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N69-14065	
(ACCESSION NUMBER)	(THRU)
17	1
(PAGES)	(CODE)
CR-98219	16
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Honeywell Report 12044-PR4 1 October 1967

CARBON DIOXIDE LASER

For Period 1 July to 15 Sept. 1967

National Aeronautics and Space Administration
Marshall Space Flight Center
Contract No. NAS8-20645

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I. Introduction

This is the fourth monthly progress report for the Contract NAS8-20645. This report is a summary of the results obtained by heterodyning two passively stabilized carbon dioxide lasers on the surface of a mercury-cadmium-telluride detector. The lasers were built on Contract NAS8-18624 and were delivered to NASA on 18 July 1967. Reported are the results on "Pressure and current dependent shifts in the frequency of oscillation of the CO_2 laser". The manuscript will be also sent to "Applied Physics Letters" for publication.

Progress made so far on the one-way communication system utilizing two CO_2 lasers will be reported on 15 October 1967.

Pressure and Current Dependent Shifts in the Frequency of Oscillation of the CO_2 Laser*

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* This work was supported by NASA Marshall Space Flight Center under Contract NAS8-20645

Pressure and Current Dependent Shifts in the Frequency of Oscillation of the CO_2 Laser

Abstract

The shift of the frequency of oscillation of the $00^{0}1 - 10^{0}0$ rotation-vibration band at 10.6 micron of a CO_2 laser has been investigated as a function of total pressure, CO_2-partial pressure, discharge current, and cavity mode position. The measurements were made by heterodyning two passively stabilized CO_2 lasers, both oscillating in a single transverse mode and single frequency at the P-branch of the $00^{0}1 - 10^{0}0$ rotation-vibration band of CO_2. The result yielded a 5-8 MHz/Torr frequency shift towards red due to an increase in total pressure and a 500-900 kHz/mA shift toward blue due to an increase in excitation. The amount of frequency shift due to excitation was found to be independent of the location of the cavity resonance with respect to the doppler center. The dependence on CO_2 partial pressure was also determined.

Since the advent of the CO_2 laser (1) increasing interest exists in obtaining high power levels from oscillation in a single frequency and in a zero order transverse mode. The long term frequency stability and the resettability of such a frequency controlled CO_2 laser is affected by pressure and current dependent shifts in the center frequency of the 00^01 - 10^00 rotation-vibration band of CO_2. Extensive data has been obtained by several authors for the 1.15 μ and the 6328 Å-transition in a He-Ne laser (Ref. 2-4). In this paper we report shifts in the frequency of oscillation in a small, single mode and single frequency CO_2 laser due to changes in total pressure, CO_2 partial pressure, excitation, and cavity mode position. The measurements were made by heterodyning on a mercury-cadmium-telluride detector (5) two passively stabilized CO_2 lasers both having a relative stability of 3 parts in 10^{10}. Both lasers were of flowing gas configuration, identic in length and performance and operated from independent gas supplies (CO_2, N_2, He), power supplies and vacuum pumps. Each laser could be tuned in frequency over approximately 100 MHz with a piezoelectric transducer. One laser was used as a reference while the other was varied in pressure, excitation and cavity mode position. Both lasers and the heterodyne detector were mounted on a spring supported granite slab (3 ton weight).

The two lasers used in these experiments were of internal mirror design. The discharge tube is sealed in a yoke made of the material Cer-Vit* (6) with an expansion coefficient $\alpha < 10^{-7}$ per degree C. The two mirrors are

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* Owens-Illinois trade name.

clamped to the front faces of the Cer-Vit yoke which is ground flat and parallel. In this way the cavity is mechanically rigid and stable and the heat dissipated by the discharge tube is thermally insulated from the cavity structure. The discharge tube (8mm diameter) has two anodes, one at each end, and a center cathode. The gas flow enters the tube at each anode and leaves it at the cathode. Doppler shifts introduced by the gas flow can produce a broadening but not net frequency shift. The cavity mode spacing is 500 MHz. One mirror made of Irtran 2 has a 85% reflecting coating, the other mirror has a 3m radius of curvature and a gold coating. Insertion of an aperture yielded single transverse mode operation. Polarization of the output was obtained by direct insertion of 3 wires 0.0001" inches in diameter perpendicular to the beam direction. Different losses are obtained for the electric vector oscillating either parallel or perpendicular to the wires, similar to the infrared wire-grid polarizer (7). Both lasers were oscillating at the same single frequency of the $00^{0}1$ - $10^{0}0$ rotation vibration band of the CO_2 transition as was evidenced with a Perkin-Elmer 99G spectrometer modified for use at 10 micron. The lasers oscillated at a power level between 3 and 7 watts.

