FREQUENCY EFFECTS IN A LASER WITH NONLINEARLY ABSORBING GAS

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We consider theoretically the frequency effects in a laser with a nonlinearly absorbing gas cell inside the resonator. It is shown that in such a laser the generation frequency is automatically stabilized as a result of production of a dip in the center of the absorption line of the cell. In the case of a large absorbing cell ($\sim 10^2$ cm) with low-pressure gas ($10^{-3}-10^{-4}$ Torr), the self-stabilization effect makes it possible to attain a frequency stability not worse than 10^{-13} with a reproducibility not worse than 10^{-11}. It is noted that formation of a supernarrow dip in the center of the absorption line can be used for self-selection of one lower transverse mode, for superhigh resolution spectroscopy within the Doppler line, and for "molecular" coupling of lasers.

1. INTRODUCTION

$\mathbf{I}$N a gas laser with a standing light wave in the resonator[1], the atoms resonantly interacting with the field have a velocity u that satisfies the condition[2,3]

$$\omega \pm ku = \omega_0, \qquad (1)$$

where ω is the frequency of the light field, ω_0 the frequency of the center of the gain line of the gas, $\pm u$ is the projection of the velocity of u on the propagation direction of each of the traveling waves making up the standing wave, and $k = \omega/c$ is the wave number. If the field amplitude is sufficient to change the level population (saturation), then such a change will occur with the atoms for which $u = \pm (\omega_0 - \omega)/k$. As a result, the plot of the gain against the frequency acquires two "holes" at frequencies $\omega' = \omega$ and $\omega' = 2\omega_0 - \omega$, with mirror symmetry relative to the center of the line ω_0, and the dependence of the gain of the standing wave on its frequency ω acquires a "dip" at the frequency $\omega = \omega_0$. This "dip" can be interpreted as the consequence of the coincidence of the two holes as $ku \rightarrow 0$. The occurrence of the dip at the center of the gain line follows from the following intuitive physical considerations. If $\omega \neq \omega_0$, then the atom can interact resonantly only with one of the traveling waves. But when $\omega = \omega_0$ both traveling waves change the population difference (gain) of the atom with $ku = 0$, and consequently the degree of saturation is twice as large in this case. The dip in the center of the gain line was investigated in detail by Lamb[3] and is called the "Lamb dip." Its experimental observation in a gas laser is discussed in[4,5]. It plays presently an important role in the theory of gas lasers and is used in practice for the stabilization of the generation frequency at the center of the gain line[6].

A gas laser with resonantly absorbing gas cell inside the resonator was proposed in[7], where it was shown that in such a gas laser, under certain conditions, self-stabilization of the frequency at the center of the absorption line sets in. This stabilization is connected with the formation of a narrow Lamb dip in the absorption line of the cell, and with the tendency of the laser to maintain the generation frequency in the region of the minimum of the losses. When the pressure of the absorbing gas is low, the width of the dip can amount to 10^2-10^5 Hz, making it possible to develop an optical frequency standard with a frequency stability and reproducibility better than 10^{-11}. Gas lasers with an absorbing cell inside the resonator were considered independently in[8,9] where the production of a Lamb dip in the absorption line of Ne with $\lambda = 6,328$ Å was observed.

The purpose of the present article is to consider theoretically the frequency effects in a gas laser with an absorbing gas cell inside the resonator. It is shown in the paper that such a gas laser can serve as a highly stable frequency standard. The conditions for self-stabilization of the frequency and the conditions for generation stability are obtained. Ways of reaching the limiting frequency stability ($\sim 10^{-12}$) are proposed. The possibility is indicated of coupling two lasers by means of the molecules in a common absorbing cell, self-selection of the lowest mode, and investigation of the structure of transitions within the Doppler width.

2. FORMULATION OF PROBLEM AND INITIAL EQUATIONS

We shall consider a gas laser with an absorbing gas cell in a resonator with flat mirrors, operating at a single axial mode. As usual, the losses, gain, and absorption will be assumed to be uniformly distributed over the volume of the resonator[3]. The field inside the resonator A(t) and the polarization of the medium T(t) will be represented in the form of slowly varying amplitudes and phases:

$$A(t) = E(t)\cos(vt + \varphi(t)),$$
$$P(t) = C(t)\cos(vt + \varphi(t)) + S(t)\sin(vt + \varphi(t)). \qquad (2)$$

Then, following Lamb[3], we have the following self-consistent equations:

$$(v + \dot{\varphi} - \Omega)E = -2\pi v(C_a + C_b), \qquad (3)$$

$$\dot{E} + \frac{v}{2Q}E = -2\pi v(S_a + S_b), \qquad (4)$$

where the indices a and b pertain respectively to the amplifying and absorbing components: Q and Ω are the quality factor and the natural frequency of the resonator mode.

