only qualitative description of the operation of the modulation system. A theoretical treatment of a laser cavity containing arbitrarily directed loss and birefringent anistropies will have to be worked out before the practical sensitivity limitation imposed by unavoidable intracavity-polarizing effects can be quantitatively predicted.

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Rotational Transition Competition in a Single-Mode CO_2 Laser

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***Abstract*—In the present work we have investigated the mechanism of rotational transition competition of a single-mode laser by studying the effect of small variations of the out-coupling loss factor. For this purpose we used on the out-coupling side one extra mirror with a reflectivity of only 1 percent. In this way the instability problem could be followed with a controllable out-coupling device having a variable reflectivity between 73.6 and 81.5 percent and a corresponding variation in out-coupling loss factor.**

Due to the nonzero rotational relaxation time we find a narrow range of the gain-to-loss ratio of respective transitions to have nonsingle oscillations. We have observed single as well as multioscillating transitions as a function of the loss factor.

Introduction

In the past [1] we have reported the simple construction of a high-power single-mode single-transition CO_2 laser having a plan-parallel germanium out-coupling flat. The reflection of this out-coupling mirror depends on the frequency of the radiation, and varied between 0 and 78 percent. The germanium out-coupling plate virtually discriminates between the available rotational transitions so that it is possible to select the one having the highest reflectivity. However, a more detailed study of the output shows that although one can observe single transition during long-term operation the laser can easily switch to several other transitions and more than one transition may oscillate at one time.

It is well known that in principle the laser can oscillate on many transitions of the 00°1–10°0 and 00°1–02°0 vibrational bands of CO_2. Approximately 100 lasing transitions on either band have been reported [2], [3] when a wavelength-discriminating device is used. However, in normal laser cavities, in general, only a few transitions will oscillate. Due to strong collision coupling between the transitions, the nonlasing transitions will transfer their energy into the lasing transitions.

Thus from experimental observations one finds on the one hand that, due to strong coupling, only a few (sometimes one) transitions lase; on the other hand, those lasing transitions are very unstable and small disturbance of the system seems quite easily to switch the laser into other oscillating transitions. *These somewhat paradoxical observations are the main subject of the present paper.*

This problem of rotational level competition has been studied before [4] using both ring lasers and a heterodyne detection system with two independent linear lasers. With these tunable lasers the gain factor $g(\nu)$ as a function of frequency can be easily shifted along each transition curve and it has been observed that within a narrow frequency interval of only several hundred kilohertz, there is a competition region where more than one

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rotational transition competes for the total inversion. This experiment shows clearly strong interrotational competition. However, there is the experimental difficulty that, due to the large longitudinal mode spacing of 600 MHz as compared with the narrow linewidth of about 60 MHz of a transition, the tuned cavity frequencies can easily leave or enter the transition regions of gain and frequency. Thus transition switches are very probable, but no information on the instability is obtained. The pressure-broadened transitions have broad maxima. In the center the $g(\nu)$ factors vary little, and at the edges they decrease rapidly with frequency so that at the observed narrow switching frequency interval, we have no knowledge of the variation of the $g(\nu)$ factor, and no indication of the instability is obtained.

We have attacked this instability problem by studying the effect of small variations of the out-coupling loss factor γ of an oscillating transition. As we have previously [5] discussed for the case of single-mode operation (TEM_{00}) and homogeneous line broadening, the important parameters for transition competition are the values of $g(\nu)/\gamma$ in the available transitions. Since the $g(\nu)$ factor of an oscillating transition, and even more, any change in $g(\nu)$ are very difficult to determine, we decided to study this instability problem by controllable variations of the loss factor.

Experimental Conditions

Since the switching mechanism is so sensitive to any slight disturbance the experimental set-up, as indicated in Fig. 1, was mounted on a 10-cm-thick 2 × 1-meter cast-iron table standing on special shock-absorbing rubbers. Acoustic vibrations were eliminated by wrapping the laser cavity in sound-absorbing wool. Further, the cavity was an integral part of the quartz tube having internal mirrors mounted directly at each end of the tube. The output intensity of this sealed-off CO_2 laser–interferometer combination was monitored by a confocal scanning interferometer and simultaneously by a Perkin–Elmer fore-prism grating spectrometer. The laser with a length of 130 cm was a 55-watt TEM_{00} mode device with a 22 percent transmitting germanium out-coupling plate, A flat Kodak Irtran 4, having a low reflectivity of about 1 percent, M_2, formed a coupled laser interferometer system with 10 cm spacing between M_2 and the output mirror of the laser. As M_2 was position-scanned, the output transition of the laser could be changed and line competition effects were observed.

