Amplified spontaneous emission and mirrorless lasers: Theory and experiment

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Investigations of oscillations in mirrorless lasers are presented for 3391 and 3507 nm in He-Ne and Xe discharges, respectively. It appears that the theory, based on the assumption of intensity saturation of the opposite waves, is only confirmed at the central and end parts of the He-Ne discharge. Stimulated reflection is proposed to explain experimental effects.

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I. INTRODUCTION

A He-Ne discharge in a long capillary tube, with a relatively high gain, generates coherent opposite beams of the 3391-nm radiation along the tube in the amplified spontaneous emission [1,2] or superstimulation [3,4]. These beams of small intensities in the discharge center attain large intensities at the discharge ends [3]. However, the above mode of the generation may be extremely changed if one of the beams is reflected into the tube. Then [3–6], the intensity of the beam running towards the mirror is radically decreased, whereas that of the opposite one, running through the tube, is strongly increased. In this paper, we shall call this intensity decreasing a negative or negligible superstimulation (NS) signal.

The NS signal may be observed in an experimental system such as Fig. 1 [4]. In the system, the radiation beam leaving one end of the tube reaches the splitting plate *P*, and its small part reflected aside is registered with the detection set *D*. The remaining part of the radiation, passing through the plate *P*, is beamed to the mirror *M* and reflected back. Between the mirror and the plate we put a mechanical chopper *R*, which gives and bars access to the mirror. When the chopper stops the beam, the detection set shows a signal proportional to the intensity of the beam emitted by the tube without a mirror. Analogously, when the chopper gives access of the beam, the detection set shows a signal proportional to the intensity of the beam emitted by the tube towards the mirror when it reflects the beam into the tube. In this way, the detected signal shows alternatively small (i_s) and large (i_l) radiation as the chopper gives and bars access of the beam to the mirror, respectively.

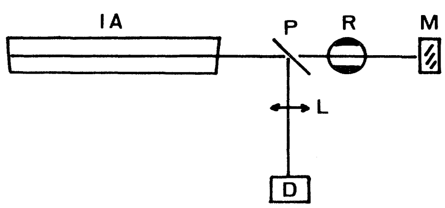

FIG. 1. Experimental setup for investigations of the NS signal. IA is an investigated amplifier, *P*, a fused quartz plate, *M*, a fully reflecting mirror, *L*, a fused quartz lens, *D*, a detection system, and *R*, a mechanical chopper.

In this paper, we present some investigations on the NS in the case of xenon and helium neon electrical discharges, the theory of the NS, and also its relation to the experimental results obtained for a He-Ne long capillary tube. The investigations also concern the pressure conditions of the NS and its dependence on the attenuation of the beam between the mirror and the plate. Such an attenuation is equivalent to a given attenuation of the mirror reflectance.

A. Experimental details

In the experiment, two discharge tubes were used: one of the capillary length of 120 cm, with a cold cathode, and the other, of 150 cm with a hot cathode. Both the tubes with Brewster's windows were made of pyrex capillaries of i.d. of 0.3 cm. The shorter tube was used both for xenon and helium neon discharges, whereas the longer one, for helium neon only.

Detection of the radiation was performed with a $Cd_xHg_{1-x}Te$ element which appeared more suitable in this case than the PbS cell [4]. The suitability of the element is due to its low sensitivity to "nonlaser radiation" below 2000 nm, so the background radiation of the tubes could be ignored. We write nonlaser radiation because the laser radiation is registered by the element even at 632.8 nm.

B. Results

1. Xenon discharge

In the xenon discharge the NS signal at 3507 nm appears at low pressure values, below 0.1 Torr [7]. Here we must admit that due to our measuring difficulties, the pressure in the range above could not be measured with satisfactory accuracy, so we do not give its exact values.

The tube of 120 cm in length was filled with xenon at the pressure of about 1 Torr. After switching on the

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discharge current, the xenon was gradually pumped out until the NS signal appeared.

In Fig. 2, we see displays of the signal at three pressure values: $p_2 > p_1 > p_0$, Figs. 2(a), 2(b), and 2(c), respectively. As is seen, a signal with chaotic pulsing increases with the pressure decreasing, whereas the pulsing is reduced, see Figs. 2(a)–2(c). The display in Fig. 2(c) obtained at the pressure a little below the optimum shows the negligible pulsing. A further pressure decrease below p_0 reduces the signal and at a still lower pressure the signal vanishes completely.

2. He-Ne discharge

The NS signal generated in the ^{3}He-^{20}Ne discharge (9:1) behaves as in the case of xenon. Namely, it appears at some pressure value, about 3 Torr, reaches its maximum at 1.2–1.4 Torr, and disappears below 0.7 Torr, see Fig. 3. Also as in the xenon case, the appearing signal shows pulsing and becomes even with the pressure decrease. The pulsing of the signal depends on the discharge current, that is, an even signal becomes pulsing again when the discharge current is radically increased.

