

where, $\alpha = \frac{a\cdot(N`1-N`2)}{N_{Sion}} + \sigma_p\cdot(N1-N4)$, α is coefficient of pump absorption, W_p is pumping power, L_p is length of pumping, V is active region volume, E_{pph} is energy of pump photon, k is parameter of energy transfer, A_0 is relative coefficient which describing the back energy transfer from working ion to sensitizer ion, $g_{i\text{-}j}$ is decay rate from i – level to j – level, m_0 – degeneracy parameter.

The density of lasing photon I can be written as:

$$\frac{\partial I}{\partial t} = \frac{L_a}{L_{c\_opt}} \cdot v_c \cdot I \cdot \left(\sigma_e \cdot \left(N3 - m_0 \cdot \sigma_{L1} \cdot (N3 - N5) \right) - \frac{I - S_0}{\tau_c} \right), \tag{6}$$

where L_a is active medium length, L_{c_opt} is resonator optical length, v_c is velocity of light, and S_0 is the initial density of luminescence.

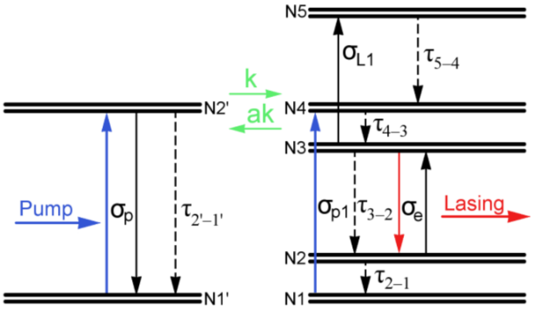

Fig. 3 – The energy levels diagram of Nd:YAG crystal

It should also be noted that for the linear resonator configuration used, the lifetime of intracavity photons can be expressed using the following equation:

$$\tau_c = \frac{2 \cdot L_{c\_opt}}{v_c} \cdot \frac{1}{-\ln\left(R_{oc} \cdot T_{sh}(t)^2 \cdot (1 - g_c)\right) + 2 \cdot g_a \cdot L_a}, \tag{7}$$

where R_{oc} is output coupler reflectivity, T_{sh} is Q-switch transmission, g_c — intrinsic resonator losses, g_a is active element dissipative losses.

Given a crystal of the 72 mm-length and a diode of the 11 mm-width, a maximum of six diodes can be used while still reserving space to fix the active element. This results in a total power output of 450 W (due to each of them has 90 W) and the pump pulse duration is 250 ns. It should be noted that a cylindrical rod lens is used for the diodes, which directs the entire flux into the gain medium, thereby increasing the efficiency of pumping. The optimization tool integrated into the system is used to calculate the reflectivity of the output mirror.

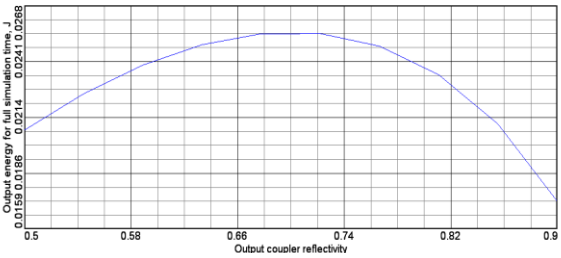

Fig. 4 – The dependence of output energy on mirror reflection coefficient

The plot in Fig. 4 depicts the output energy value for mirror's reflectivity in 0.5 to 0.9 % range. As can be observed, the curve features a plateau, indicating that a reflectance value between 0.66 and 0.74 is the most optimal choice for achieving high output radiation. Given the length of the active medium, we have designed the resonator to be 80 mm long. Taking into account all the specified parameters and components of the laser system, we can infer that the dimensions of the laser head will be 110 mm × 25 mm × 25 mm.

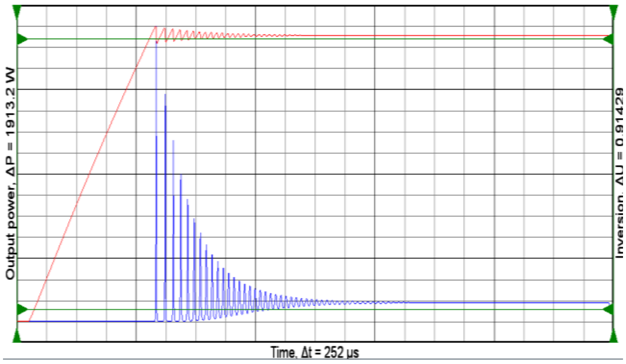

Fig. 5 – The dependence of output power versus laser pumping time

Fig. 5 shows the simulations results of the modeling laser system output power. The red curve presents pumping power Wp, meanwhile the blue curve relates to the generation energy. It can be seen that the pump radiation power increases proportionally until it reaches the value that corresponds to the saturation energy of the crystal.

