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ВЛИЯНИЕ МАТРИЦЫ НА ГЕНЕРАЦИЮ НЕПРЕРЫВНОГО КВАЗИТРЕХУРОВНЕВОГО НЕОДИМОВОГО ЛАЗЕРА ПРИ НЕОДНОРОДНОЙ НАКАЧКЕ

***В. И. ГЕРАСИМЕНКО*[1]*, И. В. СТАШКЕВИЧ*[1]**

[1]*Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Беларусь*

Анализируются генерационные характеристики неодимового лазера с квазитрехуровневой схемой для наиболее распространенных кристаллических матриц. Теоретическое исследование энергетических характеристик излучения такого лазера с различными матрицами проведено для стационарного режима генерации. Анализ выполнялся для модели лазера как с продольной накачкой лазерным диодом, так и с поперечной с учетом пространственной неоднородности пучка накачки. Результаты расчетов показывают, что учет пространственной неоднородности пучка накачки при продольном и поперечном возбуждении приводит к росту расчетного значения пороговой мощности накачки и снижению параметра эффективности генерации по сравнению с результатами для точечной модели лазера. Показано, что оптимальными значениями пороговой мощности накачки и параметра эффективности генерации обладают матрицы YAG и GGG по причине более низких значений реабсорбционных потерь.

Ключевые слова: неодимовый лазер; квазитрехуровневая схема; пространственная неоднородность пучка накачки; параметр эффективности; пороговая мощность накачки; Nd : KGW; Nd : GVO; Nd : YVO; Nd : YAG; Nd : GGG; Nd : YAP.

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Авторы:
Валерия Игоревна Герасименко – магистрант кафедры лазерной физики и спектроскопии физического факультета. Научный руководитель – И. В. Сташкевич.
Игорь Вячеславович Сташкевич – кандидат физико-математических наук, доцент; доцент кафедры лазерной физики и спектроскопии физического факультета.

Authors:
Valeryia I. Gerasimenko, masters degree student at the department of laser physics and spectroscopy, faculty of physics.
gerasimenkovaleriya.i@gmail.com
Ihar V. Stashkevitch, PhD (physics and mathematics), docent; associate professor at the department of laser physics and spectroscopy, faculty of physics.
stashkevitch@bsu.by

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THE MATRIX EFFECT ON GENERATION OF QUASI-THREE-LEVEL CONTINUOUS WAVE NEODYMIUM LASER UNDER INHOMOGENEOUS PUMPING

V. I. GERASIMENKO[a], *I. V. STASHKEVITCH*[a]

[a]*Belarusian State University, 4 Niezaliežnasci Avenue, Minsk 220030, Belarus*
Corresponding author: I. V. Stashkevitch (stashkevitch@bsu.by)

The main generation characteristics of a neodymium-doped laser with a quasi-three-level scheme are analyzed for most common crystalline matrices. The energy characteristics of radiation from such a laser with different matrices in the stationary mode are studied theoretically. The operation of both the end-pumped and transversely-pumped laser has been simulated. The results of the calculations show that allowance for the spatial inhomogeneity of the pump beam, both for longitudinal and transverse excitation, leads to the increased calculated value of the pump threshold power and to the decreased generation efficiency parameter compared to the results for the point model of laser. It is demonstrated that the two matrices YAG and GGG have optimal threshold pump powers and slope efficiencies due to lower reabsorption losses.

Key words: neodymium laser; quasi-three-level scheme; spatial beam inhomogeneity; slope efficiency; pump power threshold; Nd : KGW; Nd : GVO; Nd : YVO; Nd : YAG; Nd : GGG; Nd : YAP.

Introduction

Diode-pumped solid-state lasers featuring stable frequency of lasing, high energy efficiency and compactness are widely applied in science and technology. Nd-doped lasers are most commonly used. Due to rapid progress in the field of nonlinear optics, it is possible to realize the IR-to-visible frequency conversion with a high efficiency and hence to expand the field of applications for solid-state diode-pumped lasers. At the present state of the art, one of the important tasks is to obtain laser generation in the blue region of the spectrum to meet the requirements of information and communications technologies, hologram recording, medicine, atmospheric sounding, etc.

Coherent radiation in the blue region can be realized by the *nonlinear frequency conversion* of solid-state lasers operating in the near-IR range. To this end, Nd-doped solid-state lasers are most frequently used with a quasi-three-level scheme operating on transition from the $^4F_{3/2}$ manifold to the lower manifold $^4I_{9/2}$. When a frequency of the $^4F_{3/2} - {}^4I_{9/2}$ transition is doubled, it is possible to obtain coherent radiation over the range 450–470 nm with the use of different Nd-doped matrices. The most important parameters of an active medium are the following: Stark splitting of the levels, lifetime of the upper state, maximum concentration of neodymium ions (doping level), absorption and stimulated emission cross-sections.

