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Overview and Future Direction for Blackbody Solar-Pumped Lasers

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I. Introduction

The blackbody laser is a system that has been proposed to scale to multimegawatt power levels for space-to-space power transmission for applications such as on-board spacecraft electrical or propulsion requirements. Among the critical technical issues are the scalability to high powers and the laser wavelength, which impacts the transmission optics size as well as the laser-to-electric converter at the remote receiver.

Lasers pumped by a blackbody heat source were first demonstrated in 1969 (ref. 1.) Other research demonstrated higher laser powers and efficiences (ref. 2). Also, direct optical pumping of CO_2 and NO_2 was demonstrated through absorption of blackbody cavity radiation (refs. 3, 4, and 5). System studies (refs. 6 and 7) have indicated how such lasers could be scaled to multimegawatt power levels for space applications.

This technical note reviews the solar-pumped blackbody laser concept, addresses its present status, and suggests future research directions. A discussion of the rationale for research on blackbody-pumped lasers is followed by a detailed look at various present blackbody laser configurations such as N_2-CO_2 and CO-CO_2. Next, the technical merits of each system configuration are discussed which lead, finally, to recommendations for future research on blackbody-pumped lasers.

II. Blackbody-Pumped Laser Concept

From a conceptual point of view, blackbody-pumped lasers appear very attractive, since they can convert heat energy directly into laser energy. This heat source could not only be generated by solar light, but also by nuclear reactor heat, fossil fuel combustion, or any high temperature

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process. The heat source produces thermal radiation described by the blackbody radiation law at the given blackbody temperature. For instance, a 1500 K blackbody will produce 10 W/cm^2 at a wavelength of 2 μm which can be used to pump an appropriate absorbing gas. Thus, with a large area blackbody source, very large radiant powers can be generated, and if this power can be efficiently coupled to a lasant material (either gas, solid, or liquid), then substantial laser powers can be generated. In general, the higher the blackbody temperature, the more effective the laser pumping power. Two constraints constrict the upper temperature limit of blackbodies, one being the thermal limitation of the materials, and the other the radiation losses out of the blackbody cavity through the solar light entrance hole. Such constraints usually limit blackbody pumping systems to around 2000 K and in practical laboratory situations to 1500 K, well below the thermodynamic limit of approximately 5800 K for the sun.

Producing high temperature blackbodies is not a major technological challenge; these blackbodies have been achieved for a number of years in solar furnaces and other devices for high temperature materials processing. The unique and challenging feature is that of coupling the blackbody to the lasant. Thus, most research has focussed on thermally excited vibrational states of gas molecules for pumping appropriate lasant gases by collisional transfer of vibrational energy.

An advantage of the blackbody-pumped solar laser is the inherent thermal storage capacity of the blackbody. This could allow the laser to operate for an extended time with no solar (heat) input. Lasing would continue until some critical temperature is reached where laser threshold is no longer achieved.

Depending on the thermal storage of the blackbody, this could be from minutes to hours and might enable a laser system to operate on the dark side of Earth orbit.

Also, an advantage of the blackbody laser is the use of relatively inexpensive, nonconsumable, and noncorrosive gases, which might make the overall laser system less costly than some direct solar-pumped systems.

Concepts of two systems are outlined in schematic form in figure 1. The first is the "translational heating" concept in which the blackbody heats molecules of a transfer gas creating a Boltzman distribution of vibrational states. The molecular translational, vibrational, and rotational temperatures come into equilibrium with the blackbody temperature. The second system in figure 1 shows a schematic of the "vibrational heating" system. Here the transfer gas molecule absorbs a portion of the blackbody spectral radiation in a very narrow absorption band and becomes vibrationally excited, but the gas translational temperature remains near room temperature.

All proposed transfer blackbody laser systems fall into one of these two general categories. The basic system components are shown in figure 1 for the overall system, but at present most research has focussed on the energy transfer processes leading to lasing.

III. Blackbody Laser System Configurations

Within the "translational pumping" blackbody-laser concept, there are a number of possible configurations that will produce lasing. For ease in examining these configurations, we will use the N_2-CO_2 laser system as an example.

In the first configuration, N_2 is thermally excited by contact with the blackbody wall. In this system the N_2 gas temperature, Tgas, is equal to the vibrational temperature, Tvib, which is equal to the blackbody cavity temperature, T_{BB}; that is, all three temperatures come into equilibrium. A population inversion can only be created in CO_2 by collisionally transferring N_2 vibrational energy into the upper laser level without populating the CO_2 lower laser level through collisions with translationally "hot" N_2 molecules. Thus, it is necessary to rapidly reduce the translational temperature of nitrogen. This can be accomplished either by rapid expansion or by contact with a cooled surface.

Cooling can be accomplished through expansion in a converging/diverging nozzle assembly just before injection of the CO_2 gas, which requires the laser cavity to operate as a supersonic wind tunnel. An alternative way of removing the heat, thus reducing the translational temperature of the nitrogen, is to actively cool the nozzle by flowing liquid nitrogen through the nozzle block. As the translationally hot nitrogen passes through the cooled nozzle, the temperature is reduced substantially without adversely affecting the vibrational temperature. This has been demonstrated at NASA LaRC by a liquid-nitrogen-cooled aluminum pin-hole nozzle. Lasing is indicated in figure 2 as a result of heated nitrogen at 1400 K being passed through a pin-hole nozzle block cooled by liquid nitrogen. As the hot gas comes in contact with the cold nozzle block, the translational temperature drops, but the vibrational temperature remains high. Then, injection of CO_2 causes a transfer of vibrational energy into the CO_2 and produces lasing, which is noted in figure 2 by the spiked laser output. The nozzle, of course, heats up (inability to carry away the heat load) and reaches a critical temperature in which the nitrogen gas is so hot that it fills the CO_2 lower laser levels, and thus quenches further lasing, as shown in the figure. The key feature of this system is that it does not require supersonic flow velocities. A critical analysis of this system is given in the next section.

