NOISE AND OPERATION OF A LASER WITH A ROUGH REFLECTOR AT 3.39μ

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A laser with a rough reflector is investigated using a helium-neon discharge as the active medium operating at the wavelength of $\lambda = 3.39\,\mu$. The setup comprised two tubes in tandem with a total discharge length of 1.5 m providing the necessary high gain of the system. In a preliminary investigation the superradiance at the output of the system was studied with and without a reflector at the other end of the setup, and the power, angular distribution, and spectrum width were determined. The experiments show that reflection from tube walls causes a substantial increase (10–15 times) of the power level without affecting the width of the spectrum. The operation of the laser with the above tubes was investigated when one of the resonator mirrors was replaced by a rough reflector. The system was found to generate from 1 to 3 modes whose frequencies depended on the length of the system. A continuous variation of the angle of inclination of the rough reflector produces random changes in the powers and frequencies of generation, and in some cases an abrupt change in the number of generated modes. The size of inhomogeneities of the rough reflector did not affect the course of the processes. The investigation showed that it is not possible to obtain monochromatic output whose frequency would be independent of the length of the system.

1. INTRODUCTION

AMBARTSUMYAN and others[1, 2] consider the operation of a solid-state laser one of whose mirrors is replaced by a rough reflecting surface. According to these authors such an approach can yield a sufficiently monochromatic emission whose frequency is independent of the length of the system.

The primary goal of this paper is the investigation of an analogous system using helium-neon discharge tubes as the active medium with an emission wavelength of $\lambda = 3.39\,\mu$. Two tubes arranged in tandem had an internal diameter of 3.5 mm, a discharge length of 75 cm each, and Brewster windows at the ends. These dimensions of the active medium provided the high gain necessary in work with a rough reflector. However, the geometry of the system proved to be substantially different from that described in [1, 2]. This problem is considered in greater detail at the end of this paper.

A preliminary investigation was made of the noise intensity generated at the output of an amplifier represented by the two tubes and also when a reflecting mirror was placed at one end of the system. The latter arrangement can be considered as an approximation to the rough-reflector generator; experiments show that the spectrum of the process is only slightly disturbed if the diffuse reflection at the other end of the system is weak enough.

The noise emission at the output of the active medium having a sufficiently high single-pass gain is called superradiance (or superluminescence) in the literature. Superradiance is of interest as a source of a "narrowed" spectrum (in comparison with the transition line of the medium) with a stable mean frequency. We performed experimental studies of the power, angular distribution, and spectrum width of superradiance. The power was computed by Kogelnik and Yariv,[3] who assumed a homogeneous and infinitely wide medium.

These assumptions cannot be applied to the ordinary discharge tubes; according to experiments, the presence of a dielectric (glass) at the active medium interface substantially changes the power level.[1)] Judging from the literature, the superradiance spectrum has not yet been studied experimentally.

After investigating superradiance we studied the properties of the system consisting of the above two tubes, both in the case of ordinary laser generation and when one of the resonator mirrors was replaced by a rough reflector.

2. SUPERRADIANCE

If the transverse dimensions of a homogeneous active medium are sufficiently large, the power P of the observed radiation of the same polarization emitted by an aperture with area S into a small solid angle Ω adjoining a normal to S can be approximately written as follows, according to [3]

$$P = \alpha \frac{S}{\lambda^2} \Omega\, h\nu_0 G(\nu_0) \Pi, \quad \alpha = \frac{n_2/g_2}{n_2/g_2 - n_1/g_1}, \qquad (1)$$

where ν_0 is the mean frequency of the transition line, λ is the wavelength, α characterizes inversion in the medium (n_2 and n_1 are populations of the upper and lower levels, and g_2 and g_1 are their degeneracies), $G(\nu_0)$ is gain at the frequency ν_0 per pass of the active medium assuming that $G(\nu_0) \gg 1$, and Π is the effective spectrum band. Assuming that the transition line of the active medium is broadened mainly because of the Dop-

