POLARIZATION OF STIMULATED EMISSION OF NEODYMIUM IONS IN A GLASS BASE

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We consider the connection between the efficiency of a neodymium laser and the polarization of its emission. We present a qualitative explanation of the observed regularities with allowance for the mode interaction with the active Nd^{3+} ions in the glass base. We describe a scheme of a laser with an electrooptic shutter and unpolarized radiation. The characteristics of such a laser are presented.

THE position of the plane of polarization and the character of its rotation in stimulated emission of neodymium ions in glass vary in random fashion from pulse to pulse when the neodymium laser operates in the free-generation regime. The degree of radiation polarization V approaches 100% near the generation threshold and decreases with increasing pump energy, with

$$V = I_p / (I_p + I_{unp}), \quad (1)$$

where I_p and I_{unp} are the polarized and unpolarized components of the radiation[1].

Introduction of artificial anisotropy into the laser resonator, i.e., of a dependence of the radiation loss on its polarization, increases the degree of polarization and fixes the state of the polarization. This effect arises even in the case when the relative difference between the radiation losses of orthogonal polarizations is small ($\gamma \ll 1$)[2,3]. Here

$$\gamma = (\sigma_1 - \sigma_2) / (\sigma_1 + \sigma_2), \quad (2)$$

where σ_1 and σ_2 are the radiation losses for both polarizations. In practice such an anisotropy (as $\gamma \to 1$) occurs when the laser radiation power is increased with the aid of an electrooptic shutter[4]. Great importance attaches in this case to a clarification of the question whether the artificial anisotropy reduces the energy efficiency of the generator

$$\eta = W_{out} / W, \quad (3)$$

where W_{out} is the laser radiation energy and W is the pump energy.

A theoretical analysis of the dependence of V and η on the pump energy in the case of an isotropic active medium was made in[5] on the basis of the kinetic-equation method. It was assumed there that the distribution of the excited atoms over the orientations of the dipole moment was continuous. Account was taken in[5] of the fact that as the generation develops an increase takes place in the relative population inversion of the atoms having dipole-moment orientations close to orthogonal relative to the predominant polarization, which compensates, in final analysis for the large value of γ in the case of the radiation corresponding to these atoms.

Under these assumptions, it was found that $V \approx 100\%$ at the generation threshold, up to a certain definite pump level, after which it decreases quite rapidly to zero at $\gamma \ll 1$, while η assumes a certain constant value even in the case of weak pumping, the same value for $\gamma \ll 1$ and $\gamma \to 1$.

In ordinary neodymium-glass lasers, the random polarization of the radiation is determined apparently by the inhomogeneities of the laser resonator and of the pump radiation[3], since the transverse modes with small indices, which are present in the laser radiation, have losses that do not depend on the state of the polarization[6]. Experiment corresponds to values $\gamma \ll 1$, since the laser emission is appreciably polarized even when $\gamma \approx 0.01$[2]. The observed values of P, however, decrease smoothly with increasing pump level, and are quite high at a relatively large excess above the generation threshold[1]. On the other hand, the dependence of η on the pump level has hardly been investigated, although there is an indication in[7] that the output energy decreases noticeably when a polarizer is introduced into a laser resonator. A clarification of the indicated dependence was indeed the purpose of the following experiment.

The investigated laser has active elements of silicate glass with ~5% Nd^{3+} added; different illuminators were used, and the laser resonator was made up of flat dielectric mirrors. Inside the resonator mirror we placed either a birefringent wedge[8] with a bevel angle ~1°, which caused total polarization of the radiation as a result of the high value of γ introduced by it, or else a wedge of fused quartz, which introduced practically the same loss into the laser resonator, and imparted the usual random character to the polarization. The threshold pump energy was approximately the same in both cases. The value of η was higher in the case when the quartz wedge was present, and this regularity became all the more noticeable with increasing pump energy. A typical illustration of the foregoing is Fig. 1, which shows the dependence of η on the ratio of the pump energy to its threshold value W_0 for both wedges. The measurement error, determined essentially by the instability of the output energy, did not exceed 5–10%. The character of the obtained dependence was close to that indicated in[9]:

$$\eta = A(1 - W_0 / W), \quad (4)$$

where A depends on the characteristics of the pump and of the active medium, and also on the laser resonator parameters.

The obtained disagreement between the predictions (see[5]) and experiment is connected, in our opinion,

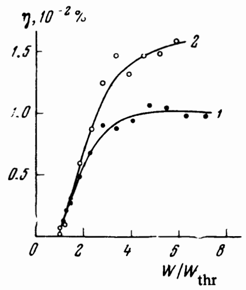

FIG. 1. Dependence of the efficiency of a neodymium glass laser on the ratio of the pump energy to its threshold value (free generation): 1—birefringent wedge in the resonator, 2—quartz wedge in the resonator.

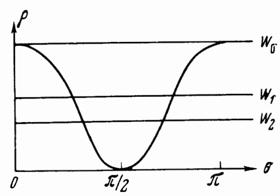

FIG. 2. Approximate dependence of the probability of excitation of the active ions in a given mode on the angle between the predominant polarization directions and the dipole moments of the ions.

