SOVIET PHYSICS JETP VOLUME 27, NUMBER 3 SEPTEMBER, 1968

CHANGE OF THE SHAPE OF THE GAIN LINE IN THE SATURATION BY THE PROPER FIELD IN A 3.39 μ LASER

M. A. GUBIN, A. I. POPOV, and E. D. PROTSENKO

Moscow Engineering-physics Institute

Submitted July 15, 1967

Zh. Eksp. Teor. Fiz. 54, 701–707 (March, 1968)

A direct observation is made of the change of the gain line of an active substance as a result of saturation in a helium-neon laser with an effective wavelength 3.39 μ. Gaps in the saturated gain line are observed when the generation threshold is greatly exceeded. It is found that the contributions of the homogeneous and inhomogeneous broadening to the total line width are approximately the same. Instability of the generation of two axial modes symmetrically located with respect to the center of the line is observed.

AT the present time, the general laws governing the variation of the shape of the gain line of the active medium of a laser at the onset of generation are known both for homogeneously and inhomogeneously broadened lines. In homogeneous broadening, the entire curve shifts downward from the unsaturated contour $K_{uns}(\nu)$ without changing shape, so that at the generation frequency ν_c there is satisfied the condition

$$K_{sat}(\nu_c) = T/(1-T), \tag{1}$$

where $K_{sat}(\nu)$ is the saturated contour and T is the resonator loss. In inhomogeneous broadening, a dip and its mirror reflection on the Doppler contour are produced at the location of the generated mode, so that condition (1) is satisfied as before. The existence of dips is indirectly confirmed by the presence of a Lamb power drop when the mode is scanned through the center of the line ν_0 [1], by the "hole" repulsion phenomenon described by Bennett [2], etc. Although the existence of dips is not subject to any doubt, no direct observations were made of the saturated gain curve in lasers for either homogeneously or inhomogeneously broadened lines.

In this paper we report direct observations of the saturated gain curve for the transition $3s_2 - 3p_4$ Ne (λ = 3.39 μ) in a helium-neon laser. We used natural neon, i.e., a mixture of the isotopes Ne^{20} and Ne^{22}.

Experimental setup. The experimental setup is shown in Fig. 1. The principle of the experiment is as follows: a weak signal (containing no perturbation) from a single-frequency scanning laser L-1 passes through the investigated traveling-wave laser L-2 along the path abc, and is amplified in the active medium. In L-2 there exists single-frequency generation at a frequency ν_c, as a result of which a certain saturated gain curve $K_{sat}(\nu)$ is established. Scanning the frequency of the first laser, it is possible to pass over the entire line $K_{sat}(\nu)$. Comparison of the form of the signal from L-1, $F_1(\nu)$, with the form of the same signal but amplified in the tube of L-2, $F_2(\nu)$, makes it possible to plot $K_{sat}(\nu)$ for L-2. Inasmuch as the frequency is tuned approximately linearly in time, the functions $F_1(\nu)$ and $F_2(\nu)$ correspond to observable (with the aid of an oscilloscope) time functions $F_1(t)$ and $F_2(t)$, so that we shall henceforth use, without further stipulation, either a frequency scale or a time scale, at our convenience.

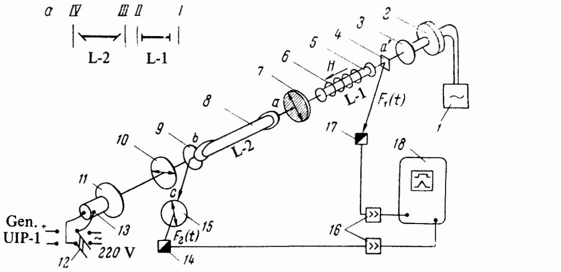

FIG. 1. Diagram of experimental setup: 1 – sound-frequency generator, 2 – telephone speaker, 3 – mirror, 4 – quartz plate, 5 – tube with end windows, 6 – solenoid winding, 7 – polarizer-mirror, 8 – tube with windows at Brewster angle, 9 – quartz plate, 10 – polarizer, 11 – mirror, 12 – switch, 13 – piezoceramic, 14 – photodiode, 15 – polarizer, 16 – amplifiers, 17 – photodiode, 18 – oscilloscope.