The confocal scanning interferometer of 75 cm length having a free spectral range of 100 MHz and a finesse of about 20 was used to observe quantitatively the output spectrum of the laser beam. The alignment of this interferometer and the attenuation of the incident beam by a small pinhole were in such a way that the scanning interferometer had no influence on the lasing transitions. We could easily see when one transition oscillated and when line competition took place, i.e., more than one line oscillated. During the competition period the observed

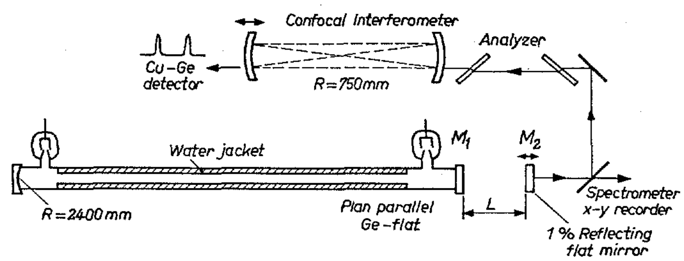


Fig. 1. Experimental arrangement of laser with adjustable out-coupling device. The output is simultaneously studied by a spectrometer and a scanning confocal interferometer.

output of the interferometer was seen to fluctuate between the originally lasing line and another transition. The observations were obtained with the scope traces of the output of a Cu–Ge liquid-helium-cooled detector. In addition, the important observation could be made so that the laser output was truly single-mode, i.e., only axial mode TEM_{00}.

The Perkin–Elmer monochromator output was plotted as a function of the position of mirror M_2. The intensity of any transition could be followed during the positional change of M_2 and the intensity would decrease from a maximum to a minimum or zero value every optical half wavelength of M_2 travel.

A dual Brewster window analyzer was used to determine the polarization of the laser output.

Experimental Observations

If the intermolecular competition effects are studied with a multimode cavity also having off-axial modes, the competition effects are determined mainly by spatial overlap of the radiation fields of the modes and much less by the cross relaxation between the rotational populations. In that case off-axial modes transitions having widely varying $g(\nu)/\gamma$ values can give stable oscillations [4]. But since we are interested in transition competition effects caused by collisional cross relaxation, we use a cavity that only oscillates in the Gaussian modes TEM_{00} so that all possible oscillating transitions fully overlap each other. The total output of the laser was about 55 watts and varies very little during tuning M_2. This indicates that as line competition is an important phenomenon, the power remains about constant but the frequency shifts, and because of a homogeneously broadened gain curve, the available population is accessible to any lasing transition.

The additional cavity described in Section II acts as an out-coupling device for the laser cavity so that we have a variable loss factor. By tuning this cavity the reflectivity as seen by the available transitions varies between a maximum R_{max} and a minimum R_{min} value. In general, the reflectivity curve of this out-coupling device as seen by the transitions will reach minimum and maximum reflectivity at different tuning positions. Thus by a little tuning of this cavity the reflectivity for one transition may increase whereas that of another transition may decrease. In this way the competition phenomena as a function of loss factor can be studied.

