EMISSION SPECTRUM OF AN He-Xe *LASER WITH NONRESONANT FEEDBACK*

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The emission spectrum of a CW He-Xe laser ($\lambda = 3.51\ \mu$) is investigated experimentally from the viewpoint of nonresonant feedback operation. Two types of nonresonant cavities are considered: (1) a scatterer and mirror system, and (2) two spherical mirrors enclosing a scatterer. The laser with a quasi-concentric resonator and scatterer generates in a non-resonant feedback mode in which the generation frequency is maintained near the peak of the amplification line with an accuracy of ± 1 MHz regardless of any variation of the geometric dimensions. In conclusion feedback due to resonance scattering by the amplifying particles alone is considered.

1. INTRODUCTION

A laser with nonresonant feedback was proposed and implemented in[1]. The Fabry-Perot resonator was replaced in this laser by a nonresonant multimode cavity[2,3]. If the mode density in the cavity is large, the modes have a low Q and strongly interact with one another, the resonance properties of the cavity vanish because of mode overlap. The resonance amplification line of the active medium thus remains the only resonant element in the laser. The spectral and statistical properties of emission from lasers with nonresonant feedback were studied in[4,5]. The dynamics of spectral narrowing was studied in[4] where it was shown that the narrowing of the spectrum towards the center of the amplification line proceeded slower than in ordinary lasers. This limits spectral narrowing in the pulse mode of generation. In[5] it was shown that the statistical properties of emission from a nonresonant feedback laser are very close to the emission from an extremely bright black body within a very narrow spectral interval. The emission from such a laser has no spatial coherence and no phase stability.

In[1,4,5] pulse-type operation was used and a ruby crystal (at 300°K[1,4] or 70°K[5]) served as the active medium. In[6] nonresonant feedback was obtained in a CW laser with a gaseous active medium (discharge in a He-Xe mixture, $\lambda = 3.51\ \mu$). Preliminary results of investigation of the spectrum and frequency stability in such a laser were reported in[6,7]. In the present work we report on the results of investigating the spectral characteristics of an He-Xe laser with various nonresonant feedback systems[6,7].

An ideal nonresonant feedback laser system is a closed cavity with a volume $V \gg \lambda^3$; the cavity has an internal scattering surface and is filled with the amplifying medium. According to the Raleigh-Jeans formula proved for any volume by Courant[8] spectral mode density in the cavity is

$$P_\nu = 4\pi\frac{V}{c^3}\nu^2 = 4\pi\frac{V}{\lambda^3}\frac{1}{\nu}. \qquad (1)$$

The irregular surface of the cavity ensures the absence of strong mode degeneracy. For example, for $V = 1\ \text{cm}^3$ and $\lambda = 1\ \mu$, the mean frequency interval between the modes $\delta\nu = P_\nu^{-1}$ is only 25 Hz. If we now introduce slight damping due to wall losses, each mode assumes a finite width. For example, if wall losses are 1% the resonance width of each mode is 10^8 Hz, i.e., 10^7 modes fit within the limits of one resonance. The spectrum of natural frequencies of the cavity becomes practically continuous in this case which is the case of a nonresonant feedback.

It is not yet possible to achieve closed-cavity generation because of the difficulties in pumping the active medium within the cavity. Therefore the currently used cavities have a geometry in which the generation angle is much smaller than 2π steradians and yet tolerates a sufficient number of transverse modes. In the experiments described below we used two types of cavities to achieve the nonresonant feedback effect: (1) a system consisting of the scatterer and a mirror, and (2) a system consisting of two spherical mirrors with the scatterer placed between the mirrors. In the first case excitation calls for a high gain that is possible only in long tubes with a small diameter. This restricts the solid generation angle and consequently the spectral mode density. In the second case the generation threshold is lower and the generation solid angle larger. Using such a cavity we were able to obtain generation with nonresonant feedback in which the generation frequency was automatically maintained near the amplification line peak with an accuracy of about ± 1 MHz regardless of the distance between the mirrors.

2. He-Xe LASER WITH SCATTERING REFLECTOR

Figure 1 shows an experimental setup used to study the emission spectrum of a He-Xe laser with a scatterer replacing one of the mirrors. The laser emission was heterodyned with that of an He-Xe scanned-frequency heterodyne laser.

