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# Introduction

Future space missions may require large amounts of power, which may someday be beamed from a central solar- or nuclear-driven laser to a multitude of receiver spacecraft, each with a relatively simple laser-to-electric converter system providing useful onboard power for electric or propulsive requirements. Such a visionary concept demands that efficient high-power lasers be developed. A system study (ref. 1) which defined some critical system elements has shown that there could be an economic payoff over solar photovoltaic power if solar-pumped lasers can achieve efficiencies (laser output divided by solar energy collected) greater than 1 percent.

One laser concept that may achieve such efficiencies is the blackbody-pumped $CO_2$ transfer laser. Such a system is called a fluid-mixing or transfer gas-dynamic laser and is shown in conceptual form in figure 1. In this system a blackbody cavity is heated by collected sunlight to a temperature of approximately 2000 K. Nitrogen gas passing through the cavity is heated to the blackbody temperature. The vibrationally excited $N_2$ then passes through a nozzle into a low-pressure laser cavity. Here $CO_2$ and He are mixed with the vibrationally excited $N_2$. A coincidence between $N_2(\nu = 1)$ and the 00°1 asymmetric longitudinal mode of $CO_2$ allows rapid transfer of the $N_2(\nu = 1)$ vibrational energy into the $CO_2$ 00°1 upper laser level. Lasing commences between the 00°1 and the 10°0 levels at 10.6 $\mu$m. Helium is added to help depopulate the lower laser level and increase diffusion of heat to the cool laser cell walls.

The gases are pumped from the laser cavity through a heat exchanger-radiator to extract excess heat. The gases are then passed through a gas separator where the $N_2$ is separated from the $CO_2$ and He($H_2O$). The $N_2$ is recompressed and then sent to the blackbody cavity while the $CO_2$ and He($H_2O$) are sent back to the mixing nozzles. Methods for separating the gases are discussed in reference 2.

Four laser cavities are shown in figure 1. Laser outputs would be combined and transmission optics would then beam energy to distant receivers for onboard electrical and propulsion requirements.

An advantage of the blackbody laser system is the inherent energy storage capability of the blackbody cavity. This could be an important advantage when sunlight is unavailable during certain orbit periods. The system also uses readily available low-cost lasant materials, which can be recycled. This system does not require any major technology breakthroughs; the major issue is the most economic means of scaling to high powers.

There are two disadvantages of the blackbody system. Probable lasing wavelengths near 10 $\mu$m will result in larger transmission optics than shorter wavelength laser systems. Also, because blackbody cavity materials will probably limit temperatures to about 2000 K, the $N_2$-$CO_2$ intrinsic efficiency will be limited to 5 percent; consequently the total system efficiency will be less than 5 percent.

Improvements in system efficiency may be possible if $N_2$ is replaced by CO, which can optically absorb solar radiation to create vibrationally excited CO. Such a system has been evaluated and efficiencies on the order of 10 percent have been predicted (ref. 3). Conversely, the calculations of McInville and Hassan (ref. 4) indicate that the $N_2$-$CO_2$ system should be more efficient than the CO-$CO_2$ system. Further research is in progress to resolve this issue.

The results reported here are an extension of the work of Fein et al. (ref. 5). We have extended their parameter studies to include system complexities and configurations for potential use in space. Parameters such as total pressure, blackbody temperature, laser mirror reflectivity, nozzle characteristics, and laser cell coolant temperature were systematically studied. Finally, the near optimum power for this experimental configuration and intrinsic efficiency were measured. The intrinsic efficiency is defined as the total power absorbed in $N_2$ within the blackbody cavity divided into the measured laser power output.

# Experimental Setup

Figure 2 is a diagram of the experimental setup. Standard purity $N_2$ flowed through a quartz tube within an electrically heated oven (with a heating volume 30 cm long by 2-cm i.d.), which in the present experiment simulates a solar-heated blackbody cavity. The oven temperature and pressure were monitored. The gas velocity was slow enough (226 cm/sec) to allow the $N_2$ temperature to come into equilibrium with the oven temperature. Once outside the oven, the $N_2$ gas and vibrational temperature drop. The lifetime of $N_2(\nu = 1)$ is approximately 50 msec (1000 K, 450 torr $N_2$) (ref. 6); thus within one lifetime the $N_2$ travels 11 cm. The distance from the oven exit to the nozzle throat was varied to observe the effect of $N_2$ vibrational loss. The $N_2$ gas passed through a water-cooled nozzle into the low-pressure laser cell (2.2-cm diameter). At the exit of the nozzle throat the gas temperature rapidly dropped, but the $N_2$ vibrational temperature remained high. $CO_2$ and He were then mixed with the vibrationally excited $N_2$ to cause a transfer of energy from the $N_2(\nu = 1)$ to the $CO_2$ upper laser level. Lasing at 10.6 $\mu$m was then established between the laser cavity mirrors (with radius of curvature of 1 m), which were mounted directly on the laser cell (no windows) with the back cavity mirror having maximum reflectivity and the output mirror

having either 99-, 97.5-, or 95-percent reflectivity. The laser cavity mirror separation was 80 cm and the gain length was approximately 60 cm. The laser cell was water cooled to help prevent excitation of the lower laser level by keeping the $CO_2$ gas as cool as possible. The pressure in the laser cell, monitored near the cell exit, was typically about 10 torr, whereas the pressure in the oven was typically 500 torr.