The laser beams were combined with a germanium beam splitter and their beat was detected with a liquid nitrogen cooled HgCdTe detector. The time constant of the detector and the connecting cables yielded a flat response up to 1 MHz and one order of magnitude signal reduction at 10 MHz. Beats up to 30 MHz were detected without preamplification of the signal. The relative stability of the lasers was measured with a panoramic spectrum analyzer and was found to be 10 kHz/sec as was determined with a sweep rate of 60 (1/sec) and an exposure time of 1 sec. Stability measurements have been made in time intervals ranging from 10^{-1} to 10^4 seconds and the obtained stability $\Delta\nu(t)$ as a function of time t (in sec) can be represented by the equation:

$$\Delta\nu_L(t) = 10^4\sqrt{t} \quad (\mathrm{Hz})$$

These measured stabilities are comparable to the measurements made by Freed (8) on sealed-off CO_2 lasers oscillating on a lower power level. Each of the measurements to be described below was made in a time span of less than 20 min. so that the maximum error due to drift was smaller then 350 kHz.

At the beginning of each measurement both lasers were operated with the same mixing ratio of the gases $CO_2:N_2:He$ and at the same absolute pressure. The laser which was to be operated at variable pressures and excitation was initially tuned with the piezoelectric transducer so it was oscillating at the doppler center. Shifts in the frequency of oscillation could be determined in two different ways (see Fig 1). Frequency shift could be read directly on the panoramic spectrum analyzer which has a calibrated range up to 26 MHz. The second method employs a low frequency a.c. modulation (200 Hz) in series to a dc voltage on the PZT element of the laser under investigation. A lock-in amplifier (PAR) which obtains the phase reference from the ac terminal, is used for phase sensitive amplification. A dc voltage tuning scan with applied ac voltage yields a typical discriminator curve with the intensity cross-over at the doppler center. The frequency width of oscillation is approximately 25-30 MHz. This frequency range is bounded on either side by a spike arising from the inter doppler competition region where the transition under oscillation is expelled by a new transition that has a higher gain at this frequency.

For the pressure and excitation measurements this method has been used in the following way: a pressure or excitation change creates a signal at the output of the lock-in amplifier. The dc voltage on the PZT element is now set to a new potential to make the signal disappear. From the calibration curve of the PZT element the corresponding frequency shift was determined. The signal to noise ratio at the detector determines the smallest required frequency excursion at which an intensity cross-over still can be observed ($\approx$ 50kHz). The direction of the frequency shifts was determined by an independent measurement of the absolute length change of the piezoelectric element as a function of the applied voltage. The calibration was found to be 28kHz/V.

The influence of pressure on the frequency of oscillation is shown in Fig 2. Both cavity modes are located at the beginning of the experiment at the center of the doppler curve. All pressure shifts are normalized to the reference laser operating at 11.5 Torr and 10mA of excitation. For the laser under investigation the excitation current was adjusted to its initial value after every change in pressure, while the partial pressure ratio was kept constant. For both described methods of determination of the frequency shift we obtain at a partial pressure ratio of CO_2:N_2:He = 1:1:3 a frequency shift of 5.3 MHz/Torr with a shift direction towards lower frequencies ("red shift"). The influence of the partial pressure of CO_2 to the center frequency shift is shown in Fig 3. With increasing partial pressure of CO_2 the frequency shift increases. The largest shifts observed at a CO_2 partial pressure of 3.6 Torr are 7.4 MHz/Torr.

The current dependent shifts are plotted in Fig 4. The frequency shifts are normalized to the reference laser oscillating at 10mA with both lasers at a total pressure of 12.0 Torr and the cavity modes tuned to the corresponding doppler centers at the beginning of the experiment. Over the entire range of excitation the frequency of oscillation increases with increasing excitation ("blue shift") and amounts to 900 kHz/mA for low excitation ($5mA/cm^2$) and reduces to 500 kHz/mA for strong excitation ($15mA/cm^2$). Over the corresponding range of excitation the output power increases from 3 to 7 Watts.

