SOVIET PHYSICS JETP VOLUME 28, NUMBER 1 JANUARY, 1969

GENERATION KINETICS, RADIATION SPECTRUM, AND DIRECTIVITY OF A RUBY LASER WITH A SPATIALLY HOMOGENEOUS INVERTED POPULATION

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Submitted February 9, 1968

Zh. Eksp. Teor. Fiz. 55, 122–129 (July, 1968)

An experimental investigation is carried out on the time dependence of the intensity, width, and structure of the spectral line and of the directivity and structure of the transverse distribution of the radiation from a ruby laser with plane mirrors in which a smoothing out of the spatial inhomogeneity of inversion due to the field distribution of the standing waves of the modes occurs. Regular generation kinetics with a spectral width $\leq 0.05\ \mathrm{cm}^{-1}$ is obtained over a range in which the threshold pumping is exceeded by 1.5 to 3 times. Deviations from the generation kinetics described by the solution of the balance equation are detected which are due to competition between modes with different transverse subscripts and to fluctuations in spontaneous emission. The causes of increase of the number of modes generated in a spike are discussed. An increase of the efficiency of selecting elements in the resonator under the investigated generation conditions in the laser is noted. It is found that under these conditions there is no frequency shift due to heating of the active rod.

INTRODUCTION

As has been shown by investigations of the free generation regime of a ruby laser (see, for example,[1,2]), the basic cause of the relatively wide spectrum (of the order of $1\ \mathrm{cm}^{-1}$) and irregular kinetics is the spatial inhomogeneity of the inverted population in the active medium due to the distribution of the fields of the standing waves of the generated modes. Under conditions when such inhomogeneity in the generation process is eliminated to some degree (e.g., by excitation of a large number of modes in a laser with a concentric resonator,[1,3] by the method of circularly polarized standing waves,[4] by moving the active medium in the resonator[5,6]) or its effect is neutralized by mode selection,[7] the generation regime agrees in its main features with that obtained from solution of the balance equations.[1] [10,11] This is obviously explained by the fact that such a regime is close to the model accepted in the cited papers, where it is assumed that there is a homogeneous distribution of the field in the active medium and excitation of one mode, and spontaneous emission is not taken into account. The last two assumptions evidently cause a disparity with experiment as regards, in particular, the dependence of the rate of establishment of the stationary regime on pumping power.[12] An analysis with these factors taken into account was carried out in [13,14], where it was shown that spontaneous emission can lead to irregularity of pulsations in the initial stage of generation, to a decrease in the rate of their decay with increased pumping for a large number of excited modes, and also to its increase with increase in the number of modes. However, experimental results were obtained in [15] which contradict the last conclusion. As far as we know, only the case of the concentric resonator has been investigated thoroughly by experiment.[16]

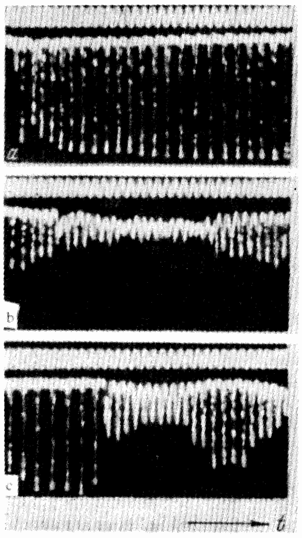

FIG. 1

In view of the above, as well as from a purely practical point of view (narrow spectrum, regular kinetics), it is of importance to investigate further the generation regimes of lasers under conditions when the spatial inhomogeneities are smoothed out. This paper communicates the results of an experimental investigation of the spectrum, kinetics, directivity, and coherence of the radiation of a ruby laser in which smoothing of the inversion inhomogeneity was effected by the authors and Krivoshchekov.[16]

EXPERIMENT

We used a laser with a ruby rod 120 mm long and 7 mm in diameter in a sapphire shell. The mirrors were plane, with reflection coefficient 0.96. The optical length of the path between the mirrors was 70 cm. On both sides of the active rod were placed KDP crystal

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[1] As was shown in [8,9], the general equations for the vectors of the field intensity and polarization of the medium reduce to these equations in the case of ruby.

plates such that the light beam passed perpendicularly to the (110) cleavage surface and its electric field intensity vector lay in the XY crystallographic plane. To both plates were fed oppositely phased sinusoidal electric fields of frequency f and amplitude E, directed along the crystal Z axis. Upon fulfillment of the condition

$$1/f \gg L/c, \tag{1}$$

where L is the length of the resonator and c is the speed of light, the principle of the action of this system can be approximated in the following way.