1)Kluver [4] investigated experimentally the power of noise emission at 3.5 μ (helium-xenon discharge tube). For comparison with theory he used a broad short tube and a system of diaphragms that practically excluded the effect of the finite width of the active medium and its inhomogeneity over the cross section. The gain of the tube was only 50.

pler effect and has a width $\Delta\nu_D$, we can obtain an approximate expression for Π (when $G(\nu_0) \gg 1$):

$$\Pi \approx \Delta\nu_D / \sqrt{\ln G(\nu_0)}. \quad (2)$$

In our case we take $\Delta\nu_D \approx 400$ MHz and $\alpha \approx 1.3$.[2)] The value of $G(\nu_0)$ was determined experimentally by passing a weak signal from another single-frequency laser through the tubes and observing the output signal at the time when the discharge was switched on and off.[3)] The tubes were pumped by dc discharge; the range of variation of the discharge current (from 8 to 20 ma) permitted us to vary $G(\nu_0)$ within the limits from $\sim 2 \times 10^4$ to 4×10^5.

In order to study superradiance within the widest possible range of gain values, and especially those causing saturation in the medium (where the above values for P and Π are no longer valid) we used three different arrangements of the experimental setup and performed three series of experiments (see Fig. 1).

In the first case mirror M was tilted with respect to the tube axis (mirror shown by dashed lines). This results in a consecutive amplification of noise by both tubes with a total gain $G(\nu_0)$. The measured power level is relatively low and there are no attenuators A_2 and A_3.

In the second case mirror M (reflection coefficient 0.95) was adjusted at right angles to the tube axis and the attenuators A_2 and A_3 were installed in place. The A_1 attenuator had a transmission coefficient $\beta = 0.017$. The noise is amplified in a double pass through the tubes; we can readily see that the effective gain is now $G_{eff}(\nu_0) = 0.95\beta^2 G^2(\nu_0)$. These values (found to be within the limits $\sim 10^5 - 4 \times 10^7$) should be used in the computation of power; on the other hand, the factor $0.95\beta^2$ should obviously be dropped in the computation of the Π band.

In the third case the attenuator A_1 was removed. As a result $G_{eff}(\nu_0) = 0.95G^2(\nu_0)$ and its values reached $\sim 2\times10^8 - 2\times10^{11}$. When the gain is as high as that, fairly small parasitic reflection from any part of the setup can seriously disturb the pattern of superradiance and can even cause parasitic generation. Therefore the possible sources of parasitic reflection were carefully examined and eliminated.

In all three cases a small portion ($\sim 10\%$) of the measured emission was split off by quartz plate Q reflected by mirror M, and allowed to enter three-mirror scanning resonator R to determine the spectrum and its width.[4)] The beam emerging from this resonator was focused by lens L_3 onto photodiode D_2. The output voltage of the photodiode was amplified and fed to oscilloscope O whose sweep voltage was the same as that used to scan the resonator. The image on the screen of the oscilloscope could thus be used to study the emis-

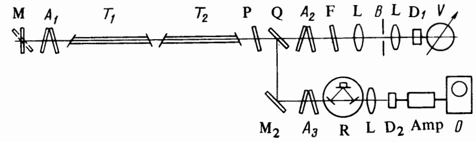

FIG. 1. M – mirror; A_1, A_2, A_3 – attenuators; T_1, T_2 – discharge tubes; P – polaroid; Q – quartz plate; F – filter, L_1, L_2, L_3 – lenses, B – diaphragm, D_1, D_2 – photodiodes; (nitrogen-cooled InSb); V – millivoltmeter; M_2 – mirror; R – scanning resonator; Amp – amplifier; O – oscilloscope.

sion spectrum. We note that with a "pure" superradiance effect, the translational motion of mirror M (mounted for this purpose on a piezoceramic cylinder fed with ac) changed neither the pattern nor the position of the spectrum. On the other hand parasitic reflections in the system caused distortions of the spectrum and its pattern changed when mirror M moved as indicated above. This provided us with a simple experimental method of detecting parasitic reflections.

