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Development of a new CW Single-Line CO Laser on the $v'=1 \rightarrow v''=0$ Band

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Abstract. CW single-line laser oscillation on the $P(7)$ to $P(15)$ transitions in the fundamental band of CO is reported. Laser operation was obtained with a liquid-nitrogen-cooled dc electrical discharge flow system using a mixture of He, N_2, air, and CO. The parameters important for the CO fundamental band laser oscillation are discussed.

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Carbon monoxide lasers usually operate on a wide range of excited vibrational transitions [1] and the inversion process is V–V pumping [2, 3]. On the other hand, it is difficult to generate laser action on the fundamental band $v = 1 \rightarrow 0$, since we need to empty the $v = 0$ state in order to build up gain. The laser plasma in a liquid-nitrogen-cooled discharge optimized for high vibrational laser transitions does not meet this requirement [4, 5]. The first $v = 1 \rightarrow 0$ CO laser was reported by Djeu [6]. He observed single-line laser transitions on three P-lines with intracavity grating selection of these lines. Brechignac and Martin [7] also achieved oscillation on two lines, but with a non-selective laser cavity, where many vibrational bands could occur simultaneously. However, they could also obtain single-line lasing [8].

In these $v = 1 \rightarrow 0$ CO lasers, the plasma has to meet two essential requirements:

(i) The CO concentration must be very low and the N_2 content high;

(ii) The uncooled discharge regions have to be flushed to keep any absorbing CO out of this volume.

We are interested in the application of CO fundamental band transitions as high precision frequency standards in the 4.8 μm region. We have taken up this project as a first step towards a Lamb-dip stabilized carbon monoxide fundamental band laser [9] and thus our intention was to build up a reliable laser system of high stability and with a wide J-manifold that is single-line selectable. In order that the laser is suitable for permanent use it should also run without expensive gas additives such as xenon.

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1. Experimental Setup

We based our experiment on an all-glass construction of a liquid-nitrogen-cooled CO laser discharge tube with internal pre-cooling, according to the design first described by Lin et al. [1]. The cooled active length of the discharge is 72 cm, with gas inlets at both ends of the cooled region. The electrodes are in the room temperature part and are attached to the center dewar by ground-glass fittings. The thin CaF_2 Brewster windows are mounted on the same supports.

Since these room-temperature end regions have to be kept free of any ground state CO and thus of all CO, part of the helium is introduced through inlets at the Brewster windows. In order to prevent diffusion of CO from the cooled region into the end volume, an extension of smaller diameter is added directly into the center cone of the ground glass fittings. The experimental arrangement is shown in Fig. 1 whilst Fig. 2 gives the details of the flushing gas inlets at the ends of the plasma tube.

To keep the temperature of the plasma as low as possible the gas that is fed into the end regions and into the main inlet is pre-cooled. This is achieved with copper coils immersed into liquid nitrogen. The cooling is very effective as can be seen from the discharge color, when a mixture of He and N_2 is fed through these end regions.

The laser resonator consists of a gold-coated concave mirror with 5 m curvature and a high efficiency grating. The grating has been ruled on a gold-coated ZKN7 glass substrate with a groove density of 320 lines/mm. The profile is saw-toothed with a blaze angle of 35°. For the fabrication the high precision interferometrically