A quite different method of achieving a low translational temperature in the blackbody cavity is accomplished by not exciting the translational degrees of freedom at all initially as shown in figure 1. This would involve optically pumping the CO, or other heteronuclear diatomic molecules, to vibrational levels without corresponding translational heating of the gas. Here, in concept, we have a nonequilibrium situation in which the gas temperature remains near room temperature, but the vibrational temperature comes into equilibrium with the blackbody temperature. Thus, with this system there is no need to cool the CO_2 gas. What emerges from the blackbody cavity is vibrationally excited CO which can transfer vibrational energy into the upper laser level of CO_2, resulting in lasing at 10.6 μm. An evaluation of these system concepts is now presented.

IV. Merits of Blackbody System Configurations

A. Translationally Heated N_2-CO_2 System

Blackbody-pumped lasing of CO_2 by transfer from heated nitrogen has been demonstrated. Although lasing can readily be achieved in the laboratory, its potential for high power and high efficiency is limited by the inefficiency in using a Boltzman distribution to create vibrational states. The maximum efficiency of this system is given by the equation

$$\eta(T) = \eta_T \cdot \eta_{QE} \tag{1}$$

where η_{QE} is the quantum efficiency of the laser (41 percent for CO_2) and η_T is the thermal efficiency or the ratio of energy in vibrational states to all the energy in translation, vibration, and rotation of the molecule. The thermal efficiency is defined as (ref. 8),

$$\eta_T = R \left[\frac{\theta_\nu}{e^{\theta_\nu/T} - 1}\right] /H(T) \qquad (2)$$

Here R is the specific gas constant, θ_ν is the characteristic temperature for vibrationally excited nitrogen (equal to 3357 K), T is the temperature of the gas, and H(T) is the gas enthalpy. Figure 3 is a plot of both η_T and $\eta(T)$ as a function of nitrogen gas temperature in the blackbody cavity. As can be seen, the efficiency rises as the temperature increases, but at the temperature limit of approximately 2000 K, we achieve an efficiency of roughly 4 percent for $\eta(T)$. This is the ideal efficiency of the N_2-CO_2 system, which does not take into account the laser system kinetic efficiency, the loss of N_2 vibrational energy through the nozzle, the blackbody cavity efficiency, and any power that must be expended in the gas cycle.

As mentioned earlier, reducing the translational temperature of the heated nitrogen can be achieved in two ways: either by rapid supersonic expansion of the nitrogen gas or by conduction cooling of the gas through a cooled nozzle at subsonic speeds.

In the first case, supersonic expansion demands high compressor powers to maintain the pressure differential required to achieve supersonic velocities. For example, a good laser design would require about Mach 5 velocities at the nozzle exit. Using standard air tables for compressible flow, the ratio of laser cavity to stagnation gas temperature would be 0.1667. Thus, for a stagnation temperature of 1500 K, the laser cavity N_2 gas temperature would be 250 K, a low enough temperature to retard excitation of the CO_2 lower laser levels. Likewise, the ratio of the laser cavity pressure to the stagnation pressure is 0.00189. Using laser cavity pressures of 20 torr N_2 would require a 10,580 torr (13.9 atm.) stagnation pressure to maintain Mach 5 flow. This would require a high capacity, high power compressor and efficient diffuser (for closed cycle continuous operation) to repressurize the N_2 from 20 to 10,580 torr. In the system study of Kelch and Young (ref. 9), a well designed CO_2 gasdynamic 5-MW laser was presented. The compressor power requirement, with a well designed advanced diffuser, was 44.5 MW. The overall system efficiency was only 2.37 percent, which would certainly be lower in a real system. Most of the system power is absorbed in circulating the gas because of the requirement of the high pressure differential across the nozzle and the high mass flow rate for high power operation.

The alternate approach of cooling the translational nitrogen gas temperature by conduction in an actively cooled nozzle array has been demonstrated. The disadvantage of this method is that to achieve low translational temperatures, the hot nitrogen must come in contact with the cool nozzle walls. Cooling then takes place, but also there is a loss of vibrational excitation due to wall deactivation. Also, slow velocities and small diameter nozzles help conduct heat away, but they also increase the probability of vibrational deactivation at the nozzle wall. Thus, one is faced with tradeoffs which do not appear to scale to high power lasers readily. When all these other considerations are taken into account, overall system efficiency of this configuration will be less than 1 percent. This suggests that letting the transfer gas come to equilibrium with the blackbody temperature may not be a desirable approach.