The superradiance power was measured with photodiode D_1 placed in the focus of lens L_2. The photodiode (together with the lens) was calibrated for this purpose with a low optical power meter. We also allowed for losses in polaroid P and in other components of the setup.

The angular distribution of the radiation was determined by means of lens L_1 and variable-aperture diaphragm B in the focus of the lens. Without the diaphragm the photodiode received practically the entire power of superradiance, while with the diaphragm the power received was limited to the solid angle of $\varphi = d/f$, where d is the aperture diameter and f is the focal length of lens L_1. According to our experiments the dependence of power on φ varied noticeably from one experimental series to another (of the three described above), and to a lesser degree with changing tube discharge current. Figure 2 shows radiation power as function of φ for average values of the discharge current. Power observed without diaphragm B was taken as unity. Curves I, II, and III correspond to the first, second, and third series of measurements respectively. Curve L is given for comparison and shows the function obtained in the usual emission mode of a laser with two flat mirrors.

If the tube walls had no effect, the angle subtended by the emission and defining the region of effective amplification would not exceed the approximate values of $\varphi_1 \approx D/L$ for the first series of measurements and of $\varphi_2 \approx D/2L$ for the second and third series. Here D is the internal tube diameter and L is the total length of

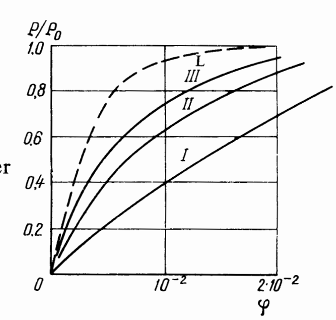

FIG. 2. Emission power P as a function of angle φ. P_0 is the power obtained without diaphragm B.

[2)] This value of α was obtained from the computation at the end of Bershtein's paper [5].

[3)] The accuracy of measurement of $G(\nu_0)$ was low, approximately ±25%.

[4)] Such a resonator does not exert a feedback reaction on the radiation source, in contrast with the Fabry-Perot scanning interferometer normally used for this purpose. This system of spectral investigation was developed by Yu. I. Zaĭtsev and will soon be described in the literature. The resolving power is determined by the resonator bandwidth; in our experiments the bandwidth was 15 – 20 MHz.

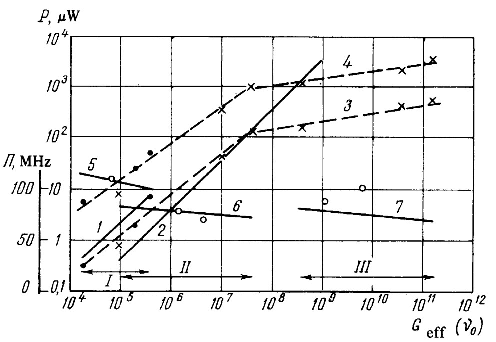

FIG. 3. Emission power P and its spectral band Π as functions of effective gain $G_{eff}(\nu_0)$.

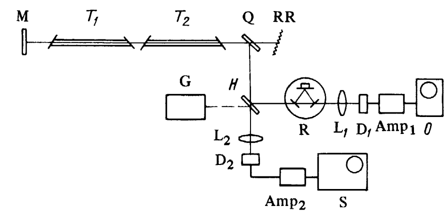

FIG. 4. M – mirror; T_1, T_2 – discharge tubes; Q – quartz plate; RR – rough reflector; G – auxiliary laser; H – semitransparent plate; R – scanning resonator; L_1, L_2 – lenses; D_1, D_2 – photodiodes (nitrogen cooled InSb): Amp_1 Amp_2 – amplifiers; O – oscilloscope; S – spectrum analyzer.

the tubes (~160 cm). In our setup $\varphi_1 \approx 2 \times 10^{-3}$ and $\varphi_2 \approx 10^{-3}$. Figure 2 shows, however, that the emission subtends a markedly larger angle; this is due to reflections from tube walls.