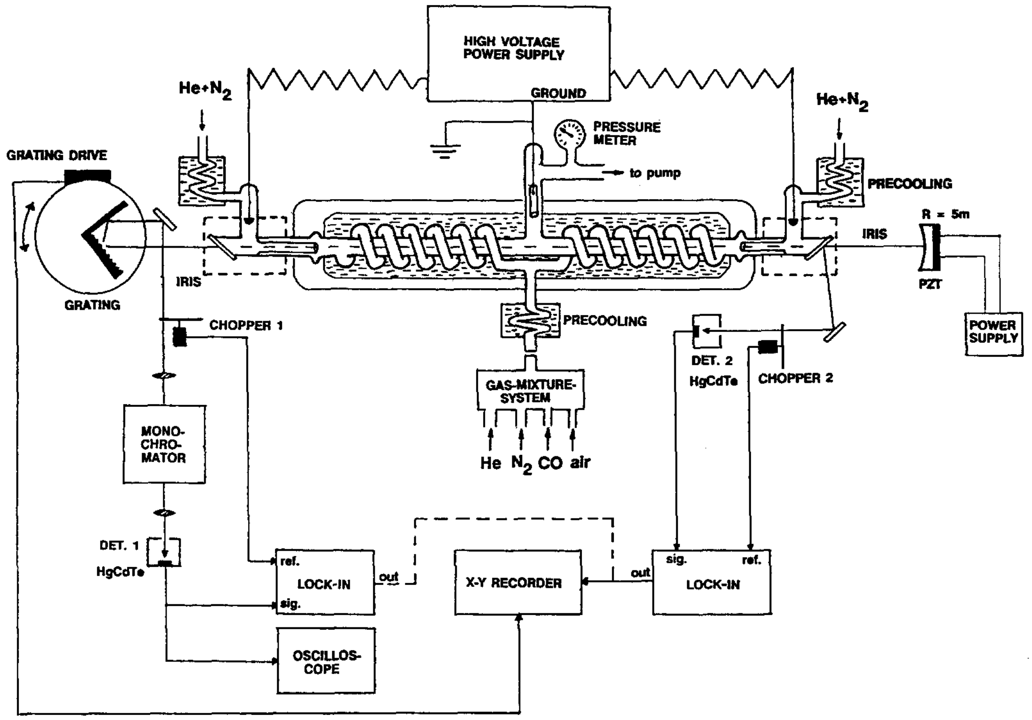

Fig. 1. Diagram of the experimental setup. The use of a flushing gas (He+N_2) and its pre-cooling are essential for the fundamental band operation. Details of the flushing gas inlets, marked by dashed boxes, are shown in Fig. 2

controlled GTK6 ruling engine (Carl Zeiss) was used. The grating was optimized for maximum efficiency at 4.7 μm and for a polarization perpendicular to the direction of the grooves. Under these operating conditions, the grating has a relatively high efficiency in the wavelength range between 3.5 and 5.3 μm due to the choice of the profile geometry. The resonator elements are mounted on a frame consisting of four invar steel rods (diameter 2 cm) that also contains two holders for the glass dewar. The curved mirror is mounted on a piezo translator and its holder is finely adjustable by means of differential screws. The grating support is a Littrow mount, where the laser radiation is coupled out via the zeroth order reflection. A monochromator is used to identify the selected laser transition and the reflection from a Brewster window monitors the spectral line distribution.

To obtain laser action under special conditions no pre-mixed gases can be used, but a gas handling and controlling system is necessary. Also, when liquid nitrogen cooling is used, no sealed-off operation is possible. A rotary pump (8 m^3/h) sustains the low pressure gas

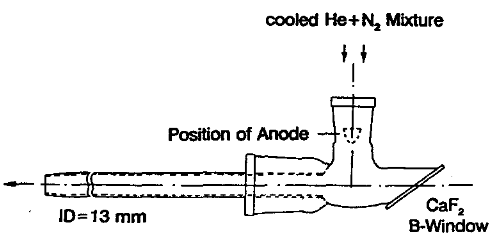

Fig. 2. Details of the end parts of the plasma tube (16 mm inner diameter). The flushing gas is introduced through the glass extension to keep any CO out of that region

conditions. The gas supply provides He, N_2, air, and CO for the main inlet and He and N_2 as flushing gases. The flow rates can be controlled by means of gas flowmeters and the total pressure is measured close to the exhaust exit near the cathode.

The anode material is solid nickel and the cathode is made of a nickel tube. The total dc discharge current is between 8 and 20 mA with two branches operated in parallel. The negative discharge characteristic is compensated by two 700 KΩ series resistors.

