DYNAMICS OF EMISSION LINE NARROWING FOR A LASER WITH NONRESONANT FEEDBACK

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The dynamics of emission line narrowing for a laser with feedback from a surface or volume scatterer is investigated theoretically and experimentally. In contrast to masers with resonant feedback, line narrowing in these lasers is a fairly slow process. Therefore the emission line width during pulsed operation is limited by the duration of oscillation.

WE have previously[1] proposed a type of laser in which feedback occurs through backscattering of emitted radiation. Feedback from scattering particles exhibits no sharp resonances at the selected frequencies that characterize Fabry-Perot resonators and is nonresonant in this sense. Laser emission with nonresonant feedback possesses properties that differ greatly from the emission properties of ordinary lasers with resonant feedback. The most important difference consists in the fact that the central emission frequency is determined by the resonant frequency of the active substance rather than by the resonator. Other important distinctive characteristics are the absence of space coherence, the dynamics of line narrowing, and the statistical properties. Some properties of emission by a ruby laser with feedback from a scatterer (intensity pulsation, space coherence, divergence) have been investigated in[2]. The present paper reports a theoretical and experimental study of another important aspect, the dynamics of emission line narrowing for a laser with feedback from surface and volume scatterers.

1. THEORY

In a laser having a Fabry-Perot resonator, after the threshold is reached generation proceeds at the spatially resonant frequencies of the electromagnetic field in the resonator. Generation begins with the amplification of spontaneous noise, but the Fabry-Perot resonator ensures effective development only of the standing waves representing its resonant modes.[3] Therefore line narrowing in lasers with resonant feedback occurs very rapidly. For example, the line width for the single mode of a Q-switched laser[4] is practically determined by the pulse duration, which is comparable with the buildup time of oscillations following Q-switching.

The narrowing of the emission line in lasers with feedback from scattering particles is of entirely different character. The absence of space resonances of the electromagnetic field here results in line narrowing through the resonant character of amplification in the active medium. Here the narrowing depends on the predominant amplification of emission at frequencies near the luminescence line maximum of the active medium. Except for the oscillation buildup time the narrowing process in a time t in a laser with nonresonant feedback resembles the narrowing of the signal in a traveling-wave amplifier of length $l = ct$, where c is the velocity of light, if the luminescence line width and the gain per unit length of the active medium are identical.

The dynamics of emission line narrowing for a laser with nonresonant feedback and with a homogeneously broadened active-medium line can be described by the rate equations for the spectral density $J(\nu, t)$ of photons and the density $N(t)$ of the active particles:

$$\frac{\partial J(\nu,t)}{\partial t} + c\gamma(\nu)J(\nu,t) = c\sigma(\nu)N(t)J(\nu,t) + W_{sp}(\nu)$$

$$\frac{\partial N(t)}{\partial t} + \frac{1}{T_1}(N - N_0) = -2N(t)\int_0^\infty \sigma(\nu)J(\nu,t)\,d\nu, \quad (1)$$

where $c\gamma(\nu)$ is the reciprocal lifetime of a photon in a stochastic resonator, $\sigma(\nu)$ is the cross section for a radiative transition between levels, N_0 is the density of inverted population, determined by pumping, in the absence of emission, $\sigma(\nu)N(t)$ is the gain per unit length at the frequency ν, and W_{sp} is the rate of spontaneous emission by active particles in the laser. Equation (1) does not include terms containing derivatives with respect to ν which are associated with the redistribution of radiation within a line such as that resulting from the Brownian motion of the scattering particles[2] etc. and which determine the finite laser emission line width. Therefore the equations (1) describe unlimited narrowing of the line. The spontaneous emission term in (1) can be neglected in calculating the emission line narrowing.

After the first equation in (1) has been integrated with respect to frequency the resulting balance equations for the total numbers of active particles and photons describe the familiar[5] damped pulsations of the total emission intensity $I(t) = \int_0^\infty J(\nu, t)d\nu$ and the subsequent steady-state yield. The temporal dependence $J(\nu, t)$ of line width is most important for our problem. We integrate the first equation in (1) with respect to time:

$$J(\nu,t) = J_0(\nu) \exp\left\{ c\sigma(\nu) \int_0^t N(t')dt' - c\gamma(\nu)t \right\}, \quad (2)$$

where $J_0(\nu) = J(\nu, 0)$ depends on the spontaneous emission line shape.

