tion and overlap, as discussed above.

[21]L. N. Tunitsky and E. M. Cherkasov, Zh. Tekh. Fiz. 37, 2038 (1967) [Sov. Phys. Tech. Phys. 12, 1500 (1968)].

[22]Bennett (Ref. 8) attempted to obtain oscillation on the 6563-Å H_α line, but was unable to obtain laser oscillation in a 3-m Ne-H_2 discharge. He did not, however, take advantage of reaction (5) in regard to the excess kinetic energy supplied to the atoms produced in the $n=3$ state. We propose to do this by cooling the discharge tube.

[23]T. Marshall, J. Appl. Phys. 36, 712 (1965).

[24]Recently, J. A. McInally [Bull. Am. Phys. Soc. 15, 431 (1970)] proposed that hydrogen atoms in the $n=3,4,5$ states are selectively produced in a neon discharge by the two-step reaction:

$$\mathrm{Ne}^* + \mathrm{H}_2 \rightarrow \mathrm{Ne} + \mathrm{H}_2^{+\nu} + e,$$

$$\mathrm{H}_2^{+\nu} + e \rightarrow \mathrm{H}^* \ (n=3,4,5) + \mathrm{H} + E_{\mathrm{K.E.}}.$$

This mechanism is consistent with the recently observed "superradiant" laser oscillations at 4861.2 and 4340.6 Å tentatively assigned to the H_β and H_γ lines. See G. J. Dezenberg and C. S. Willett, IEEE J. Quantum Electron. QE-7, 491 (1971). Similar processes may also play an important role in producing atomic-oxygen laser oscillations observed in a Ne-O_2 discharge.

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Interactions among Multiple Lines in the 8446-Å Atomic-Oxygen Laser*

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The atomic-oxygen laser oscillates at four closely spaced frequencies on the gain profile of the 8446-Å fine-structure transitions. A set of experiments is reported which studies the competition among these four lines by suppressing one of them. The results are explained on the basis of the interaction of laser lines oscillating on Doppler-broadened transitions sharing a common lower level.

I. INTRODUCTION

The atomic-oxygen laser oscillates at four closely spaced frequencies on the atomic gain profile of the 8446-Å fine-structure transitions ($3p\,^3P_{1,2,0} - 3s\,^3S_1$). In the preceding paper[1] it was explained that because of *selective reabsorption* of uv resonance radiation emanating from the lower laser level, the gain is depleted at the central portion of each fine-structure transition, and laser oscillation occurs only at the *wings* of the two fine-structure transitions with highest gains. Figure 1 illustrates again the positions of the four laser lines relative to the spontaneous-emission profile of the three fine-structure transitions. These lines are labeled A, B, C, and D in order of increasing frequency, with A and B falling on opposite sides of the $^3P_1 - {}^3S_1$ transition, and C and D falling on opposite sides of the $^3P_2 - {}^3S_1$ transition. Line D is largest due to overlap of the high-frequency wing of the $^3P_2 - {}^3S_1$ transition and the low-frequency wing of the $^3P_0 - {}^3S_1$ transition.

The present paper reports a set of experiments which studies the interactions among the four laser lines by suppressing one of them (in a manner to be described below) and observing the intensity changes of the other three. It is found[2] that suppressing the strongest line D causes line C to greatly increase in intensity, line B to increase somewhat, and line A to decrease. This is illustrated in Figs. 2(a) and 2(b), which show scanning Fabry–Perot interferometer traces of the four laser lines. Similarly, blocking line C causes line A to increase in intensity and line B to de-

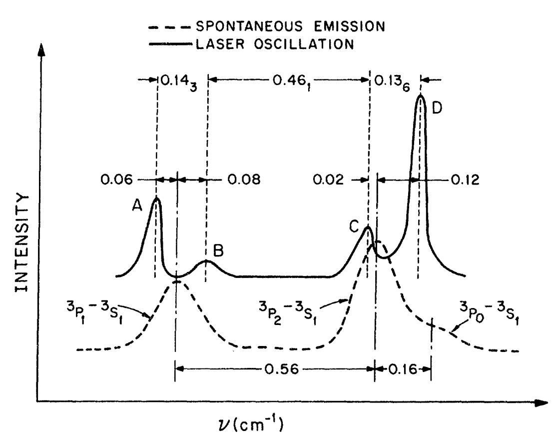

FIG. 1. The four laser lines near 8446 Å showing positions relative to the spontaneous emission of the three fine-structure transitions.

crease in intensity. [Compare Figs. 2(a) and 2(c).] Similar effects occur when lines A or B are suppressed.

