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Line shapes of a « sensitive » laser

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Résumé. — Les inhomogénéités de saturation et de population sont à l'origine d'effets de lentille dans les lasers à gaz. Ceci a pour conséquence de donner un Lamb dip dissymétrique. En général, l'une des inhomogénéités est prédominante et c'est elle qui fixe le sens de cette dissymétrie. Cependant, les paramètres géométriques du laser modifient les inhomogénéités et il peut arriver qu'elles soient du même ordre de grandeur et de signe opposé ; elles entrent alors en compétition et la forme de raie peut varier beaucoup pour un faible changement d'un paramètre. Nous appelons un tel laser un laser « sensible ». Dans cet article, nous donnons l'exemple d'un laser quasi hémisphérique à He-Ne dont la longueur (57 cm) est presque égale au rayon de courbure du miroir concave (60 cm). Nous montrons expérimentalement que le sens de la dissymétrie peut s'inverser avec le courant de décharge et que la forme de raie dépend aussi du diamètre du diaphragme. Ceci est révélateur des deux effets en compétition. Nous calculons théoriquement les formes de raies en utilisant des méthodes précédemment mises au point et nous constatons un excellent accord qualitatif avec l'expérience.

Abstract. — Inhomogeneities of population and saturation are responsible for lens effects in gas lasers. They give rise to an asymmetric Lamb dip. Generally, one of these inhomogeneities is predominant and thus determines the sense of the asymmetry. However, since the two kinds of inhomogeneities are modified by the geometric parameters, it may happen that they give lens effects of the same magnitude, but of opposite sign. In such a case of competing effects which cancel each other, the line shape may vary strongly when a parameter is changed. A laser of this kind will be called « sensitive ». In this paper we use as an example a quasi-hemispheric He-Ne laser whose length (57 cm) is almost equal to the radius of curvature (60 cm) of the concave mirror. We show experimentally that the sense of the asymmetry may be changed by the discharge current and that the line shape also depends on the diameter of the diaphragm. This behaviour reveals the competition between the two effects. We numerically calculate the line shapes by using methods which we have developed recently. Qualitatively, we find these results in excellent agreement with the experiments.

Introduction.

The asymmetry of emission lines in monomode gas lasers is determined by causes of both macroscopic and microscopic origin. Macroscopic causes for asymmetric line shapes have been the object of studies at this laboratory during the past years and a theory has been developed in

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several stages. First, the influence of saturation on the properties of the fundamental Gaussian mode of a laser beam has been studied [1]. In a second stage [2] we have included the transverse inhomogeneity (linear) of the population and the resonant diffraction by a diaphragm in the cavity. This study showed that the effects due to population and saturation may either cooperate or compete in fixing the sense of the asymmetry of a line.

It is our aim in this communication to give an equation which allows to predict, in the model case of a Gaussian beam, the dependence of these effects on the geometric parameters of the cavity. Then we study the particular case of a quasi-hemispheric laser whose length ($d = 57$ cm) is slightly less than the curvature radius ($R = 60$ cm) of the concave mirror. This is a laser in which a competition between the two above mentioned effects exists. It deserves to be called « sensitive » since a slight modification of one of its characteristic parameters (here the discharge current or the diameter of the diaphragm) results in a strong distortion of the line shape. This laser structure is particularly well suited for an experimental test of our previous theory [2]. In the second part of the present paper we give several experimental results obtained with a monomode laser working on the $3.39 \mu\text{m}$ line of ^{20}Ne . We are applying the calculational methods which we have already described [2] to various cases and we find our theoretical results in excellent agreement with experiments.

1. Model of the Gaussian beam.

In this first part we will use a Gaussian beam model in which the variation of the field due to a diaphragm is neglected. We will consider the line shape which is obtained when the total intensity of the laser output is plotted *versus* frequency. In this case the asymmetry is largely due to diffraction losses which vary with frequency as the beam diameter does. It is, therefore, necessary to look at the equation describing the variation of the beam diameter. That equation has already been given previously [1, 2]. It involves the dimensionless function

$$\eta = 2iq_0(1/\tilde{q} - 1/q), \quad q_0 = -\frac{i\omega}{2c} W_0^2 \quad (1)$$

representing (up to the constant q_0) the modification of the inverse complex curvature caused by the medium. As we are dealing with a forward beam (in positive z -direction) and a backward beam (in negative z -direction) we have to distinguish between their respective curvatures q_f and q_b . This distinction extends to all related quantities which will then appear in two versions, labelled by the subscripts « f » and « b ». The generic equation (1) holds for each of the two beams.

