INVESTIGATION OF NEODYMIUM-GLASS LASER EMISSION BY THE MOVING-ACTIVE-MEDIUM METHOD

B. L. LIVSHITZ and A. T. TURSUNOV

Institute of General and Inorganic Chemistry, Academy of Sciences, U.S.S.R.

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The moving-active-medium method is used to show experimentally that the random structure of the neodymium-glass laser emission spectra is due to the spatial inhomogeneity of the resonator-mode field and to the resulting separation of the working volumes of the various modes.

1. INTRODUCTION

THE spectral properties of neodymium-glass lasers are fairly distinct.[1-3] The nature of the observed regularities in the spectrum of these lasers is still unclear. First of all this concerns the random distribution of generation bands in the vicinity of the luminescence-curve maximum, which has a half-width of the order of several hundred Å and lies in the 1.06 μ region. The width and intensity of these bands are just as irregular as their parameter of discreteness. The purpose of this paper is to show that the random structure of the spectrum is based on the spatial inhomogeneity of the mode field with respect to the active centers.

It is widely thought that there is a strong inhomogeneous broadening of the working Nd^{3+} transition in glass at a relatively narrow homogeneous width. This concept, stemming from the impression of chaos in the emission spectrum of the neodymium-glass laser and representing an attempt to reduce the problem to an array of weakly interacting lasers operating within the same resonator, can be definitely discarded because of another feature of the generated spectrum. This feature consists in the fact that the growth of the total width of the stimulated-emission spectrum with increasing pumping gradually slows down to a point where, beginning with certain values of pump power, the total width of the spectrum reaches its limiting value of 100–130 Å.[4] If the homogeneous broadening of the active centers were of the order of 1 = 10 Å, it would mean that the generating group of active centers adjoins another group whose luminescence intensity differs little from that of the already generating group and which does not participate in generation even when the pump power is raised to levels known to exceed the threshold for these centers (see also [5]).

It should be noted that certain considerations were recently advanced in favor of a larger homogeneous width, i.e., of the order of 100–150 Å.[6]

If we assume that the theory of spectra of lasers with homogeneously broadened luminescence lines[7] is applicable to the neodymium-glass laser, we may postulate the following possible mechanism of the random structure of the laser emission spectrum: In the model of an ideal laser with frequency-independent losses and a homogeneously broadened luminescence line the axial-mode gain varies monotonically in accordance with the monotonic variation of luminescence intensity and owing to the partial separation of the working volumes of the modes, caused by their spatial inhomogeneity.[7] This results in a successive excitation of axial modes with increasing pump power and leads to a parabolic distribution of their intensities, with a peak located at the maximum of the Lorentz curve when the resonator is suitably tuned.

In real lasers, however, the inverted population n(z), where z is the resonator axis, is a random function. Since the gain is proportional to n(z), its monotonic variation due to monotonic but small (for broad luminescence lines) variation of luminescence intensity observed as we go from mode to mode can be disturbed by fluctuations of the inverted population in the working volumes of these modes. The fluctuations of the population inversion can be of a static nature, owing to conditions of impurity distribution in the specimen or to pumping inhomogeneity, or they can also be caused by dynamic factors such as ultrasonic oscillations. Therefore the fluctuations of population inversion can impose a random characteristic on the gain as a function of mode frequency even if the luminescence intensity varies monotonically, thus resulting in some randomness of the spectrum. The necessary condition of such an effect is the separation of the working volumes of the modes and consequently the spatial mode-field inhomogeneity that causes the separation. It follows that a total or partial elimination of the separation of the working mode volumes should cause the spectrum to assume a regular character governed by the shape of the luminescence line $g = g(\nu)$ and of the loss curve $\gamma = \gamma(\nu)$.

