TIME DEPENDENCE OF THE RUBY LASER SPECTRUM

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The time dependence of the generated mode spectrum of a solid state laser is investigated. The spectrum and kinetics of generation are shown to be dependent on a certain parameter t*. For small periods of time, such that $t < t^*$, the generation spectrum narrows with time and the kinetic regime is regular; when $t > t^*$ mode competition disrupts the regular spectral and kinetic regimes. At the time t* the spectral width reaches a minimum. The time t* is evaluated. Experiments with a ruby laser confirm the existence of a spectral width minimum and the resulting experimental data on the value of t* and its dependence on the angular divergence are in agreement with theory. Theory and experiment show that the generation time coincides with t* in a single-pulse or isolated-spike operation thus explaining the spectral narrowing in a single pulse. The existing qualitative concepts concerning the effect of the number of generated modes and the spectral width on the regularity of the kinetic regime are further refined.

1. INTRODUCTION

We know that the emission spectrum of a solid state laser operating with an oscillating intensity largely depends on mode competition. The spectral composition of nonstationary generation was investigated experimentally by a number of authors[1-6], although the variety of experimental facts has not yet been adequately explained. In theoretical papers mode competition is as a rule considered on the assumption of a stationary nature of generation[1,7,8]. Tang, Statz, and de Mars[1] discussed the nonstationary case merely as a numerical example. Livshitz and Tsikunov[9] considered a small deviation from the stationary case, which did not affect the generation spectrum.

Korobkin, Leontovich, and Smirnova[3] established a qualitative relation between the large number of generation modes with close values of Q and the regular generation kinetics. This relation is quite useful in the interpretation of the kinetics of generation when its spectrum permits us to estimate the number of modes.

This paper presents a semi-quantitative interpretation of the experimental data on the spectral and kinetic regimes of generation obtained under various conditions. We show that the nature of generation is adequately determined by the duration t* of the regular regime, this being a convenient measure of mode competition.

Let us clarify the above. In a laser with a nonresonant feedback[10], because of the absence of mode competition, the time variation of the emission spectrum depends only on the shape of the amplification band. Hence it follows[10-12] that the spectral width of the continuous spectrum emission diminishes in time according to

$$\delta\omega \sim \tilde{\omega}\sqrt{\tau / t}, \qquad (1)$$

where $\tilde{\omega}$ is the spectral width of luminescence and τ is the photon lifetime in the empty resonator. On the other hand in the case of an ordinary resonator with a discrete spectrum, mode competition does not become significant immediately but only after a certain time interval t* from the onset of generation. This is due to the fact that mode competition stems from a population inversion that has a certain amount of inertia. We show below that, depending on the angular divergence, t* can be varied within the limits from the period of relaxation intensity oscillations to the pump pulse length.

In the first stage of generation, when $t < t^*$ and mode competition is not yet evident, the electromagnetic field in the resonator varies in time practically as a unit; this means that the generation spectrum narrows down according to (1) and the kinetic regime is regular. When $t > t^*$, mode competition arrests the narrowing of the spectrum and disrupts the regular kinetic regime. The spectral width passes through a minimum at time t*, as we show below.

The time interval from the onset of generation to time t* can be conveniently called the region of regular spectral-kinetic regime of generation. The experimental data given below show that the t* parameter plays a fundamental role by significantly determining the nature of generation.

2. DURATION OF REGULAR REGIME

We evaluate the magnitude of t* in the limiting cases of small and large angular divergences of the light beam.

1. Let $\omega_0\theta^2/2 < \delta\omega_0$ where ω_0 is the central frequency of the amplification band, θ is the characteristic angle between the direction of light propagation and the optic axis, and $\delta\omega_0$ is the spectral interval between neighboring axial modes. Since the spectral interval covered by the generated transverse modes is smaller than the $\delta\omega_0$ interval, the axial modes are spectrally resolved. In this case the transverse modes do not affect significantly the axial inhomogeneity of population inversion and to study its effect on generation we can confine ourselves to the model of a resonator with an infinite cross section.