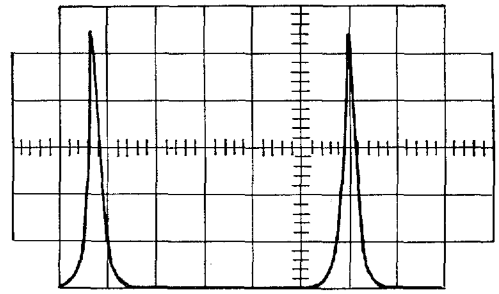
The total reflectivity R_{tot} of the additional cavity can be described with the following formula [6]

$$R_{tot} = \frac{(\sqrt{R_1} - \sqrt{R_2})^2 + 4\sqrt{R_1R_2}\sin^2\alpha}{(1 - \sqrt{R_1R_2})^2 + 4\sqrt{R_1R_2}\sin^2\alpha} \qquad (1)$$

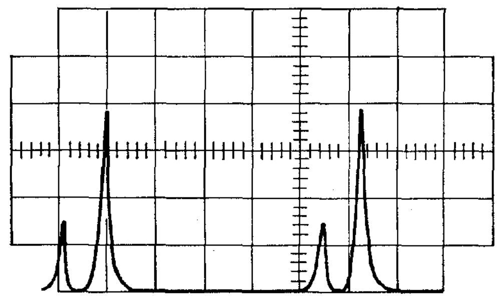
where R_1 is the intensity reflectivity of the germanium flat and R_2 is the intensity reflectivity of the end mirror of about 1 percent. $\alpha = (\omega L)/c$ is the optical phase of the additional cavity; ω, L, and c are the angular radiation frequency, the distance between the mirrors, and the velocity of light, respectively. From the low reflectivity of M_2 we find that the maximum modulation depth of the reflectivity curve is about 10 percent.

The reflectivity of the germanium plate varies between 0 and 78 percent. Since, as we mentioned before, only one or two (among many transitions) having the largest gain to loss ratios are lasing, and since even a small fraction of the reflectivity modulation is sufficient to suppress or start oscillation of a transition, we must suppose that for all oscillating transitions the germanium flat has a reflectivity close to its maximum value. Then, using this value for R_1 the reflectivity of the out-coupling device calculated with (1) varies between 73.6 and 81.5 percent. We have also observed that even a very small amount of scattered laser radiation (1 part in 10^4) back into the laser can cause instability in the line competition effects.

Fig. 2(a) shows the oscillogram of a single P transition obtained from the scanning confocal interferometer. The free spectral range and the finesse of this interferometer are 100 MHz and about 20, respectively. Thus it is seen that we are dealing with a single-axial-mode laser because we calculate that, for our laser cavity, the lowest order off-axial mode is separated from the TEM_{00} mode by about 40 MHz, which, of course, can be easily resolved from the trace of the scanning interferometer. If we tune the out-coupling device very slowly we find that at a certain position the intensity of the lasing transition decreases, and a new transition grows from a zero value. This is seen in Fig. 2(b). The spectrometer shows that the two resonance peaks in Fig. 2(b) correspond to frequencies of two different rotational transitions. The spectrometer would not resolve two adjacent axial modes within the same rotational transition. During an intermediate state (competition) both transition intensities would fluctuate but then the second transition will stabilize to a maximum value and the first transition will become a minimum or zero value. This effect is repeated every half wavelength of the M_2 mirror travel. We also see from Fig. 2(b) a small frequency shift of about 4 MHz. This shift just occurs on the appearence of the next transition and could not be observed as long as the second transition was absent. Presumably this is a line-pulling effect caused by the up-coming transition.



(a)



(b)

Fig. 2. (a) The oscillogram of a single P transition obtained from the scanning confocal interferometer. (b) Shows the oscillogram for a position of the out-coupling device for which the transition shown in (a) has decreased whereas a new transition has come up.

Fig. 3 shows the output of a lasing transition $R(20)$ as a function of the position of mirror M_2.

Each time after a tuning length of a half-wavelength the output is repeated. This tuning experiment was done very slowly and the whole recorded graph made in about 1 minute. During the subsequent time when transition has disappeared another transition, sometimes even more than one oscillates. When the intensity decreases another transition will begin to lase. The two rotational transitions would then compete for the total available population of the CO_2 (00°1) upper laser level. It was also possible to observe an M_2 position where two transitions had stable oscillations. When both oscillated the initial transition intensity was suitably diminished because of the population decrease due to oscillation of the second line. This is shown in Fig. 4 with the recorded intensities of two adjacent P transitions. Here it is seen that the stronger transition $P(20)$ is only partly suppressed on the appearance of the weaker one $P(22)$. Thus for certain values of R_{tot} it is possible to have two adjacent transitions both operating within the same spatial region. We note that the observed modulation somewhat in the center of $P(20)$ has nothing to do with the Lamb dip. We could have easily misconstrued that the variation in output of the $P(20)$ transition was caused by Lamb-dip phenomena instead of competition effect of the simultaneously oscillating $P(22)$ transition. The time constants of both detecting systems were too long to determine unequivocally whether the transitions oscillated simultaneously or not during the competition period. The time constants were not