As we already did previously [2, 3] we are further using dimensionless radial and longitudinal coordinates ρ and ζ , linked to cylinder coordinates by the scaling relations

$$\rho = r/W_0, \quad \zeta = cz/\omega W_0^2.$$

Admittedly, the scaled coordinates do not appeal strongly to our physical intuition. For instance, they contain the beam waist radius W_0 which is one of the unknowns of the beam problem. However, we believe that they are justified by the striking simplifications they permit in the analytical treatment of the beam deformation.

The beam equation in linear approximation ($|\eta_f| \ll 1$) is

$$\eta'_f + \frac{4i}{1+2i\zeta} \eta_f = -\frac{\omega^2}{c^2} W_0^2 \left(\frac{\alpha_0}{\epsilon_0} u + AT_f \right). \quad (2)$$

Prime denotes the derivative with respect to ζ . The corresponding equation for the deformation

of the backward beam is obtained by the replacement $f \rightarrow b$, $i \rightarrow -i$. The parameter u is used to describe the transverse parabolic distribution of population N . It is defined by :

$$N = N_0(1 - ur^2/W_0^2) = N_0(1 - r^2/r_0^2)$$

where the second equation follows Kogelnik's notation [4]. The right hand side of equation (2) has been split into two parts : $\alpha_0 u/\varepsilon_0$ describes the linear population inhomogeneity while AT_f represents the non-linear inhomogeneity due to saturation. T_f is proportional to the intensity and is given in reference [2] (Eq. 37). The quantity A represents an interpolating function of ζ :

$$A(\zeta) = \frac{\bar{\rho}^{-2}}{1 + 4\zeta^2} + \left[u - \frac{\bar{\rho}^{-2}}{1 + 4\zeta^2} \right] \exp(-2\bar{\rho}^2). \quad (3)$$

The quantity $\bar{\rho}$ is an adjustable parameter. The special case where $u = 0$ and $\bar{\rho} = 1$ has been treated previously [1]. The purpose of the function $A(\zeta)$ is to assure that for the saturation term the same approximation is made at all points of the axis. The quantity α_0 is the linear polarizability and the functions T_f and T_b contain the non-linear polarizabilities expressed in terms of the on-axis intensities of the forward and the backward field.

The solutions η_f and η_b of equation (2) and its backward analog will be given for the case where, on the right hand side of (2), one can neglect the variation of the field due to amplification and to losses on the mirrors (cf. [3]). Using the abbreviation $Z = 1 + 2i\zeta$ and denoting the boundary value at Z_0 by e.g. $\eta_{of} = \eta_f(Z_0)$, we find

$$\eta_f = \eta_{of}(Z_0/Z)^2 + \frac{iA_0}{6} Z[1 - (Z_0/Z)^3] - \frac{iA_1}{2Z} \left[1 - Z_0/Z + \frac{2}{Z} \cdot \ln(Z^*/Z_0^*) \right] + \frac{iA_2}{2ZZ^*} (1 - Z^*/Z_0^*). \quad (4)$$

The corresponding deformation of the backward beam is obtained from (4) by changing Z into Z^* , Z_0 into Z_0^* , and i into $-i$.

We are using the following expressions for the constants A_0, A_1, A_2 (these coefficients have nothing to do with the function A in Eq. (3)) :

$$\begin{aligned} A_0 &= \frac{\omega^2}{c^2} W_0^2 \frac{\alpha_0}{\varepsilon_0} u, \\ A_1 &= \frac{\omega^2}{c^2} W_0^2 u e^{-2\bar{\rho}^2} \left\{ \frac{\beta_1}{\varepsilon_0} |E_{of}|^2 + \frac{\beta_2}{\varepsilon_0} |E_{ob}|^2 \right\}, \\ A_2 &= \frac{\omega^2}{c^2} W_0^2 \frac{1 - e^{-2\bar{\rho}^2}}{\bar{\rho}^2} \left\{ \frac{\beta_1}{\varepsilon_0} |E_{of}|^2 + \frac{\beta_2}{\varepsilon_0} |E_{ob}|^2 \right\}, \end{aligned} \quad (5)$$

where $|E_{of}|^2$ and $|E_{ob}|^2$ are the field intensities at $\zeta = 0$.