The investigated laser consisted of two He-Xe discharge tubes with DC excitation placed between the mirror and the scatterer. The amplifying tubes had the following parameters: He-Xe mixture in a 50 : 1 ratio under total pressure of 2–3 Torr; internal diameter and length—$D_1 = 0.7$ cm, $L_1 = 50$ cm, $D_2 = 1.4$ cm, $L_2 = 35$ cm; gain per pass reached 400 in both tubes at the wavelength $\lambda = 3.51\ \mu$. The distance between the mirror and the scatterer was $L = 120$ cm. The emission was allowed to emerge from the laser through a small hole 0.5 mm in diameter in the scatterer. The mirror was

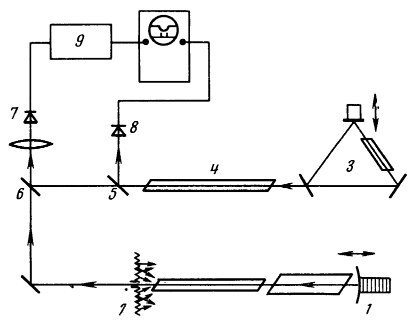

FIG. 1. Experimental setup for the investigation of an He-Xe laser emission spectrum by the heterodyning method: 1 – mirror mounted on piezoceramic; 2 – scatterer; 3 – heterodyne ring laser; 4 – amplifier tube; 5 – beam splitter; 6 – half-silvered mirror; 7 and 8 – photodiodes; 9 – amplifier, $f_0 = 34$ MHz.

mounted on a piezoceramic plate to allow for variation in the mirror-scatterer separation by $\Delta l = 7\lambda/2$.

The He-Xe heterodyne laser had a ring resonator with a perimeter $L_{het} = 68$ cm. The ring configuration was used to prevent frequency capture of the investigated laser in the reflection of light from the heterodyne resonator. The mirror reflection coefficients $r_1 = r_2 = 90\%$; the reflection coefficient of the output mirror $r_3 = 50\%$. The heterodyne frequency was scanned by oscillating one of the mirrors with a frequency of 50 Hz and amplitude of 15–20 μ. The emission of the heterodyne laser was preamplified with a He-Xe amplifier with gain of about 50. A semitransparent mirror was used to mix the beams of the heterodyne and the investigated lasers and the mixed beam was allowed to fall on an InAs photodiode. The entire apparatus was mounted on a massive concrete slab weighing 600 kg and insulated from external vibration by rubber shock absorbers.

The beats signal of the photodiode was fed to the resonance amplifier tuned to $f_0 = 34.3$ MHz and having a pass band of $\Delta f = 2$ MHz. After detection the signal was impressed on one beam of an S1-17 oscilloscope. The second oscilloscope beam recorded the ring laser output power as a function of mirror position, i.e., of the resonator frequency scanned along the Doppler line of heterodyne amplification. It is clear that the receiver system recorded the beats signal when the heterodyne generation frequency $\nu_{het} = \nu_{nres} \pm f_0$, where ν_{nres} is the optical frequency of the investigated laser with nonresonant feedback. We note that the value of f_0 was chosen sufficiently high to avoid laser frequency capture by the unavoidable weak coupling occurring in scattering by the semitransparent plate and the photodiode surface. The frequency dependence of heterodyne generation power (generation region) observed in the trace of the second beam has a maximum in the center of the Doppler line. The centers of Doppler amplification lines of the investigated and the heterodyne lasers coincided well enough (not less than 1 MHz) to show that the composition and pressure of the mixture and the excitation conditions were about the same. Therefore the location of the maxima of the beats signal in the first beam trace could be used to locate the generation frequency relative to the line center in the nonresonant feedback laser.

Figure 2 a shows the observed standard oscilloscopic traces (upper trace—heterodyne generation; lower trace—beats signal power). According to the traces the region of the beats signal is 7 MHz wide. Since the instrument width is ≈ 5 MHz the instantaneous generation spectral width did not exceed 2 MHz. The same width was obtained with the S4-8 spectrum analyzer used to observe the beats spectra of the laser and heterodyne.

Of interest was the behavior of the beats signal when the mirror-to-scatterer distance was smoothly varied up to several λ. In a laser with Fabry-Perot resonator the beats signal shifts approximately 150 MHz in the entire generation region, i.e., the laser frequency depends directly on the mirror separation. In the nonresonant feedback laser the beats signals smoothly shifted 10 MHz relative to the generation region. When the generation frequency shifted approximately by +5 MHz from the center of the line the beats amplitude decreased perceptibly and a new beat signal appeared at the opposite edge of the region (−5 MHz) and gradually displaced the first. This behavior of the generation spectrum can be explained in terms of residual resonances in our cavity with a low mode density.

The mean distance between the modes can be determined from the formula

$$\Delta\nu \approx \frac{c}{2L}\left(\frac{\lambda/a}{\varphi_0}\right)^2, \tag{2}$$

where a is the diameter of the generation region and φ_0 is the angle of generation. In our experiment $\varphi \approx 0.3°$, L = 120 cm, and a remains indeterminate due to the inhomogeneity of amplification across the He-Xe tube[9]. We can approximately assume that $a \approx D_1/2 = 0.35$ cm. In this case computation yields $\Delta\nu = 5$ MHz, which in order of magnitude is in agreement with the observed data.