The polarization coefficients C_α and S_α of the gas medium (α = a, b) were calculated by Lamb[3] accurate to third order in perturbation theory. In an approximation in which the homogeneous line width $\Delta\omega_\alpha$ is small compared with the Doppler width ku_α, these coefficients are of the form

$$C_\alpha = \frac{2p_\alpha^2}{\hbar}\frac{\omega_\alpha - \nu}{(ku_\alpha)^2}N_\alpha\Big[1$$

$$-\frac{\sqrt{\pi}}{8}\alpha E^2\frac{\Delta\omega_\alpha ku_\alpha}{\Delta\omega_\alpha^2 + (\omega_\alpha - \nu)^2}\Big]E\exp\Big[-\Big(\frac{\nu - \omega_\alpha}{ku_\alpha}\Big)^2\Big], \quad (5)$$

$$S_\alpha = \frac{p_\alpha^2}{\hbar}\frac{\sqrt{\pi}}{ku_\alpha}N_\alpha\Big\{1 - \frac{1}{4}\alpha E^2\Big[1$$

$$+\frac{\Delta\omega_\alpha^2}{\Delta\omega_\alpha^2 + (\omega_\alpha - \nu)^2}\Big]\Big\}E\exp\Big[-\Big(\frac{\nu - \omega_\alpha}{ku_\alpha}\Big)^2\Big]. \quad (6)$$

Here p_α is the matrix element of the dipole moment of the transition, N_α is the density of the level population difference ($N_a = N_{2a} - N_{1a}$, $N_b = N_{1b} - N_{2b}$), αE^2 is the saturation parameter, defined by

$$\alpha E^2 = \frac{p_\alpha^2}{2\hbar^2\Delta\omega_\alpha\delta\omega_\alpha}E^2, \quad (7)$$

where $\Delta\omega_\alpha$ is the homogeneous width corresponding to the transverse relaxation time T_2 and $\delta\omega_\alpha$ is the width corresponding to the longitudinal relaxation time T_1[10].

The homogeneous width $\Delta\omega_\alpha$ is made up of the radiation width $\gamma_\alpha = \gamma_{\alpha 1} + \gamma_{\alpha 2}$ ($\gamma_{\alpha 1}$ and $\gamma_{\alpha 2}$ are the radiation widths of the upper and lower levels), the width Γ_α due to the collisions (we are considering the simplest model of Lorentz line broadening), and the width $\tau_\alpha^{-1} = u_\alpha/d_\alpha$ connected with the finite time τ_α that the atom stays in the light field (d_α—transverse dimension of the light beam):

$$\Delta\omega_\alpha = \gamma_\alpha + \Gamma_\alpha + \tau_\alpha^{-1}. \quad (8)$$

The width $\delta\omega_\alpha$ is made up of the radiation width γ_α and the "transit width" τ_α^{-1}:

$$\delta\omega_\alpha = \gamma_\alpha + \tau_\alpha^{-1}. \quad (9)$$

We note that the transit width must be taken into account only for a low-pressure absorbing gas, when $\tau_\alpha^{-1} \gtrsim \Gamma_\alpha, \gamma_\alpha$. In this case we confine ourselves only to a qualitative allowance of the line broadening due to the collisions, and to the finite time of the stay of the atom in the light beam. The former is justified by the fact that the optimal operation of the laser in question occurs at very low pressures in the absorbing field, when the role of the collisions is small. A rigorous calculation of the influence of the collisions on the gas gain saturation was made in[9]. A rigorous calculation of the transit time τ_α through the beam, especially in the case of a strong field, requires a special analysis, but certain features of this effect will be noted below. Equations (3) and (4) can be transformed with the aid of (5) and (6) into

$$\nu + \dot\varphi - \Omega = \kappa_a c\frac{\omega_a - \nu}{ku_a}\Big[1 - \frac{a}{8}E^2\frac{\Delta\omega_a ku_a}{\Delta\omega_a^2 + (\omega_a - \nu)^2}\Big] \quad (10)$$