Let us consider the asymptotic behavior of the spectrum when the number $N(t)$ of active particles and the total emission intensity $I(t)$ are close to their steady-state values and we can assume $N(t) = N_{st} + n(t)$, with $|n(t)| \ll N_{st}$. Equation (2) can then be transformed into

$$J(\nu, t) \approx \widetilde{J(\nu)} \exp\{c[\sigma(\nu)N_{st} - \gamma(\nu)]t\}, \quad (3)$$

where we have neglected the factor $\exp[c\sigma(\nu) \int_0^t n(t')dt']$ describing small pulsations of intensity about the steady-state value.

Let us assume frequency-independent loss $\gamma(\nu) \equiv \gamma_0$ and a Lorentzian shape of the active-medium line $\{\sigma(\nu) = \sigma_0[1 + ((\nu - \nu_0)/\Delta\nu_L)^2]^{-1}\}$. Then $N_{st} = \gamma_0/\sigma_0$ and, in view of the fact that the emission line in the present asymptotic case is extremely narrower than the active-medium line ($|\nu - \nu_0| \ll \Delta\nu_L$), Eq. (3) becomes

$$J(\nu, t) \approx \widetilde{J(\nu)} \exp\left\{-c\alpha_0 t \left(\frac{\nu - \nu_0}{\Delta\nu_L}\right)^2\right\}, \quad (4)$$

where $\alpha_0 = \sigma_0 N_{st}$ is the steady-state gain of the line maximum ($\alpha_0 = \gamma_0$). From (4) we obtain the emission line width at half-maximum:

$$\Delta\nu \approx 2\Delta\nu_L(\alpha_0 ct / \ln 2)^{-1/2}. \quad (5)$$

Emission line narrowing in a laser with nonresonant feedback occurs quite slowly. For example, with a ruby as the active medium ($\alpha_0 \approx 0.1$ cm^{-1}, $2\Delta\nu_L \approx 5 \times 10^{11}$ cps) in a time $t \approx 10^{-3}$ sec the line is narrowed only to 4×10^8 cps (by a factor of 10^3).

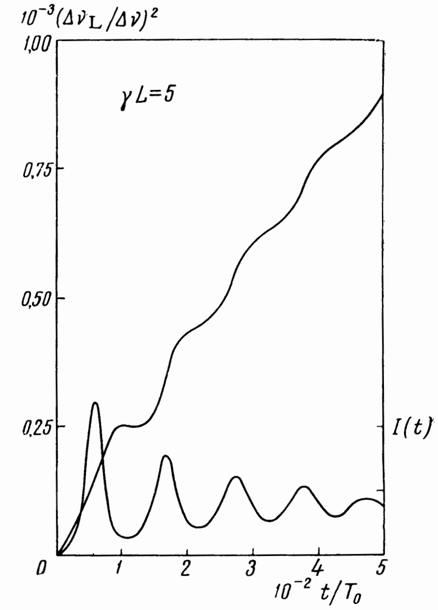

FIG. 1. Line width $\Delta\nu(t)$ and total intensity $I(t)$ of emission from a laser with nonresonant feedback in the region of intensity pulsations.

The asymptotic formula (5) for line width at time t in a laser with nonresonant feedback coincides with the formula for the output signal width of a traveling-wave amplifier of length $l = ct$.[6-8] The given narrowing by the factor 10^3 would be achieved by an amplifier of length $l \approx 300$ km!

As already mentioned, Eq. (5) applies to the region of small intensity pulsations. In the region of strong pulsations, where between spikes the gain drops considerably below α_0, the mean rate of line narrowing is reduced and the line-narrowing law approaches (5) only as the pulsations are damped. A detailed representation of line narrowing in the transition region can be obtained through numerical integration of the equations in (1). Figure 1 shows the time dependences of emission line width and emission intensity for a laser with nonresonant feedback that were obtained in this way. The horizontal axis represents time in units of $T_0 = 2L/c$ (L is the laser length); the vertical axis represents $(\Delta\nu_L/\Delta\nu)^2$ and the total intensity in arbitrary units.