B. Optically Pumped Transfer Laser System

As mentioned earlier, in an optically pumped transfer laser system, the translational temperature remains near room temperature, while the vibrational temperature of the transfer gas comes into equilibrium with the blackbody temperature at approximately 1500-2000 K. The vibrationally excited transfer gas is removed from the blackbody cavity and injected into the laser cavity where a lasant gas is mixed resulting in a vibrational energy transfer from the transfer gas into the upper laser level of the lasant gas. The rest of the system would be identical to the translationally heated systems which require both a radiator and gas separator. This system has the advantage in that excitation to the first vibrational level of CO occurs without affecting the translational temperature; thus, there is no need to remove translational energy from the CO gas. In this case, the system efficiency could approach the quantum efficiency for the lasant gas. The challenge of this particular system is to efficiently couple the transfer gas to the blackbody cavity, in which significant densities of vibrationally excited gas can be created, <u>without</u> translationally heating the gas above ambient temperature and then to transport the gas to the laser cavity without significant loss. If the gas temperature is increased, vibrational-translational (V-T) relaxation increases rapidly and becomes a serious loss mechanism. This is shown in figure 4 using as an example CO, where the CO^* vibrational lifetime is plotted as a function of translational temperature (ref. 10). The pressure is 1 atm. of either CO or Ar. The CO^* spontaneous lifetime is 30 msec. As can be seen from the figure, as the CO heats up, the V-T lifetime decreases. At 625 K for CO^* - CO, the spontaneous and V-T lifetimes are equal; thus, at gas temperatures above 625 K (1 atm. pressure), V-T relaxation is the dominant loss mechanism. The V-T lifetime can be increased significantly by using an Ar buffer gas as seen in figure 4. Under such conditions, the spontaneous lifetime would be the dominant loss mechanism.

The spontaneous and V-T lifetime dictate the velocity with which the CO must be driven through the blackbody cavity. The time rate of change of the CO vibrational density, D_1, is given by

$$\frac{dD_1}{dt} = SD_o - K_T D_o D_1 - A_D D_1 \tag{3}$$

where D_o is the ground state CO density, S is the absorption rate, K_T is the V-T relaxation rate, and A_D is the Einstein A coefficient. Assuming steady state

$$D_1(t) = SD_o \tau_o (1 - e^{-\alpha_o t}) \tag{4}$$

where

$$\alpha_o = 1/\tau_o = K_T D_o + A_D \tag{5}$$

Figure 5 is a plot of equation 4 assuming the source term (SD_o) is equal to 1. The term $\alpha_o = 33.9$ corresponds to a gas temperature of 300 K and a CO density of 1 atmosphere, typical laboratory operating conditions. After 60 msec of optical pumping, the CO^* density has reached 88 percent of its maximum value $(t = \infty)$. For a 1-m-long pumping tube, the CO velocity would be 16.7 m/sec, a reasonably slow velocity to ensure adequate pumping.

There appears to be no difficulty in pumping CO as long as the gas temperature remains near room temperature. The gas, once vibrationally excited, must be quickly mixed with CO_2 or other lasant gas to reduce both V-T and spontaneous relaxation losses of the CO vibrational states. This system has the best potential for scaling to high powers if efficient ways of exciting CO to high densities can be demonstrated at reasonable velocities and pumping tube geometries. More research emphasis is needed on this concept.

C. Other Potential Blackbody Systems

There are other potential blackbody laser systems that could have high efficiency at shorter laser wavelengths. In particular, CO might be excited directly by the blackbody cavity and result in lasing. Although this system has lased at room temperature, scaling to high power may require gas cooling at cryogenic temperatures. This needs to be further researched. An advantage of this system is that no gas separator is required. Also, the lasing wavelength would be approximately 4-6 μm, which gives a significant advantage in terms of transmission optics over the 10.6 μm laser emission of CO_2, but has the disadvantage of not coupling well to photovoltaic converters.

Ideally, one would want a heteronuclear diatomic molecule with long vibrational lifetime absorbing at the fundamental wavelength near 2 μm. This vibrational excitation would then transfer through collisions to a lasant molecule resulting in high photon energy lasing. Lasing wavelengths near visible would be ideal, since quartz optics could then be used and convenient photovoltaic converters exist. Is there potential for such a system? The answer is yes, one potential system being the CO-NO system.

Figure 6 shows an energy level diagram of this system. A solar-heated blackbody cavity would pump CO up the vibrational manifold to levels near 25. The vibrationally hot, but translationally cool CO would flow out of the blackbody cavity, and then NO would be mixed with the CO. Through collisional transfer, the CO (υ>25) would excite the A and B states of NO, the upper laser level. Note that transitions from the NO A and B states terminate on high vibrational levels of the NO ground state; at room temperature these levels would be unpopulated. Research at Calspan Advanced Technology Center (ref. 11) has demonstrated fluorescence from NO pumped by CO as shown in figure 7. Here emission from both the A and the B states is shown in the visible region. A loss mechanism producing CN emission is also shown. This system has the advantage of pumping with IR photons but lasing with UV photons.

D. Advantages and Disadvantages of Present Blackbody-Pumped Lasers

Table 1 and 2 list some of the advantages and disadvantages of present blackbody laser systems. The long laser wavelength and lack of an efficient laser-to-electric converter impact the future directions of these systems.

Table 1

Advantages of Blackbody Pumped Lasers:

- The total energy in the solar spectrum could be used to pump the laser (solar utilization high).
- The pumping of the laser tube is homogeneous around the circumference.
- Blackbodies have inherent energy storage capability thus allowing continued lasing with no solar input for short periods of time.
- Present absorbing and lasing gases are chemically inert and inexpensive.
- For optically pumped systems, overall efficiency could be high (perhaps 10 percent).

Table 2

Disadvantages of Present Blackbody Pumped Lasers:

-- The present blackbody CO_2 laser wavelength of 10.6 µm is not good for long range transmission because of large diffraction spreading, thus requiring larger area transmission optics than for visible lasers.

-- For the CO-CO_2 or N_2-CO_2 system, a gas separator has not been well characterized, which makes the overall system complex.

