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# Four-Branch Oscillation from a Dual-Polarization Cavity $CO_2$ Laser

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**Abstract.** We report here for the first time multiline oscillation of a cw-$CO_2$ laser on all the four branches 10*P*, 10*R*, 9*P*, and 9*R* where all laser wavelengths share a common gain medium. The 9*R*, 9*P* and 10*R* branch lines lased at the expense of the high-gain 10*P* branch lines for which the cavity offered very high transmission losses. The 10*P*(20) line was made to lase by constructing another cavity with orthogonal polarization, thereby easing the strong competition between this line and the relatively low-gain 9*R*, 9*P* and 10*R* branch lines within the gain medium which is common to both cavities.

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The subject of amplification of short pulses from $CO_2$ laser is of considerable importance. The short pulse possessing multiple frequencies is an essential prerequisite for its efficient amplification [1]. It is well known that if the multiple frequencies comprise the oscillating lines from both 9 μm and 10 μm branches, amplification further improves and more so if lasing simultaneously occurs on both *P* and *R* branches of these bands. $CO_2$ lasers, owing to the strong line competition, normally lase in the neighborhood of the 10*P*(20) line possessing the highest gain [2]. The line competition, however, can be rendered somewhat ineffective if the gas pressure is low enough or the laser pulses are short enough. Under normal operating conditions of both TEA and cw $CO_2$ lasers, these conditions are not usually met. Most of the techniques for achieving multiline oscillation in TEA $CO_2$ lasers reported to date can affect the same only in the 10 μm branch as offsetting the relatively high gain of the 10 μm band is somewhat difficult. Use of gaseous absorbers such as $SF_6$, $BCl_3$,$CF_3I$, $C_2F_8$, $C_4H_{10}$ and $CF_2HCl$ (see, e.g. [3]), has, however, been shown to allow 9 μm band transitions to lase, while providing absorption-loss selectively on the high-gain 10*P* branch lines. Dual band lasing has also been reported from systems with large discharge cross section (see, e.g. [4]), where cavities for the 9 μm and 10 μm bands are spatially separated in order to remove the competition effect. Obtaining more than two lines in the latter case is almost impractical as this calls for as many independent grating-tuned cavities. The former technique has also the obvious disadvantage that lasing occurs here only on a limited number of lines, that too at the expense of efficiency. For low pressure cw-$CO_2$ lasers, on the other hand, control of effective gain on a line is achievable by cavity length tuning which has been exploited in the past for the generation of multiline oscillation, although with limited success [5, 6]. It is natural to expect that owing to the strong competition effect, generation of simultaneous oscillation in a $CO_2$ laser on all four branches of rovibrational transitions sharing a common gain medium would be quite a formidable task. It is of interest to note here that we have recently operated a cw-$CO_2$ laser simultaneously on many lines spreading over the 9*R*, 9*P* and 10*R* branches at the expense of the high-gain 10*P* branch lines [7]. This was possible by utilizing a cavity, the *Q*-value of which undergoes a monotonic increase with frequency in the 9 μm to 11 μm region. In the present work, we have extended this to also include oscillation on the 10*P* branch. The strong competition between the high-gain 10*P* branch with the rest was eliminated, to a large extent, by constructing a second cavity for the 10*P*(20) line with a polarization orthogonal to that of the original cavity containing the rest of the oscillating lines. To our knowledge, this is the first report of multiline oscillation on all four branches of a $CO_2$ laser, wherein all the oscillating line share a common gain medium. Hybridization [6, 8] or injection locking [5, 9, 10] of this low-pressure laser to a high-pressure system will enable the scaling-up of the multiline intensity.

In pulsed $CO_2$ lasers, line competition can be rendered ineffective if the relaxation is not complete during the first half of the pulse [11]. Such a condition can be met by using either short-enough pulse or low-enough laser-gas pressure. Thus, when the laser is operated in continuous mode, the presence of the strong competition effect would force lasing only on one line at a time within the high-gain 10*P* branch, unless a frequency-dependent loss is introduced in the cavity in such a way that these lines suffer high losses while the net cavity round-trip gain becomes similar for a group of lines belonging to the other