2. Experimental Conditions and Results

In spite of the fact that our gain tube has only half the active length of the tubes used by Djeu [6] and by Brechignac and Martin [7], we achieved a wider J-manifold in our laser compared with that reported previously. Also there was no need to use xenon gas as additive. One reason is certainly the optimized reflection grating, but the discharge conditions also turned out to be highly relevant.

The lowest of the P-branch transitions is $P(7)$ and the highest is $P(15)$; however, not the whole manifold can be achieved at a time. To change laser lines, the discharge conditions have to be altered. Figure 3 gives line plots for three different conditions. The most crucial parameter is the CO partial pressure. With a CO pressure exceeding 0.05 mbar no fundamental band laser oscillation can be achieved. The maximum power in a single line is a little more than 1 mW (Fig. 3b). The rotational temperature of the CO plasma is strongly influenced by the discharge current, which is reflected in the shift of the rotational

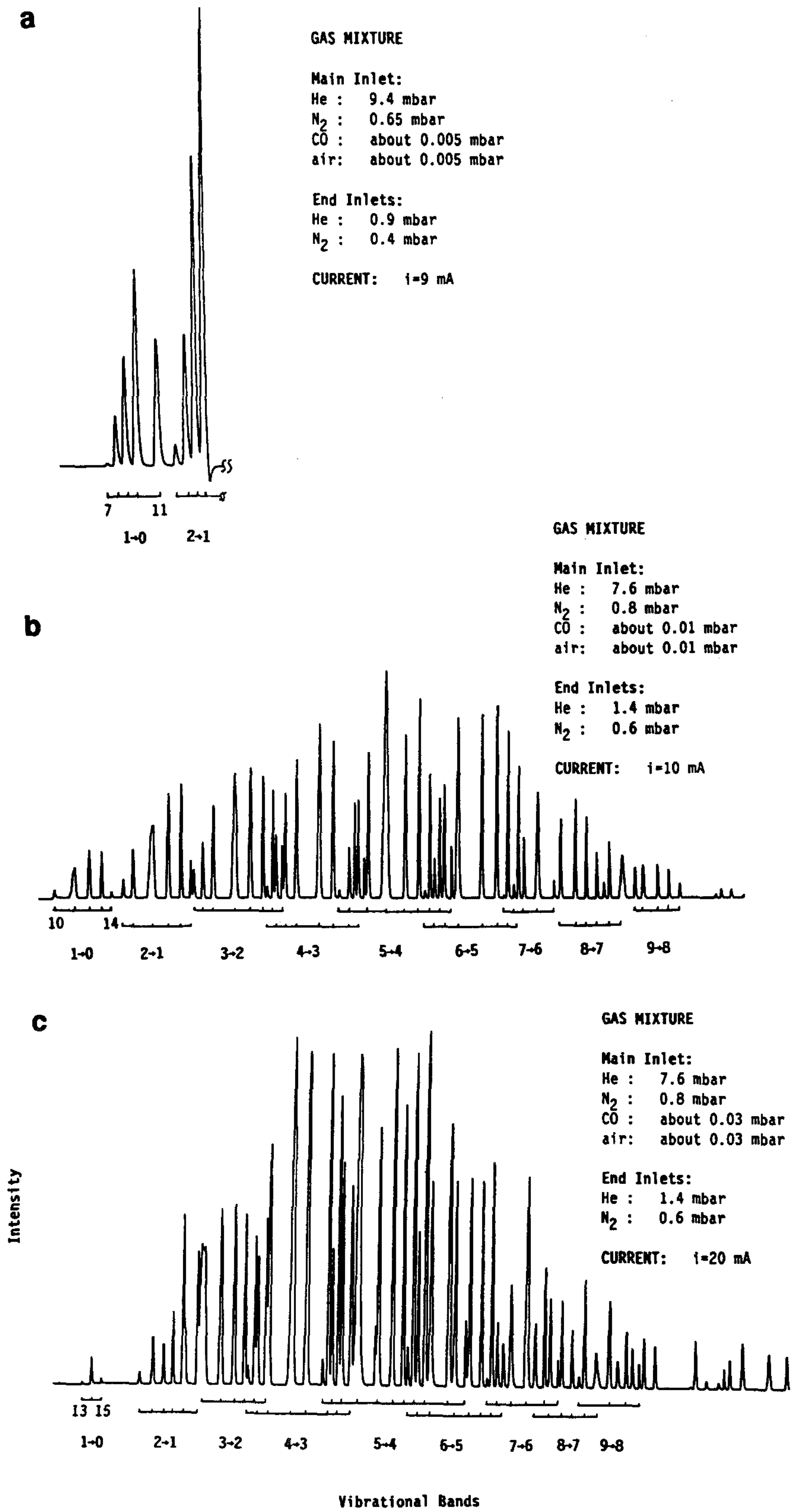

Fig. 3a–c. Line distributions for three different plasma conditions. In **a** conditions are optimized for low J-transitions. Shown are $P(7)$–$P(11)$ of the fundamental band. In **b** $P(10)$–$P(14)$ appear with a maximum output power of 1 mW for $P(12)$. The spectrum displayed in **c** contains $P(15)$, the highest J-transition that can be obtained with our setup

band distribution, as shown in Fig. 3. However, the CO partial pressure was also an essential parameter. The $P(7)$ line only occurred when the partial pressure was very low, whereas the addition of more Co caused higher J-transitions to occur.

All observed $1 \rightarrow 0$ lines are compiled in Table 1 together with transition frequencies calculated from recent data by Schneider et al. [10]. Further refinement of these data will be available in due course, when Lamb-dip-stabilized CO $v = 1 \rightarrow 0$ transitions can be directly

Table 1. Frequencies of the observed fundamental band transitions [10]

