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MEASUREMENTS AND ANALYSIS OF CARBON DIOXIDE BORON NITRIDE CHANNEL LASER

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September 1976

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Carbon Dioxide channel waveguide lasers have been constructed using hot pressed Boron Nitride. This smooth, easily machinable ceramic has high thermal conductivity and extremely low thermal expansion. These properties make it highly suitable for constructing compact, efficient, amplitude stable, tunable low power lasers. Results of measurements made are presented and analyzed

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TABLE OF CONTENTS

FIGURES

TABLE

MEASUREMENTS AND ANALYSIS OF CARBON DIOXIDE BORON NITRIDE CHANNEL LASER

1. INTRODUCTION

Optical radar and communications systems often use CO_2 laser transmitters operating near 10 um. For such purposes, as well as for certain laboratory uses, it is desirable that compact, frequency and amplitude stable CO_2 lasers having good beam qualities, high efficiency, and frequency tunability be available.

The continuous wave (CW) waveguide, or channel CO_2 lasers satisfy these criteria so long as one is content with moderate powers. In particular, we will discuss in this report the characteristics of channel lasers constructed from Boron Nitride, BN. This material is a highly machinable, smooth ceramic having high thermal conductivity and extremely low thermal expansivity.

2. BASIC THEORY OF HOMOGENEOUSLY BROADENED CW CO_2 LASERS

The equation found most useful in analyzing the characteristics of the channel CO_2 laser is given by Eq. (1). One recognizes this as the Rigrod[1] equation for a homogeneously broadened laser where Eq. (1) has been modified under the assumption that the round trip cavity losses t + L, transmission plus passive losses, are less than 20%.

$$P_{OUT} = \frac{t}{t + L} I_s A_B g_o l \left(1 - \frac{t + L}{2 g_o l}\right) \qquad (1)$$

where P_{OUT} is the laser output power,

l is the active discharge gain length,

g_o is the small signal gain described by

$$g_o = g_o(|\nu - \nu_o|) = \frac{g_o(\nu_o)}{1 + \dfrac{4(\nu - \nu_o)^2}{(\Delta\nu)^2}} \qquad (2)$$

where $|\nu - \nu_o|$ is the absolute frequency deviation from the line center frequency ν_o and $\Delta\nu$ is the Lorentzian or collision broadened linewidth, i.e., the full-width-at-half-maximum (FWHM).

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1. W. W. Rigrod, J. Appl. Phys. 36, 2487 (1965).

The most recent measurement of the broadening coefficients of the CO_2 laser line at 10.59 um has been given by Abrams[2] as follows

$$\Delta\nu = 7.58 \, (X_{CO_2} + 0.73 \, X_{N_2} + 0.6 \, X_{He}) \sqrt{\frac{300}{T}} \cdot P \qquad (3)$$

where T = the gas temperature in ^{o}K,

P = the pressure in Torr

X_i = the fractional component of the i^{th} molecule in the gas mix.

Thus,

$$\Delta\nu = \gamma P \qquad (4)$$

with typical values of γ in the range 4.5 to 5.5 MHz/Torr. The saturation intensity, I_s, is described by

$$I_s = I_s(|\nu - \nu_o|) = I_s(\nu_o) \left[1 + \frac{4(\nu - \nu_o)^2}{(\Delta\nu)^2} \right] \qquad (5)$$

and A_B is the effective area of the beam, πr_o^2, of the laser in the cavity. Inserting Eqs. (2) and (5) into (1) gives

$$P_{OUT} = \frac{t}{t + L} A_B I_s(\nu_o) g_o(\nu_o) l \left[1 - \frac{t + L}{2} \frac{1 + \frac{4(\nu - \nu_o)^2}{(\Delta\nu)^2}}{g_o(\nu_o) l} \right] \qquad (6)$$

The maximum power is extracted for an optimum transmissivity t_o which is given by

$$t_o = \sqrt{(2g_o(\nu_o)l)L} - L \, . \qquad (7)$$

From Eq. (6) one can compute the total frequency excursion, $2|\nu_n - \nu_o|$, in which the power drops by 3 dB. This is given by

$$2|\nu_n - \nu_o| = \frac{\gamma P}{\sqrt{2}} \sqrt{\frac{2g_o(\nu_o)l}{t + L} - 1} \, . \qquad (8)$$