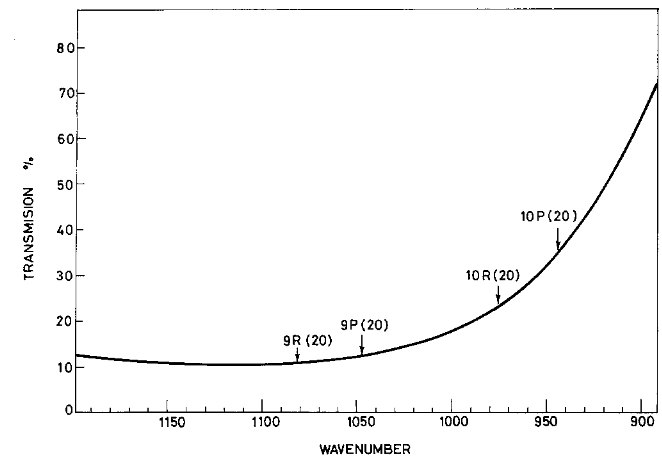


**Fig. 1.** Transmission of the output mirror $M_2$ as a function of wavelength (wave number axis is in $cm^{-1}$)

low-gain branches. By utilizing a resonator cavity, the $Q$-value of which exhibits monotonous rise with frequency in the 9 µm to 11 µm region (Fig. 1), a cw-$CO_2$ laser based on this cavity, for which the broadening was predominantly inhomogeneous, generates simultaneous oscillation on several transitions on the 9*P*, 9*R* and 10*R* branches. High transmission loss on the 10*P*-branch lines thus kept them totally from lasing, the presence of which would otherwise prevent lasing of any other low-gain branch lines. However, lasing on the 10*P* branch line can still be observed for the same inversion by constructing an orthogonal polarization cavity for this wavelength. In this case, the competition between a 10*P* branch line and other relatively weak gain lines (10*R*, 9*P* and 9*R*) would be somewhat eased since different groups of molecules would contribute to the growth of *p* and *s* polarization. Based on such a cavity, we have generated simultaneous oscillation on all four branches. Operation of a somewhat similar dual-polarization cavity $CO_2$ laser has been earlier achieved by Bertel et al. [12], although, with a different objective.

The dual-polarization cavity used for this experiment is schematically illustrated in Fig. 2. The Ge plate $B_1$, kept at Brewster's angle, reflects 78% of the light with polarization perpendicular to the plane of the paper and transmits all the light with polarization in the plane of the paper. The *p* polarization cavity is formed by a partially transmitting plane mirror ($M_2$) and a gold concave (5 m radius) mirror ($M_1$). The latter also forms the *s* polarization cavity along with another concave (5 m radius) gold mirror $M_3$. The two cavities overlap between mirror $M_1$ and the Brewster plate $B_1$ wherein the $CO_2$ discharge cell is also located. They separate out through reflection and transmission at the Brewster plate. The water-cooled discharge tube, 60 cm in length and 14 mm in diameter, was operated at a pressure of 17 mbar ($CO_2$:$N_2$:He:1:1.2:4) which resulted in the optimum performance of the laser. The two ends of the discharge tube were closed with anti-reflection coated ZnSe windows. The output mirror ($M_2$) of the *p* polarization cavity, whose transmission changed monotonically from 10% at 9 µm to 58% at 11 µm, was mounted on a piezoelectric transducer (PZT) to provide fine control of the axial-mode frequencies over the entire free spectral range (FSR) of 148.5 MHz. The output of the perpendicular polarization cavity, whose FSR was 117 MHz, was from the transmission loss through the Ge Brewster plate $B_1$ and was emitted into two directions, along with the output of the parallel cavity, i.e toward detector $D_1$, and toward detector $D_2$. Thus, the effective reflectivity of the *s* polarization cavity was 60%. Dual-cavity emission has also been obtained by replacing the Ge Brewster plate $B_1$ with a ZnSe Brewster plate in which case the effective reflectivity of the *s* polarization cavity was 25%. The inherent simplicity of alignment in the case of the ZnSe Brewster plate makes this an attractive choice. The entire output of the *s* polarization cavity could be made to emit along with the beam of parallel polarization by constructing a third cavity with the output mirror $M_2$ and the gold mirror $M_4$ (shown by the dashed line in Fig. 2). The output power of the laser was monitored with Ophir power meters (Model 30 A), while the frequency spectrum was observed on a $CO_2$ spectrum analyzer (Optical Engineering).