The solution represented in Fig. 1 was obtained for a relatively high pumping rate, when the spike spacing was small. It can be seen that practically no narrowing occurs between spikes, but only within the regions of the latter. At low pumping rates, when the spike separations increase and the emission intensity between spikes becomes comparable with the spontaneous emission level, the spontaneous noise begins to make an appreciable contribution. Spontaneous emission leads to broadening of the

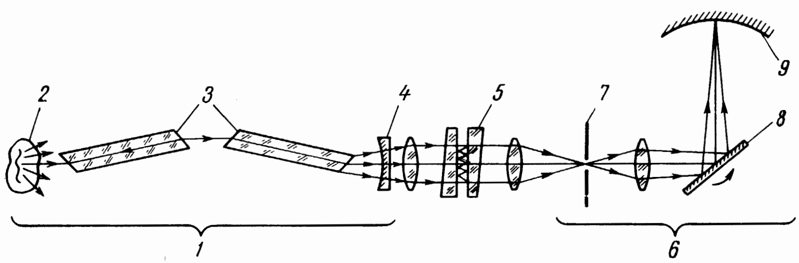

FIG. 2. Experimental arrangement. 1 – laser with nonresonant feedback, 2 – scatterer, 3 – ruby crystal, 4 – spherical exit mirror, 5 – Fabry-Perot interferometer, 6 – high-speed camera, 7 – entrance slit, 8 – rotating mirror, 9 – photographic film.

emission spectrum between spikes, i.e., to pulsations of the line width. The line is narrowed on the average, since the narrowing of the spikes exceeds the broadening between spikes, but the rate of narrowing is considerably slower than would be calculated from Eq. (5).

2. EXPERIMENT

The dynamics of emission line narrowing for a ruby laser with nonresonant feedback has been investigated experimentally. The design and parameters of the laser have been described in[1,2], and the experimental arrangement is represented in Fig. 2. The spectrum obtained with a Fabry-Perot interferometer was scanned by a high-speed SFR camera. The surface scatterers were a magnesium oxide film and matte white paper; the volume scatterers were sulfur hydrosol and smoke aerosol. With these scatterers we were able to elucidate the influence of different types of scatterers on the laser emission spectrum.

Figure 3a shows the emission spectrum obtained with the magnesium oxide surface scatterer. The separation of Fabry-Perot orders was 0.5 cm^{-1}. The gradual narrowing of the emission line during the oscillation period is clearly visible. Curve a in Fig. 4 shows the time dependence of the emission line width $\Delta\nu$ obtained from measurements on the Fabry-Perot pattern Fig. 3a ($\Delta\nu$ in cm^{-1}); the ordinate axis represents $1/(\Delta\nu)^2$. In the region of strong pulsations the line narrowing rate is slowed, but with pulsation damping the narrowing rate increases to the value given by (5). For the purpose of comparison with experiment (5) is expressed more conveniently by

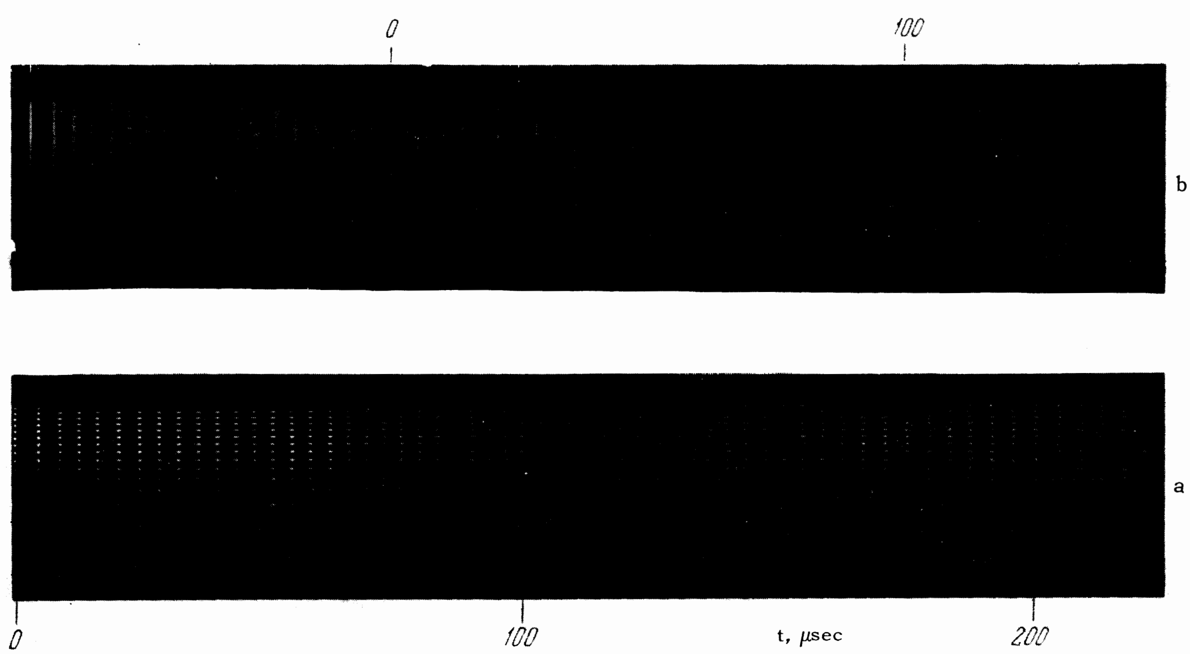

FIG. 3. Laser emission line with a) magnesium oxide scatterer, b) matte white paper scatterer.