The generation lineshape observed during a long time interval, when the mirror-to-scatterer distance could change by any magnitude, was measured in the following manner. The distance between the mirror and the scatterer was allowed to change many times by a magnitude of the order of $7\lambda/2 \sim 10\ \mu$ while the shutter of the camera recording the two-beam oscilloscope traces was held open. Fig. 2b shows one of the resulting photographs. The width of the generation line amounts to

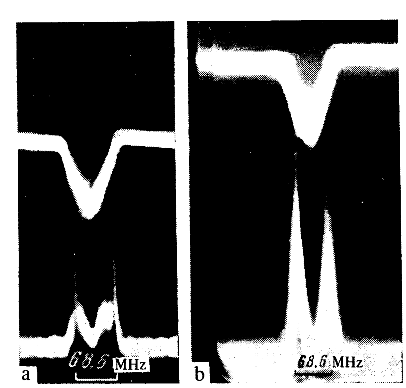

FIG. 2. Oscillograms showing heterodyne generation power (top) and beats signal amplitude (bottom) as a function of heterodyne resonator frequency. a – short-period observation; b – long-period observation covering multiple 10 μ changes in mirror-scatterer separation.

10–14 MHz after subtraction of the 5 MHz instrument width.

Thus the generation frequency in an He-Xe laser was held to the center of the line with an accuracy up to ± 5–7 MHz (the Doppler width of the $\lambda = 3.51\ \mu$ line is $\Delta\nu_{dop} = 120$ MHz); this magnitude was due to the relatively low mode density in the laser. Therefore a further effort was made to design a laser whose geometry would allow for a higher mode density. In particular we concentrated attention on the He-Xe laser with a quasi-concentric resonator.

3. GENERATION IN A QUASI-CONCENTRIC RESONATOR

Interesting features of the generation kinetics in a ruby laser with a quasi-concentric resonator were reported in a number of papers[10-12]. Such a laser was found to generate regular damped pulsations instead of the chaotic pulsations typical of lasers with plane parallel resonators. The emission properties of such a laser were investigated in detail in[12,13]. It was found that the near- and far-field emission distribution in regular operation is fairly homogeneous and easily reproducible in each spike, while the distribution is significantly inhomogeneous in the case of a plane parallel resonator. The introduction of axial or transverse mode selectors can disrupt the regular operation and cause inhomogeneities in the emission distribution. Observation of the beats spectrum from the optical emission mixing process gave a reliable indication that the emission spectrum is continuous. Furthermore the spectral width of 6 GHz reported in[12] can be ascribed to the finite time it takes for the continuous spectrum to narrow down to the line center[4]. All these phenomena find their natural explanation if we assume a nonresonant feedback in such a laser.

The presence of nonresonant feedback in a laser with a concentric resonator can be explained in the following manner. In a resonator with mirrors having a radius R and separation L the natural frequencies are degenerate for L = 2R (concentric resonator). However when the resonator is detuned slightly, by $l = L - 2R < 0$, the degeneracy of axial and nonaxial modes vanishes. The persisting degeneracy of nonaxial modes is removed by disrupting the axial symmetry of the resonator as in the case of astigmatism of the inclined plane-parallel plates in the resonator. Furthermore the condition of L < 2R gives rise to a caustic surface that decreases the losses of high-order transverse modes. The difference in behavior of diffraction losses in the case of transverse modes decreases due to the unavoidable emission scattering in the active medium itself and at the optical surfaces; the scattering mixes the modes. In the experiment described in[12] about $N = 10^6$ transverse modes could be excited and the mean inter-mode frequency distance was only $\delta\nu = 10^2$ Hz. With this mode density the mixing of various modes is possible even during a finite length of the generation pulse as short as $\sim 10^{-4}$ sec[12,13]. Consequently the nonresonant feedback effect can occur in a quasi-concentric resonator, and the results of experiments reported in[12,13] can be explained.

Of considerable interest is the nonresonant feedback effect in a quasi-concentric resonator under continuous generation conditions when the spectral width may be very small.

4. He-Xe LASER WITH A QUASI-CONCENTRIC RESONATOR

The laser consisted of two identical amplifier tubes placed between two spherical mirrors. Each amplifier tube had a length $l = 25$ cm and internal diameter D = 1.0 cm and was filled with a He-Xe mixture (50 : 1) at the pressure of 2.2 Torr. A DC discharge was used to excite the laser. By controlling the current we could vary the gain per pass of the two tubes up to 20. Two spherical mirrors with radii $R_1 = 30$ cm and $R_2 = 40$ cm and a reflection coefficient of about 90%, were placed at the distance $L \approx R_1 + R_2$ that varied by ± 5 cm relative to the concentric distance. The generation threshold was reached with a gain per pass $k_{th} = 1.5$. The maximum angle of the generated emission was $\varphi_0 = 2°$. The emission was allowed to leave the generator through a quartz plate 2 mm thick with a reflection coefficient of 4% mounted inside the resonator at an angle of 45° to the axis.

