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SURVEY OF CO_2 LASER DEVELOPMENT FOR SPACE APPLICATIONS

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SUMMARY

This report presents the status of CO_2 laser development with special emphasis on those qualities which are relevant to the needs of NASA. The first NASA application of a CO_2 laser is expected to be in the development and testing of an optical communication link from a synchronous orbit to Earth using heterodyne detection. The transmitter for this link will be a small, low-powered, space-qualified CO_2 laser with stable, single-frequency, single-mode operation, and dependable, long operating life. In this report, the brief history of CO_2 laser development is surveyed and a somethat simplified qualitative discussion of the CO_2 laser and the various additives is presented. Then the current level of development is compared to what is desired. It is found that the CO_2 laser is especially suited for single-frequency operation; stable, single-frequency CO_2 lasers have been built and tested in heterodyne communication systems in the laboratory. Many of the requirements for space qualification can be met by proper design. The most difficult design problem will probably be the cooling of the discharge tube. The major problem is that of obtaining dependable, long operating life in a sealed-off CO_2 laser. Considerable progress has been made and, hopefully, continuing research will establish a basis for designing a long-lived CO_2 laser.

I. INTRODUCTION

The purpose of this report is to examine CO_2 lasers, to see how they work, how they were developed, what the present stage of development is, and finally what further developments are needed to obtain a laser which would be suitable for a space-Earth communication link. The scope is to be limited to the CO_2 laser itself; other components of the communication system, such as modulators, detectors, and transmitting optics, will not be included.

Section II is a historical survey of how the CO_2 laser was developed. It was not intended that every CO_2 laser reported in the literature be included in the survey, but that enough be included to show the steps in its development. Commercial lasers were not included, since they are usually at an earlier developmental stage than research lasers, and the main sources of information are advertising brochures which are constrained to be conservative to allow for tolerances in quality control. For instance, a CO_2 laser made by one firm was advertised as having an operating life of at least 300 hours, whereas a research laser, the prototype for this commercial model, ran for more than 1500 hours.

Section III is a rather simplified discussion of how the CO_2 laser works and how the operation is influenced by certain additives. Some of the materials used in the construction of CO_2 lasers are also discussed.

Section IV is a comparison of what is desired in a space-qualified CO_2 laser and what has been achieved. The process of space qualification seems to be a combination of design engineering, testing, and quality control. As an example of the functions of design and quality control, consider one phase which might be encountered in the space qualification of a somewhat simpler light source, a hot filament light bulb. Assume that the light bulb is required to maintain a certain minimum level of illumination for a given period of time and to operate at maximum efficiency. The illumination depends on the surface area, emissivity, and the temperature of the filament. The fundamental determining factor in the lifetime of a perfect filament is the rate at which material is evaporated from the filament, which depends on the material used in making the filament and the temperature of the filament. But maximum efficiency requires the highest possible temperature. The designer must then select a material to provide the highest operating temperature and still have the required lifetime (usually with a safety factor to allow for quality variations). The surface area must be large enough to supply the required illumination. Other details of filament shape and construction are constrained by other requirements, such as having the appropriate resistance to match the power supply and being sufficiently rugged.

However, if the filament does not have a uniform cross-section, then the parts with the smallest cross-section would be weak points and, because they have higher resistances, they would be hotter and would burn out faster. Similarly, metallurgical imperfections would be weak points. Therefore, quality control is needed to avoid these life-limiting imperfections. Quality control must also ensure that the material does not have contaminants which might shorten life or reduce emissivity.

The distinction between design and quality control in this case was well defined; design deals with known fundamental limitations on performance, and quality control deals with detectable and avoidable imperfections which would degrade the design. In the case of the CO_2 laser, the distinction is not so clear. For instance, the fundamental limitations on the operating lifetime of the CO_2 laser are not known. The lifetime limit currently encountered may be a fundamental and unavoidable consequence of processes occurring in the discharge, or it may be a consequence of insufficient quality control of the materials used in making the laser. Research is continuing to understand the basic limitations and to determine what aspects of quality control are needed. Further details on the present knowledge of the operating limitations on the CO_2 laser will be discussed in the subsequent sections.

II. HISTORICAL SURVEY OF CO_2 LASERS

In view of what it has become, the CO_2 laser had quite a modest beginning. The first CO_2 laser was 5 meters long and produced about 1 mW (c.w.) and about 10 mW peak power when pulsed (ref. 1). The discharge tube was filled with pure flowing CO_2 at a pressure of 0.2 torr. No attempt was made to optimize the pressure, flow rate, or laser cavity in this case and the laser showed no signs of saturation in either the c.w. or pulsed mode up to the limit of the power supplies used. The most significant subsequent development was undoubtedly the mixing of the CO_2 with other gases. It is by virtue of the additives that the CO_2 laser becomes a high power device with good operating efficiency. Addition of nitrogen was prompted by the possibility of selective pumping to the upper laser level by resonant energy transfer between the metastable vibrationally excited nitrogen molecules and ground state CO_2 molecules. Supposedly, helium was added to increase the diameter of the discharge to fill a larger diameter discharge tube. The results far surpassed expectation, but the mechanisms by which helium improves power output, efficiency, and performance are still not completely understood. Some of the major steps in the growth of the CO_2 laser from milliwatts to kilowatts are summarized in Table I, and in graphical form in Figure 1. Figure 1 shows the output power following an exponential growth trend for most of the past 3 years. Further increases in output power after adding nitrogen and helium were due in part to optimization of gas composition, pressure, and flow rate, and optimization of output coupling. But most of the increase is merely an increase in the size of the laser. The efficiency on the other hand does not show a steady increase toward the theoretical maximum of about 40%. This is because the maximum power and the maximum efficiency are attained with distinctly different operating conditions and the emphasis has been on maximum power.

In addition to power output, Table I shows other "figures of merit," such as power per unit length, power per unit volume, and efficiency. In most cases, the efficiency figures are deceptive; all but one of the lasers in Table I had a flowing gas system, and by convention the power required by the vacuum pump is not included in calculation of efficiency. Another convention which is sometimes used allows one to subtract the power dissipated at the electrodes from the power input, but all of the efficiency figures in Table I include the electrode power.

The first entry in Table I is the one already mentioned which, despite its size, produced only 1 mW. Neither efficiency nor power input for continuous operation are given in reference 1, but the peak current, peak voltage, and peak output power for pulsed operation, which yield the listed efficiency, are given.

TABLE 1.--HIGH POWER CO_2 LASER DEVELOPMENT

Reference	Publication Date	Description of Laser	Length (m)	Power (W)	Efficiency (%)	Power/ Length (W/m)	Power/ Volume (W/cc)
Patel[1]	Nov. 1964	Flowing pure CO_2 (0.2 torr), 1 mm coupling hole	5	10^{-3}		2×10^{-4}	4×10^{-7}
		Same as above, but pulsed operation		10^{-2}	4.5×10^{-6}		
Patel[2]	July 1965	Pre-excited N_2 (1.8 torr) mixed in flowing system with CO_2 (0.4 torr), 8 mm coupling hole	2	11.9	3	5.95	0.0119
Moeller and Rigden[3]	Nov. 1965	Flowing. 2.7 torr CO_2, 7.8 torr He, 3.5 torr N_2	0.96	18.0	4	19	0.055
Patel et al.[4]	Dec. 1965	6 ℓ/sec flow, 0.33 torr CO_2, 1.2 torr N_2, 7.0 torr He, Inside diameter of tube equals 77 mm	2.3	106	6.2	46	0.01
Rigden and Moeller[5]	Sept. 1966	5 to 10 ft^3/hr flow, 80% He, 15% N_2, 5% CO_2, Output coupling – 20% transmission	4	300	11	75	0.2
Witteman[6]	Sept. 1966	Sealed-off, 1 torr CO_2, 2.5 torr N_2, 7.2 torr He, 0.2 torr H_2O, quartz and platinum construction	2.4	103	12.5	43	0.1
Whitehouse[7]	May 1967	115 CFM flow, 5.0 torr He, 1.4 torr N_2, 0.6 torr CO_2, folded	20	1200	17	60	0.029
Erlich et al.[8]	June 1967	Flowing. 0.45 torr CO_2, 0.75 torr N_2, and 5.8 torr He, No water cooling	55	2300	9.4	42	0.0205
Dezenberg and Merritt[9]	June 1967	2 torr N_2, 0.3 torr CO_2, 3.7 torr He, flowing, Multipath cell	6.4	425	33	66	0.0081
Paananen[11]	Nov. 1967	Flowing. 2.4 torr He, 1.1 torr N_2, 0.6 torr CO_2	3	78	11.5	26	0.013
		Same as above, but with 0.6 torr Xe added		80	14.3	27	0.013
Horrigan[12]	Jan. 1968	1.5 torr N_2, 0.45 torr CO_2, 5.25 torr He, folded structure (15 segments), flowing, 700 CFM	183	8800	13.5	48	0.024

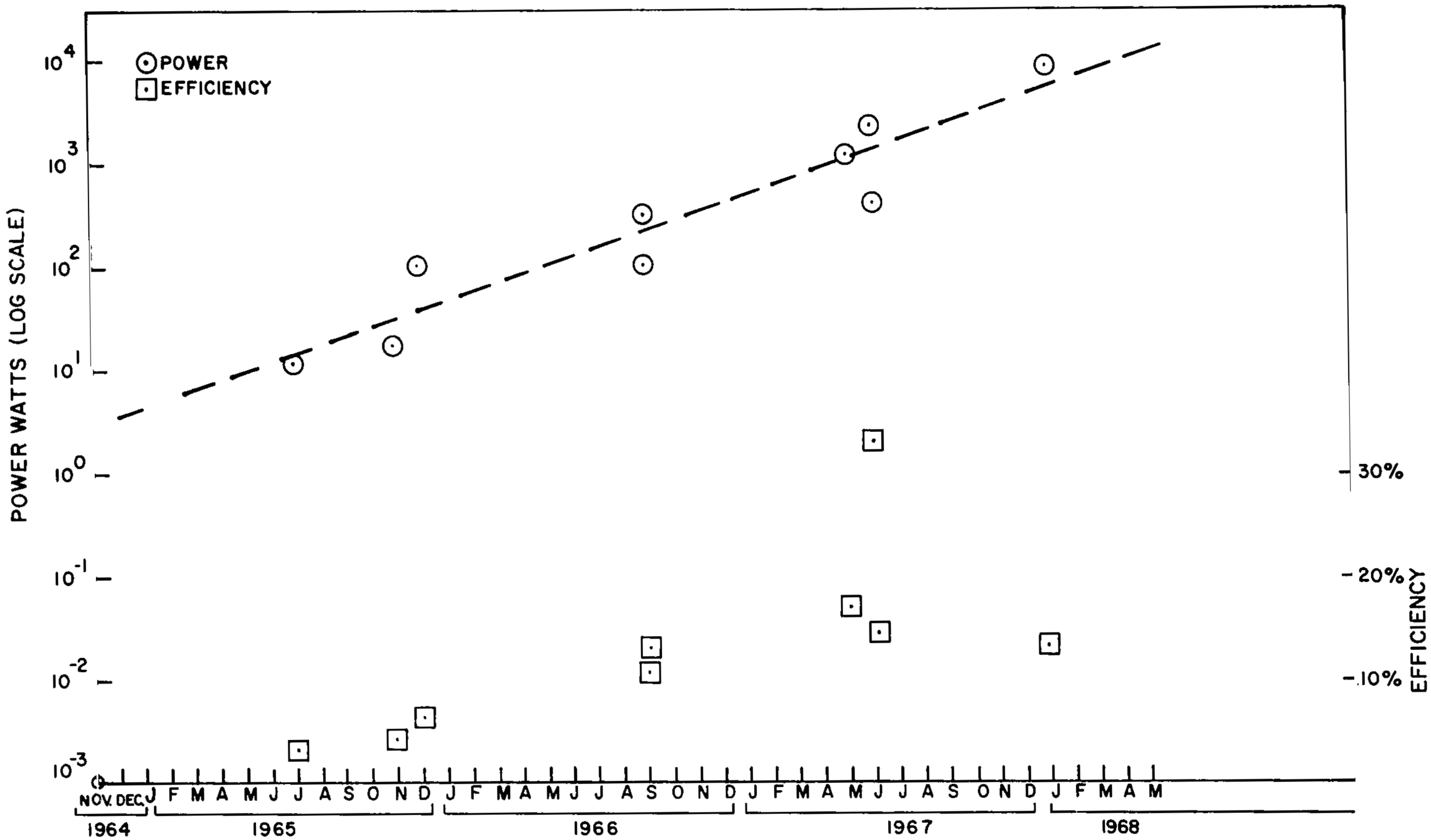

Figure 1.- Power and efficiency of CO_2 lasers as functions of time.

When nitrogen was added, the power and efficiency increased by orders of magnitude. The first CO_2-N_2 laser had a flowing gas system in which the nitrogen was excited in an electrical discharge before being combined with the flowing CO_2 in the laser active volume (ref. 2). Although this pre-excitation of nitrogen was not used in later CO_2 lasers, it is of more than historical significance; it demonstrated that vibrationally excited nitrogen molecules were stable enough to flow from the discharge to the interaction region and that transfer of excitation from the nitrogen to the carbon dioxide was very efficient. Another factor in the increased power of this laser was a more optimum output coupling. In the first CO_2 laser, power was coupled out of the optical resonator through a 1-mm diameter hole in one mirror; in this laser the coupling hole diameter was increased to 8 mm.

Still further increases of power and efficiency were achieved when helium was added to the flowing CO_2-N_2 mixture by Moeller and Rigden (ref. 3). In the same paper they reported results for a non-flowing laser containing CO_2 and helium (no nitrogen), but this will be discussed in a later section on sealed CO_2 lasers. Further power increases reported by Patel, Tien, and McFee (ref. 4) and by Rigden and Moeller (ref. 5), were realized by increases in length and more nearly optimum selection of parameters.

The Witteman entry in Table I is especially significant because it is the only sealed, non-flowing laser in the group. Other sealed lasers have been developed, but this is the only one that fits Table I by virtue of the power achieved and the time of announcement. Witteman attributes his success to careful selection of materials and geometry used in constructing the discharge tube and the addition of water vapor to the CO_2-N_2-He gas mixture (ref. 6). The last item has generated considerable controversy and more will be said about it later. Another innovation in this laser was a variable output coupling achieved by rotating a germanium flat in the optical cavity. If the germanium flat is rotated to be at the Brewster angle, no power is coupled out of the cavity. The amount of power removed from the laser is determined by the angle between the Brewster orientation and the orientation of the flat.