Transition	Frequency [MHz]
$P(7)$	63 424 961.8(05)
$P(8)$	63 302 467.8(05)
$P(9)$	63 178 959.6(05)
$P(10)$	63 054 441.5(05)
$P(11)$	62 928 918.1(04)
$P(12)$	62 802 393.7(04)
$P(13)$	62 674 872.6(04)
$P(14)$	62 546 359.4(04)
$P(15)$	62 416 858.3(04)

compared with Lamb-dip-stabilized CO_2 laser transitions [9, 11].

A few further experimental facts should be added before we begin a discussion of the results.

We examined the role of cascade pumping of the $v = 1 \rightarrow 0$ transitions, since we had found this a suitable way to generate $v = 1 \rightarrow 0$ laser emission for a V–V pumping experiment in CO [12]. As a matter of fact, with this setup and the grating replaced by a 95% reflection mirror, an all-line spectrum occurred, where we could extrapolate from the total power and the line strength distribution of the spectrum that the fundamental band oscillation delivered more than 80 mW (Fig. 4). This tells us that cascade pumping would be the most effective way to increase the fundamental band intensity. Nevertheless, this setup does not lead us to single-line tunability of the laser.

As has been shown by Luo et al. [13], one can operate a CO laser on two different transitions simultaneously from a single discharge by adding a third mirror to the Littrow-mounted setup. If these transitions belong to adjacent vibrational bands, the gain of the lower band transition is increased due to cascading effects. We used this arrangement to enhance the fundamental band power by operating higher vibrational band transitions at the same time. This was always beneficial for the $1 \rightarrow 0$ transitions, the effect being strongest using the adjacent $2 \rightarrow 1$ band for pumping. However only a factor of two in power increase could be observed. Since these two transitions mutually influence each other, thus making a future stabilization scheme more difficult, this design was not pursued further.

3. Interpretation and Discussion

From the results of our experimental investigations, we are led to the following interpretation.

