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Amplification in the Yb:YAG medium at cryogenic temperatures

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A numerical model of a disk cryogenic Yb:YAG diode-pumped amplifier with pulse energy of tens and hundreds of joules is presented. The model accounts for the change in the shape of the pump pulse spectrum during its propagation through the gain medium consisting of several active elements with different levels of doping with ytterbium ions. Amplification of spontaneous emission, which limits the inversion, is considered in the model in the 3-dimensional geometry for the real spectrum shape and for each active element according to the energy absorbed in it. The simulation results are compared with the currently published experimental data for amplifiers with pulse energies above 100 J.

Keywords: pulsed periodic lasers, amplification of spontaneous emission, Yb:YAG, cryogenic cooling, modeling.

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The today's world-practice trend in creating systems of pulsed periodic lasers with high pulse energy is using amplifier modules with diode pumping and disk active elements (AE) through the gaps between which cooling gas is pumped [1–6]. One of the most promising materials for the gain medium of such modules is yttrium-aluminum garnet doped with ytterbium ions (Yb:YAG). Yb^{3+} as an active laser ion provides long fluorescence lifetime and low quantum defect, while efficient and reliable high-power laser diodes are available at the pump wavelength. YAG possesses high thermal conductivity and mechanical strength and, if used in the ceramic form, may be produced in large sizes [7] with good optical quality. This is especially important for kJ-class laser systems, since they will need amplification stages with apertures larger than 10 cm.

Optimization of such a multi-parameter system becomes simpler if numerical models are used. The first numerical calculations of the efficiency of a pulsed Yb:YAG energy- storage amplifier were presented by Fan [8]; in subsequent works, various effects governing the amplifier efficiency were studied, such as, for instance, amplification of spontaneous emission (ASE), gain medium cooling to cryogenic temperatures, difference in the widths of the pump and absorption lines. Detailed description of the mechanisms and their influence on the efficiency of such a multi-parameter system is given in [9]. However, there is still no model calculating ASE and absorption by using experimentally measured stimulated-emission and absorption spectra, as well as the input pulse spectrum at an arbitrary pump wavelength. In this work, we propose just such a numerical model of a diode-pumped cryogenic Yb:YAG amplifier for generating high-energy ns pulses.

Pumping along optical axis z (free of gas gaps) is described by a set of equations for relative inversion $\beta(z) = N_U(z)/N_{\mathrm{Yb}}(z)$ and intensity of two-way pump emission in photons $\Phi_P^{+,-}(t, \lambda, z)$:

$$\frac{\partial \Phi_P^{+,-}(t, \lambda, z)}{\partial z} = -N_{\mathrm{Yb}}(z)\big[\big(1-\beta(z)\big)\sigma_a(\lambda) - \beta(z)\sigma_e(\lambda)\big]\Phi_P^{+,-}(t, \lambda, z), \quad (1)$$

$$\frac{\partial \beta(z)}{\partial t} = \int \Big[\big(1-\beta(z)\big)\sigma_a(\lambda) - \beta(z)\sigma_e(\lambda)\Big] \times \big(\Phi_P^{+}(t, \lambda, z) + \Phi_P^{-}(t, \lambda, z)\big) d\lambda - \frac{\beta(z) M_{\mathrm{ASE}}\big(t, \beta(z)\big)}{\tau}, \quad (2)$$

where $N_{\mathrm{Yb}}(z)$ and $N_U(z)$ is the total Yb^{3+} concentration and upper level occupation, $\sigma_e(\lambda)$ and $\sigma_a(\lambda)$ are the cross-sections of induced emission and absorption, and τ is the excited state lifetime. The pump intensity at the amplifier ends is governed by the pump pulse power $P(t)$ and spectrum $f_p(\lambda)$ ($\int f_p(\lambda) d\lambda = 1$):

$$\Phi_P^{+}(t, \lambda, 0) = \Phi_P^{-}(t, \lambda, z_m) = \frac{P(t) f_p(\lambda)}{h\nu_p S_p},$$

where $h\nu_p$ is the pump photon energy, S_p is the pump beam cross-section, $z_m = Nd$ is the absorption length N of an AE d in thickness. The first term on the right side of equation (2) determines the increase in inversion due to pump absorption; the second term determines the inversion decrease due to spontaneous decay, including ASE (factor M_{ASE}). Distribution of the pump emission intensity in the direction transverse to the optical axis is assumed to be uniform. Temperatures of all AEs are the same and independent of z. In this model, amplification of spontaneous emission, which limits the inversion is being calculated for the shape of measured spontaneous-emission spectrum in the three-dimensional geometry relevant to the