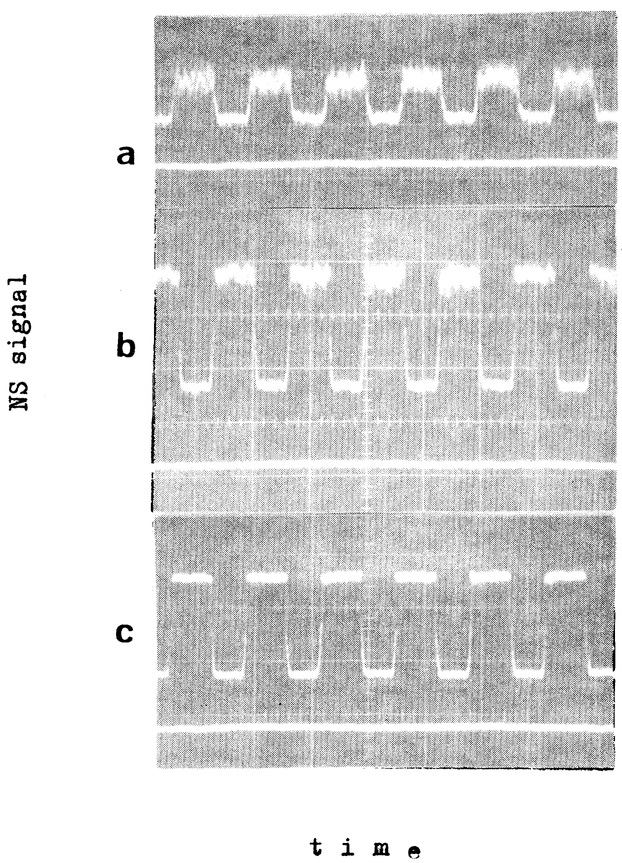

FIG. 2. The NS signal for three different pressure values of xenon. The pressure is reduced from (a) to (c). The line at the bottom of each display means the zero signal obtained when the detection element was screened by a thick block of BK7 glass not transmitting the 3391 radiation.

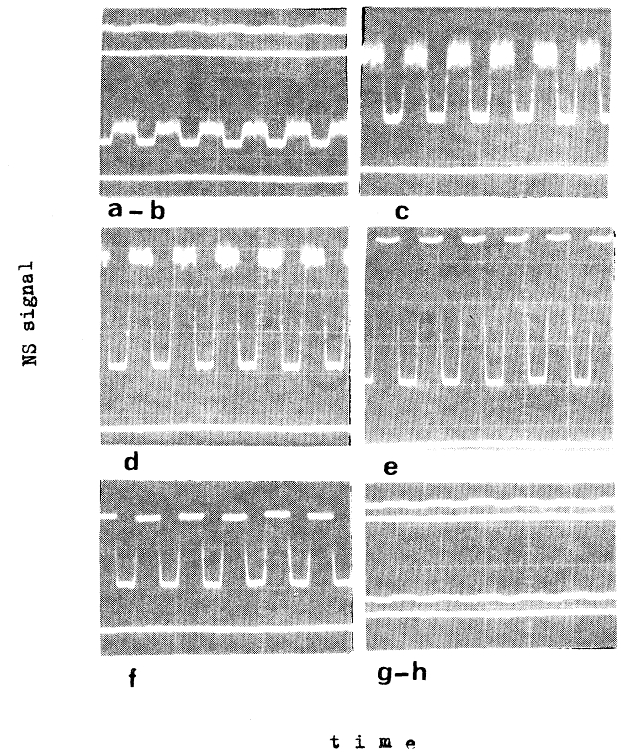

FIG. 3. The NS signal obtained for ^{3}He-^{20}Ne in the 120-cm-long tube at the following pressure values: 3, 2.2, 1.9, 1.7, 1.4, 1.0, 0.75, and below 0.75 Torr, (a)–(b), respectively.

Dependence of the alternate part of the signal on helium neon pressure is shown in Fig. 4.

Generally, the NS signal depends on the total gain of the amplifying medium, hence its dependence on discharge current, pressure of the gases, and other parameters affecting the gain.

The NS signal in the He-Ne discharge of 150 cm in length is far stronger than that of the discharge of 120 cm. Compare Fig. 5 with Fig. 3(e). The main difference between the signals above (both obtained at the optimal conditions) is that i_s in Fig. 5 is closer to the zero display

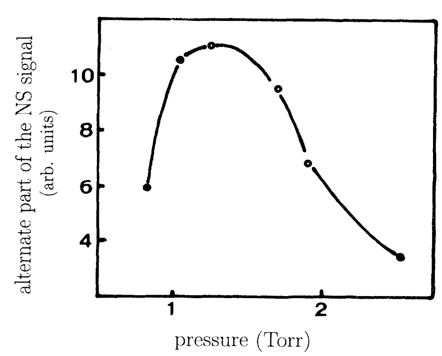

FIG. 4. Dependence of the NS signal on the pressure of the ^{3}He-^{20}Ne mixture.

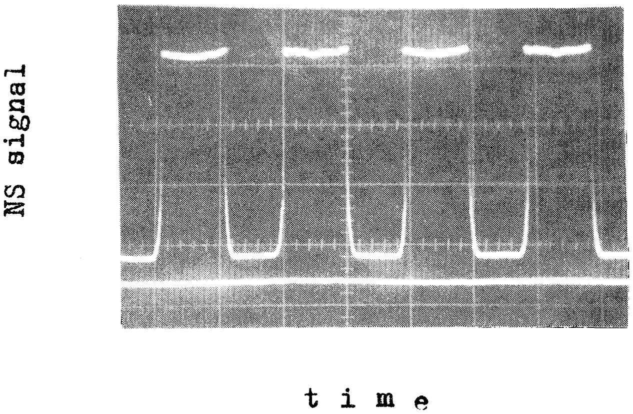

FIG. 5. The NS signal for ^{3}He-^{20}Ne mixture in the tube with discharge of 150 cm in length at the optimal pressure.

