SPECTRAL CHARACTERISTICS OF A LASER WITH AN INHOMOGENEOUSLY BROADENED LUMINESCENCE LINE

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The spectral width of a laser with an inhomogeneously broadened luminescence line is considered under the assumption of large angular divergence of the light. Under this assumption, effects connected with the inhomogeneity of the inverted population need not be taken into account. The existence of a threshold for spectral generation broadening, below which no inhomogeneous broadening of the luminescence band appears, is demonstrated. The dependence of the spectral characteristics on the pumping and parameters of the active medium is calculated. An experimental investigation of the spectral generation width as a function of pumping energy and temperature of the active medium is carried out. The experimental results are in satisfactory agreement with the theory. Comparison of theory and experiment permits one to determine the parameters of the active medium and their temperature dependence. The important role of the excitation migration is established.

As is well known, different glasses and crystals activated with rare-earth elements have inhomogeneously broadened luminescence bands. The physical cause of the inhomogeneous broadening is the random shift of the luminescence line of the rare-earth ion, owing to the irregularity of the fields produced by the surrounding atoms. The specific characteristic of the inhomogeneous broadening, as noted in[1], becomes manifest only in experiments with stimulated emission. Inhomogeneous broadening greatly influences the spectral characteristics of lasers, and leads especially to a strong dependence of the spectral width on the pump intensity.

In the cited paper[1] as well as in papers by others[2,3], qualitative considerations are advanced concerning the physical cause of the relatively large spectral width of laser emission, connected with the inhomogeneously broadened luminescence band, and concerning the role of pumping and excitation migration. We present in this paper a quantitative investigation of the dependence of the spectral width of the generated radiation on the parameters characterizing the degree of inhomogeneity of the broadening, the probability of excitation migration, and the pump intensity. To investigate the laser spectral properties connected with the inhomogeneously broadened luminescence line, it is necessary to exclude another cause of spectral broadening of laser emission, namely the spatial inhomogeneity of the inverted population, which is connected with the inhomogeneous distribution of the intensity of the longitudinal modes. A number of authors[4,5] have shown that even in the absence of inhomogeneous broadening the spatial inhomogeneity of the gain can lead to simultaneous generation of a large number of longitudinal modes subtending an appreciable spectral interval.

There exist several methods of eliminating the inhomogeneity of the inverted population and the associated spectral broadening of the generated light[6-8]. In our investigation we used a resonator with short-focus positive lenses, having strongly degenerate modes. The authors of[8,9] investigated the spectral characteristics of such a resonator with a ruby active element, which, as is well known, has a homogeneously broadened luminescence line. It was shown that introduction of sufficiently strong lenses into the resonator practically eliminates the spectral broadening of the generated light, caused by the special inhomogeneity of the inverted population. This is physically connected with the large angular divergence of the light in the resonator with lenses, that is, with generation of a large number of transverse modes. This makes the frequency essentially dependent not only on the longitudinal but also on the transverse mode indices, so that a strong degeneracy of the mode takes place. This degeneracy causes a large number of modes with different longitudinal and transverse indices to fall into a small spectral interval in the vicinity of the maximum of the amplification band, forming a very narrow peak of spectral distribution of the generated light[1)]. On the other hand, the large number of degenerate modes with close amplitudes and different spatial intensity distributions leads to a practically homogeneous distribution of the summary intensity of the generated radiation, making it possible to disregard the phase relations, which are essential only in the case of an inhomogeneous active medium.

1. THRESHOLD OF SPECTRAL BROADENING

Let us consider a laser with an active medium possessing an inhomogeneously broadened luminescence band. In accordance with the foregoing, we shall disregard the phase relations and will assume the inhomogeneous broadening of the luminescence line to be the only cause of the spectral broadening of the laser emission.