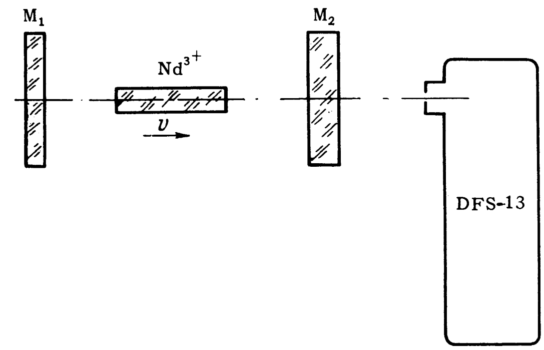

FIG. 1. Experimental setup. Nd^{3+} – glass rod doped with Nd^{3+}; M_1 and M_2 – plane dielectric mirrors, DFS-13 – spectrograph.

2. EXPERIMENTAL SECTION

One of the most effective methods of smoothing the spatial inhomogeneity of the mode field with respect to the active centers is to move the active medium along the resonator axis.[7,8,9] This is the method we used to verify the above hypothesis concerning the nature of randomness in the neodymium glass laser spectrum.

The experimental setup is shown in Fig. 1. We used a glass (baryte crown) rod doped with Nd^{3+}. The spectra were recorded on I-1030 photographic film with a DFS-13 spectrograph having a linear dispersion of 4 Å/mm. The distance between mirrors was $L = 60$ cm, the rod length was $l = 8$ cm, and the reflection coefficients of plane mirrors M_1 and M_2 were $r_1 = 99.1\%$ and $r_2 = 94.5\%$ respectively. The mirror substrate thickness was $d_1 = 4$ mm and $d_2 = 8$ mm. The flash reflector could be moved together with the rod with a maximum velocity of $v \sim 1$ m/sec; the resulting detuning of the system increased the generation threshold to a negligible extent.

Figure 2 shows photographs of the emission spectra obtained with the rod at rest (a), and with the rod moving at $v = 60$ cm/sec (b). In both cases the ratio of pump W_p to threshold W_t energies was the same, i.e., $W_p/W_t = 1.26$. We see that the randomness of the spectrum observed in case (a) vanishes when the rod moves and is converted into a spectrum of equidistant bands with a period $\Delta\nu = 0.82$ cm^{-1} that is approximately 10^2 times larger than the characteristic mode period $\delta\nu = 0.01$ cm^{-1} corresponding to the above dimensions of the system.

An increase in pump energy does not change the period and merely broadens the generation bands (Fig. 2c). A change in the resonator length (Fig. 2d) also fails to affect the period.

However doubling the substrate thickness d_1 of mirror M_1 cuts the period in half (Fig. 2e). According to Snitzer,[4] this means that the substrate modulates the resonator losses $\gamma(\nu)$ with a period

$$\Delta\nu_1 = 1/2\, d_1\mu, \qquad (1)$$

where μ is the refractive index of the glass substrate of the mirror. When $d_1 = 4$ mm, the value of $\Delta\nu_1$ computed from (1) is equal to 0.82 cm^{-1}, coinciding with the experimentally observed period $\Delta\nu$ (Fig. 2b–d). The substrate of mirror M_2 apparently also modulates the resonator losses with a period $\Delta\nu_2 = \frac{1}{2} d_2\mu$; however, since $r_2 < r_1$, the modulation depth is lower here[4] so that the period $\Delta\nu_1$ of the deeper modulation is decisive in $\gamma(\nu)$.

Discussion of Results

Since with the rod fixed we observed a random generation spectrum regardless of the loss modulation present in the laser system, it means that the relative fluctuations of the population inversion in the working mode volumes are comparable with the relative depth of loss modulation $\gamma(\nu)$. If the randomness in the emission spectrum were due to small random pulsations of the luminescence curve,[10] undetected even by instruments with a high resolving power, then the motion of the rod would not be capable of removing the random elements from the generation spectrum. However, the experiment (Fig. 2b) shows that the motion of the active medium is accompanied by a rigorously periodic spectrum with a bell-shaped intensity distribution.

We must therefore conclude that, first, the above experiment supports the hypothesis that the random nature of n(z) is instrumental in the formation of the random structure of neodymium glass laser spectrum and, second, we can assert that in neodymium glasses the luminescence curve is smooth and is characterized by a monotonic drop of intensity away from the maximum.