---

2. R. L. Abrams, Appl. Phys. Lett., 25 609 (1974).

Since one often desires adequate amplitude stability as well, it is useful to compute the total frequency excursion over which the power varies by ± 10%

$$2|\nu_{1/10} - \nu_o| = \frac{\gamma P}{\sqrt{10}} \sqrt{\frac{2g_o(\nu_o)l}{t + L} - 1} \ . \tag{9}$$

Using the value for optimum transmissivity, Eq. (7), in Eq. (9) one can write

$$2|\nu_{1/10} - \nu_o| = \frac{\gamma P}{\sqrt{10}} \sqrt{\sqrt{\frac{2g_o(\nu_o)l}{L}} - 1} \ . \tag{10}$$

The above equation makes explicit how the passive cavity losses affect the tunability of the laser. Thus, to obtain the maximum tunability as well as the maximum power from the laser, one must minimize passive losses.

Consideration of the term $\Delta\nu(=\gamma P)$ reveals that, for a given mixture ratio, the linewidth is inversely dependent on the square root of the temperature, i.e., from Eq. (3) $\Delta\nu \propto \sqrt{\frac{1}{T}}$. Additionally, it is well known that the small signal gain, $g_o(\nu_o)$ increases as the gas temperature decreases due to reduction in the population of the (01′0 level). Thus, a lower gas temperature not only increases the laser power and efficiency but also increases its frequency tunability and amplitude stability.

Consequently, the ability to reduce the gas temperature to the lowest practical value is an important consideration and explains why glass tubes are inadequate and high thermal conductivity ceramics are required. Furthermore, the choice of ceramic must also be guided by the previously stated requirement of low cavity losses.

Before proceeding with the details of the construction and measurement characteristics of the CO_2 channel laser, we will give some typical values of frequency tunability. The values chosen are based on measurements and calculations suitable to the laser under consideration.

l = 25 cm; t = 8.2%; L = 3.5%

$g_o(\nu_o)$ = 0.009/cm; P = 135 Torr

$\gamma(T)$ = 4.32 MHz/Torr at T = 400°K.

Thus, γP = 583 MHz and $2|\nu_n - \nu_o|$ = 715 MHz;

$2|\nu_{1/10} - \nu_o|$ = 320 MHz; P_{OUT} = 7.3 Watts.

A comment on the assumed gas temperature is in order. The value chosen, 400°K, is rather arbitrarily chosen to describe the average operating laser gas temperature of the wall confined channel discharge whose walls are maintained near 300°K. The analysis of Laderman and Byron[3] indicates that for our gas mixture and input power levels there is an approximate 300°K rise between the wall and centerline gas temperature. This implies a larger gas temperature than we have assumed. On the other hand, it is well known[4] that at 400°K the J = 19 rotational level of the upper laser vibrational level has the maximum population. This implies preferential operation of the laser on the P(20), 10.59 um transition of the 10.4 um band. Experimentally, it has been determined that this line dominates in the BN channel laser especially at pressures above 110 Torr. A more recent calculation by Cohen[5] for waveguide lasers indicates that for excitation rates, pressures and mixture ratios comparable to those used for the BN channel laser the gas temperature is between 350 and 400°K.

3. CONSTRUCTION OF CHANNEL LASER, MECHANICAL AND THERMAL STABILITY

As discussed in Section 2 an efficient, tunable high pressure waveguide CO_2 laser operates best when one minimizes the passive cavity losses and reduces the gas temperature to the lowest practical value. This latter requirement indicates that one should consider fabricating the laser from high thermal conductivity dielectric ceramics. There are three primary candidates readily available: Beryllium oxide (BeO), Alumina (Al_2O_3) and Boron Nitride (BN). Of these three, BeO has the highest thermal conductivity and Al_2O_3 the lowest although all are much higher than quartz or pyrex. BeO has fabrication difficulties associated with the toxicity of its airborne fine powder and Al_2O_3 is a very hard material requiring diamond wheels and bits for accurate machining. BN on the other hand can be very easily and safely machined.