The laser beam was multimode, filling the output mirror aperture. The beam diameter was approximately 1.5 cm at the output mirror.

## Results

A number of system parameters were varied to study their effect on $CO_2$ laser output. The objective was to determine the critical scaling parameters which will enable higher power operation and efficiencies. The results of the parameter scaling studies are now discussed in detail.

In figure 3, laser output is shown as a function of $CO_2$ and He partial pressures at a fixed $N_2$ partial pressure of 2.4 torr for an oven temperature of 1430 K. Peak lasing occurred in a pressure range around 0.4 torr $CO_2$ and 3 torr He. The optimum laser mixture was approximately $1CO_2/7.5He/6N_2$.

In figure 4, the laser output is shown as a function of the reflectivity of the output laser cavity mirror. The 97.5-percent mirror gave a higher output than either the 99- or 95-percent mirror.

In figure 5, the effect of water temperature in the laser cell cooling jacket on laser output is shown. As the water temperature decreases, the laser output increases. There is a 33-percent decrease in laser output when the cooling water temperature increases from 5° to 40°C. Gas heating, as a consequence of lasing, is an important consideration in the $CO_2$ laser since excitation of the lower laser level can occur at gas temperatures slightly higher than room temperature. Helium helps conduct heat to the cool cavity walls and thus contributes to improved laser output.

The distance from the oven to the nozzle throat was varied and its effect on laser output noted. As shown in figure 6, as the distance increases, laser output decreases. The minimum separation distance possible was approximately 30 mm. As the distance increases, the $N_2(\nu = 1)$ suffers more collisional deactivation with the quartz tube wall and the laser output correspondingly decreases. Such systems should be designed with the oven-to-nozzle distance less than a few centimeters. Laser output decreased at a rate of 0.7 percent per mm of separation. At the exit of the nozzle, the $N_2$ gas is supersonic and thus experiences little deactivation before mixing with injected $CO_2$.

To assess the effect on laser output of different nozzle throat areas, three water-cooled nozzles were constructed having nozzle throat diameters of 1.07, 1.5, and 1.8 mm. The results are shown in figure 7 where the laser output is plotted as a function of $N_2$ oven pressure for each nozzle. The optimum nozzle diameter is 1.5 mm ($1.76$ mm$^2$). If the 1.5-mm nozzle is replaced by the 1.07-mm nozzle at a fixed $N_2$ pressure, for example, 400 torr, the laser output decreases since the $N_2$ partial pressure in the laser cell is now below the optimum of 4 torr. In figure 8, the laser cavity $N_2$ pressure is plotted as a function of oven pressure for each nozzle. To achieve optimum lasing conditions, the oven pressure must be increased to approximately 650 torr so that the laser cell $N_2$ partial pressure is again at the optimum of 4 torr. The laser output (fig. 7) of the 1.07-mm nozzle at 650 torr is less than that of the 1.5-mm nozzle at 400 torr, probably because of the increased collisional deactivation of $N_2(\nu = 1)$ at the higher pressure. Alternatively, if the 1.5-mm nozzle is replaced by the 1.8-mm nozzle, the laser output again decreases (at a fixed $N_2$ pressure of 400 torr) because the laser cell $N_2$ pressure is now higher than the 4 torr optimum pressure (see fig. 8). To achieve optimum lasing conditions, the oven pressure must now be decreased to approximately 250 torr. The optimum laser output of the 1.8-mm nozzle is less than that of the 1.5-mm nozzle, probably because of the increased $N_2$ velocity in the oven. Increasing the velocity does not allow sufficient time for the $N_2$ temperature to come to equilibrium with the oven temperature resulting in less excitation of the $N_2$ gas.