The work of Whitehouse pushed the CO_2 laser into the kilowatt region (ref. 7). The first step in achieving this power was a detailed study to optimize the parameters. The laser was made of eight sections which were 2-1/2 meters long with a folded optical path so the package length was 10 meters. One of the major difficulties in going to this power range is that the power is very hard on optical materials (windows, etc.). Still, Ehlrich et al (ref. 8) have built a 55-meter laser with an output power of 2.3 kW (ref. 8). While the laser of Dezenberg and Merritt (ref. 9) does not achieve the power of the two listed before it, it does have the highest efficiency yet reported and has the potential for much higher power. They used a new technique to achieve this, that of "multiple optical paths" through the active medium. The beam is reflected back and forth through the active medium many times before it begins to retrace its path. In previous lasers, which had single optical paths through the active medium, it was found that the maximum power output was nearly independent of the diameter of the discharge tube (ref. 10) when the diameter was great enough that diffraction losses were not dominant. There would be a number of advantages to increasing the diameter rather than the length to increase the power. Extremely long objects are always unwieldy; also the voltage required to run the discharge tube is less for the larger diameter. Dezenberg and Merritt found that the output power reached the limit of their tube (21 feet long and 4 inches diameter) when the number of paths was increased to 20. They also showed that their multipath cell technique was useful for CO_2 laser amplifiers.

The next entry in Table I shows another technique which may lead to further improvement in the performance of CO_2 lasers. Paananen (ref. 11) showed that addition of xenon to a flowing CO_2-N_2-He laser increased the laser power and efficiency and reduced the impedance of the discharge. Addition of xenon has also been useful in sealed off lasers, which will be discussed later. The final entry shows the largest continuous power attained from any laser thus far (ref. 12). This laser was constructed of 15 sections of 40-foot length each in a rather unusual folded path configuration. The total length was 600 feet, or 183 meters, and the maximum power output was 8.8 kW.

Thus far, no one has yielded to any temptation to report his achievement in horsepower. The largest of the reported laser powers, 8.8 kW, is equivalent to about 12 horsepower. Of course, power is just one aspect of the CO_2 laser development, but it does serve to illustrate the progress which has been made, and it has been one of the major considerations in the research efforts. Also, since people are impressed by power, whether in cars or lasers, the achievements of higher power have been more widely publicized than other developments in CO_2 lasers.

Considerable effort has been directed toward making the CO_2 laser an effective communications transmitter. There are several features of the CO_2 laser (in addition to high power output) which make it attractive for this purpose. For example, single-frequency operation is relatively easy because of the narrow line width (about 50 MHz) of the particular vibration-rotation spectral line and because the spacing of the Fabry-Perot resonances can be made much larger than 50 MHz since the high gain enables one to use short lasers. Most of the research effort on CO_2 lasers for communications use has been to obtain frequency stability in single-frequency operation. Other research efforts on modulation and detection techniques which are relevant to communications use are considered beyond the scope of this report.

Another way in which the raw power of the CO_2 lasers is being refined is in the elimination of higher order modes from the output of high power lasers. The mode of a laser refers to the angular distribution of the radiated power; a high order mode will have a large number of maxima and minima in the far-field pattern. Some examples of mode patterns are shown in Figure 2. In general, the higher order modes show more beam divergence, more degeneracy (and near degeneracy) in operation frequencies, and more diffraction loss than low-order modes. It is this latter property which enables one to eliminate the higher modes (by inserting an aperture) and avoid the undesirable consequences of the first two properties. Perhaps it is a sign of advancing maturity in the laser industry that at least one company has produced a commercial high-power CO_2 laser in which the higher order modes have been eliminated. According to the advertising literature, this laser emits 180 watts in the TEM_{00} and TEM_{01} transverse modes (the two lowest order modes). When the beam from this laser is focused, the resulting power density is about 3 times greater than that in a similarly focused beam of a typical kilowatt laser with higher order modes. The higher order modes have greater beam divergence and do not focus to such a small spot as the lower order modes. (Of course, similar observations had been made with earlier lasers, such as ruby.) Minimum beam divergence is also required in a laser transmitter in a long range communications link.

Frequency stability in a laser is dependent upon length stability; one must maintain the reflectors of the resonant cavity at a constant spacing. Both passive and active stabilization have been explored. Passive stabilization is accomplished by mounting the reflectors on a spacer made of material with a low coefficient of thermal expansion and controlling the temperature as closely as possible. For active stabilization one inserts a sample of material the length of which is easily varied (piezo-electric, for example), the frequency of the laser oscillation is compared to a reference, and the resulting error signal is fed back into the length controller. In either case, one must guard against vibration and fluctuating air density in the optical cavity.

In the CO_2 laser, if one can ensure that oscillation occurs on only one line in the vibration-rotation band, then the frequency stability is already better than 6 parts in 10^7, since the spectral line width is only about 50 MHz. However, as the frequency drifts off the peak of the gain curve of the desired

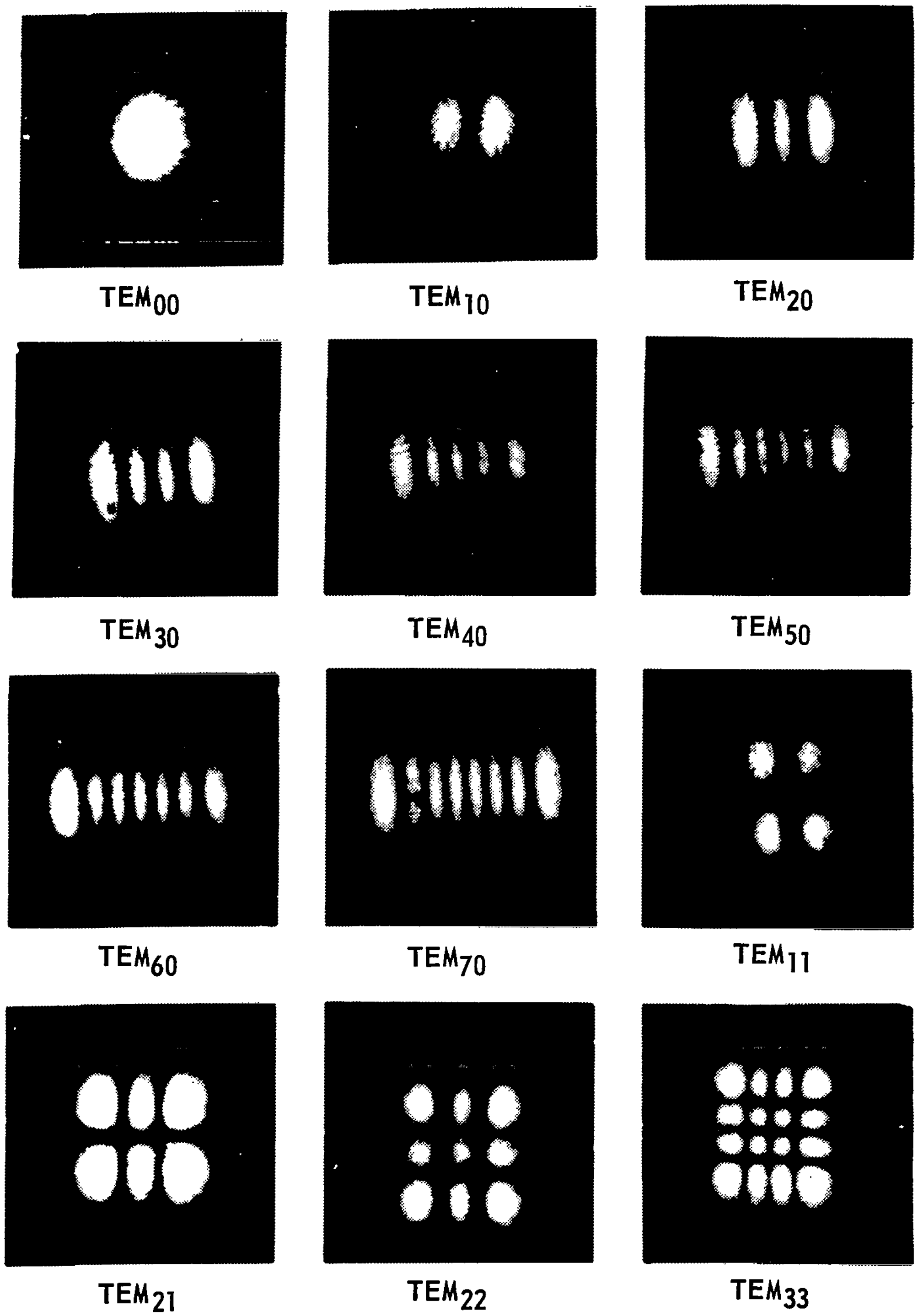

Figure 2.- Radiation patterns of several Fabry-Perot modes.

spectral line, a large jump in frequency will occur when conditions for oscillation at another line in the band become more favorable. The mechanism for this is shown in Figure 3. If the cavity length changes by $(-\Delta\ell)$, then the Fabry-Perot resonance frequencies shift according to $\Delta f/f = -\Delta\ell/\ell$. Before the change in length occurred, a Fabry-Perot resonance (indicated by the solid lines) was above threshold amplification for the P_i rotational transition but not for P_j, hence oscillation occurs at P_i. After the change in length occurred, the Fabry-Perot resonances in the new positions (indicated by the dashed lines) are below threshold of P_i and above threshold at P_j. Hence the oscillation will shift from P_i to P_j. Even when Fabry-Perot resonances are placed at positions with above-threshold amplification in more than one rotational transition, it is usually observed that only the Fabry-Perot resonance with the highest gain will oscillate. This is a consequence of the rapid thermalization of the rotational levels, which will be discussed later. The shift from one rotational transition to another as a laser is varied in length is shown in Figure 4. Note that single frequency oscillation is attained over most of the tuning range. In most cases where multiple frequency oscillation occurs, one is on a P transition ($\Delta J = +1$) and the other is on an R transition ($\Delta J = -1$). Of course, it is possible to limit oscillation to one spectral line by discriminating against the others, using gratings, prisms, and other selective optical elements in the resonant cavity.

Most of the work on frequency stabilization has used passive techniques. Freed (ref. 13) observed an average short term stability of 20 kHz in 1 second using short lasers with invar rods to stabilize the resonant cavity length. There was no attempt to control the temperature of the invar rods, but the discharge tube was water-cooled. Single-frequency operation was easily attained since the laser was so short. The frequency stability was measured by monitoring the difference frequency beat note of two lasers. The figure of 20 kHz in 1 second represents a combination of drift caused by temperature change and jitter caused by vibration, discharge instability, and atmospheric fluctuations.

Mocker and Gustafson have reported a short term stability of 10 kHz in 1 second and a long term stability of 1 MHz in 10^{-4} sec in a passively stabilized CO_2 laser (ref. 14). For the resonant cavity construction, they used a material which has a thermal expansion coefficient of $+1.0 \times 10^{-7}/^{\circ}C$. The laser is 30 cm long and produces up to 7 watts using a flowing gas system. One of the mirrors is attached to a piezo-electric transducer so the laser can be tuned. The mirrors are internal and, in the absence of Brewster angle windows, the beam is polarized in a rather novel way (ref. 15). Three small wires were inserted into

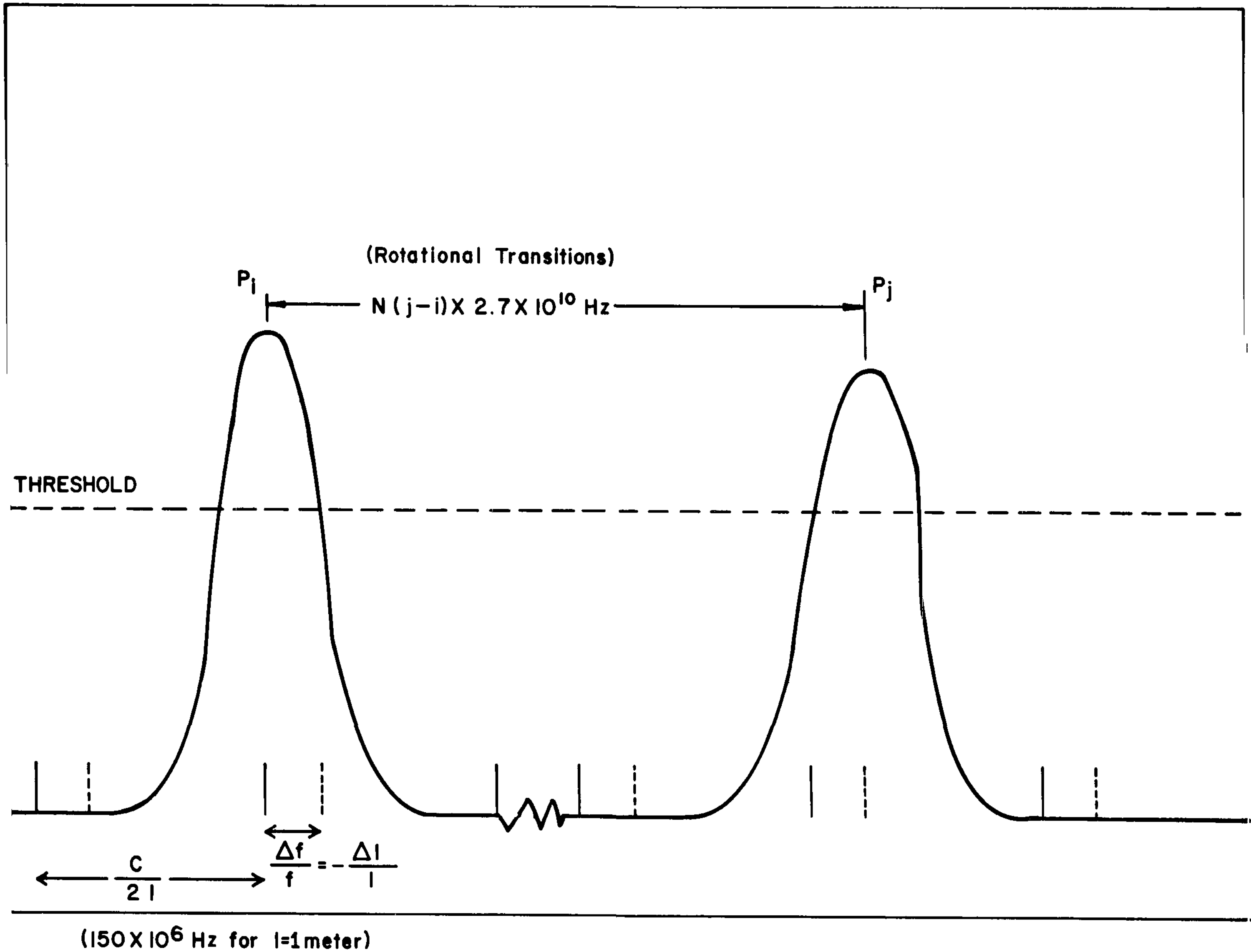

Figure 3.- Role of Fabry-Perot resonance frequency in determining which rotational and transition will oscillate.