Under the action of the applied field the indices of refraction of the plates n varies by an amount $\pm\Delta n$. Thus, for an unchanged optical length of the resonator, the field pattern of the standing wave will be shifted during a half-period, 1/f, with an average rate equal to $4fl\Delta n$ (l is the length of the crystal plates). In order to effectively establish the formation of spatial inhomogeneity of inversion, it is necessary that this shift, during a time of the order of establishment of oscillations in a spike τ should be not less than the length of the standing wave in the active medium with refractive index n_m, i.e., the following condition should be fulfilled:

$$f\Delta n > \lambda / 8\tau l n_m \tag{2}$$

The relations (1) and (2) determine the requirements on the frequency and amplitude of the modulating field. In our experiment, $f = 5 \times 10^6$ sec^{-1}, $l = 60$ mm, $E \approx 2 \times 10^3$ V cm^{-1}. If one determines Δn from a known method based on the electrooptical effect[16] and takes $\tau = 5 \times 10^{-7}$ sec (the magnitude usually observed in practice), then calculation shows that the left-hand side of (1) is two orders and of (2), one order, larger than the righthand side.

In our work we investigated the integrated spectrum with an IT-51-30 etalon and the changes in the spectrum during generation, for which a slit scan of the interferogram was photographed with an SFR-2 apparatus. The spatial coherence was investigated by framewise photography with the SFR-2 of the interference pattern from two slits of width 0.15 mm, 5 mm apart at the output mirror. We investigated the distribution of radiation in the near and far zones and its development in time, for which, in the first case, the slit was located in the image plane of the output mirror, and in the second, in the focal plane of the input objective of the SFR-2.

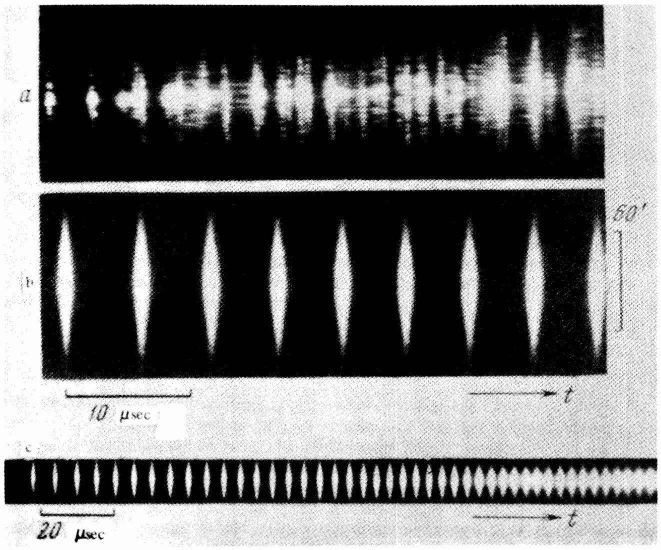

FIG. 2

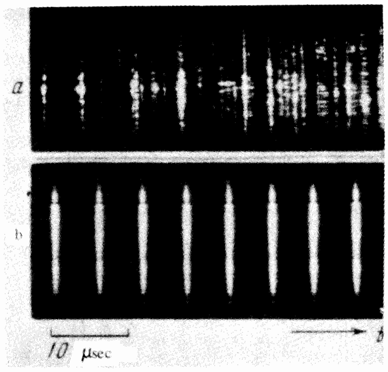

FIG 3.

RESULTS

In the overwhelming majority of the registered flashes of generation (about 200 in all) the generation kinetics was as predicted by the balance equations[10,11] as pumping varied from 5% to three times in excess of threshold; that is to say, it consisted of decaying regular pulsations with monotonically increasing frequency and length as the constant component increased. Figure 2c shows a typical time scan of the radiation distribution in the far zone (first third of the duration of generation). However, the rate of decay of the pulsations varied by 3 to 5 times from flash to flash for the same pumping energy, and no definite dependence of the rate on the pumping level was observed. As a rule, it was positive in the first half of generation and changed sign in the second half. In a number of cases it was negative almost from the very beginning of generation (Fig. 1a) or changed sign and magnitude gradually or suddenly several times during a single flash (Fig. 1b, c, first third of generation). The stepwise change always occurred from a level with small constant component. The average frequency of spike succession compared to the usual generation regime ($E = 0$) decreased by 4 to 8 times depending on the pump level, and their average duration increased 2 to 3 times. The generated energy and pumping threshold remained constant to within ±3%.