Probably the most important parameter of any laser system is efficiency. The experimental intrinsic efficiency is defined as the measured laser power output divided by the calculated enthalpy of the $N_2$ at the oven temperature. This efficiency is then compared with the calculated maximum intrinsic efficiency. The maximum intrinsic efficiency is defined as

$$\eta = (QE)(TE) \tag{1}$$

where QE is 0.41, the quantum efficiency of the $CO_2$ laser transition, and TE is the thermal efficiency, or the energy in the vibrational modes of $N_2$ divided by the $N_2$ gas enthalpy. Thus,

$$TE = E_{N_2}(T)/H(T) \tag{2}$$

where

$$E_{N_2}(T) = \frac{\theta R}{\exp(\theta/T) - 1} \tag{3}$$

where $R$ is the specific gas constant, $\theta = 3357$ K, the characteristic vibrational temperature, and $T$ is the $N_2$ gas temperature (ref. 7). The $N_2$ gas enthalpy $H(T)$ is given in J/g-mole by (ref. 8)

$$H(T) = 29.0(T_2 - T_1) + (0.11 \times 10^{-2}(T_2^2 - T_1^2)$$
$$+ (0.19 \times 10^{-5})(T_2^3 - T_1^3)$$
$$- (0.72 \times 10^{-9})(T_2^4 - T_1^4) \tag{4}$$

where $T_2$ and $T_1$ are the final and initial $N_2$ gas temperatures (°C).

Equation (1), the maximum intrinsic efficiency, is plotted in figure 9 as a function of $N_2$ gas oven temperature. As the $N_2$ temperature increases, the maximum efficiency also increases and is a maximum of 2.9 percent at 1500 K. The experimental intrinsic efficiency shown in figure 9 was defined as the measured $CO_2$ laser power divided by the total power absorbed in the $N_2$ gas. The power absorbed in $N_2$ at an oven temperature $T$ is given by

$$P_{N_2} = H(T)(\text{SCCM})/(1.34 \times 10^6) \qquad (5)$$

where $H(T)$ is given in equation (4) and SCCM is the flow gauge reading in standard $cm^3/min$. The experimental intrinsic efficiency also increases with temperature and is approximately a factor of 4 lower than the maximum efficiency at 1500 K. Laser output is also plotted in figure 9 and increases with temperature to 1 watt at 1473 K, the oven limitation. The $N_2$ oven pressure was fixed at 440 torr.

In figure 10, the laser power and intrinsic efficiency are plotted as a function of $N_2$ oven pressure. The experimental intrinsic efficiency is seen to be constant at approximately 0.7 percent. If the coolant temperature is decreased to 5°C, experimental intrinsic efficiency increases to 0.93 percent. Both laser power and energy absorbed in $N_2$ are directly proportional to the $N_2$ oven pressure; thus the efficiency (laser power divided by $N_2$ power absorbed) is constant as shown by the maximum intrinsic efficiency curve.

With the system parameters optimized (laser cell coolant temperature 30° C), laser power increased with pressure to 1.4 watts at 700 torr $N_2$. The maximum oven temperature was 1473 K and flow rate of $1.17 \times 10^{-4}$ kg/sec. Thus specific power was $1.2 \times 10^4$ J/kg. This is about a factor of 2 lower than predicted from a gasdynamic $N_2$-$CO_2$ laser system (ref. 9). Higher laser outputs could be achieved with higher oven temperatures and pressures.

## Conclusions

Blackbody-pumped transfer laser systems, which are relatively simple to construct, will convert broadband solar radiation into narrow-band laser light. Continuous lasing of $N_2$-pumped $CO_2$ at 10.6 $\mu$m has been achieved for periods of hours with simulated solar pumping. The major laser parameters were investigated and optimized for maximum intrinsic efficiency and laser power. An intrinsic efficiency of 0.7 percent (0.93 percent with laser cell coolant at 5°C) was achieved at a laser power output of 1.4 watts. The specific power at 1.4 watts was found to be $1.2 \times 10^4$ J/kg. The maximum intrinsic efficiency was calculated to be 2.9 percent. Further improvements in efficiency can be

achieved by increasing the blackbody temperature, lowering the laser cell gas temperature, and decreasing the collisional losses near the $N_2$ nozzle, but maximum intrinsic efficiencies will be limited to 5 percent for the $N_2$-$CO_2$ transfer laser system. To overcome this efficiency limitation, other systems must be investigated such as the $CO$-$N_2O$ or $CO$-$CO_2$ transfer laser systems. With these systems, intrinsic efficiencies of greater than 10 percent have been predicted.

## Acknowledgment

## References

1. Holloway, Paul F.; and Garrett, L. Bernard: *Comparative Analyses of Space-to-Space Central Power Stations.* NASA TP-1955, 1981.

2. Taussig, R.; Bruzzone, C.; Quimby, D.; Nelson, L.; Christiansen, W.; Neice, S.; Cassady, P.; and Pindroh, A.: *Design Investigation of Solar Powered Lasers for Space Applications.* NASA CR-159554, 1979.

3. Taussig, R.; Bruzzone, C.; Nelson, L.; Quimby, D.; and Christiansen, W.: Solar-Pumped Laser for Space Power Transmission. AIAA Paper 79-1015, June 1979.