We write the kinetic equation for the number of excited atoms [1) [13]]:

$$T\frac{\partial\nu(z,t)}{\partial t} = -(1+\nu)-(1+\nu)w(z,t)+(1+\zeta) \equiv -\nu - w(1+\nu)+\zeta \qquad (2)$$

Here z is the longitudinal coordinate, ν is the relative excess over the threshold number of excited active centers, ζ is the relative excess over the threshold pump power, T is the period of spontaneous emission, and w is the intensity of stimulated emission in arbitrary units. In the right-hand side of (2) the first term describes spontaneous emission of excited atoms, the second stimulated emission, and the third the pumping effect. Under normal experimental conditions (except for the case of a high-power single pulse) we have the inequality[11,12]

$$\nu \ll 1, \quad \nu \ll \zeta. \qquad (3)$$

The energy of stimulated emission can be distributed among the axial modes:

$$w(z,t) = \sum_m B_m(t)\sin^2\frac{\pi mz}{l} = \frac{1}{2}\sum_m B_m(t)\left(1-\cos\frac{2\pi mz}{l}\right). \qquad (4)$$

The time dependence of the amplitude of the m-th mode is described by

$$\dot{B}_m = B_m\left[-\frac{1}{\tau}+\frac{v}{l}\int_0^l \varkappa(\omega_m, z)\left(1-\cos\frac{2\pi mz}{l}\right)dz\right]. \qquad (5)$$

Here τ is the photon lifetime in the empty resonator, v is the velocity of light in the material, $\kappa(\omega, z, t)$ is the gain, and l is the resonator length. In (5) the gain is averaged over z and weighted according to the spatial intensity distribution of the mode under consideration. The gain can be expanded in a power series of the small quantities ν and $\omega - \omega_0$:

$$\varkappa(\omega_m) = \frac{1}{\tau v}(1+\nu-\xi_m), \qquad (6)$$

where

$$\xi_m = (\omega_m-\omega_0)^2/\tilde{\omega}^2, \quad \omega_m = m\delta\omega_0, \quad \delta\omega_0 = \pi v/l. \qquad (7)$$

The coefficient in front of (6) is selected so as to have the light losses per unit length, which are equal to $1/\tau\nu$, offset by the gain when $\nu = 0$ (corresponding to the generation threshold) and $\omega = \omega_0$.

We note that Eqs. (2) and (5) used here take into account phase relationships in space only, and not in time. Basov, Morozov, and Oraevskiĭ[14] showed that such an approximation is valid provided that

$$\Delta\omega_{min} \gg T_0^{-1}, \qquad (8)$$

where $\Delta\omega_{min}$ is the minimum spectral interval between the generated modes, and $T_0 = T/(1+\zeta)$ is the lifetime of the excited state taking spontaneous and stimulated emissions into account. If the inequality (8) does not hold, the consideration of phase relationships leads to qualitatively new effects due to the instability of the stationary regime[14]. In a ruby or neodymium-glass laser the interval between the neighboring axial modes exceeds T_0^{-1} by several orders, thus justifying the use of (2) and (5).

Substituting (6) into (5) we have

$$\tau\dot{B}_m = B_m(\bar{\nu}-\nu_m-\xi_m), \qquad (9)$$

where

$$\nu_m = \frac{1}{l}\int_0^l \nu(z)\cos\frac{2\pi mz}{l}dz, \quad \bar{\nu} = \frac{1}{l}\int_0^l \nu(z)dz. \qquad (10)$$

Equation (2) can be simplified in the region

$$t \ll T_0 \equiv T/(1+\zeta). \qquad (11)$$

Assuming that in (2) $\nu \sim \nu/t$ and using (11) and the relation[2)]

$$\frac{1}{t}\int_0^t w\,dt \to \zeta \text{ as } t\to\infty, \qquad (12)$$

we neglect the quantity ν in the right-hand side of (2) compared with its left-hand side. We then have

$$T\dot{\nu} = \zeta - w. \qquad (13)$$

As we know, T_0 is the characteristic damping time of relaxation oscillations, i.e., it is the period of stabilization of the stationary regime. Therefore the region (11) is characterized by an essentially nonstationary generation. From now on we consider only this region[3)].