A. Modulation of output power. One of the symptoms of nonresonant feedback is the independence of the generation frequency from the distance between the mirrors. In an ordinary laser a $\lambda/2$ change in the distance L shifts the frequency by the fairly large amount of c/2L. On the other hand if the generation frequency is constantly bound to the center of the amplification line the output power of the laser is constant when the mirror separation is scanned through $\lambda/2$. Thus the absence of output power modulation during periodic variation of mirror separation can be taken as a convenient indirect indication of nonresonant feedback.

Figure 3 shows the experimental setup for measuring percent modulation of the output power during resonator frequency scanning and for investigating the beats of the photoelectric current. The resonator frequency was scanned by small shifts of mirror 7 mounted for this purpose on piezoceramic plate 8. A DC voltage applied to the piezoceramic displaced the mirror up to 10 μ.

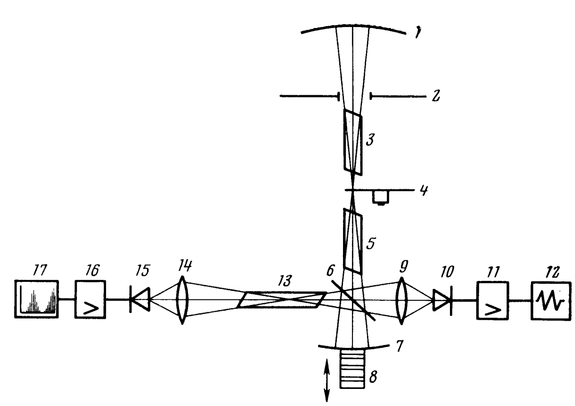

FIG. 3. Setup for measuring percent modulation of He-Xe laser output power with scanned resonator frequency and for investigating the photocurrent beats spectrum. 1 – mirror 40 cm in radius; 2 – iris diaphragm; 3 and 5 tubes with active medium; 4 – modulator; 6 – emission output plate; 7 – mirror 30 cm in radius mounted on piezoceramic 8; 9 and 14 – focusing lenses; 10 and 15 – photodiodes; 11 – resonance amplifier; 12 – oscilloscope; 13 – amplifying tube; 16 – wideband amplifier; 17 – panoramic spectrum analyzer.

The resonator contained modulator 4 and iris diaphragm 2. A part of the laser emission was focused with a quartz lens on In-As photodiode 10. The photodiode signal was measured simultaneously with the recorded spectrum of photocurrent beats.

The distance between the mirrors corresponding to the concentric configuration was equal to $L_0 = R_1 + R_2 - \delta = 69.2$ cm ($R_1 = 30$ cm, $R_2 = 40$ cm, $\delta = 0.8$ cm), taking into account the fact that the resonator had four quartz windows 3.3 mm thick mounted at the Brewster angle and that the quartz output plate was 2 mm thick. Figure 4 shows percent modulation as a function of pump excess over threshold for various differences $l = L - L_0$ between the actual mirror separation L and the concentric separation L_0. The pump power excess over threshold is expressed through the ratio of gain per pass k of the two tubes for a given pump power to the threshold gain per pass k_{th}. The accuracy of measurement of the percent modulation was $\sim 3\%$.

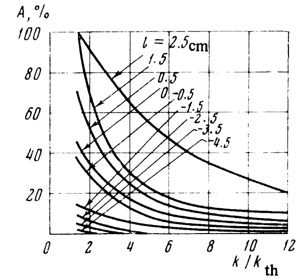

FIG. 4

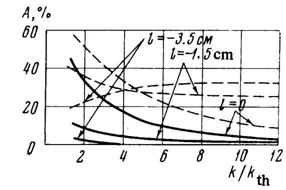

FIG. 5

FIG. 4. Emission percent modulation as a function of pump excess over threshold for various magnitudes of detuning $l = L - L_0$ of mirror separation L relative to the concentric position L_0.

FIG. 5. Emission percent modulation as a function of pump excess over threshold for two values of receiver angle ($\psi = 2°$, solid lines; $\psi = 1°$, dashed lines) and for various mirror separations.

The decrease in percent modulation accompanying an l shift toward confocal position ($l < 0$) can be naturally ascribed to the removal of mode degeneracy and to the decrease of the diffraction losses of the modes assuring effective continuity of the mode resonance curves. The actual observation of this tendency validates the initial assumptions. The increase in percent modulation for $l > 0$ is ascribed to the lower density of the natural frequency spectrum due to a sharp increase of diffraction losses.

