Effect of Redistribution of Energy Density in the Cavity on Laser Generation

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The effect of spatial distribution of mode energy in a plane resonator on stimulated laser emission is investigated experimentally and theoretically. The time and spectral modulation of the emission resulting from the displacement of the dielectric boundaries within the cavity are studied. The results shed light on some features of generation kinetics of solid-state lasers.

ACCORDING to experiments reported by a number of authors[1-3], the time and spectral regimes of stimulated emission in optical plane resonators with external mirrors depend significantly on whether the active medium is fixed or moves axially. It was shown earlier[4,5] that displacement of internal dielectric boundaries parallel to the mirrors (in particular, due to heating) causes a periodic variation of the spatial distribution of mode energy in the resonator. This energy redistribution is largely responsible for the spectral and time generation regimes[4-8].

The present paper deals with experimental and theoretical study of generation kinetics accompanying the redistribution of energy density within the resonator.

In our experiments energy is redistributed by moving a plane dielectric layer (selector), with faces parallel to the mirrors[4], along the resonator axis while the active medium is fixed. The fixed active medium reduces the effects due to the motion of active centers relative to the electromagnetic field of the resonator.

We used the laser design shown in Fig. 1. The faces of the active medium were cut at the Brewster angle α_B to the mirrors to eliminate the effect of the active-medium boundaries[5].

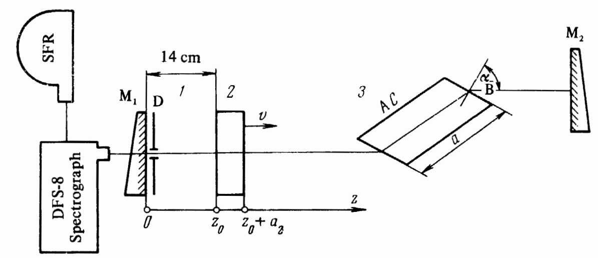

FIG. 1. Diagram of the experimental setup. M_1, M_2—plane mirrors of resonator; AM—active medium; a—length of active medium.

I. THEORY

1. Our theoretical analysis is limited to those natural oscillations of the resonator field (axial modes) for which the wave vector $k_i = 2\pi\lambda_i^{-1}$ (λ_i is the emission wavelength) coincides with the z axis outside the active medium and is inclined to the z axis at an angle $2\alpha_B - \pi/2$ inside the medium. Furthermore we neglect the axial mode frequency variation[5] due to the selector motion, assuming that $k_i = \pi L_0^{-1} i$ ($i = 1, 2, 3, \ldots$) where L_0 is the optical length of the resonator (along the broken line M_1M_2). According to an estimate, the displacement of a glass selector can produce at most change of $\sim 0.03\lambda_i$ in the position of mode nodes and antinodes in the center of the resonator when k_i is changed. The shifts of the nodes and antinodes decreases as mirror M_2 is approached.

As pumping intensity increases, generation occurs in those modes for which $\bar{n}_i$ (average linear inverted-population density for the i-th mode[5]) reaches the threshold value of n_i^n.

The threshold value n_i^n is proportional to the ratio of losses of the i-th mode to the probability of stimulated emission in it. Let us assume that there are no absorption and scattering losses in the selector. The i-th mode losses are then proportional to $\gamma_1 W_1^i + \gamma_3 W_3^i$ and the stimulated emission probability proportional to $g_i W_3^i$. Here W_1^i, W_3^i and γ_1, γ_3, are the energy density and loss coefficients respectively in regions 1 and 3 (Fig. 1) (γ_1 and γ_3 are independent of the mode number), while g_i is the luminescence line intensity at the frequency of the i-th mode. Therefore

$$n_i^n = \frac{A}{g_i}\left(\frac{W_1^i}{W_3^i} + \xi\right), \quad \xi = \frac{\gamma_3}{\gamma_1}, \tag{1}$$

where A is a constant independent of the selector position.

2. According to[4] the ratio of energy density of the axial modes in regions 1 and 3 is

$$\frac{W_1^i}{W_3^i} = \frac{1 - \chi\cos 2k_i(z_0 + \mu_2 a_2)}{1 - \chi\cos 2k_i z_0}, \quad \chi = \frac{\mu_2^2 - 1}{\mu_2^2 + 1} \tag{2}$$

and consequently

$$n_i^n = \frac{A}{g_i}\left[\frac{1 - \chi\cos 2k_i(z_0 + \mu_2 a_2)}{1 - \chi\cos 2k_i z_0} + \xi\right] \tag{3}$$

Here z_0 is the distance from mirror M_1 to the selector, a_2 is the thickness of the selector, and μ_2 is its refractive index.