Its surface smoothness is good since the grain sizes used in its fabrication are 1 to 5 um range, smaller than that of the other two ceramics. Thus, the achievable smoothness of the channel is better than that of BeO and Al_2O_3. However, it must be admitted that small bores cannot be easily or routinely achieved in BN since ordinary drill bits quickly bind and freeze. This is not a real drawback since, in addition to a smooth bore

3. A. J. Laderman and S. R. Byron, J. Appl. Phys. 42, 3138 (1971).

4. A. J. DeMaria, Proc of IEEE, 61, 731 (1973).

5. S. C. Cohen, IEEE J. Quant. Electron. QE-12, 237 (1976).

or channel, one desires to maintain a high straightness of the laser guide. Machining a channel in a BN block easily achieves a channel which is straight to 0.001 inch over any reasonable length. The uniformity of the channel width is also excellent and the smoothness appears adequate. Pictures taken with a scanning electron microscope of BeO, Al_2O_3 and BN are consistent with the qualitative discussion given above. Figure 1 shows a picture of the end view of such a square channel in an early laser model while Figure 2 shows the 12-inch long BN laser for which results are reported here. The laser made of hot pressed HBR grade BN from Union Carbide had a transverse thermal conductivity near 0.08 cal/sec/cm/$^oC/cm^2$ and an axial thermal expansivity of $1 \times 10^{-6}/^oC$. More recent lasers, constructed from a different grade of BN, have a higher thermal conductivity ($\approx$ 0.10 cal/sec/cm/$^oC/cm^2$), considerably lower expansivity ($\approx 10^{-7}/^oC$ or less). The end flat mirrors are mounted and aligned in invar O-ring holders with invar screws. The mirrors are mounted 2.5 mm from channel end. This construction not only minimizes diffraction coupling losses but also minimizes mechanically induced laser frequency fluctuations. Alignment of the end mirrors is trivially easy. As seen in Figure 2, the laser is cooled by being clamped in contact with a tap water cooled aluminum block. The dimensions of the laser of Figure 2 are summarized below:

Length of BN Channel	30 cm
Active Discharge Length Two Discharge Sections Excited in Parallel	25 cm
Square Channel - Area	$(1.60\ mm)^2$
Distance Between Mirrors	30.5 cm
Active Discharge Volume	$0.64\ cm^3$
Total Channel Volume	$0.77\ cm^3$

The compact nature of this channel laser can be thought, in principle, to create difficulties in maintaining operation on a single laser vibrational rotational transition. For example, if the operating Fabry-Perot resonance frequency of the laser drifts too far off line center, generally due to thermal length variations, the gain of that particular line can be less than that of another laser line. This can lead to

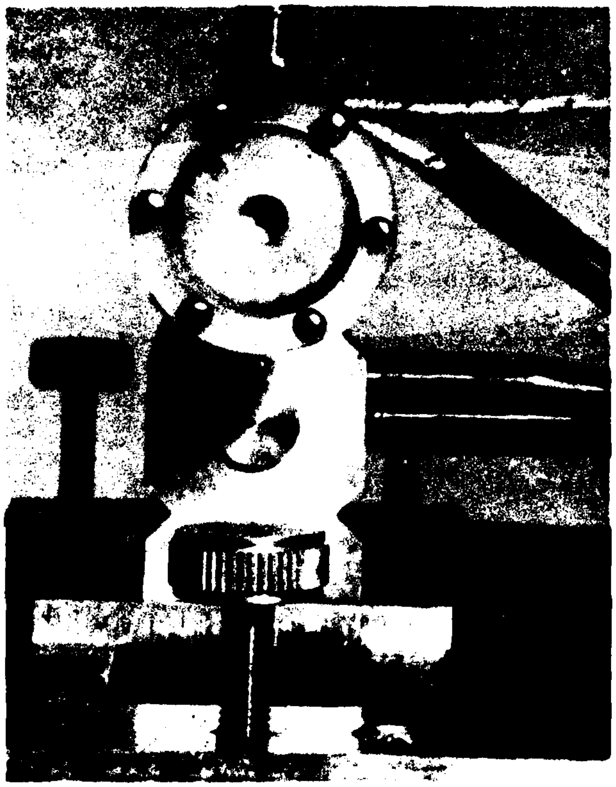

Figure 1. End view of early model of channel laser.