It will be shown in this paper that these interactions result from two facts: (i) The laser oscillations on the $^3P_2 - {}^3S_1$ and $^3P_1 - {}^3S_1$ transitions, which share a common level, are coupled at certain frequencies and compete; (ii) there is a small additional line-shape asymmetry which, in the $^3P_1 - {}^3S_1$ transition, causes the A and B lines to be slightly asymmetrically placed with respect to the $^3P_1 - {}^3S_1$ center frequency (Fig. 1).

The paper is divided as follows: The experimental setup is described in Sec. II. Section III, which discusses laser oscillations on coupled transitions, is subdivided into three parts: A, an explanation of the laser-induced line-narrowing effect; B, its application to the atomic-oxygen laser; and C, an explanation, based on A and B, of the experimental observations. In Sec. IV the asymmetrical placement of the laser lines is discussed. Some interesting competition effects expected at lower operating pressures are discussed in Sec. V. Section VI is the conclusion.

Some additional experimental information on the pulsed-laser system is deferred to the Appendix.

II. EXPERIMENT

Most of the experimental work reported here was done separately on two versions of the oxygen laser, one using a continuous direct-current discharge, and the other a high-voltage pulsed discharge. The two systems behaved very much alike with respect to the phenomenon of interest in this paper, and differed mainly in that the pulsed system had a higher over-all gain. Most of our discussion will treat the data taken with cw and pulsed lasers as similar unless otherwise noted. Details of the pulsed system are deferred to the Appendix.

A 1.5-m quartz discharge tube of 12-mm in diam. with hot cathode and a water-cooling jacket was used. The optical resonator consisted of two 2-m radius mirrors spaced by 2 m (confocal), or one 2-m and one flat mirror (hemispherical). With a pulsed discharge (voltage: 20 kV; pulse duration: 1.8 μsec; repetition rate: 2500–3000 pulses/sec), external mirrors of reflectivity 99.2% and 98.5% would suffice to have all four lines lasing, but with a cw discharge (optimum current: 180–220 mA) a combination of 99.8% and ~100% reflectivity mirrors were required, one of which was internal, to obtain oscillation on four lines.

Because oxygen was very heavily adsorbed onto the walls and cathode of our tube, we found it difficult to maintain statically the optimum pressure of oxygen reported by other workers (36 mTorr of O_2 in 1.3 Torr of Ar according to Bennett *et al.*[3]), and instead arrived at the following method: The tube was filled with 1 Torr of argon, and a reservoir was filled with an equal pressure of oxygen. When a connecting valve was opened, oxygen would diffuse through the argon and collect on the tube walls, resulting effectively in a flowing-oxygen system. Unfortunately, we are left without accurate knowledge of the resulting oxygen pressure in the active region; it is estimated to be at least 100 mTorr, somewhat higher than the values quoted by other workers.[3,4] This system would break into oscillation after "cooking" for about 5 min (presumably the time to establish a certain atomic-oxygen density by means of dissociation), and would then run for about 10 min before losing gain.

All the laser-line spectra and also the spontaneous-emission profile were observed with a piezoelectrically scanned Fabry–Perot interferometer having a free spectral range of 1.16 cm^{-1} and a finesse of about 40, for a resolution of 0.03

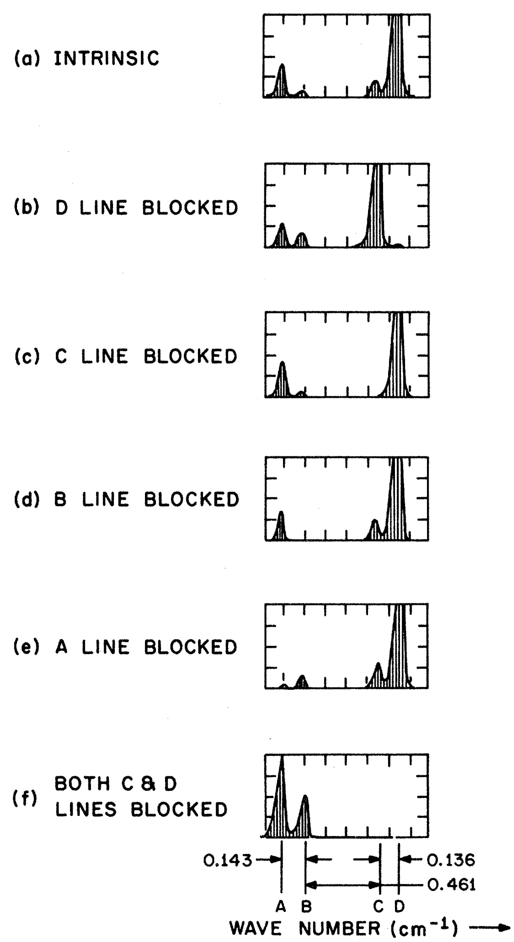

FIG. 2. Oscilloscope traces of Fabry–Perot scans showing the laser output behavior when one of the four laser lines is selectively blocked.