For the meaning of the constants β_1 and β_2 see reference [2]. The constant A_0 is proportional to u and represents the linear inhomogeneity of the population while A_2 , proportional to the intensity, represents the non-linear inhomogeneity due to saturation. A_1 is a mixed term which depends on both types of inhomogeneities.

We are applying this equation to a quasi-hemispheric cavity containing an amplifying medium. We will assign the coordinate ζ_2 to the position of the concave mirror and we will use it as the

reference point corresponding to ζ_0 in equation (4). The plane mirror is at $\zeta_1 = 0$. The boundary conditions generally state that

$$\eta_f + \eta_b = 0 \quad (6)$$

has to be satisfied at the position of each mirror, in our case at the two points $\zeta_1 = 0, \zeta_2$. When they are written with (4) and the corresponding expression for η_b (the deformation of the backward beam), one has a system of two linear equations for the beam deformations (forward and backward) at ζ_2 , which gives, e.g.,

$$\eta_f(\zeta_2) = \frac{i}{4} \left\{ A_0 \left(1 - \frac{4}{3} \zeta_2^2 \right) + A_1 \left[\frac{\arctg 2 \zeta_2}{\zeta_2} - 1 \right] + A_2 \frac{1}{1 + 4 \zeta_2^2} \right\}. \quad (7)$$

We are now returning to conventional notation. Let us denote the real (imaginary) part of a complex quantity by a superscript r (i). Then, with $\delta W/W^3 = -\eta_f/4 W_0^2$, we find

$$\frac{\delta W}{W^3} = \frac{1}{16 W_0^2} \left\{ A_0^r \left[\frac{4}{3} \zeta_2 - 1 \right] + A_1^r \left[1 - \frac{\arctg 2 \zeta_2}{\zeta_2} \right] - A_2^r \left[\frac{1}{1 + 4 \zeta_2^2} \right] \right\}. \quad (8)$$

The variation of the beam diameter is thus composed of the three terms

$$\delta W/W^3]_{\text{population}} = \frac{1}{16 W_0^2} \left(\frac{4}{3} \zeta_2^2 - 1 \right) A_0^r, \quad (9)$$

$$\delta W/W^3]_{\text{saturation}} = \frac{-1}{16 W_0^2} \frac{1}{1 + 4 \zeta_2^2} A_2^r, \quad (10)$$

$$\delta W/W^3]_{\text{mixed}} = \frac{1}{16 W_0^2} \left(1 - \frac{\arctg 2 \zeta_2}{\zeta_2} \right) A_1^r. \quad (11)$$

We observe that, depending on the length of the laser (i.e. ζ_2), the terms in (9) and (11) may alter their sign. This is not possible for the saturation term in (10) : since A^r has the form of a dispersion curve with the maximum on the side of the lower frequency, this term always diminishes the diameter of the beam, thus increasing the intensity on the low frequency side of the line.

For a specific laser geometry ($d = 57$ cm, $R = 60$ cm ; see Fig. 1a) we have $\zeta_2 = \lambda d/2 \pi W^2 = 2.18$, which gives

$$\delta W/W^3]_{\text{population}} = (4 W_0)^{-2} 5.33 A_0^r, \quad (12)$$

$$\delta W/W^3]_{\text{saturation}} = - (4 W_0)^{-2} 0.05 A_2^r, \quad (13)$$

$$\delta W/W^3]_{\text{mixed}} = (4 W_0)^{-2} 0.38 A_1^r. \quad (14)$$

Now, when comparing the orders of magnitude of (12), (13) and (14), we have to take into account the fact that A_0 and A_1 contain u as a factor. Let us consider an example. For a tube of 6 mm diameter, a parabola with the maximum on the axis ($r = 0$) and a zero at the wall corresponds to $r_0 = 3$ mm, $u = 1.5 \times 10^{-2}$; for $r_0 = 4$ mm, one has $u = 8.8 \times 10^{-3}$.