Figure 1 shows the energy level diagram for an active ion and transitions in a neodymium laser based on a quasi-three-level scheme.

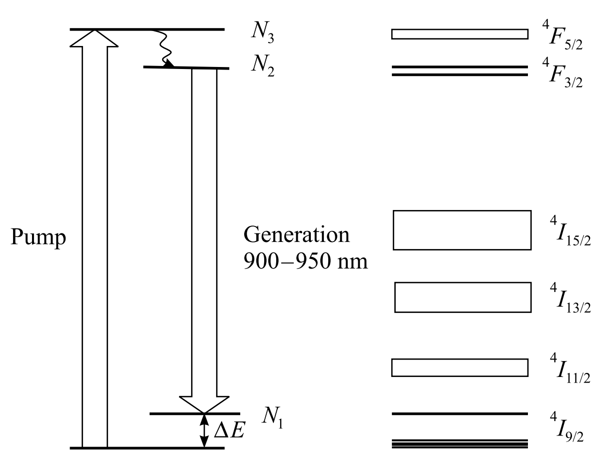

Fig. 1. Energy level diagram and transitions in a neodymium laser based on a quasi-three-level scheme. Populations of the upper and lower laser levels are given by N_2 and N_1, respectively

The diagram in its general form is the same for all crystals, only the energy levels of the excited $^4F_{3/2}$ and ground $^4I_{9/2}$ manifolds vary. A lifetime of the $^4F_{3/2}$ level is on the order of 10 ns; transitions to the metastable upper $^4F_{3/2}$ level are nonradiative. Generation occurs between the lower energy level of the $^4F_{3/2}$ manifold with the population N_2 and the upper energy level of the ground $^4I_{9/2}$ manifold with the population N_1.

This paper presents the results of numerical simulation for the performance of a longitudinally and transversely pumped quasi-three-level neodymium laser with different matrices. The threshold and slope efficiencies are calculated taking into account the spatial distribution of pump beam in the radial direction. The results obtained have been compared with the data given in [1] for a point model of laser. All spectroscopic characteristics of the matrices (YAG, YVO, GVO, GGG, YAP, KGW) were taken from [1; 2].

Simulation and calculations

Calculations for quasi-three-level Nd-laser with longitudinal pumping. The model of a quasi-three-level laser used in this article is valid for the general energy level diagram of fig. 1, with the population density of the lower laser level N_1 assumed to have a low thermal population [3].

Relative populations of the levels in the lower manifold are given by the Boltzmann distribution. Then the lower laser level is given by

$$N_1 = \frac{N_l}{Z_l}\exp\left(-\frac{E_{l5}}{kT}\right) = f_1 N_l,$$

where N_1 is the lower laser level population, E_{l5} is its energy, N_l is the population of the lower manifold $^4I_{9/2}$, $Z_l = \sum_{i=1}^{m}\exp\left(-\frac{E_{li}}{kT}\right)$ is the partition function of the lower manifold, f_2 is the fraction of the total $^4F_{3/2}$ population density at the lower Stark-splitting energy level, f_1 is the fraction of the total $^4I_{9/2}$ population density at the upper Stark-splitting energy level, k is the Boltzmann constant, T is the temperature. In the case of steady-state pumping, relative populations of the levels in the upper manifold can also be described by the Boltzmann distribution if relaxation between the levels in the upper manifold is rapid. Exact values of f_1 and f_2 are given in table 1.

Table 1

Theoretically calculated values of f_1 and f_2

Matrix	YAG	YVO	GVO	GGG	YAP	KGW
f_1	0.008	0.049	0.057	0.01	0.019	0.077
f_2	0.60	0.52	1.00	0.55	0.65	0.62