We find the Fourier coefficients for both sides of (13). Considering (4) and integrating with respect to time we obtain

$$\nu_m = \frac{1}{4T}\int_0^t B_m(t')dt' \qquad (14)$$

(at the start of generation t = 0, $\nu(z) = 0$, and $\nu_m = 0$). We then substitute (14) into (9), divide the result by B_m, and integrate with respect to time:

$$B_m(t) = f(t)\exp\left\{-\frac{\xi_m t}{\tau}-\int_0^t\frac{dt'}{4T\tau}\int_0^{t'}B_m(t'')dt''\right\}. \qquad (15)$$

Here f(t) designates some time-dependent function that is independent of the index m. In the exponent of the right-hand side of (15) the first term describes a consistent variation of mode amplitudes, and the second the effect of mode competition. When the time intervals are small the second term depends on t squared and can be dropped, so that (15) assumes the form

$$B_m = B_{m_0}(t)\exp\left(-\frac{\xi_m t}{\tau}\right) = B_{m_0}(t)\left(1-\frac{\xi_m t}{\tau}+\ldots\right) \qquad (16)$$

(the index m_0 corresponds to the maximum of the spectral distribution). Hence the spectral narrowing rule (1) follows when (7) is taken into account.

We substitute (16) into the right-hand side of (15) to obtain t* when mode competition begins to affect the generation spectrum. We also note that according to (12) $B_{m_0} \sim \zeta/M$, where M is the number of generated modes. Carrying out the integration in (15) with respect to time we have

$$B_m(t) \sim B_{m_0}(t)\exp\left\{-\frac{\xi_m t}{\tau}\left(1-\frac{t^2\zeta}{24T\tau M}\right)\right\}. \qquad (17)$$

It follows that the spectral width passes through a minimum at the time

$$t^* \sim \sqrt{8MT\tau/\zeta}. \qquad (18)$$

Since several axial modes are usually generated in a

[1)] To simplify our notation we consider an equation for a four-level system although all the results are applicable to the three-level laser if we make the substitution $\zeta \to \zeta\rho$, where ρ is the ratio of light losses in the resonator with an unexcited active medium to losses in the empty resonator.

[2)] This relation follows from (2) when (3) is taken into account.

[3)] Generation in a regime close to the stationary was investigated by Livshitz and Tsikunov [9].

plane resonator, the value of (18) approximately coincides with the period of intensity oscillations[11].

2. Let the angular divergence be sufficiently large to satisfy the condition[4])

$$\frac{1}{2}\omega_0\theta^2 > \delta\omega_\parallel \equiv \left(\frac{3\zeta\delta\omega_0\tilde{\omega}^2}{\zeta+1}\right)^{1/3}. \qquad (19)$$

When (19) holds the spectral interval covered by the generated transverse modes exceeds the spectral emission width $\delta\omega_\parallel$ of the plane parallel resonator[7] so that each generated axial mode spectrally overlaps all the other modes. The resulting strong compression of the spectrum of the generated modes causes a significant reduction in the spectral width in the stationary regime[8]. In the nonstationary case under consideration this spectral compression also causes a reduction in $\delta\omega$, due to increasing t^*. In fact, using p to denote the maximum index of the generated transverse modes, we have

$$M \sim p^2\delta\omega / \delta\omega_0 \qquad (20)$$

(the first factor is the number of generated transverse modes, and the second the number of axial modes[5]).

