PARAMETERS OF THE DIP IN THE TRANSITION LINE OF AN ACTIVE GASEOUS MEDIUM

I. L. BERSHTEĬN and V. A. ROGACHEV

Radiophysics Institute, Gor'kiĭ State University

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The shape of the dip and the transition line of an active gaseous medium is determined experimentally. To this end, radiation from two lasers, operating at a wavelength 3.3 μ, is passed through a discharge tube with a helium-neon mixture. Radiation from one laser is the source of the dip, and that from the other, which is much less powerful, is frequency-scanned. The frequency dependences of the weak radiation, which is amplified by the tube, are observed on an oscilloscope screen with and without the more powerful radiation present. The depth and frequency characteristic of the dip are determined from a comparison of the curves. The experiments were performed under different conditions and have shown that the frequency characteristic differs appreciably from the Lorentz shape that follows from the theory. The discrepancy is due to the molecule collisions, which are not taken into account in the theory.

IT is known that the transition line of an active (inverted) gas medium is inhomogeneously broadened; this causes dips, which were first considered by Bennett[1], to appear in the gain curve of the medium when a sufficiently powerful monochromatic radiation is made to pass through the medium. The location of the dips on the gain curve of the medium and their parameters are of importance for the analysis of the question of simultaneous generation of oscillations of different frequencies by lasers, the stability of these oscillations, etc. In accordance with the analysis performed in[1], the dip has a Lorentz shape, and its width is determined by the natural width of the transition line of the molecule and by the power level of the wave causing the dip. These premises were the basis of calculations in many subsequent investigations. However, we know of no investigation in which the parameters of the dip in the gain line of the medium were directly determined experimentally. It was our purpose to perform such an investigation.

For a clear and direct observation of the dip in the gain curve of the medium, we used the relatively simple method of passing through a discharge tube with a helium-neon mixture, simultaneously, the radiation of two lasers operating at 3.39 μ. One laser was relatively powerful, and produced a dip in the transition line. The radiation of the second laser was weak (its power was 10—300 times smaller than the power of the first), making it possible to determine the sought parameters of the dip in the gain curve of the discharge tube. Of course, the power of the first wave greatly varied along the tube (unlike an ordinary laser, which operates in a regime that is close to that of a standing wave). Therefore the depth (and to a certain degree also the width) of the dip varied along the tube; however, if the dip in each section of the tube had a Lorentz shape, then the resultant effect along the entire tube should have had the same shape with a width determined by a power close to the power at the output of the tube.

This method makes it also readily possible to investigate the following question, which has not been discussed in the literature: what is the angular (polarization) characteristic of the dip. In other words, how does the dip influence the passage of the weak radiation if its polarization does not coincide with the polarization of the powerful radiation. For an experimental solution of the question it is sufficient only to change the polarization of the weak radiation.

Let us consider first briefly certain quantitative relations. We assume that the total number of molecules taking part in the creation of the inversion dip has a frequency distribution proportional to

$$\frac{1}{1+[2(\nu-\nu_m)/\Pi_1]^2}, \tag{1}$$

where ν is the running frequency, ν_m the radiation frequency producing the dip, and Π_1 the width of the dip [1)]. If we now assume that the natural line width of the molecule (at a Lorentzian line shape) is equal to Π_2, then a simple calculation shows that the total inversion dip of the medium will have a Lorentz shape with a band width $\Pi_1 + \Pi_2$.

Let us proceed to the angular (polarization) characteristic of the dip. We consider the question without taking into account the rotation of the acts of molecules. The initial inversion (without the dip) can be assumed to be isotropic in space. The interaction of the field with the molecule is proportional to the square of the cosine of the angle between the directions of the field and the dipole moment; it is therefore natural to assume that the magnitude of the dip for any direction in the medium is proportional to $\cos^2\psi$, where ψ is the angle between this direction and the direction of the radiation field producing the dip. Under such assumptions, calculation has shown that for a wave propagating the medium with a polarization rotated through an angle θ relative to the polarization of the powerful wave, the inversion dip will be proportional to $2 + \cos 2\theta$. In par-

1)The result (1) was obtained for a Doppler line width much larger than the natural width. A calculation similar to that presented by Gordon et al.[2] (which is based on the calculation of the number of moelcules at each level) has shown that the frequency dependence of the molecule dip is determined by the product of the Lorentzian law (1) and the factor $\exp[-((\nu-\nu_0)/0.6\Pi_D)^2]$, where ν_0 is the average frequency of the transition line of the medium and Π_D is its Doppler width. Allowance for this factor is of no importance in what follows.