In Fig 5 we have plotted the frequency shifts due to current changes as a function of the relative cavity mode position. The reference laser was oscillating at the doppler center while the cavity mode of the second laser was placed a measureable amount off the doppler center to higher and lower frequencies. Excitation increases and decreases were made by $\Delta I = \pm$ 1mA at each mode position and the frequency shifts were measured. Although a total frequency range of over 25 MHz was investigated no dependence of the frequency shift with cavity mode position was found. The two horizontal lines in Fig. 5 for $\Delta I = \pm$ 1mA represent the arithmetic average of all measurements over the 25 MHz scanning range.

To summarize the experimental results we have found a red shift with increasing pressure and a blue shift with increasing excitation, the latter independent of the cavity mode position with respect to the doppler center. These results can be interpreted on the basis of a change in plasma parameters as a function of pressure and excitation. The index of refraction of a plasma is given by the equation (9):

Index of refraction

$$n = 1 - \underbrace{\frac{1}{2}\frac{N_e e^2}{m\epsilon_0\omega^2}}_{\text{electrons}} + \underbrace{2\pi\,\alpha_m N_m}_{\text{atoms or molecules in ground state}} + \underbrace{2\pi\sum_i \alpha_i N_i}_{\text{ions and excited atoms}} \qquad (1)$$

contribution from

An increase in pressure enhances the magnitude of the second term and therefore reduces the frequency of oscillation. α can be evaluated from the Lorentz-Lorenz equation. For the gas mixtures and pressures as used in our experiments typical contributions to the frequency shift are 10-12 MHz/Torr which compares with the measured value of 5-8 MHz/Torr. The term due to ionized components cannot be evaluated due to little knowledge of the dissociation rates in the gas mixture. The contribution from the electron term is determined by the electron density. Measurements of the electron density by Carswell and Wood (10) for a CO_2:N_2:He mixture at a pressure of 5 Torr yielded an electron density of $N_e = 2 \times 10^{10}$ (1/cm^3) and measurements made by Witteman (11) for a N_2:He = 1:7 mixture yielded a value for N equal 2×10^{11} (1/cm^3). If all of the observed frequency shift with increasing excitation is attributed to a change in electron density the corresponding electron density changes between 5 and 15mA/cm^2 amounted to approximately 2×10^{12}(1/cm^3) which is a large but not unreasonable number for the large current densities and pressures used in the reported experiments. A significant contribution to the reduction in index may arise from dissociation of CO_2 molecules and creation of components such as CO and NO that have a smaller polarizability than CO_2 and therefore contribute to an increase in the frequency of oscillation.

Acknowledgment is made to P. Gustafson for assistance in the design of the lasers and to B. Stinson for laboratory assistance.