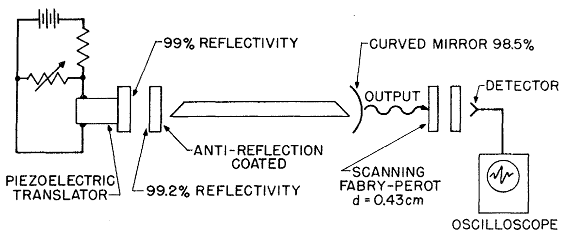

FIG. 3. Optical cavity using Fabry–Perot interferometer as one end mirror. This arrangement can selectively block oscillation of the four laser lines, one at a time.

cm^{-1}.

Interactions of the four laser lines were studied with a special arrangement at one end of the cavity, illustrated in Fig. 3. The flat mirror of the hemispherical cavity was replaced by a Fabry–Perot interferometer consisting of a pair of flats each coated for 99% reflectivity at 8446 Å. The inside flat mirror was antireflection coated on the side toward the Brewster window, and the outside flat could be translated by means of a piezoelectric mount. The free spectral range of this "end cavity" was 1.32 cm^{-1}. As a part of the over-all optical cavity, this device acted as a very high reflectivity mirror (> 99.9%) except over narrow spectral regions of high transmission 0.03 cm^{-1} wide and spaced 1.32 cm^{-1} apart. These narrow regions of resonant transmission became "rejection notches" for the laser cavity, and their positions could be manually adjusted by varying the dc voltage on the translator. It was thus possible to tune the end cavity so as to selectively block the oscillation of any one of the four laser lines A, B, C, or D. (Adjacent rejection notches fell 1.32 cm^{-1} away where they had no effect.)

The results (Fig. 2), described briefly in the Introduction, will be more fully discussed in Sec. IV in conjunction with the explanation of the effect. However, one important additional result should be noted here: By narrowing the spacing of the end-mirror etalon to 1 mm we were able to make a rejection notch broad enough to simultaneously block oscillation on *both* C and D, thus allowing A and B to be seen free of their influence. The result is shown in Fig. 2(f), where it is seen that A remains about twice as big as B. This residual asymmetry is indicative of a small asymmetry in the $^3P_1 - ^3S_1$ gain profile. Such an asymmetry is also sugested by the asymmetrical placement of the A and B lines with respect to the $^3P_1 - ^3S_1$ atomic-center frequency (Fig. 1), already mentioned in the Introduction. (It should be noted that the positions of the A and B lines are unchanged when lines C and D are suppressed.) The existence of this asymmetry, further discussed in Sec. IV, is important to a complete understanding of the experimental results.

III. LASER OSCILLATION ON COUPLED TRANSITIONS

A. Laser-Induced Line-Narrowing Effect

The line shape of a Doppler-broadened transition is dramatically altered by the presence of an intense standing-wave laser field resonating with a second Doppler-broadened transition sharing a common level. The standing-wave field selectively interacts with atoms whose velocities Doppler shift one of its traveling-wave components into resonance. This produced changes in the level populations over two narrow intervals symmetrically located about the center of the velocity distribution. These changes reflect themselves in the gain profile of the coupled transition, scanned by means of a weak monochromatic probe field colinear with the standing-wave field: Two narrow Lorentzian resonances appear superimposed upon the broad background signal at frequencies symmetrically located about the corresponding line center. This phenomenon, called laser-induced line narrowing, has been treated extensively by several authors.[5]

The situation is illustrated in Fig. 4 for the case of a common lower level. A laser oscillation which is displaced (for some reason) from its atomic line center ω_2 to a frequency $\omega_2 + \delta$ will produce gain depletions in four different regions:

(a) the gain immediately about laser oscillation will be depleted. The extent of the depletion does not concern us here.[6]