Thus the ratio W_1^i/W_3^i and therefore also n_i^n changes with z_0. The range of variation of W_1^i/W_3^i for a given axial mode depends on k_i, μ_2, and a_2, with the following results:

a) If the selector subtends an even multiple of $\lambda i/4\mu_2$ (even modes), then $W_1^i/W_3^i = 1$ and the threshold for these modes does not change when the selector is moved.

b) If the selector subtends an odd multiple of $\lambda_i/4\mu_2$, then for such modes (j), which we call odd, we have $\lambda_j = 4\pi_2 a_2/(2j' + 1)$, where j' is an integer. The frequency interval between such neighboring modes is $\Delta\nu_0 = (2\mu_2 a_2)^{-1}\ cm^{-1}$. The ratio W_1^i/W_3^i varies from μ_2^{-2} to μ_2^2 and thus the threshold n_j^n depends significantly on the position of the selector, varying from $(n_j^n)_{min}$ to $(n_j^n)_{max}$ when the selector is displaced by $\lambda_j/4$. If $\xi = 0$, then $(n_j^n)_{max}/(n_j^n)_{min} = \mu_2^4$.

c) If the selector subtends a fractional multiple of $\lambda_i/4\mu_2$, then the range of values of W_1^i/W_2^i and the ratio $(n_j^n)_{max}/(n_j^n)_{min}$ have intermediate values between cases (a) and (b).

If $L_0 \gg \mu_2 a_2$, the axial modes of the resonator always include modes whose frequencies are sufficiently close to (or coincide with) the frequencies of the odd modes.

According to (3) the lowest (highest) threshold occurs in the odd mode when the electric-field antimode (node) falls on the left face of the selector. No lower (higher) threshold (or rather $n_i^n g_i$) can occur in any other mode.

Consequently the dielectric layer acts as mode selector and, for a given position of the selector, the frequency interval between axial modes with the lowest threshold is a multiple of $\Delta\nu_0$. For example, for $z_0 = m\mu_2 a_2$ the lowest (when m is odd) or the highest (when m is even) generation threshold occurs simultaneously in all odd modes (selection with period $\Delta\nu_0$). For $z_0(j) = (m + \frac{1}{2})\mu_2 a_2 - \lambda_j/8$, the odd modes have the lowest threshold when $m + j$ is odd and the highest threshold when $m + j$ is even. If the odd modes of interest are situated in the wavelength interval $\lambda_{j0} \pm \Delta\lambda$, then $|z_0(j) - z_0(j_0)| \le \Delta\lambda/8$. In the case $\Delta\lambda/2\lambda_{j_0} \ll 1$ (in generation of Nd^{3+} in glass, $\Delta\lambda/2\lambda_{j_0} \sim 10^{-3}$) $z_0(j) \approx z_0(j_0)$ and the odd modes with the lowest threshold for $z_0(j_0)$ fall on every other mode location (selection with period $2\Delta\nu_0$).

3. In generation the linear inverted-population density $\overline{n}_i$ of the i-th mode for nongenerating modes depends not only on the pumping intensity but also on the spatial distribution of the generating mode fields. Consequently the sequence of modes starting to generate as the pumping power increases may fail to coincide with the sequence of increasing values of n_i^n. However, it can be shown that if the competition to generate involves modes with significantly different numbers, $|i_1 - i_2| \gg 1$ (for example, $|j_1 - j_2| \ge 200$ for odd modes j with $\mu_2 a_2 = 0.3$ cm, and $L_0 = 60$ cm, such modes commence generation in the order of increasing thresholds when the pumping is increased.

