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A sealed-off waveguide CO_2 laser*

TADEUSZ MACHOWSKI, MAREK STRZELEC

Institute of Quantum Electronics, Military Academy of Technology, Warszawa, Poland.

This paper deals with the design, construction and performance characteristics of a sealed-off, pyrex waveguide CO_2 laser, which can produce single-mode output powers of up to 0.28 W/cm of waveguide length, with discharge efficiencies of up to 15%. Our measurements of several materials for a waveguide laser and the influence of gas pressure, gas composition and discharge current on the laser power output of the sealed-off device are described. Furthermore, life tests of such a laser are presented for various preprocessing of laser tubes. It will be shown, that it is possible to obtain a simple, 5 W output power, single-mode and sealed-off waveguide CO_2 laser with a long operating life, a high passive frequency stability and with small ($4 \times 4 \times 25$ cm^3) overall dimensions.

1. Introduction

In the recent years significant advances have taken place in the development of cw carbon dioxide gas waveguide lasers [1–4]. Their advantages over conventional CO_2 lasers can be shown by considering the results of resonator theory for hollow laser waveguides and the similarity laws for two gas discharges of different diameters [1].

The modes of propagation and their losses for hollow circular guides were described in [5] and for hollow waveguide laser resonators in [6]. EH_{11} hybrid mode has the lowest propagation losses. It can be effectively coupled into the guide with the three main resonator configurations. According to Figure 1 [6] these low-loss configurations are:

I — flat mirrors placed directly against the guide, $\beta = 0$,

II — mirrors of large radius curvatures, of which centres lie approximately at the guide entrance, $\beta \cong 1$,

III — mirrors with curvatures such that $a = 2.415$, placed at a distance of one-half of the curvature from the guide.

In the above configurations and with the guide acting as an EH_{11} fundamental mode filter, the waveguide laser is an effective single mode laser.

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Let us now consider some practical reasons for the resonator to be appropriate for a given laser application. As far as compactness is concerned, case I is to be preferred, unless the tube design or the inclusion of internal optical elements prevent the placement of the flat near the guide. If the latter is true, case III is generally the appropriate alternative, since the mirror separation d is always much smaller than that in case II for a given bore diameter, hence, the wasted resonator length is kept minimum.

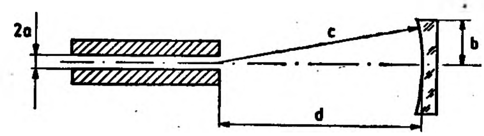

Fig. 1. A schematic diagram of the waveguide resonator. Characteristic parameters are: $\alpha = (ka^2)/c$, $\beta = d/c$, $\gamma = b/a$, $k = (2\pi)/\lambda$ (where a – guide radius, c – mirror curvature, d – mirror-guide distance, b – mirror radius, k – wave number, λ – wavelength)

For the smallest bore diameter, the additional difficulty or expense in fabricating mirrors of very short radius of curvature might also prompt the decision in favour of case II, for which the mirror curvatures and separations are much more manageable.

If tunability is required, careful attention must be paid to the total resonator length, since the tunability from line centre is limited to one-half of the free spectral range or $c/4L$, where c is the light velocity and L is the total resonator length. Again, case I is to be preferred.

The similarity laws, presented in Table 1, are essentially the same as the well known relations for a similar gas discharge with the same electron and gas

Table 1

Quantity	Relation	No.
Gas temperature (T_g)	$T_{g_2} = T_{g_1}$	1
Electron temperature (T_e)	$T_{e_2} = T_{e_1}$	2
Gas pressure (p)	$p_2 D_2 = p_1 D_1$	3
Gas number density (N)	$N_2 D_2 = N_1 D_1$	4
Electron density (n_e)	$n_{e_2} D_2 = n_{2_1} D_1$	5
Current density (J)	$J_2 D_2 = J_1 D_1$	6
Current (I)	$I_2/D_2 = I_1/D_1$	7
Electric field (E)	$E_2 D_2 = E_1 D_1$	8
DC resistance (Z)	$Z_2 D_2^2 = Z_1 D_1^1$	9
Input power/length (P_{in}/L)	$[P_{\mathrm{in}}/L]_2 = [P_{\mathrm{in}}/L]_1$	10
Gain coefficient (x)	$x_2 D_2 = x_1 D_1$	11a
	$x_2 = x_1$	11b
Saturation flux density (S)	$S_2 D_2 = S_1 D_1$	12a
	$S_2 D_2^2 = S_1 D_1^2$	12b
Output power/volume (P_{out}/V)	$[P_{\mathrm{out}}/V]_2/D_2^2 = [P_{\mathrm{out}}/V]_1/D_1^2$	13
Output power/length (P_{out}/L)	$[P_{\mathrm{out}}/L]_2 = [P_{\mathrm{out}}/L]_1$	14
Efficiency (η)	$\eta_2 = \eta_1$	15

temperature. Relations (1)–(10) involve only the discharge parameters, while the remaining ones involve moreover optical interactions. Relations (11), (12) are given for both Doppler- and pressure-broadened lines.

It is clear that when the tube diameter is made smaller and pressure is kept constant (Doppler-broadened line) the gain increases. On the other hand, when the tube diameter is made smaller, the optimum pressure increases, the gain remains the same (pressure-broadened line), but the laser bandwidth and tunability increase. The power per unit length and the efficiency remain the same, and it is possible to design a very compact CO_2 laser with a high tunability and frequency stability.

