Blackbody-Pumped CO_2 Laser Experiment

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An experiment to demonstrate the physics of blackbody-pumped lasers has been performed. An electrically heated oven simulates the equivalent solar-heated blackbody cavity. The initial experiments were conducted in a nonsteady manner, obtaining a peak power of 4 mW with a corresponding lasing duration of about 4 s. Flowing cooled nitrogen through an annulus created by placing a second tube around the original laser tube gave rise to a continuous-wave laser output. The steady-state power achieved was also about 4 mW. A simplified model is presented and used to calculate the small signal gain for the weakly pumped blackbody-pumped CO_2 laser.

Introduction

THE success of high-power, continuous-wave (cw), space-based lasers depends upon development of a scheme whereby sunlight can be efficiently converted to laser light. Direct conversion methods using broadband pumping may be one approach. In the past decade, there has been some study of broadband pumping of gas lasers[1] and recently an optically pumped iodine laser has been demonstrated using a solar simulator.[2] Solar pumping of bound-bound absorption transitions, typical of infrared lasers, is possible but would normally be very inefficient due to the fact that the absorption bandwidths of many potential gas laser media are small in relation to the effective bandwidth of the solar spectrum. Consequently, only a very small fraction of the solar energy can be absorbed and converted into laser light.

Alternatively, a concept for efficient optical pumping of an infrared laser medium has evolved wherein an intermediate blackbody cavity, heated by focussed sunlight, is used as the optical pumping source.[3] The laser tube can be placed inside the blackbody cavity as shown in Fig. 1. This scheme allows the entire solar flux to contribute to the lasing because of the thermodynamics of the blackbody cavity. As shown in Fig. 2, if the cavity radiation is withdrawn via the pumping bands of the laser medium, the nonequilibrium part of the radiation field in the cavity is returned to a blackbody by thermal re-emission of the hot walls. In the scenario shown schematically in Fig. 2, radiation emitted by the walls at 1 impinges on a transparent tube containing the laser gas. The gas absorbs a narrow bandwidth which results in the spectral distribution shown at 2. This radiation is then reabsorbed and thermalized by the walls and re-emitted in the original spectral distribution as shown at 3, and the process is repeated. In this way the pumping radiation of this type of lasers is continuously replenished and all of the energy source is utilized, resulting in a potential efficiency that is orders of magnitude greater than when sunlight is used directly with media having narrow-band absorption.[3] Utilizing the blackbody pumping concept, scaled models of a laser capable of high power levels have been made,[4] where the overall efficiency of conversion of solar radiation to laser radiation was estimated to be 10-20%.

An experiment has been carried out to demonstrate a blackbody-pumped laser. Optically pumped laser media can be chosen from those systems already lased by other means, such as the electric discharge method. The most direct approach is to find a lasing gas having a spectral absorption band connecting the upper laser level to the ground state. It is also feasible to use other atomic or molecular gases that can contribute their absorbed energy via collisional transfer. Because of the relatively weak specific intensity of broadband thermal sources (only 1.6 kW/cm^2 for concentrated sunlight) and the low pumping rate within a band, the best laser candidates are those systems with low threshold requirements.

While a range of potential candidates exists, CO_2 seems to be a good choice for demonstrating the physics of blackbody lasers. Furthermore, the kinetics of CO_2 and the theoretical aspects of modeling this molecule are well known. This paper presents results from a blackbody-pumped CO_2 laser, which uses an electrically heated oven to simulate the solar-heated blackbody cavity, and discusses some of the physics of this system. Two sets of experiments were conducted: in the first the laser was operated in a nonsteady manner and the optimum conditions were determined and in the second cw lasing was achieved.

Experimental Apparatus

The experimental setup is shown in Fig. 3. The initial nonsteady experiments were conducted with only the inner sapphire laser tube and with no active cooling, although the laser gas was flowed through a dry ice-acetone cold trap. This bath precooled the gas slightly and removed any water vapor. The laser tube is 60 cm long, but only the central 50 cm is placed within the blackbody cavity, thus allowing all of the optics to be external to the electrical oven. The inner tube has an i.d. of 8 mm and an o.d. of 9.5 mm. For the cw lasing experiment, the outer tube (i.d. = 14.35 mm) is placed around the original laser tube and cooled nitrogen (which does not absorb the blackbody radiation) is flowed through the annulus. The nitrogen is cooled by flowing through a heat exchanger immersed in a cold bath of either liquid nitrogen or dry ice-acetone slurry. The cooling gas and the laser gas are counterflowed so that the maximum cooling occurs where the gas is no longer precooled.

