Refractive Index Saturation Effects in Saturated Absorption Experiments

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Saturation effects, occurring when a laser beam tuned close to a resonance propagates through an absorbing gaseous medium, were observed by means of a second beam sent in a nearly opposite direction. In addition to the well-known signal of saturated absorption, a signal directly related to the variation of the refractive index of the medium was observed. An experiment was performed to obtain simultaneously the signals of saturated absorption and saturated dispersion of iodine vapor.

In the past, the techniques of laser saturation spectroscopy that eliminate Doppler broadening by spectral hole burning have essentially been restricted to the study of the gain saturation.[1,2] We report in this Letter experimental results which demonstrate the saturation of the dispersion as well as of the absorption.

A narrow-band laser beam sent through an absorbing gaseous medium changes the susceptibility of a velocity group of molecules, those which can absorb at the frequency of the saturating light. The absorption coefficient and the refractive index are saturated: i.e., dependent on the intensity of the saturating beam. With regard to the refractive index the medium around the saturating beam then has the behavior of a lenslike medium.[3] A weak beam (probe beam) propagating in a nearly opposite direction to the saturating beam will interact with it if both light waves interact with the same molecules: that is, those with essentially vanishing axial velocity if the two beams have the same frequency corresponding to the frequency of a resonant transition. It is now well known that one can obtain the signal due to the saturation of the absorption coefficient by monitoring the total intensity of the probe beam; the action upon the beam due to the saturation of the refractive index has not yet been reported. We have performed a very simple saturated-absorption experiment[1] in iodine which demonstrates the deviation effect of the lenslike medium on the probe beam and have derived, from this experiment, an experimental setup which allows us to separate the effects due to absorption from those due to dispersion.

In a saturated-absorption experiment as the one we reported previously,[4] the following schematic effects upon the probe beam are to be expected when the laser is tuned close to a molecular resonance: (i) an enhancement of the intensity due to the saturation of the absorption; (ii) a deviation Δi_0 and a displacement Δx of the axis of the beam due to the saturation of the refractive index (see Fig. 1); and (iii) a distortion of the beam profile due to the same cause as the previous effect. The first affects the intensity of the beam while the two others affect only its geometry. For this reason we will refer to them, in the following, as "geometrical effects."

Hence if we record the total intensity of the beam with a detector whose sensitive area is larger than the beam section, we will obtain a pure saturated-absorption signal. In another way, if we use a detector whose sensitive area is smaller than the section of the beam, the spatially nonuniform intensity in the beam (Gaussian beam) makes it sensitive to the variations of intensity as well as to the geometrical effects. The characteristics of the geometrical-effects signal will be, of course, strongly dependent upon the arrangement of the two beams in the cell and the position of the detector in the probe beam.

The fundamental arrangements of the beam in the cell and the expected resulting geometrical effects are summarized below. If the two beams are collinear, only focusing and defocusing of the

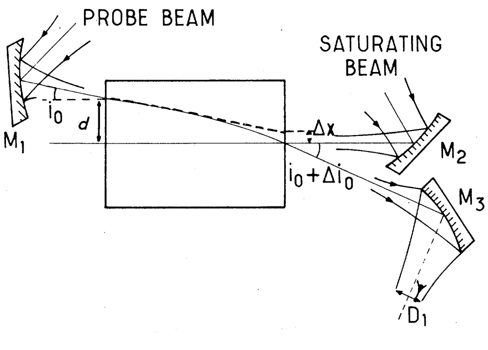

FIG. 1. Schematic representation of the beam directions in the iodine cell and the detector position in the probe beam.

probe beam occur; no deviation nor displacement are to be expected. If the two beams are crossed with a small angle at the center of the cell, the deviation and displacement must vanish and only a small distortion occurs. In all the other arrangements, the displacement, deviation, and distortion are to be expected together. A case of great interest is the one in which the two beams are crossed at one end of the cell, the deviation being maximum in this configuration (Fig. 1).