4. McInville, R. M.; and Hassan, H. A.: Conversion of Blackbody Radiation Into Laser Energy. AIAA-82-0871, June 1982.

5. Fein, Michael E.; Verdeyen, J. T.; and Cherrington, B. E.: A Thermally Pumped $CO_2$ Laser. *Appl. Phys. Lett.*, vol. 14, no. 11, June 1, 1969, pp. 337–340.

6. Taylor, Raymond L.; and Bitterman, Steven: Survey of Vibrational Relaxation Data for Processes Important in the $CO_2$-$N_2$ Laser System. *Rev. Mod. Phys.*, vol. 41, no. 1, Jan. 1969, pp. 26–47.

7. Anderson, John D., Jr.: *Gasdynamic Lasers: An Introduction.* Academic Press, Inc., 1976.

8. Himmelblau, David M.: *Basic Principles and Calculations in Chemical Engineering,* Fourth ed. Prentice-Hall, Inc., c.1982.

9. Young, W. E.; and Kelch, G. W.: *Closed-Cycle Gas Dynamic Laser Design Investigation.* NASA CR-135130, 1977.
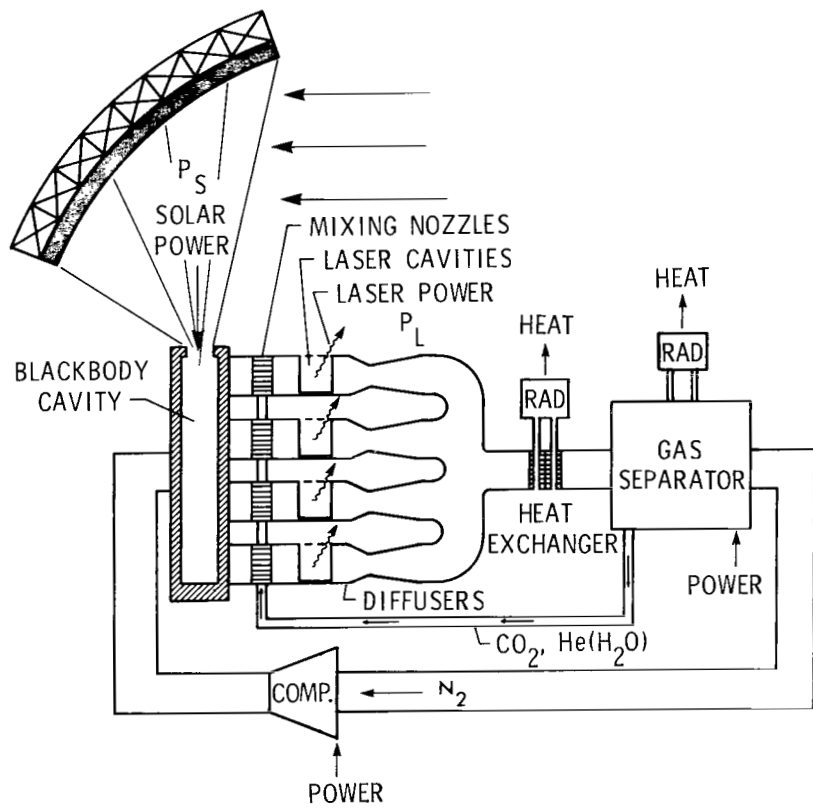
Figure 1. A conceptual design of a space-based blackbody $N_2$-$CO_2$ transfer laser.

Vacuum pumps

$CO_2$ + He Input

Water Jacket

Output Laser
Cavity Mirror

Back Laser
Cavity Mirror

Nozzle (water cooled)