-- A blackbody system based on "thermally" heated gas will result in system efficiencies of 1 percent or less.

-- Present blackbody laser wavelengths cannot make use of simple photovoltaic laser-to-electric converters.

V. Future Direction

Blackbody-pumped lasers have been demonstrated in terms of "proof of principle." The dominant issue is which system can most attractively be scaled to high powers at laser wavelengths that can be easily converted to electricity. No such system has emerged to date; each system has certain disadvantages which make commitment to scale-up difficult.

Another important issue with blackbody-pumped lasers is laser wavelength. Laser power station system studies (ref. 12) have indicated that one of the major subsystem components in terms of cost and mass is the laser transmission optics. Laser wavelength is a determining factor in the size of these optics and suggests that lasers in the visible region are much preferable to infrared laser wavelengths. Also, it is very difficult to convert laser wavelengths greater than 1.3 µm by use of photovoltaics into electricity. Other techniques such as laser magnetohydrodynamics could be used, but this conversion system would be more complicated and costly than photovoltaic conversion. Thus, unless blackbody lasers can eventually produce laser radiation less than 1.5 μm, they are at a disadvantage with regard to other shorter wavelength solar-pumped lasers from an overall system standpoint.

Research on space-based solar-pumped lasers has progressed to the point where several system characteristics are beginning to emerge. These characteristics should now be applied to blackbody-pumped lasers to help guide future experimental research on these systems. The system characteristics are listed below.

1. Research should concentrate on blackbody lasers with wavelengths less than 1.3 μm to minimize transmission optics mass and allow photovoltaic conversion to electricity.

2. The laser should operate with system efficiency from 2 to 10 percent to minimize the size of the solar collector and radiator.

3. The lasant should operate efficiently at temperatures above 300 K to minimize radiator mass and not require supersonic flow to produce the population inversion.

Presently, the only blackbody laser system that could potentially meet the above characteristics is the CO-NO laser. Thus, research on blackbody systems should focus on this system with the goal of a continuous wave laser demonstration followed by scaling studies. Also, future potential blackbody laser systems should meet the system characteristics as stated above.

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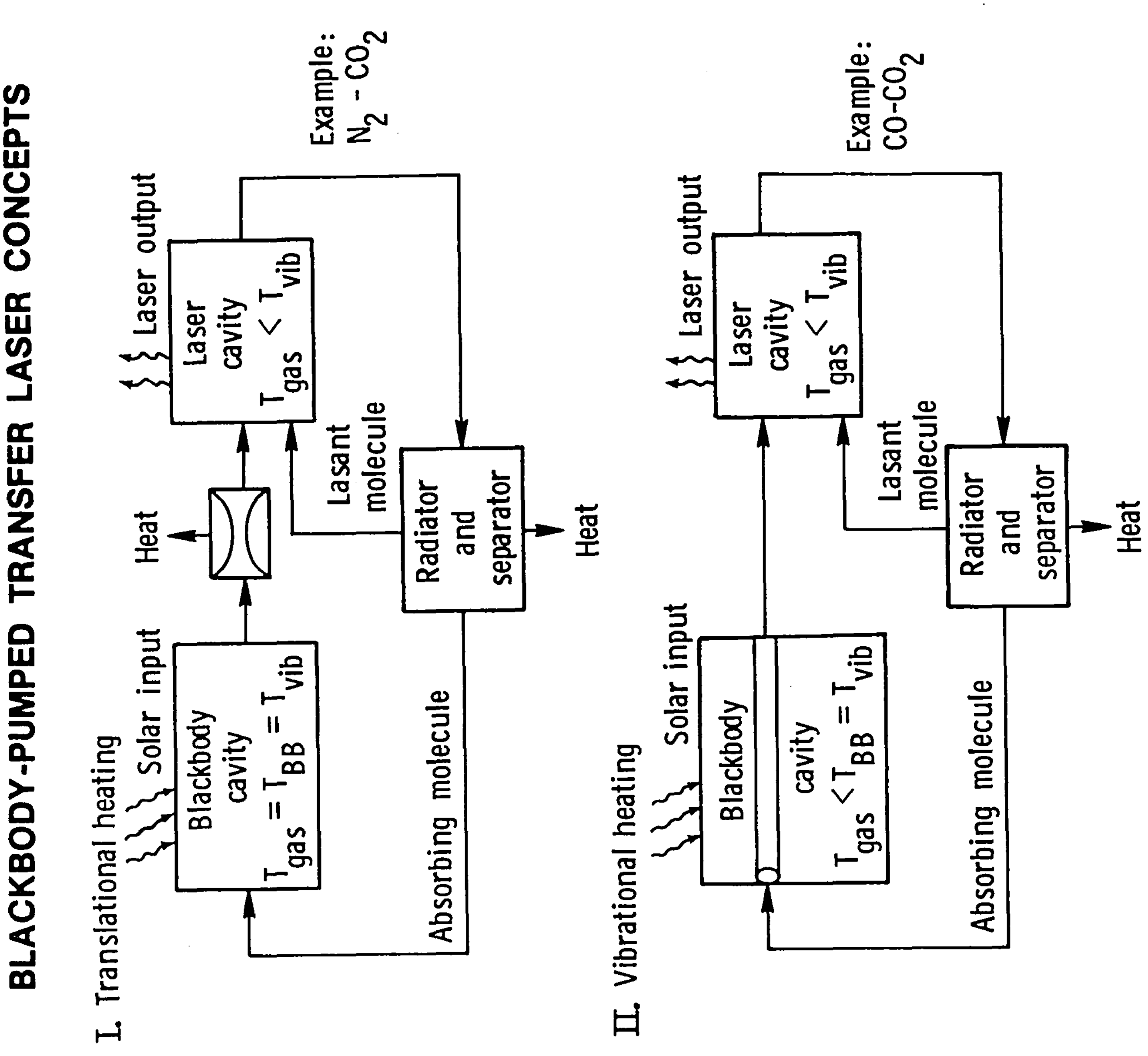