(b) the gain on the opposite side of the same transition will be depleted over a Lorentzian profile, centered at $\omega_2 - \delta$, of width (full width at half-maximum in units of circular frequency)

$$\Gamma_L = \gamma_L + \gamma_2 \quad , \tag{1}$$

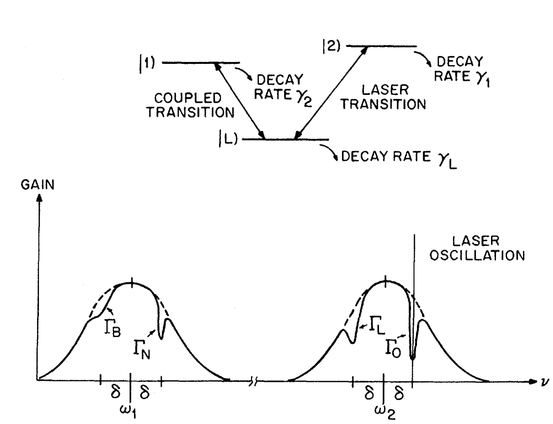

FIG. 4. Gain depletions produced by a standing-wave laser field interacting with coupled Doppler-broadened transitions.

where γ_2 and γ_L are the relaxation rates of the upper and lower levels of the laser transition, respectively, as determined by radiative decay and collisions. This effect is well known.[7]

(c) On the *coupled* transition, whose atomic-center frequency is ω_1, there will be a *narrow* zone of gain depletion centered at $\omega_1+\delta$, Lorentzian in shape, of width

$$\Gamma_N=\gamma_1+\gamma_2 \tag{2}$$

(in the special case of transitions of approximately equal frequencies, the case which concerns us here).

(d) Finally, on the opposite side of the coupled transition, at frequency $\omega_1-\delta$, there will be a *broad* gain dip, also Lorentzian in shape, of width

$$\Gamma_B=\gamma_1+\gamma_2+2\gamma_L \ . \tag{3}$$

So the difference between Γ_B and Γ_N is twice the "width" of the lower level. If the lower level is relatively broad, which is usually the case in laser transitions, Γ_B and Γ_N can be observably different. Such observations have been made recently by several workers[8–10] in different experimental contexts.

It is important to notice that these gain depletions can differ considerably in magnitude from one another. The area (gain$\times$frequency) of the Γ_L dip is usually much larger than the areas of the Γ_N and Γ_B dips, which are equal to each other. The ratio of the areas is given by

$$\frac{\text{area of } \Gamma_N \text{ or } \Gamma_B}{\text{area of } \Gamma_L}=\frac{\gamma_2}{\gamma_2+\gamma_L}\frac{|\mu_1|^2}{|\mu_2|^2}, \tag{4}$$

where μ_j is the matrix element connecting levels j and L.

In regard to the relative positions of the gain depletions (Fig. 4) the Γ_L dip is always positioned symmetrically across the laser gain profile from the laser frequency, the narrow dip is always located a frequency interval δ above (below) the atomic line center of the coupled transition as the laser oscillates δ above (below) its line center, and the broad dip Γ_B is always symmetrically located across the gain profile from Γ_N. If the laser oscillates at the atomic-center frequency ($\delta=0$), the broad and narrow dips on the gain profile of the coupled transition will coalesce.[11]

In case several laser modes are simultaneously oscillating, as in the oxygen laser, each one will produce its own set of depletions. Then the gain profile depletions will take the form of combs of adjacent dips.

B. Application to Atomic Oxygen

As explained above, the atomic-oxygen laser not only has closely spaced transitions sharing a common lower level, but in addition has its laser oscillations intrinsically displaced from the atomic line centers because of the selective reabsorption mechanism that greatly depletes the gain there.[1,12] So the broad and narrow depletions in the gain profiles of coupled transitions should be well separated. Thus, at certain frequencies, the four oxygen laser lines should interact in gain and compete with one another. This has been clearly observed in our experiments.

Figure 4 should now be interpreted as a simplified picture of one part of this effect in the oxygen laser. If we identify the $^3P_2-{}^3S_1$ transition as the ω_2 transition and the $^3P_1-{}^3S_1$ transition as ω_1 [so that $(\omega_2-\omega_1)\approx 17$ GHz], then the laser line illustrated corresponds to the main and strongest laser oscillation, denoted as the D line in Fig. 1. (Note that the depleted centers due to selective reabsorption have not been shown in Fig. 4.) The displacement of the D line above the $^3P_2-{}^3S_1$ atomic line center was measured by Patel *et al.*[13] to be 0.07 cm^{-1} and in our present experiments, at higher pressures, we find this displacement to be 0.12 cm^{-1}.