The values of t^*; M, and $\delta\omega$ can be determined from three equations: (1), (18), and (20). Finally,

$$t^* \sim \left(\frac{\tilde{\omega}^2}{\delta\omega_0^2}\frac{\tau^3T^2p^4}{\zeta^2}\right)^{1/5}. \qquad (21)$$

Equation (21) is a quantitative expression of the effect of the number of generated modes on the degree of regularity of the kinetic regime as observed in[3]. The physical meaning of this result is that the simultaneous generation of many modes with different spatial field distribution causes a significant smoothing of the "inhomogeneities" of the medium. As a result, the actual amplification of the modes is practically independent of the spatial phase relationships and their amplitude variation is similar within the period of time t^*. The more modes are generated the more "homogeneous" is the active medium and the longer is t^*.

3. PASSAGE OF THE SPECTRAL WIDTH THROUGH A MINIMUM

The experimental proof of the conclusion that the spectral width passes through a minimum is conveniently carried out in the case of a large angular divergence of light when t^* is much longer than the period of the relaxation oscillations. Therefore in the experiments we used a ruby laser with a relatively short mirror separation (l = 32 cm) and with short-focus reflectors (we used spherical mirrors having a radius of curvature R = 25 cm and also plane mirrors behind lenses having a focal length of F = 22 cm). The angular divergence can be determined from the formula[15,16] $\theta \cong d/\sqrt{2lF}$ for a resonator with two lenses or from $\theta \cong d/\sqrt{2lR}$ for a spherical resonator (d is the diameter of the generating region of the ruby rod). In the case of ruby rods 1.2 cm in diameter and 12 cm long used in our experiment, d = 0.7 cm and θ = 0.02, so that (19) holds (the left-hand side is one-and-a-half to two times larger than the right-hand side). For the ruby laser with the above geometric parameters and average excess power over threshold, according to (21), $t^* \sim 300$ μsec so that $\delta\omega$ reaches minimum in the middle of the pumping pulse.

The experiment consisted in a simultaneous investigation of the spectrum and the generation kinetics. The spectral composition was studied with a Fabry-Perot interferometer with intermediate rings of 10 and 3 mm; the time resolution of the spectrum was performed with an SFR camera. Oscilloscopic traces were obtained by passing the signal from the F-5 photocell to the input of the OK-17M oscilloscope. The spectral width of the emission was determined by photometry of the interference patterns (half-width of the density curve).

Figure 1 shows a time-resolved interference pattern of the emission obtained in a resonator with two lenses (F = 22 cm). The corresponding oscilloscopic trace shows (Fig. 2a) that almost the entire generation process follows the regular kinetic regime.

The time dependence of the spectral width of generation is shown in Fig. 3. The abscissa axis represents the quantity $n^{-1/2}$, where n is the number of the spike counted from the beginning of the regular series (in view of the approximate constancy of the period we may assume that t is proportional to n). According to Fig. 3 the spectral narrowing rule (1) is followed with an accuracy of experimental error through the first 20 spikes (i.e., about 100 μsec). Beyond that time mode competition causes the experimental dependence of the spectral width to deviate from (1) and the width passes through a minimum. We were unable to measure the spectral width of the first spike because of the overlapping orders of interference. Figure 3 shows that it amounts to 0.19 Å (the interference patterns obtained with the 3 mm intermediate ring yield close values of $\delta\omega$ for the first spike). According to (1), when $\tau \sim 2\times10^{-9}$ sec and $t \sim 3\times10^{-6}$ sec we have $\delta\omega \sim 0.02\,\omega \sim 0.2$ Å (t is the half-period of oscillations at the beginning of the regular series) for the first spike.