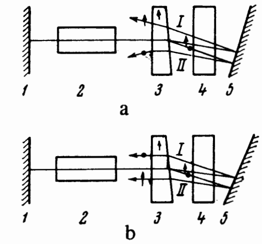

FIG. 3. Ray paths in a laser resonator with a Kerr cell (a—shutter closed, b—shutter open); 1, 5—reflectors, 2—active element, 3—polarizer, 4—Kerr cell.

with failure to take into account the mode character of the interaction between the radiation and the excited Nd^{3+} ions. A qualitative explanation of the results of the experiment consist in the following.

Simple transverse modes with small indices for open resonators can be connected with the rather arbitrary polarization of the radiation [6]. Let us assume, however, that a mode produced in a certain pulse retains during the course of the laser operation the same predominant polarization direction. Figure 2 shows the approximate character of the dependence of the radiation probability of the active ions at the given mode on the angle θ between the predominant directions of polarization and the dipole moments of the ions. At the generation threshold (line W_0 on Fig. 2), only the ions with $\theta \approx 0$ and π interact effectively with the mode having the smallest loss. The degree of polarization of the radiation will be high. With increasing pump energy (lines W_1 and W_2 in Fig. 2), an increasing number of ions with other values of θ interact with the given mode. Obviously, the efficiency of such an interaction decreases as $\theta \to \pi/2$. When $\gamma \ll 1$, as a result of this fact and also as a result of the increase of the relative population inversion for orthogonal polarization [5], a transition to other modes with different polarization states may be more convenient. The degree of polarization of the radiation will decrease smoothly with increasing pump level. The predominant polarization direction may change in different radiation pulses. All this makes it possible for practically all the active modes to take part in the generation.

The situation is entirely different when $\gamma \to 1$ (neodymium-glass laser with a polarizing device, or a ruby laser). The threshold pump energy remains practically the same as for the mode having the small sources, and the different radiation-states are practically equivalent. With increasing pump level, only the modes corresponding to the same linear polarization of the radiation will take part in the generation. In view of this, the dipole moments with $\theta \to \pi/2$ will give an ever decreasing contribution to the generation (Fig. 2), leading to a reduction of η compared with the case $\gamma \ll 1$ at large pump values.

The described model allows us to advance a hypothesis concerning the reason why it is possible in the case of a ruby laser to observe distinct patterns of transverse modes in the laser emission [10], whereas for the neodymium glass laser no such observation was made. The indicated phenomenon is connected with the noted tendency of such a laser, operating with $\gamma \ll 1$, to generate modes with different states of polarization in the same pulse. Such modes have shifted intensity distribution [6], which produce more uniform patterns upon superposition.

Starting from this model, we can expect the efficiency of the laser, when operating the Q-switching regime, to decrease when $\gamma \to 1$ (polarizer in the laser resonator), for in this case the initial population inversion is high, causing dipoles with $\theta \to \pi/2$ to take part in the generation. Consequently, it is of interest to construct a generator with an electrooptic shutter, having equal losses at any polarization when the shutter is opened [11]. The ray paths in such a laser are shown in Fig. 3. The polarizer 3 employed here is a birefringent wedge, although any other refracting prism with optical contact can be used [8]. The optical axis of the wedge material lies in the plane of the figure and is parallel to the left face of the wedge. The electrooptic delay 4, in this case a Kerr cell, is oriented in such a way that the plane of its electrodes makes an angle 45° with the directions of polarization in the extraordinary ray I and in the ordinary ray II, which emerge from the wedge 3 on the right (in the case of a flat reflector 5). Reflector 5 is so oriented as to make equal angles with the incident rays I and II. In such an arrangement, ray I returns to the polarizer 3 parallel to the initial direction of ray II, while ray II returns parallel to the initial direction of ray I. When no voltage is applied to the cell (Fig. 2a), the deflection of both rays from the initial direction of incidence on the polarizer 3 (along the resonator axis) is [8]

$$\delta = \Phi(n_0 - n_e). \tag{5}$$

Here Φ is the bevel angle of the wedge, and n_0 and n_e are the refractive indices of the ordinary and extraordinary rays in the wedge material (Iceland spar). When $\Phi = 30°$, we have $\delta \approx 29'$ for $\lambda = 1060$ nm. In the position shown in Fig. 3a, the shutter is closed. When a voltage is applied to the cell and produces a path difference $\lambda/4$, rays I and II interchange polarization direction after the second passage through the cell to the left, and in accordance with the correspondence principle they emerge from the polarizer 3 on the left parallel to the resonator axis. In the position of Fig. 3b, the shutter is open.

We investigated the characteristics of a laser operating in accordance with the described scheme, using an active element of silicate glass 120 mm long and 50 mm in diameter, and a helical pump lamp. The temporal characteristics were measured with the aid of an FEU-22 photomultiplier and an S1-11 oscilloscope. The output power of the generator reached ~ 20 MW, the signal consisted of one pulse of ~ 20 nsec duration at the 50% level, and ~ 30 nsec at the 10% level. The dependence of the signal duration on the pump energy (which was 1—1.8 times the threshold energy) and on the length of the plane-parallel resonator (0.6—1.25 m) was weak. The polarization of the laser emission had no predominant direction.

The foregoing results offer evidence that a neodymium-glass laser with unpolarized radiation has high efficiency. The obtained data agree with the qualitative model in which the modes in the laser emission interact with the active ions.

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