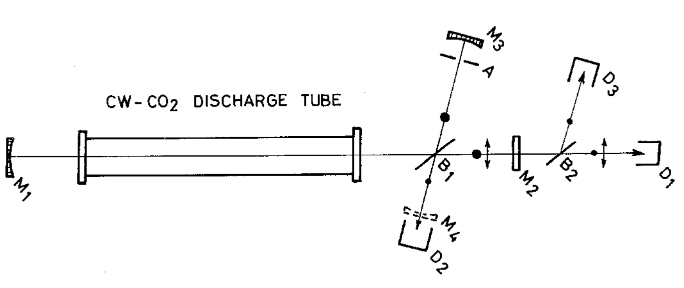


**Fig. 2.** Schematic of the dual-polarization optical cavity. $M_1$, $M_3$ and $M_4$ are gold concave mirrors. The partially transmitting mirror $M_2$ is mounted on a piezoelectric transducer. $B_1$ and $B_2$ are Brewster plates. $D_1$, $D_2$ and $D_3$ are detectors. A is an intracavity variable aperture

The quality factor of the parallel cavity is such (see Fig. 1) that the high-gain 10*P* lines are unable to lase as they suffer very high transmission losses, while the net cavity round-trip gain on a few transitions in each of the 10*R*, 9*P* and 9*R* branches is nearly the same, resulting in their simultaneous growth. The presence of spatial hole burning is also exploited to an advantage with regard to the multiline oscillation here since this is a slow-flow axial laser and thus the longitudinal drift time over a quarter of a wavelength is more than the inversion life time, which is again more than the rotational relaxation time. The presence of spectral hole burning, as the broadening here is predominantly inhomogeneous, will further aid the multiline oscillation by reducing the competition to some extent. Simultaneous lasing on up to 12 lines belonging to the 9*R*, 9*P* and 10*R* branches has been observed from this cavity. Since the transmission loss on all the transitions was nearly the same in the *s* polarization cavity, lasing here mostly occured on the 10*P*(20) line possessing the highest gain. Under optimum conditions the output of the two cavities were nearly the same. Exchange of energy between the two cavities was achieved in a controllable manner through the introduction of an intracavity variable aperture (A) in the *s* polarization cavity. Gradual closure of the aperture reduces the power on the *s* polarization which was found to reappear in the *p* polarization so that the sumtotal of the output from the two cavities always remains the same. The

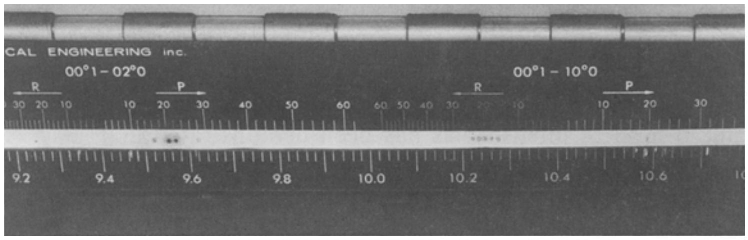


**Fig. 3.** A typical multiline spectrum of the dual-polarization cavity laser showing simultaneous oscillation on 9*R*(24), 9*P*(16, 20, 22, 28), 10*R*(16, 18, 20, 22, 24) and 10*P*(20)

measurement of *s* polarization power was achieved by placing a second ZnSe Brewster plate $B_2$ beyond the output mirror $M_2$ which reflects 50% of the *s* polarization incident on it towards detector $D_3$. The measurement of the reflected power, in turn, resulted in the determination of the total *s* polarization power emitted with the *p* polarization beam. It was found that in the case of Ge Brewster plate $B_1$ the *s* polarization power emitted towards detector $D_1$ was 1.25 times that which was emitted towards detector $D_2$, while for the ZnSe Brewster plate $B_1$ this factor became 2. This is obvious since the *s* polarization beam, while undergoing transmission losses on the Brewster plate in the direction of the parallel polarization cavity output will always be enriched more in photons than when the transmission losses occur in the other direction. Figure 3, which has been directly photographed from the screen of the spectrum analyzer, shows a typical multiline output of this dual-cavity laser containing oscillation on each of the four branches 9*R*, 9*P*, 10*R* and 10*P*.

Next we measured the intensity of each of the lines of this figure using the spectrum analyzer in conjunction with a slit of appropriate width and a power meter. The intensity distribution obtained this way is shown in Fig. 4. The exchange of energy between 10*P*(20) and the rest of the lines in this spectrum was possible by controlling the size of the aperture *A*. However, the number of lasing lines from the *p* polarization cavity and the intensity distribution on them could also be varied somewhat controllably, without significantly affecting the intensity of the 10*P*(20) line, by tuning the *p* polarization cavity length over its FSR.

The competition between the two lasing cavities was estimated by measuring the maximum deviation of the *s* polarization power from the average power and it was found to have a strong dependence on the parallel cavity length, as shown in Fig. 5. This is because the standing-wave patterns of the oscillating wavelengths in the parallel cavity will continuously shift with respect to the standing-wave pattern of the *P*(20) line in the perpendicular cavity, which remains stationary with respect to the tuning of the parallel cavity length. As expected, the competition was found to be less when the two cavities generate almost the same power (trace *a*), and was found to increase, in general, if one becomes weaker compared to the other. This is demonstrated in the traces *a* to *c* of Fig. 5, which have been obtained by gradually shutting off the intracavity aperture *A* in the *s* polarization cavity.