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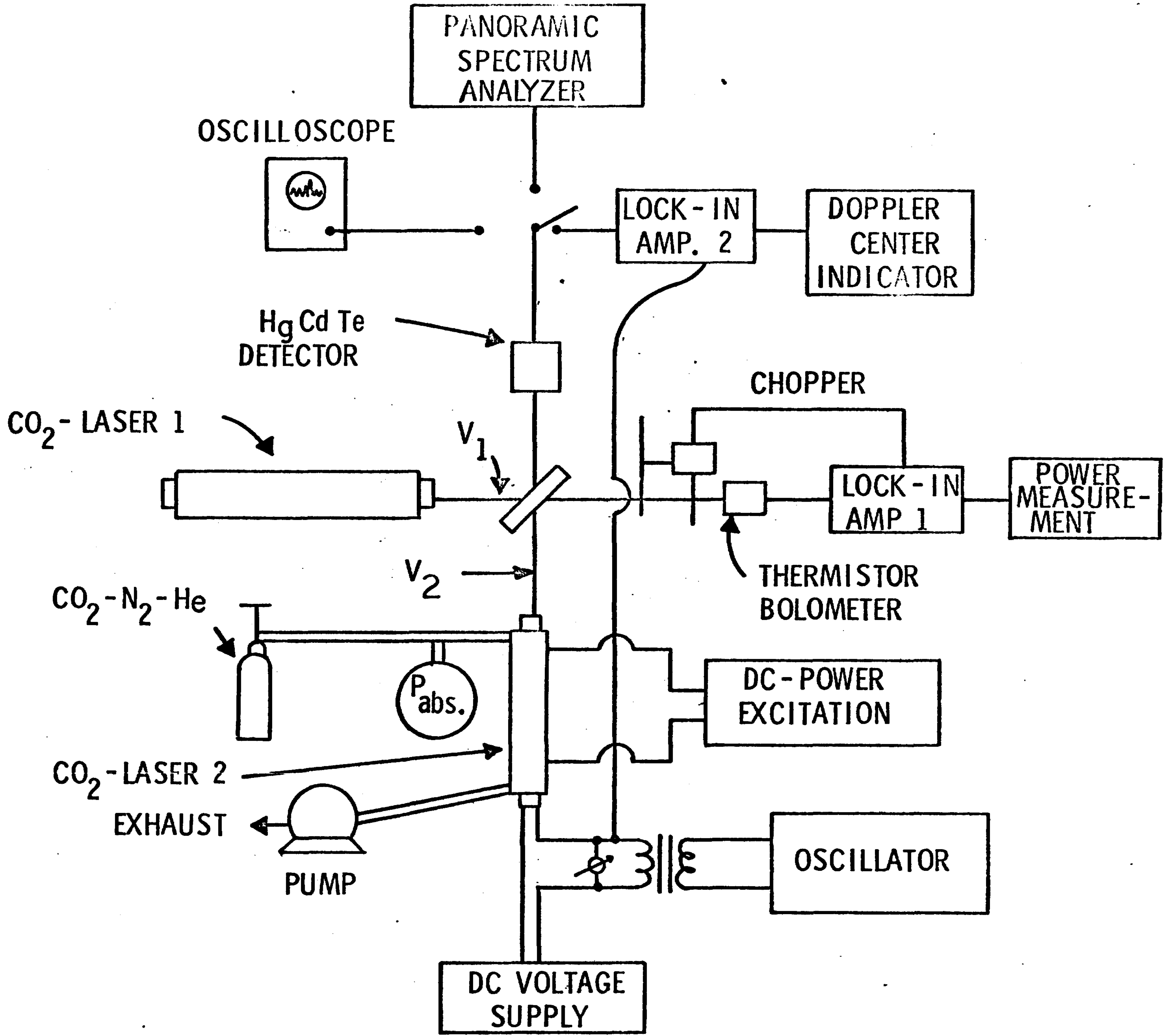
Figure 1: Experimental set-up of the frequency shift measurement with spectrum analyzer and doppler center indicator.

Figure 2: Shift in frequency of oscillation of the $00^{0}1 - 10^{0}0$ rotation vibration band of CO_2 as a function of total gas pressure. Gas mixing ratio $CO_2:N_2:He = 1:1:3$. Excitation current: 10mA (Reference laser operating at 11.5 Torr with 10mA excitation).