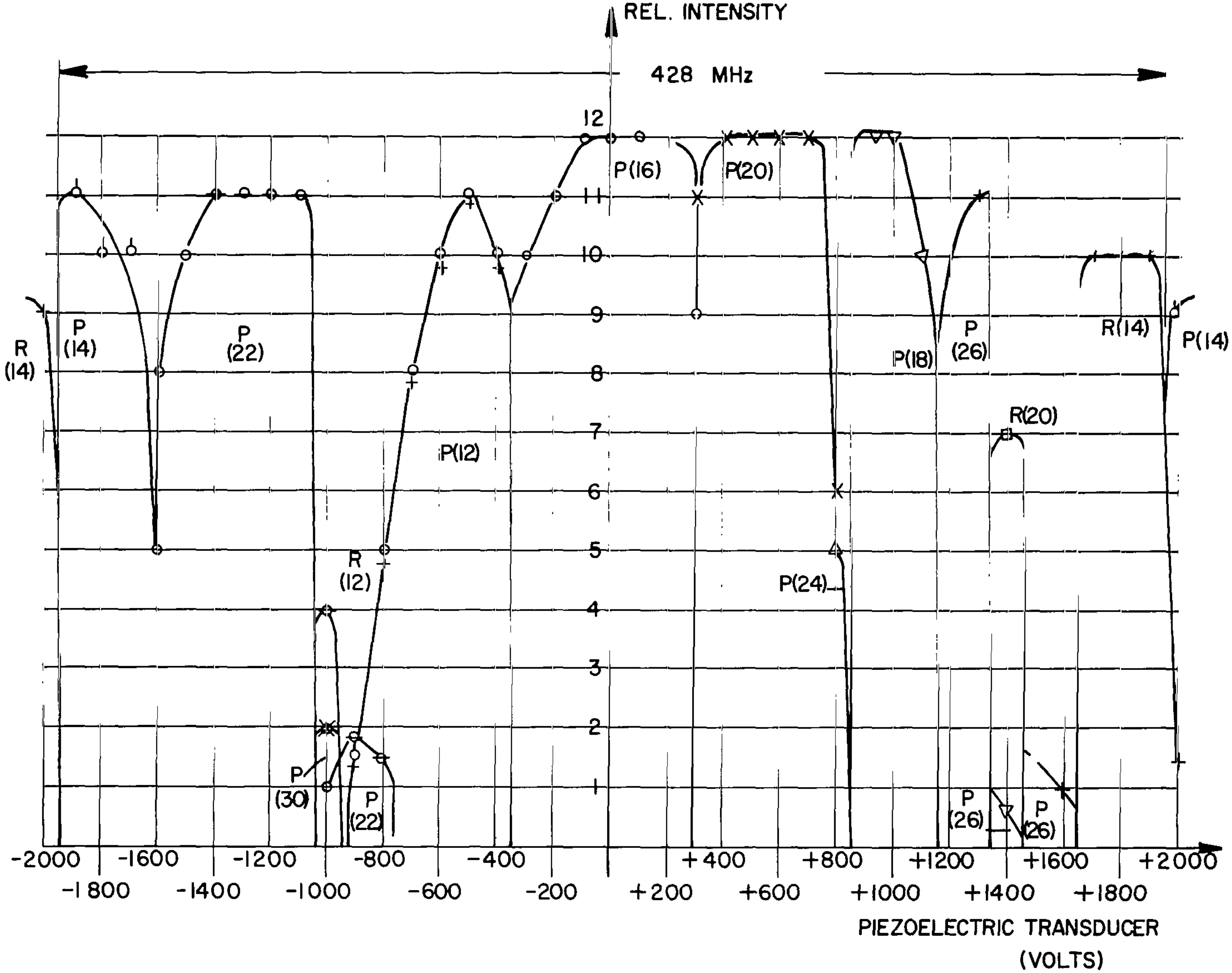

Figure 4.- Tuning scan for a CO_2 laser ($\Delta \ell$ is proportional to the piezoelectric transducer voltage)

the cavity perpendicular to the beam direction; the losses for the oscillating electric field perpendicular to the wire and the losses for the oscillating electric field parallel to the wire are different enough to produce a polarized beam. The stability figures were obtained by monitoring the beat note of two lasers and again no attempt was made to regulate the temperature. The spacer was shielded from the heat of the discharge tube by two aluminum heat shields. Nearly all of the long-term change in frequency is slow drift because of temperature changes. They point out, however, that stability of about one part in 10^9 could be obtained if the cavity temperature is controlled to 0.01°C with commercially available temperature controllers.

Mocker has used the difference frequency beat note of two lasers to measure the dependence of the oscillation frequency on the pressure of the gas in the discharge tube and on the discharge current (ref. 15). He also devised a method for comparing the laser oscillating frequency with the Doppler center of the spectral line. Using this method, he found that the center of the line did not vary with pressure or current. The changes in the frequency of laser oscillation then must be caused by changes in the index of refraction of the gas in the discharge.

Several experiments on higher power, sealed-off, stable, single-frequency CO_2 lasers are being done (ref. 16). With a 2-meter long laser (discharge length of 155 cm) which was sealed off and water cooled, about 12 watts in multi-line, multi-mode operation were obtained. Putting a prism or grating in the cavity did not yield single-frequency operation because of resonance modes involving glancing reflections from the inside wall of the discharge tube. This made it possible for oscillation to occur at wavelengths at which the optical path was misaligned by the dispersive element. When large surface irregularities were placed on the wall to break up these resonance modes, single-frequency operation was achieved. An alternate method of achieving single-frequency operation was to use a small Fabry-Perot etalon for wavelength selection instead of the prism or grating. Reynolds (ref. 16) has used another method for obtaining high-power, single-frequency operation which is perhaps a better one, a combination of a laser oscillator and laser amplifier. The laser oscillator can be made short and hence more amenable to single-frequency operation and stabilization. Using this approach, he has attained 35 watts of stable, single-frequency power. With passive stabilization (invar rods with temperature control), the short-term stability is better than 30 kHz and long-term stability is about 3 MHz. Reynolds has also used an active stabilization technique based on a technique for comparing the laser oscillation frequency with that of the peak of the gain curve which was proposed by Siegman (ref. 17). It is based on the conversion of frequency modulation to amplitude modulation that occurs in a narrow band amplifier when the carrier oscillation frequency does not coincide with the peak of the gain curve. Since power detectors respond to amplitude modulation but not to frequency modulation, and since the amount of amplitude modulation is a function of the difference between the carrier frequency and the peak of the gain curve, one can obtain an error signal to control the cavity length. The process by which amplitude modulation occurs is essentially one of gain distortion. If the carrier frequency is off the peak of the gain curve, then during one half of the FM cycle the frequency is closer to the peak of the gain curve and the signal is amplified more than it is in the other half of the FM cycle when the frequency is moved away from the peak of the gain curve. Thus the amplifier power output is modulated as the frequency is modulated. If the carrier frequency is at the peak of the gain curve, then the frequency moves off the peak of the gain curve in both halves of the FM cycle. The amplifier output power is thus modulated at twice the FM frequency, but not at the FM frequency (if the gain curve is symmetric about the peak).

The basic difference between Siegman's technique and Reynolds' is where the frequency is modulated. Siegman proposes to place the modulator between the laser oscillator and a separate laser amplifier so that the laser oscillator is not modulated. On the other hand, Reynolds modulates the laser oscillator frequency itself by vibrating one of the reflectors using a piezo-electric transducer. Another variation has been proposed by Rabinowitz et al (ref. 18). In this variation, the laser amplifier used by Siegman would be replaced by a CO_2 absorption cell. The operating principle is much like Siegman's except that the reference is one that does not need to be excited. However, it does have to be heated in order to populate the lower level of the laser transition.

In addition to the work of Reynolds, the only other experimental work on active stabilization of CO_2 lasers thus far reported is apparently that of Mocker (ref. 15). He has developed a CO_2 laser heterodyne communications system, shown in Figure 5, in which one laser (the local oscillator of the receiver) is stabilized relative to the laser transmitter so as to maintain a 10-MHz difference frequency. Also, his "Doppler center indicator" (ref. 15) can be used for active stabilization upon completing the feedback loop.

Other schemes for active stabilization of lasers have been proposed and some have been successfully used in stabilizing helium-neon lasers. However, many of these schemes are based on Zeeman splitting or the "Lamb tuning dip" and cannot be easily applied to the CO_2 laser because these effects are small in CO_2 (ref. 17).

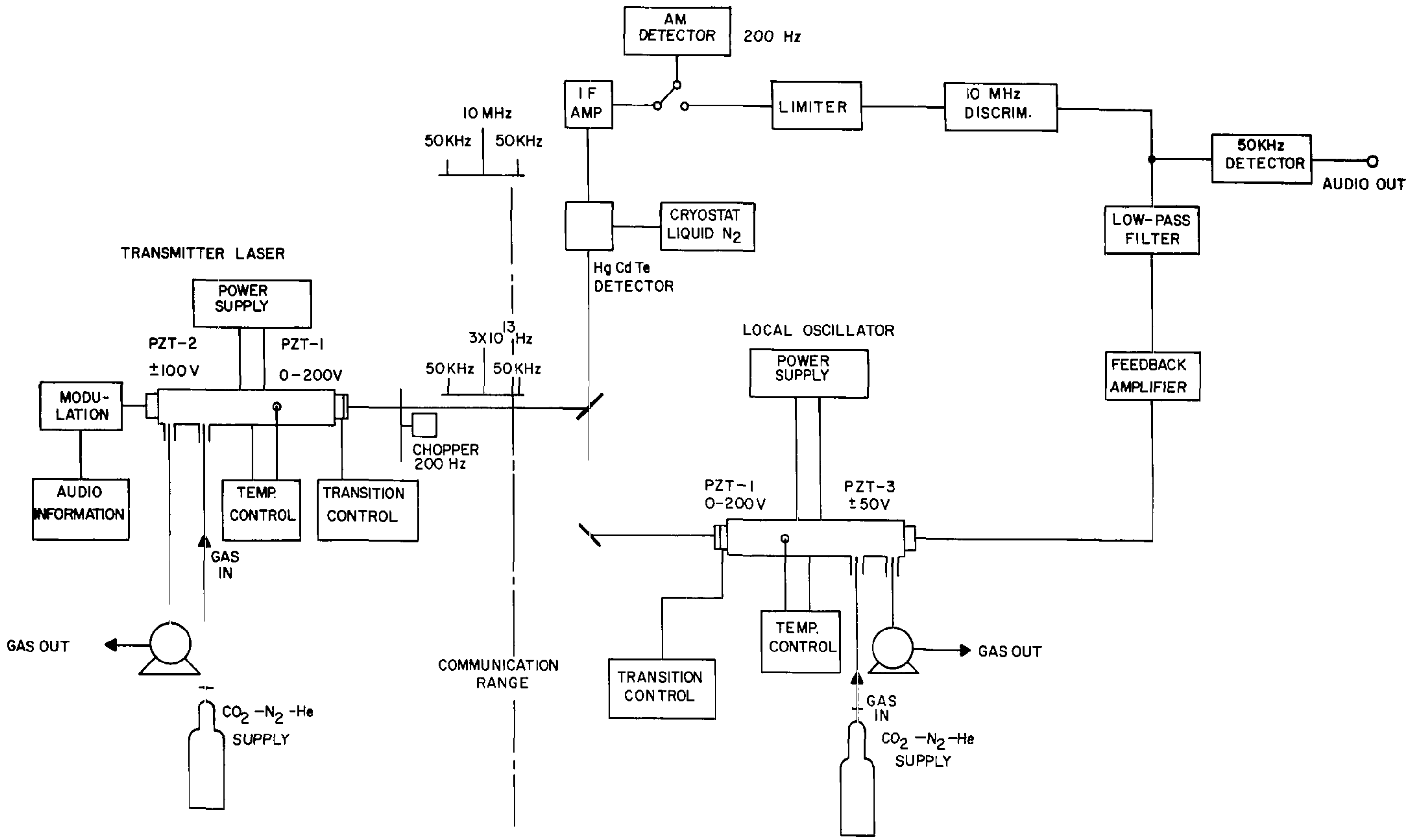

Figure 5.- Optical communication system (10.6-micron).

Sealed-off CO_2 Lasers

Most of the early CO_2 lasers and many of the current ones have used flowing gases. Most of the early attempts at sealed-off CO_2 lasers consisted of merely stopping the flow. This was an unsatisfactory procedure and the poor results led to pessimism about the prospects for sealed-off CO_2 lasers. Fortunately, Dr. W. J. Witteman of Phillips Research Laboratories in Eindhoven did not accept the pessimistic outlook and showed that it was possible to construct high-power, long-lived, sealed-off CO_2 lasers (ref. 19). Since then, others have made significant developments in sealed-off CO_2 lasers, but none has been able to duplicate Witteman's results.

