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SCALING BLACKBODY LASER TO HIGH POWERS

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SUMMARY

Lasers pumped by solar-heated blackbody cavities have potential for multimegawatt power beaming in space. There are two basic types of blackbody lasers--cavity pumped and transfer system. The transfer system is judged to be more readily scalable to high power. In this system, either N_2 or CO is heated by the blackbody cavity then transferred into the laser cavity where CO_2 is injected. The N_2-CO_2 system has been demonstrated, but probably has lower efficiency than the CO-CO_2 system. The characteristics of potential transfer laser systems are outlined.

SCALING BLACKBODY LASER TO HIGH POWERS

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Introduction

This technical memorandum will address the potential of scaling the blackbody laser concept to high (>1 MW) laser output powers. Within the blackbody laser concept there are two scenarios. The first is the CO_2 blackbody-pumped cavity laser; the second is the fluid mixing (N_2-CO_2, CO-CO_2, etc.) blackbody-pumped laser. Each system offers unique advantages, depending on the application. The major parameters which relate to scaling, efficiency, and system complexity, are now discussed.

CO_2 Blackbody Pumped Cavity Laser

The CO_2 blackbody cavity laser is pumped by blackbody radiation, from a blackbody cavity, which has been heated by focused sunlight to approximately 2,000 K. Figure 1 shows a schematic of this system. Many tubes, such as KCl, which are transparent to 4.25 μm radiation, are placed within the cavity. These tubes contain CO_2 which absorbs the blackbody radiation within a narrow band ($\sim 4 \times 10^{-4}$ μ) around 4.25 μm, as shown in figure 1. This absorbed radiation excites the (001) upper laser level of CO_2 and in a proper optical cavity the CO_2 will lase at 10.6 μm. Such a system has been experimentally verified, producing laser outputs on the order of 5 mW.[1] A conceptual system study of this particular laser system was done by Mathematical Sciences Northwest (MSNW) in 1979[2]. In their study, they scaled the blackbody cavity laser to 1 megawatt power levels. The scaling of laser power, P_L, in this system is given by

$$P_L = \sigma T_B^4 \, \eta_{exc} \, \eta_L \, NW(2\pi R \ell) \qquad (1)$$

Where σT_B^4 is the power emitted by the blackbody cavity walls, 90W/cm^2 at 2,000 K; η_{exc} is the fraction of σT_B^4 going into CO_2 excitation, 0.0046 at 2,000 K; η_L is the CO_2 laser intrinsic efficiency, 10-20 percent, highly dependent on gas temperature; N is the number of layers of KCl tubes; W is the number of tubes per layer; ℓ is the length of each KCl tube; and R is the laser tube radius. From this equation, we can see the strong dependence of laser power on blackbody temperature, but as the temperature of the blackbody increases, so do the reradiated losses. These losses are due to the solar entrance hole and also the holes needed for the laser cavity optics. Materials constraints and reradiation losses will probably limit temperatures to ~2,000 K. The fraction of the blackbody power absorbed is extremely small because of the narrow absorption linewidth near 4.25 μm in CO_2. Mathematical Sciences Northwest (MSNW) has done calculations for this system, and assuming a net laser power of 1 megawatt, the total KCl tube length was calculated to be 5,400 m. Such large lengths of KCl tubes are needed because of the small optical absorption (W/cm^3). For homogeneous pumping of the CO_2, low pressures are necessary. As an example, at 1650 K blackbody temperature, the absorbed power in a mixture of 12 torr CO_2 and 12 torr of He at 4.25 μm, is 0.33 W/cm^3. If the intrinsic efficiency is 10 percent, the available laser power is then 0.033 W/cm^3, and for 1 megawatt of laser power at total volume of 30 m^3 is necessary. These characteristics would limit or tend to make the laser system very large and thus limit its practicality in terms of high powers. The manufacturing of kilometers of KCl tubes is a formidable and costly industrial process. Because of these and other potentially scaling problems, this system was not recommended by MSNW for high power applications[3]. Although this system does not appear realistically feasible for scaling to multimegawatt power levels it may have potential applications for laser power requirements of 100 watts or less.