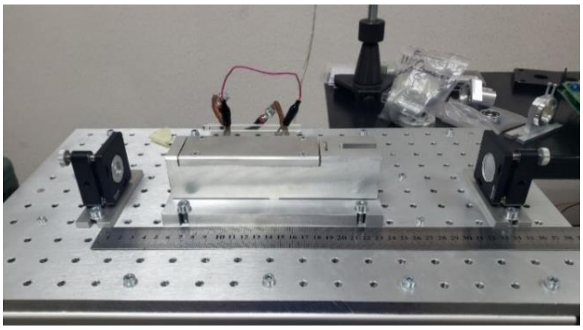

Fig. 6 – The diode – pumped Nd:YAG solid state laser experimental setup

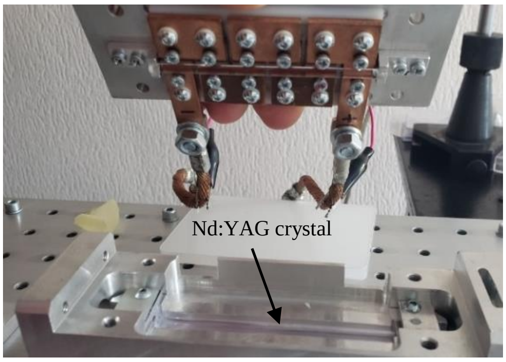

Fig. 7 – Nd:YAG active crystal and laser diodes

As we can estimate, the first giant pulse after pumping started was reached up at 59 μs, with output power of 25 mJ and efficiency of laser system of 22 %. Additionally, the generation of next pulses of radiation time interval was 4 μs. Considering all obtained results, we could determine optimal parameters value for practical setup.

As one can see from the Fig. 6, the overall dimensions of the laser setup are 350 × 25 × 25 mm. The Fig. 7 displays the photo of the active element of the yttrium aluminum garnet crystal doped with neodymium ions, which pumped by optical diode array with pump pulse duration 250 ns. It should be noted, we apply a cylindrical rod lens, in order to have a direct photon flux into the active element, consequently, it increases the pump efficiency. The low heat dissipation in the gain material of a SSL with semiconductor diode pump eliminates the need for water cooling, which in turn reduces the overall mass and size of the device. In addition, it leads to decrease of thermal stresses in the laser gain medium, and that allows to form a high spatial-angular brightness laser beam.

4. CONCLUSIONS

The parameters of the design of a Nd:YAG laser pumped by pulsed laser diode arrays with a passive cooler have been calculated. The optimal output mirror reflection coefficient was chosen as 70 %. The effective small-sized laser with diode pumping of 450 W and output total emission of 25 mJ has been simulated and as a result, the optical design of a novel structure has been proposed. Afterward, the optimized Nd:YAG laser pumped by pulsed laser diode arrays with a passive cooler was built. Thus, an effective compact diode-pumped laser with high power for further implementation as a range finder was presented. For the further optimization, an active Q-factor modulator can be proposed to add. The results obtained in this work make it possible to practically obtain an ultra-compact solid-state laser with diode pumping (80 × 25 × 25 mm) and a high output energy of 25 mJ, as well as an efficiency of 22 %.

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Конструкція та оптимальні параметри малогабаритної Nd:YAG-лазерної установки з діодним накачуванням

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Дана стаття присвячена моделюванню, проектуванню та подальшій розробці практичної установки малогабаритного твердотільного лазера з середовищем посилення Nd:YAG та діодною накачкою. Твердотільні лазери існують близько 50 років і зазнали як позитивних, так і негативних аспектів під час своєї еволюції. Тим не менш, вони завжди займали важливе місце в багатьох галузях промисловості, наукових дослідженнях і повсякденній діяльності. На сьогоднішній день, такі пристрої широко використовуються та розвиваються в локації, виробництві, медицині та військовій техніці. Тому розробка та оптимізація їх структури залишається актуальною та важливою проблемою. Виявлено основні параметри компонентів компактного Nd:YAG лазера з діодною накачкою, які можуть бути реалізовані в конструкції далекоміра. Основні результати роботи. Розроблено та промодельовано Nd:YAG лазер з габаритними розмірами 350 × 25 × 25 мм; розміри лазерної активної головки 110 × 25 × 25 мм. Діодна накачка являє собою матрицю з шести діодів потужністю 90 Вт кожен, які працюють в імпульсному режимі тривалістю 250 нс. Резонатор складається з двох дзеркал, з коефіцієнтом відбиття на виході від 0,66 до 0,74. Активний елемент має довжину 72 мм. З такими параметрами лазера перший гігантський імпульс після початку накачування був досягнутий за 59 мкс, вихідна енергія 25 мДж і ефективність лазерної системи 22 %. Додатково генерувалися наступні імпульси випромінювання з інтервалом часу 4 мкс. Отримані в роботі результати дозволяють створити твердотільний лазер з діодною накачкою з енергією випромінювання на виході до 25 мДж і компактними розмірами резонатора близько 80 × 25 × 25 мм.

Ключові слова: Лазерний діод, Потужність випромінювання, Накачування, Твердотільний лазер, Активна зона, Глухе дзеркало, Довжина хвилі, Лабораторна установка.