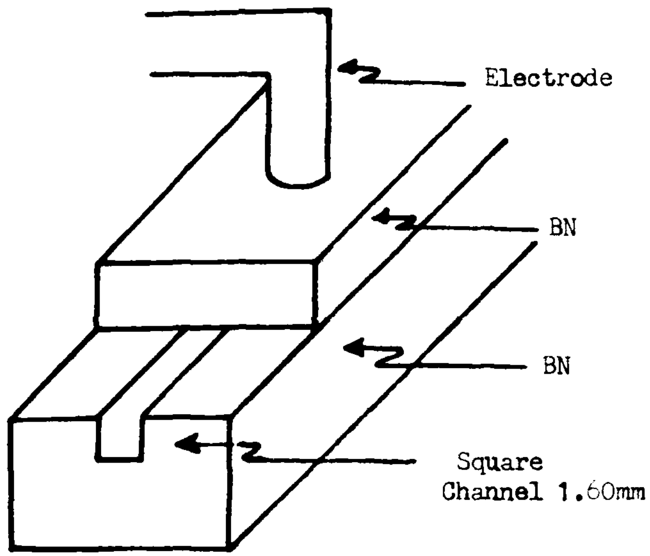

Figure 2. Sketch of BN channel laser indicating construction and photograph of 12-inch long channel laser on Al cooling block.

line hopping and gross amplitude and frequency fluctuations. To prevent this occurrence, long CO_2 lasers have Fabry-Perot resonances so close as to prevent this. However, for reasonable operating pressures in the channel laser constructed this is not possible. For example, considering the typical optimum laser operating conditions given in Section 2, one obtains a value $\Delta\nu$ equal to 583 MHz. From Eq. (2) one notes that a 5% decrease in gain, generally enough to encourage line hopping, results when the total frequency deviation from line center, $(\nu - \nu_0)$, changes by $\pm$ 65 MHz. For completely reliable single line operation a grating can be used. Very efficient (better than 99%), compact three mirror cavities, one mirror being the grating, are possible and practical for CO_2 waveguide lasers[6] but will not be discussed here. It is noted however, that under ordinary laboratory conditions little line hopping occurred in the channel laser under consideration. Typically, at pressures above 120 Torr the laser settled on a single line (generally P(20)) during the period, 4 to 5 hours, over which measurements were conducted. The long term power variation was very small as is understandable from the following discussion of the thermal stability.

To analyze the frequency variations of the laser Fabry-Perot cavity resulting from a length variation δL, note that

$$\frac{\delta\nu}{c/2L_o} = \frac{\delta L}{\lambda/2} \quad . \tag{11}$$

This equation can be obtained from the well known Airy equation of a flat plate Fabry-Perot interferometer. L_o is the overall cavity length, λ is the wavelength, and c is the velocity of light. Rearranging terms and noting that $\nu_o = \lambda/c$ one can write

$$\frac{\delta L}{L_o} = \frac{\delta\nu}{\nu_o} \quad . \tag{12}$$

The thermal expansion of the cavity is given by $L = L_o\ (1 + \alpha\Delta T)$, where α, the thermal expansion of the BN and invar end pieces is $1 \times 10^{-6}/^oC$. Thus $\delta L/L_o = 10^{-6}/^oC$ and for $\lambda = 10$ um where $\nu_o = 3 \times 10^{13}$ Hz one finds

$$\delta\nu = 30\ \text{MHz}/^oC.$$

The improved grade of BN currently in use reduces this value by about 10. Of course, in a full analysis one must also consider the thermal expansion of the mirrors. This effect is small and can be further reduced by using ZnSe or other lower absorbing mirror materials in place of Ge.

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6. These have been used successfully over a period of time by scientists at United Technology Research Laboratories, e.g., see R.J. Freiberg, C.J. Buczek, M.L. Skolnik, P.P. Chenausky and A.R. Clobes, "High Power CO_2 Laser Devices," ECOM R&D TR 0124-F, November 1973.