Sapphire was chosen because it transmits quite well ($\sim$85%) in the infrared to 5-6 μm, thus transmitting the 4.3 μm light that is in turn absorbed by the CO_2. The laser cavity is nearly confocal with a 1 m optical path. Experiments were performed with 1.5 and 5% output couplers. The oven consists of two half-shell eletrical heaters and is well insulated so that the surroundings remain at room temperature. This insures that the laser tube (which sits adjacent to and outside the heater as shown in Fig. 3) will not be preheated. After achieving the proper oven temperature ($\approx$1200-1500 K), the oven is moved around the laser tube to start the pumping action. Data are taken and the heater is then removed from

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around the laser tube, thus completing the cycle. The cavity is initially aligned using the short electric (glow) discharge laser shown in Fig. 3. Care is taken to insure that the beam from this laser is centered in the sapphire laser tube. In the cw lasing experiments, the output power is optimized by adjusting the mirrors once lasing has begun.

Experimental Results

Initially the experiment was conducted in a nonsteady manner; that is, an uncooled laser tube was exposed only briefly to the blackbody radiation. Lasing occurred until the sapphire laser tube and the gas within became hot. Several gas mixtures were tested and the results from a 16% CO_2/4% He/80% Ar mixture are shown in Fig. 4. The peak power and duration are plotted vs pressure for this mixture. These results were obtained using a 1.5% output coupler. The solid lines in Fig. 4 were produced by applying a polynomial least squares fit to the data. The peak occurs at between 8 and 10 Torr and corresponds to about 4.2 mW power, as measured with a pyroelectric detector, and 4 s duration. The results are fairly reproducible, with the scatter between data taken under similar conditions being within 20%. The duration is consistent with estimates based on preliminary measurements of the rate of heating of the sapphire tube due to radiation and convection in the oven.[5] This set of experiments allowed for a limited parametric study of the gas mixture and the flow conditions without the additional complications introduced by temperature control.

Cooling of the laser tube was then introduced as described above and cw lasing was achieved. The losses caused by the presence of the second sapphire tube were more than compensated for by the lower temperature of the laser tube. For the same gas mixture (16% CO_2 flowing at approximately 10 Torr) and 1.5% output coupling a cw power of ~4 mW was measured, whereas with 5% output coupling a steady-state power of ~4.5 mW was obtained. A typical oscilloscope trace is shown in Fig. 5. The laser beam was chopped at 30 cycles/s and was measured with a pyroelectric detector. Also shown is the signal from a chromel-constantan thermocouple placed at the outlet of the cooling gas. It is seen that the initial laser power is as much as two times greater than the steady-state power. This higher output power corresponds to a lower outlet temperature of the cooling gas and therefore to a lower average temperature of the lasing gas. That is, the laser power decreases as the average temperature of the cooling gas increases, until they both reach a steady-state value. For the case shown in Fig. 5, this factor of two corresponds to a 65°C change in temperature.

Thermocouples were placed at the inlet and outlet of the cooling gas annulus and the change in temperature across the length of the tube was measured. The nitrogen had an inlet temperature nearly equal to the bath temperature and an outlet temperature of 350 K. The mass flow of this cooling gas was estimated by monitoring the pressure drop in the supply tank during a typical 30 s run. A heat balance using this estimate and the measured temperature conditions showed that the power being removed by the cooling system was of the same order as the power being transferred into the tube through radiation and convection.