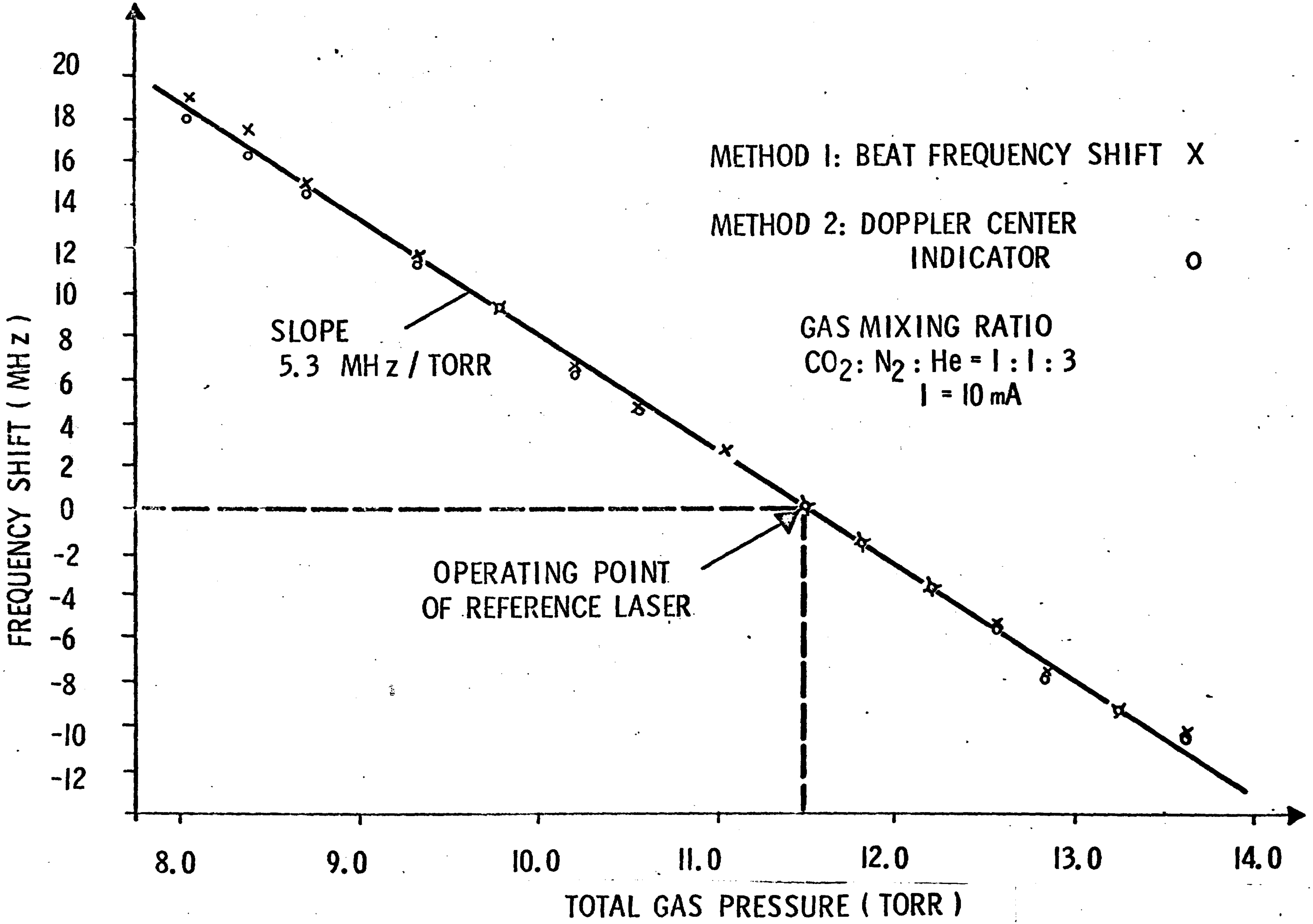
Figure 3: Absolute pressure gradient of frequency shift as a function of P_{CO_2}/P_{TOT}.