One notes that in our case the population term (12) influences the variation of W as much as the saturation term (13) does, and it extends that influence over the line shape, as one may show by placing a diaphragm on the concave mirror. Thus we may expect that in the case of a long laser the line shape is sensitive to the population inhomogeneity. In a laser which is much shorter, e.g. with $d = 30$ cm, $R = 60$ cm, i.e. $\zeta_2 = 0.5$, we would have $\frac{4}{3} \zeta_2^2 - 1 = -0.67$, $(1 + 4 \zeta_2^2)^{-1} = 0.5$ and $1 - (\arctg 2 \zeta_2)/\zeta_2 = -0.57$, and the line shape would be quite insensitive to the popula-

tion inhomogeneity ! Besides, it has been shown experimentally [5, 6] that u , the parameter which fixes the distribution of amplifying atoms, depends on the discharge current : for weak currents one has $u > 0$ and the maximum of the gain is on the axis. For stronger currents, u becomes negative and the maximum of the gain is near the wall. Since this effect is caused by collisions of atoms among themselves and with the wall, it is clear that it will strongly depend on the pressure and composition of the gas and on the diameter of the tube. We are considering the case $d > 3 R/4$. If u is positive, the effects of population and saturation add up to give a maximum of intensity on the lower frequency side of the line profile (asymmetry of type l.f.). For $u < 0$ (very strong current), the two effects have opposite signs : if the population effect is dominant, the maximum of intensity is on the high frequency side (asymmetry of type h.f.). Thus one can predict a change of the type of asymmetry when the discharge current is allowed to become sufficiently strong. However, this will not happen in our experiment where the change will be due to other causes.

Equation (4) may also be applied to a cavity which is not completely filled by the amplifying medium. With the notation of figure 1b we get

$$\eta_{r4} = \frac{-i}{8\zeta_2} \frac{(1 + 2i\zeta_2^2)^2}{(1 + 2i\zeta_4^2)^2} \left\{ \frac{2}{3} A_0 [\zeta_4(4\zeta_4^2 - 3) - \zeta_3(4\zeta_3^2 - 3)] + \right. \\ \left. + 2A_1 [\zeta_4 - \zeta_3 + \arctg 2\zeta_3 - \arctg 2\zeta_4] + \right. \\ \left. + 2A_2 \left[\frac{\zeta_3}{1 + 4\zeta_3^2} - \frac{\zeta_4}{1 + 4\zeta_4^2} \right] \right\}. \quad (15)$$

We notice that the saturation term (last line in preceding equation) may change sign depending on the length of the tube, as it has been predicted previously [8]. If the tube is centred in the cavity, we find that this change happens for

$$z_3 = \frac{1}{2} \{ d - \sqrt{d(5d - 4R)} \}.$$

Fig. 1. — Sketches of the laser structures. r and z are the laboratory coordinates while ρ and ζ are scaled. r_0 is the radius of the tube and R is the radius of curvature of the concave mirror. In Fig. 1a the medium fills the entire cavity, in Fig. 1b it is limited to the region between ζ_3 and ζ_4 .

We have, of course, to assume $d > 4 R/5$. For $R = 60$ cm and $d = 57$ cm we get $z_3 = 3.2$ cm. Hence, for an amplification length of 50 cm as used in our experiment, the saturation term is small compared to the other terms. In such a laser it is therefore impossible to interpret the line shapes without taking into account the population effects, even when they are small ! Equation (15) is another proof for the sensitivity of the laser, this time, however, the sensitivity with respect to the length (fixed by $\zeta_4 - \zeta_3$) and the position (fixed by ζ_3) of the amplifying tube.