In the case shown in Figs. 1a and 2a mode competition is fairly weak; this is evidenced by the shallow minimum of $\delta\omega$ and by the fact that the kinetic regime stays regular when $t > t^*$ (mode competition merely causes an increase of the oscillation period in the region $t > t^*$). The value of t^* depends on the optical homogeneity of the ruby and on the resonator alignment. When the alignment is very precise, t^* can approach the pumping pulse length and the minimum of the spectral width is then less pronounced. On the other hand when the alignment is poor or the ruby is inhomogeneous t^* can shorten down to the length of several oscillation periods and the resolved spectrum will have a form similar to that in Fig. 1b[6]).

Figures 1b and 2b show the spectrum and kinetics of generation obtained under the same conditions as above except for a diaphragm in the form of a black circle a millimeter in diameter cemented to the center of the lens. The diaphragm reduces the angular divergence (that is now limited by the solid angle between two coaxial conical surfaces) and consequently t^*. In view of the

[4])We omit the intermediate case when the spectral structure is much more complex.

[5])In the experiments described below the spectrum is not compressed enough to violate condition (8).

[6])Experimental results [3] also show that the spectral width passes through a minimum.

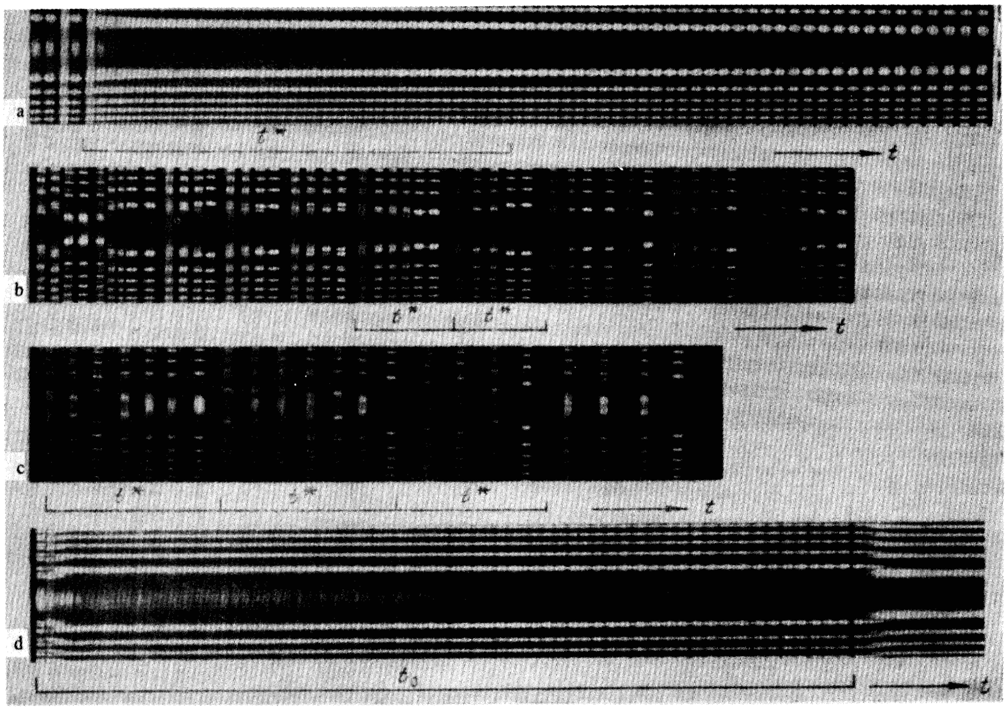

FIG. 1. Scan of emission spectrum with large angular divergence (interval between interference orders is 0.24 Å, l = 32 cm). a – two lenses, F = 22 cm; b – the same with diaphragm; c – two lenses, F = 50 cm; d – spherical mirrors, R = 25 cm.