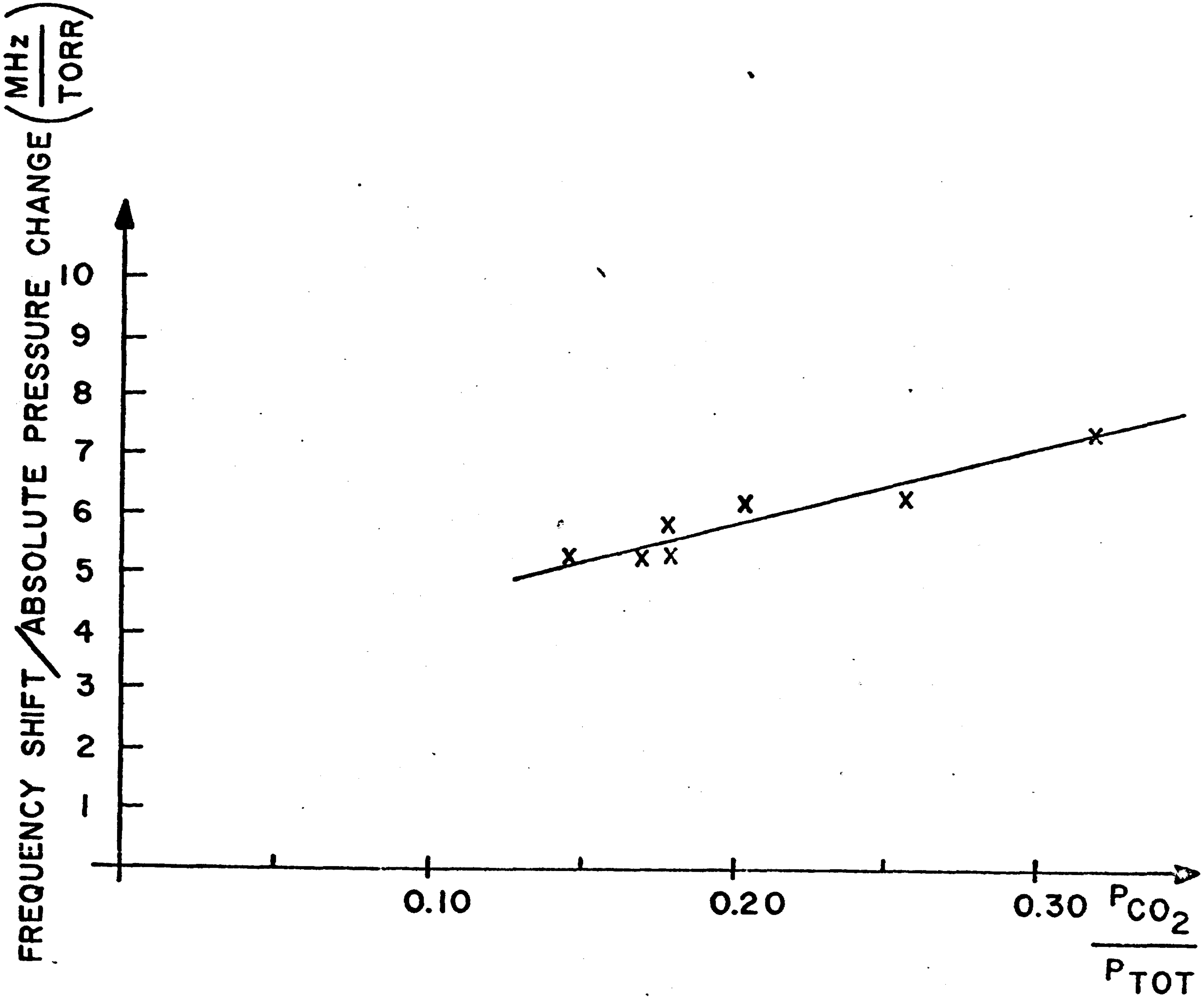
Figure 4: Shift in frequency of oscillation of the $00^{0}1 - 10^{0}0$ rotation vibration band of CO_2 and output power as a function of discharge current. Gas mixing ratio: $CO_2:N_2:He = 1:1:3$. (Reference laser operating at 12.0 Torr and 10mA excitation).