Fluid Mixing Blackbody-Pumped Laser

The second blackbody laser concept is the fluid mixing or transfer blackbody pumped laser as shown in figure 2. With this concept, CO,N_2, or potentially some other diatomic molecule, is vibrationally excited within a solar heated blackbody cavity. The vibrationally excited high pressure gas is then transported through a nozzle into a lower pressure laser cavity region, where it is mixed with CO_2 and other selected gases. The vibrationally excited CO or N_2 collisionally transfers energy to the CO_2 or other lasant, which in turn lases at 10.6 μm in an appropriate optical cavity. The gas mixture is then removed from the optical cavity and the constituent gases are separated, the CO or N_2 going back to the blackbody cavity and CO_2 and other gases going to the laser cavity. A gas separation system is needed in this process to separate the gases which will require some input power.

In the transfer laser concept, there are two ways to excite the gas within the blackbody cavity. First, the N_2 or CO gas could be heated so that the gas temperature (also vibrational temperature) comes into equilibrium with the blackbody temperature. Then, we would have a Boltzman vibrational population distribution given by

$$N_\nu = N \exp(-\nu\theta_\nu/T) \; (1-\exp(-\theta_\nu/T)) \qquad (1)$$

where N is the total number of ground state molecules, ν is the fundamental vibrational frequency, θ_ν is the characteristic vibrational temperature ($h\nu/k$), and T is the equilibrium gas temperature. The density of vibrational states depends on the gas pressure and blackbody temperature. Care must be taken to insure that the CO or N_2 gas actually does come into equilibrium with the blackbody temperature; flowing the gas too quickly could result in lower gas temperatures.

Figure 3 is a plot of efficiency as a function of blackbody temperature. Here efficiency is defined as thermal efficiency (energy in the vibrational modes of N_2 divided by the N_2 gas enthalpy) multiplied by the CO_2 quantum efficiency (.41), thus

$$E_{N_2} = [\theta_\nu R(\exp(\theta_\nu/T)-1)^{-1}][.41]/H(T) \quad (2)$$

It is seen that this efficiency peaks around 5 percent for blackbody temperatures of practical interest. Thus, when other system inefficiencies are accounted for, the total system efficiency will be lower, perhaps near 1 percent.

This laser concept has been demonstrated experimentally, producing in a small scale device CW powers greater than 1 watt.[4] A maximum efficiency of 0.9 percent was achieved at a blackbody temperature of 1473 K. This should be compared to the theoretical efficiency of 2.8 percent. The specific power was 1.2 x 10^4 J/kg, about a factor of 2 lower than predicted from a N_2-CO_2 system study.[5]

The other way to excite the transfer gas in a blackbody cavity is by direct absorption of a 4.67 μm photon creating a vibrationally excited CO molecule without raising the gas temperature above room temperature, as shown in figure 2. Here the gas and vibrational temperatures are not in equilibrium; the vibrational temperature being much higher than the gas or translational temperature. This concept can only use hetronuclear molecules which have a strong absorption from the ground to the first vibrational state, such as CO. Such a system would result in an improvement in system efficiency over the N_2-CO_2 system, since energy is absorbed directly into vibration with little or no translational energy of the CO gas.[2] Thus, a major reduction in reflector size and thus system weight could result as compared to the N_2-CO_2 system. The major inefficiencies are the kinetic loss and the blackbody cavity heat loss. The laser intrinsic efficiency now approaches the quantum efficiency.