$$- \kappa_b c\frac{\omega_b - \nu}{ku_b}\Big[1 - \frac{b}{8}E^2\frac{\Delta\omega_b ku_b}{\Delta\omega_b^2 + (\omega_b - \nu)^2}\Big],$$

$$\dot E + \frac{\Delta\omega_r}{2}E = \frac{\kappa_a c}{2}E\Big[1 - \frac{a}{4}E^2\Big(1 + \frac{\Delta\omega_a^2}{\Delta\omega_a^2 + (\omega_a - \nu)^2}\Big)\Big]$$

$$- \frac{\kappa_b c}{2}E\Big[1 - \frac{b}{4}E^2\Big(1 + \frac{\Delta\omega_b^2}{\Delta\omega_b^2 + (\omega_b - \nu)^2}\Big)\Big], \quad (11)$$

where κ_a and κ_b are the gain and absorption coefficients of the weak field per unit length at the generation frequency:

$$\kappa_\alpha = 4\pi\frac{\nu}{c}\frac{p_\alpha^2}{\hbar}\frac{\sqrt{\pi}}{ku_\alpha}N_\alpha\exp\Big[-\Big(\frac{\nu - \omega_\alpha}{ku_\alpha}\Big)^2\Big]; \quad (12)$$

$\Delta\omega_r = \nu/Q$ is the line width of the empty resonator.

3. SELF-STABILIZATION OF THE GENERATION FREQUENCY

Let us consider with the aid of (10) and (11) the stationary generation regime. The self-excitation condition has the usual form

$$\kappa_a > \kappa_b + \Delta\omega_r / c. \quad (13)$$

The stationary value of the amplitude E_{st} is unique in the approximation under consideration, and is defined by the expression

$$E_{st}^2 = 4\Big(\kappa_a - \kappa_b - \frac{\Delta\omega_r}{c}\Big)(\kappa_a a' - \kappa_b b')^{-1}, \quad (14)$$

where we introduce the abbreviated symbol

$$a' = a\Big[1 + \frac{\Delta\omega_a^2}{\Delta\omega_a^2 + (\omega_a - \nu)^2}\Big] \quad (a = a, b). \quad (15)$$

It is easy to show that the stationary regime is stable when

$$a'\kappa_a > b'\kappa_b. \quad (16)$$

The generation frequency ν is determined by (10) with $\varphi = 0$ and $E = E_{st}$. The corresponding exact expression is cumbersome, so that we shall first present a qualitative discussion.

It follows from (10) that in a weak field (at the threshold) the generation frequency is "attracted" to the center of the gain line ($(\nu - \Omega)/(\omega_a - \nu) = \kappa_a c/ku_a$) and is "repelled" from the center of the absorption line ($(\nu - \Omega)/(\omega_b - \nu) = -\kappa_b c/ku_b$). When the field amplitude is increased, the attraction to the center of the gain line is replaced by nonlinear repulsion (at $aE^2 > 8\Delta\omega_a/ku_a$, $|\omega_a - \nu| < \Delta\omega_a$), and the repulsion from the center of the absorption line is replaced by attraction (when $bE^2 > 8\Delta\omega_b/ku_b$, $|\omega_b - \nu| < \Delta\omega_b$). The latter effect is quite significant, since the position of the absorption line center can be much more stable than the frequency of the gain line center (at low gas pressure and small radiation width). In order for the nonlinear attraction of the generation frequency to the center of the absorption line (self-stabilization) to be decisive, it is necessary to satisfy several conditions. First, the generation frequency must lie in the self-stabilization region, i.e., within the limits of the homogeneous absorption line width:

$$|\omega_b - \nu| < \Delta\omega_b. \quad (17)$$

Second, the effect of nonlinear attraction to the center of the absorption line should be appreciable, meaning, in accordance with (10), that

$$S_1 = \frac{8\,\Delta\omega_b}{bE^2\,\kappa_b c} \ll 1. \quad (18)$$

Finally, this effect should prevail both over the linear attraction and the nonlinear repulsion from the center of the gain line. To this end, according to (10), it is neces-

sary to satisfy respectively the following two conditions:

$$S_2 = \frac{8}{bE^2} \frac{\varkappa_a}{\varkappa_b} \frac{\Delta\omega_b}{ku_a} \ll 1, \quad (19)$$

$$S_3 = \frac{a}{b} \frac{\varkappa_a}{\varkappa_b} \frac{\Delta\omega_b}{\Delta\omega_a} \ll 1. \quad (20)$$