Figure 3 shows the results of measuring the power and the spectrum band of the emission. The values of $G_{eff}(\nu_0)$ in a logarithmic scale are laid off along the abscissa axis, while the emission power in a logarithmic scale and the spectrum band are along the axis of ordinates. The arrows denote the ranges of values of $G_{eff}(\nu_0)$ used in each of the three series of measurements. Curves 1 and 2 (they are practically straight lines) yield the values of P computed according to (1) and (2) when $\Omega = \frac{1}{4}\pi\varphi_1^2$ in the first series, and when $\Omega = \frac{1}{4}\pi\varphi_2^2$ in the second and third series of experiments. Curve 3 is a plot of experimental data obtained with the same values of Ω, and curve 4 represents corresponding data for the full power of superradiance (without diaphragm B). The experimental values are denoted by points for the first series and crosses for the second and third series of experiments. The computed values of Π are shown by curves 5, 6, and 7; experimental data are denoted by circles.

Examination of Fig. 3 leads to the following conclusions: the emission power increases approximately in proportion to the gain up to power values of ~1 mW; any further increase in gain sharply limits the rise of power because of the saturation of the medium.

When the saturation effect is absent, the experimental power data obtained at the above values of Ω do not differ by more than a factor of 2–2.5 from the computed values. Such a discrepancy is quite reasonable if we consider that the computation is approximate and does not account for the cross sectional inhomogeneity of the active medium, and also that the accuracy of measurements was low. However, the full power of superradiance exceeds the computed value approximately 10–15 times. This can be explained by the presence of emission beams emerging from the origin of the system outside the above angle φ_1 (or φ_2) and reflected from the tube walls.[5)] These reflections do not noticeably affect the spectrum band Π and the experimental data are in a good agreement with computations when the medium is free of saturation; the values of Π increase with rising saturation as can be expected from elementary considerations.

The minimum value of the band was ~70 MHz in our experiments. A photograph illustrating the superradiance spectrum is shown in Fig. 5.

3. A LASER WITH A ROUGH REFLECTOR

The peculiarities of a laser with a rough reflector are made clearer by a brief description of our system operating as an ordinary laser. When two plane mirrors were placed at both ends of the tubes at right angles to the tube axis we found that the system generated only a single frequency at high discharge currents (~20 mA). When the discharge currents were somewhat lower, the system generated two frequencies whose difference c/L (~160 MHz) was equal to the double frequency difference between the neighboring longitudinal modes. This can be explained by the fact that the high generation power causes a wide break in the spectral transition line of the material (commensurate with the frequency difference of the neighboring modes) and the phenomenon called "mode competition" reduces the number of generation frequencies. A further decrease in discharge current increases the number of frequencies whose difference becomes equal to c/2L. Tilting one of the mirrors causes the appearance of transverse modes along with the longitudinal modes in the spectrum.

A smooth translation of one of the resonator mirrors produces a smooth change in the generation frequency within a certain range, followed by discontinuous changes ("jumps") in the frequency values.

After this series of experiments, one of the mirrors was replaced by a rough reflector. The experimental setup is shown schematically in Fig. 4. The rough reflector was represented by opal glass, a plate coated with $BaSO_4$, various grades of emergy cloth coated with a thin (≪ λ) silver layer, mat-finish paper, rubber with fine pores, etc. The three dimensional reflector was a suspension of tooth powder in carbon tetrachloride placed in a vessel with a Brewster window. Thus we used reflectors with various dimensions of inhomogeneities: shorter than the wavelength, comparable to the wavelength, and exceeding the wavelength by 1–2 orders of magnitude. The phenomena described below occurred with any type of reflector.