In our resonator, small thresholds $(n_i^n)_{min}$ may be possessed by odd and close-to-odd axial modes, such as those whose numbers $i = j \pm \Delta i$ are associated with minimal thresholds $(n_{j\pm\Delta i}^n)_{min}$ (for $g_j \approx g_{j\pm\Delta i}$) that differ comparatively little from the minimum value $n_{j\,min}^n$:

$$\frac{(n_{j\pm\Delta i}^n)_{min} - (n_j^n)_{min}}{(n_j^n)_{min}} = \pi^2 \frac{\mu_2^2 - 1}{\mu_2^2 + 1}\left(\frac{\mu_2 a_2}{L_0}\right)^2 \frac{(\Delta i)^2}{1 + \mu_2^2 \xi}. \qquad (4)$$

The minimum values of thresholds of odd and close-to-odd modes are reached when the electric mode fields have an antinode at the right-hand face of the selector. Therefore simultaneous generation can occur in modes whose antinodes and nodes approximately coincide in

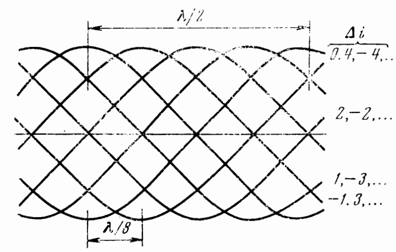

FIG. 2. Spatial distribution of amplitudes of standing waves with adjacent axial indices $j \pm \Delta i$ in the vicinity of $z = L_0/4$.

the region of the selector. Consequently the set of generating (odd and close-to-odd) modes depends on the position of the selector and varies with its displacement. Figure 2 shows the spatial distribution of the standing-wave amplitudes for $z_0 = L_0/4$. It is apparent that simultaneous low thresholds are possessed by modes whose number difference is a multiple of four. The selector locations corresponding to minimum thresholds for neighboring modes differ by $\lambda_i/8$. Near $z_0 = L_0/q$ (where q is an integer) low thresholds may be possessed at fixed z_0 by modes whose numbers differ by q, while for the neighboring modes the selector locations corresponding to minimum thresholds differ by $\lambda_i/2q$.

4. If the selector moves along the resonator axis at the rate v ($z_0 = vt$), with $v \ll \lambda_i c/L_0$ (c is the velocity of light), then the energy density distribution at any instant is determined by the position of the selector at that instant[4]: consequently we may use the results obtained for a fixed selector.

The intensity of each generating mode is modulated[5] with a period $\tau_i = \lambda_i/2v$. This modulation is synchronized in time for all odd modes at $z_0 = m\mu_2 a_2$ and is shifted in time at other values of z_0. The depth of modulation of the odd modes can be very large and when z_0 changes by $\lambda_j/4$ the threshold value of population inversion varies by a factor of μ_2^4 for $\xi = 0$ (by a factor of ~5 in glass). This variation of n_j^n makes generation discontinuous; generation occurs only when z_0 is such that n_j^n for odd and near-odd nodes assumes near minimal values. Generation does not occur at other values of z_0.

At low pump intensities, only modes with the lowest threshold, i.e., odd modes, are capable of generating. Furthermore the number of odd generating modes for a given pump level depends on z_0 and on the half-width of the luminescence line.

5. As we noted above, modes adjacent to the odd modes may have a low threshold whose minimum values (during the motion of the selector) are reached when n_n^j for odd modes is large. These modes ($j \pm \Delta i$) may also generate, provided the time elapsed between the termination of generation of an odd mode and the minimum threshold of the $j \pm \Delta i$ mode is long enough to increase the inverted population in the active medium by a factor $(n_{j\pm\Delta i}^n)_{min} - (n_j^n)_{min}$.

6. Assume that scattering and absorption losses are present in the moving selector. Since the mode energy density in the selector changes by a factor of μ_2^2 as the selector moves through $\lambda_i/4$, mode losses also change with a period τ_i; this also modulates the stimulated-emission intensity.

7. If the optical thickness of the selector is different at different points of its cross section (step-like selector), each region of the cross section (with $\mu_2 a_2 = \text{const}$) has its own set of odd modes, i.e., modes capable of having the lowest generation thresholds. When the imhomogeneity of the optical thickness of the dielectric is $\gtrsim \lambda_i/4$, there will be no frequency selection in the spectrum integrated over the cross section.