Our preliminary experiments, reported in [7], were performed with a simple flowing gas $CO_2 : N_2 :$ He laser system. In this paper we wish to describe our successful experiments in which dielectric waveguide techniques and a sealed-off and much more efficient device were used. In the next Section we present the way of choosing the best dielectric waveguide materials for our purposes.

In the succeeding Sections we present the design, construction and preliminary performance characteristics of a sealed-off waveguide CO_2 lasers. Furthermore, we present life tests of such a laser and preliminary measurements of frequency stability.

2. Materials for dielectric waveguides

In order to maximize the output power from any laser system it is necessary to minimize the so-called dissipative cavity losses, which do not contribute to output coupling. One of such sources of loss, being of particular importance in waveguide lasers, is that associated with the propagation of the optical field within the waveguide structure alone.

Theoretical values of the attenuation coefficient of the fundamental EH_{11} mode of our interest, can be easily obtained from the complex refractive index of the waveguide material and waveguide geometry [5]. Furthermore, it can be seen, that theoretical attenuation in guides with diameters larger than 1.5 mm is acceptable practically for all discharge tube materials — fused quartz, pyrex, alumina, beryllia and boron-nitride, though BeO waveguides are almost ten times less lossy than others.

During our initial works on a waveguide CO_2 laser, we have found that identical laser tubes exhibit different output powers. After visual inspection of these tubes we decided to perform attenuation measurements. The experimental arrangement is shown in Fig. 2. A sealed-off, stable CO_2 laser, tuned to the centre of the P^{20} 10.6 μm transition, served as a source of input signal for the capillary-bore guide.

The output power was detected with a thermopile power meter. Attenuation measurements were made by observing the transmitted power with the quide along and outside the radiation axis. Care was taken to match the radiation to the guide by means of proper choice of the matching lens, and to align properly the guide around the axis of laser radiation. We have performed our studies on several available materials listed in Table 2.

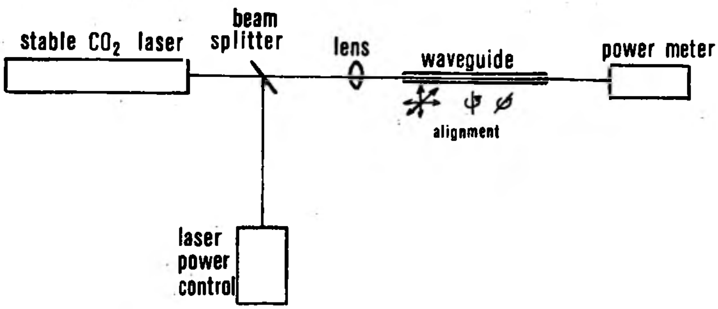

Fig. 2. Experimental arrangement for measurement of real waveguide attenuation coefficient

Most of the capillary tubes were not tested by the manufacturer with respect to the straightness, smoothness and inner bore tolerances and could be the most serious factors increasing waveguide attenuation. The results of our measurements for various mechanical and chemical processing of inner surface are summarized in Table 3.

Table 2

Material	Bore diameter [mm]	Thermal conductivity [cal/cm × deg]	Theoretical attenuation [cm^{-1}]	Manufacturer (remarks)
Fused quartz	1–3	3.5×10^{-3}	2.35×10^{-4}	Glass-works, Ożarów
Pyrex	1–3	2.9×10^{-3}	1.54×10^{-4}	Sovirel, France
Alumina Al-19	1–3	7×10^{-2}	3.75×10^{-4}	CEMI, Warsaw, Al_2O_3 produced for high temperature thermopiles (shield)
Beryllia BeO	2	0.46	5.6×10^{-6}	Morganite Intern. Ltd. Material in small 30 mm raw pieces

Let us now comment these results. Beryllium oxide, the best material for waveguide CO_2 laser, showed a high attenuation coefficient as compared with the theoretical value. The long BeO tubes were fabricated by means of soldering several small pieces. A slight mismatch was possible and the quality of these short pieces was also very poor (see the first line of Table 3). After an expensive and long-term processing, the propagation losses were almost ten times less, but still about 2%.

The same problems concerned alumina and fused quartz waveguides. The inner bore appeared to be not so well rounded, polished and straight as in pyrex tubes manufactured by Sovirel.

Table 3

Material and geometry of the waveguide	Diameter [mm]	L [mm]	Processing	Measured attenuation [cm^{-1}]
Beryllia	2	30	–	1.2×10^{-2}
,,	2	150	–	1.4×10^{-2}
,,	2.1	150	Polished with corundum powder 302, cleaned and washed	9.3×10^{-3}
,,	2.2	150	Polished with powder 302, washed, polished with ceria, etched	5×10^{-3}
,,	2.3	150	The upper process repeated 5 times	2×10^{-3}
Alumina	2	280	–	2.8×10^{-3}
,,	2.2	280	Polished (302, ceria), etched	1.8×10^{-3}
,,	2.3	280	Polished and etched 5 times	7.2×10^{-4}
Fused quartz	2	150	Straightened in flame, washed	1×10^{-3}
Pyrex	2	150	–	1.3×10^{-3}
,,	2.6	150	–	3.7×10^{-4}

As far as the attenuation is concerned, the best material was pyrex, where losses were within the limit of our measurement errors (0.5%).