Figure 2 (a, b) shows time scans of the radiation in the far zone and Fig. 3, at the mirror (in both cases, pump level twice threshold, beginning of generation) for the case $E = 0$ (a) and $E \neq 0$ (b). As is seen, in the ordinary regime generation begins from spikes with small divergence and small volume of excitation. This was noted in[17], where it was pointed out that generation first begins in a small volume on account of pumping inhomogeneity, and since, as was established in the same paper, modes of a spherical resonator are generated in a laser with plane mirrors, small divergence

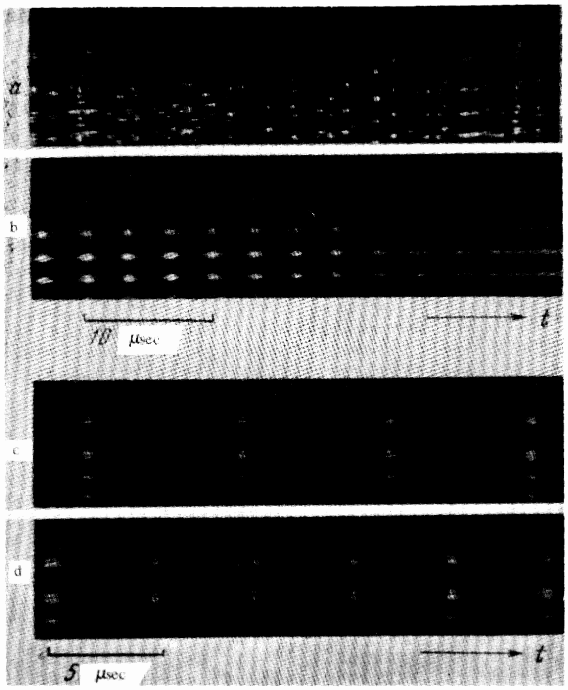

FIG. 4

goes along with modes with small volume. In the case E ≠ 0, as can be seen from the photographs here, modes with large transverse subscripts are excited already in the first spike. As shown by photometry, the spindle-shaped form of the spikes in Fig. 2b reflects a change in divergence of the radiation during generation of the spike. Consequently, the greater the transverse subscript of the mode, the later it breaks out into generation and the earlier it dies. This is confirmed by the character of the time dependence of the radiation distribution at the mirror (Fig. 3b), which shows that generation first arises in a small volume, then propagates over all of it, and at the end of the spike the volume of excitation is again reduced. Figure 3b also shows that there exist at least three independent generation regions, which is evidently due to pumping inhomogeneity.

Investigation of the spatial coherence showed that the disappearance of a discrete structure in the field distribution in the near and far zones in the case E ≠ 0 is due, as in [2] (where, however, a concentric resonator was used) to excitation of a large number of transverse modes. If in the interference pattern from two slits sharp bands are seen for E = 0, then when E ≠ 0 they are completely washed out.

Fluctuations in divergence from spike to spike completely disappeared when E ≠ 0. The total angle of divergence of the radiation measured at half-intensity varied from 4 to 36′ when the pumping level was respectively 1.05 and 2 times threshold and from 60 to 80′ at the 0.1 intensity level under the same pumping conditions. The latter figures show that an important increase in the transverse subscript of the generated modes does not occur.

Figure 4a gives a time scan of the spectrum for the case E = 0 and Fig. 4b for E ≠ 0. The dispersion region of the etalon was 0.2 cm^{-1}. The pumping level was twice threshold. From the comparison it is seen that the spectral width of radiation generated in the spike in the regular regime is greater, as a rule; however, the frequency jumps from spike to spike completely disappear, as a result of which the integrated width of the spectrum is decreased by more than an order of magnitude and amounts to $\leq 0.05\ \text{cm}^{-1}$ at half-height, as measured by photometry.

As is seen from Fig. 4b, no marked change in the spectrum occurs during the decay of the oscillations. Measurements showed that its width decreased by about 10% during decay of the oscillations to the level of the constant component.

In Fig. 4c, d are given scans of the spectrum for cases when the pump power exceeded threshold by respectively 1.5 and 3 times. It is clearly seen that the same modes generate (6 to 7 in all; the gap is evidently due to random selection in the resonator).