8. The above results were obtained on the assumption of parallel mirrors and faces of the selector. If this requirement is not met, the following assumptions can be made, although no detailed analysis has been performed:

a) If the selector faces are inclined at a small angle β to the mirrors, the transverse structure of odd generating modes (near field) has, in the presence of frequency selection with a period equal to a multiple of $\Delta\nu_0$, a periodic character with a linear period of $\lambda_i/2\beta$. As a selector moves along the resonator axis, this structure shifts in a transverse direction and the time scan of the spectrum shows no modulation with period τ_i, provided, of course, the generated-beam diameter is larger than $\lambda_i/2\beta$.

b) If the selector is misaligned by a large angle, the frequency-selection mechanism[9] has a different character and the even modes have the highest Q. In this case the frequency-selection period equals $\Delta\nu_0$ regardless of the position of the selector.

9. If a line with spectrally inhomogeneous broadening is generated, the motion of the selector can transform a "forked" spectrum[10,11] into a spectrum that is continuous in terms of the odd modes.

II. THE EXPERIMENT

1. According to Sec. I above, the redistribution of energy density in the resonator causes considerable changes in both the time and spectral structure of the stimulated emission. We attempted to determine experimentally whether the energy-density redistribution due to the displacement of internal dielectric boundaries is indeed a decisive factor in the operation of lasers with external plane mirrors.

Figure 1 shows a diagram of the experimental setup. The optical length of the resonator is $L_0 = 56$ cm. The active elements were rods of LGS-228-2 glass activated with Nd^{3+}, 8 mm in diameter and 160 mm long. The plane parallel end faces of the rods were cut at the Brewster angle. Two IFP-2000 xenon flash lamps served as the optical pumping sources. The plane mirrors of the resonator had reflection coefficients of 80% (M_1) and 99.5% (M_2). The mirror substrate wedge angle was ~10°. A circular diaphragm D, 1.5 mm in diameter, and selector 2 in the form of a plane parallel glass plate parallel to the resonator mirrors were introduced into the resonator. Thus selector 2 is the only element that can affect the frequency selection of the axial modes. The energy density was redistributed in our experiments by moving the selector along the resonator axis. The selector was mounted on a trolley that could move at speeds from 5 to 35 cm/sec.

The laser beam was allowed to fall on a DFS-8 spectrograph with a linear dispersion of 6 Å/mm and

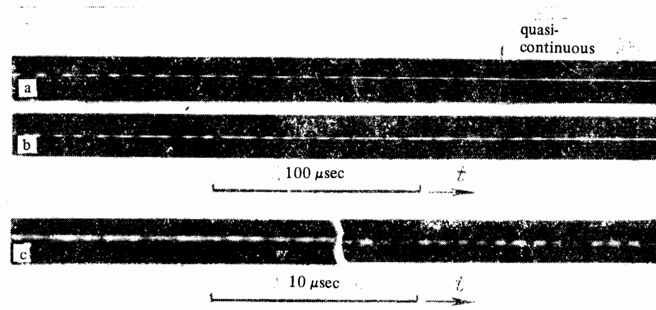

FIG. 3. Time scan of generation. Diaphragm of 1.5 mm diameter; a) selector omitted; b) selector fixed (a_2 = 10 mm); c) selector moving, v = 25 cm/sec.

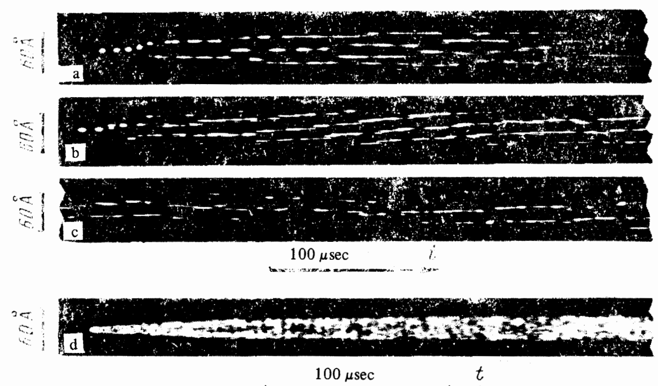

FIG. 4. Time scan of generation spectrum. Diaphragm of 1.5 mm diameter; a) selector omitted; b, c) selector fixed (a_2 = 10 mm); d) selector moving, v = 25 cm/sec.

the spectrum was projected onto the focal plane of an SFR high-speed camera operating in a slit scanning mode. To study generation kinetics without spectral resolution, the spectrograph grating was set to the zeroth order and a reduced image of mirror M_1 was projected onto the focal plane of the SFR camera.