$$\frac{1}{(\Delta\nu)^2} = \frac{ct}{\ln 2(2\Delta\nu_L)^2}\frac{\ln k}{L}, \quad (6)$$

where k is the threshold gain in one passage through the active medium, L is the distance between the scatterer and the mirror, and c is the average velocity of light in the laser. In our experiment $k \approx 150$, $L \approx 100$ cm, $c \approx 2.4 \times 10^{10}$ cm/sec, and $2\Delta\nu_L \approx 12$ cm^{-1}. The solid rectilinear portion of curve a in Fig. 4 is the theoretical dependence calculated from (6). As already mentioned, the reduced rate of line narrowing in the transition region is accounted for by the fact that gain in the intervals between spikes is lower than in the spikes themselves.

Figure 3b shows the oscillation spectrum obtained with matte white paper as the surface scatterer. The separation of Fabry-Perot interference orders is 0.2 cm^{-1}. In this case, because of the lower albedo we have the threshold gain $k \approx 250$. Curve b in Fig. 4 represents the experimental function $1/(\Delta\nu)^2$ measured from the Fabry-Perot pattern Fig. 3b and the theoretical dependence (the solid curve) calculated from (6). The agreement between experiment and the theoretical formula (6) in the region of its applicability can be considered satisfactory.[1)]

The dynamics of emission line narrowing can be investigated suitably by interrupting oscillation with a strong external signal (laser quenching) and observing the renewed oscillation. This procedure provides more accurate observation of the threshold time t_0. Quenching was performed experimentally as follows. A pulse from a conventional ruby laser with modulated Q was directed at the scatterer. A portion of the radiation was scattered into the active medium of the laser with nonresonant feedback; this dropped the gain below threshold. Oscillation was interrupted and the renewed oscillation began with a broader line. The frequency of the external pulse differed from oscillation frequency by ~1 cm^{-1}. Figure 5 shows the emission spectrum of a laser with feedback from a matte white paper surface scatterer. The separation of the Fabry-Perot interference orders is 0.2 cm^{-1}. Figure 6 shows line widths measured on the Fabry-Perot pattern in Fig. 5. Oscillation was interrupted at time t = 0. The (solid) theoretical curve fits the experimental points.

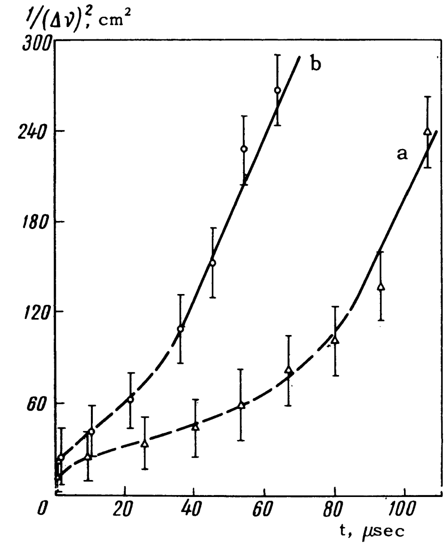

FIG. 4. Time dependence of the emission line width obtained by measuring the Fabry-Perot patterns in Fig. 3.

The dynamics of line narrowing for a ruby laser with nonresonant feedback from a scatterer is in good agreement with the foregoing theory for a homogeneously broadened line of the active medium.