Another problem is to minimize the output power by means of the highest possible rate of heat transfer from the discharge. Waveguide CO_2 lasers operate with considerably higher current densities than the conventional CO_2 lasers, while the area of cooled wall enclosing the discharge gas decreases proportionally with the tube radius. The best material is again BeO (Tab. 2), but in our case glass materials are only slightly less effective, chiefly due to very thin walls of the pyrex tubes (0.5 mm) used in the experiments.

The CO_2 waveguide lasers presented here were fabricated from pyrex, 2.6 mm bore capillary tubes.

3. Output power. Experimental study and results

The construction of the laser discharge tube is discussed with reference to Figure 3. Lasers were constructed from 2.6 mm bore capillary pyrex tubes. Waveguide lengths of 200 mm were used. Care was taken to avoid bendings and deformations of the waveguide segment during fabrication. The laser Brewster-angle windows made from zinc selenide. Electrodes consisted of a cylindrical nickel cathode and an anode placed around the axis of the laser to maximize the laser efficiency and to improve discharge stability. The ends of the waveguide served as a shield for electrode material sputtering to the guide. A coolant jacket surrounding the capillary tube was used for the flowing tap water. The construction of electrodes and Brewster windows made it impossible to use flat mirrors placed close to the end of the guide. We employed here the second configuration of optimal waveguide resonator (Sec. 1) by means of two spherical mirrors, $R = 523$ mm, placed approximately 520 mm from the ends of the waveguide. Fortunately, this resonator configuration is useful for other future

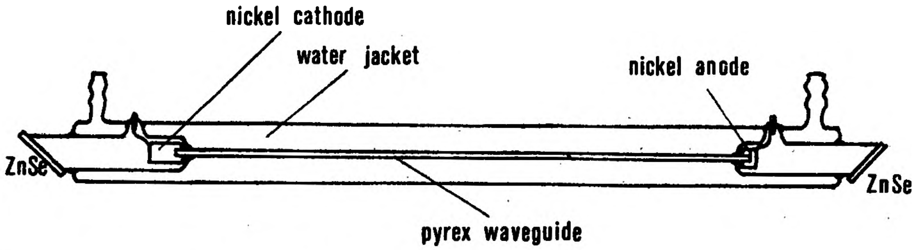

Fig. 3. Waveguide laser tube

experiments on pulse formation and modulation techniques. One mirror was gold-coated for 100% reflectivity, the other being 90% reflecting germanium mirror.

The mirror at the rear (non-output) end of the laser could be mounted on a piezoelectric bimorph bender [8]. This device consists of two 0.25–0.30 mm thick discs of lead zirconate titanate and beryllium copper bonded together and polarized so that, when a voltage is applied, one plate expands radially while the other contracts. This causes the bender to dimple in the centre. This device offers a major advantage over the more generally used crystal stacks because of its greatly increased displacement per volt. With a small (2.5 cm in diameter) disc we can obtain displacement over a full free spectral range of the laser cavity with the application of only 100 V.

For each series of output power measurements, the appropriate high-purity spectral gases were thoroughly mixed and metered into the laser tube. In this manner, power measurements were made as a function of gas mixture and total pressure.

The choice of gas mixture was generally based on our earlier unpublished gain measurements of similar waveguide amplifier tubes. Although the optimum laser gas mixture parameters do not correspond to the optimum gain parameters, due to variations of saturation parameter with mixture, pressure and discharge current, it was possible to obtain qualitative results. The following conclusions summarize these results with respect to various parameters which could be changed.

Xenon aids in the minimization of the laser prime power by reducing slightly the discharge operating voltage, but $CO_2 : Xe$ mixtures containing more than 1/4 of Xe degrade the laser gain. At low discharge current the highest gain is obtained without N_2 but the low prime power is manifested in low output laser power. For discharge currents ranging within 2–8 mA, the addition of N_2 up to about $1 : 1$ ratio of $CO_2 : N_2$ increases the gain. The pressure at which the gain is the highest depends primarily on the He : CO_2 mixture ratio. While decreasing this ratio from 8 : 1 to 1 : 1 the optimum pressure decreases about 100 Tr to 20–30 Tr.

Our output power measurements were made with a chosen variety of gas mixtures and pressures discussed above. It has been found, that the best choice is $CO_2 : N_2 : Xe$ mixture of 4 : 2 : 1. Laser output power vs. discharge current for various He : CO_2 ratios and optimum total pressure is shown in Fig. 4. The best two mixtures are He : CO_2 : N_2 : Xe = 16 : 4 : 2 : 1 and 12 : 4 : 2 : 1, the last one with slightly decreased (2%) laser efficiency.