The scaling of laser power for the fluid mixing $CO-CO_2$ laser is

$$P_L = \eta_L \; V \; E \tag{3}$$

where η_L is the intrinsic efficiency of the CO_2 laser that is the ratio of laser power output to power absorbed in the CO gas, V is the volume of excited CO gas within the blackbody cavity, and E is the power deposited in CO gas per unit volume. The intrinsic efficiency, η_L, would be perhaps 20 percent (reduced from 41 percent by kinetic losses) and E the power absorbed for slab geometry is

$$E = \int_\nu \alpha_\nu \, \Phi_\nu \, d\nu \tag{4}$$

where α_ν is the absorption coefficient, and Φ_ν the total flux is

$$\Phi_\nu \, (E) = 2\pi \, I_{\nu o} \left[E_2(\xi) + E_2 \, (\xi_L - \xi)\right] , \tag{5}$$

where E_2 is the exponential integral of order 2, $I_{\nu o}$ is the incident blackbody flux, and ξ is given by

$$\xi = \int_0^x \alpha_\nu \frac{dx}{\cos\,\theta} , \quad 0 < x < L , \tag{6}$$

where L is the slab thickness. As an example for 760 torr CO with a slab thickness of 3 cm, a blackbody temperature of 2000 K and six CO isotopes, the power absorbed at the edge of the slab is 5.25 W/cm^3 and at the center is 1.36 W/cm^3. The CO gas temperature is 300 K. For a laser power of 1 megawatt the excited CO gas volume would be approximately 1.5 m^3.

The $CO-CO_2$ system may have a specific power of 4.2×10^4 J/kg,[3] for a 1 megawatt space-based laser system. This system has the potential for higher efficiencies and lower radiator weights when compared to the N_2-CO_2 laser system.

Other Blackbody Pumped Lasers

Other blackbody laser systems could potentially be interesting for their higher efficiencies or shorter wavelengths. The CO-N_2O system has a better resonance than the CO-CO_2 system, thus increasing efficiency. The blackbody excited CO could lase directly if supersonically expanded to 150 K. Multiple lasing wavelengths would result from 4 μm to 6 μm. This system requires large compressor power to provide the supersonic expansion at high mass flow rates.

In the CO-C_2H_2 (C_2N_2) system, a close resonance exists between CO(ν = 1) and the upper laser level of C_2H_2, which will lase at 8 μm. This has been demonstrated experimentally by vibrationally exiting CO by laser pumping.[6]

Blackbody absorbing gases other than CO are needed which will have a close resonance with the lasant molecule. Lasing wavelengths less than 10 μm are advantageous for efficient long distance laser power transmission.

Conclusion

In table I are shown some important characteristics of present transfer laser systems. Only the N_2-CO_2 system has been experimentally demonstrated. The lasing wavelengths are all near 10 μm; $\Delta\varepsilon$ is the energy off resonance between the absorbing and lasant gas; η_{max} is the theoretical maximum laser efficiency; η is the experimentally demonstrated laser efficiency--only N_2-CO_2 has been pumped in a blackbody cavity, the other systems were pumped by lasers; $\dot{m}$ is the mass flow rate for a 1 megawatt laser; and K is the transfer rate coefficient of absorbing-gas to lasant gas.

Blackbody transfer lasers appear to be most readily scalable to megawatt power levels. Experiments should focus on the demonstration of high laser efficiencies by using CO as the absorbing gas.

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Table I.- Characteristics of Transfer Systems

	N_2-CO_2	CO-CO_2	CO-N_2O	CO-C_2H_2
λ (μm)	10.6	10.6	10.8	~8
$\Delta\varepsilon$ (cm^{-1})	-19	-206	-81	+69
η_{max}(%)	2.9 (1500 K)	~40	~40	~50
η (%)	0.9 (blackbody)	7.3	5.6	1.5
$\dot{m}$ (kg/sec)	85 expt., 44_{study}	24_{study}	-	-
K ($\frac{1}{sec\ torr}$)	1.9×10^4	2.9×10^3	1.5×10^5	?