Pressure gauge
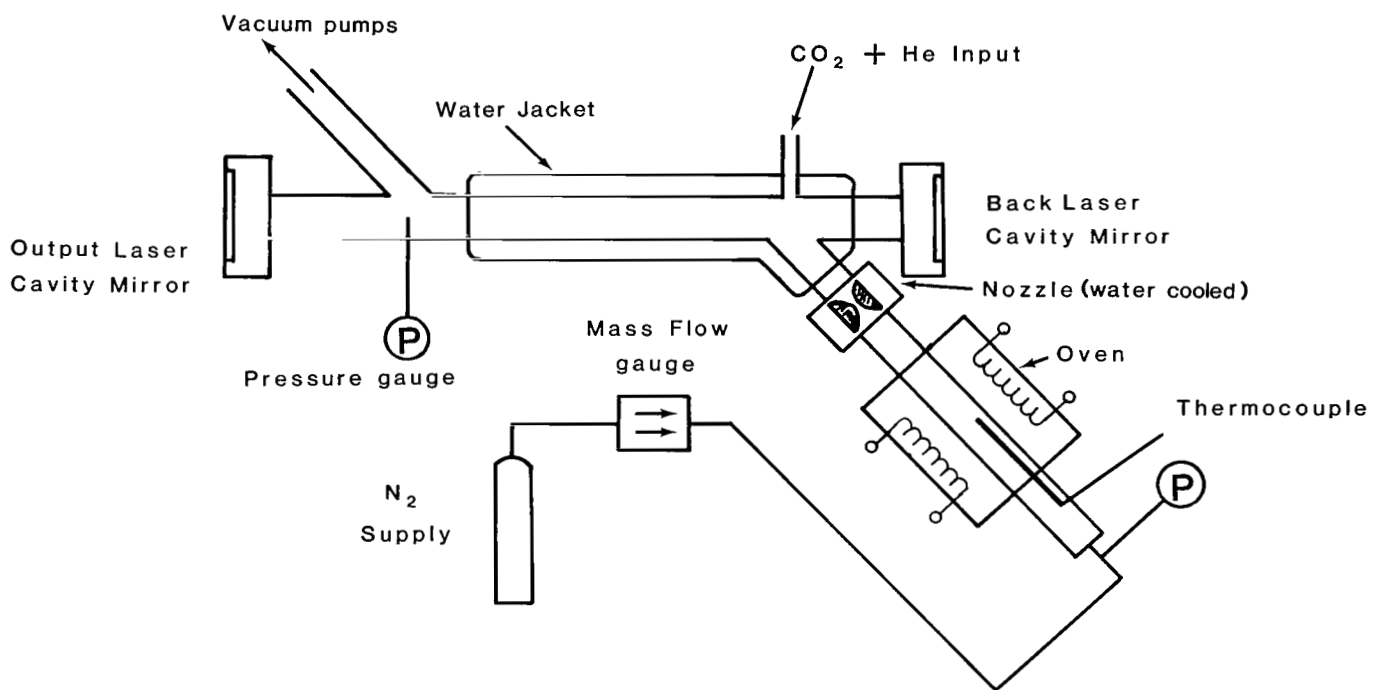
P

Mass Flow
gauge

Oven

Thermocouple

$N_2$
Supply

P

Figure 2. Experimental setup of blackbody-pumped $N_2$-$CO_2$ transfer laser.
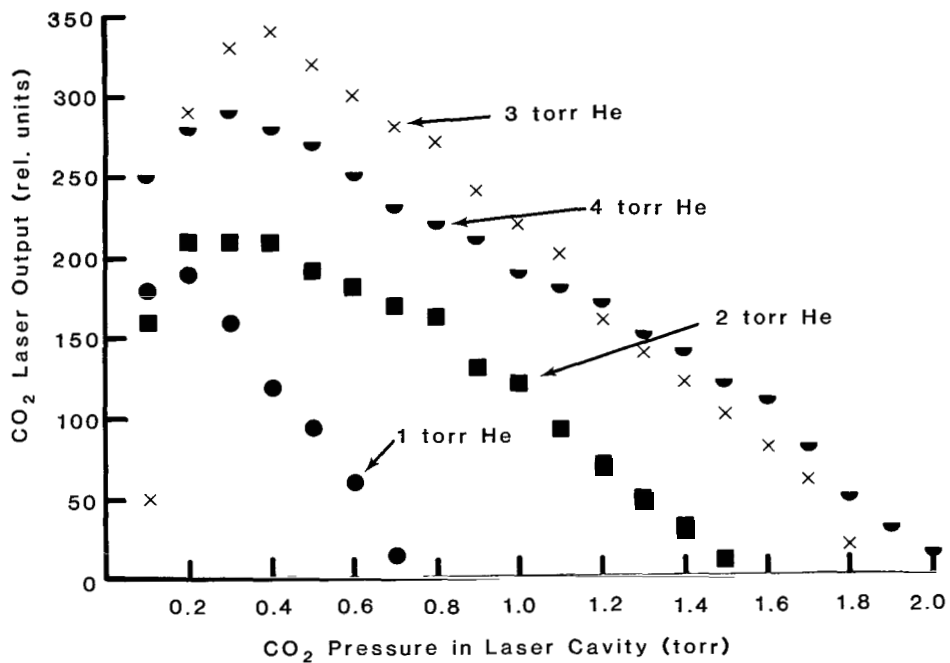
Figure 3. Laser output as a function of $CO_2$ and He partial pressures at a fixed $N_2$ pressure of 2.4 torr. The optimum partial pressure ratio was $1CO_2/7.5He/6N_2$.
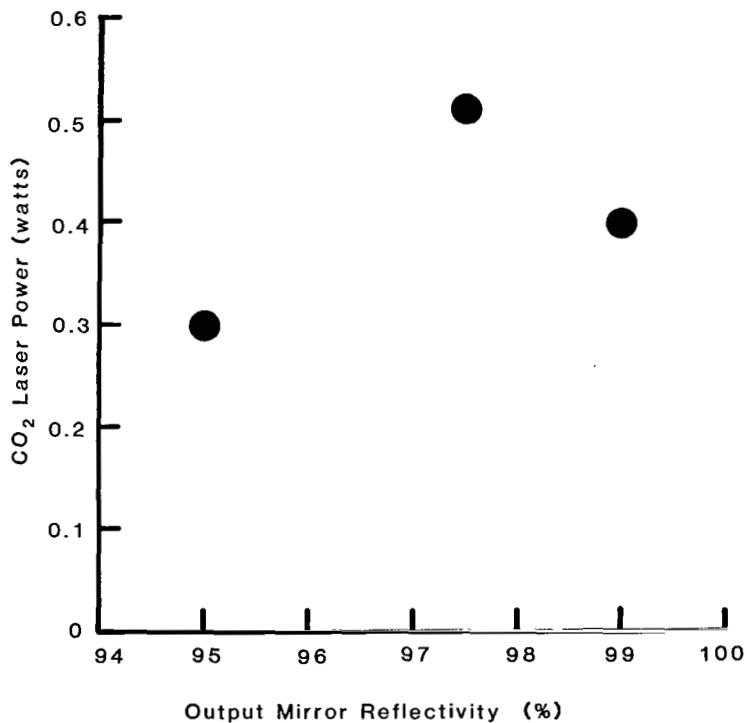