Decoupling the lasers. To exclude the mutual influence of the lasers, we use polarizers of calcite [3], 7 and 10, with crossed axes. The radiation of both lasers is polarized linearly and mutually perpendicularly. Polarizer 7 is simultaneously a mirror with small transmission (~1%) for both lasers. The radiation of L-1 passes through mirror-polarizer 7, becomes strongly attenuated as a result of the small transmission of the mirror coating (so that the condition of smallness of the investigated signal is satisfied), passes through the tube of L-2, is partially reflected by quartz plate 9, and is further fully absorbed by polarizer 10. It is important to emphasize that in spite of the fact that all the mirrors are adjusted relative to one axis, mirror 11 has no influence on the resonator of L-1, nor does mirror 3 affect the resonator of L-2. Otherwise, all kinds of regenerative couplings would be produced and the consideration of two separate resonators becomes meaningless. The use of the common mirror 7 is connected to the fact that in the case of a 4-mirror scheme (Fig. 1a) mirrors I, II, and III constitute a compound resonator for L-1. This distorts the emission spectrum of L-1, making the experiment practically impossible.

Structural features of L-1 and L-2. The investigated laser (L-2) had at the single-frequency mode a distance of 800 MHz between modes, and unsaturated gain

3.9 ± 0.1, and a tuning range Δ of approximately 500–600 MHz.

The probing laser (L-1), naturally, requires a broader frequency range Δ than the investigated one. An important factor in this case is the constancy of the signal in the tuning range. The point is that when one frequency is scanned within the limits of the atomic line $K(\nu)$, the plot of the output power is a bell-shaped curve. The steep decrease of the power at the edges, which is further aggravated in the amplified signal by the resonant characteristic of the atomic gain, greatly increases the experimental errors and masks the shape of the atomic gain of the active medium.

It is possible to tune L-1 in a certain frequency range near ν_0 while maintaining a constant output power, by placing the laser in a longitudinal magnetic field H. If the lines of the Zeeman doublet are split approximately by a distance equal to the width γ of the transition, then the total gain for an unpolarized signal will be represented by a curve with a flat top of width γ. The output power of such a laser will also have a similar flat top, provided there is no anisotropy in the resonator of L-1. The presence of polarizer 7 complicates somewhat the picture described above. For example, it turns out that when $H \neq 0$ the loss line already depends on the frequency. In practice, a flat-top power curve can be attained in the single-frequency regime relatively easily (see Fig. 4e below) by choosing H and the initial tuning range Δ (at $H = 0$) by adjusting, using diaphragms, etc. (this regulates Δ by varying the loss T). The magnitude of the initial tuning range Δ should ensure single-frequency laser operation in the presence of a field.

The slight inclination of the flat top (see Fig. 4e) is apparently connected with the asymmetry of the line. The width of the flat top in such a scheme depends strongly on the initial loss, and the largest flat-top width, defined as one in which the power decreases not more than 10%, was 650–700 MHz.

Detecting scheme. The radiation detectors employed were cooled InSb photodiodes (14, 17), the signals from which where fed through low-noise amplifiers to a two-beam oscilloscope (18). Power from the cavity of L-1 was extracted by means of a quartz plate 4, which directed the radiation to receiver 17. Detector 14 received simultaneously the radiation of L-2 and the radiation of L-1 amplified in the tube of L-2 ($F_2(t)$). The signals could be readily separated by using the orthogonality of their polarization.

Achievement of single-frequency generation. Both generators operate in a regime in which two longitudinal modes cannot exist simultaneously in excess of the losses. However, to obtain a single frequency it is also necessary to ensure the presence of only one transverse mode. A characteristic feature of the single-frequency regime is, first, the uniform bell-shaped generation maximum when the mode passes through the line and, second, the constant shape of the observed scanning curve following plane-parallel displacement of the receiver within the limits of the generation spot.