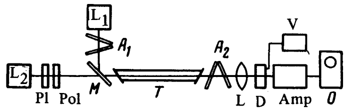

FIG. 1

ticular, at $\theta = 90°$, the effectiveness of the dip should be one-third as large as when $\theta = 0$.

We now proceed to a description of the performed experiments and their results. A diagram of the main elements of the setup is shown in Fig. 1. The laser L_1 is the radiation source producing the dip in the inversion of the discharge tube T. Its radiation, after passing through attenuator A_1 and being reflected from the quartz plate with dielectric coating M, was amplified by tube P; after passing through attenuator A_1 and lens L it was incident on the photodiode D (InSb cooled with liquid nitrogen). The output signal from D was fed to a (dc) millivoltmeter V, the readings of which made it possible to determine the power level at the output of the tube; to this end, the equipment was calibrated against a low-optical-power meter. The purpose of A_2 was to limit the power fed to D, so that the latter operated in a strictly linear regime.

Laser L_2 was the source of the weak radiation[2]. A quarter-wave plate P1 and a polaroid Pol made it possible to vary the polarization at this radiation. The radiation of L_2 was also fed through the weakly transmitting plate M into the input of tube T and, after amplification, to photodiode D. It is important to note that the level of this radiation was so low, that the tube T operated in a strictly linear regime with respect to it (this was verified by a number of experiments). The frequency of the laser L_2 was scanned at a frequency ~ 200 Hz; to this end, as usual, one of the mirrors of the resonator was mounted on a piezoelectric cylinder, to which an alternating voltage was applied of magnitude such as to ensure a swing of the resonator-length somewhat larger than $\lambda/2$, as well as a constant voltage whose manual regulation has made it possible to set the average value of the frequency. The output signal from the photodiode D was fed, following the amplifier Amp, to an oscilloscope O, to the sweep of which was fed a fraction of the alternating voltage applied to the piezoelectric cylinder for the scanning of the frequency of L_2. Thus, the generation zone of L_2 was observed on the screen of O; the frequency scale along the x axis could be readily determined. The pictures on the screen of O were photographed and suitably processed. In particular, by blocking the radiation of L_1 and carrying out observations with the tube T ignited and extinguished, it was possible to determine the frequency characteristic of the active medium of the tube (it was necessary in this case, of course, to vary in practice either the attenuator A_2 or the gain of Amp or O).

The frequency of the laser L_2 could be changed by regulating manually the voltage of the piezoelectric cylinder on which one of the mirrors of its resonator was mounted. This made it possible to establish the center of the inversion dip in any section of the generation curve of L_2 as observed on the screen of O. Usually

[2]The tubes of both lasers L_1 and L_2 had Brewster windows and operated with one longitudinal mode.

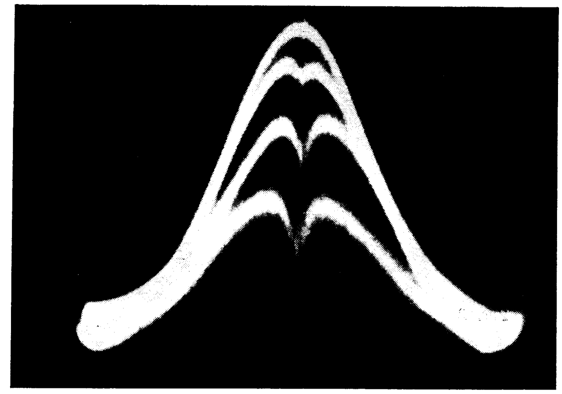

FIG 2.

we set the center of the dip at the middle of the generation zone. On the other hand, variation of the attenuator A_1 made it possible to vary the power and consequently also the depth of the dip.