2. Without the selector and diaphragm, in the resonator, the generation has the usual spiking nature. The 1.5 mm diameter diaphragm significantly changes the time behavior of generation: the randomly timed spikes of various intensities are replaced by regular intensity oscillations with a frequency of ~10^5 Hz (relaxation oscillations), which change sometimes into a quasi-continuous regime (Fig. 3a). The quasi-continuous evolution of the generation process in a resonator with a diaphragm but without selector elements was pointed out some time ago by A. T. Tursunov.

In this case the time scan of the stimulated emission spectrum (Fig. 4a) clearly shows the "forked" pattern due to spectrally inhomogeneous broadening of the luminescence line[10,11].

3. The introduction of a fixed selector with thickness $a_2 = 10$ mm and $\mu_2 = 1.53$ into the resonator in addition to the diaphragm again changes the time and spectral emission regimes. The time structure of generation (Fig. 3b) consists of separate and comparatively regular flashes of emission intensity appearing with a frequency of ~10^5 Hz; these do not change into

the quasi-continuous regime that is observed in the absence of the selector (Fig. 3a).

In this case the time scan of the emission spectrum (Fig. 4b, c) resembles the forked spectrum in the absence of the selector (Fig. 4a), although the "tines" of the fork are either slanted (Fig. 4b) or bent in a wave-like manner (Fig. 4c), i.e., the frequency of the "tines" varies during generation. This is probably due to the instability of geometric and optical parameters, viz., oscillation, shifting, and heating of the selector. According to Sec. I, the displacement of selector faces along the resonator axis causes a change in the numbers of odd (or near-odd) modes with low thresholds, i.e., a change in the generation frequency.

The generation at a given frequency has a time period connected with the rate of displacement of selector faces: $\tau_i = \lambda_i/2\nu$. For example in the case illustrated in Fig. 4b the effective selector-face speed is ~ 2 cm/sec. The displacement of selector faces could be due to heating by stimulated emission. However we think that heating of the selector is not the principal factor since the "bends" in Fig. 4c (with the frequency ~ 2.5 kHz) are probably due to the mechanical oscillation of the lever holding the selector, i.e., to uncontrollable displacements. Heating would cause a monotonic variation of the "tine" generation frequency.

4. The above results were obtained for a "fixed" selector whose uncontrollable displacements could have a speed of ~ 2 cm/sec. Further experiments were performed with a selector moving along the resonator axis at $v \gg 2$ cm/sec as a rule. Figure 3c shows the time scan of generation with moving selector ($a_2 = 10$ mm) at the speed $v = 25$ cm/sec. As we see some regions have modulation with a period $\tau_i/2$ and others have a quasi-continuous generation. The time scan of the generation spectrum (Fig. 4d) yields a "solid continuous" spectrum (analogous to that obtained by Livshitz and Tursunov[12]). However, a careful inspection of this spectrum reveals regions of modulated emission intensity with a period of $\sim 5\mu$ sec.

According to Sec. I, the periodic modulation of the emission in various modes can be either synchronized or shifted in time, depending on the position of the selector. This is the factor determining the type of generation time scan (Fig. 3c), where modulation is sometimes present and sometimes absent. The possible causes of the appearance of the period $\tau_i/2$ rather than τ_i are discussed below. Modulation with the period τ_i is not observed in the spectrum time scan (Fig. 4d), owing to the low sensitivity of film, which made it necessary to take the pictures of the type shown in Fig. 4d with insufficient exposure and spectral resolution (wide entrance slits of the spectrograph and SFR camera). Therefore further experiments were performed with a glass selector 2 or 1 mm thick (the frequency selection period increased 5–10 times). To increase its sensitivity, the film was hypersensitized before exposure[13]. This significantly increased the spectral and time sensitivity of the setup and showed that the spectrum (Fig. 4d) is neither "solid" nor "continuous."

5. During generation the 2-mm selector was at a distance of $z_0 \approx L_0/4$ from mirror M_1 and moved along the resonator axis at a speed of $v = 25$ cm/sec. The time scan of the emission spectrum in Figs. 5a-c has the form of regularly spaced "ladders." The frequency interval between the "rungs" of the ladders is 1.64 cm^{-1} and coincides with the frequency period of the selector.