The decrease of percent modulation with increasing pump power can be explained as follows. The gain in an He-Xe tube is inhomogeneous in cross section[9]. The gain is maximum in the center and gradually drops off along the radius of the tube. Such an inhomogeneity of gain tends to favor lower-order transverse modes, i.e., it acts as mode discriminator, preventing the occurrence of nonresonant feedback. As pump power increases it causes gain saturation in the center of the tube and equalization of the radial gain distribution. This decreases transverse mode discrimination and promotes nonresonant feedback. Saturation of the transition by a strong electromagnetic wave may also possibly play some role here.

The data shown in Fig. 4 were obtained by recording the output emission within the solid angle of $\varphi_0 = 2°$. If the reduction of percent modulation of the output emission is due to the excitation of various transverse modes whose generation frequency is near the amplification line center, then a decreasing angle of the recorded emission should significantly increase percent modulation. This assumption was verified experimentally and the results are shown in Fig. 5. Percent modulation was measured for two angles of reception, ψ, 2° and 1°. In the first case we recorded almost the entire output emission and in the second, that contained in one quarter of the solid angle. The measurements were made for various pump levels and three values of mirror separation ($l = 0, -1.5$, and -3.5 cm).

A sharp increase in percent modulation in the case of $l < 0$ can be understood on the assumption that generation is confined only to modes coinciding with the center of the amplification line. As the generation frequency is scanned, various packets of transverse modes participate in generation in turn and their frequencies coincide with the amplification line center in each time instant. However the instantaneous direction of propagation of these modes varies within the limits of the solid angle of generation. If the emission is recorded in a narrow solid angle the scanning of the resonator frequency is accompanied by a scanning of the emission direction causing power modulation of the emission incident on the photodiode. Of course if the emission is recorded over the entire solid angle of generation such a direction scanning does not result in power modulation.

B. Beats spectrum in optical mixing. The output emission spectrum of a He-Xe laser with quasi-concentric resonator was also investigated by observing the photocurrent beats spectrum. The experimental setup is shown above in Fig. 3. A portion of the laser emission was amplified by He-Xe amplifier 13 (tube 50 cm long and 0.7 cm in internal diameter) having a gain of about 60; the amplified emission was focused with quartz lens 14 on InAs photodiode 15. The photodiode signal entered panoramic spectrum analyzer 17 via wideband amplifier 16. The scanning period of the spectrum analyzer in photographic operation was 4 sec. The spectrum was recorded within the range from 0.1 to 30 MHz.

Figure 6 shows the variation of the beats spectrum in the frequency band up to 30 MHz for the case of $l = -5.5$ cm with varying pump power. The narrowing of the beats spectrum is clearly apparent (as k/k_{th} varies from 1.3 to 12 generation power doubles). This can be explained by narrowing of the generation spectrum of transverse modes near the amplification line center upon the approach of nonresonant feedback regime. As the resonator detuning l is reduced the narrowing of the beats spectrum weakens and disappears altogether when $l > 0$. Figure 7 shows the variation of the beats spectrum of the photocurrent for the case of $l = +1.5$ cm. As we can see no perceptible narrowing of the beats spectrum can be observed in this case.

We also investigated the beats spectrum as a function of the solid angle of generation. The laser generation angle was varied with an iris diaphragm placed within the resonator. Figure 8 shows the results of these measurements consisting of the beats spectra obtained at a maximum generation angle of $\varphi_0 = 2°$ (a), at an

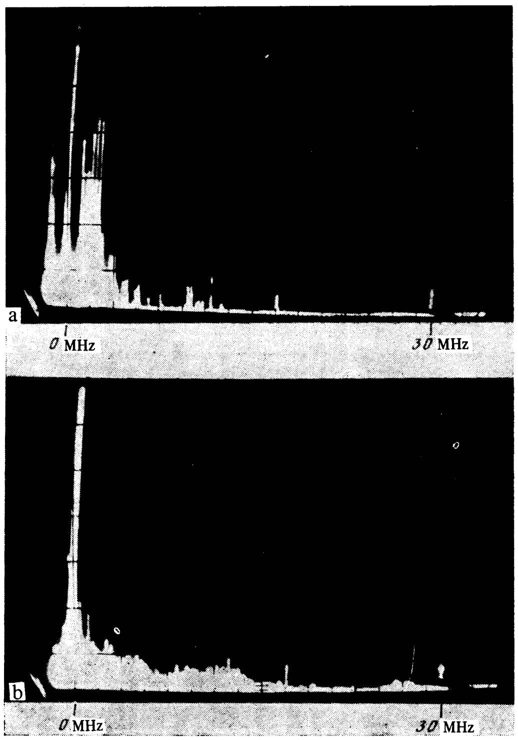

FIG. 6. Photocurrent beats spectrum in a frequency band up to 30 MHz for the case of $l = -5.5$ cm and different pump powers. a – $k/k_{th} = 1.3$; b – $k/k_{th} = 12$.