Some of the steps in the development of sealed-off CO_2 lasers are summarized in Table II. The results of Moeller and Rigden (ref. 3) are quite typical of flowing lasers which were sealed-off. The laser output would stabilize in a few minutes at about half of that achieved with flowing gases. The power would then decline and the laser would be out of operation in a few hours. The initial rapid change was caused by the decomposition of carbon dioxide into carbon monoxide and oxygen which proceeds to an equilibrium condition quite rapidly in the discharge. Figure 6 shows the chemical composition of the gases in a discharge tube initially filled with 2 torr of CO_2. The CO_2-CO-O_2 equilibrium in the discharge actually occurs much faster than indicated here; the time required for the pressure measurements to stabilize is determined by diffusion rates. The slower decline of power was more difficult to explain. At first, it was believed that compounds of nitrogen, such as N_2O, NO, and C_2N_2, were being formed in the discharge and causing the loss of laser power. However, various chemical analyses of the discharged gases showed only traces of any nitrogen compounds. The real difficulty was found to be removal of gases, especially oxygen, by chemical reactions and adsorption of the electrodes and tube surfaces. Also, the flowing systems were not constructed in accordance with the ultra-clean practices generally required for sealed-off discharge tubes, thus increasing the probability of contamination.

However, Witteman followed good clean vacuum procedures and produced good results in sealed-off CO_2 lasers. He used fused silica (quartz) for the discharge tube, platinum for the electrodes, and germanium for the windows in order to have inert surfaces which would not react with the reactive species produced by the discharge (ref. 19). He thoroughly cleaned and baked these surfaces to minimize contamination of the discharge gases. He arranged the cathode geometry so as to minimize the deleterious effects of sputtering. He also added a small amount of water vapor and obtained a factor of 2 increase in laser power.

TABLE II.--DEVELOPMENT OF SEALED-OFF CO_2 LASERS

Name	Publication Date	Type and Description	Output Power	Efficiency	Discharge Length	Discharge Diameter	Reservoir Volume	Lifetime
Moeller and Rigden[3]	Nov. 15, 1965	2.2 torr CO_2, 19.2 torr He, (Flowing laser with flow stopped)	10W	?	96cm	2.1cm	?	~20 hrs
Witteman[20]	Aug. 15, 1965	Platinum hollow cathode 1 torr CO_2 and 2 torr N_2 1 torr CO_2 and 2 torr N_2 and 1/2 torr H_2O	X 1.8X	?	1m	3cm	?	?
Witteman[6]	Sept. 1966	1 torr CO_2, 2.5 torr N_2, 7.2 torr He, 0.2 torr H_2O	103W	12.5%	240cm	2.3cm	?	?
Witteman[19]	June 1966	1 torr CO_2, 2.5 torr N_2, 0.2 torr H_2O	20W	12%	200cm	2.4cm	?	?
Witteman[1,22]	Dec. 1967	1 torr CO_2, 2.5 torr N_2, 11 torr He, 0.2 torr H_2, and 0.1 torr O_2	60W	11%	150cm	2.0cm	none	1500 hrs (50W) (35W) at ~2000 hrs
Whitney and Graham[23]	~May 1967	CO_2 and He (no nitrogen)	1.4W	1%	92cm	10mm	?	1100 hrs* (90%)
Clark	To be published	3.5 torr CO_2, 1 torr Xe 12 torr He	6W	?	50cm	10mm	?	2800 hrs*
Carbone[26]	March 1968	2 torr CO_2, 2 torr N_2 7 torr He Heated Nickel electrode	6W	?	60cm	1cm	2000cc	1100 hrs*
Deutsch[27]	Jan. 1968	1 torr CO_2, 2.5 torr N_2 14 torr He, 1 torr Xe	35W	14%	135cm	27mm	?	1080 hrs (16W)

*Limit set by factors besides chemical change in gas.

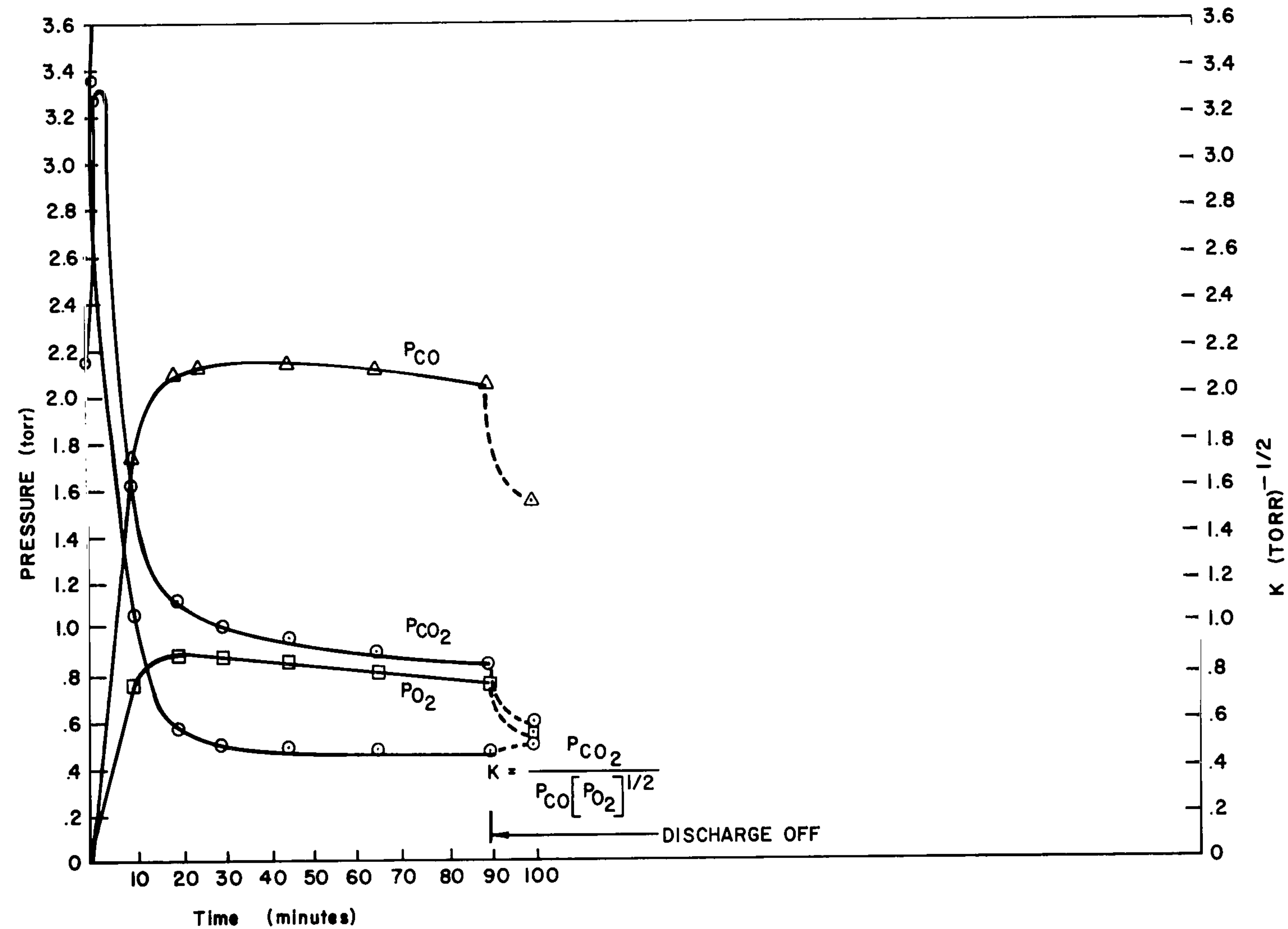

Figure 6.- Measurements of CO_2, CO, and O_2 pressures as functions of time in a discharge initially filled with CO_2.

The controversy and discussion arising from this last item is somewhat unfortunate in that it overshadowed his other achievements. (The effect of water vapor and the controversy will be discussed in a later section of additives.)

Note that Witteman's first article (ref. 20) on sealed-off CO_2 lasers actually appeared quite early in the chronology of CO_2 laser development. However, he did not give any lifetime results in his first two papers. In the third paper, he presented data on power output as a function of running time covering a space of nearly 2000 hours (ref. 21). He attributed the long lifetime partly to the water vapor, and demonstrated this by showing that a laser that was identical except for the absence of water vapor stopped working after about 900 hours. The water vapor increases the laser lifetime by reducing the amount of dissociation of the CO_2 (ref. 22), but the details of this have not yet been resolved. Witteman and others have found an inverse relation between laser power per unit length and lifetime. By reducing the power to 7 watts, Witteman obtained a lifetime of 4300 hours for his laser. It should be emphasized that these lifetimes were obtained without using any ballast volume or other sources of additional gas.

Whitney and Graham operated their laser for 1100 hours before arbitrarily ending the experiment (ref. 23). The power remained within 10 percent of the initial value during this time. They attribute its longevity to exclusion of nitrogen, clean vacuum, and construction of electrodes to minimize hot spots and sputtering. The low power per unit length and low efficiency is attributed to the relatively high absorption of the Irtran II used for the Brewster angle windows.

Carbone found that power could be restored to a decaying laser by heating the nickel cathode to about 300°C (ref. 24). The restoration was caused by the liberation of adsorbed gas (CO_2, CO, and O_2). Heating of the anode or glass tubing did not restore laser power, which shows that adsorption of gas at the cathode was responsible for the deterioration of the laser. The restoration of laser power upon heating the cathode showed that the gases were mostly reversibly adsorbed; this was confirmed by measurement of the total pressure and mass spectrometer analysis of the gases. Some irreversible losses also occurred in the form of carbon deposits, but the irreversible loss rate was much smaller than the reversible adsorption rate.

It is also known that some metals, such as platinum and nickel, when heated act as catalysts for the recombination of carbon monoxide and oxygen. Taylor et al demonstrated the effectiveness of this by installing a heated platinum wire in a CO_2 laser (ref. 25). Carbone then constructed a CO_2 laser with a heated nickel cathode to take advantage of both effects, the catalytic recombination, and the reduced adsorption at higher temperature (ref. 26). The cathode was maintained at a temperature between 300 and 500°C. The upper temperature limit is set by the formation of metal carbides and other irreversible processes which are favored at higher temperatures. The discharge was 60 cm long and 1 cm in diameter. There was a reservoir volume which was about 40 times the volume of the discharge tube. The laser operated at the 6-watt level for almost 1100 hours where the test was terminated because of deterioration of the NaCl brewster angle windows. At this time, the CO_2 pressure was still 92 percent of the original pressure. The last two entries in Table II are sealed CO_2 lasers with xenon added. Clark* used a pyrex tube with one nickel electrode and one tantalum oxide electrode. The discharge contained no nitrogen, but Clark does not claim that nitrogen exclusion is necessary to obtain long-term operation. For the first 2200 hours, the laser was ac-excited and produced a constant output power of 3 watts. Then the discharge was dc-excited using the nickel electrode as the cathode; the power output increased to 6 watts and remained at that level for 450 hours more. Then the power output dropped, presumably because of damage of the NaCl Brewster angle windows.

Deutsch used a quartz discharge tube with nickel electrodes, which was conditioned by running a discharge in oxygen for about 19 hours before filling with the CO_2-N_2-He-Xe mix (ref. 27). The power declined slowly from an initial level of 35 watts to 16 watts at 1080 hours. Then the power dropped to zero suddenly and the discharge changed color, presumably because the chemical composition in the discharge tube had changed.

While much progress has been made in sealed-off CO_2 lasers, the power obtained from a sealed CO_2 laser probably will never equal that from a flowing gas laser of similar size. There are a number of reasons for this. First, the CO_2 dissociates to form CO and O_2. It has been shown that addition of O_2 in a flowing gas laser reduces the power (refs. 10, 28). This is because the metastable vibrationally excited O_2 molecule can transfer energy to a CO_2 molecule and thus populate the lower level of the CO_2 laser transition in the same way that nitrogen populates the upper level. CO is also somewhat harmful because it furnishes an additional process for de-excitation of the nitrogen. Excited CO molecules can selectively populate the upper level of the CO_2 laser transition in the same way as

*Clark, P.O., and Wada, J.Y.: The Influence of Xenon on Sealed-Off CO_2 Lasers, IEEE J. Quantum Electronics (to be published).

nitrogen does, but the process is less efficient for reasons to be discussed later.

Also, it is estimated that about 25 percent of the heat dissipated in the discharge can be removed by the exhaust gases. Whitehouse also discusses the increased cooling derived from turbulence occurring at very high flow rates (ref. 7). In a sealed laser, the heat must be removed by conduction through the walls of the discharge tube. The gas temperature is therefore lower in the flowing laser and this improves the performance of the laser.

Another advantage of the flowing gas laser is the ease of construction. Since impurities are rapidly carried away by the gas stream, high vacuum techniques are not required. This allows for much easier sealing techniques in the assembly of flowing gas lasers.

However, if portability is desired, then the necessary tanks of gas and vacuum pumps can be a big disadvantage. Sealed lasers should have a higher absolute efficiency, because the power furnished the pump must also be included in a flowing system. Thus, except for those applications where the chief requirement is the highest possible output power per unit length, a sealed CO_2 laser would usually be preferable. The convenience and portability of a sealed CO_2 laser have motivated a growing effort to develop long-lived, sealed-off CO_2 lasers.

III. MECHANISMS AND MATERIALS IN CO_2 LASERS

The Laser Transitions in CO_2

The energy levels of CO_2 which are involved in the laser are several of the vibration-rotation bands of the electronic ground state, which are shown in Figure 7. Figure 7 also shows the types of motion which characterize the various modes of vibration and the approximate distribution over the rotational levels within each vibrational level corresponding to a temperature of 400^oK. Vibrational energies are generally an order of magnitude smaller than electronic energies (in the visible range), so the CO_2 laser operates at a wavelength of about 10 microns. The upper level of the laser transition is the lowest of a certain class of vibrational excitation levels (asymmetric stretch mode) and is 2349 cm^{-1} above the ground level. The lower level of the usually observed laser transition (10.6 microns) is the lowest in another class of vibrational excitation levels (symmetric stretch mode) at 1388 cm^{-1} above the ground level. There is a third class of vibrational excitation levels (bending mode); the lowest excited level is at 667 cm^{-1} and the second is at 1334 cm^{-1}. The close coincidence between the first of the symmetric stretch modes and the second of the bending modes is one of the set of fortunate circumstances that makes the CO_2 laser so powerful and efficient. It provides a very effective means for depopulating the lower laser level, transfer of energy in collisons with CO_2 molecules in the ground state. At these long wavelengths, spontaneous emission is generally less effective than collision processes in determining excited state lifetimes, even if there are allowed transitions. Since the upper laser level is the lowest of the asymmetric stretch vibration modes and since there are no other vibration modes close enough for near resonant transfer of energy, its relaxation rate is slower than that of the lower laser level. The net relaxation rate of the lower laser level is limited by the accumulated population in the lowest bending mode. The relaxation rate of the latter is very slow since it is the lowest of all the vibrational levels and can relax only by collisions with the wall, spontaneous emission of radiation, or conversion of vibrational to translational energy in a collision.

