SCALING BLACKBODY LASER TO HIGH POWERS

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by

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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 \( \text{N}_2 \) or \( \text{CO} \) is heated by the blackbody cavity then transferred into the laser cavity where \( \text{CO}_2 \) is injected. The \( \text{N}_2-\text{CO}_2 \) system has been demonstrated, but probably has lower efficiency than the \( \text{CO}-\text{CO}_2 \) system. The characteristics of potential transfer laser systems are outlined.
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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 CO₂ blackbody-pumped cavity laser; the second is the fluid mixing (N₂-CO₂, CO-CO₂, 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.
CO₂ Blackbody Pumped Cavity Laser

The CO₂ 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 CO₂ which absorbs the blackbody radiation within a narrow band (~4 x 10⁻⁴ μ) around 4.25 μm, as shown in figure 1. This absorbed radiation excites the (001) upper laser level of CO₂ and in a proper optical cavity the CO₂ 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, PL, in this system is given by

\[ P_L = \sigma T_B^4 \eta_{exc} \eta_L N W (2\pi R \ell) \]  

(1)

Where \( \sigma T_B^4 \) is the power emitted by the blackbody cavity walls, 90W/cm² at 2,000 K; \( \eta_{exc} \) is the fraction of \( \sigma T_B^4 \) going into CO₂ excitation, 0.0046 at 2,000 K; \( \eta_L \) is the CO₂ 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; \( \ell \) 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 CO₂. 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/cm³). For homogeneous pumping of the CO₂, low pressures are necessary. As an example, at 1650 K blackbody temperature, the absorbed power in a mixture of 12 torr CO₂ and 12 torr of He at 4.25 μm, is 0.33 W/cm³. If the intrinsic efficiency is 10 percent, the available laser power is then 0.033 W/cm³, and for 1 megawatt of laser power at total volume of 30 m³ 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, CO₂N₂, 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 Boltzmann vibrational population distribution given by

$$N_v = N \exp(-v\theta_v/T) (1-\exp(-\theta_v/T))$$  \hspace{1cm} (1)

where $N$ is the total number of ground state molecules, $v$ is the fundamental vibrational frequency, $\theta_v$ is the characteristic vibrational temperature ($hv/k$), 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

\[
E_{N_2} = \frac{\theta_v R(\exp(\theta_v/T)-1)^{-1}}{H(T)} \cdot .41 / H(T). \tag{2}
\]

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 \( 1.2 \times 10^4 \) 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 \( \mu m \) 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 heteronuclear 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-CO₂ laser is

$$P_L = \eta_L V E$$  \hspace{1cm} (3)

where $\eta_L$ is the intrinsic efficiency of the CO₂ 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, $\eta_L$, would be perhaps 20 percent (reduced from 41 percent by kinetic losses) and $E$ the power absorbed for slab geometry is

$$E = \int \alpha_v \phi_v \, dv$$  \hspace{1cm} (4)

where $\alpha_v$ is the absorption coefficient, and $\phi_v$ the total flux is

$$\phi_v(E) = 2\pi I_{vo} [E_2(\xi) + E_2(\xi_L-\xi)]$$  \hspace{1cm} (5)

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

$$\xi = \int_{0}^{x} \alpha_v \frac{dx}{\cos \theta} , \hspace{0.5cm} 0 < x < L ,$$  \hspace{1cm} (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/cm³ and at the center is 1.36 W/cm³. The CO gas temperature is 300 K. For a laser power of 1 megawatt the excited CO gas volume would be approximately 1.5 m³.

The CO-CO₂ system may have a specific power of $4.2 \times 10^4$ J/kg, \cite{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 
N₂-CO₂ laser system.

Other Blackbody Pumped Lasers

Other blackbody laser systems could potentially be interesting for 
their higher efficiencies or shorter wavelengths. The CO-N₂O system has a 
better resonance than the CO-CO₂ 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-C₂H₂ (C₂N₂) system, a close resonance exists between 
CO(ν = 1) and the upper laser level of C₂H₂, 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 N₂-CO₂ system has been experimentally demonstrated. The lasing wavelengths are all near 10 μm; Δε 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 N₂-CO₂ has been pumped in a blackbody cavity, the other systems were pumped by lasers; ṁ 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

<table>
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<th>$N_2$-$CO_2$</th>
<th>CO-$CO_2$</th>
<th>CO-$N_2O$</th>
<th>CO-$C_2H_2$</th>
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<td>$\lambda$ ($\mu$m)</td>
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<td>10.6</td>
<td>10.8</td>
<td>-</td>
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<tr>
<td>$\Delta \varepsilon$ (cm$^{-1}$)</td>
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<td>-206</td>
<td>-81</td>
<td>+69</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$ (%)</td>
<td>2.9 (1500 K)</td>
<td>-40</td>
<td>-40</td>
<td>-50</td>
</tr>
<tr>
<td>$\eta$ (%)</td>
<td>0.9 (blackbody)</td>
<td>7.3</td>
<td>5.6</td>
<td>1.5</td>
</tr>
<tr>
<td>$\dot{m}$ (kg/sec)</td>
<td>85 expt., 44 study</td>
<td>24 study</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$K$ ($\frac{1}{\text{sec torr}}$)</td>
<td>$1.9 \times 10^4$</td>
<td>$2.9 \times 10^3$</td>
<td>$1.5 \times 10^5$</td>
<td>?</td>
</tr>
</tbody>
</table>
BLACKBODY PUMPED CAVITY LASER

Solar collector

Blackbody cavity

Radiator

Laser

Figure 1
Figure 2
Quantum—Thermal CO₂ Laser Efficiency

N₂-CO₂ TRANSFER LASER

Figure 3

Efficiency (%) vs. N₂ Gas Temperature (°K)
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 \( \text{N}_2 \) or \( \text{CO} \) is heated by the blackbody cavity then transferred into the laser cavity where \( \text{CO}_2 \) is injected. The \( \text{N}_2\text{-CO}_2 \) system has been demonstrated, but probably has lower efficiency than the \( \text{CO}\text{-CO}_2 \) system. The characteristics of potential transfer laser systems are outlined.
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