The observed luminescence band consists of elementary bands corresponding to individual luminescence centers; these elementary bands will be regarded as differing only in the position of the maximum, but not in shape. Considering for concreteness a four-level

[1)] Snitzer [3] reports a practically continuous/generation spectrum of a laser with a large beam divergence.

scheme, we write for the gain as a function of the frequency

$$\varkappa(\omega)=Bn\int P(\omega-\omega')\nu(\omega')d\omega'. \quad (1)$$

Here n is the number of excited luminescence centers per unit volume, $\nu(\omega)$ is their distribution function with respect to the position of the luminescence maximum ($\int \nu\, d\omega = 1$), P(ω) is the form of the elementary luminescence band, and B is a constant expressed in terms of the spectral characteristics of the luminescence centers and the oscillator strength.

Assuming for simplicity that the generation is stationary, we write the following equation for ν:

$$\dot{n\nu}=0=-\frac{n\nu(\omega)}{T}-\frac{vBn\nu(\omega)J}{\hbar\omega_0}\int P(\omega-\omega')\rho(\omega')d\omega' + \frac{Nz(\omega)}{\hbar\omega_0}-\frac{sn\nu(\omega)}{T}+\frac{snz(\omega)}{T}. \quad (2)$$

Here T is the time of spontaneous de-excitation of the atoms, v the velocity of light in the medium, ω_0 the frequency corresponding to the maximum observed luminescence band, J the volume density of the stimulated-emission energy, $\rho(\omega)$ its spectral distribution, N the pump power absorbed per unit value, z(ω) the distribution of the unexcited atoms (luminescence centers) with respect to the position of the luminescence maximum, and s the probability of migration of the excitation between two centers within the time T. All the aforementioned distribution functions are normalized to unit area:

$$\int z(\omega)d\omega=1, \quad \int \nu(\omega)d\omega=1, \quad \int \rho(\omega)d\omega=1. \quad (3)$$

The first two terms of the right side of (1) describe the spontaneous and stimulated emission of the excited atoms, the third the excitation of the atoms by the pump, and the last two the migration of the excitations. We took into account the fact that the probability of the stimulated emission of centers of a given type is proportional to the integral of the overlap of their elementary amplification band with the spectral distribution of the generated light. On the other hand, the energy of the pump and of the migrating excitations is distributed among the different types in proportion to their number in the ground state (this number is assumed to be large enough not to depend on the pump intensity).

In Eq. (2) we did not take into account the dependence of the probability of excitation migration between two centers on the mutual placement of their elementary luminescence bands. This dependence (which leads, in general, to a diffusion character of the cross relaxation of the excited centers with respect to frequency) does not play an essential role in the present investigation, since we shall consider below a case when the excitations migrate only between centers with closely lying elementary bands (see the end of Sec. 1).

Solving (2) with respect to ν and substituting in (1), we have

$$\varkappa(\omega)=\frac{Bn}{1+s}\left(\frac{NT}{\hbar\omega_0 n}+s\right)\int\frac{P(\omega-\omega')z(\omega')d\omega'}{1+(u^2-1)\int P(\omega'-\omega'')\rho(\omega'')d\omega''} \quad (4)$$

We have introduced here the parameter

$$u=[1+BvTJ/\hbar\omega_0(1+s)]^{1/2}, \quad (5)$$

which is a measure of the energy of the stimulated emission.

To simplify the calculations we shall assume the function z and P to be Lorentzian:

$$P(\omega)=\bar{\omega}^2/(\bar{\omega}^2+\omega^2), \quad P(0)=1; \quad (6)$$

$$z(\omega)=\frac{q\bar{\omega}}{\pi}\frac{1}{(\omega-\omega_0)^2+\bar{\omega}^2q^2}, \quad \int z\,d\omega=1. \quad (7)$$

Here ω_0 is the maximum of the observed luminescence band, and $2\bar{\omega}$ is the half-width of the elementary band. We have introduced a parameter q, which will play an important role later, and which is equal to the ratio of the scatter of the elementary luminescence bands with respect to the maximum position to the width of the elementary band. This parameter characterizes the degree of inhomogeneity of the broadening of the observed luminescence band.