The full manifestation of these gain interactions in oxygen via the broad and narrow dips is evidently quite complicated. Each of the four lines A, B, C, D produces a gain dip Γ_L on the other side of its own gain profile, and a broad Γ_B dip and a narrow Γ_N dip on the other transition, all placed according to the simple rules already stated. However, the fact that the D line is much stronger than A, B, or C leads to a basically simple experimental situation.

The linewidths for Γ_L, Γ_N, and Γ_B are given by Eqs. (1)–(3) and depend upon the relaxation rates γ_1, γ_2, and γ_L. The known radiative widths are $\gamma_1=\gamma_2=4.5$ MHz and $\gamma_L=60.5$ MHz.[14,15] At gas mixtures of approximately 1-Torr collisions contribute an additional 5–10 MHz to the decay rates. (The exact value is not critical.) Therefore, the expected linewidths are

$$\begin{aligned}&\Gamma_L\approx\gamma_L+\gamma_2\simeq 80\ \text{MHz},\\&\Gamma_N\approx\gamma_1+\gamma_2\simeq 25\ \text{MHz},\\&\Gamma_B\approx\gamma_1+\gamma_2+2\gamma_L\simeq 150\ \text{MHz}.\end{aligned} \tag{5}$$

As explained above, the D line—the most intense line—consists of a set of adjacent longitudinal modes spanning over 0.05 cm^{-1}. Consequently, the D line produces a set of Γ_N dips on the $^3P_1-{}^3S_1$ (ω_1) transition in the vicinity of the B line (Fig. 4). Since the axial mode spacing of our 2-m laser is 75 MHz, these narrow dips tend to run together in a sawtooth pattern rather than remaining a comb of distinct holes. Continuing to refer to Fig. 4, the D line also produces a set of Γ_L dips on the $^3P_2-{}^3S_1\,(\omega_2)$ transition near the C line, and a set of Γ_B dips on the $^3P_1-{}^3S_1\,(\omega_1)$ tran-

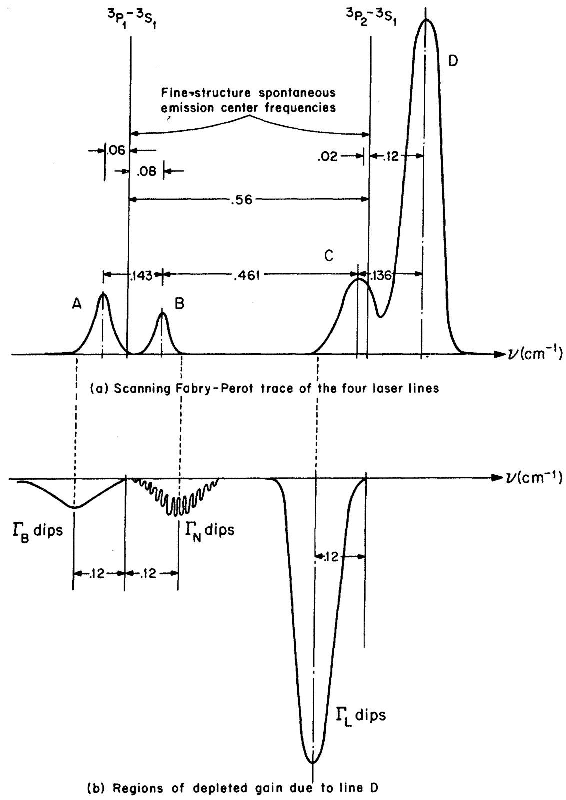

FIG. 5. Fabry-Perot scan of laser lines A, B, C, D (shown upwards) compared to expected gain dips due to line D alone (shown downward).

sition near the A line. Since the width of the Γ_L and Γ_B dips is broader than the laser-mode spacing, each set of dips runs together, depleting broad regions of the respective gain profiles.

The three over-all gain depletions differ considerably in magnitude: Since $\gamma_L \approx 5\gamma_2$, the over-all Γ_L depletions near line C are about six times as deep as the Γ_N depletions near line B [Eq. (4)]. It is seen from Eqs. (5) that the Γ_B dips are about six times broader than the Γ_N dips. But the areas of Γ_N and Γ_B are equal, and the combs of Γ_N dips have peaks and valleys such that their average value is about equal to the value of the broad flat region of depletion produced by the multiple overlapping Γ_B dips.