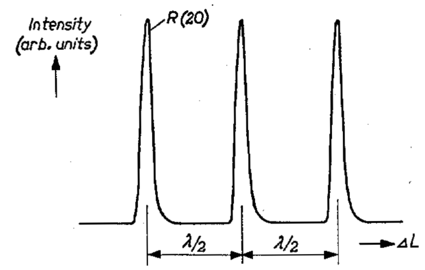


Fig. 3. The output of the lasing $R(20)$ transition over a range of M_2 travel.

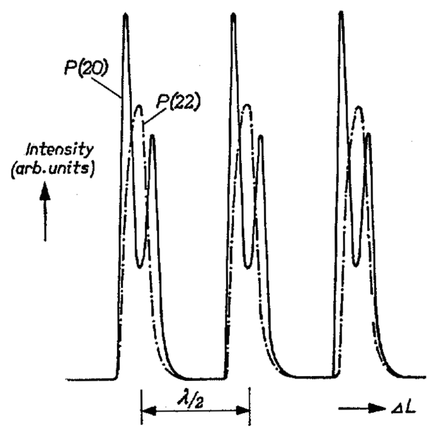


Fig. 4. The recorded intensities of two adjacent P transitions. It is seen that the new transition $P(22)$ suppresses only partly the $P(20)$ transition.

long enough to effect the measured output decays that are believed to be caused by the competition effects.

Considering Fig. 3 we again assume that since the transition appears each time after the out-coupling device has passed another half-wavelength, these appearances coincide with the positions of maximum reflectivity. Using (1) and assuming maximum output at $R_{tot} = R_{max}$ we find that the reflectivity of the out-coupling device at the point where the oscillation starts is about 76.5 percent. Thus we observe that if the reflectivity of a particular transition is only increased from 76.5 to 81.5 percent, this transition starts oscillation and interacts with the total inversion.

We have also analyzed the direction of polarization of each oscillating transition by means of two germanium plates at the Brewster angle (76°) as indicated in Fig. 1. It was determined that the output was always linearly polarized for the initial line as well as for the second line, which oscillates on moving M_2. The polarization was the same for all observed transitions even during the interval when competition effects were important.

Discussion

Rotational transition competition is a very important physical process in the performance of a CO_2 laser. All those transitions are highly competitive in the sense that they are strongly coupled to each other due to fast molecular collisions and that each of them competes to oscillate, not only on its own inversion but on the total inversion of the same and higher vibrational levels and their rotational sublevels. The rotational levels are thermally connected by fast collisions characterized by the rotational relaxation time, which, for the experimental conditions of a CO_2 laser, is of the order of 10^{-7} second. In principle each transition is subjected to two different physical mechanisms, i.e., either to oscillation on its own inversion and in this way converting the energy of excited states into radiation, or thermally transfering its energy into another oscillating transition for which the rotational population density has been considerably decreased by its interaction with the radiation field.

If we were dealing with a homogeneously fully broadened vibrational transition, which would be the case, for instance, if the rotational energy exchange were extremely fast, then very probably [5] only the transition having the largest g/γ value would oscillate. Although for a CO_2 laser there is much evidence that the line-broadening mechanism is closely approaching homogeneous broadening [7]–[9], it is expected that due to the nonzero time for rotational energy exchange there is a limited range of g/γ values of the respective transitions to have nonsingle oscillation. This indeed seems to be the case, although the range is very small. We have observed that during a reflectivity increase for a certain transition of 5 percent from 76.5 to 81.5 percent of a transition and a comparable decrease in reflectivity for another transition, the first transition will build up to oscillate from zero to its maximum value, whereas at the same time the original oscillating transition will decrease or will even disappear. Further, we have seen in other cases that even for two adjacent transitions the difference between the respective g/γ values is apparently too small to suppress completely the oscillation with the lowest value.