The investigation of the characteristics of the inversion dip in the middle of the tube T reduced to a comparative analysis of the curves on the oscilloscope screen in the presence of radiation of L_1 and without it. Let us denote the power of the weak radiation at the input of the tube by $p(\nu)$, and the output power by $p_0(\nu)$ in the absence of radiation from L_1 and by $p_1(\nu)$ in the presence of this radiation. We can write

$$\frac{p_0(\nu)}{p(\nu)} = e^{\alpha\varphi_0(\nu)}, \quad \frac{p_1(\nu)}{p(\nu)} = e^{\alpha\varphi_1(\nu)}, \tag{2}$$

where α is a certain constant and $\varphi_0(\nu)$ and $\varphi_1(\nu)$ are the frequency characteristics of the inversion of the medium in the absence and in the presence of the dip. We have already noted above that the parameters of the dip vary along the tube, and therefore $\varphi_1(\nu)$ should be taken to mean the averaged characteristic (it follows from qualitative considerations that it will reflect approximately the situation in the media near the end of the tube).

It follows from (2) that

$$\ln\frac{p_0(\nu)}{p_1(\nu)} = \alpha[\varphi_0(\nu) - \varphi_1(\nu)]. \tag{3}$$

Consequently, by comparing the logarithms of the ratio of the ordinates of the indicated two curves at different values of ν, we obtain the frequency dependence of the inversion dip[3]. Although the accuracy of such an analysis is low, it nevertheless makes it possible to reveal the main regularities.

The length of the discharge tube T was 65 cm and its inside diameter 3.5 mm; the discharge was fed with direct current. The ratio of He to Ne was 5.6 : 1. The experiments were made with mixture pressures 0.4 and 1.2 Torr. The gain of the weak signal in the center of the band was approximately 30 in the former case (discharge current 28 mA), and approximately 400 in the latter case (discharge current 18 mA).

By way of illustration, Fig. 2 shows a combined

[3]The passage of two radiation with different frequencies through the tube cases the appearance of new combination frequencies due to the nonlinearity of the midum; this leads to a certain increase of the values of $p_1(\nu)$. It can be seen, however, from the data presented by Close[3], that the power of these additional oscillations is relatively small and allowance for it exceeds the accuracy of out experiments.

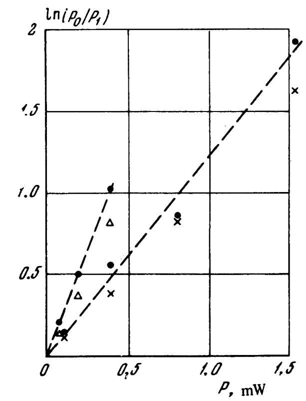

FIG. 3

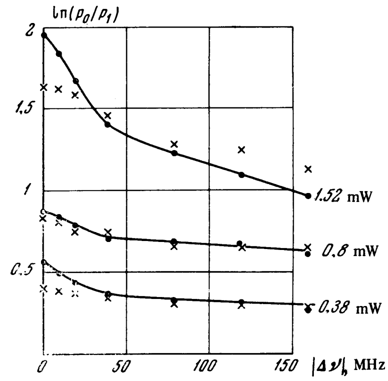

FIG. 5

photograph of the curves obtained on the screen of O when working with a tube filled to a pressure of 1.2 Torr at different values of the attenuation A_1. The picture shows a curve without a dip (radiation of L_1 blocked) and three curves with different dip depths. The faint vertical lines in the centers of the dips are the result of the zero beats occurring when the frequencies of the two radiations coincide; if the polarizations are orthogonal ($\theta = 90°$), these lines obviously disappear. A qualitative examination of Fig. 2 shows that besides the narrow hole in the center of the dip there occurs an appreciable decrease of the signal level (i.e., of the gain of the medium) in the entire frequency band. This does not agree with the deduction that the dip has a Lorentz shape. We have also carried out control experiments in which we varied the attenuation coefficient A_2 with the tube T extinguished, to make the photodiode operate approximately in the preceding regime. Turning on the radiation of L_1 did not change in this case the curve of the generation band of L_2, and only the zero-beat line appeared (just as in Fig. 2).

The results of a qualitative reduction of the obtained curves are shown in Figs. 3, 4, and 5.