The over-all situation is represented in Fig. 5. Figure 5(a) shows a Fabry–Perot scan of lines A, B, C, and D all oscillating together. Note the large extent of laser oscillations at D, the relative intensities, and especially the placement of the four lines relative to the line centers of the two main fine-structure components. Line D is centered about 0.12 cm^{-1} above the $^3P_2 - {}^3S_1$ center frequency, whereas line C is only 0.02 cm^{-1} below it. Lines A and B fall 0.06 cm^{-1} below, and 0.08 cm^{-1} above the $^3P_1 - {}^3S_1$ center frequency, respectively.

Figure 5(b) is a sketch showing the positions, extent, and relative strengths of the gain depletions due to line D only (drawn extending downward). The widths and relative strengths are roughly to scale: The Γ_L dips are about six times stronger than the Γ_N and Γ_B dips, and the Γ_N and Γ_B dips have equal average values.

The balance of expected interactions is clear from this picture. First, because of its large extent (and the fact that Γ_L dips are quite deep), line D can heavily suppress line C, despite the fact that the Γ_L dips are centered quite far (0.10 cm^{-1}) from the center of line C. Second, line D also suppresses both lines A and B through the Γ_B dips and Γ_N dips, respectively. However, line B is suppressed more, since the Γ_N dips are centered closer to the peak of line B (0.04 cm^{-1}) than the Γ_B dips to line A (0.06 cm^{-1}). We are now prepared to understand the results pictured in Fig. 2.

C. Line Interactions

Taking into account the three kinds of dips produced by the D line, and noting their relative strengths, where they fall relative to lines A, B, and C (Fig. 5), and the asymmetrical placement of lines A and B about the $^3P_1 - {}^3S_1$ center frequency, we can now account for the experimentally observed intensity changes. As described earlier in Sec. II, by varying the spacing of the end-mirror cavity, we could inhibit oscillation on one line, and in doing so also remove the Γ_L, Γ_N, and Γ_B dips it produces. The resulting intensity changes could be clearly observed.

The results are shown in Fig. 2 which uses the data from the pulsed system. The cw data were entirely similar, except that the intensity ratios f the four lines were slightly different. Figure 2(a) shows the intrinsic situation, with the spectral position of the rejection notch placed away from the four laser lines. In Fig. 2(b) oscillation of the D line is prevented by placing the transmission resonance of the end cavity at the spectral position of D. As discussed above, line D heavily suppresses line C even though C lies in the wing of the Γ_L dips due to D. The Γ_N dips of line D suppress line B more than the Γ_B dips do line A. Hence, upon suppressing line D, and thus removing the gain dips it produces, both lines C and B are expected to increase in strength. As line B grows, line A should decrease, since A and B compete through their own Γ_L dips and line B's Γ_L dip (near A) increases as B rises.

This is exactly what is seen in Fig. 2(b), where line D is "blocked," and line C, ordinarily weak, jumps to an intensity almost equal to that of the old D line. The intensity of line B increases about 90%, and that of line A falls off.

As line C grows, the Γ_L, Γ_N, and Γ_B dips associated with *it* grow too and become important. Note that the placement of the Γ_N and Γ_B dips due to line C tends to reinforce the increase of line B and the decrease of line A. Of course, the dips due to line C are weakly present even when C has its smaller initial value.

In Fig. 2(c) the oscillations of line C are blocked. D gets a bit stronger, thus depressing B, and A gains 50% in intensity over the intrinsic value because the Γ_N dips due to C are lifted, depressing B further. In general the A line tends to increase and decrease in strength along with the D line, and the B line changes up or down as the C line does.

Figures 2(d) and 2(e) show, for completeness, the effects of blocking the B and A lines. Blocking the B line enhances A over its intrinsic strength by removing the Γ_L dip due to B. Blocking the A line enhances B and also slightly enhances C. This demonstrates that the A line produces small dips back on the $^3P_2 - {}^3S_1$ transition, as expected.

All of these interactions can be understood by the above considerations. The weak $^3P_0 - {}^3S_1$ transition can be neglected except that it is the source of asymmetry that causes D to be generally favored over C in two separate ways: First, D enjoys gain from both the upper $^3P_2 - {}^3S_1$ wing and the lower $^3P_0 - {}^3S_1$ wing; second, the tails of a set of Γ_N dips due to D oscillating on the low-frequency wing of the $^3P_0 - {}^3S_1$ transition react back on the low-frequency wing of the $^3P_2 - {}^3S_1$ transition (near the C line) to further depress the gain there. (Angular momentum selection rules forbid three-level interactions between the $^3P_0 - {}^3S_1$ and $^3P_1 - {}^3S_1$ transitions for fields of the same polarization, as in our Brewster-window system.)