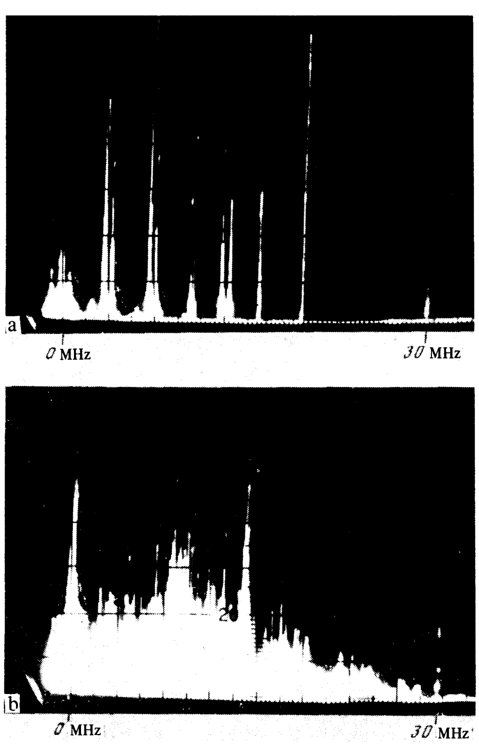

FIG. 7. Photocurrent beats spectrum in a frequency band up to 30 MHz for the case of $l = +1.5$ cm and different pump powers. a – $k/k_{th} = 1.3$; b – $k/k_{th} = 12$.

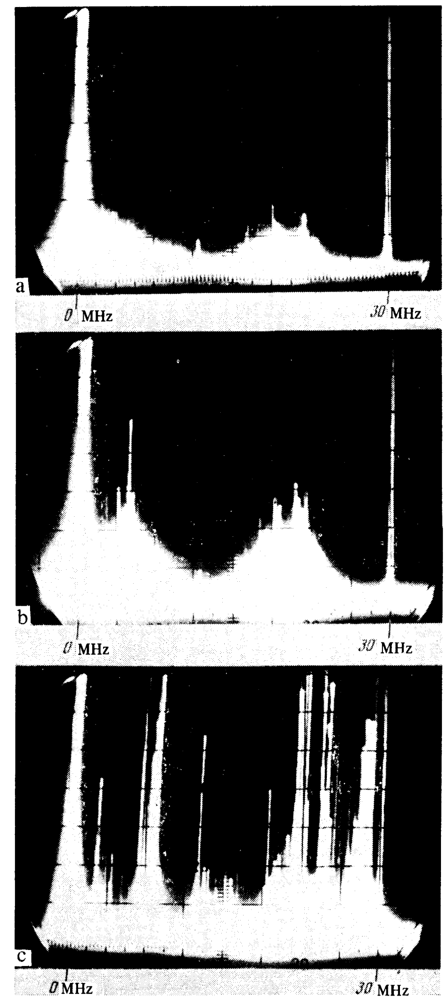

FIG. 8. Variation of photocurrent beats spectrum with reduced generation angle for the case of $l = -1.5$ cm, $k/k_{th} = 12$. a – maximum (2°) generation angle; b – generation angle reduced 1.8 times; c – generation angle reduced 2.4 times.

angle reduced by a factor of 1.8 (b), and at an angle reduced by a factor of 2.4 (c), for the case of $l = -1.5$ cm and $k/k_{th} = 12$. A sharp broadening of the spectrum and an appearance of intense discrete frequencies with decreasing generation angle can be readily observed. Such a behavior of the beats spectrum can be readily explained in terms of nonresonant feedback. At the maximum solid angle of generation the transverse mode density in the resonator is high enough for continuity. In such a case generation is limited to modes near the center of the amplification line. With decreasing generation angle the mode density falls off perceptibly (in the third case mode density is reduced by a factor of 6) and mode overlap becomes small. In this case only the individual high-Q modes are generated and these may lie far from the center of the amplification line.

C. Heterodyne beats spectrum. The frequency stability of He-Xe laser emission was investigated experimentally by the heterodyning method using a setup analogous to that shown in Fig. 1, except for the fact that the investigated He-Xe laser had a quasi-concentric resonator with increased solid angle of generation. The parameters of the investigated laser were as follows:

discharge tube length, 34 cm, internal diameter, 14 mm, mirror reflection coefficients, $r_1 = 90\%$, $r_2 = 35\%$. This method was described in Sec. 2 and only the results of measurements are given here.