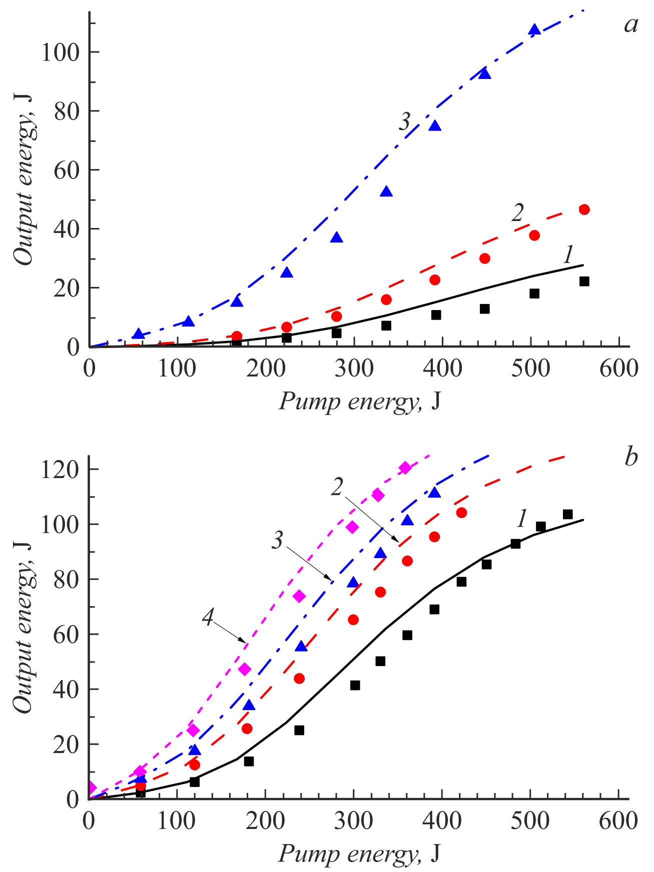

Figure 1. Output energy versus pump energy (experimental dependences (symbols): *a* — [4], *b* — [5]) and theoretical dependences at different input pulse energies: *a* — 0.5 (*1*), 1 (*2*) and 5 J (*3*) for the AE temperature of 175 K; *b* — 2.6 (*1*), 5.6 (*2*) and 8.2 J (*3,4*) for the AE temperatures of 150 (*1–3*) and 130 K (*4*).

amplifier design; for each AE, ASE is being calculated in accordance with energy absorbed in it. The major part of ASE incident onto the surface of a particular AE at angles greater than that of total internal reflection is absorbed in the AE peripheral region (cladding) and depends only on the energy absorbed in this AE. The remaining part of emission can pass through several AEs; thus the intensity of emission from the pumped region depends both on the pump energy distribution over AE and absorption length z_m.

The model's input parameters are the number of AEs and their size, ytterbium ion concentration in each AE, AE temperature, wavelength, spectrum, pump duration and power, absorption spectrum and spontaneous emission spectrum. In this work, we used in calculations cross-sections of the absorption and spontaneous emission obtained with resolution of 0.1 nm in the wavelength range of 852.6–1046 nm for the temperatures of 125, 150, 175 K; however, there are also available data for 100, 200, 225, 250 and 300 K. Time dependences of distributions along the optical axis of the population inversion, absorbed and stored energy, and small signal gain were calculated. Based on these dependencies, we found such characteristics averaged along the optical axis as, e.g., time dependences of the small signal gain and stored energy. Knowing the stored energy for a given pump duration, it is possible to find the dependence of the output pulse energy on input pulse energy at an arbitrary number of amplifier passes for various total losses in the amplification channel. The shape (in time) of the input pulse may be varied, for instance, set to rectangular or Gaussian.

Figs. 1 and 2 illustrate the comparison of experimental [4–6] and theoretical dependences. In [4,5], six AEs 8.5 mm thick were installed in the amplifier, while in [6] the amplifier comprised ten AEs 1 cm thick. The pumped region transverse sizes were approximately the same and equaled 8×8 cm. Distributions of ytterbium ion concentrations over the AE presented are 0.4, 0.6, 1% in [4,5] and 0.35, 0.45, 0.5, 0.7, 1%. in [6]. To pump the amplifiers, two diode modules 250 and 280 kW in power were used in [4,5], while in [6] there were used eight 125 kW modules; in contrast to jcite4,5, the pump emission wavelength in [6] was reduced from 940 to 935 nm and got into the absorption peak but with a smaller absorption cross-section than at