IV. ASYMMETRIC PLACEMENT OF THE LASER LINES

In the experiments described above we have found line D to interact more strongly with line A than with line B. Similarly, line C is found to interact more strongly with line B than with line A. Our explanation of this preferential coupling is based upon small asymmetries observed in the intensities of lines A and B and in their relative displacements from the $^3P_1 - {}^3S_1$ spontaneous-emission center frequency. These asymmetries are observed even when both lines C and D are prevented from oscillating. Figure 2(f), which is a Fabry–Perot scan of lines A and B oscillating with C and D both blocked, clearly shows the intensity asymmetry. A careful comparison of Fig. 2(f) with Fig. 2(a), the intrinsic situation (all lines free to oscillate), shows that the A-B positions are unchanged when lines C and D are suppressed, and the "residual" asymmetry in the displacements of lines A and B is the same as that shown in Fig. 1.

The cause of this asymmetry is uncertain. It cannot be due to overlap as in the case of the C-D lines, where the $^3P_0 - {}^3S_1$ low-frequency wing contributes to the gain of the D line. A tentative explanation is the presence of O^{18}, which has a natural abundance of 1 : 500. The isotope shift of the O^{18} transitions at 8446 Å is quite large, about 0.14 cm^{-1} to the high-frequency side of the O^{16} transitions,[16] and is comparable to the observed Doppler widths (full width at half-maximum ~0.15 cm^{-1}).[1] Accordingly, the O^{16} gain profile at each fine-structure component is modified by a small O^{18} component, displaced about half a linewidth upward in frequency. As explained in Ref. 1, the central portion of each O^{16} fine-structure gain profile is in the absorbing phase.[12] Estimates based on the density of atomic O^{18} similar to those given in Ref. 1 indicate that the centers of the O^{18} fine-structure gain curves also may be depleted, producing a small reduction at the high-frequency wing of each fine-structure gain profile, but leaving the low-frequency wings unaffected. This asymmetry would be most noticeable in the $^3P_1 - {}^3S_1$ fine-structure transition, and is probably masked by overlap effects in the other components. The slight asymmetry would be intensified by the regenerative effects of laser oscillation.

At any rate, further studies, such as variation of the O^{18} abundance, will be necessary to ascertain the detailed causes of the line-shape asymmetry.

V. COMPETITION EFFECTS AT LOWER OXYGEN PARTIAL PRESSURE

It should be pointed out that our results may be quite specific to the oxygen concentrations (over 100 mTorr) used in our experiments. Earlier observers,[3,17,18] working at lower oxygen partial pressures (Bennett *et al.*, Ref. 3, quote an optimum value of 36 mTorr) found a considerably smaller displacement of the D line (about 0.07 cm^{-1} instead of our value of 0.12 cm^{-1}). This smaller displacement is expected from the considerations of Ref. 1. Furthermore, at lower pressures the $^3P_1 - {}^3S_1$ line-shape asymmetry (which causes the A-B asymmetries) discussed in Sec. IV might be reduced. Therefore, the Γ_B and Γ_N dips produced by line D would be more closely centered on lines A and B, respectively, as compared to the higher-pressure case studied in this paper. Also, the separation between line A and the center of the Γ_B dips would be closer to that between line B and the Γ_N center. Thus, the asymmetry which, at high pressures, makes the Γ_N dips more influential than the Γ_B dips would be reduced if not entirely

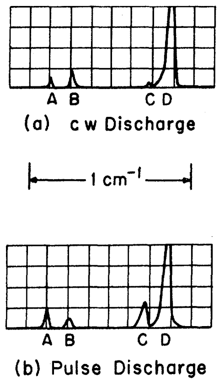

FIG. 6. Oscilloscope traces of Fabry-Perot scans for the four laser lines, comparing the cw (a) and pulsed (b) behavior. In the pulsed trace about 200 individual pulses occur during a scan. The horizontal scale is 0.127 cm^{-1}/div. The vertical scales in (a) and (b) differ by about an order of magnitude. In both cases the D-line intensity is off scale.

removed.