Fig. 1 Schematic diagram of blackbody-pumped transfer laser system. I. Translational heating and II. Vibrational heating

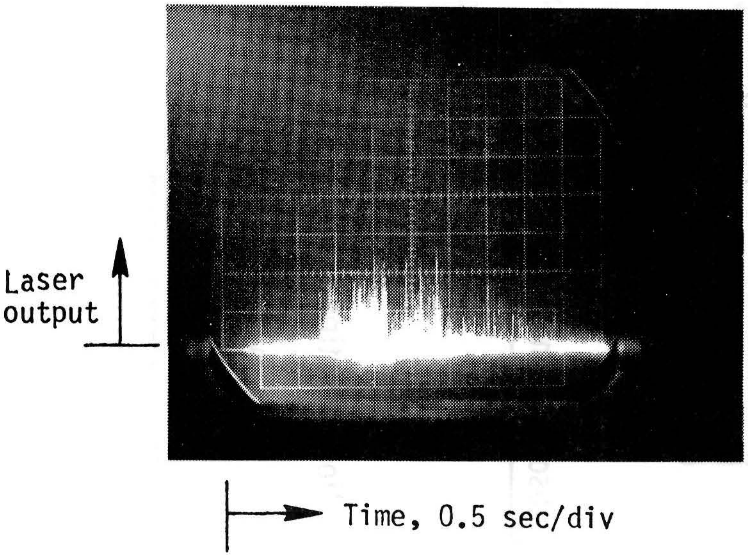

Fig. 2 Typical CO_2 laser output from liquid nitrogen cooled nozzle block transfer N_2-CO_2 laser.

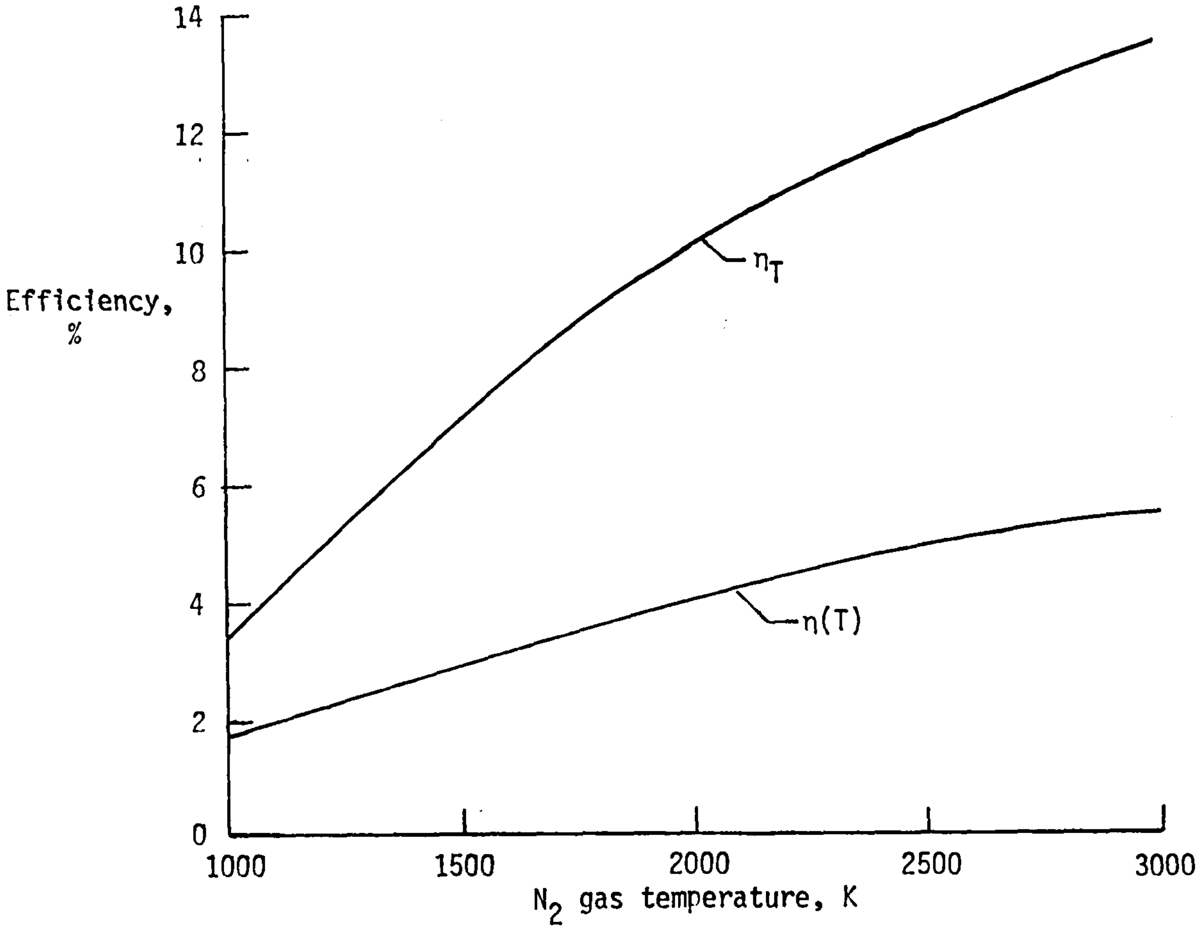

Fig. 3 Maximum laser efficiency $\eta(T)$ for translationally heated N_2-CO_2 blackbody pumped system as a function of blackbody temperature. η_T is the ratio of energy in vibrational states to all the energy in translation, vibration or rotation of the N_2 molecule.