5)On the other hand, one may say that the tube walls increase the number of modes allowed to propagate in the system with sufficient gain. Nevertheless, the complex geometry of the system as a whole and the cross sectional inhomogeneity of the active medium make a quantitative analysis difficult.

We first note that the spectrum of the process as determined by the pattern on the oscilloscope screen O usually consisted of separate flashes whose width (as in the case of the usual laser action) depended on the bandwidth of the scanning resonator (~20 MHz). This serves as a basis for the assumption that the system generates various modes with various frequencies. We observed from one to three such modes.

A smooth rotation of the rough reflector about the tube axis produced an irregular random variation in the spectral pattern in terms of the number of modes, their power levels, and frequency values. These effects were confined to the range of the angles of rotation from 0 to ~60°. A smooth translation of mirror M shifted the generation frequencies so that regions of smooth variation alternated with "jump" changes of frequency. When two or three modes were generated, their frequency difference did not equal c/2L, and further analysis revealed the presence of a single longitudinal mode with one or two transverse generation modes. When the transverse modes vanished, the power of the longitudinal mode increased 5 to 10 times. A reduction in the tube discharge current did not change the above pattern and merely decreased the emission power. Similarly no changes were observed when plane mirror M was replaced by a spherical mirror with a radius of curvature of 2.5 m.

The above observations are illustrated by the spectrum photographs in Fig. 5. The frequency scale on the abscissa axis is determined by the perimeter of the scanning resonator; the distance between recurring flashes is $c/l \approx 450$ MHz. The vertical scales used in the photographs vary.

Figure 5a shows the spectrum (approximately 75 MHz wide) of the superradiance mode of operation. As we noted above, neither its position nor its form are affected by the motions of mirror M. Figure 5b was obtained with the reflector set at an angle; the reflecting surface was opal glass. The low reflection coefficient and a well selected mirror angle resulted in a photograph of the spectrum only slightly distorted as compared to a "pure" superradiance spectrum. Figs. 5c, d, e show typical spectra obtained with a rough reflector; cases of single, double and triple frequency generation are evident.

Since the resolving power of the scanning resonator is low, we used a heterodyning method to obtain a more accurate width of the emission spectrum in rough reflector operation. Plate H (see Fig. 4) received the beam from an auxiliary laser G capable of single-frequency operation and continuous frequency tuning. Photodiode D_2 was exposed to radiation from the auxiliary laser and to the investigated emission. Appropriate adjustment of the equipment produced a frequency difference at the output of the photodiode. The signal was amplified by amplifier Amp_2 and fed to spectrum analyzer S of the S4-8 type. The screen of this instrument displayed the oscillation pattern within the range 1–10 MHz. The frequency difference was not stable because of the low mechanical stability of the investigated system; the setup was comparatively long. However, within the interval of seconds the spectrum defined by the 20 KHz bandwidth of instrument S was the same as that obtained from the ordinary laser action (i.e., when the rough reflector was replaced by a conventional mirror).

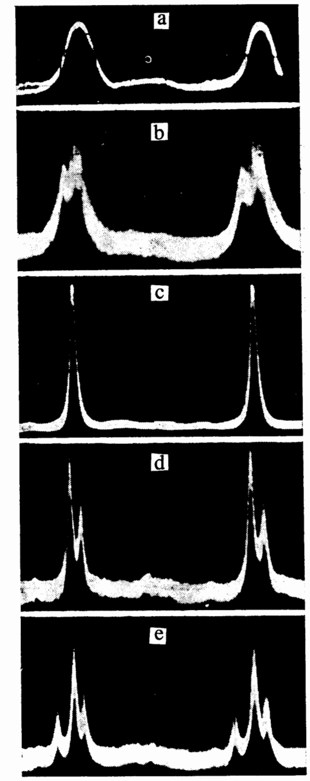

FIG. 5. Photographs of the spectra.