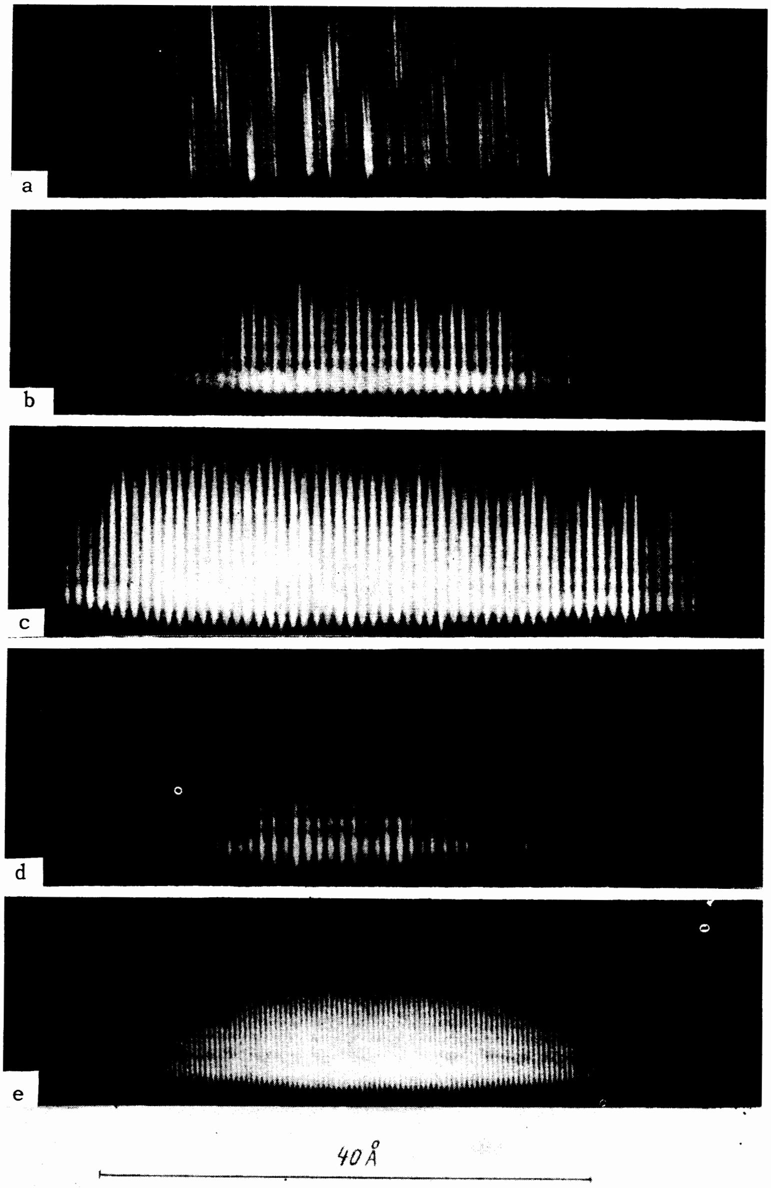

FIG. 2. Emission spectra of neodymium glass laser. a – fixed rod; b - e – moving rod; c – increased pumping; d – increased resonator length, e – identical thick substrates for mirrors, $d_{1,2} = 8$ mm.

It should be noted that an increase in the depth of modulation by using mirror substrates of equal thickness ($d_1 = d_2$) results in an approximate periodicity in the emission spectrum even if the rod is fixed (Fig. 3a, $d_1 = d_2 = 4$ mm). The band intensity, however, still remains irregular. The motion of the rod again creates a distinct periodic spectrum with the characteristic bell-shaped intensity distribution (Fig. 3b).

Returning to the above hypothesis, we can also note another possible cause of randomness of the bands in the laser emission spectrum. The fluctuation of population inversion can be accompanied by fluctuations of various mode losses due to the inhomogeneity of internal losses within the medium. We shall now show that this dispersion of passive losses in lasers occurs in the presence of spatial inhomogeneity of the mode field and, in contrast with the dispersion of active losses, does not depend in the first approximation on the field structure in the resonator.