It is noted that the use of BeO or Al_2O_3 would give a thermally induced frequency variation 5 to 7 times larger than the value given above. This would be associated with a correspondingly larger power variation as discussed in Section 2. More serious is the fact that a modest temperature change, say $\pm 0.4^{\circ}C$, could shift the cavity resonance frequency sufficiently to cause line hopping.

The significant point here is that, given a stable power supply, a BN channel waveguide laser will operate on a single line without need of external piezoelectric transducer (PZT) or grating control with very small thermal and mechanically induced frequency variations.

4. MEASUREMENTS

a. Gain

A single premixed gas was used throughout these measurements with a $He:CO_2:N_2$ composition in the ratio 80:12:8. The current was fixed at 4 mA for the gain and power measurements. However, at pressures below 110 Torr equal or higher gains and higher efficiencies are obtained with discharge currents below 3.5 mA. The measured gain of the P(20), 10.59 um line as a function of pressure is given in Figure 3. Since the laser was not vacuum tight, a slow flow had to be maintained. However, this flow was so slow that it is expected to have minimal effect on the measurements reported here. The only significant effect of the flow is to reduce buildup of discharge impurities, although well constructed sealed off CO_2 lasers can also reduce these effects. Thus, it is believed that these measurements accurately reflect the situation to be expected in sealed off lasers. The results of Figure 3 are consistent with the published results of a sealed off CO_2 laser gain tube reported by Abrams and Bridges.[7] That is, for nearly comparable mixtures, quantitatively similar gains were obtained.

b. Output Power, Efficiency, Polarization

Experimentally, it was determined that the laser whose dimensions were listed in Section 3 had a near optimum mirror transmissivity of 8.2% for pressures between 110 and 150 Torr. The flat Ge mirrors used were dielectrically coated with the front mirror having a transmissivity of 8% and the highly reflective rear mirror, $R \approx 99.5\%$, was experimentally estimated to have a transmission near 0.2%. Figure 4 shows the output power emerging from the front mirror as a function of gas pressure. Also included is the calculated electrical efficiency. Inclusion of the power exiting from the rear mirror would increase the peak power to 7.3 Watts and increase the peak efficiency to 8.8%.

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7. R. L. Abrams and W. B. Bridges, IEEE J. Quant. Electron. QE-9, 940 (1973).

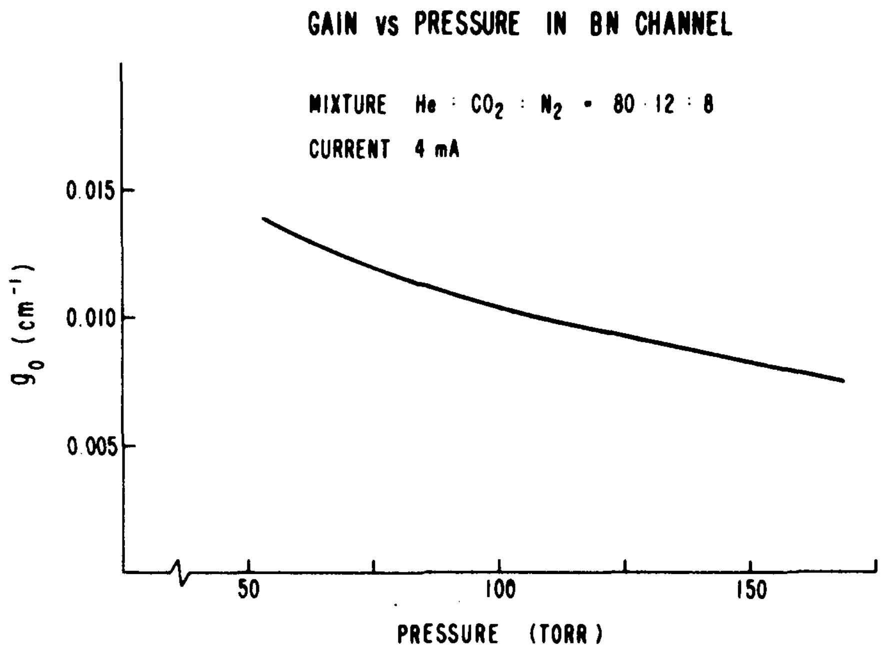

Figure 3. Gain versus pressure in BN channel laser.