Let us note the order of magnitude of the power emitted by the system. For this purpose a portion of the radiation split off by plate Q was allowed to fall directly on the photodiode, bypassing the scanning resonator. A similar splitting of power was arranged near mirror M (the arrangement is not shown in Fig. 4). In ordinary laser operation, the power in each split-off beam was approximately equal, reaching ~0.6 mV. When one of the mirrors was replaced by the rough reflector, the split-off power was ~0.2–0.3 mW; this power was about 100 times lower near mirror M. Consequently a considerable part of the active medium operated close to the traveling-wave mode. The generation of only one longitudinal mode in the system could conceivably be ascribed to this situation.

In summation we can say that the use of the rough reflector failed to yield radiation whose frequency was independent of the length of the system.

We now consider the results obtained with the use of the rough reflector. Since a quantitative analysis of the processes observed in the system is difficult we are limited to qualitative considerations that may serve to explain the basic experimental facts.

At first we do not consider reflection from tube walls. The radiation falls on the rough surface and we assume that the linear dimensions of the illuminated region equal diameter D of the discharge tube. Reflection causes a random distribution of the electric field on the plane directly adjacent to the rough surface. The propagation pattern of the reflected radiation can be evaluated by expanding it into a series of plane waves limited by a diaphragm with diameter D. The directions of wave vectors of these waves form angles with the normal that differ by the quantity $\sim\lambda/D$.

The radiation travels a path L along the active medium, is reflected from the mirror, and returns to the rough surface. However the angle limiting the effective gain along this path is approximately equal to D/2L. In our case $\lambda/D \approx 10^{-3}$ and $D/2L \approx 10^{-3}$. Therefore, roughly speaking, only one or two waves of the above wave series experience effective gain, and generation conditions are met at frequencies that satisfy the necessary phase relations. The saturation effect ("mode competition") apparently inhibits generation at more than one frequency. Nevertheless it is significant that small changes of L change the generation frequency by altering the phase distribution along the system.

The amplitudes and phases of plane waves comprising the emission reflected from a totally random rough surface are random and uncorrelated. This is due to the fact that insignificant changes of the angle of inclination of the rough surface cause substantial changes in the emission spectrum, such as discontinuous variations in the generation frequencies.

The presence of reflections from the tube walls significantly increases the number of effectively amplified modes (and consequently the number of possible generation frequencies) and apparently is the main cause of transverse modes in the system. It is obvious that the values of these frequencies and powers are also subject to random changes.

The parameters of the system described by Ambartsumyan and others[1, 2] had a substantially different order of magnitude. According to their data, $\lambda/D \approx 4\times10^{-5}$ and $D/2L \approx 10^{-2}$.[6)] Under these conditions there is an effective amplification of a fairly large number of individual waves and apparently it is possible to generate many beams with various frequencies (we do not consider stabilization processes connected with pulse operation).

We take this opportunity to thank K. A. Goronina for a fairly useful discussion of the experimental results and Yu. I. Zaĭtsev for useful advice on the method of investigating the spectra of the processes.

[1] R. V. Ambartsumyan, N. G. Basov, P. G. Kryukov, and V. S. Letokhov, Zh. Eksp. Teor. Fiz. **51**, 724 (1966) [Sov. Phys.-JETP **24**, 481 (1967)].

[2] R. V. Ambartsumyan, P. G. Kryukov, and V. S. Letokhov, Zh. Eksp. Teor. Fiz. **51**, 1669 (1966) [Sov. Phys.-JETP **24**, 1129 (1967)].

[3] H. Kogelnik and A. Yariv, PIEEE **52**, 165 (1964).

[4] J. W. Kluver, J. Appl. Phys. **37**, 2987 (1966).

[5] I. L. Bershteĭn, Izv. vyssh. uch. zav., Radiofizika **9**, 835 (1966).

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141

[6)] The distance 2L corresponds here to a location within the geometric-optics range, since $p = \sqrt{2L\lambda}/D \approx 0.06$. In our experiments, $p \approx 1$.