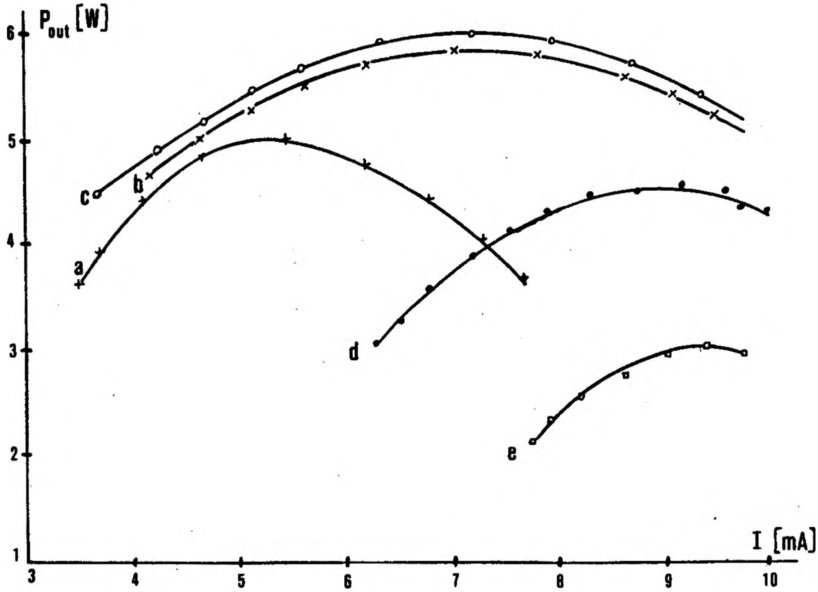

Fig. 4. Output laser power vs. discharge current for various He:CO_2 mixtures and optimum total pressure. $CO_2 : N_2 : Xe$ = 4 : 2 : 1. a — He : CO_2 = 8 : 1, b — 4 : 1, c — 3 : 1, d — 2 : 1, e — 1 : 1

Figure 5 shows the variation of output power with current for total gas pressure within the range of the optimum output, and in Fig. 6 we show the output power at the optimum current measured over the range of pressures between 30 and 100 Tr. These results indicate that the highest output power of 5.8 W was obtained at 60 Tr, with the measured discharge parameters of 6 kV and 8 mA. This corresponds to the extraction efficiency of plasma of 0.29 W/cm and to the electrical to optical energy conversion efficiency of 12%. Taking into account a ballast resistor of 0.5 MΩ, a total efficiency of the device will be about 7%.

The output power per unit length is slightly larger than the value of 0.22 W/cm reported by Abrams [1] and lower than that of 0.41 W/cm reported in [2]. However, these data refer to the studies on BeO waveguide CO_2 lasers and this is much more favourable waveguide material.

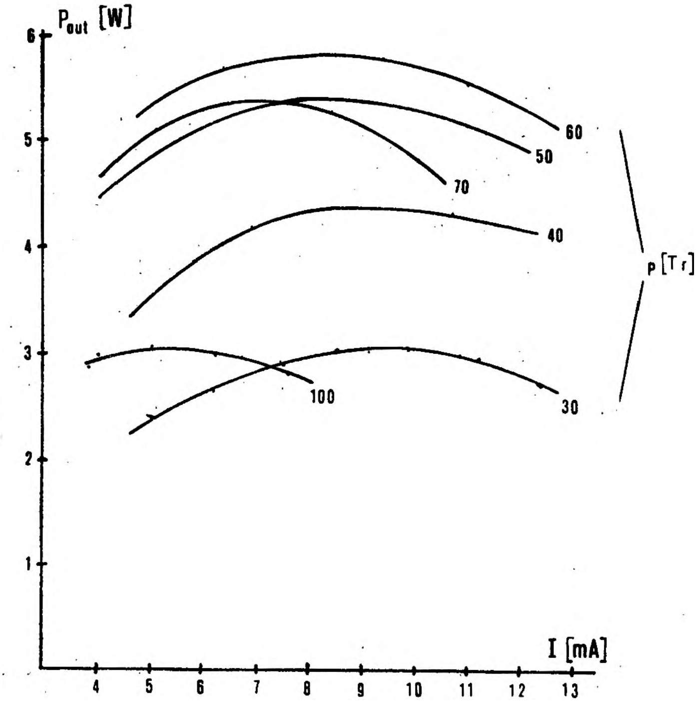

Fig. 5. Output laser power vs. discharge current for various total pressures. Mixture of He : CO_2 : N_2 : Xe = 16 : 4 : 2 : 1

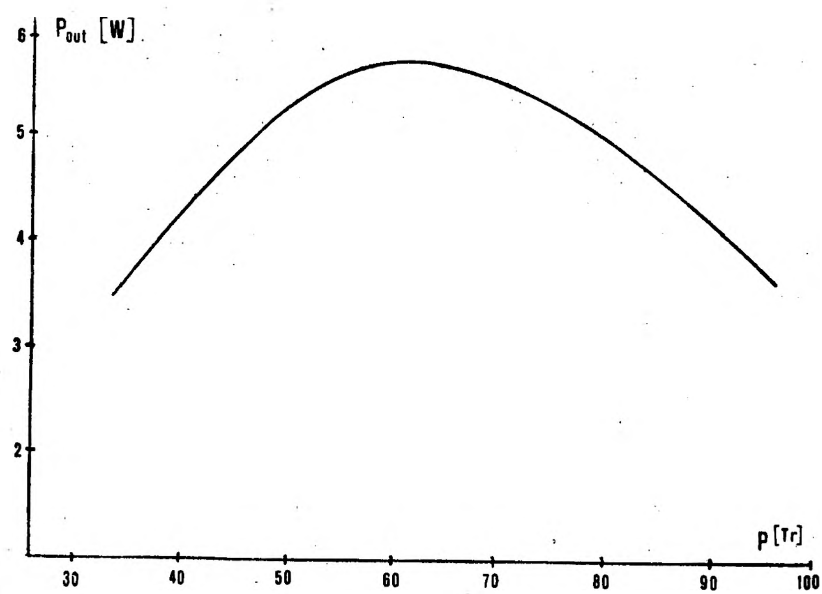

Fig. 6. Output laser power vs. total pressure for optimum discharge current. Mixture of He : CO_2 : N_2 : Xe = 16 : 4 : 2 : 1

4. Sealed-off performance

Long-life operation of conventional sealed-off CO_2 lasers has been reported by several authors [9–12] using different techniques and catalytic processes. In Table 4 the results reported have been summarized by introducing a universal parameter showing the number of hours of sealed-off operation per unit number of CO_2 molecules (h/cm² Tr). We have found this parameter to be very similar to those for similar techniques reported by different authors, even if the gas ballast volumes and CO_2 partial pressures were different.