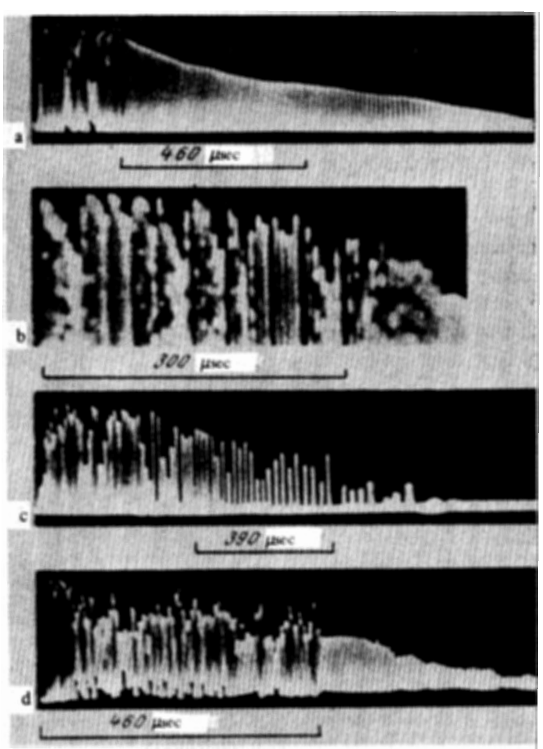

FIG. 2. Oscilloscopic traces of emission with large angular divergence. The marked regions in traces a, b, c, d correspond to the scans in Fig. 1 designated by the same letters.

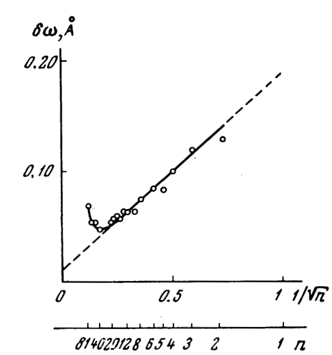

FIG. 3. Spectral width as a function of spike number for the case shown in Figs. 1a and 2a.

smaller number of generated modes their competition is more pronounced than before; this in turn disrupts the regular kinetic regime at the time $\delta\omega$ passes through the minimum. As a result the spikes break down into series t* long, within each of which $\delta\omega$ decreases monotonically according to (1); these series are clearly visible in Figs. 1b and 2b. The initial spike of each series has the same spectral width as the first spike in the regular series of scan a (Figs. 1 and 2).

In the case of a resonator with "weak" lenses that do not satisfy criterion (19) the scan of the interference pattern is broken down into analogous series of spikes (Figs. 1c and 2c). However the spectrum here is more complex because the deviation from criterion (19) results in a clearly expressed discrete spectrum (absent in case a) and in selection of modes that tend to distort the investigated relationships.

4. EMISSION SPECTRUM IN AN ISOLATED SPIKE REGIME

As shown in Sec. 2 the duration of the regular regime of generation is comparable to the intensity oscillation period in a plane parallel resonator. Therefore the regular regime can be represented either by a single-pulse regime or by spikes separated by sufficiently long time intervals (each spike arises independently if the light energy left over in the resonator from the preceding spike has time to approach zero before the onset of the next). For the sake of brevity we use the term isolated spikes in this case.

In the isolated spike regime the position of the generated line coincides with the maximum of the amplification band and the spectral width is determined by (1) in which t denotes the length of the initial generation stage preceding each spike and comprising approximately a half-period of relaxation oscillations[17]. Consequently the spectral width of each spike should coincide with the initial value of the spectral width in the regular regime (Fig. 1a) and should amount to approximately 0.2 Å (as shown below, mode selection causes a considerable reduction of this value).

The experimental verification of the above was performed by introducing a weak solution of a passive Q-switch, kryptocyanine, into a plane-parallel resonator. The concentration of kryptocyanine was adjusted so as to allow for the generation of both ordinary (interdependent) and isolated spikes (the latter occur mainly at the end of generation when pumping intensity is reduced) in the course of a single pumping pulse. The scan of the generation spectrum obtained under these conditions is shown in Fig. 4a. According to the figure, the spectral lines of the isolated spikes (marked by arrows) always occupy the same position that apparently coincides with the maximum of the amplification band. On the other hand the frequencies of the remaining (interdependent) spikes are randomly distributed within the spectral interval between the neighboring orders of interference (amounting to 0.8 Å).