DISCUSSION

The results obtained can be explained in the framework of the following model of the dynamics of the laser investigated. As was shown in [17], optical inhomogeneities in ruby arising during its growth, as well as nonuniform heating during pumping, significantly affect the excitation of modes. Obviously, these inhomogeneities may have a random spatial distribution. Considering that the field of the standing wave of a mode is not distributed uniformly in space, it is natural to suppose that the difference in action of these inhomogeneities in combination with fluctuations in spontaneous emission in different modes will play an important role at the stage of origin and linear development of the modes (when it is possible to neglect competition between them). The modes first reaching the stage of nonlinear development (spike generation) lift the inversion, thereby preventing the remaining modes from breaking out into generation. This explains why there are only a few modes radiating in a spike in the free generation regime.

In the investigated case the spatial distribution of the fields of the modes becomes uniform to a marked extent; hence all the enumerated factors act on each of them equally, which evidently leads to simultaneous generation of a large number of modes. This is confirmed by the results of the investigation of the coherence, by the disappearance of discrete structure of the radiation distribution in the near and far zones, and also by the fact that the spectrum in the spike is, as a rule, wider in the regular regime.

Modes with small transverse subscripts have a larger Q and therefore break out earlier, as shown by the spindle-shaped form of the spikes in Fig. 2b, c. The fact that such a sequence of excitation of modes in a spike is less expressed in the case E = 0 (Fig. 2a), is also probably an indication of the influence of the factors enumerated above again, along with the effect of Q.

Since the inversion is lifted uniformly over the entire length of the active rod, the stepwise change in frequency from spike to spike disappears and the kinetics becomes regular. Its deviation from that described by the solutions of the balance equations can evidently be explained in the following way. Sharp jumps in the rate of decay of the oscillations always occur from a level with small constant component. This corresponds to the skipping from one dynamic trajectory to another under the influence of spontaneous emission, an effect predicted in [14]. It is also known (see, for example,[13]) that the time of decay of oscillations decreases with increasing Q and near the stationary regime is expressed by the formula

$$t_0 = 2 / WBt_c,$$

where W is the pumping rate, B is the Einstein coefficient, and t_c is the time constant of the resonator. Hence for modes with higher Q the oscillations will decay more rapidly. Then as the constant component increases, the frequency of pulsation for these modes will increase, and thus modes with higher transverse subscripts will emit in the spikes less and less as time goes on. However, on account of several different volumes of excitation, this leads to accumulation of inversion in that region of the active medium that is not common to the two groups of modes. And this, in its turn, leads, beginning at a certain time, to the threshold conditions again beginning to be fulfilled for modes with ever increasing transverse subscripts. The volume of excitation of the latter includes the volume of excitation of modes with higher Q, and the competition between them may lead to a smooth change in the sign of the rate of change of the constant component of the radiation in these modes (Fig. 1b, c). The above considerations are confirmed by the results of photometry, which showed a decrease of divergence in the spikes and a reduction of the dimensions of the excitation region at the mirror with an increase in the constant component. The divergence of the constant component of the radiation between spikes is approximately 1.5 times less than in a spike.

Measurements made at pumping energies from 1.8 to 2.5 kJ (threshold 1.2 kJ) for ten generation flashes did not disclose any significant shift of the center of gravity of the spectrum on account of heating of the ruby. As is known, the principal reason for this shift is the shift of the luminescence line, which occurs with the rate of 0.13 cm^{-1} per degree.[18] According to [19], ruby with a chromium concentration of 0.03% (it was 0.026% in our experiment) will be heated 1°C during the generation time (for a change in the integral of the pumping power from threshold to 2.5 kJ). Even if the heating amounted to only 0.5°C because of design differences, the shift would have been 0.065 cm^{-1} and should have been noticed in the etalon dispersion region of 0.2 cm^{-1}. The absence of this shift is evidently explained by the fact that generation in each successive spike begins from a level of constant component containing the same frequencies that were generated in the preceding spike.

The number and arrangement of the generated modes (Fig. 4c, d) are probably a result of random selection in the resonator. The fact that they do not vary with a significant change in pumping level is due to the fact that in the laser investigated (since isolated modes will lift the inversion over the whole volume) the efficiency of selective elements ought to increase greatly.

In conclusion, it should be mentioned that changing the frequency and amplitude of the modulating voltage within the limits ±50% while satisfying the inequalities (1) and (2) had no noticeable effect on the parameters of the output radiation.

The authors are grateful to S. G. Rautian and A. M. Leontovich for helpful advice and discussions, to G. V. Krivoshchekov for his interest in the work, and to B. N. Anikeev for assistance in the experiments.

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Translated by L. M. Matarrese
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