Conditions (17)—(20) guarantee high stability of the generation frequency in the vicinity of the absorption-line center. This can be shown by direct calculation of the generation frequency. When $|\omega_\alpha - \nu| \ll \Delta\omega\alpha$, Eq. (10) yields the following value of ν:

$$\nu = \omega_b + \left[(\Omega - \omega_b) + \frac{\varkappa_a c}{ku_a}\left(1 - \frac{a}{8}E^2\frac{ku_a}{\Delta\omega_a}\right)(\omega_a - \omega_b) \right]$$

$$\cdot \left[\left(1 + \frac{\varkappa_a c}{ku_a} - \frac{\varkappa_b c}{ku_b}\right) + \frac{b}{8}E^2\frac{\varkappa_b c}{\Delta\omega_b}\left(1 - \frac{a}{b}\frac{\varkappa_a}{\varkappa_b}\frac{\Delta\omega_b}{\Delta\omega_a}\right) \right]^{-1} \quad (21)$$

If the self-stabilization conditions (18)—(20) are satisfied, then the generation frequency is given by

$$\nu = \omega_b + S_1(\Omega - \omega_b) + (S_2 - S_3)(\omega_a - \omega_b), \quad (22)$$

where it is also assumed that $\varkappa_a c/ku_a - \varkappa_b c/ku_b$ $\approx \Delta\omega_r/ku_a \ll 1$. It follows from (22) that when S_1, S_2, S_3 $\ll 1$, the generation frequency stabilizes in the region of the absorption-line center.

Simultaneous satisfaction of conditions (18)—(20) is possible if the homogeneous width of the absorption line is sufficiently small and the degree of absorption saturation is noticeable. At an absorbing-gas pressure 10^{-1}–10^{-2} Torr, a dip width $\Delta\omega_b \approx 10^4$–$10^5$ Hz is realistic. The homogeneous width of the gain line is usually $\Delta\omega_a \approx 10^7$–$10^8$ Hz, and the Doppler width is $ku_a \approx 10^8$–10^9 Hz. At $\varkappa_b c \approx 10^7$–$10^8$ Hz and a degree of absorption saturation $bE^2 \approx 0.3$ (which still agrees with the considered third-order perturbation-theory approximation, $bE^2 \ll 1$), values [1] $S_1 \approx 10^{-2}$ and S_2, $S_3 \approx 10^{-3}$ are quite realistic.

The obtained relations pertain to the case of weak saturation, but the effect of self-stabilization exists also in the case of strong saturation. However, there are many significant features here.

First, in a strong field the width of the dip in the absorption line increases, since the homogeneous width is increased by the saturation effect[12]. The width of the dip in a strong monochromatic field is given by[13]

$$\Delta\omega_b' = \Delta\omega_b(1 + bE^2)^{1/2}. \quad (23)$$

From the point of view of frequency stability, the saturation region $bE^2 \approx 1$ is apparently optimal. In this case the attraction to the center of the absorption line is maximal, and the width is practically minimal.

Second, the saturation of the gain or absorption at the center of line is determined by the more general expression[3,13]:

$$S_\alpha = \frac{p_\alpha^2}{\hbar} \frac{\overline{\sqrt{\pi}}}{ku_\alpha} N_\alpha(1 + aE^2)^{-1/2} \quad (\alpha = a, b). \quad (24)$$

In this case the equation for the generation amplitude is

$$\dot{E} = \frac{c}{2} E\left(\frac{\varkappa_a}{\sqrt{1 + aE^2}} - \frac{\varkappa_b}{\sqrt{1 + bE^2}} - \frac{\Delta\omega_r}{c} \right), \quad (25)$$

where $|\omega_\alpha - \nu| \ll \Delta\omega\alpha$. We see therefore that when

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[1] The influence of the instability of the gain-line center can be greatly reduced by operating under conditions where the nonlinear gain-line center is compensated by linear attraction. To this end it is necessary to have $S_2 = S_3$ or $aE^2 ku_a/8\Delta\omega_a = 1$.

$b > a$ stationary values of the amplitude exist even when the self-excitation condition (13) is not satisfied. This corresponds to a hard self-excitation regime, which is not unexpected for a laser with a saturable absorber. In this case the smallest of the stationary values of the amplitude is unstable. It corresponds to the threshold value of the amplitude $E_{thr} > 0$ necessary for self-oscillations to occur. If E_{thr} is close in order of magnitude to the level of the spontaneous noise then, generation can nevertheless set in spontaneously.