Table 4

Technique	Normalized parameter [h/cm³Tr]	Typical life-time* [h]
Typical vacuum process, mixture of $CO_2:N_2:He(M)$	0.2	28
The addition of xenon M : Xe	0.5	70
The addition of hydrogen M : Xe : $H_2(H_2O)$	1	140
The addition of xenon and self-heated nickel cathode	1.5	210
The addition of hydrogen and self heated nickel cathode	3	420
Heterogeneous platinum catalyst	10	1400
Oxidized cathode	50	7000

* – gas laser volume of 70 cm³ and CO_2 partial pressure of 2 Tr.

In a simple CO_2 laser, baked and filled with $CO_2:N_2:He$ mixture, the output power decreases rapidly (first line of Table 4). The principal reason is that chemical reactions occurring in the gas discharge lead to an irreversible loss of the carbon dioxide. The dominant loss mechanism is dissociation into carbon monoxide and oxygen caused by collisions of electrons with the gas molecules, and O_2 cleanup in the laser volume.

The operating life-time of the sealed-off CO_2 laser can be prolonged in many ways, not only be means of special catalytic techniques. The typical method ("trick") is to employ a gas ballast reservoir, a slightly elevated CO_2 partial pressure and decreased discharge current. The two last modifications can lead to a slightly decreased laser output power.

We have employed several techniques (presented in Table 4) to the waveguide CO_2 laser, presented in the preceding Section. Since it is much faster to study the sealed-off laser behaviours in small gas volumes and since small dimensions are typical of the waveguide laser, the total gas volumes were about 3 cm³, including active region and the volumes between the end of the waveguide and Brewster windows. The CO_2 partial pressure was about 10 Tr and the mixture contained $He : CO_2 : N_2 : Xe : H_2$.

The tubes were processed in a system capable of high vacuum and extensively degassed with heat. Research-grade gases from Norsk-Hydro were used in all tests. The gas pressures were measured with an oil manometer (± 0.2 Tr). The results of the measurements are presented in Table 5.

Table 5

Technique	Normalized parameter (Table 4)	Predicted life-time*	Measured parameter	Life-time
	[h/cm³Tr]	[h]	[h/cm³Tr]	[h]
Typical vacuum process, mixture M of $He : CO_2 : N_2$	0.2	6	0.5	15
$M : Xe$	0.5	15	1	30
$M : Xe : H_2$	1	30	1.3	40
Mixture of $M : Xe$ and self-heated nickel cathode	1.5	60**	1.55	62
Mixture of $M : Xe : H_2$ and self-heated nickel cathode	3	120**	2	80

* – gas laser volume of 3 cm³, CO_2 partial pressure of 10 Tr.
** – gas laser volume of 4 cm³, CO_2 partial pressure of 10 Tr.

The first test can be referred to the first line of Table 4. The laser was evacuated up to about 10^{-7} Tr and filled with the mixture of $He : CO_2 : N_2 = 8 : 2 : 1$. The gases being mixed for a sufficiently long time the laser was sealed-off. After a careful adjustment in a separate arrangement the output power was measured at 2 h time intervals. The operating time of the laser was defined by the 50% drop of output power of its initial value under equilibrium conditions. In the first test the initial output power was about 2 W and the life-time about 15 hours.

Next, xenon was added to gas mixture to form the $He : CO_2 : N_2 : Xe$ mixture of $16 : 4 : 2 : 1$. The output power increased to about 3.5 W and the life-time was 30 hours.

In the third test, which is not shown in Table 5, the laser tube was treated with 10 Tr hydrogen discharge (10 mA, several minutes). After being filled again with the same laser mixtures, it again operated 30 hours and the output power remained the same. The evident mistake was caused by cathode, which being intensively cooled by means of water jacket, could not serve as a hydrogen source.

At this stage of experiments the laser tube was regenerated, filled with the previous mixture, hydrogen gas was added directly to the laser volume. The initial laser output power and the life-time increased to about 4 W and 40 hours, respectively.

To study the self-heated cathode effects our laser tube had to be modified. The cathode was removed from the cooling region and the total gas volume increased to 4 cm^3. These modifications were taken into account in the results shown in Table 5. This new design was first tested with the hydrogen-free mixture and self-heated nickel cathode. The output power was slightly lower than in the previous tests, but the life-time of the laser exceeded 60 hours of operation. After hydrogen preprocessing of the nickel cathode, the laser output power slightly increased and the normalized life-time parameter increased again.

It must be stated that in this paper we present our initial results of operation of sealed-off waveguide CO_2 lasers. The catalytic and filling procedures were only partially optimized being based in general on our earlier studies of sealed-off conventional CO_2 lasers [13]. It can be seen, that better results were achieved for a simple mixture design and the effects of cathode material sputtering and gas cleanup have probably masked the effects of hydrogen and self-heated nickel cathode. These problems as well as other catalytic methods will be the subjects of next publications.