The $v = 1 \rightarrow 0$ laser does not acquire its gain mainly from V–V pumping as do normal CO lasers. The very low CO concentration in the plasma does not allow an effective vibrational energy transfer. This is indicated by the cutoff of the laser emission after $v' = 10$. This phenomenon suggests that the process of CO electron excitation investigated e.g. by Schulz [14] becomes dominant, especially for the fundamental band transitions.

But there is another pumping mechanism due to the presence of nitrogen in the plasma. It is well known that excited nitrogen can transfer vibrational energy to CO via collisions. The strong dependence of the fundamental band oscillation power on the nitrogen concentration indicates that this mechanism is much more important for the $1 \rightarrow 0$ band laser than it is for a conventional CO laser operating on higher vibrational bands. So it seems justifiable to assign to the nitrogen the role of a pump gas [6].

To complete the picture it should be mentioned that besides the direct involvement in the pumping process, nitrogen has another enhancing effect on the laser emission due to the improvement of the plasma properties for CO electron excitation [15].

In previous fundamental band CO lasers [7, 8] the end regions were only flushed with He. We found it more effective to use a He+N_2 mixture and to pre-cool it. This observation certainly supports the role of N_2 in pumping the CO.

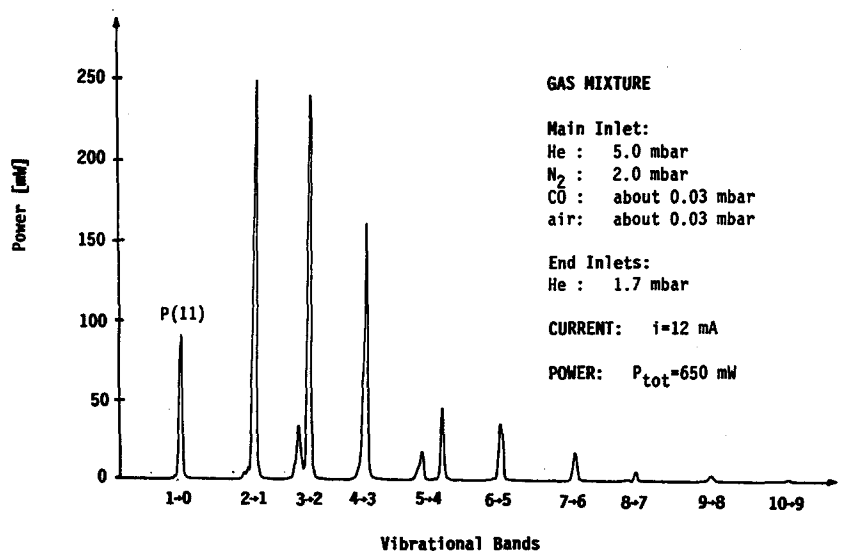

Fig. 4. Spectrum of multiple-line operation. Due to cascading effects the power of the fundamental band transition increased by nearly two orders of magnitude compared with the single-line results

The efficiency of cascade pumping for the fundamental band emission is certainly an interesting point. But not only the $1 \rightarrow 0$ transitions are affected. Figure 4 shows that the intensity distribution of the multiple-line spectrum is increased and shifted to lower bands compared with the single-line results. This observation proves that induced radiation processes have a substantial influence on the vibrational distribution of the CO molecules, dominating other relaxation mechanisms such as V–T and V–V processes. Thus the pumping efficiency is effectively increased and a large fraction of the energy transferred to the CO is available for laser emission.

4. Conclusion

We have developed a CO laser oscillating on the fundamental band that can be easily operated and provides all the requirements for Lamb-dip stabilization. Preliminary experiments have already been successful and it seems quite easy to get high quality stabilizing signals [9]. Frequency measurements in progress indicate that the CO laser stabilized to the CO fundamental band transitions will become a new secondary frequency standard in the mid infrared. Absolute frequency data on a series of CO fundamental transitions will be available in due course.

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