Thus, since the relaxation rate of the upper level is lower than that of lower levels, population inversion and laser action can occur under certain conditions. Population inversion depends on a delicate balance between the processes tending toward selective population of given levels and the processes tending toward thermal equilibrium. This balance can be shifted by various changes in the discharge or by the increase in the relaxation rate of the upper laser level caused by stimulated emission, which eventually leads to saturation of the amplifier.

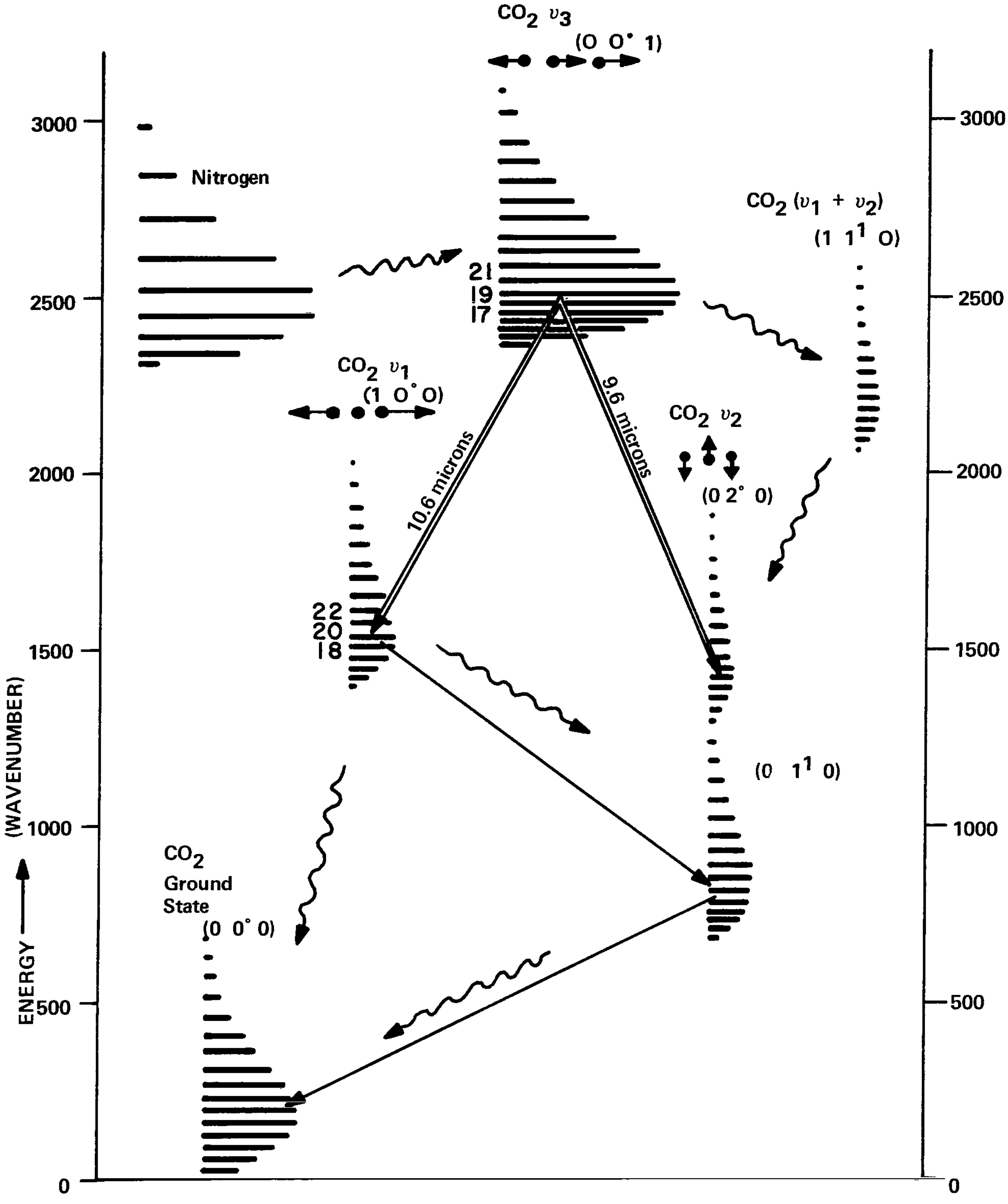

Figure 7.- Energy level diagram showing vibrational-rotational structure of electronic ground state.

Each vibrational level is split into a group of closely spaced levels according to the rotational angular momentum quantum number J. The distribution over the rotational energy levels [proportional to J(J + 1)] at thermal equilibrium is the Boltzmann distribution weighted by the degeneracy, 2J + 1. In the CO_2 laser, the peak of this distribution occurs near J = 20, which corresponds to a temperature of 400 to 500°K, which is about the same as the gas (translational) temperature in the discharge. The vibrational temperature is much higher, approximately equal to the electron temperature, since vibrational excitation is coupled with electron energy more strongly than with the gas translational temperature.

Thermalization, the natural enemy of population inversions, serves a very useful purpose in the CO_2 laser. Thermalization among the rotational levels occurs much more rapidly (times on the order of 1 μsec) than among the vibrational levels (about 1 msec)(ref. 29). This allows the entire group of rotational levels of the vibration band to act as a reservoir for the upper level of the laser transition having the highest gain. Similarly, the influx into the lower level caused by stimulated emission can be effectively spread out over this entire group of rotational levels. This enables the laser to reach a higher power level before saturating and laser oscillation to be confined to a single line in the band.

Since conditions for operating sealed-off CO_2 lasers for thousands of hours are now known, the lasing behavior of isotopic species of CO_2 takes on much more significance than before. Of particular interest is the emission by the isotopic species containing carbon twelve (C^{12}) and oxygen eighteen (O_2^{18}). It has been reported that this species, $C^{12}O_2^{18}$, emits its laser radiation at wavelengths near 9.3 microns (ref. 31)*. A study of the isotopic shifts of the vibration-rotation bands by Hanst and Morreal* shows that in the case of the $C^{12}O_2^{18}$ the lasing shifts from the (anti-symmetric stretch → symmetric stretch) transition to the (anti-symmetric stretch → bending mode) transition. The isotopic shifting of the vibrational energy levels influences either the transition probabilities or the relaxation rates, or both, to an extent sufficient to move the wavelengths of highest laser gain from one band to the other. Since O_2^{18} is not expensive, any sealed-off CO_2 laser can easily be converted to a 9.3-micron laser which might have certain operational advantages. For example, the inert and non-hydroscopic crystal calcium fluoride can be used for windows at 9.3 microns, but not at 10.6 microns. Also, nitrogen-cooled detectors, such as gold-doped germanium,

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*Also, Hanst, P.L., and Morreal, J.A., A Wavelength Selective Repetitively Pulsed, CO_2 Laser (to be published).

can have considerably higher detectivities at 9.3 microns than at 10.6.

Additives

Nitrogen--That possible benefits might be derived from the addition of nitrogen to the CO_2 laser were recognized by several people almost simultaneously (refs. 2, 31). This is not surprising; the relevant facts were well known and made nitrogen a very logical additive. It was known that the lowest vibrationally excited level was metastable since the transition to the ground state is forbidden. Experimental measurements showed that about 30 percent of the N_2 molecules in a pure nitrogen discharge could accumulate in the lowest vibrationally excited level (ref. 32). It was also known that the energy of the first vibrationally excited level of N_2 was very close to the energy of the upper level of the laser transition in CO_2. Thus the upper level of the laser transition could be selectively excited by near-resonant energy transfer from the metastable N_2 molecules in inelastic collisions with ground state CO_2 molecules. It had also been experimentally observed that the lifetime of the metastable N_2 molecules could be drastically reduced by addition of CO_2 to the discharge (ref. 33).

Nitrogen was added to a flowing CO_2 laser and the results were as anticipated; the laser power increased by an order of magnitude (ref. 2). Some believed that nitrogen should not be added to sealed CO_2 lasers because it would react in the discharge to form NO, N_2O, or $(CN)_2$ which adversely affect the operation of the laser. However, it now seems that this fear was unfounded, since several long-lived sealed-off CO_2 lasers containing nitrogen have been built. Also, chemical analyses of the products of the discharge reveal only trace amounts of nitrogen compounds (refs. 24, 26, 34).*

Carbon Monoxide--The vibrational energy level spacings in CO are approximately the same as in N_2; therefore CO would be expected to perform the same function as N_2 in a CO_2 laser. However, CO is expected to be less effective than N_2 for two reasons: (1) The CO-CO_2 energy match is not so close as the N_2-CO_2 energy match, and (2) the first excited vibrational level of CO is not metastable. These expectations have been confirmed experimentally in flowing lasers (ref. 10) and in sealed-off lasers (ref. 23).** CO is produced in the discharge by

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*Also Lawrence, T.R., Chemical Equilibrium in a CO_2-N_2-He Discharge (to be published).

**Also Clark, P.O., and Wada, J. Y., The Influence of Xenon on Sealed-off CO_2 Lasers, IEEE J. Quantum Electronics (to be published).

dissociation of CO_2, but it takes several seconds for sufficient CO to accumulate, so the power output of a fast flowing He-CO_2 laser is less than a slowly flowing or non-flowing He-CO_2 laser.

The power output of an optimized He-CO-CO_2 laser is about half of that from an optimized He-N_2-CO_2 laser, whether flowing or non-flowing. However, should it ever be demonstrated that the operating life of a sealed CO_2 laser is actually shortened by the addition of nitrogen, then the longer life may be worth the sacrifice in power.

In the dissociation of CO_2, O_2 is obtained in addition to CO. It has been shown experimentally that O_2 reduces the laser power (ref. 10). This is because O_2 can selectively excite the lower laser level in the same way that N_2 excites the upper.

Helium--The mechanism by which helium increases the laser power is quite complex and perhaps not fully understood yet. Initial speculation involved energy transfer from metastable He atoms. However, this was easily disproven by observing that the emission spectrum of the discharge contained no lines of helium. Also, the excitation energy of the lowest excited state of helium is considerably higher than the ionization energy of the other species in the discharge. It therefore seems unlikely that metastable helium atoms would be present in the discharge. A more thorough and logical explanation, in which helium did three things to improve the lasers performance, was offered by F. Horrigan (ref. 10). The first of these was to cool the rotational and gas temperature by virtue of the high thermal conductivity of helium. This would move the peak of the distribution over rotational levels to a lower value of J and increase the population inversion by dividing the population of the vibrational level over fewer rotational levels. The second effect was to increase the cross relaxation rate among the rotational levels, or to decrease the time required for the rotational distribution to come to thermal equilibrium. This would increase the laser power by allowing one laser transition to draw upon the population of other rotational levels. The third effect is to increase the relaxation rate of the lowest vibrational level of CO_2 and thus to reduce the population of the lower laser level. Helium atoms are present in relatively large numbers and are found to be more effective than heavier molecules in converting vibrational to translational energy during collisions. The effect of helium may be summarized as being a selective cooling. Experimentally, it is found that the addition of helium allows one to go to a much higher input power before the output power saturates. At low power inputs, where the rate of pumping into the upper laser level limits the output power, the helium has little effect; at higher power inputs, where the accumulation in the lower laser level limits the output power, helium has a very pronounced effect.

Other mechanisms for explaining the effect of helium have been proposed but not yet confirmed. Horrigan has suggested that the large helium concentration may promote volume recombination of CO and O by providing a third body for the conservation of momentum and energy (ref. 10). However, the experimental data do not indicate that helium changes the equilibrium of CO_2 and its dissociation products.* Witteman claims that helium increases the population of the upper laser level, presumably by increasing the electron temperature (refs. 21, 22).

Water Vapor or Hydrogen--Addition of water vapor alone to the CO_2 laser may or may not produce the improvements claimed by Witteman, but it certainly has produced controversy. The basis of the controversy is that others have not observed the two-fold increase in power reported by Witteman when they added water vapor to their lasers. In most cases, the water vapor or hydrogen was added to a flowing gas laser and either no change or a decrease in output power was observed. Similar observations were made on sealed-off lasers. Recently, Deutsch has observed only about a 10 percent increase when water was added to a sealed-off CO_2-N_2-He laser. One possible explanation for the discrepancies is that Witteman's three-component laser was not optimized before adding the water. On the other hand, the output power per unit length of Witteman's laser is probably the highest yet achieved in a non-flowing system. Of course, there is no reason to assume that the optimum pressures of CO_2, N_2, and He are the same in a four-component system (with H_2O) as they are in a three-component system.

Witteman's analysis of the mechanism by which the water vapor should increase the laser power seems reasonable and straightforward, and it seems as though it should work. The lowest vibration energy level of the H_2O molecule is very close to the energy of the lower laser level. The lower laser level can then be depopulated in collisions with water molecules with near resonant energy transfer. Furthermore, the lifetime of the excited water molecule is very short, so the depopulation process should be very effective. It remains unclear why it is still a "one-man process" that will not cooperate with others.

Since it is supposed that the water vapor and helium serve somewhat the same purpose in the CO_2 laser, it is interesting to compare the optimum amounts for each, how they perform, and to see what happens when both are added. In Witteman's laser, which was 2 meters long and 2 cm in diameter, the maximum power was about 9 watts when the tube was filled with 1 torr CO_2 and 2.5 torr N_2. As water vapor was added, the power rose to a maximum of 20 watts (efficiency of 12 percent) when the water vapor pressure was about 0.2 torr. The power was about doubled by the presence

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*Also Lawrence, T. R., Chemical Equilibrium in a CO_2-N_2-He Discharge (to be published).

of water vapor. When helium was added to the CO_2-N_2 laser, the maximum power occurred when the helium pressure was about 10 torr and about 3 times the maximum power obtained without helium. Now, when water vapor was added to a 1.5-meter laser containing 1 torr CO_2, 2.5 torr N_2, and 11 torr He, the maximum power output was about 63 watts, again occurring at a water vapor pressure of 0.2 torr. The maximum power without H_2O was 39 watts, but this fell rapidly to about 25 watts as the laser ran. The power output of the laser with 0.2 torr H_2O fell only to about 60 watts in the same length of time. Thus, in both cases (with and without helium) the maximum power was achieved at 0.2 torr of water vapor and this power was approximately double that obtained without water vapor. Another way of saying this, of course, is that the power obtained from a laser with optimum helium pressure is approximately three times the output power of the same laser without helium whether the laser contains water vapor or not. Thus, it seems that the functions of the helium and water vapor additives are completely independent of each other and do not overlap as supposed above.