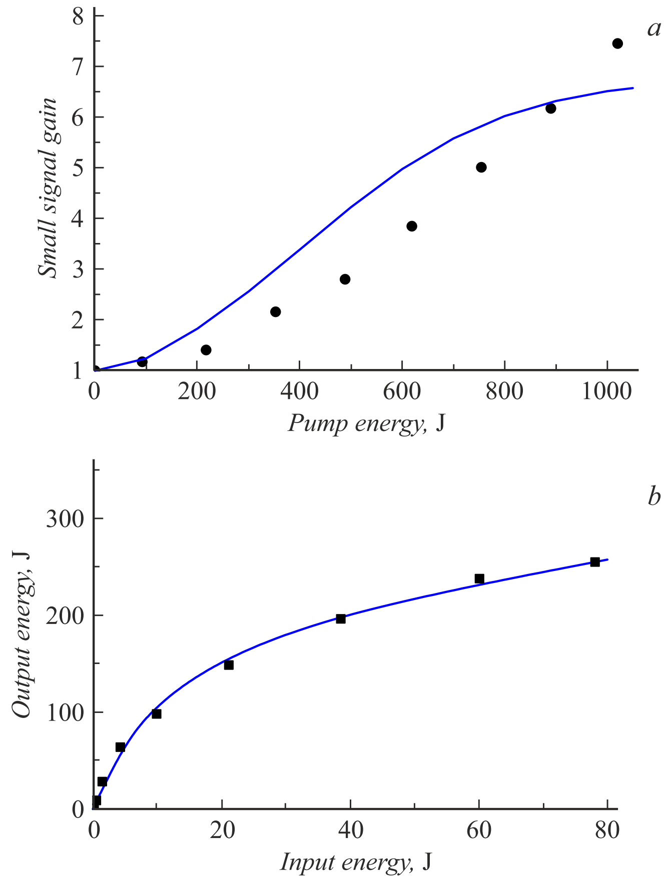

Figure 2. Experimental (symbols) [6] and theoretical dependences of the small signal gain (E_{out}/E_{in}) on pump energy (*a*) and those of output energy on the input pulse energy for the AE temperature of 175 K (*b*).

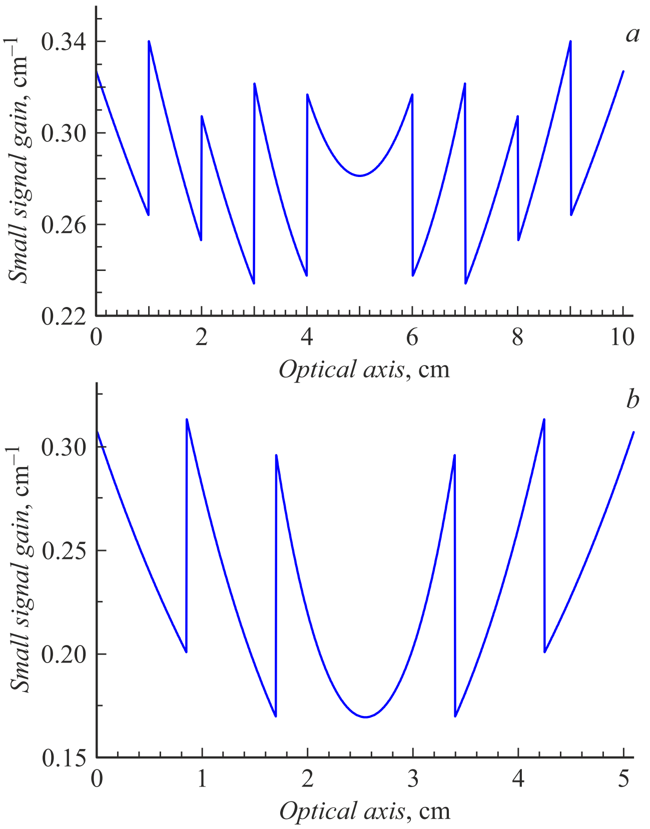

Figure 3. Theoretical dependence of the gain along the amplifierś optical axis (without gas gaps) [6] (*a*) and [5] (*b*) after pumping during 1 ms at the AE temperature of 175 K.

940 nm. Therefore, mean concentrations of ytterbium ions in AE (0.67% [4,5] and 0.75% [6]) differ only slightly though absorption length in the active medium z_m at the setup described in [6] is almost 2 times longer than that in [4,5]. The maximum pulse energy obtained in [4–6] was 107, 120 and 253 J, respectively.

Figs. 1 and 2 clearly demonstrate a good agreement between the experimental and theoretical results. The only exception is that in Fig. 2, *a* theoretical dependence of the weak signal gain at medium absorbed energies lies higher than the experimental one, while that at maximum absorbed energies passes lower. Obviously, the calculated ASE effect on the stored energy and, hence, gain, is stronger than experimental one. To clarify this discrepancy, extra research with the use of experimental data from other sources is needed.

Fig. 3 presents theoretical dependences of the gain along the amplifierś optical axis [6] (*a*) and [5] (*b*) after pumping for 1 ms. Noteworthy is a significant gain inhomogeneity over AE in the amplifier [6]. For instance, the gain averaged over AE is lower in the third and fourth AEs (counted from the outside) than in the others. Calculations also show that in the case of amplifier described in [6] a significant pump emission fraction (13%) is not absorbed in AE. In the amplifier considered in [5], the gain distribution along the optical axis is more uniform, and pump energy loss does not exceed 4%. This is why, the middle-element gain droops are greater in the amplifier from [5] than in that from [6]. Apparently, it is possible to make the amplifierś output pulse energy somewhat higher by optimizing the ytterbium ions content in AE [6].

Thus, the model proposed in this work can be used to optimize and predict amplification properties of the disk cryogenic Yb:YAG amplifier with bidirectional diode pumping in the temperature range from 100 to 300 K at an arbitrary pump wavelength and linewidth.

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Conflict of interests

The authors declare that they have no conflict of interests.

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