Experimental curves. Figure 2a shows the waveform of the investigated signal $F_1(t)$, and Figs. 2b, c, d show the form of the signal $F_2(t)$ amplified in L-2, with both lasers operating in a single-frequency regime and at different positions of the mode of the cavity of L-2. Since the signal $F_1(t)$ is approximately constant in the 600 MHz range, the amplified signal $F_2(t)$ in the same region represents, with sufficient degree of accuracy, also a plot of the gain of the active medium of L-2. As noted above, elimination of the mutual influence of the resonators (feedback) is in principle essential for the performance of the experiment. It is convenient, however, not to eliminate this feedback completely, for which purpose the angle between the polarizers 7 and 10 (Fig. 1) is set somewhat different from 90°. In this case, when the investigated signal passes through the position of the mode ν_s of L-2 (ν_s is fixed), a weak interaction between the frequencies arises in a narrow region near ν_s, and distorts insignificantly the amplified signal at this point. This distortion "marks" the position of the load of L-2 and makes it possible to observe the shifts of the mode to the desired position relative to ν_0 (these "markers," additionally designated by arrows, are shown in Fig. 2). If both lasers emit at only one frequency, then only one "marker" appears and serves as an additional verification of lack of distortion in the experiment.

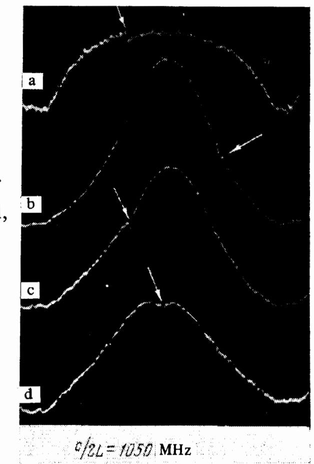

FIG. 2. Saturated gain curve of L-2: a – shape of investigated signal, b – $|\nu_s - \nu_0| \approx 215$ MHz, c – $|\nu_s - \nu_0| \approx 130$ MHz, d – $\nu_s \approx \nu_0$.

Figures 2b, c, d show the drop of the L-2 gain curve with increasing shift of the load towards the center of the atomic line, i.e., with increasing saturation. The unsaturated curve is not shown in the figure, but it lies only slightly above curve b, which corresponds to the largest detuning of the L-2 mode from the center of the line ν_0. Attention is called to the flat top of the unsaturated curve (Fig. 2d) with a small dip in the center. Curve c has only a small dip in the region of the marker, and curve b is somewhat lower than the unsaturated curve and is almost perfectly similar to it. Approximate estimates show that for curve d the excess above threshold is $\eta = K_0/K_{thr} = 1.5–2$, where $K_{thr} = T/(1 - T)$ is the generation threshold, and in this case there is neither a clear-cut dip nor a similarity to the unsaturated curve (or to curve b, which is close to it).

Thus, the general behavior of the saturated curve cannot be set in unique correspondence in this case either with purely homogeneous behavior or with purely inhomogeneous behavior. This can be explained qualitatively by assuming an intermediate character of the broadening of this transition, namely by assuming

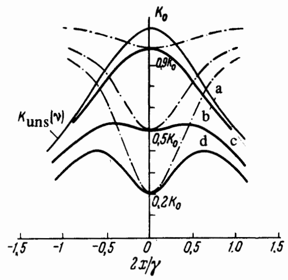

FIG. 3. Construction of saturated gain curve.

the contribution of the homogeneous broadening γ_{hom} comparable with the total width γ, in agreement with the results of our earlier paper[4]. In addition, it is necessary to take into account the influence of the excess η on the results of subtraction from the unsaturated curve $K_{uns}(\nu)$ of the dip with width γ_{hom} and height $K_0 - K_{thr}$. Figure 3 shows the change of the form of the saturated gain curve (heavy lines) at $\gamma_{hom}/\gamma = 1/2$ and at three values of η, namely 1.1, 2, and 5.