Figure 9a shows the beats spectrum of two lasers in short-period (of the order of 0.5 sec) observation. The figure shows that the spectrum consists of two discrete components at a distance of 17 MHz. However the beats spectrum of a single laser with quasi-concentric resonator has no such components and we must assume that the generation frequency jumped 17 KHz during the observation period. Figure 9b shows the beats spectrum of two lasers in long-period observation during which the mirror separation was repeatedly varied by several λ. The figure shows that the spectrum consists of several discrete components extending over 20 MHz. As pumping increases the discrete components vanish but the spectrum broadens up to 25—30 MHz. The broadening of the spectrum seems to be due to the saturation of the peak of the amplification line and the disappearance of the individual components can be ascribed to mode competition in interaction via the active medium.

To enhance intermode coupling in a quasi-concentric resonator we used a scattering plate in the form of a mica sheet with dulled sides. (Mica is transparent to 3.5 μ radiation). Figure 10 a shows the beats spectrum of two lasers photographed with a 0.5 sec exposure. The beats spectrum can be seen to consist of a single component whose width equals the instrument width inherent in the method (5 MHz). During long-term observation when the mirror separation of the quasi-concentric resonator varied through several λ the number of components in the beats spectrum failed to increase (Fig. 10b) although the beats signal had the typical cigar shape. The spectral width measured at the $\frac{1}{2}$ level was $\sim$ 6—7 MHz[1)]. If the instrument width (5 MHz) is subtracted from this value the spectral width is then equal to 1—2 MHz. This means that the generation frequency shifts by not more than 2 MHz when the resonator length changes by several λ.

5. FEASIBILITY OF FEEDBACK THROUGH RESONANCE SCATTERING

So far we considered lasers with nonresonant feedback due to nonresonant surface scattering. However nonresonant feedback can also be achieved by means of nonresonant volume scattering by centers that are directly distributed in the active medium. These laser models were investigated theoretically in[15,16]. We now show that a completely homogeneous amplifying medium can be self-excited by resonant scattering by the amplifying particles themselves. This mechanism can become dominant in amplifying media with radiative relaxation.

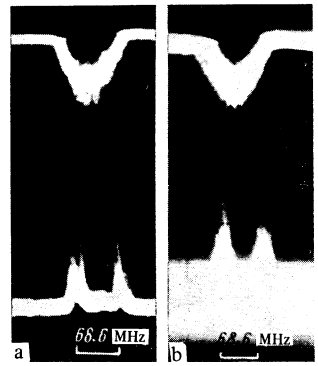

FIG. 9. Beats spectrum of emission from a laser with quasi-concentric resonator and a heterodyne laser. a – short-period observation (of the order of 0.5 sec); b – long-period observation.

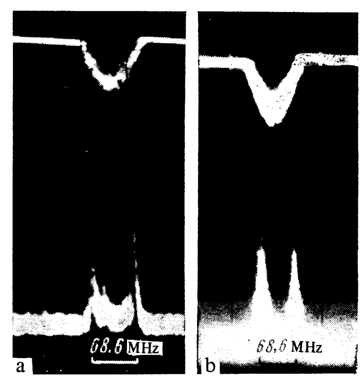

FIG. 10. Beats spectrum of two lasers due to a scattering mica plate introduced into the quasi-concentric resonator. a – spectrum photographed in 0.5 sec; b – spectrum photographed for a long period.

The resonance scattering (resonance fluorescence) cross section of a photon within a solid angle $\Delta\Omega$ is[17]

$$\sigma_s = \frac{\beta^2\omega^4}{c}\sin^2\theta\,\Delta\Omega, \tag{3}$$

where β is particle polarizability and θ is an angle between the incident wave polarization vector and the direction of observation. The particle polarizability in resonance field is in the stationary case[18]

$$\beta = \frac{\sigma_0 c}{4\pi\omega}(\rho_{22}-\rho_{11}) = \frac{p^2 T_2}{\hbar}(\rho_{22}-\rho_{11}), \tag{4}$$

where ρ_{11} and ρ_{22} are population probabilities of the lower and upper levels, p is the dipole transition moment, $T_2 = 2/\Delta\omega$ is the polarization relaxation time (transverse relaxation time), and σ_0 is the radiative transition cross section between the levels. The resonance scattering coefficient per unit length is

$$\varkappa = \sigma_s(N_1+N_2)_{\Delta\omega}, \tag{5}$$

where subscript $\Delta\omega$ means that we consider particles within the spectral interval $\Delta\omega$ corresponding to homogeneous broadening. We can write (5) in the form

$$\varkappa = \frac{\sigma_0^2}{16\pi^2}\frac{\omega^2}{c^2}\frac{(N_2-N_1)^2{}_{\Delta\omega}}{(N_1+N_2)_{\Delta\omega}}\sin^2\theta\,\Delta\Omega, \tag{6}$$

in which we used the relation

[1)]In this experiment and in that described in Sec. 2 the axial mode separation of $c/2L = 430$ MHz of the heterodyne laser cannot be used as the frequency scale for spectral width measurements because of the generation frequency pulling toward the center of the heterodyne amplification line. In the computation of the beats signals this distance must be increased by the factor [15]

$$1+\frac{c}{2L}\frac{1}{2\pi}\ln\frac{1}{r_1r_2r_3}(\Delta\nu_a)^{-1} = 1.6,$$

where $\Delta\nu_a = 120$ MHz is the Xe amplification line width.