If depletion of a population in the ground state can be neglected, the laser rate equations for the population density in the upper and lower laser levels can be written as

$$\frac{dN_2(r, z)}{dt} = f_2 R_p \varphi_p(r, z) - \frac{N_2(r, z)}{\tau} - \frac{f_2 c\sigma\left[N_2(r, z) - N_1(r, z)S\varphi_l(r, z)\right]}{n}, \tag{1}$$

$$\frac{dN_1(r, z)}{dt} = -f_1 R_p \varphi_p(r, z) - \frac{N_1(r, z) - N_s f_1}{\tau} - \frac{f_1 c\sigma\left[N_2(r, z) - N_1(r, z)S\varphi_l(r, z)\right]}{n}, \tag{2}$$

where $R_p = \frac{P_{\text{inc}}\left[1 - \exp[-\alpha l]\right]}{h\nu_p}$ is the total pump rate; P_{inc} is the incident pump power; $h\nu_p$ is the pump photon energy; α is the absorption coefficient; c is the speed of light; σ is the stimulated emission cross section; n is the index of refraction; τ is the upper state lifetime; N_s is the doping level [cm^{-3}]; $\varphi_p(r, z)$ and $\varphi_l(r, z)$ are the spatial distributions of the pump beam and laser beam, respectively. It has been assumed that relaxation from $^4F_{5/2}$ to the upper laser level is extremely fast. The energy transfer upconversion and excited state absorption may be neglected. Since we are considering the stationary mode, the time derivatives are equated to zero.

The total number of photons in the cavity S as a function of the incident pump power at the threshold is found from the equation derived from the radiative transfer equation:

$$\frac{ds}{dt} = \frac{c\sigma}{n} \iiint\limits_{\text{crystal}} \Delta N(r, z) S \varphi_l(r, z) dV - \frac{s}{\tau_q} = 0,$$

where $\Delta N(r, z) = N_2(r, z) - N_1(r, z)$ is the inversion-population density at thermal equilibrium from equations (2) and (3); $\tau_q = \frac{2l_c^*}{c(2\gamma l + T)}$ is the cold-cavity photon lifetime; T is the output transmission; γ is the intrinsic cavity loss factor [cm^{-1}]; l is the length of the active medium; $l_c^* = l_c + (n-1)l$ is the optical path length of the cavity; P_{out} is the laser output power from the cavity; $h\nu_l$ is the laser photon energy. This equation enables one to calculate the incident pump power at the threshold. To calculate the slope efficiency, it is necessary to take into account the effect of overlapping pump and laser fields [3].

Relation between the total number of photons in the cavity S and the output power from the laser cavity is given by:

$$S = \frac{2l_c^* P_{\text{out}}}{ch\nu_l T}.$$

The pump and laser beams are modeled as circularly symmetric (TEM$_{00}$) Gaussian beams which do not diffract significantly within the active medium. It is assumed that the pump light passes just once through the gain medium, so the unabsorbed pump light is assumed not to be reflected back into the active medium.

In this calculation a length of the active medium is l = 3 mm, the mode waist ratio $\frac{\omega_p}{\omega_L}$ is equal to 1, ω_p = 200 μm, the output transmission T is 3 %, the intrinsic loss coefficient in the cavity is $\gamma = 2 \cdot 10^{-3}$ cm^{-1}.

Figure 2 shows the laser output power as a function of the incident pump power for different matrices.

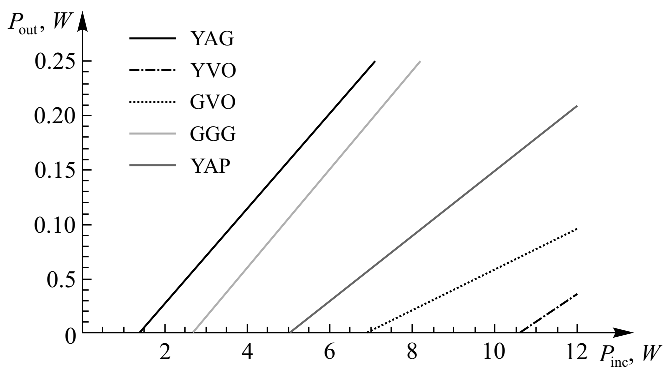

Fig. 2. Calculated laser output power as a function of the incident pump power

Theoretically calculated values of the slope efficiencies and the threshold pump powers for different matrices are given in table 2.

As seen, the maximum slope efficiency corresponds to matrices GGG and YAG since they have lower reabsorption losses because of the lower population N_1 of neodymium ions at the upper energy level of the ground manifold ($\Delta E > kT$ [1]). To increase the slope efficiency, the doping level can be lowered: for example, for the KGW matrix with a doping level of 2 at. % the slope efficiency is growing to 18 %. A similar situation is observed for the threshold pumping power – minimum values correspond to two given matrices with minimal reabsorption losses.