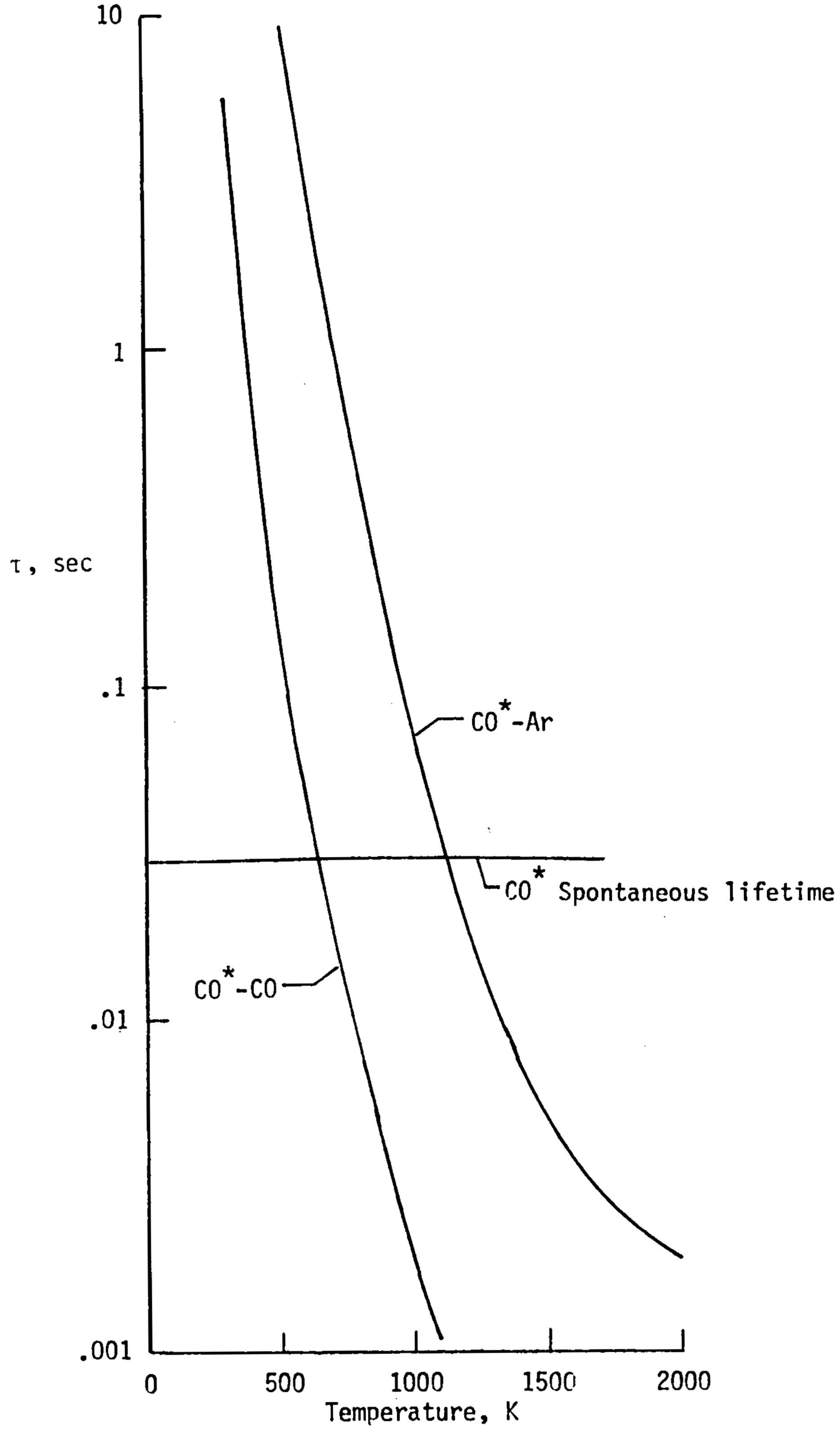

Fig. 4 Lifetime of vibrationally excited CO as a function of CO temperature.