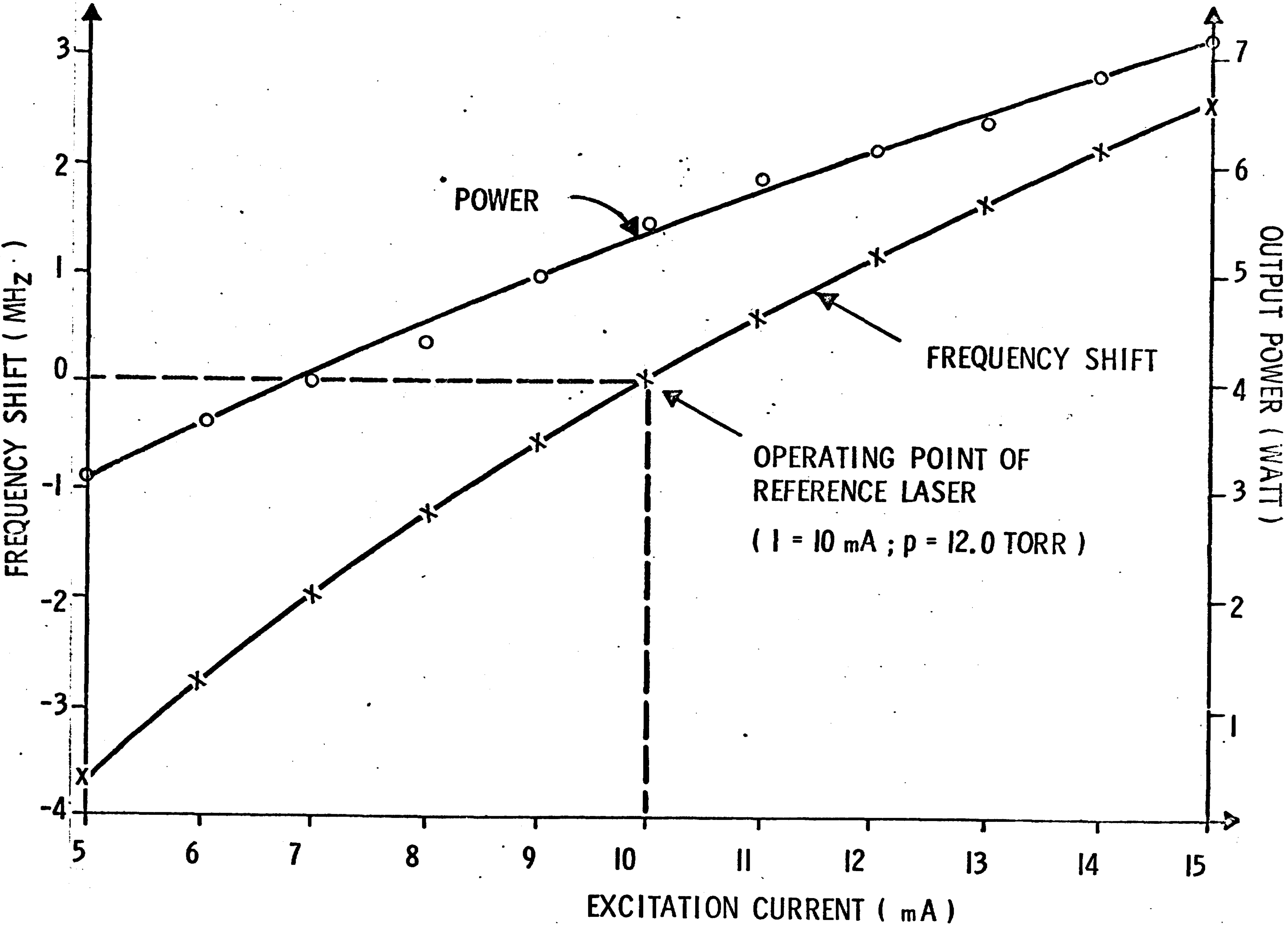
Figure 5: Shift in frequency of oscillation for a change in excitation of $\Delta I = \pm 1$mA for different cavity mode positions. (Reference laser operating at 12.0 Torr and 13.0mA excitation).