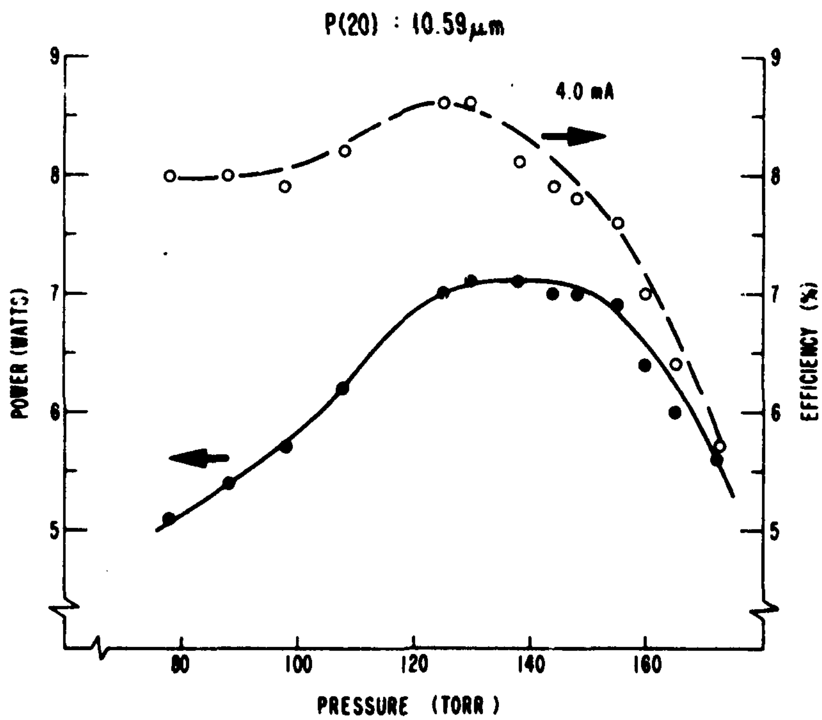

Figure 4. Output power and electrical efficiency of BN channel laser having 25 cm active discharge length. Current was maintained at 4 mA.

Higher powers, to 7.8 watts, were achieved at pressures of 130-140 Torr when higher excitation currents of 4.4 mA were used. However, due to increased gas heating the efficiency decreased to 8.3%.

Both higher powers and electrical efficiencies, 8.9 watts at 10%, were achieved when cooling of walls was increased. At pressures below 110 Torr, it was not unusual to obtain electrical efficiencies of 10% on the P(20) 10.59 um line when smaller currents were used. This is attributed to the fact that, at these lower power input levels, the laser ran cooler. In addition, computation of the E/N values of the discharge at 4.0 mA reveals values between 2.25 and 1.50 x 10^{-16} V cm^2 corresponding to pressures between 75 and 175 Torr. From the published results of Nighan and Bennett,[8] these values imply that between 60 and 75% of the electrical discharge energy goes into vibrational excitation of the first 8 vibrational levels of N_2 and the upper laser vibrational level of CO_2, while only about 10 to 15% goes into population of lower CO_2 vibrational levels. Combining these results with the 40% quantum efficiency of the laser transition leads to expectation of efficiencies between 18 and 25%. The fact that these are not achieved is attributed to the thermal population of the lower CO_2 vibrational levels and the small but significant passive cavity losses.

It is instructive to compare the values of power output per unit volume and per unit length obtained in our case with other published results. We use the published data of Abrams and Bridges[7] and Burkhardt, et al,[9] in this comparison. The data of reference 7 refer to a sealed-off, water cooled, BeO capillary tube 18 cm long with a bore diameter of 1.5 mm while the data of Burkhardt, et al., refer to a 1 mm bore BeO capillary tube 10 cm long which was cooled either with tap water or methanol cooled by dry ice. Only the data of Burkhardt, et al, which refer to low gas flow is considered in this comparison

Table 1. Comparison of power per unit length and power per unit volume of BN channel laser with published results.