In plotting the curves we used the following simplified mathematical model. We approximated the form of the unsaturated line $K_{uns}(x)$ by a Lorentz curve of width γ:

$$K_{uns}(x) = \frac{K_0}{1+(2x/\gamma)^2} \quad (x = \nu - \nu_0). \tag{2}$$

This assumption does not lead to any significant errors, since, first, when $\gamma_{hom}/\gamma \sim 1$ the form of the contour should be some sort of an average between the Doppler and the Lorentz forms, and, second, all the distortions under consideration lie near ν_0 within an interval of γ in which both contours coincide within 5%. Further, we write down the connection between the saturated and unsaturated lines in the form

$$K_{sat}(x) = \frac{K_0}{1+(2x/\gamma)^2} - (K_0 - K_{thr})\frac{1}{1+(2x/\gamma_{hom})^2}, \tag{3}$$

where the last term describes the formation of a dip at the center to a depth to K_{thr} with an initial width γ_{hom}. When $\gamma_{hom}/\gamma \ll 1$ we get from (3) a narrow Lorentz dip at the center against the background of a slightly-varying gain contour outside this dip.

When $\gamma_{hom} = \gamma$, i.e., the entire width γ is due to homogeneous broadening, we get from (3)

$$K_{sat}(x) = \frac{K_{thr}}{1+(2x/\gamma)^2}, \tag{4}$$

i.e., a similar lowering of the contour to K_{thr}, as should be the case for homogeneous broadening.

It is seen from Fig. 3 that at small values of η there is no dip at all in the $K_{sat}(x)$ curve (Fig. 3b). With increasing η, a dip appears and becomes deeper and broader as η grows (Figs. 3b, c). It is obvious that the closer the ratio γ_{hom}/γ to unity, the larger the value of η necessary to observe the dip. Conversely, at a given ratio γ_{hom}/γ, the larger η the sooner the dip becomes noticeable.

Before we proceed to describe the observation of the dips, it is necessary to indicate one more effect connected with the position of the markers in Figs. 2b, c, d relative to the zero power level.

There is no doubt that in the steady lasing regime, regardless of the character of the broadening, the gain at the frequency of the generating mode is constant and equal to $K_{thr} = T/(1-T)$, regardless of the position of the mode relative to the line contour. Since the marker coincides identically with the position of the mode of L-2, the gain at this point should also be constant. Assuming that the input signal $F_1(t)$ is constant, this means that markers with different positions relative to the line contour should lie at the same height above the zero level. Actually, when the marker is far from the center, its height is usually distinctly lower. Thus, if we ascribe to the marker of Fig. 2d a height of 100 units, then the markers of Figs. 2c and 2b are respectively at heights 87, 80, with due allowance for the change in the amplitude of the signal $F_1(t)$ (Fig. 2a) on going from marker to marker.

This effect can be apparently explained in the following manner. The radiation of L-2 is contained inside the resonator in a caustic with maximum field amplitude at the center of the tube (the simplest case of the 00 mode), so that the largest excitation of the inverted population takes place at the center of the tube, and the edge regions near the walls remain untouched. The distribution of the radiation of L-1 over the cross section in the tube of L-2, on the other hand, is smoother, owing to the divergence (which is equal to 7×10^{-3} rad), and therefore it encompasses not only the "excited" regions of the laser tube cross section, but also the "untouched" edges.

Thus, the gain $K_{sat}^{ext}(\nu)$ of the saturated line for an external signal is somewhat larger than the constant gain for the internal radiation. The more pronounced the distribution of the inversion over the cross section, i.e., the more intense the mode, the larger this difference. It is clear therefore that the largest difference $K_{sat}^{ext} - K_{sat}^{int}$ is realized when $\nu_S = \nu_0$; on the other hand, when the mode is detuned off center, the difference decreases and the marker "slides down" to the lower limit (1).