We would, in this case, expect another aspect of the line-narrowing effect to manifest itself. If the Γ_N and Γ_B dips of line D were more or less centered on the lines A and B, respectively, then the modes oscillating on line B would be sensitive to the comb of individual gain depletions within the Γ_N region. If the modes fell on the peaks of the depletions, then oscillation at B would tend to be suppressed; if the modes fell between the peaks the suppression effect would be diminished. At A, on the opposite side of the $^3P_1 - {}^3S_1$ gain profile, there would be no such effect, since the individual Γ_B gain depletions are much wider than those of Γ_N and completely run together. The resulting competition between lines A and B would depend on the relative placement of the modes of line B with respect to the Γ_N dips—line A would dominate when the B modes fell on the depletion peaks, line B would dominate when the B modes fell between them. The relative placement of the B modes depends, of course, on the precise length of the laser cavity, and the relative intensity of lines A and B would be a sensitive periodic function of the cavity length. The separation d between adjacent positions of maximum suppression of line B is given by

$$d = 1/2\Delta\sigma \text{ cm},$$

where $\Delta\sigma$ is the $^3P_2 - {}^3P_1$ separation in cm^{-1}. Thus, line B would be expected to pass through a maximum every 0.9 cm of traversal of one end mirror.[19]

In the course of our experiments we searched for alternations in the intensities of lines A and B as the laser cavity length was varied by several cm, but found no evidence of such behavior under our discharge conditions, neither pulsed nor cw.

VI. CONCLUSION

We have observed competition among the four fine-structure laser lines in atomic oxygen at 8446 Å. These competition effects can be explained on the basis of the interaction of laser lines oscillating on Doppler-broadened transitions sharing a common lower level. The detailed manifestations of the coupling effects may be different at lower oxygen partial pressures.

Taken as a whole, the 8446-Å oxygen laser presents a beautiful combination of interesting gas-laser phenomena.

ACKNOWLEDGMENTS

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APPENDIX: PULSED-DISCHARGE SYSTEM

Some additional experimental information about the pulsed-discharge oxygen-argon laser may be of interest. The gain in this case is much higher

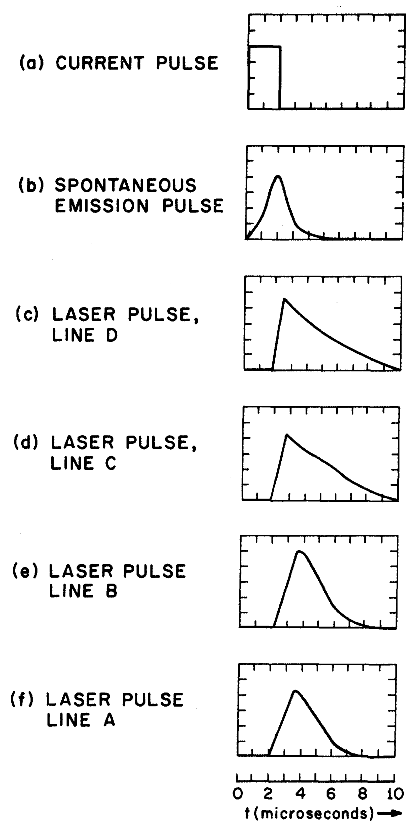

FIG. 7. Relative time dependence of current pulse, spontaneous-emission signal, and laser output from lines A, B, C, and D. The time (horizontal) axis is 1 μsec/div. The intensity (vertical) axes have all been normalized.

than for the cw case, with peak pulse powers of 250 mW (average power about 1 mW with a 2000 pulses/sec repetition rate). The intensity of the laser lines, especially of the weak pair of lines A and B, was found to be strongly dependent on the voltage, duration, and repetition rate of the current pulses, the whole behavior being highly resonant in character. Apparently, this was due to plasma resonances in the discharge tube. However, with optimum settings at a fixed pressure the four lines took on the definite intensity ratios shown in Fig. 2(a), with the A line second strongest to the D line. A cw-discharge produces slightly different ratios. Figure 6 shows interferometer traces of the four lines, comparing pulse and cw excited systems.

In order to ascertain whether or not the pulsed A, B, C, and D lines actually did occur at the same time, and so could be expected to interact via the coupled-transition mechanism as in the cw case, the following experiment was tried. The output of the pulsed laser was passed through a piezoelectrically scanned Fabry–Perot interferometer into a fast photomultiplier, which was observed on an oscilloscope triggered by the power supply pulse. The Fabry–Perot could be set manually with a dc voltage to pass the pulses from only one of the four lines at a time. The results are shown in Fig. 7. The A and B pulses lag about 1 μsec behind C and D pulses and are shorter, but they completely overlap with C and D. Reducing the gain of the D line to the level of the A or B lines changed the D-pulse time dependence to the *same* as that of A, so the difference in timing can be completely accounted for by the differences in gain of the four lines.

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