	BN CHANNEL	ABRAMS AND BRIDGES[7]	BURKHARDT BRIDGES AND SMITH[9] LOW GAS FLOW
P/L	0.31 W/cm 20°C	0.22 W/cm 20°C	0.08 W/cm; 20°C 0.12 W/cm; -60°C
P/V	12.2 W/cm^3 20°C	12.6 W/cm^3 20°C	10 W/cm^3; 20°C 14.5 W/cm^3; -60°C

8. W. L. Nighan and J. H. Bennett, Appl. Phys. Lett., 14, 240, (1969).

9. E. G. Burkhardt, T. J. Bridges and P. W. Smith, Optics Commun. 6, 193 (1972).

Current densities in the BN channel laser were nearly identical to those of Abrams and Bridges in the above table, namely 170 mA/cm^2. The value of P/V for the BN channel was increased to 13.5 W/cm^3 when increased cooling was supplied and P/L was increased to 0.36 W/cm. Thus, at this time, it is obvious that for channel or small bore CO_2 lasers, one can reliably obtain the following characteristics:

$$\frac{P}{V} = 10 \rightarrow 15 \ W/cm^3$$

$$\frac{P}{L} = 0.2 \rightarrow 0.4 \ W/cm$$

Efficiency 7 → 10%.

The improved characteristics, especially the electrical efficiency of the BN channel laser, is attributed to the reduction of diffraction coupling losses by using flat mirrors to terminate the guide ends.

The polarization of the beam exiting the front mirror of the channel laser was determined to be linearly polarized. It is believed that polarization selectivity is due not to the amorphous BN material used, but to the tool marks introduced in machining the channel.

c. <u>Transverse Mode Structure</u>

When the mirrors were properly aligned for the BN channel laser a perfectly circular spot appeared on a thermal image plate. This spot was easily achieved and the mirrors when so aligned gave peak power output as well. To determine the radial intensity distribution, a pyroelectric detector, 0.7 mm square, was scanned across the laser beam in the far-field of the laser. Figure 5 shows a plot of the measured points. The solid line is a computer Gaussian fit to these points. The fit is seen to be excellent. Thus, the laser beam is taken to expand from the guide end as a Gaussian beam having waist radius w_o and a beam radius of w(z) at distance z from the guide end.[10]
Thus,

$$w^2(z) = w_o^2 \left[1 + \left(\frac{\lambda z}{\pi w_o^2} \right)^2 \right] \tag{13}$$

---

10. H. Kogelnik and T. Li, Appl. Optics, 5, 1550 (1966).

The quantitative measurements of Figure 5 allow one to compute w_o. Taking the "effective guide diameter" 2 a to be equal to 1.60 mm, i.e., the channel width one finds that

$$\frac{w_o}{a} = 0.67 \qquad (14)$$

The far field full divergence angle is given by $2\lambda/\pi w_o$ and is equal to 11.6 milliradians.

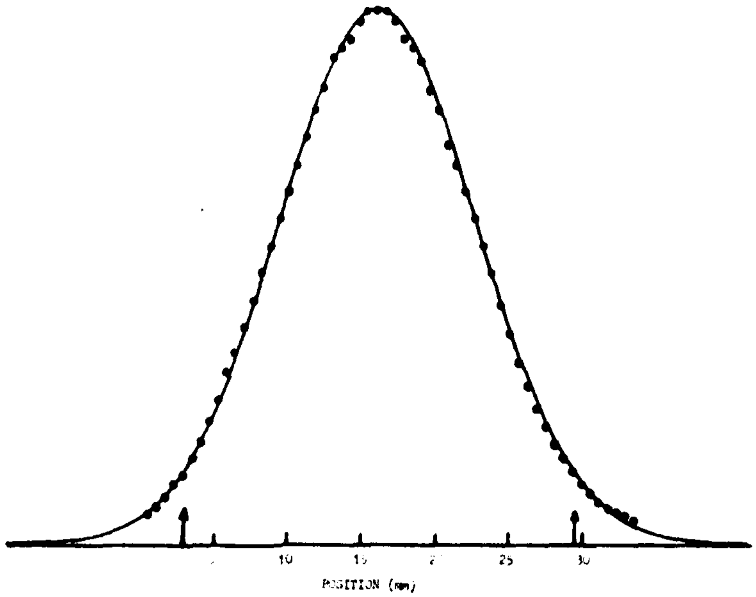

Figure 5. Radial intensity distribution of BN channel laser in far field. Arrows indicate e^{-2} points of the intensity.