Table 2

Theoretically calculated laser parameters

Matrix	Incident pump power at the threshold, P_{inc}, W	Slope efficiency, $\frac{dP_{\text{out}}}{dP_{\text{inc}}} \cdot 100$ %
YAG	1.40	43.8
YVO	10.6	26.1
GVO	6.92	19.0

Ending table 2

Matrix	Incident pump power at the threshold, P_{inc}, W	Slope efficiency, $\frac{dP_{out}}{dP_{inc}} \cdot 100$ %
GGG	2.70	45.4
YAP	5.04	30.1
KGW	57.7	4.7

If the spatial distribution of the pump beam is taken into account, the threshold pump power significantly increases in comparison with the data calculated using the point model of laser since the latter takes into account neither the spatial distribution of the pump radiation along the cylindrical coordinates z and r nor the presence of reabsorption losses. The point model of laser gives higher values of the slope efficiency for the same reasons.

Figure 3 shows the threshold pump power depending the length of the gain medium with the same doping level as in [1]. On the one hand, with an increase in the length of the active medium, the absorbed pump power increases and, on the other hand, the reabsorption losses increase too. Therefore, for each matrix there is an optimal length of the gain medium associated with a minimal threshold pump power.

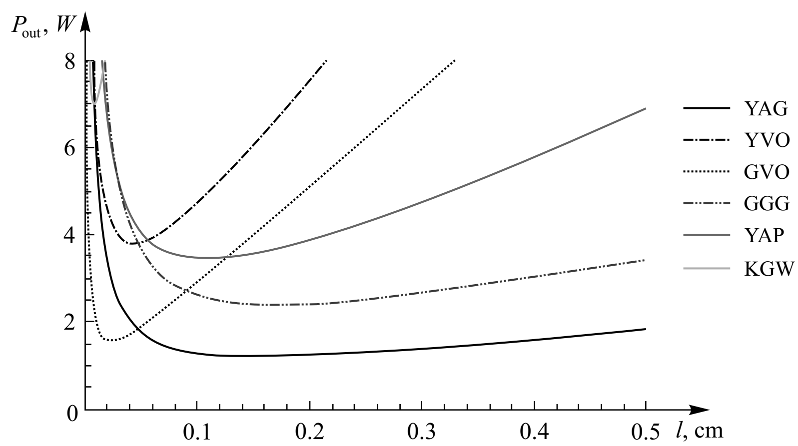

Fig. 3. Pump power at the threshold depending on the length of the gain medium

Calculations for quasi-three-level Nd-laser with transverse pumping. Assuming that the distribution of pump radiation along the z coordinate is uniform, the spatial distribution of the pump beam is given by

$$\varphi_p(x, y) = \frac{1}{\sqrt{1 + \left(\frac{\lambda x}{\pi w_0^2}\right)^2}} \exp\left[-2\frac{y^2}{w_0^2\left[1 + \left(\frac{\lambda x}{\pi w_0^2}\right)^2\right]}\right].$$

Table 3 shows the calculated values of the absorbed pump power at threshold and the slope efficiency in the case of transverse pumping.

Table 3

Theoretically calculated laser parameters

Matrix	Absorbed pump power at the threshold, P_{abs}, W	Slope efficiency, $\frac{dP_{out}}{dP_{abs}}$, %
YAG	3.1	28.4
YVO	31.7	10.8
GVO	21.6	7.1

Ending table 3

Matrix	Absorbed pump power at the threshold, P_{abs}, W	Slope efficiency, $\frac{dP_{out}}{dP_{abs}}$, %
GGG	5.8	30.5
YAP	12.6	14.9
KGW	190.0	1.5

The gain rod (l = 10 mm) is directed along the z axis with a cross-sectional diameter of 5 mm (plane XY). Laser diode bars (three-side pumping scheme) were chosen as a pump source 10 mm in length. The angular divergence of the pump beam in the XY plane is 30°. For transverse pumping the situation is similar: minimal threshold pump powers correspond to two matrices YAG and GGG.

Summary

In this paper, the main generation characteristics – the threshold pump power and the slope efficiency – of a neodymium doped laser with the quasi-three-level scheme are calculated and analyzed. Two matrices – YAG and GGG – have the optimal threshold pump powers and slope efficiencies due to lower values of the reabsorption losses. Optimum lengths of the active medium are different for different matrices. The results obtained are associated with the parameter values which are identical for all the matrices but not optimal for some of them.

To reduce reabsorption losses, one can lower the doping level, thereby reducing the threshold pump power. The latter can also be reduced by choosing an optimal length of the active medium for the considered matrices. The proposed model takes into account both the spatial distribution of the pump radiation along the cylindrical coordinate r and the reabsorption losses. The model may be improved further by inclusion of the non-Gaussian spatial distribution of the generated beam.

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