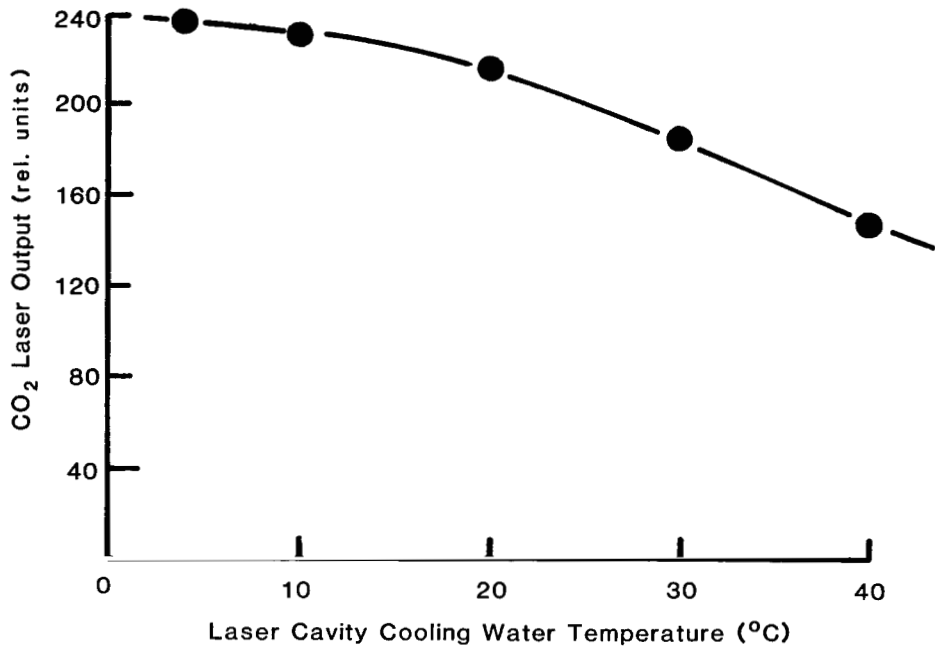Figure 4. Laser output as a function of output cavity mirror reflectivity.

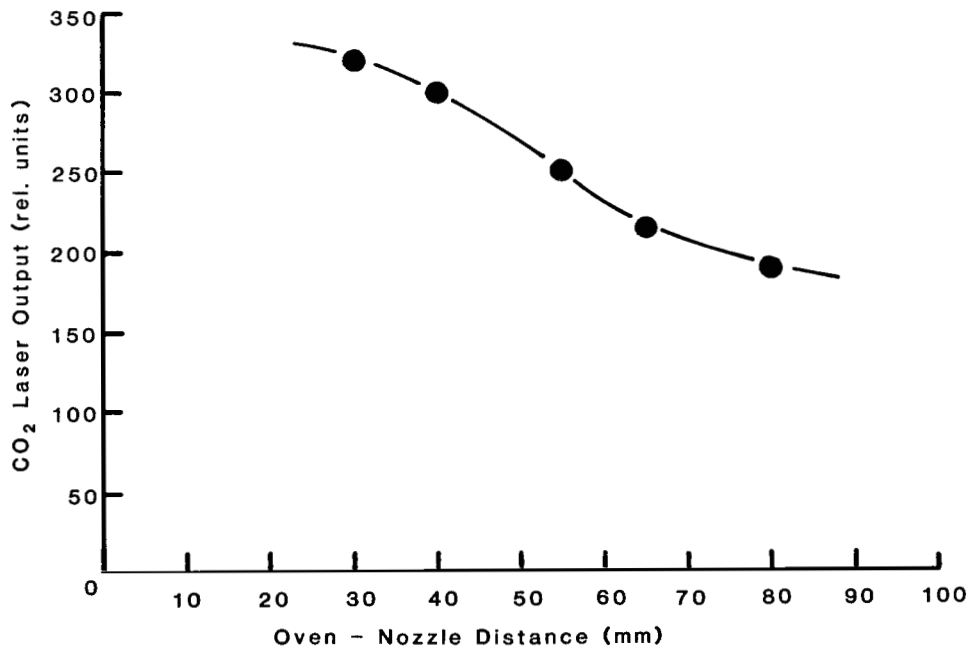Figure 5. Laser output as a function of water temperature in laser cell cooling jacket.