In this case, under the assumption of a propagation law $n \cos i = \text{const}$, d larger than the saturating-beam radius $\omega_0 = 150$ μm, the same intensity-dependent variation Δn_{sat} in the index of refraction for all the points of the saturating-beam axis, and i_0 small ($i_0 \simeq 10^{-2}$ rad), the deviation Δi_0 and displacement Δx are given by $\Delta i_0 \simeq \Delta n_{\text{sat}}/i_0$ and $\Delta x \simeq \frac{1}{2}\sqrt{\pi}\,\omega_0 \Delta i_0/i_0$. In our experiments where the distance D from the cell to the detector was 3 m, much larger than $\omega_0/i_0 = 1.5 \times 10^{-2}$ m, the displacement could always be neglected. The deviation range is obtained by use of an evaluation of the maximum value of Δn_{sat} versus the frequency[5]: $(\Delta n_{\text{sat}})_{\text{max}} \simeq (16\pi)^{-1} \lambda \alpha_0 \chi$, where α_0 is the absorption coefficient per length unit at the center of the line, and $\chi = I/I_{\text{sat}}$.[1] With $\alpha_0 = 0.4$ m^{-1}, $\lambda = 0.59$ μm, and $\chi = 0.1$, $\Delta i_0 \simeq 0.5 \times 10^{-7}$ rad corresponds to a displacement of the beam on the diode of $\delta = D i_0 = 0.15$ μm. When the detector, supposed to be small, is situated at a distance off the probe-beam axis equal to the probe-beam radius ω on the detector (situation where the dispersion signal is maximum), an estimate of the amplitude ratio of the dispersion signal S_d to the absorption signal S_a is given by $S_d/S_a = (1/4\pi^{3/2})\lambda D/\omega_0 \omega$. For D much larger than $\pi \omega_0'^2/\lambda$, where ω_0' is the radius of the probe beam at the waist, the ratio S_d/S_a is independent of D and equal to $(1/4\pi^{1/2})\omega_0'/\omega_0$. With $\omega_0 = \omega_0'$ the calculated ratio is 0.14. Although this calculation based on ray optics does not take into account the wave-front distortion, and then is a rough approximation, it shows that the geometrical effects are strong enough to be observed in a usual saturated-absorption experiment.

Another very important feature is that the variation of the position of the detector in the probe beam leads to the knowledge of the predominant effect. If two signals are recorded for two positions of the detector, symmetrical with respect to the axis of the probe beam and located in a plane defined by the two beams, the two signals will be of a contrary sign if they are due to deviation, and will remain with the same sign if they are due to distortion.

The first experiments reported here were performed with use of a cw dye laser and an iodine vapor cell. The cw dye laser was described previously[4]; it operated in single mode from 580 to 620 nm with an output of 10 mW when pumped with 1.5 W of the 5145-Å line of an argon laser. The frequency stability of the laser was good enough to allow its use without frequency locking. The linewidth was on the order of 1 MHz for the average time of 1 sec and the drifts were less than 5 MHz/min. Continuous tuning could be accomplished over intervals of 2.8 GHz. With a beam splitter and two mirrors M_1 and M_2 a probe beam and a saturating beam were sent through the 20-cm-long iodine cell. The angle between the two beams was varied during the experiments. M_1 and M_2 were two spherical mirrors with curvature radii of 2 m. They reduced the radii of the beams within the cell to $\omega_0 = 150$ μm. The output of the laser was typically of the order of 3 mW with 2 mW for the saturation beam and 0.05 mW for the probe beam, the monitors and reflection losses accounting for the rest. The signal was recorded by monitoring the intensity of the probe beam with a HP 4207 *p-i-n* diode whose sensitive area was 0.8 mm^2. The distance from the I_2 cell to the diode was 3 m. The mirror M_3 (see Fig. 1) was a spherical mirror with a curvature radius of 3 m. It decreased the radius at $1/e$ of the probe beam on the diode to $\omega = 3$ mm. In order to record only the nonlinear signal and to obtain a convenient signal-to-noise ratio, the saturating beam was modulated at a frequency of 10 kHz and phase detection was used.