We shall consider below a region of sufficiently low pumping, in which the following condition is satisfied

$$\delta\omega \ll \bar{\omega}, \quad (8)$$

where $\delta\omega$ is the spectral width of the generation. We can then regard $\rho(\omega)$ as a δ function. Substituting (6) and (7) in (4) and carrying subsequently an elementary integration, we get

$$\varkappa(\omega)=\frac{Bn}{1+s}\left(\frac{NT}{\hbar\omega_0 n}+s\right)\frac{q}{u^2-q^2}\left\{\frac{1-q}{q}\frac{\bar{\omega}^2(q+1)^2}{\bar{\omega}^2(q+1)^2+(\omega-\omega_0)^2}-\frac{1-u}{u}\frac{\omega^2(u+1)^2}{\omega^2(u+1)^2+(\omega-\omega_0)^2}\right\}. \quad (9)$$

Using (8), we expand this expression in powers of $\omega-\omega_0$:

$$\varkappa(\omega)=\frac{Bnq}{1+s}\left(\frac{NT}{\hbar\omega_0 n}+s\right)\left\{\frac{1}{qu(q+u)}+\frac{f_2(u)-f_2(q)}{u^2-q^2}\left(\frac{\omega-\omega_0}{\bar{\omega}}\right)^2-\frac{f_4(u)-f_4(q)}{u^2-q^2}\left(\frac{\omega-\omega_0}{\bar{\omega}}\right)^4+\ldots\right\}. \quad (10)$$

We have introduced here the notation

$$f_2(q)=\frac{1-q}{q}\frac{1}{(q+1)^2}, \quad f_4(q)=\frac{1-q}{q(q+1)^4}. \quad (11)$$

A plot of $f_2(q)$ is shown in Fig. 1.

Let us fix the parameter q and let us vary u, that is, the energy of the stimulate emission. Let at first $q < 1$; then, as can be seen from Fig. 1, the coefficient of the quadratic term of the expansion (10) is negative for all values of u from the allowed interval $(1, \infty)$; therefore, for any value of the light energy, the spectral dependence of the gain has a maximum at a frequency ω_0. This means that if the gain at the point ω_0 compensates for the optical losses, then when $\omega \neq \omega_0$ such a compensation is impossible. Consequently, when $q < 1$ generation takes place only at the frequency ω_0, and inhomogeneous broadening of the luminescence band does not lead to a spectral broadening of the generated radiation. (We shall not deal with other causes of spectral broad-

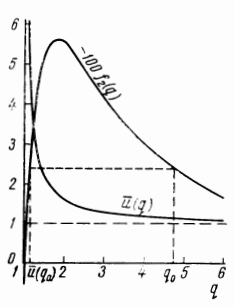

FIG. 1. Plots of the functions $f_2(q)$ and $\bar{u}(q)$ (the law governing the correspondence between q and $\bar{u}$ is shown).

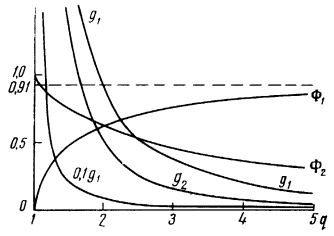

FIG. 2. Plots of the functions that determine the spectral characteristics of the laser.

ening; they are discussed in the introduction and in Sec. 3.)

Let now $q > 1$. Then at the point $u = \bar{u}(q)$ satisfying the equation

$$f_2(\bar{u}) = f_2(q), \quad \bar{u} \neq q \tag{12}$$

(Fig. 1), the coefficient of the quadratic term in (11) vanishes and when $u > \bar{u}(q)$ this coefficient becomes positive; on the other hand, the coefficient of the third-degree term is negative. Consequently, when $u > \bar{u}$ the gain reaches a maximum not at the point ω_0, but at two other symmetrically located points. Therefore generation cannot occur only at the frequency ω_0, and subtends a spectral interval whose order of magnitude is the same as the interval between maxima (for more details see the next section).