The time behavior of the generation at a specific frequency is modulated with a period of τ_i at a low pump level (Fig. 5a). As the pump level rises the period decreases at first to $\tau_i/2$ (Fig. 5b) and then to $\tau_i/4$ (Fig. 5c). Such a generation pattern is in our opinion due to the fact at only odd modes j generate at low pump levels. Modes with numbers $j \pm 1$ and $j \pm 2$ have somewhat higher thresholds than the modes j (see Sec. I). Although these thresholds are reached at selector positions for which there is no generation of j modes (this is specific of the $z_0 \approx L_0/4$ position of the selector), the rate of increase of population inversion after termination of the j-th mode generation is so low that modes $j \pm 1$ and $j \pm 2$ fail to generate. When pumping is increased the $j \pm 2$ modes begin generating earlier than the $j \pm 1$ modes (whose threshold is lower); this may be due to different spatial field distribution of these modes. Experimental results (Figs. 5a-c) indicate that the inverted region of the active medium was in our case situated in such a way that termination of odd-mode generation left the average population inversion density for $j \pm 2$ modes larger than that for $j \pm 1$ modes. Therefore increased pumping caused the $j \pm 2$ modes to generate earlier. A further increase of the pump intensity increases the duration of generation in each mode; it thus lengthens the "rungs" and increases the number of generating modes in each "rung." In our case, according to Sec. I, at $z_0 \approx L_0/4$ the odd mode can generate simultaneously with modes $j \pm 4p$ (p is an integer). The spectral sensitivity of the setup was not sufficient to resolve resonator modes with adjacent numbers; however, we can assume that only j modes and no $j \pm 4p$ modes can generate at the modulation periods τ_i and $\tau_i/2$ (Fig. 5a, b).

6. The slope of the "ladders" changes in the course of generation (Figs. 5b, c). The slope change is due to the dependence of the time modulation period τ_i on the wavelength λ_i, which varies monotonically from "rung" to "rung." According to Sec. I, at $z_0 = m$ the modulation is synchronized in all "rungs" and the "ladder" is vertical (left-hand side of Fig. 5b). Displacement of the selector disrupts this synchronization and each "rung" has its own modulation period, so that the "ladder" becomes inclined (right-hand side of Fig. 5b). At $z_0 \approx (m + 1/2)\mu_2 a_2$, generation of neighboring odd modes is spatially separated by $\lambda_i/4$ (Fig. 5a). We see that the nature of the spectral time scan changes significantly when the selector is displaced by $\Delta z_0 = 0.5\,\mu_2 a_2 = 1.5$ mm. Owing to technical reasons, the selector position in the experiments was indeterminate within $\sim$1–2 mm at the instant of generation; therefore we observed uncontrollably spectra with different slopes of "ladders" of the type shown in Figs. 5a-c.

With a moving selector and adequate pumping, we sometimes observed spectra with quasi-continuous time structure in each mode group: the "ladders" merged into an approximately continuous line (Fig. 5d).