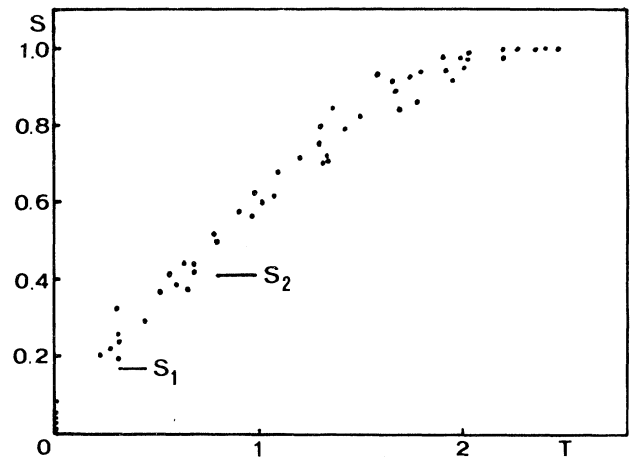

FIG. 6. Dependence of the intensity of the NS signal on attenuation of the 3391 beam between the plate P and the mirror M.

than the one in Fig. 3(e), although in both cases the amplitudes of the alternate part of the signals are nearly the same. To define accurately the above property, we introduce a parameter I, the intensity of the signal, as the ratio of i_l to i_s, measured in respect to the zero signal i_0, developed at the bottom of each display. The theory [1] supplies a relation between I and the amplifier gain, so in the further parts of the paper, we shall present the theory and confront it with the experimental results in detail. Now we may say: the larger I, the greater the gain of the amplifier.

C. Attenuation of the NS signal

The NS signal may be attenuated in a controlled way by putting a number of absorbing plates with well-known transmitivities in front of the mirror M. In this experiment, we used for this purpose soda glass plates each 1 mm thick and of the transmittance of 0.51 at 3391 nm. The transmittance value above was checked by putting each plate in front of the detection element and measuring the attenuation of the alternate part of the signal.

Double absorption of the beam running towards the mirror and back causes that i_s goes up to i_l, and the intensity I decreases to 1. Putting in front of the mirror a plate with transmittance α we have the same situation as if the mirror had the reflectance of α^2. So, in this way, we are able to find out the dependence of the intensity I versus the mirror reflectance.

Notice that the absorbing plates have to be tilted towards the beam, because otherwise a false signal appears as a result of the dispersed reflection from the plates. The same problem concerns the chopper R. For that reason we pasted its blades with black paper and also tilted them towards the laser beam [4]. However, in spite of the precautions above, some small trace of the NS signal due to the chopper was still observed.

In the experiment, I was measured versus attenuation $\alpha=(\alpha_0)^n$ of the n number of plates placed in front of the mirror, where α_0 is the transmittance of a single plate and n followed from one to maximum eight. In Fig. 6 the experimental results are presented in the form of a relation between $S=1-\log_{10}I$ and $T=-\log_{10}\alpha$. Such a form seems to be the most suitable for presentation of the results in the whole range of the measurements. The points in Fig. 6 are spread around the hypothetical curve and this spreading gives us an idea about errors in the experiment. The results in Fig. 6 may be used to estimate the reflectance of various materials such as, Schott Glass BK7, silicon, fused quartz, and so on. The two values S_1, S_2 marked in Fig. 6 were obtained for silicon plates, one with a shiny and the other with a roughly polished surface. Their reflectance values are 0.4 and 0.06, respectively.

Our experiment shows that the NS signal is also induced when instead of the mirror M another He-Ne discharge sample is used. However, in such a case the signal is registered when the discharge in the sample shows a population inversion of the laser levels. It is the experimental fact that the NS signal is not induced by a pure neon sample. One may say, the sample does not reflect back the 3391 radiation of the He-Ne tube.

II. THEORY

In one of my papers [3] I tried to explain the NS by zero interaction, in one-photon transitions, between atoms and the opposite waves. However, long before the above-mentioned paper appeared, Casperson had presented a theory in which the NS may be explained by the gain saturation in the strong amplifiers [1]. So, now I present the main points of Casperson's theory and in the next part I apply it to the results obtained in experiments on a He-Ne discharge in which the NS occurs. The theory describes the evolution of the opposite waves inside the amplifier with an extremely large gain.

A. Free amplifier

To present the theory, let us consider an amplifier of the length l and the diameter d, and two waves falling into the amplifier at the opposite ends. Let the axis of the amplifier be a z coordinate with zero or one starting point at its left end. The question is: how do the intensities of the waves change along the amplifier, assuming that the gain saturation takes place? Following Casperson, in the homogeneous limit, the problem may be described by differential equations:

$$\frac{x^+(z)}{dz}=g_0\frac{x^+(z)}{1+x^+(z)+x^-(z)} , \tag{1a}$$

$$\frac{dx^-(z)}{dz}=-g_0\frac{x^-(z)}{1+x^+(z)+x^-(z)} , \tag{1b}$$

and symmetry and boundary conditions: $x^+(z)=x^-(l-z)$, $x^+(0)=x^-(l)=x_0$, where $x^+(z)$, $x^-(z)$ are intensities of the waves running in the positive and negative z direction, respectively, whereas x_0 is the primary intensity of the waves, and g_0, the unperturbed amplifier gain at the frequency of the atomic transition. The intensities above are expressed in the units of the so-called saturation intensity. Solving Eqs. (1) we obtain [1]