BLACKBODY PUMPED CAVITY LASER

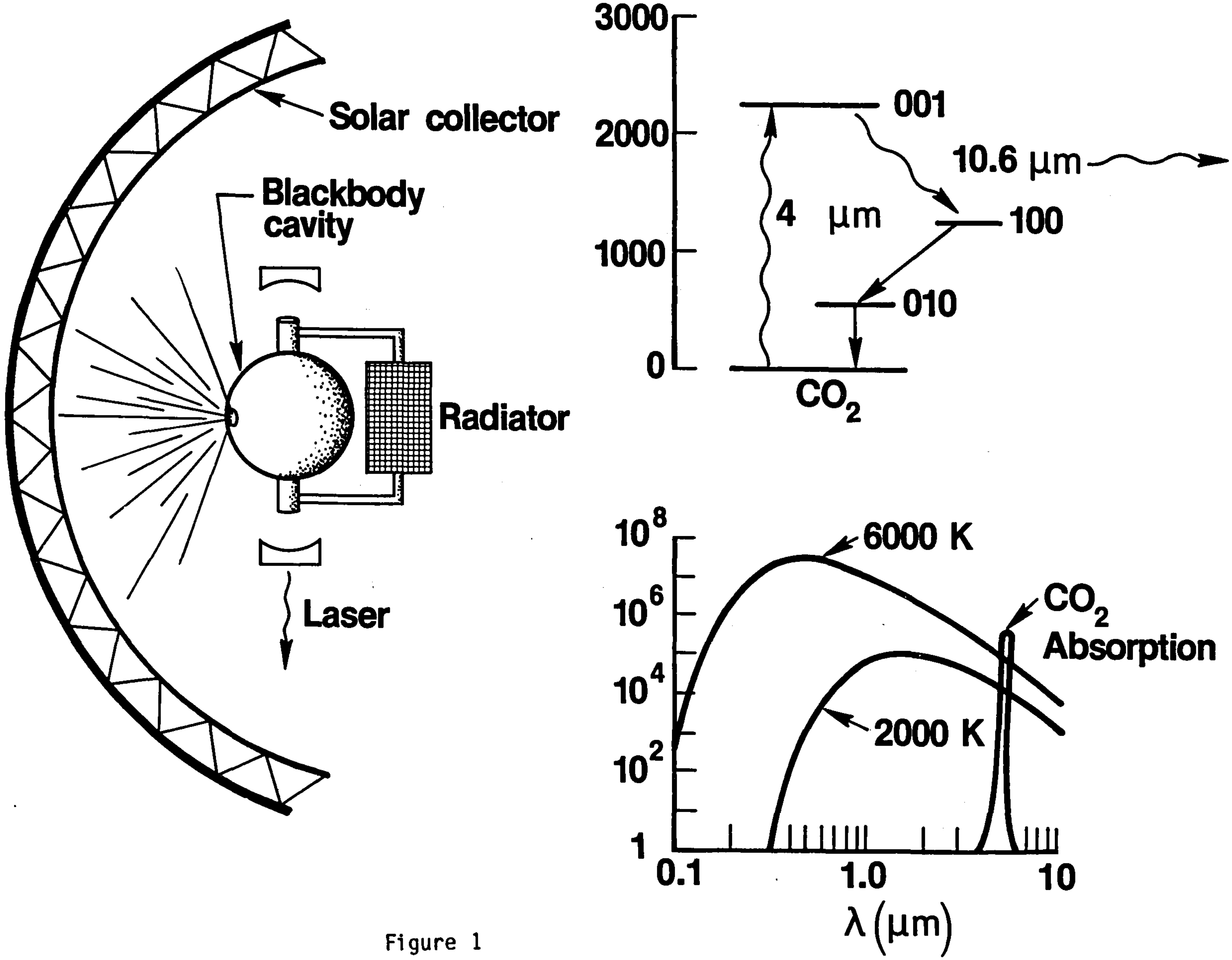

Figure 1

BLACKBODY PUMPED TRANSFER LASER