We have applied equation (15) and tested its ability to predict experimental line shapes in the case of other lasers [9]. It is interesting to note ⁽¹⁾ that when the amplifying medium has a scaled length ζ_a very short as compared to the other dimensions and when it is placed at the centre of the laser, one finds the result given by Le Floch *et al.* [10]. We write $\zeta_4 = \zeta_2/2 + \zeta_a/2$ and $\zeta_3 = \zeta_2/2 - \zeta_a/2$ and make a first order expansion in ζ_a in (15). We then find that the coefficients of A_0 , A_1 and A_2 change their sign at $\zeta_2 = 1$ (i.e. at $d = 4 R/5$) ! We have already given [11] this result in the context of the mean field approximation for the coefficient of A_0 . Before leaving equation (15) note that it represents the variation of complex curvature at ζ_4 : in this case the geometric factors of α_0 or β_1 and β_2 are complex. It then appears that both the imaginary and real parts of polarizabilities contribute to δW . If a diaphragm is placed elsewhere than on the mirrors our formulas [3] show that we have to take these two parts into account in finding line shapes. This is a new result not obtainable with usual *ABCD* matrix theory [10] where only the dispersive part of β_1 and β_2 is retained.

2. Numerical and experimental studies.

The discussions up to here and the model [3] on which they are based do neither take account of losses on the mirrors nor of the field variation due to a diaphragm. These effects are taken care of in the numerical methods developed in reference [2]. They allow us to predict and interpret line shapes and field distributions as well as the frequency dependence of curvature and diameter of the mode. In this section we are giving the results of the numerical calculation with input data corresponding as closely as possible to the experimental set-up which was described above : the amplifying tube has a length of 50 cm and a diameter of 7.5 mm. The cavity is quasi-hemispheric (curvature radius 60 cm) and has a length of 57 cm. The ensemble « plane mirror and window » has a coefficient of reflection 0.9, while the ensemble « concave mirror and window » has 0.64. The numerical results we have obtained for different parameters demonstrate the sensitivity of this laser : in order to achieve satisfactory agreement with experiments, the data given for the calculation have to be as close as possible to the corresponding parameters of the experiment, in contrast to some lasers we have tested earlier [3].

The numerical and experimental results were obtained for three different diameters of the diaphragm (placed on the concave mirror) and for several values of the gain, i.e. discharge current. We have chosen a parameter value $u = 8.8 \times 10^{-3}$ to represent the population inhomogeneity.

Figures 2a-b show the measured line shape for a diaphragm diameter of 5 mm. Figure 2c gives the calculated line shapes for different gain. All curves exhibit an asymmetry of type l.f. which is essentially due to the population inhomogeneity. Figure 2d pictures the field intensity along the laser axis. One notes that diffraction effects are weak so that we are allowed to use our Gaussian beam model in this case.

Figure 3 shows the measured line shapes for a diaphragm diameter of 4 mm, but this time for various discharge currents (Figs. 3a, c, e). The line shape changes from the l.f. type to the h.f. type when the current is increased, as shown in the magnifications (Figs. 3b, d, f). Figure 3g gives the calculated line shapes which exhibit this phenomenon. It is due to the competition

⁽¹⁾ We thank the referee who attracted our attention on this interesting point.

Figs. 2a-b. — (a) Single mode laser output power vs. frequency. Intensities are in arbitrary units and frequencies increase from left to right. One division is 42 MHz for this cavity. The two profiles result from the hysteresis of the piezo-electric ceramic. The tube is filled with 0.09 torr of ^{20}Ne completed with natural helium up to a total pressure of 0.4 torr. The discharge current is 4 mA. (b) Magnification of the Lamb dip region showing the 1.f. type asymmetry (magnification factors : Y 5 times, X 2.5 times).

Figs. 2c-d. — (c) Theoretical line shapes as calculated from our previously described method [2]. The ratio of the natural line width to the Doppler width is taken to be 0.2. The curves are for different gain, as indicated. Also shown are the asymmetry factors $f = 2(H - h)/(H + h)$ where H and h are respectively the low and high frequency maxima of the intensity. The decrease of f with increasing intensity shows the tendency of the saturation inhomogeneity to give rise to an h.f. type asymmetry. This is due in part to the diaphragm's action and also to the fact that the medium does not fill the cavity. (d) Resonant field distribution along the laser axis for 3 reduced frequencies x . These curves show the non-uniformity of the field and, thereby, the longitudinal inhomogeneity of saturation.

Fig. 2. — Diaphragm diameter 5 mm.

Figs. 3a-f. — 3a, 3c, 3e show the entire line shape while 3b, 3d, 3f are magnifications of the Lamb dip regions. Magnification factors are 5 (Fig. 3b) or 10 (Figs. 3d, 3f) for intensities, and about 2.5 for frequencies. Figs. 3a and 3b are taken with a current of 5.3 mA, Figs. 3c and 3d with 5.8 mA, Figs. 3e and 3f with 6 mA. The asymmetry of the line evolves from the l.f. type at weak currents to the h.f. type for higher currents.