$$x^+(z)=ae^{u(z)}, \quad x^-(z)=ae^{-u(z)} , \tag{2}$$

where $u(z)$ fulfills the following differential equation,

$$g(z)=\frac{du(z)}{dz}=\frac{g_0}{1+2a\cosh u(z)} , \tag{3}$$

which solved with the symmetry condition gives,

$$u(z)+2a\sinh u(z)=G_0\left[\frac{z}{l}-\frac{1}{2}\right] . \tag{4}$$

The constant a may be computed from

$$a=x_0\left[\frac{T}{x_0}+1\right]^{1/2} , \tag{5}$$

$$\ln\left[\frac{T}{x_0}+1\right]+2T=G_0 , \tag{6}$$

where $T=W-x_0$ and W is the intensity output of the waves, and $G_0=g_0l$, the total gain of the unperturbed amplifier. As we see, having x_0 and G_0 we may compute T from (6), next the a from (5), and so on. Equation (3) presents the gain of the amplifier as the function of the z coordinate. The gain attains its maximum at $z=0.5l$; the amplifier central part,

$$g_{\max}=\frac{g_0}{1+2a} , \tag{7}$$

and its minimum at $z=0$ and $z=l$; the amplifier ends,

$$g_{\min}=\frac{g_0}{1+T} . \tag{8}$$

It is clearly seen from the symmetry condition that $u(0.5l)=0$, and that the constant a expresses intensity of the waves in the central part of the amplifier.

B. Amplifier with mirror

Equations (1) may also be used in case of the amplifier with one mirror, such as in Fig. 1. Assuming the mirror of 100% reflectivity is placed at $z=0$, the boundary conditions are: $x^-(l)=x_0$, $x^+(0)=x^-(0)$, and $x^+(l)=W^*$, so we obtain

$$u(z)+2a^*\sinh u(z)=G_0\frac{z}{l} , \tag{9}$$

$$a^*=x_0\left[\frac{T^*}{x_0}+1\right]^{1/2} , \tag{10}$$

$$\ln\left[\frac{T^*}{x_0}+1\right]+2T^*=2G_0 , \tag{11}$$

where a^* means the intensity of the waves at $z=0$, at the place where the mirror M is situated, and $T^*=W^*-x_0$, where W^* is the intensity of the wave leaving the amplifier at the end $z=l$. As seen from (11), the amplifier with a fully reflecting mirror corresponds to the double amplifier with the total gain of $2G_0$. Naturally, in such an amplifier the gain is defined by (3) with a replaced by a^*, and attains its maximum at $z=0$, that is, where the mirror is placed,

$$g_{\max}=\frac{g_0}{1+2a^*} , \tag{12}$$

and its minimum at $z=l$,

$$g_{\min}=\frac{g_0}{1+T^*} . \tag{13}$$

C. Mirrorless and one-mirror lasers

Generally, the solution of Eqs. (1) concerns the problem of outer opposite waves penetrating the amplifier, or the same amplifier with a mirror. If we want to apply it to the lasers, we must assume that $x^+(z)$ and $x^-(z)$ develop without any outside waves, and originate from a spontaneous emission input. The assumption above means [1],

$$x_0=\frac{\lambda^2}{8\pi A} , \tag{14}$$

where λ is the wavelength of the generated waves and A the cross sectional area of the amplifier. Then, formulas (4)–(8) refers to the mirrorless laser, whereas those of (9)–(13), the one-mirror laser.

Discussing the experimental results we must not forget that in the He-Ne discharge the inhomogeneous gain profile dominates over the homogeneous one assumed in the theory presented here. Some aspects of the theory in the inhomogeneous limit we find in Casperson's work. However, not discussing this problem in detail, we may state that, in the first order of approximation, the theoretical results should be averaged in some range of the total gain values, according to the inhomogeneous gain profile.

Finishing this chapter, let us notice that we shall obtain the absolute intensities of the waves by multiplying x^+ or x^- by the so-called saturation intensity given by [1],

$$I_s = \frac{4\pi^2 h\nu\Delta\nu}{\lambda^2} A \ , \tag{15}$$

where ν and $\Delta\nu$ are the frequency at the atomic transition and the homogeneous line width, respectively, and h is Planck's constant.

III. THEORY AND EXPERIMENT

A. Intensity of the NS signal

Now let us apply the theoretical formulas to our experimental results, so let us estimate x_0. This may be done with formula (14) which gives $x_0 = 6.5\times10^{-8}$ at 3391 nm. With the x_0 above we computed W and a^* for any given value of G_0. Next, the obtained results we present in the form of W/a^* as a function of G_0, see Fig. 7, curve B. In Fig. 7 (for comparison) we also present the results obtained under assumption $x_0 = 10^{-4}$, see curve A. Let us notice that introduced here W/a^* corresponds to $I = i_l/i_s$ measured in the experiment. In this way, with experimentally measured intensity I we may obtain the total gain of the discharge tube (G_0) from the curve B in Fig. 7. Computed by this method G_0 for the ^{3}He-^{20}Ne discharge of 150 cm in length equals 10.7 ∓ 0.2.