Equations (5) and (6) indicate that in our laser the emission line should be narrowed to about 0.03 cm^{-1} during an oscillation period of the order 100—300 μsec. On the other hand, we have observed narrowing to 0.005 cm^{-1} during this period of time,[2] which would seem at first glance to conflict with the theory. A detailed investigation of this discrepancy showed that it is associated with frequency pulling by the Fabry-Perot system constituted by the faces of the laser exit mirror of thickness d = 1 cm.[2)] Fresnel reflection (4%) from the front face and 70% specular reflection from the exit face of the mirror give maximum reflection at frequencies $\nu_k = kc/2dn$, where k is an integer and n is the refractive index of the glass mirror. Since the separation of the frequencies ν_k is very much smaller than the ruby linewidth ($c/2dn \ll \Delta\nu_L$), the narrowing of the emission line is not determined by the resonance properties of the amplifying material [$\sigma(\nu)$], but rather by the resonance properties of the loss $\gamma(\nu)$. It can easily be shown that in this case narrowing is represented by an expression similar to (5):

$$\Delta\nu = 2\Delta\nu_r[c\alpha_0 t/\ln 2]^{-1/2}, \quad (7)$$

where $\Delta\nu_r$ is the resonance width of the loss $\gamma(\nu)$. In our case we have, in order of magnitude, $\Delta\nu_r$

[1)]Figure 3 shows that the oscillation line is sometimes rebroadened and that oscillation sometimes is interrupted. This effect appears to be associated with instability of the gain at the oscillation frequency, due, for example, to shifts of the ruby luminescence line. Figure 4 shows values of the linewidth for the most stable oscillation periods.

[2)]The experiments described in [2] were performed with a plane exit mirror, which in the present experiments were replaced by a spherical mirror.

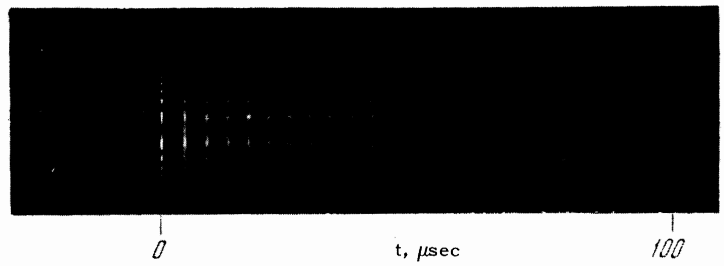

FIG. 5. Laser emission with feedback from a matte white paper surface scatterer with interruption of oscillation by a strong external light pulse.

$\approx 1/2dn \approx 0.3$ cm^{-1}. Therefore the first spike ($t = 5$ μsec, $\alpha = L^{-1} \ln k \sim 0.06$ cm^{-1}) has the line width $\Delta\nu \approx 0.01$ cm^{-1}. When oscillation terminates ($t \approx 300$ μsec) the line has been narrowed to 10^{-3} cm^{-1}, which is outside the measuring accuracy limits in[2], where the maximum resolving power of the Fabry-Perot interferometer was ~ 0.003 cm^{-1}. Oscillation frequency pulling by a Fabry-Perot interferometer with a plane mirror is obviated by using a spherical mirror with no resonant reflection loss. We note, finally, that the insertion of various resonance elements in a laser with feedback from scattering particles does not result in space resonances of the electromagnetic field nor does it impair the nonresonant character of the feedback (provided that the latter does not depend on those elements).

We also investigated the oscillation emission line obtained with feedback from volume scatterers. Figure 7a shows the oscillation spectrum obtained with a smoke aerosol. The line narrowing occurs very rapidly, since the threshold gain k is large because of small backward scattering from the aerosol. Figure 7b shows the spectrum obtained with a sulfur hydrosol. The separation of Fabry-Perot orders in both figures is 0.2 cm^{-1}. For feedback from the hydrosol we observe splitting of the emission line into several components and random variation of the magnitude of splitting from spike to spike. This effect is evidently associated with local currents created in the liquid by radiation heating (the hydrosol is opaque), with consequent random Doppler shifts of the frequency. The possibility of this effect was mentioned in[2].

Figure 7c shows the emission spectrum for the hydrosol that was obtained with a Fabry-Perot interferometer having a 15-cm air space. For more rapid line narrowing we used a plane exit mirror. The average separation of the split-line components was $\sim 10^{-3}$ cm^{-1}. To achieve this same result through Doppler shifts the velocity of the local currents in the liquid would have to be $\sim 10^3$ cm/sec. The formation of such currents is quite possible through the absorption of a few tens of Joules of spontaneous and generated light. The hydrosol can evidently be used in low-power lasers (such as gas lasers) with nonresonant feedback.

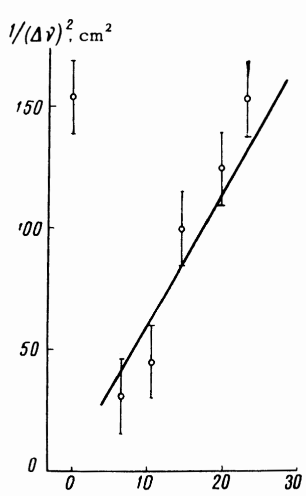

FIG. 6. Measurements of emission line width on the Fabry-Perot pattern of Fig. 5.