Fig. 3g. — Numerical results for different gains. The f -factor varies from a positive to a negative value indicating a variation of asymmetry.

Fig. 3h. — Resonant field distribution for two values of the reduced frequency x .

Fig. 4a. — $i_c = 7.5$ mA, $f = 0.032$. Fig. 4b. — $i_c = 8.0$ mA, $f = 0.027$.

Fig. 4c. — $i_c = 9.5$ mA, $f = 0.005$.

Figs. 4a-c. — Show the evolution of the line shape : an increasing discharge current i_c leads to decreasing asymmetry.

Fig. 4d. — Theoretical line shapes for different gains. The evolution of the line shape is noticeable : f decreases with increasing gain and even changes its sign.

Fig. 4e. — Resonant field distribution along the laser axis for 3 different values of the reduced frequency x . Comparing this and Figs. 2d and 3h one observes a displacement of the intensity maximum towards the centre of the laser when the diameter of the diaphragm is decreased. This is in agreement with the results already obtained in a non-resonant case (7) and shows the focusing properties of diaphragms.

Fig. 4. — Diaphragm diameter 3 mm.

between the two inhomogeneity effects : the population effect is linear and is not affected by the diaphragm, thus retaining its previous role and giving a l.f. type asymmetry. In contrast, the field distribution which determines the saturation is strongly influenced by the diaphragm, as one can infer by comparing figures 2d and 3h, and later, figure 4e. The consequence, not foreseeable by the model described in section 1, is the occurrence of an h.f. type asymmetry caused by saturation inhomogeneity if a small diaphragm is used ! One is thus faced with a competition between the two effects whose consequence is the change of asymmetry with a change of discharge current. At weak intensity the saturation is also weak and it is the population effect which dominates, while at strong currents the saturation effect prevails. Presumably, that evolution is further reinforced by the decrease of u with increasing current.

Figure 4 shows the same kind of results for a diaphragm diameter of 3 mm. One notes a clear evolution of the line shape with increasing current which is due to the same reasons as in the preceding case. However, here it is essentially the population inhomogeneity which fixes the line shape.

It is interesting now to link the results given here to those previously reported [1, 2, 8, 10-13, 15]. A first study [1] of line shapes was based on a homogeneous medium filling the entire cavity. The asymmetry was found to be of the l.f. type whatever the length of the laser. An experimental verification [12] confirmed the role played by the « R effect ». It was then discovered [10] that the type of asymmetry depends on the length of the laser, but almost immediately it was realized [8, 13] that it depends also on the length and the position of the amplifying tube. Another step is given in reference [15] where the variation of the diameter of the diaphragm is shown to influence also the asymmetry. In another paper [9], we illustrate the role of the diameter of the amplifying tube and we have shown here the importance of the discharge current. It appears now that many factors influence the line shape, sometimes in a critical manner [2]. In the previous paper by one of us [8] the theoretical conclusion was correct despite the experimental illustration where, as shown above, the asymmetry was due to the population effect. It is likely that the symmetric line shape obtained in reference [10] for the « critical length » results from a balance between various effects which compensate each other (this feature can be experimentally verified by varying the discharge current in such a laser [14]). It appears now that the position and the length of the active tubes are not the only quantities needed to predict the asymmetry : bore diameter, pressure and composition of the gas, discharge current and position and size of the diaphragm are also necessary. It is that complexity which limits the application of too simple models.

Conclusion.

In this work we have applied our general methods for the investigation of laser line shapes to a special physical situation and we have found that in this case the line shape is extremely sensitive to a variation of various macroscopic parameters. Our results permit us to obtain for the first time experimental evidence concerning the respective roles played by the two kinds of transversal inhomogeneities in the formation of line shapes. Our methods also give a good understanding of cooperation and competition between the effects caused by these inhomogeneities. We have shown that all parameters of a laser are participating, in mutual interdependence, in the formation of line shapes.

This work may be followed up by the construction of lasers designed to allow the observation of particular effects under the best possible conditions.

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