To confirm that the long time sealed-off operation of the waveguide CO_2 laser is possible, we have built a simple waveguide laser tube with a gas ballast volume of 130 cm^3 placed coaxially with water jacket. The overall dimensions of the laser tube with Brewster windows and water connectors are $4 \times 4 \times 25$ cm^3. The preliminary results are shown in Fig. 7.

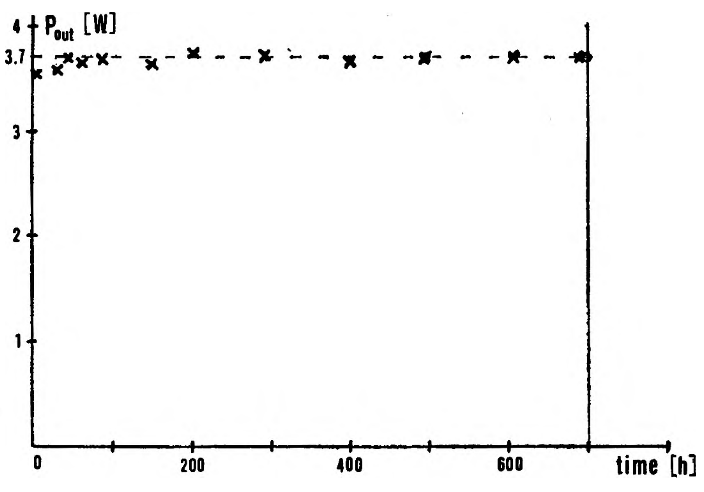

Fig. 7. Sealed-off waveguide CO_2 laser power output vs. time of operation. A gas ballast volume of 130 cm^3, $He : CO_2 : N_2 : Xe = 16 : 4 : 2 : 1$

The laser was filled with the mixture of $He : CO_2 : N_2 : Xe$ of $16 : 4 : 2 : 1$ and sealed-off at a total pressure of 57 Tr. After 700 hours of operation, 8–10 hours a day, there was still no change in the laser output power and discharge characteristics. The laser was destroyed after an accidental water-supply break. Taking into account the absence of hydrogen in the laser tube, the predicted life-time was about 1300 hours, the value acceptable for practical applications.

The output power of 3.7 W, lower than the value of 5.8 W presented in Section 3 was due to a lower quality of ZnSe Brewster windows used. The windows have contributed 3% absorption losses due largely to the repolishing processes. Standard flat mirrors, placed on the ends of the waveguide give the possibility to extract substantially much more power from the laser. A photograph of the sealed-off waveguide laser is shown in Fig. 8.

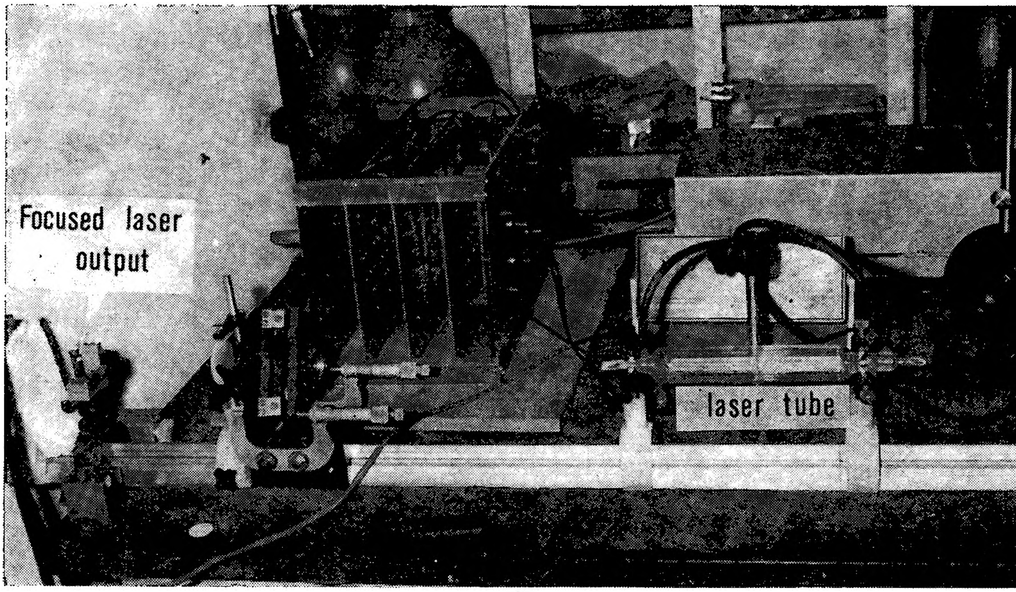

Fig. 8. A photograph of the sealed-off waveguide laser during the life test

5. Output power spectrum and stability

A number of applications require not only compact size of CO_2 lasers but also very good performance in terms of radial intensity distribution and of amplitude-frequency stability of the laser output.

With the spherical resonator geometry used here, the laser resonator mode is effectively coupled into the single mode EH_{11} resulting in fundamental mode in laser output. Higher order waveguide modes have been observed, particularly in lasers with plane-plane resonator geometry and with much shorter waveguides or where high currents were used. In the actual experiments the sealed-off waveguide CO_2 laser is a single-mode laser, even for plane-plane geometry. The experimental measurements of the radial intensity distribution indicate that the spot size is nearly the same as for Gaussian mode launched.