B. Population and gain

In this part, we shall show how to compute the total gain G_0 having a population of the levels and making use of the formula (13). Let us remember that the formula gives the minimal gain ($g_{\min}$) as a function of the intensity of the outgoing wave generated in the one-mirror laser. Since the intensity, at a given x_0, is determined by G_0, it is possible to compute $g_{\min}/g_0$ as a function of G_0. Such a function was computed and the results are presented in the form of the plot B in Fig. 8; the plot A was obtained under assumption $x_0 = 10^{-4}$.

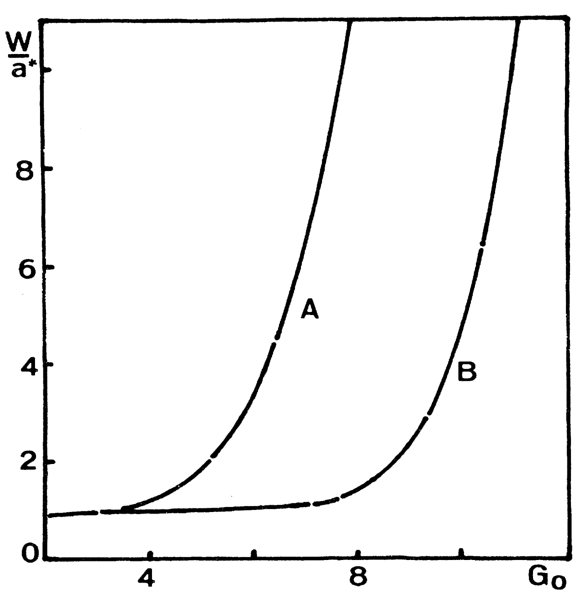

FIG. 7. Dependence of the intensity of the theoretical NS signal on the total gain G_0; the plot A is for $x_0 = 10^{-4}$ and $B, x_0 = 6.5\times10^{-8}$.

Now let us consider how $g_{\min}/g_0$ depends on the populations of the laser levels. Such a dependence we find in the well-known Fuchtbauer's and Ladenburg's formula of gain which applied in our case gives:

$$g_{\min}/g_0 = \frac{\dfrac{N_2}{g_2} - \dfrac{N_1}{g_1}}{\dfrac{N_2^0}{g_2} - \dfrac{N_1^0}{g_1}} \ , \tag{16}$$

where N_2, N_2^0, N_1, and N_1^0 are perturbed and unperturbed populations of the upper and the lower laser levels and g_2, g_1, their statistical weights equal 3 and 5, respectively. Introducing into (16)

$$\delta N_2 = 1 - \frac{N_2}{N_2^0}$$

and

$$\delta N_1 = \frac{N_1}{N_1^0} - 1$$

we obtain

$$g_{\min}/g_0 = 1 - \frac{\delta N_2 + \dfrac{N_1^0}{N_2^0}\dfrac{g_2}{g_1}\delta N_1}{1 - \dfrac{N_1^0}{N_2^0}\dfrac{g_2}{g_1}} \ . \tag{17}$$

The population changes δN_2 and δN_1 are very convenient in experimental works because they can be expressed by percentage changes of 543- and 342-nm lines emitted spontaneously in optical transitions from the $5s'[1/2]_1^o$ and $4p'[3/2]_2$ levels, respectively, registered in the side light of the He-Ne discharge. Also N_1^0/N_2^0, may be spectroscopically measured by the so-called

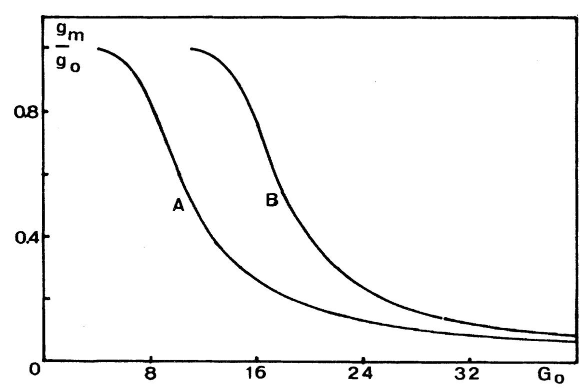

FIG. 8. Dependence of the minimal gain on the total gain G_0; x_0 for the plots A and B as in Fig. 7.

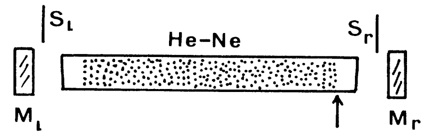

FIG. 9. Experimental setup for measurements of the total gain G_0 making use of the population changes of the levels involved by the mirror M_l and M_r separately. The arrow shows the discharge end where the level populations are measured. S_l and S_r are screens for blocking the mirror M_l and M_r, respectively.

transparency method [5,8], or using the population rate equations [9]. The changes $\delta N_2, \delta N_1$ were measured with a grating monochromator SPM-2 with a photomultiplier detection. The discharge tube was situated between two mirrors M_l and M_r, see Fig. 9, which fully reflected the 3391 radiation into the tube.

Intensities of the lines emitted, for example, by the right end of the discharge (marked by the arrow in Fig. 9) were measured in two experimental situations, when the right mirror M_r was blocked, and vice versa. In the first situation we measure (in arbitrary units) the perturbed populations N_2, N_1 determining $g_{\min}$ for the tube with mirror M_l, whereas in the latter, the populations determining $g_{\max}$ for the laser with mirror M_r.