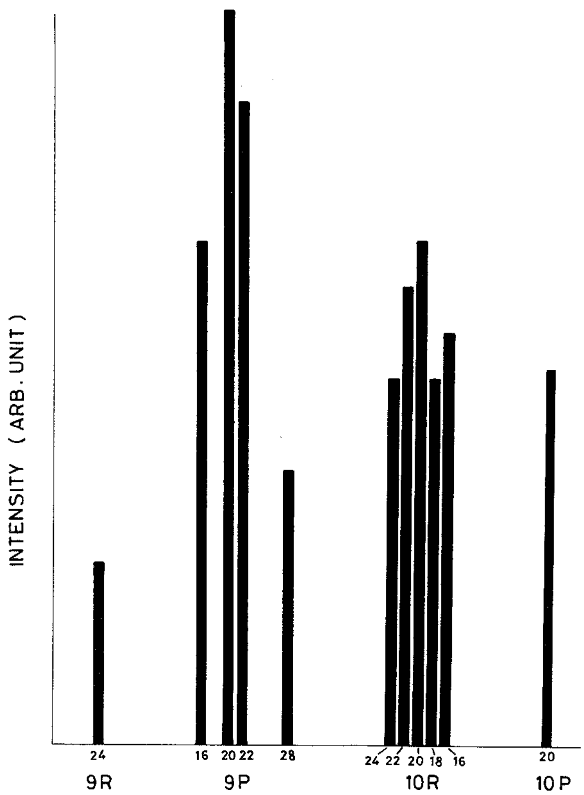


**Fig. 4.** Intensity distribution on each of the oscillating lines of Fig. 3

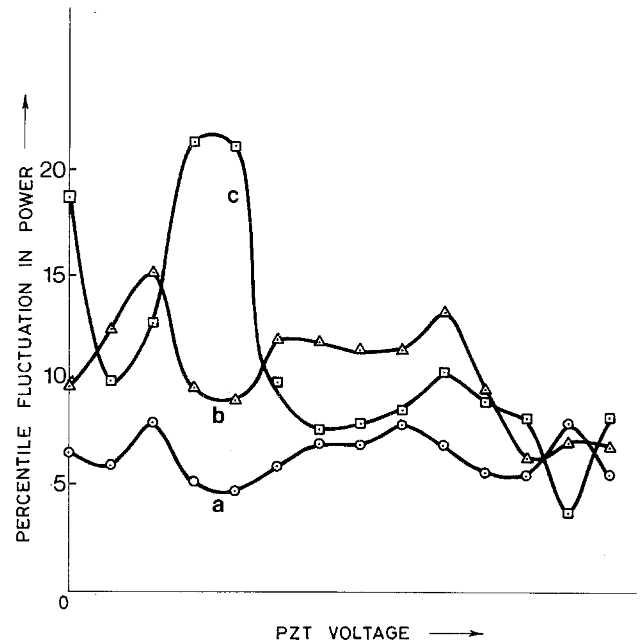


**Fig. 5a–c.** The competition between the two cavities as the modes of the *p*-polarization cavity are tuned over its FSR. The traces (a–c) have been obtained by gradually closing the intracavity aperture *A*

Owing to the low operating pressure of this laser, the intensity on the oscillating lines is small. However, even hybridization of this low-pressure laser to a high-pressure gain cell will enhance these multiline photons to the required level of intensity, as has been demonstrated first by Biswas et al. [6] for a hybrid $CO_2$ laser, in which the low-pressure section was pulsed, and subsequently by Mehendale et al. [8] also for a hybrid laser but with the low-pressure section operating in continuous mode. It should, however, be noted here that owing to the presence of anomalous gain on the $P(20)$ line in the high-pressure section, enhancement of the multiline photons in this section is possible only if the photons corresponding to the $P(20)$ line is scarce in the initial distribution [6]. Experimental realization of such an initial distribution of multiline photons in our system is thus quite straightforward as the intensity of the $P(20)$ line can be well controlled by means of the intracavity aperture $A$. Such an enhancement of the multiline intensity can also be somewhat effected by injecting these photons into a slave high-pressure cavity. The slave cavity, however, may not simultaneously resonate at all the seed photon frequencies, the number of which can be maximized by tuning the slave-cavity length over its FSR. We further note that many of the oscillating lines in our system had powers near to a watt with which injection-locking may be possible [9] in the high-pressure gain section, as injection seeding of a non-dispersive slave cavity is not uncommon [5, 9, 10].

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