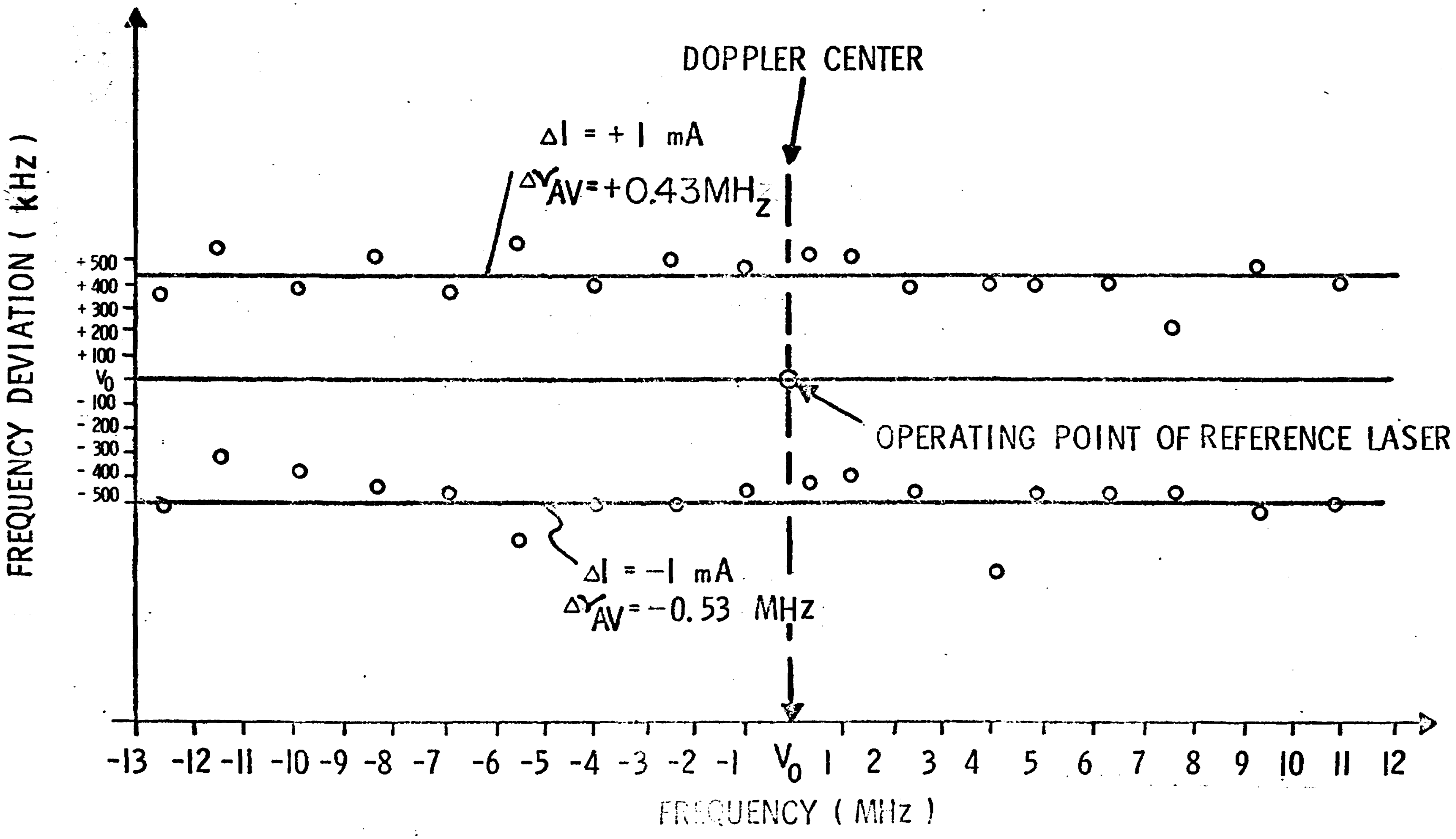


PANORAMIC SPECTRUM ANALYZER
OSCILLOSCOPE
LOCK-IN AMP. 2
DOPPLER CENTER INDICATOR
HgCdTe DETECTOR
CHOPPER
CO_2- LASER 1
V_1
LOCK-IN AMP 1
POWER MEASURE-MENT
THERMISTOR BOLOMETER
V_2
CO_2-N_2-He
$P_{abs.}$
DC-POWER EXCITATION
CO_2-LASER 2
EXHAUST
PUMP
OSCILLATOR
DC VOLTAGE SUPPLY


20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
FREQUENCY SHIFT (MHz)
8.0
9.0
10.0
11.0
12.0
13.0
14.0
TOTAL GAS PRESSURE (TORR)
METHOD 1: BEAT FREQUENCY SHIFT X
METHOD 2: DOPPLER CENTER INDICATOR o
SLOPE 5.3 MHz / TORR
GAS MIXING RATIO
CO2 : N2 : He = 1 : 1 : 3
I = 10 mA
OPERATING POINT OF REFERENCE LASER


FREQUENCY SHIFT / ABSOLUTE PRESSURE CHANGE $\left(\frac{MHz}{TORR}\right)$
1
2
3
4
5
6
7
8
9
10
0.10
0.20
0.30
$\frac{P_{CO_2}}{P_{TOT}}$


POWER
FREQUENCY SHIFT
OPERATING POINT OF
REFERENCE LASER
(I = 10 mA ; p = 12.0 TORR)
FREQUENCY SHIFT (MHz)
OUTPUT POWER (WATT)
EXCITATION CURRENT (mA)
3
2
1
0
-1
-2
-3
-4
7
6
5
4
3
2
1
5
6
7
8
9
10
11
12
13
14
15


DOPPLER CENTER
ΔI = + 1 mA
ΔνAV = +0.43MHz
OPERATING POINT OF REFERENCE LASER
ΔI = −1 mA
ΔνAV = −0.53 MHz
FREQUENCY DEVIATION (kHz)
+500
+400
+300
+200
+100
V0
-100
-200
-300
-400
-500
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 V0 1 2 3 4 5 6 7 8 9 10 11 12
FREQUENCY (MHz)