The output spectrum which can be obtained from this laser is typical of cw CO_2 lasers of this general size. Thus for resonator optics which is non-dispersive in the CO_2 laser spectral region, it consists of several lines, particularly in the P

and R branches of the 00⁰–10⁰0 transition. The complete laser signature can be traced out as the cavity optical length is tuned through one complete free spectral range. If the frequency interval between the longitudinal laser modes is smaller than the frequency width of laser gain profile, the ambiguity error may be introduced into the results of these experiments. At the 60 Tr operating pressure used in our laser, the width is collision-broadened with a FWHM of about 300 MHz. The frequency interval between the longitudinal modes is connected with laser resonator length. For the arrangement presented in the Section 3

$$\Delta\nu = \frac{c}{2L_{res}} \simeq 120 \text{ MHz}$$

where $\Delta\nu$ — inter-mode frequency interval,
c — velocity of light,
L_{res} — resonator length.

Fortunately, another shorter resonator configuration could be employed by means of two mirrors ($R = 109$ mm) placed approximately 100 mm from the ends of the waveguide. For this arrangement the intermode interval was about 375 MHz. In spite of quite large coupling losses and the lower quality of mirrors employed the output power obtained could be as high as about 2 W. The cavity length tuning was accomplished by applying a ramp wavefront voltage to the PZT bender at the rear end of the laser. A typical trace of the signature is shown in Fig. 9.

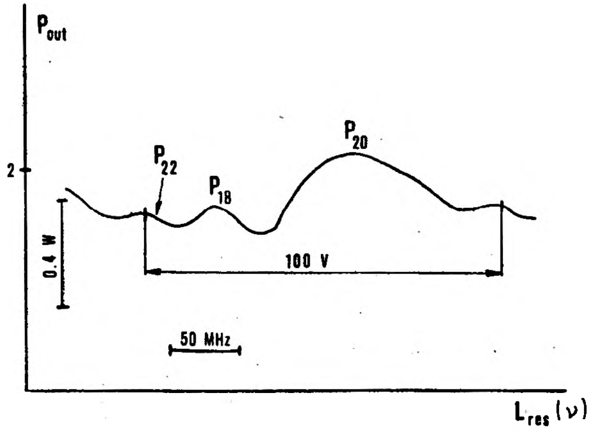

Fig. 9. CO_2 waveguide laser signature. Total resonator length of 40 cm

The full line selection over the free spectral range may be accomplished with a diffraction grating. A typical grating acts as a plane mirror, so it is necessary to place it near the end of the waveguide or to employ a special resonator configuration. To reduce the mode coupling losses for a grating placed far from the end of the guide, we have employed a cavity configuration with the grating placed behind an intracavity lens of focal length of 15 cm, located approximately 15 cm from the end of the waveguide (Fig. 10).

The lens is to collimate the divergent beam from the waveguide onto the grating, and then to refocus the grating reflection back into the waveguide. The spectrum of lines that could be obtained in grating-tuned operation included P_{12} through P_{26} and R_{10} through R_{22} in the 10 μm band and P_{16} through P_{24} at 9 μm. A small output power of 1.2 W observed for P_{20} line at 10.6 μm was

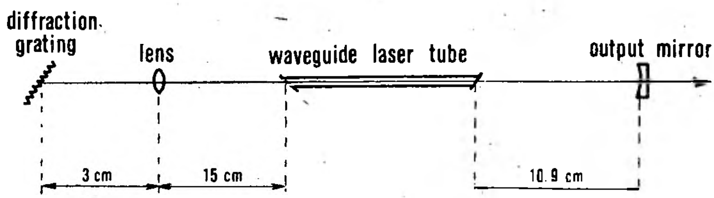

Fig. 10. Waveguide laser resonator configuration for the full line selection

probably due to the increased absorption, misalignment and coupling losses in the laser cavity. The tuning range on each line was limited by cavity losses (FWHM of netto gain of about 100 MHz) rather than by free spectral range of about 330 MHz.

If frequency stability is needed the presented sealed-off waveguide CO_2 laser is not applicable in its actual form, due to the large resonator length and nonrugged construction. However, the actual frequency stability was determined in the arrangement shown in Fig. 11.