The role of the spatial inhomogeneity in the formation of the dispersion of passive losses in lasers can be explained by means of the kinetic equations.

The equation for the number of photons in the i-th mode is usually written in the axial model as follows (see, for example, [7]):

$$\frac{dN_i(t)}{dt} = -\gamma_i N_i(t) + \int_0^L D g_i N_i(t) n(z, t) \left(1 - \cos\frac{2\pi m_i z}{L}\right) dz, \quad (2)$$

where $N_i(t)$ is the number of photons in the i-th

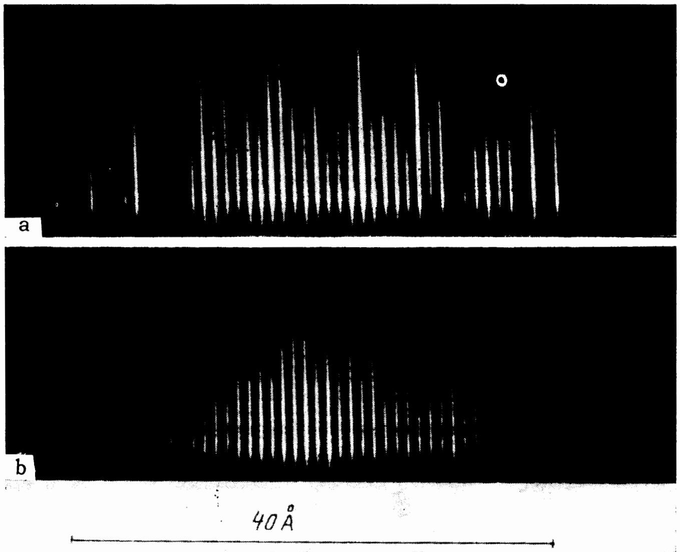

FIG. 3. Laser emission spectra obtained with identical thin mirror substrates. a – fixed rod; b – moving rod.

axial mode, γ_i is the loss coefficient in the i-th mode per unit time, Dg_i is a coefficient proportional to the probability of stimulated transition in the i-th mode, L is the optical length of the resonator, and $m_i = 2L/\lambda_i$, where λ_i is the wavelength of the i-th mode.

In the presence of inhomogeneous internal losses $\tilde{\gamma}_i(z)$, the loss coefficient in layer (z, z + dz) equals

$$d\gamma_i(z) = [\gamma_{0i}^0/L + \tilde{\gamma}_i'(z)]\,dz, \tag{3}$$

where γ_{0i}^0 is the coefficient of active losses in the i-th mode. The total losses in the i-th mode are expressed by the integral over the length of the resonator:

$$-\gamma_i N_i(t) = -\int_0^L d\gamma_i(z) N_i(t)\left(1 - \cos\frac{2\pi m_i z}{L}\right)dz, \tag{4}$$

in which the factor $1 - \cos 2\pi m_i z/L$ describes the spatial structure of the i-th mode. Transforming (4) and taking account of (3), we obtain

$$\gamma_i = \gamma_{0i}^0 + \int_0^L \tilde{\gamma}_i'(z)\,dz - \int_0^L \tilde{\gamma}_i'(z)\cos\frac{2\pi m_i z}{L}\,dz. \tag{5}$$

If the density of internal losses is independent of the frequency, we have

$$d\gamma(z) = \left[\frac{\gamma_0^0}{l} + \tilde{\gamma}'(z)\right]dz.$$

Nevertheless, the total losses in the i-th mode depend on its number according to (5):

$$\gamma_i = \gamma_0^0 + \int_0^L \tilde{\gamma}'(z)\,dz - \int_0^L \tilde{\gamma}'(z)\cos\frac{2\pi m_i z}{L}\,dz, \tag{6}$$

or

$$\gamma_i = \gamma_0 - \gamma(i), \tag{7}$$

where

$$\gamma_0 = \gamma_0^0 + \int_0^L \tilde{\gamma}'(z)\,dz, \tag{8a}$$

$$\gamma(i) = \int_0^L \tilde{\gamma}'(z)\cos\frac{2\pi m_i z}{L}\,dz. \tag{8b}$$

It follows from (7) and (8) that if the active losses and the density of the internal losses are independent of frequency, i.e., if $\gamma_{0i}^0 \equiv \gamma_0^0$ and $\tilde{\gamma}_i'(z) \equiv \tilde{\gamma}'(z)$, then the total losses contain the dispersion term $\gamma(i)$ described by (8b). If $\tilde{\gamma}'(z) \neq \text{const}$, i.e., if the internal losses are inhomogeneous, $\gamma(i) \neq 0$.