An analogous situation occurs when the isolated spikes are generated in a plane resonator whose mirrors are slightly out of alignment (without the Q-switch). The emission spectrum scan of such a resonator is shown in Fig. 4b. We see that the spectral lines of the isolated spikes as a rule occupy the same position (exceptions are due to mode selection discussed below). The width of individual lines in Fig. 4b amounts to 0.06–0.07 Å. In the case shown in Fig. 4a the line width also amounts to several hundredths of an Angstrom [7]. The disparity between this width and the 0.2 Å mentioned above is due to mode selection that cuts the generation spectrum (the selection of axial modes occurs at the faces of the ruby rod and the reflector substrates perpendicular to the optical axis). If the interval between the selected modes is comparable to the magnitude of the spectral interval (1) within which they are generated, only one or two axial modes are actually generated and their spectral region is small in comparison to the value of (1). (The generation of a single axial mode in a laser with a passive Q-switch was observed in[6,18] [8]; a precise measurement of the width of individual lines was not the purpose of the present work).

Mode selection also causes an insignificant frequency shift of the isolated spikes with respect to the maximum of the amplification band (the magnitude of this shift does not exceed one-half the interval between the selected modes). If the maximum of the amplification band, continuously shifting during the heating of ruby, falls in the center between two selected lines, both lines participate in generation (this seems to be the explanation for the double line in Fig. 4b marked by a double arrow). The role of mode selection becomes quite clear when we compare Figs. 4a, b with Fig. 4c showing the scan of the generation spectrum in a plane resonator with two lenses (F = 22 cm) and with a weak kryptocyanine solution. In this case the axial mode selection is totally eliminated; as a result the frequencies of all spikes coincide precisely with the amplification band maximum and their spectral width is approximately 0.25 Å in accordance with (1).

5. INERTIA OF THE EMISSION SPECTRUM

An interesting phenomenon can be observed in a resonator with a large angular divergence that satisfies criterion (19), i.e., in the region of large t^*. If the resonator with spherical mirrors is well aligned the regular regime shown in Figs. 1a and 2a is preceded by a prolonged generation with a practically constant spectrum and relatively random kinetics (Figs. 2d and 1d). This experimental fact seems to be connected with the axial mode selection at the initial generation instant when the generating region of the ruby rod is narrow enough to render the reflecting surfaces practically parallel within its limits. All the selected lines except one that is closest to the amplification maximum vanish during the first two or three spikes due to spectral narrowing according to the (1) rule (this evolution of the spectrum can be observed in the scan shown in Fig. 1d). Owing to the rapid rise of the pumping pulse, the diameter of the generating region then approaches its maximum value and consequently criterion (19) of strong mode degeneracy[8] takes hold causing a significant homogeneous spectral compression and weakening mode competition. Under these conditions stimulated emission that was initially established in the resonator determines the generation spectrum over a fairly long period of time. In other words a resonator with strongly degenerate modes has an emission spectrum with a pronounced inertia that preserves the effect of the initial mode selection over several tens of oscillation periods. It is obvious that the reduction of the number of generated modes due to selection disrupts the regular kinetic regime.

The role played by selection is also indicated by the fact that the duration of generation t_0 with a constant spectrum is strongly dependent on the precision of resonator alignment; in the case of a plane resonator with spherical spectacle lenses t_0 is considerably shor-

[7]Fig. 4 a cannot be used to estimate the width of the spectral lines of isolated spikes because these lines are overexposed (due to the large differences in spike intensities). The strong effect that overexposure exerts on the width of the lines recorded on film seems to be due to the fact that modes that fail to satisfy the selection conditions are not fully eliminated but merely attenuated and can be recorded in film during long exposures. In a certain sense the width of overexposed lines coincides with the spectral width of generation without taking mode selection into account (this is apparent from the comparison of Figs. 4a and 4c)

[8]In the case of active Q-switching the initial generation stage is much shorter than in the case of passive Q-switching [17] and the spectral emission width in a single pulse is correspondingly larger; this is confirmed by experiment [6].