Witteman, in fact, does explain his observations on the basis of different functions for the two additives. The H_2O depopulates the lower laser level in the manner already described. The helium, on the other hand, increases the pumping rate into the upper level by increasing the electron temperature so that more electrons are available at the peak for excitation of N_2 at 2.5 electron volts. This increase in electron temperature is found at the higher discharge current and is probably quite sensitive to small amounts of impurities with low ionization potential. Further, he claims that small amounts (10^{-2} torr) of H_2, Ar, Kr, Xe, or even the impurities liberated from a pyrex tube in a few minutes, can cause a noticeable drop in output power, presumably by lowering the electron temperature. This observation has also caused some controversy which will be discussed later.

Of course, two of the three functions assigned to helium in the previous section, lowering the rotational temperature and shortening the rotational relaxation time, are also separate from what water vapor does. On the other hand, water vapor does something more; it provides an effective means for regenerating CO_2 and thus counteracting the dissociation of CO_2 into CO and oxygen. This has been confirmed by others (ref. 34). Chemical analysis of the contents of the discharge tube shows that far less CO_2 is dissociated into CO and O_2 when water vapor (or hydrogen) is present (see Figure 8). For these reasons, one would expect that the optimum four-component gas laser would produce more power than either of the optimum three-component lasers, as Witteman observes. It is therefore important to find out why other observations differ and to end the controversy.

The most unfortunate aspect of this controversy is that it temporarily overshadowed the real importance of Witteman's

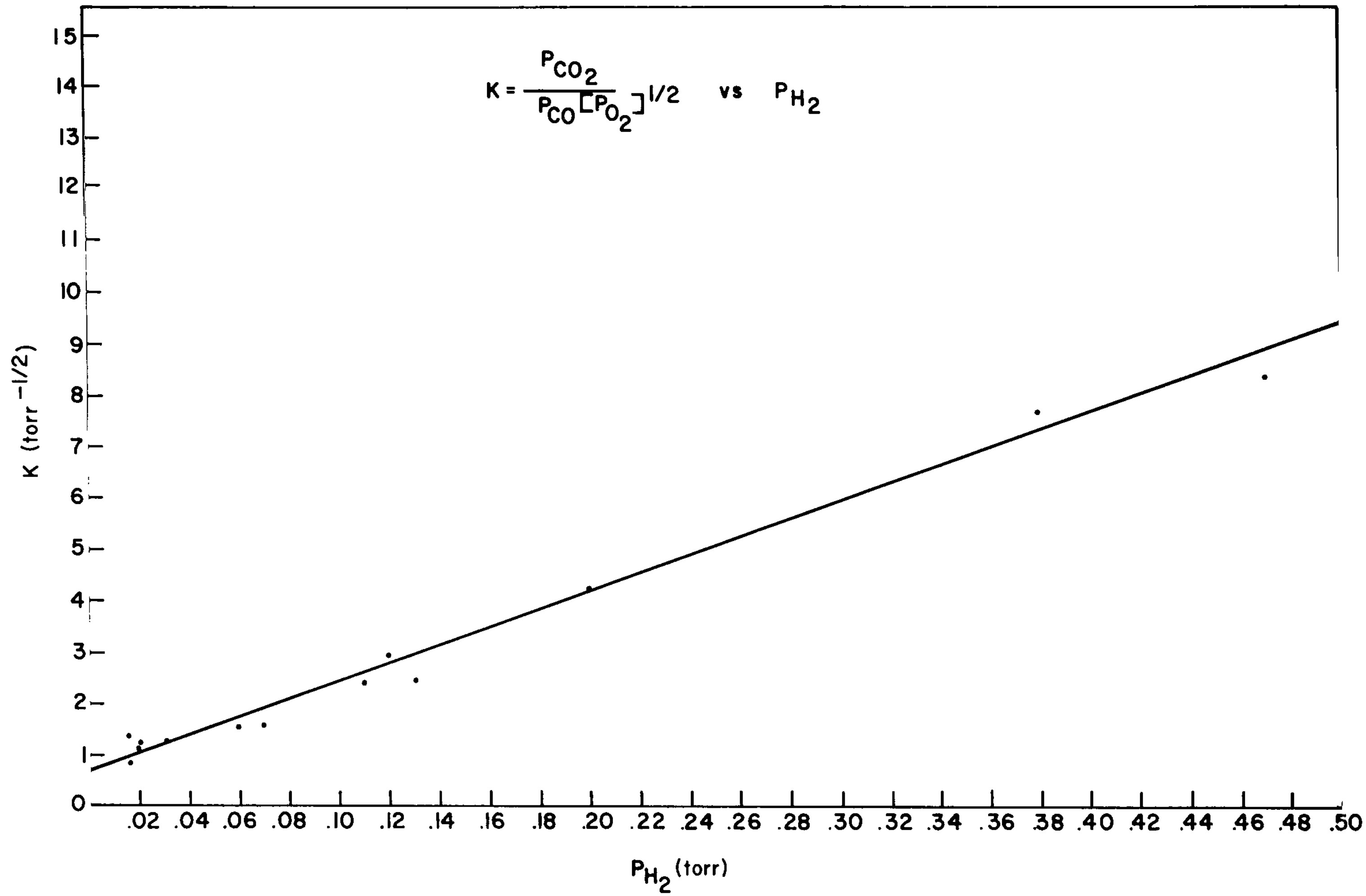

Figure 8.- Graph of amount of CO_2 dissociation in a discharge as a function of pressure of hydrogen additive.

development. He showed the fallacy of the prevailing belief that a long-lived, high-power, sealed-off CO_2 laser could not be built. He claimed this was accomplished by careful selection of materials, cleanliness, general care in construction, and addition of water vapor. He showed that a laser with H_2O operated for more than 1500 hours, whereas an identical laser without water vapor operated less than half as long and at half the power.

It could be that much of the difficulty concerning water vapor is due to its "stickiness." This makes it difficult to control the amount of water vapor in the system or even measure the pressure. If one puts 0.2 torr of H_2 and 0.1 torr of O_2, into a clean discharge tube, along with the CO_2, N_2, and He, mass spectrometer analysis shows the H_2 disappearing without a corresponding increase in H_2O pressure as H_2O is adsorbed by the various surfaces. This can be counteracted by conditioning the discharge tube by running discharges in water vapor. But, to complicate matters, a heated surface can release water vapor (among other gases) into the system. For instance, Carbone shows (without comment) that hydrogen gradually accumulates in his laser discharge and this is accompanied by increasing CO_2 pressure and decreasing CO and O_2 pressures (ref. 26). After about 800 hours, the H_2 pressure leveled off at about 0.2 torr and the CO_2 pressure went nearly back to its initial value. It is also interesting to note that the laser power remained quite constant in spite of the considerable range of CO_2 pressures during the course of his experiment.

Carbone also observed that the radiation in the Angstrom bands of CO decreased markedly as the H_2 pressure increased. He believed this to be caused by deactivation of the upper level of the angstrom transition in inelastic collisions with H_2 molecules according to the reaction:

$$CO\ (^1E^+) + H_2 \rightarrow CO + 2H.$$

This means that atomic hydrogen may be present in sufficient abundance to influence the chemical processes in the discharge. The mechanism by which CO_2 is regenerated in the discharge when water vapor is present is not yet understood; the simple gas phase reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

does not explain all of the experimental observations. One must therefore look for other possibilities involving available species or heterogeneous reactions. When one adds H_2O to the system, the discharge produces H_2, H, OH, and other species. There is one report of hydrocarbons being generated in such a system, but others have observed neither hydrocarbons nor nitrogen-hydrogen compounds.

In short, the influence of the water vapor additive to the CO_2 laser is not yet understood 3 years after the initial report. Since one person has obtained good results using this additive, it is essential to clear up the confusion and to understand why others do not confirm these results.

<u>Xenon</u>--The effect of the xenon additive on the CO_2 laser performance is also the subject of some controversy. Witteman included xenon in a list of impurities which degrade the performance of the laser. However, R. Rempel and J. Goldsborough experimented with xenon in sealed-off CO_2 lasers, and obtained higher power, higher efficiency, and longer operating life when xenon was added. Although they did not publish their observations, they did manage to publicize their discovery by other means. Then R. Paananen (ref. 11) added xenon to a flowing laser and found that the output power was essentially unchanged, but that the impedance was lowered and the efficiency was increased. Clark and Wada observed a 25 percent increase in output power and a 15 percent increase in efficiency when they added xenon to a sealed-off laser*. They also attained a 2800-hour operating life, which they attributed to the xenon. The increased power and efficiency is believed to be due to the increase in electron density caused by the easily ionized xenon. They found that the optimized CO_2-Xe-He laser discharge had 45 percent more electron density than the optimized CO_2-N_2-He laser and that the electron temperature was about the same for both.

However, in every case where xenon has been added, the visible spontaneous emission of CO and N_2 has decreased, which seems inconsistent with the constant electron temperature and increasing electron density suggested above. One must then conclude that the xenon decreases the number of high-energy electrons in the discharge while increasing the number of low and intermediate energy electrons in a way that leaves the average energy of the electrons essentially unchanged. This means that the distribution of electron temperatures is non-thermal. Electron temperature then is not defined, since the concept of electron temperature is associated with a specific (thermal) distribution of electron energies.

The reason for the increased operating lifetime with xenon added is not clear at this time. Chemical analyses with the gas chromatograph and mass spectrometer show that the degree of dissociation of the CO_2 is not influenced by the addition of xenon**. The most likely explanation for the longer life is that the ions formed in the discharge strike the cathode with less energy because of the lower ionization potential of xenon and therefore

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*Clark, P. O., and Wada, J. Y., The Influence of Xenon on Sealed-off CO_2 Lasers, IEEE J. Quantum Electronics (to be published).

**Lawrence, T. R., Chemical Equilibrium in a CO_2-N_2-He Discharge (to be published).

are not trapped in the cathode. Also, xenon would probably be the most numerous ionic species and would be less reactive than other species such as oxygen.

Carbone has pointed out that the xenon may eventually separate from the lighter gases in a dc discharge. This process has been observed and can be identified by a variation of color along the length of the discharge. Clark and Wada did not indicate that this was occurring in their laser, but it is a possibility that should be kept in mind when adding xenon to lasers.

Other Additives--No other useful additives have been reported thus far. Some have been tried, but have produced no improvement. N_2O is found to decrease CO_2 laser power because N_2O can compete with CO_2 for the N_2 excitation. O_2 decreases laser power by selection excitation of the lower laser level. Other additives, such as argon, nitric oxide (NO), and light hydrocarbons, also decrease the CO_2 laser power for one of several reasons (refs. 10, 28). In some cases, the impurities supposedly reduce power by lowering the electron temperature.

Role of Construction Materials

The importance of careful selection of materials used in making sealed-off CO_2 lasers was demonstrated by Witteman. Several of his recommendations about specific materials have been disputed by others. However, it is clear that a surface that releases impurities into the discharge must be avoided. A surface that removes one or more components from the discharge must also be avoided. Furthermore, heterogeneous reactions between gas phase and condensed phase components are very important in determining the chemical composition of the discharge and are often very sensitive to the nature of the surface. The object, therefore, is to select materials which do not release impurities, absorb desired components, or catalyze undesirable reactions. The surface should catalyze desirable reactions, such as regeneration of CO_2, and not change their characteristics as the discharge is run.

The materials used in the construction of a laser fall into three functional classes: the vacuum envelope, electrodes, and optical components. Each of these will be considered separately.

Vacuum Envelope (Discharge Tube)--So far, two materials have been used for the envelope--fused quartz and pyrex. Witteman used fused quartz very successfully and claimed it was the only suitable material. Pyrex, he said, even after thorough cleaning and baking out, released enough impurities in 15 minutes of operation to reduce the laser power to 25 percent of the initial power (ref. 6). This is contrary to the findings of Carbone, Deutsch, Clark, and others who used pyrex quite successfully. They ran their lasers for 1000 hours or more sealed-off. Again, one can only speculate about the reasons for the discrepancy. Some have suggested that European pyrex may be inferior to American pyrex. On the other hand, it may be that only Witteman has attained a degree of cleanliness in his system where one can realize the increase in electron temperature that he has observed upon adding helium. In other words, it may be that the other systems were sufficiently contaminated that the further contamination from the pyrex made no difference. The difficulty with this explanation is that the major contaminants which pyrex might contribute are H_2O, CO_2, and CO which are already present in Witteman's laser. Furthermore, it assumes an ineptness in vacuum technique on the part of American scientists who supposedly are the world leaders in ultra-high vacuum technology.

It is also possible that the pyrex adsorbs some of the components, especially water, more strongly than quartz or that the heterogeneous reactions have different rates and produce different chemical compositions in the two cases. The obvious first step in resolving the matter would be for Witteman to identify the impurity or other chemical change produced by the pyrex which reduced the laser power.

Quartz does appear to have a number of advantages. It is generally used in systems where a high degree of cleanliness is essential because it is more inert. Water vapor, for instance, is adsorbed to a lesser extent on silica and other glasses with a low alkali content (ref. 21). Also, quartz has a lower coefficient of thermal expansion than pyrex and most other glasses. There are also several disadvantages to quartz. For instance, quartz is hard to work because it has a high softening point and a relatively narrow range of temperature over which it can be worked. Also, the rate of helium permeation through fused quartz is about 10 times faster than through pyrex. A fused quartz discharge tube with typical dimensions and no reservoir would lose half of its helium in about 11,500 hours at 25°C or in about 1500 hours at 100°C.

Electrodes--In general, thermionic (hot) cathodes are not applicable to CO_2 lasers because of the chemical reactivity of some of the gas components, especially oxygen. One exception is a hot cathode containing $BaSrO_3$ used by McNair (ref. 35). He found this cathode to be a better emitter in the oxidizing atmosphere than in an inert atmosphere, and it has a long operating life. However, its influence on the chemical stability of the gases in a sealed laser is not yet determined.