The abscissas in Fig. 3 represent the radiation power P of laser L_1 at the output of tube T, and the ordinates represent the depth of the dip, i.e., $\ln(p_0/p_1)$ at the center of the dip ($\nu = \nu_m$). The points designate the data obtained at a pressure 0.4 Torr at $\theta = 0$ (coincidence of the polarizations of both radiations), and the triangles correspond to $\nu = 90°$. The data at a pressure 1.2 Torr are designated by points in the case of $\theta = 0$ and by

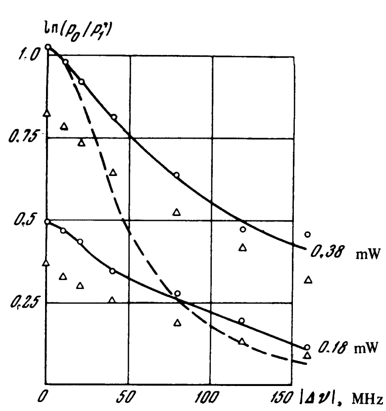

FIG. 4

crosses when $\theta = 90°$. It follows from Fig. 3 that the depth of the dip is approximately proportional to the power P (the straight lines are shown dashed), the proportionality coefficient at 0.4 Torr being approximately double that for 1.2 Torr. At $\theta = 90°$, the depth of the dip is only 5—25% smaller than at $\theta = 0$.

It is useful to compare the values of P obtained in our experiments with the intensity of the wave (in any particular direction) in the active medium of an ordinary laser. The latter can be estimated as being equal to P_{out}/τ, where P_{out} is the laser output power and τ is the transmission coefficient of the resonator mirror. For a wavelength 3.39 μ we can put $P_{out} = 0.05$—0.5 mW and $\tau = 0.1$, and we then obtain $P_{out}/\tau = 0.5$—5 mW.

The frequency variation of the dip is shown for the case of 0.4 Torr in Fig. 4 and for 1.2 Torr in Fig. 5. The abscissas represent here the quantity $|\Delta\nu| = |\nu - \nu_m|$—frequency deviation from the dip center, and the ordinates represent the corresponding values of $\ln(p_0/p_1)$; the given p_0/p_1 obtained at $\pm\Delta\nu$ were averaged in order to decrease the influence of the random errors occurring when the $p_0(\nu)$ and $p_1(\nu)$ are superimposed for the data reduction. The triangles and crosses correspond as before to the case $\theta = 90°$. The corresponding values of P are marked near the plotted curves.

It follows from Figs. 4 and 5 that the frequency variation of the dip differs greatly from Lorentzian (the Lorentzian curve corresponding to a band of 90 MHz and plotted in accordance with the initial course of the experimental curve is shown in Fig. 4 by way of illustration). The reason for the discrepancy is undoubtedly the molecule collisions, which were not taken into account in the theory [4)]. Apparently, an appreciable role can be played by both elastic and inelastic collisions. The fact that at $\theta = 90°$ the effect of the dip differs from the case $\theta = 0$ can be attributed to rotation of the molecules, which is also connected to some degree with the collisions. This can be assessed from the fact that at 1.2 Torr the data obtained at $\theta = 90°$ differ less from the data at $\theta = 0$ (and are "smeared" somewhat more in frequency) than in the case of 0.4 Torr.

It follows from the results that the role of the collisions cannot be reduced to a certain effective increase

[4)]The collisions are taken into account in an analysis of the process of inversion production, but are usually neglected in the analysis of the interaction between the field and the molecules.

of the dip width. Spiller[4] proposes that the transition line of the active medium contains dips of Lorentzian shape, but a general "sinking" of the entire curve results from the collisions. Our attempts to resolve the curves of Figs. 4 and 5 into a part that does not depend on $\Delta\nu$ (it could be regarded as a result of a certain homogeneity of the transition-line broadening) and a part having a Lorentz shape did not lead to reasonable results.

In conclusion we wish to note the following: the frequency characteristic of the dip is particularly important in an analysis of problems involved in simultaneous generation of different frequencies by a laser. Yet, in those papers where these questions are discussed, particularly the widely known paper by Lamb[5], the collisions are regarded only as sources of inversion in the medium. It seems to us, therefore, that the conclusions arrived at in these papers can claim only a qualitative description of the phenomena taking place in a real system.

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[1] W. R. Bennett, Jr., Phys. Rev. **126**, (1962).
[2] E. I. Gordon, A. D. White, and J. D. Rigden, Optical Masers, Polyt. Inst. of Brooklyn, N. Y. (1963), p. 309.
[3] D. H. Close, Appl. Phys. Lett. **8**, 300 (1966).
[4] E. Spiller, Z. Physik **182**, 487 (1965).
[5] W. E. Lamb, Jr., Phys. Rev. **134**, A1429 (1964).

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