The signal obtained when the laser was continuously tuned across a resonance was a superposition of an absorption curve corresponding to the saturated-absorption signal broadened by the residual Doppler effect, and a dispersionlike curve corresponding to the geometrical effects. The wings of the recorded signal were determined by the dispersionlike curve which is broader than the absorption curve. Figure 2(a) shows the signal obtained for the geometry of the beams and detector depicted in Fig. 1. The angle between the two beams was 13 mrad. As expected the wings of the curve image the variations of the intensity-dependent part of the anomalous dispersion. For instance, the decrease of the refractive index on the low-frequency side of the transition[5] leads to a negative part in the signal. Figure 2(b) demonstrates the disappearance of the geometrical effects when the probe beam was

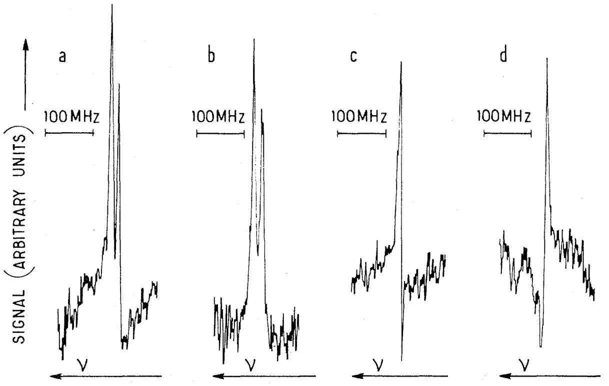

FIG. 2. Parts of the hyperfine structure of an iodine line near 5900 Å. (a) Probe beam defocused. (b) Probe beam focused on the detector. (c), (d) Two positions of the detector symmetrical with respect to the axis of the probe beam.

focused on the detector with a short focal lens. A similar signal was recorded when the beams were crossed at the center of the I_2 cell. Figures 2(c) and 2(d) illustrate the shape of the signal for two positions of the detector in the probe beam. The beams in the cell were arranged as in Fig. 1. Figure 2(c) was for the detector located as in Fig. 1 and 2(d) was for a position of the detector symmetrical to the previous one with respect to the axis of the probe beam. The change in the sign of the signal shows clearly the predominance of the deviation caused by the geometrical effects. This result was confirmed by the change of the sign of the signal when the saturating beam was moved such that the crossing point was located at the opposite side of the cell with respect to Fig. 1. Results concering a situation where the distortion was predominant will be published later. We have demonstrated from the previous experiments that if only a part of the intensity of the probe beam is monitored, the signal is the sum of the well-known saturated-absorption signal plus a signal which describes the refractive-index variation associated to it. This last signal has been called saturated dispersion and observed with an interferometric setup by Borde *et al.*[6] We report below an experiment which allows us to record the saturated-absorption signal and the saturated-dispersion signal separately at the same time.

The experimental setup differed essentially from the previous one as follows: The cw dye laser was locked to a transmission fringe of a high-finesse optical cavity (Tropel 216 V, finesse 200, free spectral range 300 MHz) with a wide-band servo system (0–25 kHz) which applied corrections to the optical length of the dye-laser cavity with two piezoelectrically driven mirrors.[7] The linewidth of the laser was then reduced to 0.6 MHz full width at half-maximum and the long-term stability was imposed by the reference cavity (3 MHz/°C). A reference beam monitored by a detector D_3 was used to increase the signal-to-noise ratio by a differential method.[4] The probe beam was divided into two beams. One was focused by a short focal lens on the sensitive area of a detector D_1 (HP 4207); the other was sent to a detector D_2 (HP 4207), which monitored only a part of the total intensity, since the diameter of the beam at the diode was 6 mm. The two beams in the I_2 cell and the diode D_1 in the probe beam had the arrangement of Fig. 1. After formation of the difference between D_1 and D_3 and phase detection, the signal of saturated absorption was recorded on the first channel of a recorder. The difference between D_2 and D_3 gave, after phase detection, the sum of the saturated absorption plus the saturated dispersion. The signal of saturated dispersion was obtained from a new difference between the outputs of the two phase detectors and plotted on the second channel of the recorder. It is important to remark that in the signal $D_2 - D_3$ the maximum of the saturated-absorption curve is not affected by the signal of saturated dispersion if the studied line is well resolved. This feature eases the offset of the output of the two phase detectors, offset which has to be done very carefully to obtain a pure saturated-dispersion signal.