It is clear from the foregoing that the quantity $\bar{u}(q)$, which is connected with the light energy by the relation (5), is the threshold of spectral broadening; namely, inhomogeneous broadening of the luminescence band leads to a broaeening of the spectral line of the laser only when $u > \bar{u}(q)$. A plot of $\bar{u}(q)$ is shown in Fig. 1.

Let us express the variable u in terms of the more illustrative parameter ζ, which is equal to the relative excess above the pump threshold energy. To this end we use two equations relating the unknowns n and u with the pump power:

$$\varkappa(\omega_0) = \varkappa_1, \quad \int \nu d\omega = 1$$

(κ_1—light loss per unit length). We can use here for κ formula (9) and for ν the solution of (2). We obtain ultimately

$$(1+q)\zeta = u^2(1+s) + qu - s - q - 1. \tag{13}$$

from which we get the relative excess of the threshold pump power corresponding to the threshold of spectral broadening

$$\bar{\zeta} = \frac{\bar{u}^2(1+s) + q\bar{u} - s - q - 1}{q+1} \equiv g_1(q) + g_2(q)s, \tag{14}$$

where

$$g_1(q) = \frac{\bar{u}(\bar{u}+q) - 1 - q}{1+q}, \quad g_2(q) = \frac{\bar{u}^2 - 1}{q+1}. \tag{15}$$

Plots of the functions $g_1(q)$ and $g_2(q)$ are shown in Fig. 2. It is seen from the figure that these functions decrease monotonically with increasing q, that is, with increasing degree of inhomogeneity of the broadening.

We present asymptotic expressions for $\bar{\zeta}$:

$$\bar{\zeta} = 2(1+s)/(q-1), \quad q - 1 \ll 1; \tag{16}$$

$$\bar{\zeta} = 4q^{-2} - 8q^{-3} + \ldots + s(8q^{-3} - 32q^{-4} + \ldots), \quad q \gg 1. \tag{17}$$

The obtained results can be easily interpreted physically. The broadening of the spectral line of the laser is connected with the independent excitation of the optical centers of different types (the type of the center is determined by the position of the maximum gain). In the case of small excess over the generation threshold ($\zeta < \bar{\zeta}$) the density of the optical energy is not high enough to noticeably alter the form of the amplification band; the latter has a maximum at $\omega = \omega_0$ (just as in the absence of generation), so that generation occurs only at the frequency ω_0. At a finite excess above threshold, it is necessary to take into account the fact that the generated electromagnetic field causes emission predominantly from those excited atoms from which the maximum of the elementary luminescence band ω_{max} is close to the field frequency ω_0; at the same time, the pump excites atoms with all values of ω_{max}. In the case of sufficiently strong pumping ($\zeta > \bar{\zeta}$) the number of excited atoms with $\omega_{max} \neq \omega_0$ increases to such a degree that generation becomes possible not only at the point ω_0, but also at other frequencies; in other words, inhomogeneous broadening of the luminescence band leads to a spectral broadening of the generated light[2)]. It is clear that the larger q, that is, the more pronounced the inhomogeneous character of the broadening, the less $\bar{\zeta}$; when $q < 1$ we have $\bar{\zeta} = \infty$.

It is easy to understand from the physical point of view also the role of the excitation migration. We note first that the distribution of the excited atoms $\nu(\omega)$, which determines the shape of the absorption band, coincides in the absence of stimulated emission with the distribution of the non-excited centers $z(\omega)$. This follows from (2) if we put in it $J = 0$.

The migration of the excitations tends to bring the distribution of the excited centers with respect to ω closer to the distribution of the non-excited centers. This statement is physically obvious, since the migrating excitations become redistributed among centers of different types in proportion to their number in the ground state (this follows also from Eq. (2), from which we see that when $s \to \infty$ we get $\nu(\omega) \to z(\omega)$). Thus, the migration of the excitations smoothes out the influence of the stimulated emission on the form of the amplification band, bringing it closer to the case when there is no stimulated emission. By the same token, the migration increases the threshold of spectral broadening.