Another feature of the regime with strong saturation is the possibility of pulsations of the radiation intensity in the case when the self-excitation is satisfied, but the stability condition is not. When $b\varkappa_b \gg a\varkappa_a$, the pulsations of the intensity have the character of the pulsations that occur when self-switching of the laser Q takes place[14,15].

4. SUPERNARROW "DIPS" IN THE ABSORPTION LINE

To obtain maximum frequency stability it is necessary to narrow down the width of the absorption-line dip, which at a given absorption coefficient per unit length $\varkappa_b = \lambda^2\gamma_b N_b/4ku_b$ is defined by relation (8):

$$\Delta\omega_b = \gamma_b + 4\frac{\varkappa_b}{\lambda^2}\frac{ku_b}{\gamma_b}\langle\sigma_b u_b\rangle\frac{N_0}{N_b} + \tau_b^{-1}, \quad (26)$$

where σ_b is the cross section for line broadening by collisions in the absorbing cell, N_b is the density of the population difference of the absorbing molecules, and it is assumed that the molecule free path is smaller than the cell dimensions and the radiation width γ_b is due only to the working transition. It is easy to see that at a definite radiation width γ_b^{min}, equal to

$$\gamma_b^{min} = \frac{2}{\lambda}\left(\varkappa_b ku_b\langle\sigma_b u_b\rangle\frac{N_0}{N_b} \right)^{1/2}, \quad (27)$$

the minimum of the homogeneous width $2\gamma_b^{min}$ is attained. Thus, at a wavelength $\lambda = 3\mu$ with $\varkappa_b$ $= 10^{-3}$ cm^{-1}, for the customary gas parameters ku_b $\approx 10^9$ sec^{-1}, $\langle\sigma_b u_b\rangle \approx 2 \times 10^{-10}$ cm^3 sec^{-1}, and N_0/N_b ≈ 10 (for example, as a result of the rotational structure of the molecules), the optimal radiation width is $\gamma_b^{min} = 3 \times 10^2$ sec^{-1}. In this case the homogeneous width due to the radiative transitions and collisions is $2\gamma_b^{min}$ $= 6 \times 10^2$ sec^{-1}.

In order to attain the minimum dip width $\Delta\omega_b$ $= 2\gamma_b^{min}$, the time of interaction of the molecules traveling parallel to the wave front and the beam should be τ_b $\gtrsim (2\gamma_b^{min})^{-1}$, i.e., the effective interaction length is l_{eff} $\gtrsim u_b/2\gamma_b^{min}$. For the numerical example considered above, $\tau_b \gtrsim 1.6 \times 10^{-3}$ sec and $l_{eff} \gtrsim 70$ cm ($u_b \approx 4$ $\times 10^4$ cm/sec). It is perfectly possible in principle to ensure such an interaction time, for example by multiple parallel passage of the beam through the absorbing field (see the figure). In this case the larger saturation is experienced by molecules which cross several beams

Diagram of optical frequency standards with multiple-passage nonlinearly-absorbing gas cell inside the resonator.
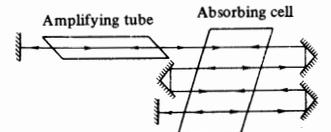
parallel to their wave fronts[2]. They give rise to a dip in the absorption line, with width $(D/u_b)^{-1}$, where D is the total path of the molecule from the first to the last beam. To be sure, in such a scheme the only molecules that take part in the formation of the dip are those traveling parallel to the wave front and cross at the same time all the beams. This leads to an increase of γ_b^{min} by $\sqrt{D/d_b}$ times, where d_b is the diameter of one beam. In such a scheme, apparently, it is realistically possible to attain a total dip width of several hundred Hz. This value, which is of the same order as the limiting value of the line width in the optical band 10^{-12}, which is determined by the transverse Doppler effect and by the effect of recoil produced when a quantum is emitted (absorbed).