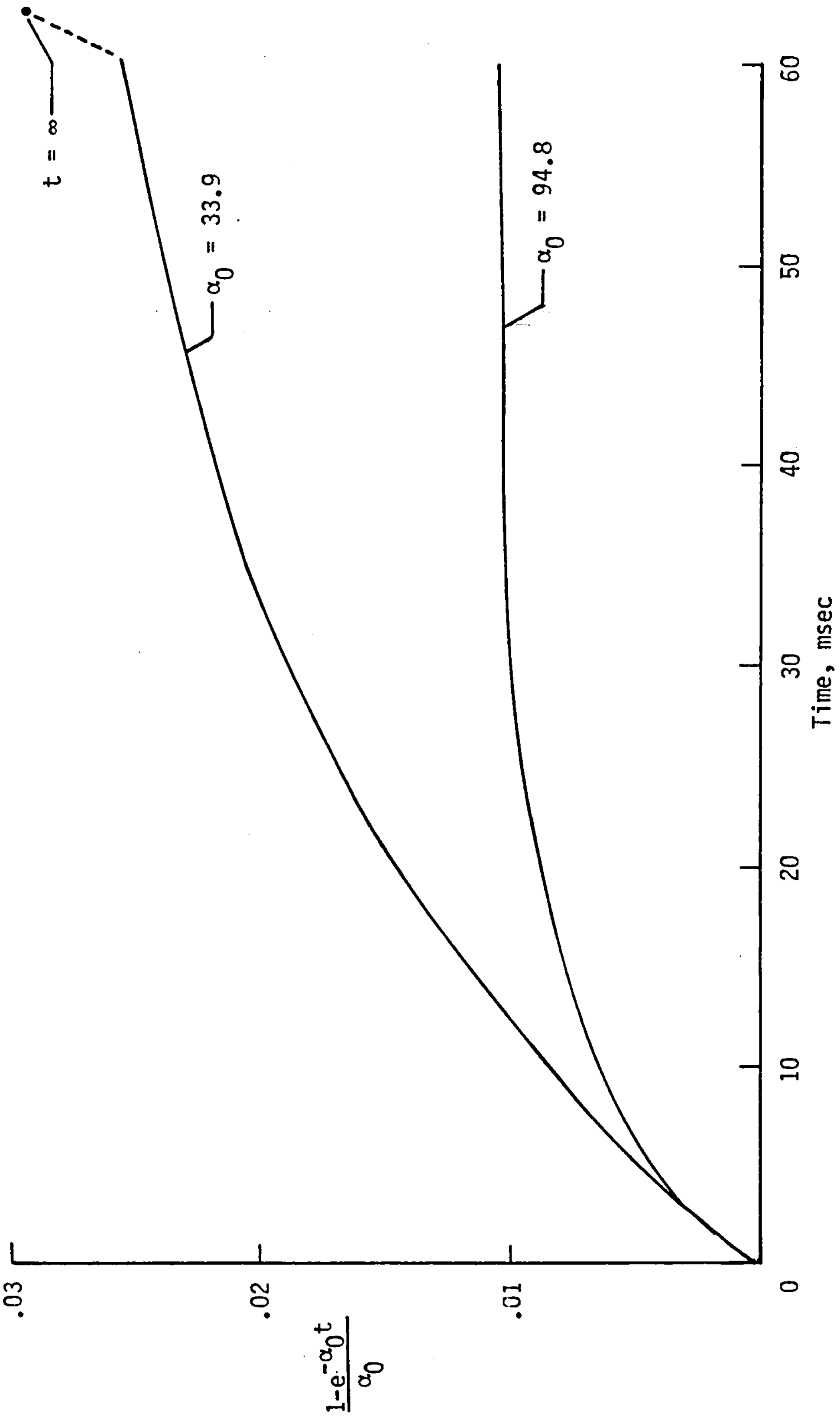

Fig. 5 Relative density of vibrationally excited CO as a function of optical pumping time.