We note that under condition (8) the stimulated emission deforms the amplification band only in a small vicinity of its maximum, not exceeding the width of the elementary band $\bar{\omega}$. It is this spectral region to which the action of the excitation migration tending to restore the initial form of the amplification band, is limited. The foregoing justifies our writing down the fundamental equation (2) without allowance for the diffusion character of the cross relaxation with respect to frequency.

2. DEPENDENCE OF THE SPECTRAL WIDTH ON THE PUMP INTENSITY

Let us consider the spectral width of the generated radiation with $\zeta > \bar{\zeta}$, and assume for simplicity that the excess above the threshold of spectral broadening is

[2)]It will be shown below that the generation spectral width $|\delta\omega$ is a continuous function of the pump intensity, and consequently condition (8) is satisfied at sufficiently small excess above the spectral-broadening threshold ζ.

sufficiently small to satisfy the condition (8). Then expression (10) for κ is valid, and has a maximum at two frequencies that are symmetrical with respect to ω_0. The spectral generation width is of the order of the distance between these maxima; hence[3)]

$$\frac{\delta\omega}{\Delta\omega} \cong \Phi_1(q)\left[\frac{\zeta-\bar{\zeta}(q)}{1+s\Phi_2(q)}\right]^{1/2}. \quad (18)$$

Here $\Delta\omega$ is the half width of the observed luminescence band

$$\Phi_1(q)=\left\{\frac{5f_2(u)}{6(1+q)(2\bar{u}+q)[f_4(\bar{u})-f_4(q)]}\right\}^{1/2},\ \Phi_2(q)=\frac{2\bar{u}}{2\bar{u}+q}.$$

Plots of the functions $\Phi_1(q)$ and $\Phi_2(q)$ are shown in Fig. 2; their asymptotic expansion takes the form

$$\Phi_1=\sqrt{5/18}\sqrt{q-1}+\ldots,\quad \Phi_2=1-\sqrt{q-1}/4+\ldots,\ q-1\ll 1; \quad (19)$$

$$\Phi_1=\sqrt{5/6}-o(q^{-2}),\quad \Phi_2=2q^{-1}-4q^{-2}+\ldots,\ q\gg 1. \quad (20)$$

Thus, when $\zeta > \bar{\zeta}$ the spectral width increases with increasing pump in proportional to the square root of the excess above the spectral-broadening threshold. The coefficient of this square root, as seen from (18) and Fig. 2, increases with the parameter q, which characterizes the inhomogeneity of the broadening of the luminescence band, and decreases with increase in the number of excitation migration access.

3. EXPERIMENTAL RESULTS

An experimental investigation of the spectral generation width was made on samples of neodymium-activated glass; this active medium, as is well known, has an inhomogeneously broadened luminescence band. In all the experiments we used KGSS-7 glass; the samples were in the form of cylinders 240 mm long and 20 mm in diameter.

The experimental setup is shown in Fig. 3. The active rod 1, placed in a water jacket, was pumped by four IFP-500 lamps, placed at the foci of a four-lobe reflector (the active rod was in their common focus). The water was circulated with the aid of a TS-4 thermostat, which made it possible to stabilize its temperature accurate to $\pm 1^\circ$. As in our preceding investigation[8,9], we used a resonator consisting of two plane-parallel mirrors 2 and 3, and two positive lenses 4 and 5, arranged symmetrically on both sides of the active sample and coaxial with it. The spectral composition of the radiation was investigated with the aid of an IT-28-30 Fabry-Perot interferometer 8, with air gaps 0.3 and 0.1 mm (in the latter case, a safety blade was used as a liner). To obtain uniformly illuminated rings, a ground-glass plate 7 was placed in front of the Fabry-Perot

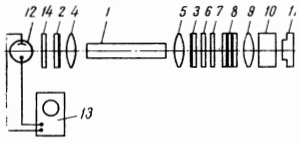

FIG. 3. Diagram of setup for the investigation of the spectral composition and the spectral characteristics of the laser.

interferometer. The interference pattern was focused with the aid of lens 9 on the cathode of an electron-optical converter 10, having a resolution of 40 lines per mm, and was photographed with a camera 11. The linear operation of the electron-optical converter was ensured by means of the neutral filters 6.