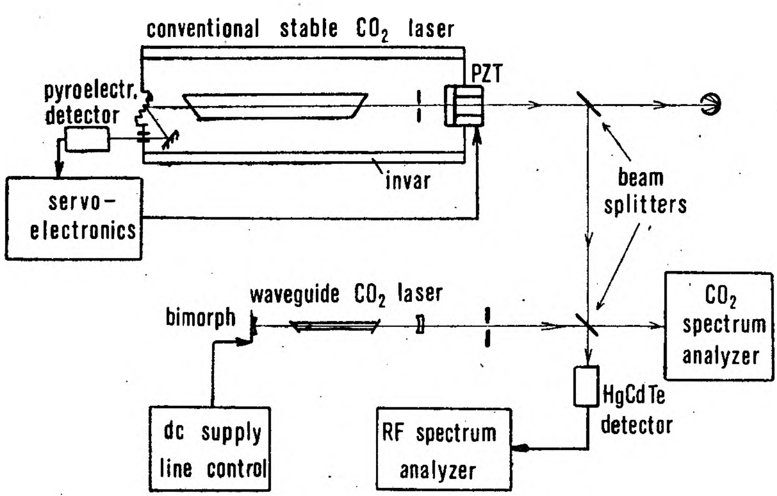

Fig. 11. Frequency stability measurement arrangement

The reference laser was a water cooled, conventional sealed-off CO_2 device. It used external output germanium mirror and diffraction grating with a plasma tube closed off by salt windows oriented at Brewster's angle. The cavity length was held constant by use of four invar spacing rods between the mirror holders. This minimized frequency drifting is due to thermal changes. A variable beam-limiting aperture was placed in front of the spherical output mirror to give the desired fundamental mode. The output mirror was mounted on a piezoelectric transducer to control automatically the length of the laser cavity, thus allowing the control of the laser frequency. An active *dither* stabilization scheme that was applied to this configuration, gave better than 10^8 long term frequency stability. We were able to obtain at least 80 lines in the 00^01–02^00 and 00^01–10^00 bands with the greatest output power of 9 W (P_{20} line).

The PZT disc was applied to control the desired transition in the sealed-off waveguide CO_2 laser. For control purpose, the small fraction of the output power was fed to the CO_2 optical spectrum analyzer and observations were made during the voltage tuning of the waveguide laser.

After a careful alignment, the two laser beams were recombined by an Irtran 2 (ZnS) beam-splitters. The recombined beam was detected with a room-temperature fast HgCdTe photoresistor. The beat frequency was analysed with a Hewlett-Packard 855 spectrum analyzer.

The short time frequency fluctuation, defined as the FWHM of the heterodyne signal, was about 1.25 MHz corresponding to the observation time of 0.7 ms. For the observations of the long term frequency deviations, the spectrum analyzer was operated in the interval trigger mode with storage. That allowed the integration of many traces. For the exposure time of 1 min. the frequency excursion was about 12 MHz. It may be seen that bad environmental conditions, in particular vibrations coupled with long nonrigid resonator, caused poor short-term stability and that there is no correlation between the frequency stability and the time of observation.

We have studied another waveguide CO_2 laser made from fused quartz, with internal flat resonator mirrors based on the quartz cooling jacket (Fig. 12).

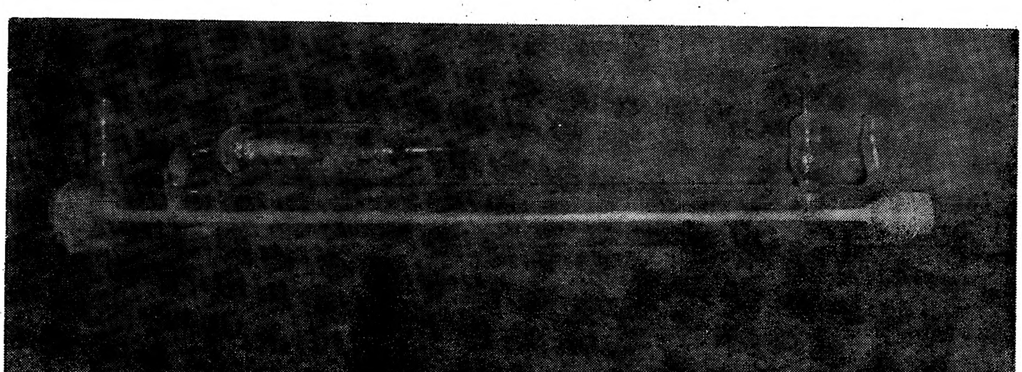

Fig. 12. Fused quartz waveguide CO_2 laser with internal flat resonator mirrors

In the sealed-off conditions the output power achieved was about 0.5 W which was high enough to adjust and heterodyne with the reference laser. In this case, the short-time frequency drift was about 20 kHz for the observation time of 0.7 ms. It implies an absolute short-time stability of 1.4×10^9. The long term stability was 2 MHz for the observation time of 1 min.

The far better results obtained for this laser were due not only to more rigid construction but also to the use of a short resonator of about 25 cm.

The measurements described here have been considered only in a preliminary manner in order to examine some of the design features of the laser and to facilitate the right choice among the different approaches pertaining to more refined constructions and measurements. We hope, that future experiments with improved lasers and experimental set-up will result in better stability characteristics. In particular, sealed-off pyrex waveguide CO_2 laser with a high output power and a stable short resonator design will be studied.

6. Conclusions

We have designed, constructed and operated a sealed-off CO_2 waveguide cw laser which is capable of producing a specific output power of 0.29 W/cm. Such a laser having pyrex waveguide length of 200 mm, operated at 60 Tr pressure and 50 W electrical power, has generated more than 5.5 W of 10 μm radiation.

The laser described here exhibited an excellent mode selectivity and quite acceptable line discrimination with nondispersive resonator optics. The losses of the resonator can be further reduced by using plane mirrors located directly at the ends of the waveguide tube. This would increase laser power output and also decrease the resonator length resulting in a larger tunability. The technology, based on methods similar to those used for the ordinary CO_2, seems to solve the life problems of the longitudinally excited CO_2 waveguide laser. To date, such a laser has operated for 700 hours with constant output power.

Finally, we have presented a waveguide laser design which can be implemented with very modest expenditure and machining effort. After some improvements of sealed-off time of operation, resonator and tube design, it can serve as a very compact and reliable 10 μm source of infrared radiation for many applications, including heterodyne receivers, tunable oscillators for infrared spectroscopy, thermal sources for interferometry, material testing and working, laser studies and optical pumping.

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