Experiments [3] and theory show that the latter populations are very close to the unperturbed ones. Theoretically, they are close because a^* in the formula (12) is very small, far below 1. For example, it equals 10^{-3} at $G_0=20$. Hence $g_{\max}$ is close to the unperturbed gain g_0 and that means that the level populations are also unperturbed.

With populations measured in the situations above we have obtained $\delta N_1=0.92$, and $\delta N_2=0.42$ which with $N_2^0/N_1^0=5$ or 3.6, obtained by the transparency or rate equations method, give $g_{\min}/g_0=0.41$ or 0.32, respectively. Next, for the tube without a mirror, these values, used together with the plot B (Fig. 8), give $G_0=9.9$ or 10.9, respectively.

C. Attenuation

The total gain G_0 may be also estimated by measuring the limit attenuation when the NS signal is reduced to zero. The idea of this method is the following: when the radiation coming back to the tube is attenuated in such degree that its intensity nears x_0, then the NS effect disappears. In our experiment, eight soda glass plates, each of the transmittance of 0.51, reduced the NS signal to zero. The result means $x_0=W(0.51)^{16}$ (each plate attenuates the radiation twice), and according to (6) gives $G_0 \cong 10.8$. Taking into account the fact that the NS signal is eliminated when the eighth plate is used, we must draw a conclusion that the maximal G_0 is larger than 9.4 and smaller than 10.8. (Finally, we assume $G_0=10.5$.)

D. Population inversion

Casperson's theory does not answer the following question: "What is the distribution of inversion of the level populations along the He-Ne discharge?" It only gives the distribution of the gain, see formula (3). However, formula (17) may give some information about our question. Namely, we may replace $g_{\min}$ by $g(z)$ and use such a formula for any point or small discharge slab whose position is determined by a z coordinate. Many experiments [9–11] show that $\delta N_1 \cong 2\delta N_2$ provided the N changes are caused by stimulation transitions at 3391 nm. Putting $\delta N_1/\delta N_2=2.2$ (see previous results) into (17) with $g_{\min}$ replaced by $g(z)$ and with $N_2^0/N_1^0=5$, we obtain

$$Q=\frac{N_2N_1^0}{N_1N_2^0}=\frac{24+\dfrac{55g(z)}{g_0}}{200+\dfrac{121g(z)}{g_0}} . \quad (18)$$

In this way, if we know $g(z)$, we may compute and plot the distribution of the population inversion Q along the discharge.

The results are plotted in Fig. 10 for $G_0=10$, 20, 30, 40, and 10^5 as functions of z/l. The plots show only halves of the Q distributions, those starting at the discharge center ($z/l=0.5$) and going toward the right discharge end ($z/l=1$). The other halves of the distributions, those starting at the discharge center and going toward the left discharge end ($z/l=0$) have been omitted. In Fig. 10, we also see a plot marked by (a). This plot was obtained for $G_0=20$ under the assumption that $N_2^0/N_1^0=3.6$. Its role is to show how the Q distribution changes when N_2^0/N_1^0 is changed.

The plots in Fig. 10 may also be considered as the full Q distributions for the discharge with the mirror situated to the left of the tube. In such a case, however, we must assume $z/l=0.5$ and $z/l=1$ to be the coordinates of the left and right discharge ends, respectively. Then, also the numbers marked at the plots are of double values of the total gain for the discharge without a mirror.

The circles in Fig. 10 are experimental results of Q measured for the ^{3}He-^{20}Ne tube of 150 cm in length with

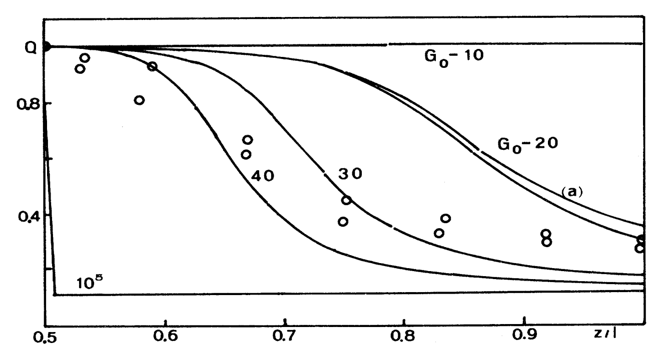

FIG. 10. Theoretical and experimental distribution of the population ratio of the $5s'[1/2]_1^0$ and $4p'[3/2]_2$ neon levels Racah notation along the He-Ne discharge.

a gold and flat mirror placed to the left of the discharge. The results were obtained by measuring intensities of 543- and 342-nm lines for various discharge slabs whose positions in the coordinate system as in Fig. 10 were determined by $(z+l)/2l$, where z is the distance of a given slab from the left discharge end. Notice that similar experimental results of population inversion distribution were already presented in my works [3,4].

IV. DISCUSSION

In the previous parts of the paper we presented measurements of the total gain G_0 made with three various methods, that is, by measuring the following: the intensity I of the NS signal, the populations of the levels, and the limit attenuation of the NS signal. It seems that the first two methods contain an error, resulting from the homogeneous limit assumed in the theory, whereas the third method simply gives the maximal value of G_0, the one at the center of the inhomogeneous gain profile. As we see, the values of G_0 obtained with the methods above are quite close to one another (10.7, 9.9 or 10.9,10.5) so, it is sensible to assume a negligible error resulting from our homogeneous gain simplification. Consequently, the negligible error also suggests that the generation develops close to the center of the inhomogeneous gain profile. The suggestion above is in agreement with experimental fact that, among several practical applications, the mirrorless and one-mirror lasers are used as the absolute wavelength standards [1].