Figure 6. $CO_2$ laser output as a function of oven-to-nozzle distance.
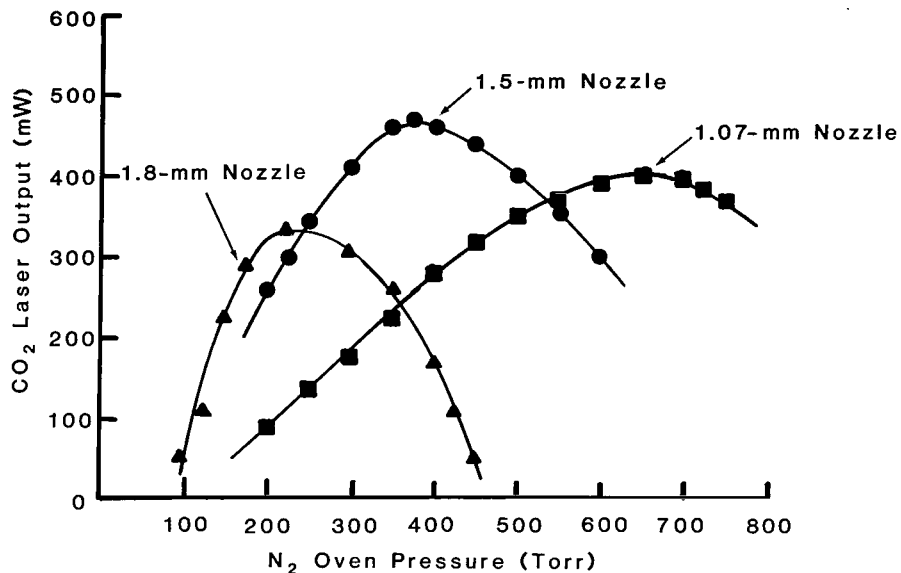
Figure 7. The effect on laser output of various nozzle throat diameters. He pressure was 4.5 torr, $CO_2$ pressure was 0.7 torr, and oven temperature was 1160°C.
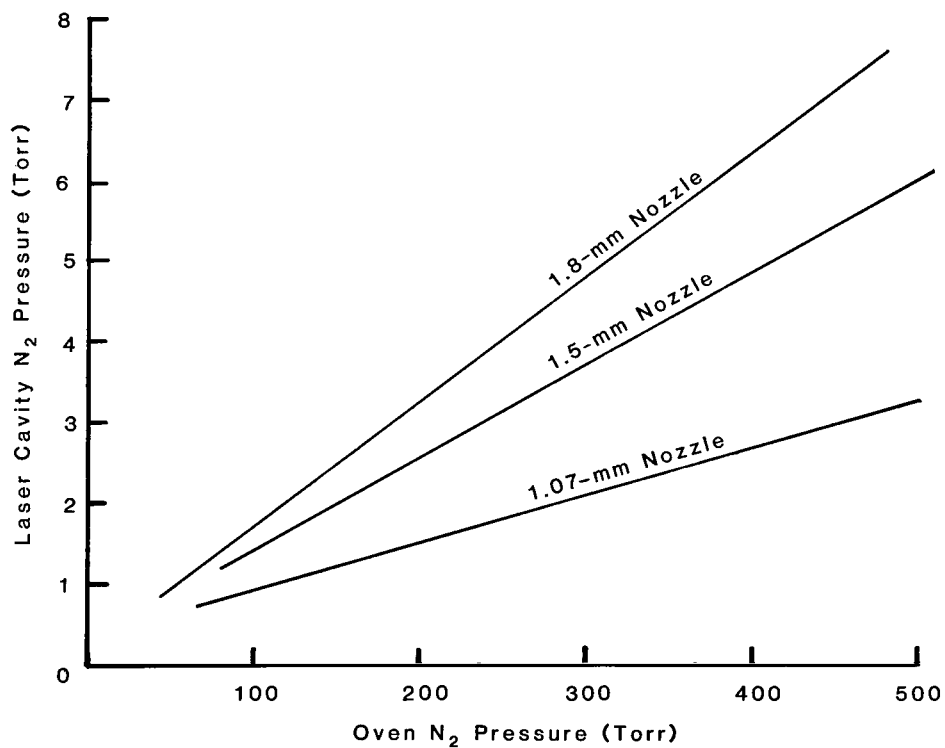