3. CONCLUSION

The dynamics of emission line narrowing is an important characteristic of lasers with nonresonant feedback. The investigation of this effect elucidates the physical processes of emission without a Fabry-Perot resonator. The agreement of the theory and experiment shows that the feedback from scattering particles is nonresonant and that the emission frequency is determined by the resonant frequency of the active material.

Further investigations of lasers with nonresonant feedback will include the study of the statistical properties of emission and the action of laser emission on the scatterers. Some periodic rearrangement of the scattering particles in the field of a light wave is possible in principle; this would

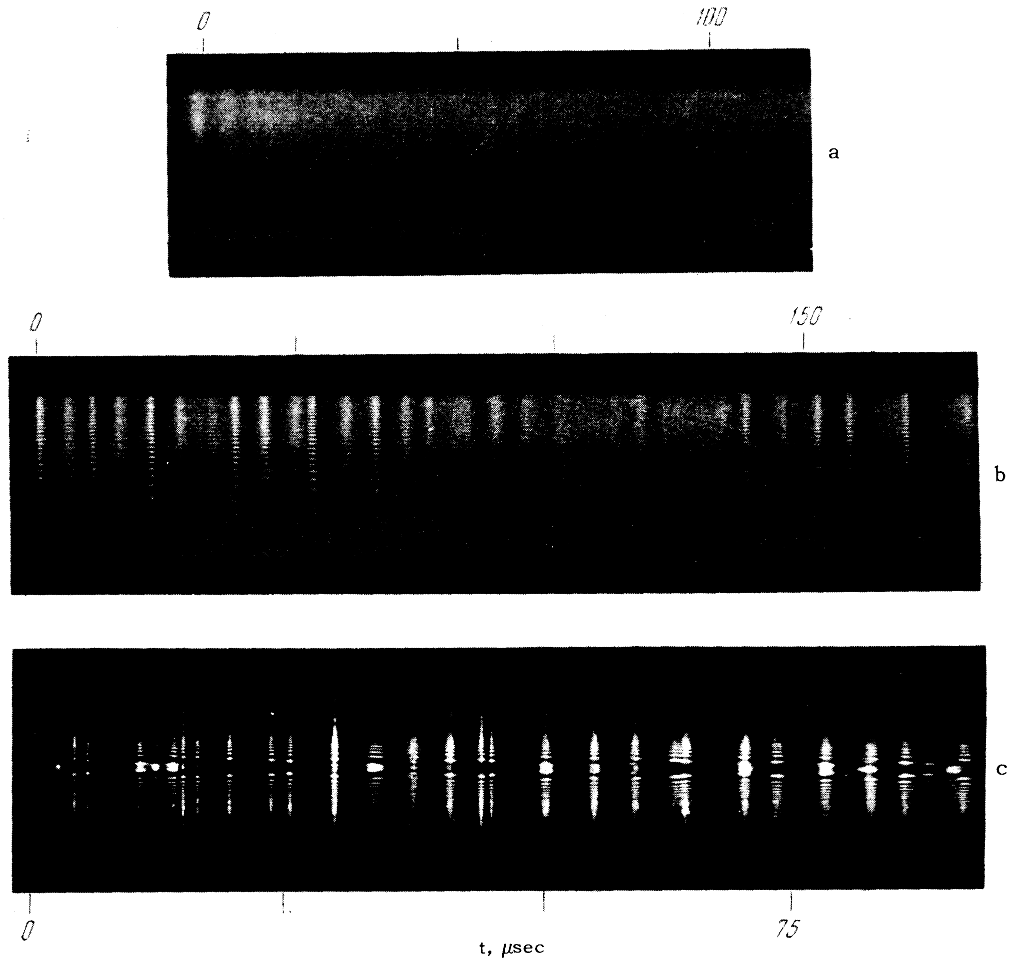

FIG. 7. Emission spectrum of laser with feedback from a space scatterer. a – smoke aerosol, b,c – sulfur hydrosol. Separation of Fabry-Perot orders: a,b – 0.2 cm^{-1}, c – 0.033 cm^{-1}.

enhance backward scattering at certain frequencies. Oscillation with nonresonant feedback would then become autoresonant feedback.[9]

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