Now let us turn to the subject of the theoretical and experimental results presented in Fig. 10. The experimental results (circles) are presented for two extremely different series of the measurements. As we know, they were obtained for the He-Ne discharge, with measured $G_0=10.5$, when the gold and flat mirror was placed to the left of the discharge end. Hence, the theoretical Q distribution of such a discharge should be described by a plot close to that of $G_0=20$. As is seen, there are two places in the discharge where the theory is in an agreement with the experiment: these are the discharge ends, $z/l=0.5$ and $z/l=1$. Next, let us notice that the discharge part close to the end $z/l=0.5$ does not show (both in the theory [1] and experiment [3]) "any perturbation" of the level populations. According to the theory, these populations should show a visible perturbation only at an extremely large gain. For example, a 20% reduction of the population ratio (at $z/l=0.5$) requires $G_0=10^5$. Because this value of G_0 is unobtainable in the He-Ne discharge, so the theory cannot be verified in this place.

The remaining experimental results show large deviations from the theoretical ones. It seems that the deviations cannot be explained by the error resulting from the homogeneous limit assumption. Because, including the inhomogeneous gain profile should give values of the perturbed population ratio bigger than those obtained in the homogeneous limit assumption.

The experimental values of the population ratio smaller than the theoretical suggest a larger number of the 3391 stimulated transitions and also greater output powers of the lasers than those theoretically calculated. To verify the suggestion above, we have measured the output powers and received 12.5 and 1.5 mW for the tube with and without the mirror, respectively.

On the other hand, theoretical output powers may be computed by multiplying the saturation intensity I_S by the intensities of the outgoing waves, W and W^*. Since I_S, in our case, equals 4.3 μW, W equals 2.4×10^{-3} and W^* equals 2.0, the following theoretical output powers are obtained, 10^{-2} and 10 μW, respectively; far smaller than the ones we obtained in the experiment.

Even if, in contrast to our previous conclusion, we assume that the generation develops in a large frequency range, say 300 MHz, and that the homogeneous width of the stimulated transition is 3 MHz [12,13], the theoretical output powers will be: 1 mW for the tube with the mirror and 1 μW for the tube without a mirror. As we see, even under the assumption above, the theory will also not be in agreement with the experiment, in particular for the tube without a mirror.

Measuring the output powers, we must not forget that any stray radiation at 3391 nm dispersed from a power meter changes the generation and populations of the laser levels. To avoid this negative effect we tilted the power meter face towards the measured beam in such a way that changes in populations of the laser levels could be ignored.

The next question is an experimental observation that the NS signal also appears when, instead of the mirror M, another He-Ne discharge, a sample tube, is used. The question is well known and "clear" when the sample tube is identical with that one in which the NS signal is observed (Ref. [3]). Then, the NS is the same as that induced by the fully reflecting mirror. Naturally, a shorter He-Ne discharge sample induces a smaller signal, as in the case of the attenuation of the mirror reflectance. However, the NS appears only when the discharge, used in place of the mirror M, shows population inversion of the laser levels. In other words, no effect is observed when, for example, instead of the mirror a pure neon discharge is used.

In our opinion, the phenomenon above is very interesting. So, let us make the following conclusions. Let us imagine two aligned He-Ne tubes. Let one tube be short, with a small gain, and the other, in which the NS may be observed, long. The long tube emitting a 3391 radiation beam (wave) into the short one induces in it stimulated emission, which in turn, enhances the primary wave. This is exactly as in the case of an excited atom in which the wave causes stimulated emission. On the other hand, the short tube induces the NS in the long one. This fact may be interpreted that some part of the wave emitted by the long tube is reflected back by the discharge in the short tube. For a single excited atom above that would mean some small, but not zero, probability of the stimulated emission in the opposite direction to the inducing wave, say, a stimulated reflection. (I define the stimulated reflection as an atomic process in which the stimulated wave is coherent with the stimulating one but their propagation directions are opposed.) Naturally, the stimulated reflection will not occur when the atom is in the absorption state for the inducing wave or, in the case of the atomic ensemble, more atoms absorb the wave than gain the wave. This very controversial suggestion would obtain strong support if we could state that the radiation coming back from the short tube is coherent with that one running to it or, in other words, the radiation is really reflected; not randomly emitted by the short tube. Also it seems that stimulated reflection could substantiate the existence of an intrinsic feedback in the mirrorless laser and mutual coupling between the opposite waves.

As to the theory, a question arises whether x_0 assumed as a spontaneous input in the mirrorless laser is a good approximation. The theory assumes x_0 to be constant, whereas the spontaneous input should undergo time fluctuations. It seems, however, that in the mirrorless laser the intrinsic feedback may cause time stability and also some small increase of x_0, in particular, at large values of the total gain G_0.

Also, Casparson's theory does not take into account the interference effects in the central part of the amplifier. There the standing wave is settled, which should lead to instabilities of the generation, as it happens in the normal lasers, with full resonator, when the opposite waves interact with the same atoms (Ref. [6]).