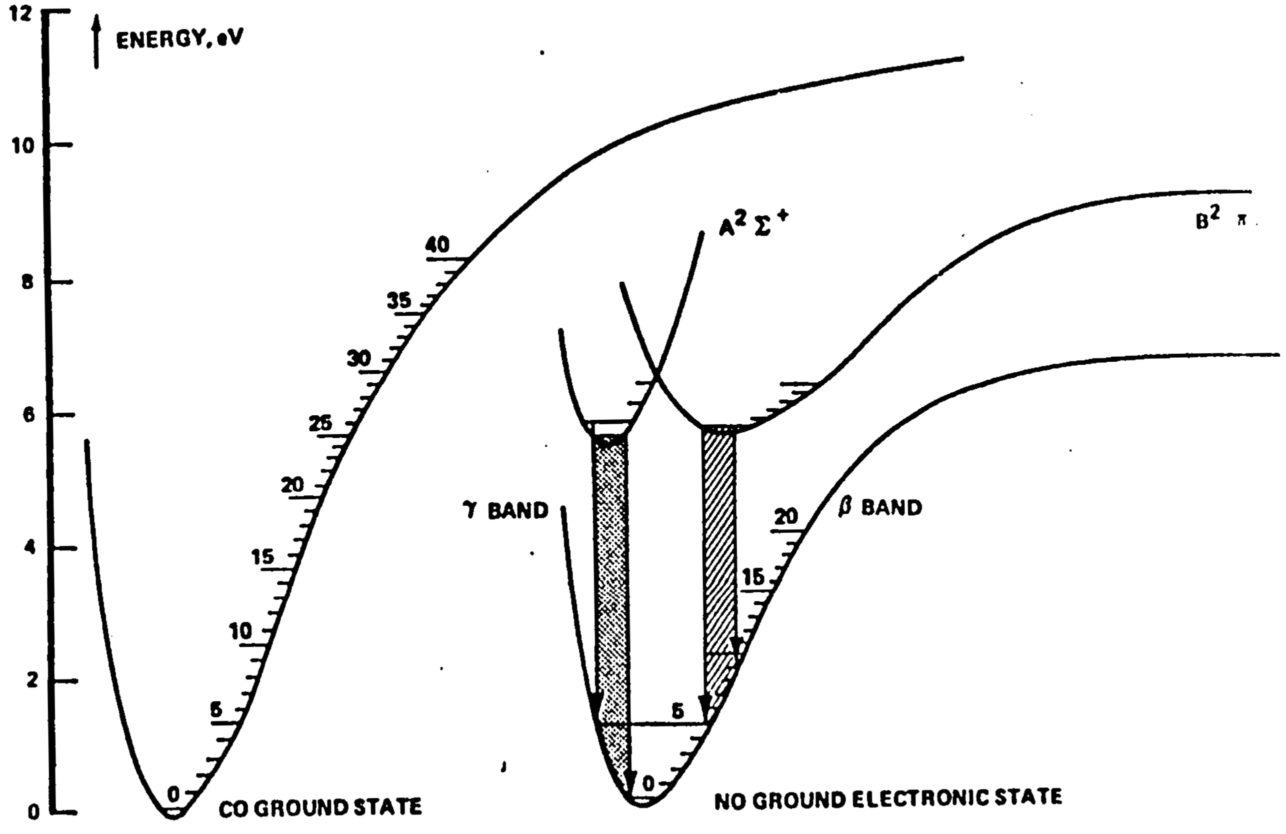

Fig. 6 Energy level diagram of the blackbody-pumped CO-NO laser system.

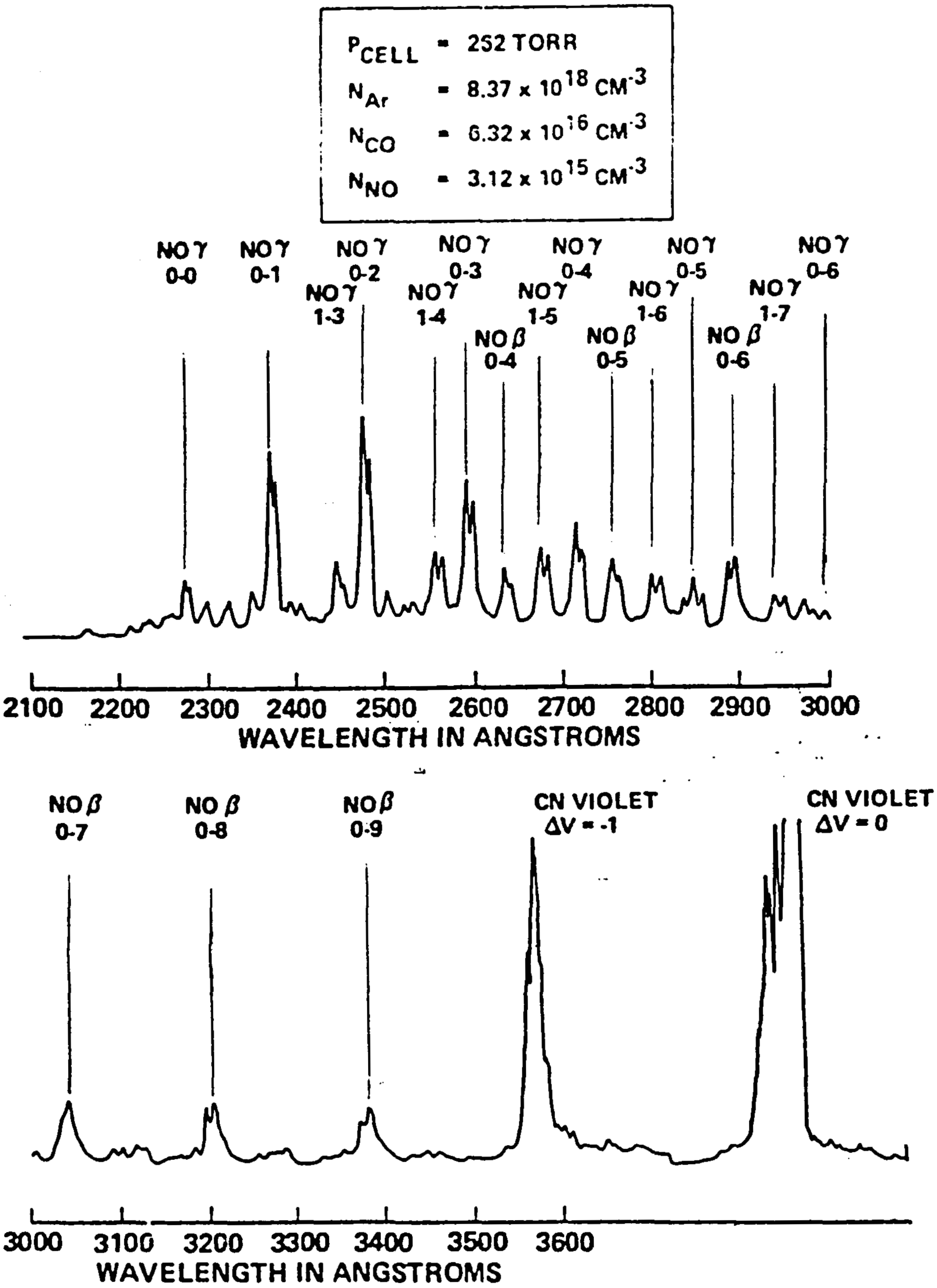

Fig. 7 Emission from NO when collisionally pumped by vibrationally excited CO.

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16. Abstract

A review of solar-pumped blackbody lasers is given which addresses their present status and suggests future research directions. The blackbody laser concept is one system that has been proposed to scale to multimegawatt power levels for space-to-space power transmissions for such applications as on-board spacecraft electrical or propulsion needs. Among the critical technical issues are the scalability to high powers and the laser wavelength which impacts the transmission optics size as well as the laser-to-electric converter at the receiver. Because present blackbody solar-pumped lasers will have laser wavelengths longer than 4μm, simple photovoltaic converters cannot be used, and transmission optics will be large. Thus, future blackbody laser systems should emphasize near visible laser wavelengths.

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