In some cases, the discharge is excited by radio frequency voltages with external electrodes. However, in most cases dc excitation is used with cold cathodes of the hollow variety. The size and shape of the hollow cathode is very important. If the cathode geometry is correct, electrons will be emitted only from the inner surface; hence sputtering will be minimized. Sputtering is the transport of material from the cathode to other nearby surfaces and occurs when energetic positive ions from the discharge dislodge metal atoms upon striking the cathode surface. If the discharge is confined to the inner surface of the cathode, sputtering is likewise confined. However, if the discharge strikes the outer surface of the cathode, the sputtered material can be deposited on nearby glass surfaces. This process can rapidly deplete the gas supply in the discharge tube; in fact, there is a class of ultra high vacuum pumps based on this process.

One of the metals most widely used for cathodes in CO_2 lasers, platinum, is a notorious sputterer. Therefore, careful design of the cathode geometry is especially needed where platinum is used. Witteman advocates the use of platinum electrodes because platinum is especially resistant to attack by the very reactive components in the discharge, such as oxygen and nitrogen atoms. Also, platinum does not react with CO to form volatile carbonyls as do many metals, such as iron, tungsten, and nickel. However, Carbone and others have successfully used electrodes of high purity nickel in sealed CO_2 lasers. Nickel is more resistant to sputtering than platinum, but it does react slowly with the components of the discharge to form nickel oxide, nickel carbonyl, and nickel carbonate. Carbone showed that these compounds decomposed and returned the CO_2 back into the discharge when the cathode was heated to about 300°C. He further showed that the adsorption processes would be suppressed by maintaining the cathode at 300°C. More recently, Deutsch has designed a laser in which the cathode is maintained at 300°C by the discharge itself (ref. 27).

No other materials seem to have been used for electrodes in long-lived, sealed-off CO_2 lasers. Carbone has suggested that palladium is a possibility based on its low heat of chemisorption for CO and CO_2, but apparently no one has tried it yet.

Perhaps one of the most difficult questions about materials used in making electrodes is how the heterogeneous reactions, which significantly influence the chemical composition of the gas, depend upon subtle differences in the surface characteristics. It is often found that the effectiveness of a solid catalyst is quite sensitive to adsorbed impurities, for instance. In line with this, Deutsch has reported that a laser tube which has failed can be revived and will operate at initial power output for a short time after replacing the lost CO_2. The revived laser may operate about 50 hours before the second failure, whereas the first failure may have occurred after 1000 hours of operation. He also found that a new discharge tube put together with nickel electrodes, which had previously been used for several thousand hours, failed after about 70 hours. Clark has reported similar observations of a dependence of cathode performance on its history. Thus, the problem is more than finding materials which are initially favorable to maintaining the best chemical composition; one must also prevent the surface from changing to something less favorable as the discharge is run.

Windows and Mirrors--The quartz or pyrex used for the discharge tube envelope does not transmit the 10.6-μ radiation; therefore, it is necessary to have a window of some material which does. At least one end of the discharge tube will need such a window; the other end may have either a window or an internal non-transmitting mirror. For both the window and the mirror, the materials used must have suitable vacuum properties. The requirements are not so severe as for the envelope or the electrodes, since the windows and mirrors can be kept away from the discharge and the unstable reactive species contained therein. However, it is clear that the materials should be inert in regards to the more stable species of the discharge and not release gaseous impurities into the discharge. Furthermore, one must have a method for sealing the window or mirror onto the remainder of the vacuum envelope, which is suitable for ultra-high vacuum applications.

Materials which transmit visible radiation have been studied for many years and so the optics for the visible range is highly developed. In contrast, studies of the 10-micron region of the infrared were begun quite recently so the optics are not so well developed. As an added handicap, the photon energy (frequency) at 10 microns is in the region of chemical bond energies and lattice vibration frequencies so that many solids have very strong absorption at this wavelength. Some of the ionic salt crystals, e.g., NaCl, KCl, and KBr, do transmit 10 microns; so do some of the semiconductor materials, such as germanium and gallium arsenide.

The most widely used window materials are NaCl, germanium, and some of the "Irtran" materials (polycrystalline zinc selenide). Fresh salt windows transmit very well, but they deteriorate due to moisture damage, and the like. Furthermore, they apparently react with components in the discharge; Clark has observed a coating of sodium nitrate on the side nearest the discharge, for instance. When used in high power lasers, the surfaces of the salt windows soon lose their optical finish and acquire a ripply (orange-peel) appearance.

Germanium windows work quite well in low powered lasers in spite of having some absorptivity. The absorptivity is temperature dependent, increasing as the temperature increases, which can lead to "thermal runaway" in high power lasers. There seems to be some problem with optical quality control with germanium. At present, quality is controlled according to electrical resistivity, and presumably high electrical resistivity is indicative of good optical transmissivity. According to Carbone, however, this is not true; he has found a wide range of optical quality in germanium specimens with nominally equal electrical resistivity.

As techniques for making gallium arsenide improve, it may be more widely used. Reynolds has used gallium arsenide windows and feels they have good potential in spite of some initial difficulty encountered in using them. Some of the Irtran materials make good windows, but are quite expensive.

Non-transmitting mirrors are usually a metal coating, such as gold, evaporated onto a suitable substrate. At first, transmitting mirrors were usually non-transmitting mirrors with holes in them. More recently, the industry has advanced to multi-layer dielectric mirrors for 10-micron use. They are already widely used.

IV. ANALYSIS AND PROSPECTS FOR SPACE QUALIFICATIONS

Before discussing what requirements must be met for space-qualification of the CO_2 laser, perhaps the reasons for wanting the device in space in the first place should be reviewed. First of all, as everyone knows, the golden glow of lasers in general has been seen and appreciated most devotedly by those interested in communications systems of the future. They look at the coherence and high carrier frequency and see a high rate of information transmission. They look at the small beam divergence and see either a spy-proof communications link or a long-range communication link with low transmitter power, depending on whether they are military-minded or space-minded. They look at the present "state-of-the-art" and see a lot of work to be done, providing, of course, they take a good look. High data transmission rates depend upon stable, single frequency operation of the laser and development of high-frequency modulators and detectors. It also depends on making the data available to the transmitter at the same high rate. Long-range communication links will depend on having large, high quality telescopes and highly accurate pointing capability for the transmitter.

To test the concepts of optical communications from space and to explore anticipated problem areas and uncover unanticipated problems (if any), NASA is planning to put a laser communications satellite experiment (LCSE) into a synchronous orbit. The LCSE might carry two laser transmitters with appropriate modulators, a 16-inch transmitting telescope with aiming equipment, one or more optical receivers, and the more traditional telemetry equipment to monitor and control the laser communications systems. Figure 9 shows a block diagram of the satellite transmitter configuration for a proposed LCSE experiment requiring several lasers. The LCSE space-qualified components will be developed separately with the lasers being started first since they will require more time.

The helium-neon was the first laser selected for space qualification and the preliminary design (Figure 10) was completed in February 1968. The helium-neon laser was the first selection because it was already the most highly developed of the gas lasers. Its wavelength (6328Å) was such that photomultiplier detection could be used and there was a fair modulation capability.

The space-qualified He-Ne laser now being developed will have single-mode, multi-frequency operation, and will be used in an intensity modulated, incoherent detection communication system. However, recent advances in stabilization techniques and mode locking may make it possible to use coherent detection for helium-neon lasers in the not-too-distant future.

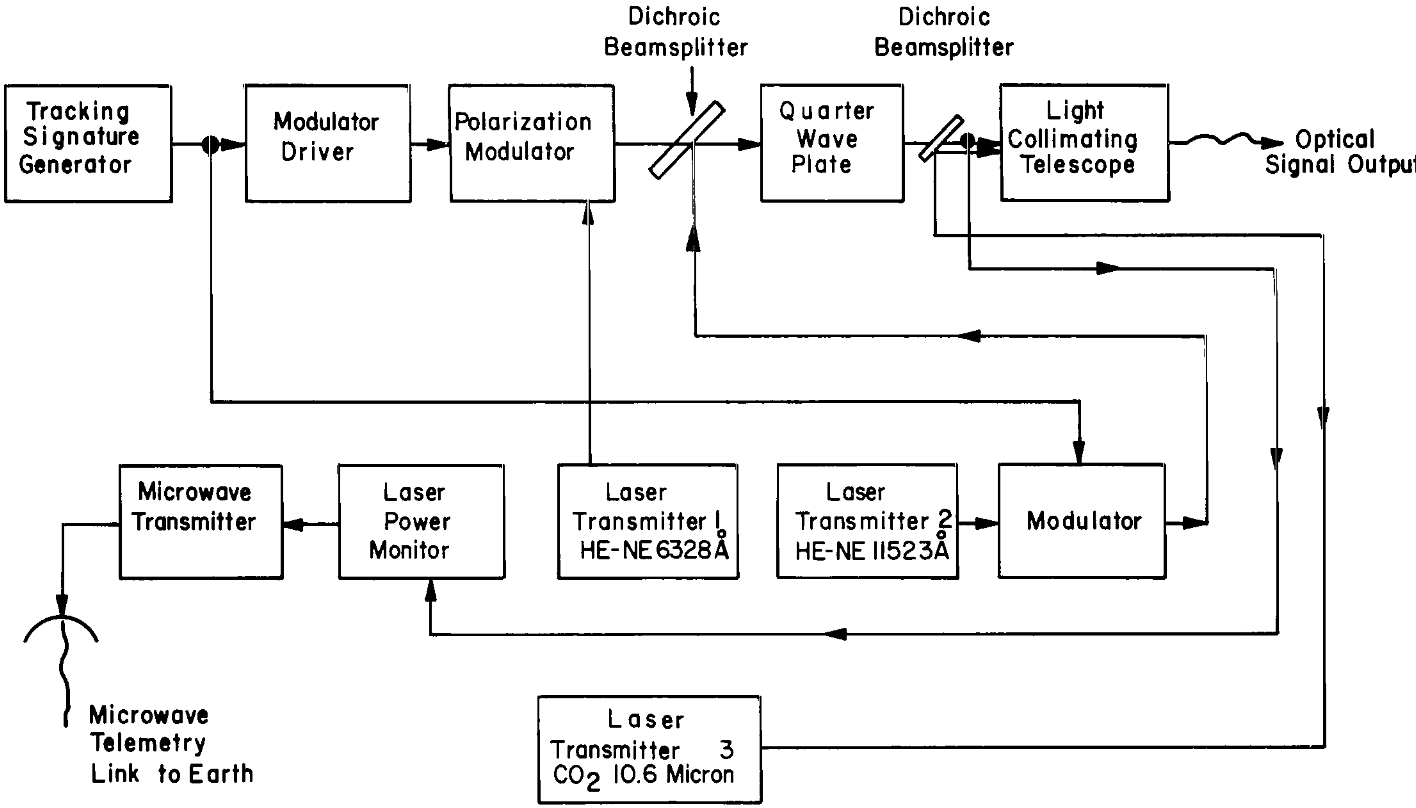

Figure 9.- Block diagram of satellite transmitter configuration for scintillation experiment.

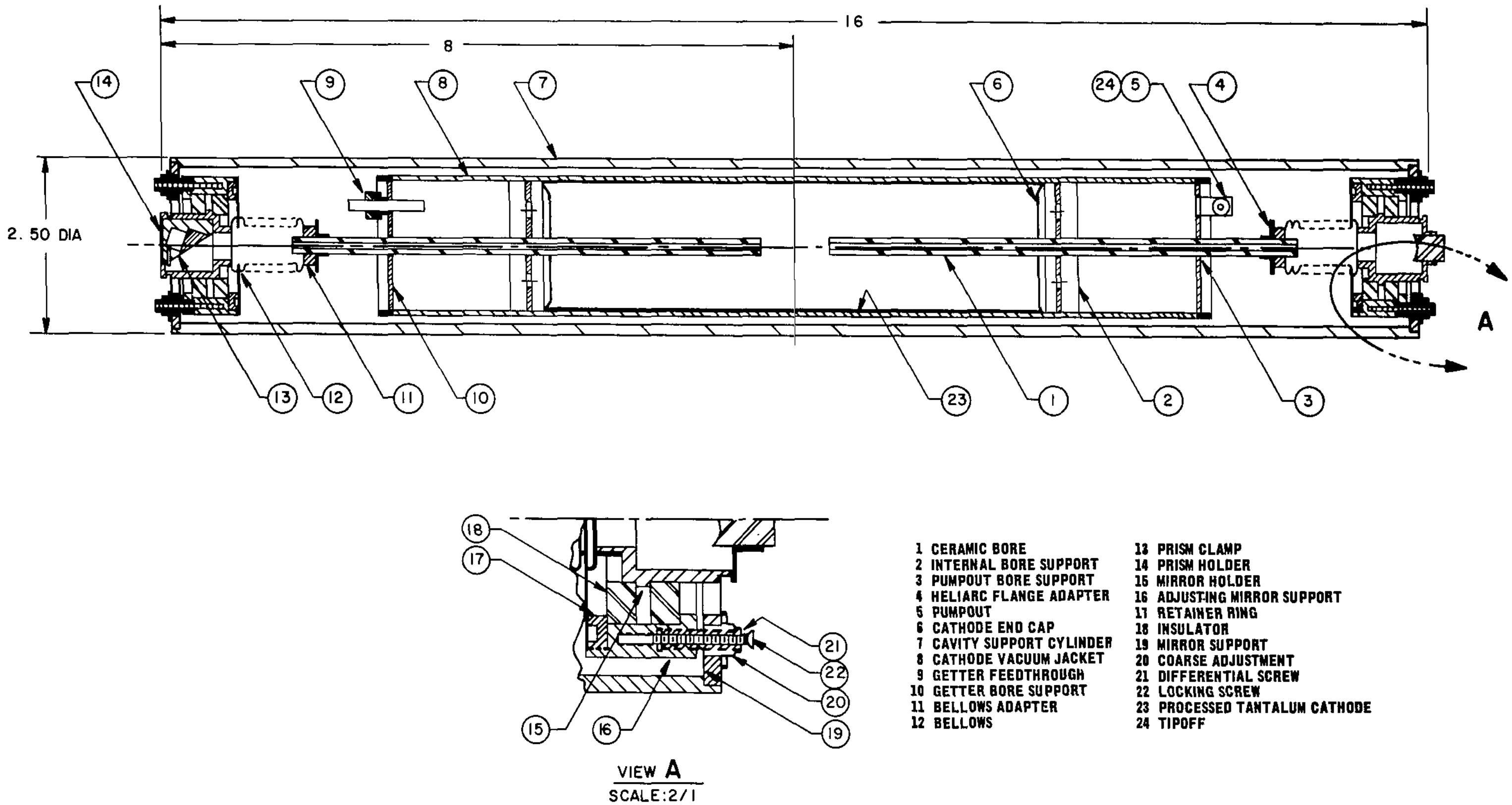

Figure 10.- Drawing of helium neon laser designed for space use. (The laser and its power supply will be packaged in a pressurized, hermetically sealed container with dimensions 5x5x16 inches)

The CO_2 laser was the next selection in spite of the rather extensive development effort still needed. The CO_2 laser has the highest power and efficiency of the existing gas lasers, but this should be examined closely if it were the sole basis for selecting the CO_2 laser for this application. Consider, for instance, the diffraction-limited, beam-divergence angle which increases in proportion to the wavelength for a given aperture. Then for fixed transmitter and receiver apertures and separation, the fraction of transmitted power which is collected at the receiver is about 300 times less for the CO_2 laser than for the He-Ne laser, since the CO_2 wavelength is about 17 times longer. In fairness to the evaluation of the CO_2 laser, however, it should be pointed out that the longer wavelength would allow a proportionate relaxation in the dimensional tolerances in the transmitting and receiving telescopes. Hence, for a fixed budget, one could make larger telescopes for the CO_2 laser wavelength and regain some of the beam divergence loss. The CO_2 laser is further handicapped by being out of the photomultiplier range. Currently available photoconductors have good efficiency, but suffer from large dark currents and associated noise which limits the sensitivity. The net efficiency of the spaceborne CO_2 laser would be further decreased if it were necessary to supply power for refrigeration cooling of the laser. CO_2 lasers do not work well if the temperature of the outside wall of the discharge tube rises much above room temperature. Laboratory CO_2 lasers are usually water-cooled, but outer space does not provide running water.