Concluding, Casperson's theory gives formulas that are useful in experiments on the mirrorless laser, however, some discrepancies between the theory and the experiment suggest that also other effects than those resulting from the intensity saturation take place in the He-Ne mirrorless laser.

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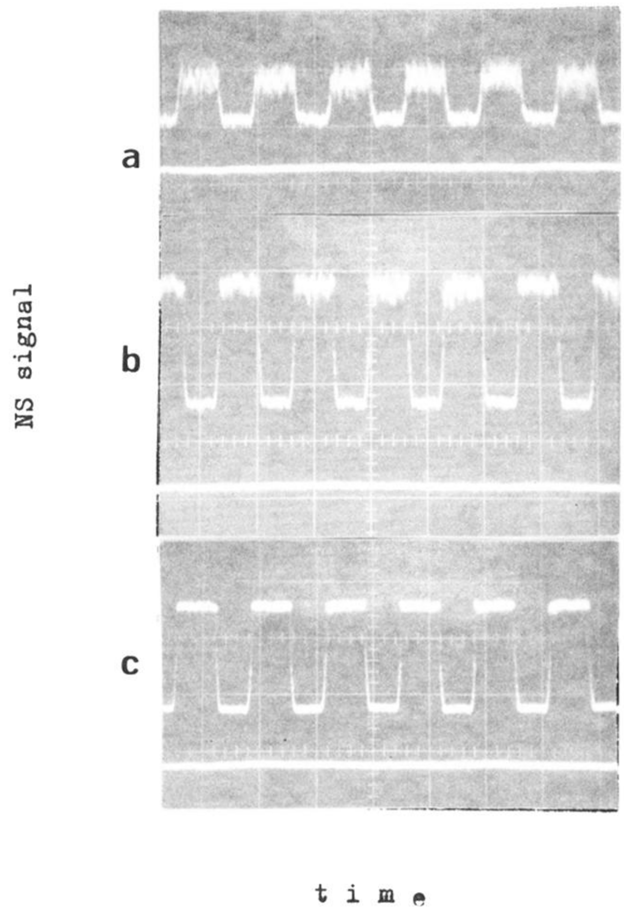

FIG. 2. The NS signal for three different pressure values of xenon. The pressure is reduced from (a) to (c). The line at the bottom of each display means the zero signal obtained when the detection element was screened by a thick block of BK7 glass not transmitting the 3391 radiation.

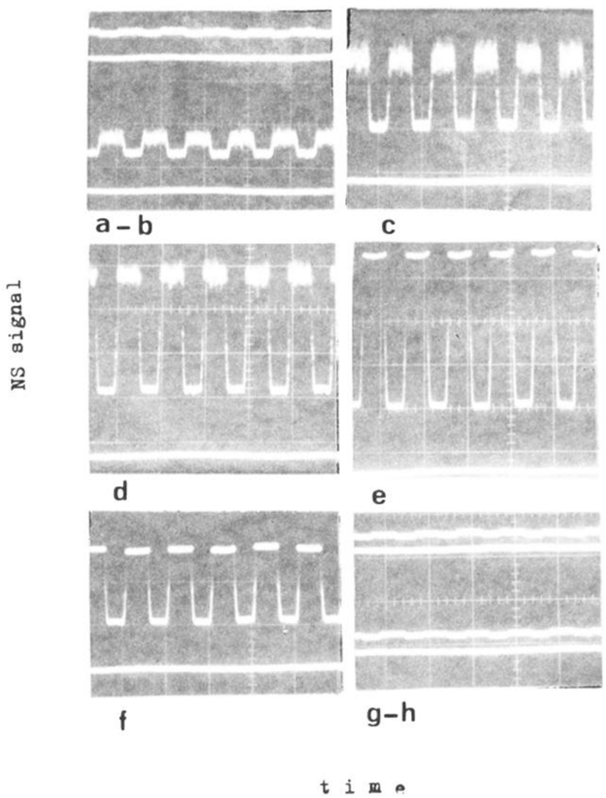

FIG. 3. The NS signal obtained for ^{3}He-^{20}Ne in the 120-cm-long tube at the following pressure values: 3, 2.2, 1.9, 1.7, 1.4, 1.0, 0.75, and below 0.75 Torr, (a)–(b), respectively.

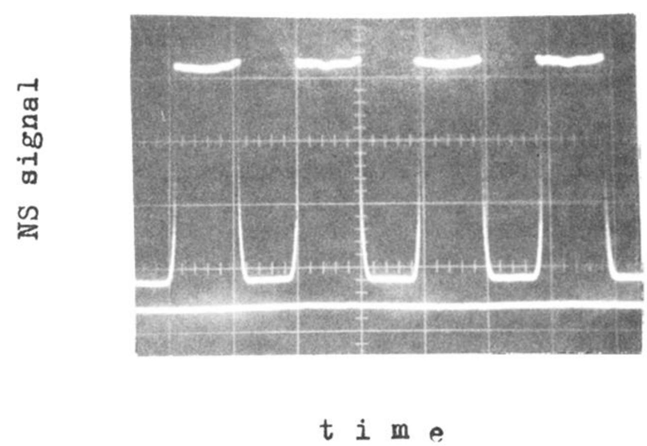

FIG. 5. The NS signal for ^{3}He-^{20}Ne mixture in the tube with discharge of 150 cm in length at the optimal pressure.