Figure 8. The relationship of $N_2$ pressure in the oven to the pressure in the laser cell for each nozzle diameter at a fixed oven temperature of 1160°C.
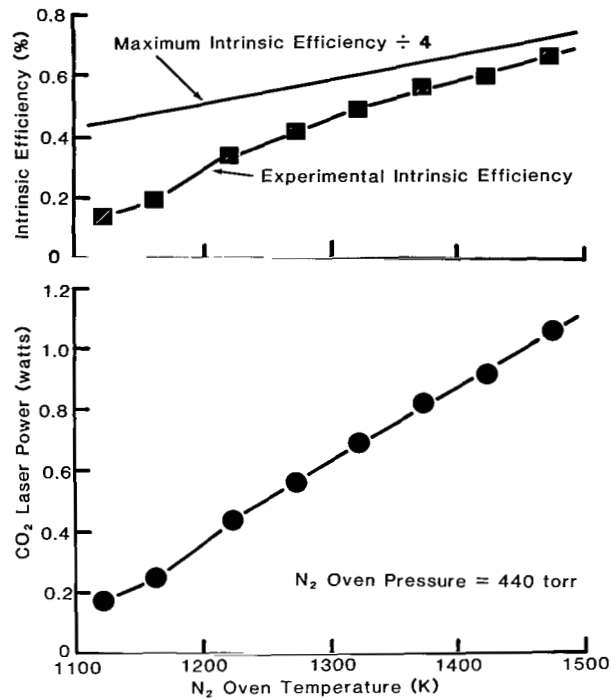
Figure 9. Laser output and experimental intrinsic efficiency as a function of oven temperature for a partial pressure ratio of $1CO_2/7He/5N_2$. The maximum intrinsic efficiency (eq. (1)) is also shown.
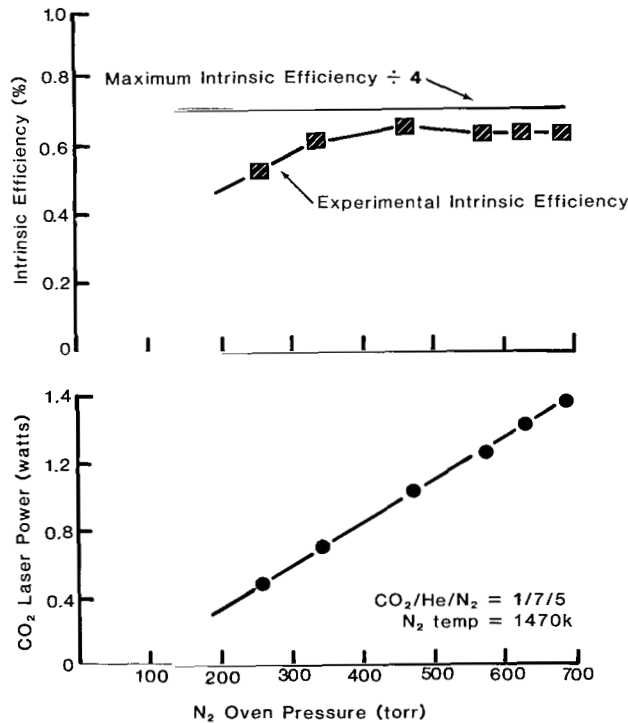


Figure 10. Laser output power and experimental intrinsic efficiency as a function of $N_2$ oven pressure for a fixed oven temperature of 1473 K and a partial pressure ratio of $1CO_2/7He/5N_2$. The maximum intrinsic efficiency (eq. (1)) is also shown.

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15. Supplementary Notes

16. Abstract

A compact blackbody-pumped $CO_2$-$N_2$ transfer laser was constructed and the significant operating parameters were investigated. Lasing was achieved at 10.6 $\mu$m by passing preheated $N_2$ through a 1.5-mm-diameter nozzle to a laser cavity where the $N_2$ was mixed with $CO_2$ and He. An intrinsic efficiency of 0.7 percent was achieved for an oven temperature of 1473 K and $N_2$ oven pressure of 440 torr. The optimum laser cavity consisted of a back mirror with maximum reflectivity and an output mirror with 97.5-percent reflectivity. The optimum gas mixture was $1CO_2/7.5He/6N_2$. The variation of laser output was measured as a function of oven temperature, nozzle diameter, $N_2$ oven pressure, He and $CO_2$ partial pressures, nozzle-to-oven separation, laser cell temperature, and output laser mirror reflectivity. With these parameters optimized, outputs approaching 1.4 watts were achieved.

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