Simultaneously with the spectral composition, we investigated also the kinetics of the generation. The radiation receiver was a TsV-3 photocell 12, the signal from which was fed to an IO-4 oscilloscope 13. Attenuating optical filters 14 were also placed in front of the photocell.

It was shown in[8,9], that the spectral width of the generation and the regularity of the kinetic regime greatly depend on the distance between reflectors, on the optical strength of the lenses, and on their position in the resonator. In accordance with the data of these papers, the experiments were performed at optimal values of the resonator parameters, namely the focal distance of the lenses was 220 mm and the distance between lenses was approximately 400 mm, and the distance between reflectors 420 mm. At such an arrangement of the lenses, their foci did not go beyond the limits of the sample, and the sum of the focal distances of the lenses (with allowance for the refraction of the light in the active rod) greatly exceeded the distance between the lenses.

We investigated the width of the emission spectrum on the pump energy at different active-element temperatures. The results of the experiments are shown in Fig. 4 and 5.

At not too large an excess above generation threshold, we observed in the entire investigated temperature range (from 20 to 90°C) one spectral line of width 3—5 Å. The structure of this line was not resolved on the interference pattern obtained with a ring of thickness 0.3 mm (Fig. 4a).

The solid lines of Fig. 5 show the experimental dependence of the spectral generation width on the relative excess above the pump energy threshold ζ. As seen from the figure, the spectral width remains practically unchanged when ζ increases up to a certain value $\bar{\zeta}$, corresponding to the spectral-broadening threshold.

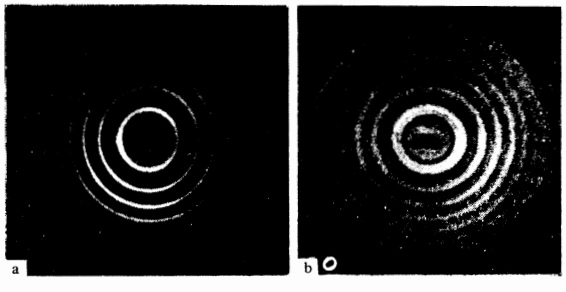

FIG. 4. Fabry-Perot interference patterns at 20°C for an air gap thickness 0.3 mm: a – relative excess over the generation threshold $\zeta = 0.2$, b – $\zeta = 0.3$.

[3)] Apparently two maxima of the amplification band cannot be realized in the stationary regime. It is more likely that over the extent of the generation band the amplification coefficient approaches a certain constant valve (but is not strictly constant). The existence of two maxima when $\zeta > \bar{\zeta}$ follows from formula (4) in the zeroth approximation in the small parameter. Allowance for the higher terms of the expansion in this parameter would lead to an insignificant deformation of the amplification band, with its area remaining constant, as a result of which, apparently, the gain would approach a constant value over the generation line. The numerical coefficient in (18) was determined with allowance for this circumstance.

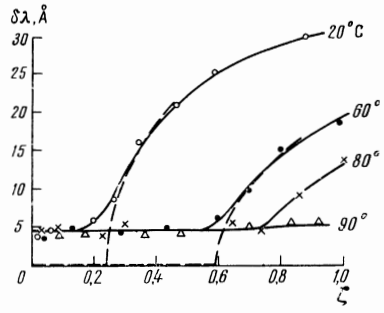

FIG. 5. Dependence of the spectral radiation width on the relative excess over the generation threshold of different temperatures. Solid lines – experimental data, dashed – calculated curves.