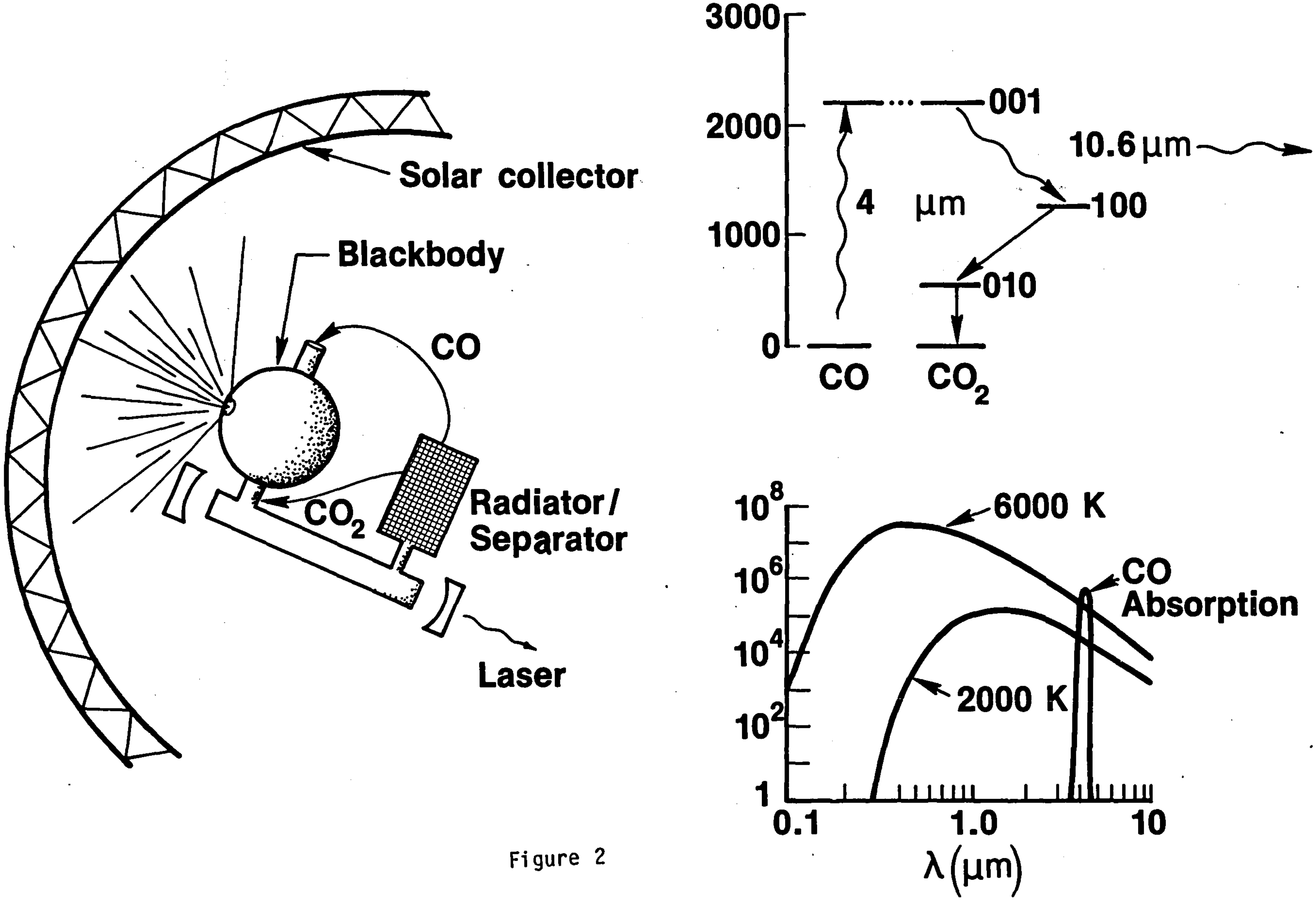

Figure 2

Quantum—Thermal CO_2 Laser Efficiency

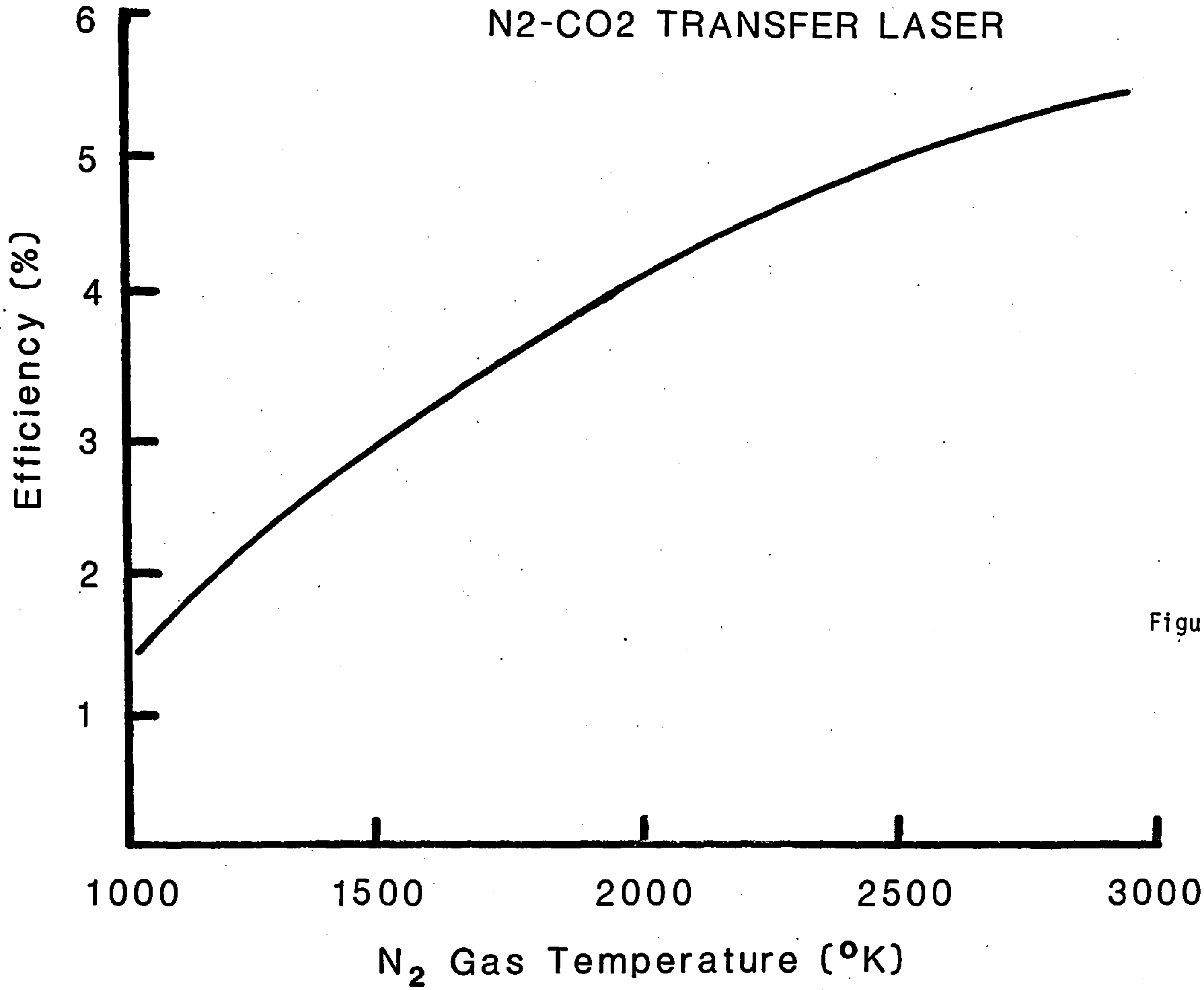

Figure 3

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16. Abstract

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