Using for M_2 a mirror having much larger reflectivity than 1 percent, so that R_{tot} will reach much higher values than was possible in this experiment, we observed many oscillating transitions over a large range of M_2 travel. This can be understood from the fact that due to the higher reflectivity of M_2, R_{tot} will have much higher and broader maxima over which its value changes less. Furthermore, due to a smaller loss factor, the mechanism of stimulated emission of a transition becomes much stronger as compared with the collisional energy exchange so that more than one transition will oscillate.

Acknowledgment

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High-Power Pulsed Xenon Ion Lasers

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***Abstract*—Output and threshold characteristics of small-bore pulsed xenon ion lasers are presented in detail as a function of current and gas pressure for ranges of these parameters that are consistent with high optical power output in the green–blue spectral region. It has been found that six wavelengths characteristic of xenon exhibit peak output powers greater than 100 watts, from a 5-foot laser tube over a limited (8–24 mtorr) range of xenon tube pressure. Laser action has also been obtained at high peak powers for longer current pulse (5–50 μs) operation of the tube.**

In addition, observation of three new laser wavelengths 5340, 5501, and 5590 Å is reported. These lines are only observed at very low tube pressures and very high peak currents.

IN THIS paper we characterize the operation of small-bore pulsed xenon ion lasers that we have found will deliver exceptionally high peak output intensities for laser lines in the green–blue spectral region.

The lines of primary interest here are as follows: 4954.1, 5007.7, 5159.0, 5352.9, 5394.6, and 5260.2 Å. These lines were first reported by Bridges and Chester [1], and, independently, by Dahlquist [2], who obtained relatively high peak power for short-pulse operation. They have recently been referred to, in part, as the "unclassified" group by Bridges and Mercer [3]. Jarrett and Barker [4] have reported that in pulsed operation the 5352.9-Å line of ionized xenon is more intense than the well-known 5145-Å ArII line. We have found that all six of the lines quoted above are considerably more intense than the 5145-Å ArII line (or any other non-self-terminating laser transition to our knowledge). Furthermore, these lines operate at unusually high output powers in the longer pulse mode.

In addition, we have observed lasing at 5340, 5501, and 5590 Å. These xenon ion laser lines appear to be unlisted [5].

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The data we report here were gathered from a tube having an active length of 5 feet and a bore diameter of 2.3 mm. Observations supporting the primary data were made with a number of different lasers, all of the same basic construction, ranging from 3 inches to 10 feet in active length, and from 1.5 to 3.0 mm in diameter.

All these lasers utilized a ceramic bore and gas-bypass configuration [6]. An indium cold cathode was employed as the high-current source. The properties of this remarkable cathode will be described elsewhere [7]. For those lasers discussed here, it has reliably delivered over 1500 amperes peak current with no apparent signs of fatigue or degradation; furthermore, it has enabled us to obtain reliable discharge initiation at xenon pressures as low as 2 mtorr.

Our data are summarized in Table I and in Figs. 1 and 2. Table I lists parameters associated with the six wavelengths of primary interest. All of the numbers quoted in this table were obtained with one set of mirrors, each having radius or curvature of 78 inches, and separated by approximately 72 inches. One mirror is nominally 100 percent reflecting over the green spectral range 5400–4800 Å, the other is approximately 12 percent transmitting over this same range. This configuration has proven to give near optimum coupling for argon ion spectral lines (for which this tube was originally used). No systematic attempt to optimize power output for xenon through variation of mirror coupling was made. No external magnetic fields have been applied.

Short current pulses (0.5–5.0 μs) were obtained by discharging 0.1–0.4-μF capacitors, charged to 5–10 kV, through the laser tube. (Pulses ranging from 5 to 80 μs duration were obtained with a variety of capacitance and inductance combinations in the discharge line. The curves of Figs. 1 and 2 refer, however, to short-pulse operation.)

For all xenon ion lines, power output increases rapidly with increasing current just above threshold, saturates for current densities three to five times greater than