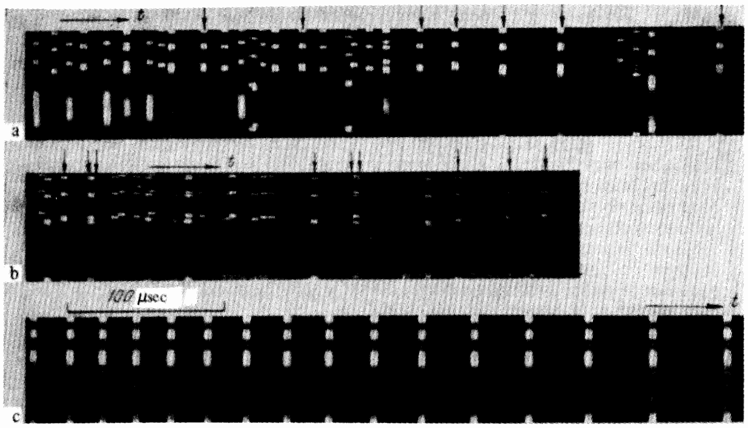

FIG. 4. Scan of emission spectrum containing isolated spikes (interval between interference orders is 0.8 Å). a – plane resonator with kryptocyanine; b – plane resonator with mirrors 15′ out of alignment; c – resonator with lenses (F = 22 cm) and kryptocyanine.

ter than in the case of a spherical resonator. However if the central region of the lens half a millimeter in diameter is blocked, the effect is practically eliminated.

Because of spectral inertia the maximum of the amplification band undergoes a slight shift from the generated lines in time t_0 (Fig. 1d shows that this shift amounts to about 0.1 Å). It is this shift that may be the reason for the frequency jump in the transition to the regular regime. As Fig. 1d clearly shows, in the beginning of this transition in the resonator along with the initial narrow line there appears a broad line that coincides with the maximum of the amplification band. While weak at first, in the course of several spikes this line displaces the narrow line that is now too far from the amplification maximum. In the region of regular regime, the spectral inertia causes the generated line to lag behind the amplification band maximum that is being displaced by the heating of the active element. This is sometimes accompanied by a frequency jump after which the spectrum again follows (1) where t is counted from the time of the jump. These frequency jumps were observed by Korobkin, Leontovich, and Smirnova[3]. We note that the larger the angular divergence of light satisfying (19) the more pronounced the inertia of the spectrum.

6. CONCLUSIONS

1. The duration of the regular kinetic regime and spectral narrowing significantly depends on the angular divergence θ. When θ is large enough to satisfy (19) the entire generation proceeds in the regular kinetic regime and its spectrum is substantially narrowed in comparison with the case of a plane resonator[5,8].

2. The narrowing of the spectrum of a plane or concentric resonator in a single-pulse mode occurs when the generation period (comprising a half-period of relaxation oscillations in the case of passive modulation) coincides with the duration of spectral narrowing. Under this condition axial mode selection causes an additional substantial narrowing of the spectrum (the spectral region of free-running generation exceeds the interval (1) and contains several selected modes).

3. The emission spectrum possesses inertia in a resonator with strongly degenerate modes satisfying criterion (19). This allows us to predetermine the generation spectrum by introducing a priming light energy with a narrow spectral line into the resonator (the priming radiation can be obtained for example from a second laser operating in a single pulse mode with a passive Q-switch).

4. The regular kinetic regime depends directly on the number of generated modes and does not depend on the spectral width of the emission. If the spectral narrowing is related to a large angular divergence it is accompanied by a regular kinetic regime; if however the spectrum narrows down because of mode selection (and more than a single mode is generated), the regular generation kinetics becomes disrupted.

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