When the active medium moves we have

$$\gamma(i) \equiv \gamma(i, t) = \int_0^L \tilde{\gamma}'(z)\cos\frac{2\pi m_i(z + vt)}{L}\,dz. \tag{9}$$

Averaging (9) over t for the period t_0 during

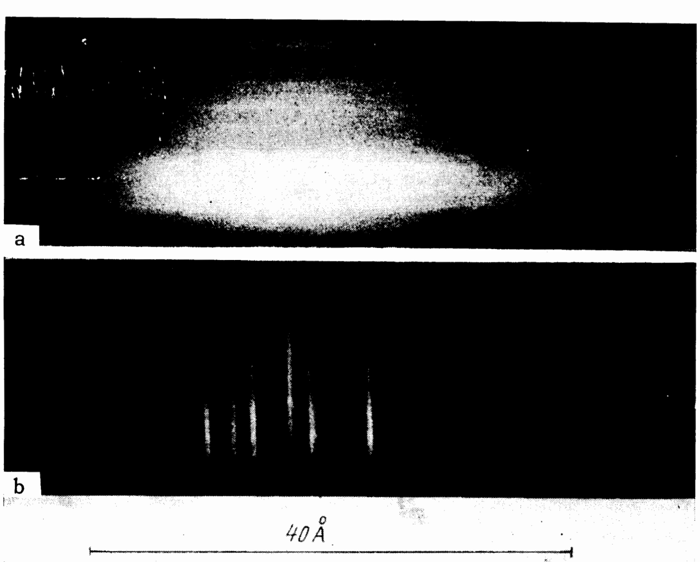

FIG. 4. Laser emission spectra obtained with nonparallel substrate surfaces for mirrors. a – fixed rod; b – moving rod.

which $N_i(t) \approx$ const, provided that $2\pi m_i v t_0/L \approx 2\pi$, or

$$v \approx \frac{L}{m_i t_0} \approx \frac{\lambda}{2t_0} \tag{10}$$

(λ is the wavelength of laser emission), we obtain the result that $\gamma(i) = 0$.

Condition (10), which causes the dispersion of the passive losses to vanish, yields in the case of a free running neodymium-glass laser ($\lambda \approx 10^{-4}$ cm, $t_0 \approx 10^{-5} - 10^{-6}$ sec):

$$v \approx 10 \div 100 \text{ cm/sec}$$

The proposed mechanisms do not exhaust all the possibilities. Nevertheless, any mechanism that creates a random structure of the laser emission spectrum (regardless of the nature of the luminescence line emitted in laser action) is based on spatial inhomogeneity of the mode field with respect to active centers, since the smoothing effect caused by the active medium moving in the direction of the field inhomogeneity results in a regular emission spectrum. This is the main conclusion that follows from the above experimental results.

We should note that if the above considerations are valid, then elimination of the dispersion in the active resonator losses should give rise to continuous generation spectra with a bell-shaped intensity distributions (the term "continuous" is understood of course to mean a consecutive sequence of axial mode indices). This was confirmed by a control experiment in which we replaced the plane parallel mirror substrates by wedges (within the limits of the resolving power of the DFS-13 spectrograph, which was ~ 0.1 cm^{-1}). Figure 4 shows the laser emission spectra for a fixed rod (b) and a rod moving at 80 cm/sec (a) (the mirror substrates consisted of $\sim 1°$ wedges).

In conclusion we note that the random structure should be a universal property of the emission spectra of solid-state lasers. The randomness in the laser spectra can be removed, retaining the high directivity of the emission, by moving the active medium without disturbing the resonance structure of the field within the resonator.

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