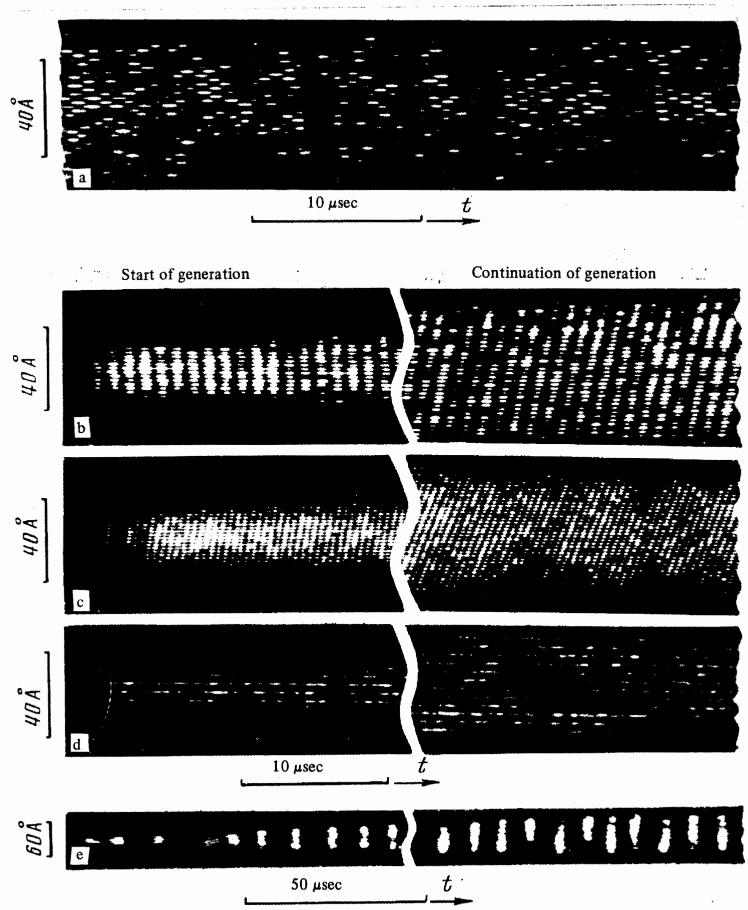

FIG. 5. Time scan of generation spectrum. Diaphragm of 1.5 mm diameter. Selector a_2 = 12 mm (a, b, c), a_2 = 1 mm (d), a_2 = 10 mm (e); a) v = 35 cm/sec, pump excess over threshold A = 1.8; b) v = 30 cm/sec, A = 2.25; c) v = 25 cm/sec, A = 3.25; d) v = 25 cm/sec, A = 2; e) v = 5 cm/sec, A = 2.25.

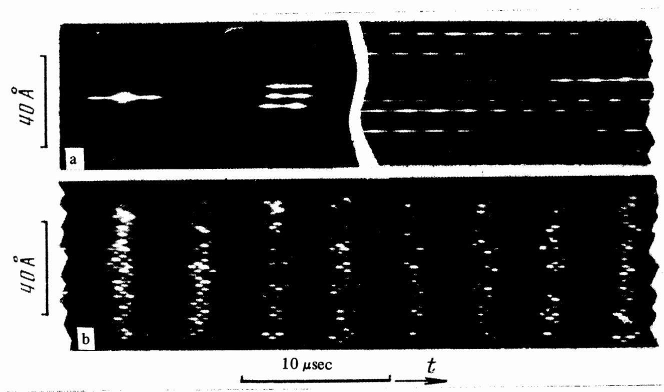

FIG. 6. Time scan of generation spectrum with moving misaligned selector; a_2 = 2 mm, v = 25 cm/sec; a) misalignment 1.5′; b) misalignment 40″.

This may be due to various causes. Since our apparatus was not capable of frequency resolution of axial modes with adjacent numbers, the increasing duration of generation of odd modes j and the adjacent modes j ± 1 and j ± 2 could cause the time scan of the spectrum to be left with only frequency modulation, while time modulation, although present in individual modes, was not observed. According to Sec. I, the same result can be obtained by slight misalignment of the selector. Furthermore, the active rods deteriorated after prolonged operation, i.e., their generation threshold increased and depended strongly on the particular region of the rod cross section covered by the diaphragm. The deterioration of the rods was accompanied by an increase in the relative number of spectra with continuous "rungs" (Fig. 5d) as compared to spectra with distinct "rungs" of the ladders (Figs. 5a-c). This is due to the increase of the losses (ξ) in the active medium; according to (4) this decreases the difference between the thresholds of the odd and adjacent modes smears out of the observed time modulation pattern.

7. It is of interest to determine whether the effect of energy redistribution on the generation regime has a resonant characteristic, so that even small periodic perturbations can cause modulation[14,15]. To do this we vary the frequency τ_i^{-1} of laser perturbation.

The time scan of the spectrum obtained with a selector (a_2 = 10 mm) moving at a speed of 5 cm/sec is shown in Fig. 5e. We see that generation consists of separate spikes that are comparatively regular in time. The mean period of spike succession corresponds to $\tau_i = 2_i/2v$. Some deviation from the equal time separation of the spikes is attributed to the uncontrollable mechanical oscillations of the selector. These uncontrollable perturbations are the cause of generation quenching (spikes) in each mode when the selector is "immobile."

Thus, the frequency of the external perturbations varied in our experiments by a factor of 7 and in all cases we observed deep modulation of the emission. Furthermore (see Fig. 5b,c,e), modulation with the period τ_i occurred directly without transient processes typical of resonance phenomena. We think therefore that resonance effects were not significant under our conditions.