A typical experimental spectrum is shown in Fig. 3 (pressure in the iodine cell was 0.27 Torr). Three components of the hyperfine structure of an iodine line situated near 5900 Å were investigated. The line shapes of the saturated-absorption and saturated-dispersion signals were numerically calculated[8] from the expression of the complex susceptibility of the saturated medium and the value of the residual Doppler effect resulting from the noncollinearity of the beams in the cell. The absorption curve was fitted with use of the imaginary part of the complex susceptibility under the assumption of a saturation parameter χ of 0.13 and a Doppler residual parameter of 1.5 MHz. This calculation led to an homogeneous broadening of 5.8 MHz. This result agrees with the value found by others[9] in similar experiments. The dispersion curve was then calculated from this parameter and was found to be in great agreement with the experimental data.

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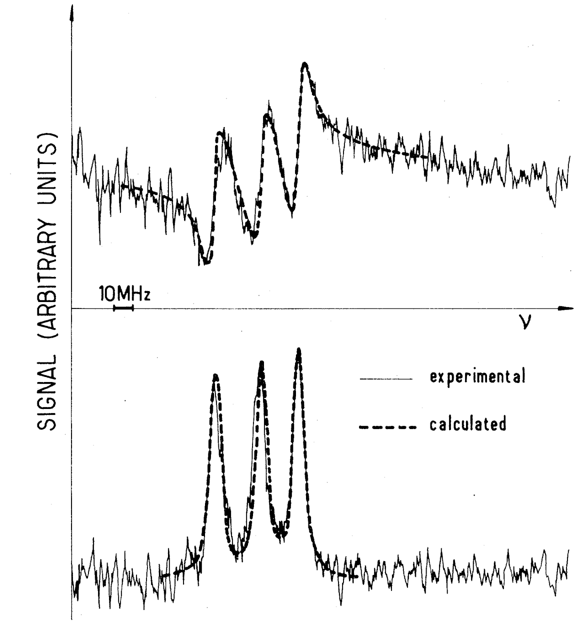

FIG. 3. Saturation spectra of three hyperfine components of an iodine line near 5900 Å: upper part, saturated-dispersion spectrum; lower part, saturated-absorption spectrum. Experimental conditions: angle between the beams, 13 mrad; frequency sweep rate, 0.9 MHz/sec; time constant, 0.1 sec.

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Plasma Heating by Lower-Hybrid Parametric Instability Pumped by an Electron Beam

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We study experimentally the interaction of an electron beam modulated near the lower-hybrid frequency with a longitudinally magnetized inhomogeneous plasma. At high levels of beam modulation above a certain threshold, the beam pumps the parametric decay instability into the lower-hybrid wave and ion-acoustic wave, and correspondingly plasma heating takes place rapidly. The instability threshold is determined in a parameter space. These results are compared with theory, and reasonable agreement is obtained.

The interaction of a modulated electron beam with a longitudinally magnetized plasma is one of the most familiar themes in plasma physics. By use of the collective and internal interaction, several linear and nonlinear phenomena have been studied. In particular, the interaction near the lower-hybrid frequency ω_{LH} is of considerable interest from the viewpoint of plasma heating, since the electrostatic instabilities at $\omega \simeq \omega_{\mathrm{LH}}$ have large growth rates together with a high level of saturation.[1] In fact, rapid plasma heating has been reported in such a beam-plasma system.[2,3] No established theory, however, has been made for the heating mechanism. Modulating the beam by a high-power transmitter, we have proposed recently[4,5] that the energetic ion production above appears to be due to the lower-hybrid parametric mode conversion that is pumped by the beam, rather than due to beam-plasma instabilities or linear mode conversion. In this Letter, we wish to present in detail these experimental results on the nonlinear interaction in the