The spectral-broadening threshold $\bar{\zeta}$ increases rapidly with increasing temperature ($\bar{\zeta}$ triples in the interval from 20 to 80°C). After the spectral-broadening threshold is reached, the spectral width begins to increase rapidly with increasing pump, and new lines appear in the spectrum (Fig. 4b).

It is seen from Fig. 5 that the experimental points fit quite well a curve of the form $\delta\omega/\Delta\omega = a\sqrt{\zeta - \bar{\zeta}}$ (shown dashed in the figure). Equating the experimental values of a and $\bar{\zeta}$ to the expressions obtained for these parameters in the preceding sections, we obtain two equations for the two unknown parameters q and s, which describe the properties of the active medium. When $q \gg 1$ it is easy to obtain solutions for these equations in explicit form. Using formulas (17), (18), and (20), and confining ourselves to the lowest terms of the asymptotic expansions, we get

$$q = \sqrt{\frac{10}{3a^2\bar{\zeta}}}, \quad s = \sqrt{\frac{5}{6a^2\bar{\zeta}}}\left(\frac{5}{6a^2} - 1\right) \quad \text{for } q \gg 1. \quad (21)$$

Thus, the experimental dependence of the spectral width on the pump makes it possible to determine uniquely each of the parameters q and s.

The experimental curves shown in Fig. 5 can be explained only by assuming $q \gg 1$. For example, when T = 20°C, the experimental value of $\bar{\zeta}$ is 0.25; it follows from (14) that in this case we always have $g_1(q) < 0.25$, so that $q > 3.7$ according to Fig. 2. This allows us, in comparing theory with experiment, to use the asymptotic formulas presented above. We obtained in this manner the following values of the active-medium parameters[4)]: q = 13 and s = 90 at T = 20°C, and q = 12 and s = 190 at T = 60°C. (Following Snitzer[3], we assumed the half width of the luminescence spectrum to be 180 Å.) The presented values of q agree sufficiently well with Snitzer's data[3], according to which the half-width of the elementary luminescence band is 20 Å.

It must be noted that the values obtained by us for q and s are only estimates. This is connected both with certain non-principal assumptions which were made in the preceding sections to simplify the calculation, and with the heating of the active sample during the pumping.

The dashed curves in Fig. 5 are plots of the spectral width against the pump, calculated from formulas (14) and (18) with the values of q and s obtained by us. It is seen from the figure that the theory developed above describes sufficiently well the experimentally observed dependence of the spectral generation width on the pump intensity. Some discrepancy between the theoretical curves and the experimental data occurs in the region $\zeta < \bar{\zeta}$, where the observed spectral width has a nonzero value near 5 Å, which practically is independent of the pumping. This is connected with other causes of the spectral broadening of the generated light, which have no bearing on the inhomogeneous broadening of the luminescence band[5)] and are not taken into account in the theory. Apparently, the dependence of the position of the maximum of the luminescence on the temperature, which varies during the course of the generation, comes into play here.

As regards the spectral broadening connected with the spatial inhomogeneity of the gain, it apparently plays no noticeable role here. In fact, in all the described experiments, the generation was effected in a regular kinetic regime (regular damped oscillations were observed). Yet, as shown in[8], in those cases when the spatial inhomogeneity of the gain leads to a spectral broadening of the generation, it is accompanied also by disturbance to the regular kinetic regime.

The foregoing results offer evidence of the strong temperature dependence of the spectral generation width. This dependence is predominantly connected with the temperature dependence of the excitation-migration probability. The migration of the excitations is also manifest in the fact that a large number of migration axes causes the generation spectral width to be small compared with the luminescence spectral width. The foregoing agrees qualitatively with the data of Snitzer[3], namely that the spectral width of the generation increases with decreased concentration of the luminescence center and with lowering of the temperature.

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4) These values of q and s were obtained with allowance for the higher terms in the asymptotic expansions.

5) This follows from the fact that the influence of the inhomogeneous broadening, by virtue of the mechanisms described above, would lead to a substantial dependence of the spectral characteristics on the pumping.