8. During generation, the stimulated-emission spectrum sometimes becomes rearranged: the time scan has the form of "ladders" in some regions and represents fragments of "forked" generation in others. We attribute this to the misalignment of the selector during generation. According to Sec. I, a large misalignment of the selector can cause both the absence of time modulation and the "forked" spectral structure where each "tine" of the fork contains even and adjacent axial modes of the resonator[9].

9. A study of the effect of a moving selector misalignment on the generation regime showed that deliberate misalignment of the selector by 3′ and more causes the stimulated emission spectrum at the beginning of generation to follow the "forked" development (similarly to Fig. 4a). After 100–200 μsec the spectrum becomes stabilized, retaining frequency selection in individual "tines" with a period $\Delta\nu_0$. Time modulation with a period τ_i is totally absent. Misalignment by 0.5′–1.5′ resulted in two types of spectra (Figs. 6a,b). In spectra of the first type (Fig. 6a) the spectral composition stabilized 200–300 μsec after the start of generation, producing a clear frequency selection with a period of $2\Delta\nu_0$. Furthermore, time modulation with period τ_i was observed at all frequencies and any pump power. The second type of spectra consists (Fig. 6b) of spikes broad in frequency and regular in time, appearing with a frequency of ~200 kHz (relaxation oscillations?). Each such spike has an internal time and frequency structure analogous to that shown in Fig. 5a (but with a period $\tau_i/2$). We note that the correlation between the spectral changes and selector misalignment is somewhat hypothetical, since the misalignment of a moving selector at the instant of generation was not monitored.

III. CONCLUSION

1. The basic result of this work is the experimentally established strong effect of small $(\sim\lambda_i/4)$ displacements of dielectric boundaries within the cavity on the spectral and temporal regimes of the generation.

2. The pattern of generation in each mode in the case of a moving selector (Figs. 5a,b,c,e) is essentially that of an ordered spiking regime. Analogous quenching of generation due to energy redistribution is observed also in the absence of the selector when the active medium moves, if the active medium boundaries are parallel to the mirrors[7]. All this offers a new approach to the problem of spiking in some solid-state lasers.

Stationary generation is possible only under the condition that the position of internal dielectric boundaries parallel to the mirrors does not change during generation. As a rule this does not happen in real lasers[6], especially in pure generation in which the boundaries are displaced because of heating of the active rods by the pumping light and because of uncontrollable vibration. The modulation period τ_T associated with heating of the active medium can be readily computed. Let the dimension of the active medium be 10 cm, its linear expansion coefficient 10^{-5} deg^{-1}, and the temperature rise rate $dT/dt = 10^4\,^\circ$K/sec. Then the modulation period is $\tau_T = 5 \times 10^{-5}$ sec. We see that τ_T is close to the mean time interval between spikes in free-running generation.

We assume that the main cause of spiking in the above resonators is the energy redistribution that accompanies the displacement of boundaries. The random time distribution of the spikes in free-running generation can be due to temporally uneven heating of the active medium by the pumping light and to other uncontrollable perturbations. This is confirmed, in particular, by the experiment with a slowly moving selector (Fig. 5e).

3. Of course, the above factors do not exhaust all possible laser instabilities that cause spiking. However, the modulation of the threshold n_i^n due to the translation of dielectric boundaries that coincide with the equiphase surfaces of the standing wave is deep enough to overshadow other causes whenever it is present.

4. According to[6,14,15], small periodic perturbations of the laser system can cause spiking if the period of the perturbation is close to that of natural oscillations of the laser. The laser variation of the threshold considered by us does not exhaust all the possible ways in which the energy density redistribution in the resonator with external mirrors can affect generation. Effects with less deep modulation are also possible. Some possible modulation mechanisms are as follows:

a) Since the laser resonators are not ideal, the inhomogeneity of optical path over the cross section, as noted earlier[4,5], leads to different generation conditions in different cross-section regions for a given frequency. The transverse cross section of generation (near field) has a mosaic structure. Displacement of the boundaries (by heating in particular) causes the transverse mosaic structure to vary periodically with period τ_i. Since the diffraction losses depend significantly on the transverse distribution of the generating-mode intensities, these losses also vary with period τ_i.

b) A similar modulation of diffraction losses with period τ_i occurs also upon displacement of plane boundaries of a homogeneous active medium in a resonator with spherical mirrors[5].

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