A recently published analysis of modes in dielectric waveguides shows that such waveguides support only the hybrid EH_{nm} modes and the EH_{11} is the dominant, i.e., lowest loss, mode.[11] Additionally,[11] this analysis reveals that the beam-waist value, $w_o/a = 0.69$, allows the EH_{11} mode to couple into the free space Gaussian with an efficiency of 98%.

11. K. D. Laakman and W. H. Steier, Appl. Optics, 15, 1334 (1976).

d. Cavity Losses

Experimentally we have determined that at approximately 130 Torr a mirror transmissivity of 8.2% was near optimum for power extraction. Using Eq. (7) and Figure 3 one can estimate the round trip cavity losses to be of the order of 3%. Round trip mirror losses are estimated at 1% (see below) leaving the passive losses of the BN channel to be about 2%. This round trip loss in the 30 cm channel is quite small and certainly comparable to the best attainable values with the other ceramics used.

Round trip mirror losses are estimated as follows: Degnan and Hall[12] give a formula for the diffraction coupling loss of HE_{11} mode at a flat mirror as

$$\text{Fractional Loss} \approx 6.05 \left(\frac{d}{ka^2}\right)^{3/2} \qquad (15)$$

where d is the distance of a flat mirror from the guide end and a is the guide radius. In our case d was 2.5 mm and the equivalent channel radius a is taken to be 0.8 mm, as previously mentioned in section c. The loss at each mirror is then found to be 0.3%. Estimating mirror absorption and scattering loss to be 0.2% per mirror gives a 1% round trip reflection loss.

e. Saturation Intensity

Using Eq. (1) as well as the measured values of g_o, and power from Figures 3 and 4 as well as values of $t = 8.2\%$, $L = 3\%$, one can compute the saturation intensity for a given value of A_B ($A_B = \pi r_o^2$). To be consistent with previously published data,[6] r_o is taken to be the e^{-1} intensity radius of the Gaussian beam, i.e., $r_o = w_o/\sqrt{2}$, which in this case is equal to 0.473 a. In the pressure range of optimum performance (110 to 140 Torr), and 4 mA excitation current, the calculated values of I_s range between 10 and 14 kW/cm^2.

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12. J. J. Degnan and D. R. Hall, IEEE J. Quantum Electron., QE-9, 901 (1973).

5. CONCLUSION

We may note that the analytical work of Cohen[5] predicts gains similar to those measured in the BN channel laser. He also calculates the importance of reducing the wall temperature to improve the gain. This result is consistent with experimental observations. Finally, he calculates the maximum possible tunability of a waveguide laser, at excitation rates similar to those used for the BN laser, as a function of pressure for various cavity losses. It is obvious that the small losses of the BN channel laser, less than 0.005 cm^{-1}, leads to large values of tunability. The use of a higher reflectivity front mirror, as well as more strenuous cooling to increase the gain and $\Delta\nu$, could certainly lead to tunabilities of 1 GHz without greatly decreasing the reported laser powers.

The potential of the CO_2 waveguide laser was apparent at an early stage and considerable effort expended in its development. H. Mocker of Honeywell has successfully built and incorporated sealed off waveguide lasers into a variety of optical systems.[13] His measurements of laser frequency stability, using heterodyning techniques, show excellent short term stability (30 kHz in 0.1 second). His other measurements indicate good sealed off lifetime, excellent transverse mode output and a value of 0.22 W/cm for power per unit length at 8% efficiency.

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13. H. W. Mocker, Final Report for Department of the Navy, May 1975, Contract No. N60530-75-C-0103; Honeywell Document No. F0103-F. Additional literature and private discussions with Dr. Mocker of Honeywell Systems, Minneapolis, Minn., are acknowledged.