$$\rho_{22} - \rho_{11} = (N_2 - N_1)_{\Delta\omega} / (N_1 + N_2)_{\Delta\omega}.$$

The ratio of the coefficient of scattering κ into solid angle $\Delta\Omega = \sin\theta\ \Delta\theta\ \Delta\varphi$ to gain per unit length

$$\alpha = \frac{\lambda^2}{2\pi}\frac{\Gamma}{\Delta\omega}(N_2 - N_1)_{\Delta\omega}$$

then equals

$$\frac{\varkappa}{\alpha} = \frac{1}{8\pi}(\rho_{22} - \rho_{11})\frac{\Gamma}{\Delta\omega}\sin^2\theta\,\Delta\Omega, \qquad (7)$$

where Γ is the probability of radiative transition between the levels. The coefficient of resonance scattering in reverse direction into solid angle 2π steradians is

$$\varkappa_{\text{rev}} = \frac{\alpha}{6}(\rho_{22} - \rho_{11})\frac{\Gamma}{\Delta\omega}. \qquad (8)$$

As we see κ_{rev} is always smaller than α and in the optimal case ($\rho_{22} = 1$, $\rho_{11} = 0$, $\Gamma = \Delta\omega$) the magnitude of $\kappa_{\text{rev}} = \alpha/6$.

Resonance scattering at the characteristic gain length of $1/\alpha$ reflects back a portion of the incident radiation equal to $\sim\kappa_{\text{rev}}/\alpha$. Such a medium will be clearly self-excited if gain per pass $k = e^{\alpha L}$ equals

$$k \approx \frac{\alpha}{\varkappa_{\text{rev}}} = \frac{6}{\rho_{22} - \rho_{11}}\frac{\Delta\omega}{\Gamma}. \qquad (9)$$

We note that feedback due to resonance scattering is nonresonant in the sense that there are no spatial field resonances (modes), but at the same time it has resonant character since the scattering cross section has a maximum precisely in the center of the amplification line.

In the optical range $\kappa_{\text{rev}} \ll \alpha$, first due to the smallness of the factor $\Gamma/\Delta\omega = \Gamma/(\Gamma + \gamma_1 + \gamma_2)$ (γ_1 and γ_2 are probabilities of radiative decay of the levels that is not due to the transition between the levels; usually for amplifying media $\gamma_1 \gg \Gamma$) and, second due to the smallness of the solid angle $\Delta\Omega$ in real amplifying gas-discharge tubes. This phenomenon however can apparently be observed at the amplification lines of He (3.51 μ) and Ne (3.39 μ).

Self-excitation due to resonance scattering can play a significant role in an attempt to achieve generation at the lines of the characteristic electron spectrum of internal atomic shells in the x-ray region, due to the very high transition probabilities Γ ($10^{13}-10^{16}$ sec^{-1}). The absence of good reflectors in this range calls for a considerable gain per pass ($\gtrsim 10$). However in this case the resonance back scattering can be sufficient for self-excitation. The lack of directivity of emission in such a generation process hampers its observation. The only reliable criterion of amplification and generation in such a case is the narrowing of the emission spectrum.

Theory predicts self-excitation in galactic amplifying clouds of OH[19,20] postulating a generation process in which feedback occurs through resonance scattering by the OH molecules. The gain per pass required for self-excitation lies in the range of 10^3-10^5. This value is less than that required to explain the observed emission spectral width at the wavelength λ = 18.5 cm in the laser amplifier model[21]. However this problem deserves a separate discussion.

6. CONCLUSION

The above experiments show that nonresonant feedback allows us to obtain narrow emission lines bound to the center of the amplification line regardless of the stability of the geometric dimensions of the laser. In the He-Xe laser with quasi-concentric resonator and internal scattering plates we obtained a frequency stability of ± 1 MHz (relative stability of 10^{-8}). A further increase in stability should depend on the successful generation in a wider solid angle in an active medium of low pressure gas. The currently available active media fail to yield stabilities much better than 10^{-8}. However the method of nonresonant feedback can in principle yield stabilities of 10^{-10} without any special frequency tuning systems.

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53