In a laser with a low-pressure absorbing cell (10^{-3}–10^{-4} Torr) of large dimensions, the stability factors S_1, S_2, and S_3 amount to $S_1 \approx 10^{-4}$ and S_2, $S_3 \approx 10^{-5}$. It is perfectly realistic to stabilize the center of the gain line with accuracy 10^{-8} and the center of the resonator line with accuracy 10^{-9}. In this case the relative frequency stability will be not worse than 10^{-13}. The absolute stability will be somewhat worse, owing to the hyperfine structure of the line, the shift of the absorption-line center upon collision of the atoms with the walls, the asymmetry of the line, and the shift of the center of the dip due to the correlation of the Doppler broadening and broadening as a result of the interaction[11,17], the possible line shift in the light wave, etc. However, attainment of absolute stability better than 10^{-11} is perfectly realistic.

5. OTHER EFFECTS AND APPLICATIONS

The effect of self-stabilization of the generation frequency is the most important in the laser in question, but there exists also a number of other important and interesting effects. Let us indicate briefly some of them.

A. The formation of dips in the velocity distribution of the absorbing molecules can be used for the so-called "molecular" coupling of lasers. If two lasers have a common absorbing cell with low-pressure gas, such that the molecule mean free path exceeds the distance between the laser beams, and the beams in the cell are sufficiently parallel, then the two lasers will produce a common single dip in the center of the absorption line. As a result, the laser generation frequencies will be close, with an accuracy determined by relation (22), and a slight photon exchange will suffice for phase synchronization of the laser oscillations[18].

B. Inasmuch as the width of the dip in the absorption line is much smaller than the distance between the axial modes of the laser, self-selection of a single axial mode is obviously realized in the laser. However, if the mean free path of the molecules in the absorbing cell is comparable with the transverse dimension of the laser beam, then the greatest saturation will be caused by the lowest transverse mode TEM_{n00}, since it has a constant sign of the phase along the wave front. On the other hand, if the distance between neighboring transverse

modes (usually 10^6–10^7 Hz) exceeds the width $\Delta\omega_b$ of the dip, then self-selection of the lowest transverse mode TEM_{n00} will take place.

C. The formation of a supernarrow dip in the center of the absorption line of the gas under the influence of a standing light wave can be a very effective method of investigating the structure of the levels within the Doppler width[19]. If the absorption line is made up as a result of overlap of several lines, and the distance between them exceeds the width of the dip γ_b, then, by scanning the frequency of the standing light wave, it is possible to obtain minimum absorption at the center of each line. Apparently the limiting resolution of such a method is 10^{11}–10^{12}.

6. CONCLUSION

The foregoing results offer evidence that the laser proposed in[7], with nonlinearly absorbing gas inside the resonator, has potentially a very high optical-frequency stability, which is attained as a result of self-stabilization of the generation frequency. The limiting stability of such a laser is close to the limiting stability of beam lasers[16,20] and the construction is much simpler.

To realize the proposed optical frequency scatter it is necessary to choose atoms or molecules having absorption at the generation frequency of known cw lasers. In many cases, the atoms or molecules of the amplifying medium itself are suitable for this purpose. For example, for a CO_2-N_2-He laser ($\lambda = 10.6 \mu$) in an absorbing cell it is possible to use CO_2 at low pressure, and for an Ne-He laser ($\lambda = 0.63, 1.15, 3.39 \mu$) it is possible to use Ne at low pressure, etc.

There are also several known pairs with different amplifying and absorbing molecules: 1) the 3.3913-μ line of the He-Ne laser coincides with the 2.947.906-cm^{-1} absorption line of the CH_4 molecule, accurate to 0.003 cm^{-1}, with an absorption coefficient $\kappa_b \approx 0.17 cm^{-1}/Torr$ and $\Gamma_b = 5$ MHz/Torr[21]; 2) the 3.5070-μ line of the Xe-He laser coincides with the 2850.608-cm^{-1} absorption line of the H_2CO molecule with accuracy 0.007 cm^{-1} at $\kappa_b \sim 0.1 cm^{-1}/Torr$[22]; 3) the $\lambda = 10.59 \mu$ line of the CO_2-N_2-He laser coincides with the strong 940-cm^{-1} absorption line of the SF_6 molecule[14]. To be sure, these pairs do not yield the narrowest dips in the absorption line, since the radiative transition probabilities are smaller by two orders of magnitude than the optimal probability determined by (27), and therefore the required pressure in the absorbing cell will be 10^{-2}–10^{-1} Torr. The most suitable atoms or molecules are those with a radiative transition probability $\gamma_b \approx 10^2$–10^3 sec^{-1}.

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[2] In the case of strong saturation, it is possible even to invert the populations of the absorbing molecule, similar to the inversion of molecules in a beam [16]. Then the dip in the absorption line becomes amplifying.

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