Observation of "dips" in the case of a multiple-frequency regime of L-2. As follows from Fig. 3, to observe a dip in the unsaturated curve at $\gamma_{hom}/\gamma \sim 1$ it is necessary to increase as much as possible the excess of K_0 above threshold, i.e., to increase η. Unfortunately, we were unable to obtain an increase of η while maintaining single-frequency emission from L-2, since, first, to increase K_0 it is necessary to increase the length of the tube and consequently the length of the resonator, and second, at large gains it is difficult to separate one transverse mode without greatly increasing the losses. It is also impossible to increase η at the expense of lowering the losses, since the latter are governed primarily by polarizer 10 in the resonator of L-2 (approximately 25% per pass).

To observe the dips we used in L-2 a tube of length 24 cm and diameter 0.75 mm, which gave a small-signal gain by a factor 9—10. The experimental setup was supplemented with a glass wedge (not shown in Fig. 1), which was introduced between mirror 11 and polarizer 10 in order to regulate the loss in the resonator of L-2. The feedback was completely eliminated, since the position of the mode could be determined quite readily even without the "markers," by means of the dips. The generation in L-2 was realized at least at two transverse modes.

Figures 4a, b, c, d show the unsaturated curve am-

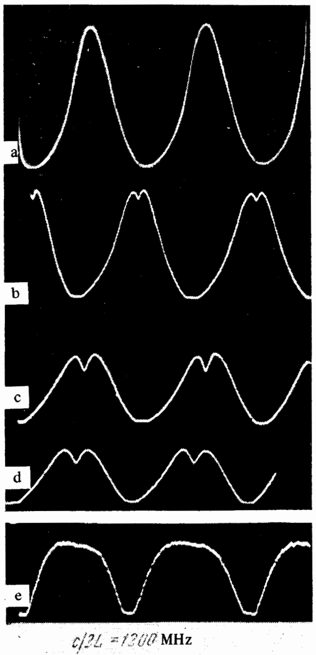

FIG. 4. Broadening and deepening of dip with increasing saturating field.

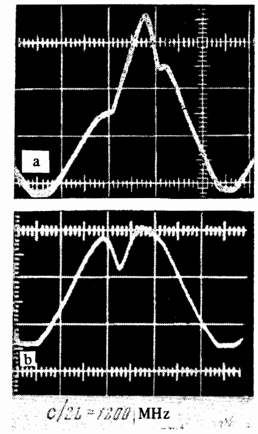

FIG. 5.

plified in the tube of L-2 in the absence of generation (Fig. 4a), and the three saturated gain curves with a dip at the center, corresponding to a decrease of the losses, and consequently to an increase of the generation level in L-2 (Figs. 4b, c, d). It is assumed here that at the given position of the spectrum relative to the line, only one of the two existing transverse modes present in the spectrum generates predominantly. A deepening and broadening of the dip from 90 to 240 MHz is seen (the measurements were made between maxima) in the saturated curve $K_{sat}(\nu)$ when the loss is decreased.

Figures 5a, b show the change of the form of $K_{sat}(\nu)$ at constant loss following a certain shift of the spectrum, as a result of which the central dip (Fig. 5b) is shifted to the left, and a dip due to the second transverse mode appears on the right side. It is obvious that Fig. 5a corresponds to a drop in the intensity of the L-2 emission at the first mode and to an increase at the second mode.

No "mirror" dips were observed, this being more readily due to the non-equivalence of the feedback for the oppositely traveling waves in the L-2 resonator. Indeed, the wave traveling in the direction ba is practically totally reflected from mirror 7 (Fig. 1), while the wave traveling in the direction ab, after passing thrice through the polarizer 10 and the plate 9, returns to the tube attenuated by more than two times.

For the two axial modes located above the threshold an instability of the simultaneous generation regime was observed at the instant when they were symmetrical relative to the center of the gain line.

[1] W. E. Lamb, Phys. Rev. **134A**, 1429 (1964).

[2] W. R. Bennett, Phys. Rev. **126**, 580 (1962).

[3] T. I. Bridges and I. W. Keuver, Appl. Optics 4, 1121 (1965).

[4] M. A. Gubin, A. I. Popov, and E. D. Protsenko, Optika i spektroskopiya 24, (1968).

Translated by J. G. Adashko
83