There are some advantages to the long wavelength provided by the CO_2 laser. It is in a region where the atmospheric transparency is good. Furthermore, it is expected that atmospheric turbulence and scattering will be a lesser problem than at shorter wavelengths. One of the purposes of LCSE is to evaluate this problem.

The main reason for wanting to send a CO_2 laser into space is the comparative ease of obtaining single mode, single frequency operation in lasers up to one meter long. This feature and the circumstances that contribute to it have already been discussed. The important thing now is that the single-frequency carrier allows one to use the techniques developed for radio communication, such as heterodyning, frequency modulation, or coherent detection. The heterodyning principle has already been demonstrated for CO_2 lasers in the laboratory (ref. 36) and it appears quite feasible to extend the range to outer space.

Requirements for CO_2 Laser in Space

Some of the requirements for the space-qualified CO_2 laser, such as single mode, single-frequency operation, and diffraction-limited beam divergence, have already been mentioned. Frequency stability and linear polarization are implied but not explicitly stated. Clearly, the long-term stability must be good enough to keep the laser oscillating on the same vibration-rotation spectral line. Experimental measurements have shown that a typical tuning range of about 30 MHz can be covered before the laser oscillation jumps from one vibration-rotation line to another. This implies a relative stability of one part in a million for the frequency and hence for the cavity length. If the mirror spacing is set by a spacer made of material with a thermal expansion coefficient of $1\times10^{-7}/^{o}C$, then the temperature must be held in a $10^{o}C$ interval. It has been found that the oscillation frequency is also a function of the gas pressure in the discharge tube and the discharge current (ref. 15). Therefore, it seems unlikely that passive stabilization will furnish the necessary long-term stability.

Active stabilization has been demonstrated using piezoelectric transducers for length control. It is not yet clear whether it would be more advantageous to control the transducer voltage from the ground or to incorporate the transducer in an automatic control system. The short-term stability required depends on the desired modulation bandwidth and signal/noise. A stability to within 3 kHz in 0.1 second (one part in 10^{10}) should meet the requirements for the LCSE.

Some calculations show that a power output of 1 watt would be sufficient (ref. 37). However, the power should be large enough to allow for unforeseen transmission losses, beam acquisition and tracking if the orbit is not synchronous, and operation during the least favorable daylight hours. Therefore, a goal of 5 watts output power capability is recommended, if this can be reconciled with the limitations on the size. The size limitation of 5×5×16 inches is set by a desire to guarantee interchangeability of the CO_2 laser with the He-Ne laser.

Then, of course, the hostile environments of launching and space impose special requirements. The laser and all associated equipment must be rugged enough to survive the strains and shakings associated with launching. The laser cavity structure must be rigid enough that the mirror alignment will not be changed when atmospheric and gravitational forces are removed. The structure should have no resonant frequencies in the range of acoustic vibrations apt to be encountered. This is further motivation for keeping the structure short and rigid so that resonant frequencies are higher than 20 kHz*.

*Brian Woodcock of the Raytheon Company suppresses these low frequency resonances in a long laser by clamping the supporting rods together at unequal intervals. This is an interesting notion and should be examined for more applications.

The predominant feature of outer space is the vacuum which causes several problems. First, one must allow for changes in critical dimensions caused by elasticity or even compressibility upon removal of atmospheric pressure. Second, the only way of removing heat dissipated in the spacecraft is by radiation. This means that the spacecraft temperature must rise until the radiated power equals the power input. The temperature can be calculated in specific cases. Unless refrigeration is used, the temperature limit of the most sensitive component will determine the maximum amount of heat which the spacecraft can dissipate. The radiant energy from the sun must also be considered. For instance, the temperature of a spherically perfect black body with good thermal conductivity will be $5^{o}C$ when the only source of power is the sun at 149×10^{6} kilometers. A third consequence of the space vacuum is a possible high-voltage insulation problem. A perfect vacuum is a good electrical insulator. However, if there are any gas sources on the spacecraft, then the vacuum may become degraded to the point where an electrical discharge can be sustained, thereby short circuiting the high voltage.

Components which are apt to be damaged by high energy radiation must be adequately shielded from such radiation. There are several varieties of high energy radiation, such as short ultraviolet, Van Allen belts, or solar wind, which may damage sensitive components.

Of course, the prime requirement for space qualification is dependability. The component must perform satisfactorily in space and continue to do so for the duration of the mission. The foregoing discussion was merely consideration of some of the factors having adverse affects on dependability which are above and beyond those encountered in a ground based laboratory. The component must first of all be developed to the point where it displays sufficient dependability in the laboratory environment. Then another (but not unexpected) requirement for the space-qualified CO_2 laser must be considered--long lifetime.

The required lifetime depends on the forecast duration of the mission. However, the duration and even the scope of the mission have not yet been ascertained. Conceivably, one might want to study the 10.6-micron communication link in detail under a wide variety of conditions to look for day/night variations in transmission quality, seasonal variations, and the like, which might take one or more years. Therefore, a 10,000-hour operating lifetime with a 3-year operating plus storage lifetime seems to be a desirable goal. If this goal cannot be met, it would be necessary to reduce the scope of the experiment or to plan on launching several experiments. The expense of sending equipment into space dictates that reasonable effort should be directed toward achieving the desired lifetime. As a further concession to the expense of launching the experiment into space, the weight and power requirement of the laser should be minimized.

Comparison of Specifications with Present Level of Achievement and Prospects for Improvement

In such a comparison, one should cover the most favorable aspects first. Single-mode, single-frequency operation of CO_2 lasers with the required frequency stability has already been achieved in several laboratories. Extending this achievement from the laboratory environment to the space environment seems to be purely a matter of design. Likewise, the procedures of ruggedization, weight minimization, and minimizing the power requirement seem to be matters of design. The toughest design problem will probably be cooling the discharge tube. CO_2 lasers operate best if the outside wall is kept at or below room temperature and the power output drops markedly as the temperature rises. Of course, the temperature of the gas in the discharge tube is the primary consideration, and it may be possible to allow higher tube temperatures if a material with higher thermal conductivity than glass is used. The main problem is to conduct or otherwise transfer the heat from the discharge tube to the outer surface of the spacecraft which is cooled by radiation.

Several of the requirements are still beyond the level of achievement in the laboratory. For instance, no one has obtained the required 5 watts from a sealed CO_2 laser of this size in single-mode, single-frequency operation. It has been done with a flowing gas CO_2 laser. Furthermore, Witteman has achieved up to 60 watts per meter in long sealed CO_2 lasers in multimode operation. The difficulty is that the resonator losses do not decrease as the length is decreased. Also when one eliminates higher order modes by increasing their diffraction losses, one also increases the diffraction loss in the lowest order mode. One can decrease losses due to absorption and scattering by improvement of the quality of the optical components in the resonant cavity, but one cannot reduce the diffraction losses below an optimum value and still retain single-mode operation. If 5 watts cannot be attained with a total laser length of 16 inches after a reasonable effort, there are several alternatives. The power specification can be reduced to 1 watt, a folded laser could be used, or a longer laser could be allowed. There is no compelling reason for selecting any of these alternatives at the moment. However, even if 1 watt should prove to be enough, there is at least one advantage to overdesigning in this respect. In several cases, significant increases in operating lifetime were obtained by operating the laser at a fraction of its maximum power. Therefore, if the laser is designed for 5 watts with provision for reducing the power to 1 watt, the 10,000-hour operating lifetime (at 1-watt) may become more attainable.

The 10,000-hour operating lifetime appears to be the most difficult of the specifications, because no CO_2 laser has operated anywhere near this long in the laboratory yet. In most cases, the cause of failure after a few hundred hours of operation is known to be depletion of the CO_2 in the discharge. Presumably, this depletion is caused by adsorption of CO_2 or its dissociation products on the cathode surface. This kind of problem is often solved by using a reservoir, which is a volume of reserve gas much larger than the volume of the discharge. A large reservoir volume would be undesirable for space use, and it is not clear that the large reservoir would serve the purpose anyway. The reservoir would be effective if the loss rate of CO_2 were constant. However, the CO_2 laser typically loses power quite slowly until near the end of its operating life when the power drops very rapidly. This indicates that either the laser power is quite insensitive to the CO_2 pressure over quite a wide range or that the CO_2 loss rate is not constant. There is conflicting evidence on the first possibility; parameter studies by Whitehouse (ref. 7) show that power output is a sensitive function of CO_2 pressure, whereas Carbone's data show the output power remaining nearly constant as the CO_2 pressure varies from 2.0 to about 0.7 and back to 2.0 torr (ref. 26). Until the matter is resolved, it seems easier to believe that laser power does depend on CO_2 pressure. In this case, one is led to the conclusion that the loss rate of CO_2 is slow at first but becomes much more rapid after the laser has been operated for a while. If this is true, then adding a large gas reservoir will not be an effective method for making long-lived CO_2 lasers; reserve cathodes may be more effective. Apparently, the surface characteristics of the cathode change as the discharge runs and the cathode becomes more adsorbent for (or reactive with) one or more of the components in the discharge. The nature or cause of this change is not yet clear. However, enough data are available to indicate that the operating time before the change occurs can be lengthened by several techniques. Operating at reduced power is one technique, but probably not the most desirable. Addition of xenon is another technique, which is probably related to the first one in that the energies of ions striking the cathode are lowered; however, the laser power output is not lowered, which is an advantage. Operation with a heated nickel cathode is a third technique which has not yet been fully explored. Carbone's experiment (ref. 26) with the nickel cathode heated to 300°C was terminated at about 1100 hours before the CO_2 pressure began to decrease. Further tests are needed to determine the operating lifetime which can be attained using the heated cathode technique and to determine what the optimum cathode temperature is. It has been shown that a heated platinum surface catalyzes the regeneration of CO_2 (ref. 25); hence platinum electrodes may also have an optimum temperature for long operating life.

A possible fourth technique in this category is the addition of water vapor or hydrogen to the discharge. However, none of Witteman's papers tells the reason for the ultimate failure of his lasers with water additive. Furthermore, no one else has worked extensively enough with the platinum-quartz discharge tube to be sure that it fails for the same reason as the nickel-pyrex discharge tube. For instance, helium diffuses through quartz more rapidly than through pyrex, so loss of helium may be a reason for the deterioration. When water vapor is present, the laser may be less sensitive to the helium pressure; thus the operating life is longer. One confirmed advantage of water vapor or hydrogen in the discharge is that the amount of dissociation of CO_2 is markedly reduced. The most difficult aspect of putting water vapor into the discharge tube is that the pressure is hard to control since the water vapor tends to adhere to surfaces, which may be a factor in the controversy about the water additive.

This controversy should not be left unresolved, partly in the interest of producing better lasers, but mostly to preserve the good name of experimental science. If two sources report different results for experimental measurements of the same quantity, then the measured quantity must be a function of one or more variables which were different or uncontrolled in one or both of the experiments. Examples of such variables in this particular case are: impurities in the gas fill of discharge tube, impurities from discharge tube surfaces, contamination of cathode surface, cathode material and purity, cathode size and shape, size and shape of vacuum envelope around the cathode, cathode temperature, gas temperature, temperature of the inside wall of discharge tube, and metallurgical properties of cathode, such as crystal sizes and orientations.

Once the functions of additives, such as water vapor and xenon, are understood, and the optimum materials, temperatures, and geometry of the cathode and discharge tube are known, the problem of obtaining a long-lived, sealed-off CO_2 laser may be reduced to one of quality control. It remains to be seen which properties of what must be considered in the quality control.

To conclude, the immediate prospects for obtaining a space-qualified CO_2 laser with the desired power output, frequency stability, and operating lifetime seem only fair. There are some problems to be solved for this laser which were not so severe in the helium-neon case. For instance, the helium-neon laser was not required to be single-frequency or frequency-stabilized. However, single-frequency operation with the necessary frequency stability has been achieved for CO_2 lasers in several laboratories. Cooling also presents a greater problem; CO_2 lasers do not function well when the tube temperature rises much above room temperature, whereas the helium-neon laser can operate at quite high temperature. Finally, the 10,000-hour operating lifetime was somewhat of a problem in the helium-neon laser where there are only noble gases; the CO_2 laser has some very reactive species and the problem is much more severe. Even so, considerable progress has been made toward this goal; several sealed CO_2 lasers have been operated for 1000 hours or longer. If 1000 hours can be achieved, why not 10,000 hours?

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