Simplified Model

In its simplest terms, the kinetics of an optically pumped CO_2 laser are little different from other forms of the laser and can be treated as such once the pumping has been specified. The level of small signal gain and its relationship to the blackbody temperature had been previously calculated using a model for the case of an optically thin gas.[6] The calculations assumed a transmission coefficient of 85% through the sapphire tube at 4.3 μm based on reflection coefficient estimates. Inhomogeneous and homogeneous broadening effects on the gain profile were added to the model presented in Ref. 6 so that the effects of adding a buffer gas could be studied.[7] As shown in Fig. 6 by the curve labeled $D=0$, this model predicts high gains at low pressures (e.g., a 1 Torr mixture of 0.8 Torr CO_2 and 0.2 Torr He) and decreasing gain as argon is added because of the increased vibrational-to-translational losses. The initial experimental attempts were made at those low-pressure conditions and no lasing was observed. Lasing did not occur until enough argon was added to bring the total pressure up to at least 5 Torr.

It is believed that this effect is caused by catalytic wall deactivation of the excited states. Measurements[8] of CO_2 indicate that the deactivation probability η is of order 20%. Because the tube and the laser beam mode cross section have such small diameters, diffusion of excited states to the wall and outside of the beam would seem to be a significant effect. The gain model has therefore been revised so as to include diffusion and wall deactivation losses.

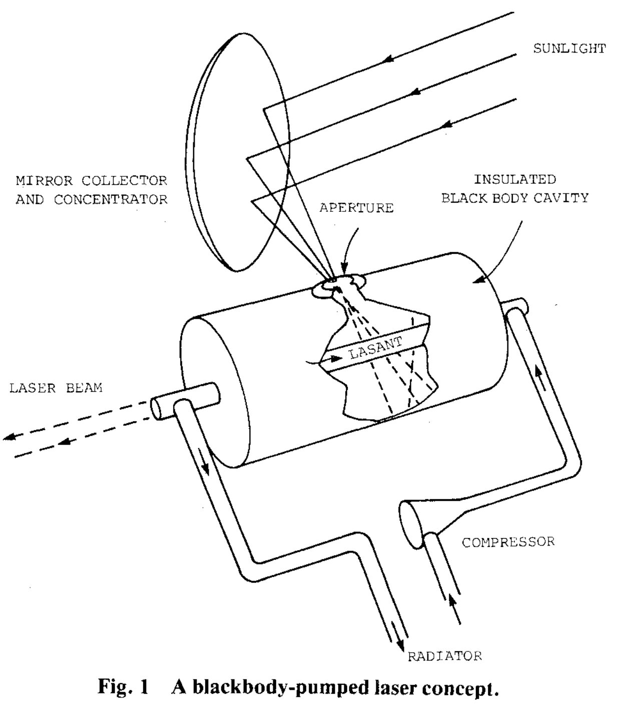

Fig. 1 A blackbody-pumped laser concept.

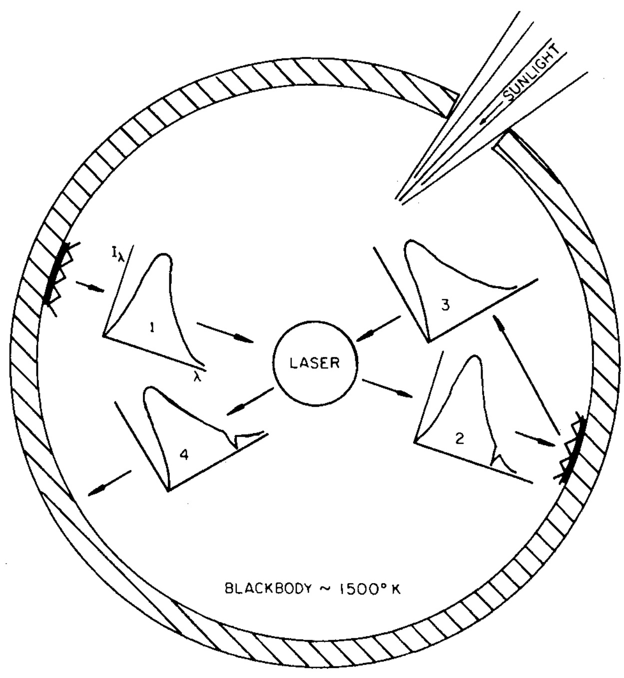

Fig. 2 Thermalization of a nonequilibrium radiation field by a blackbody.

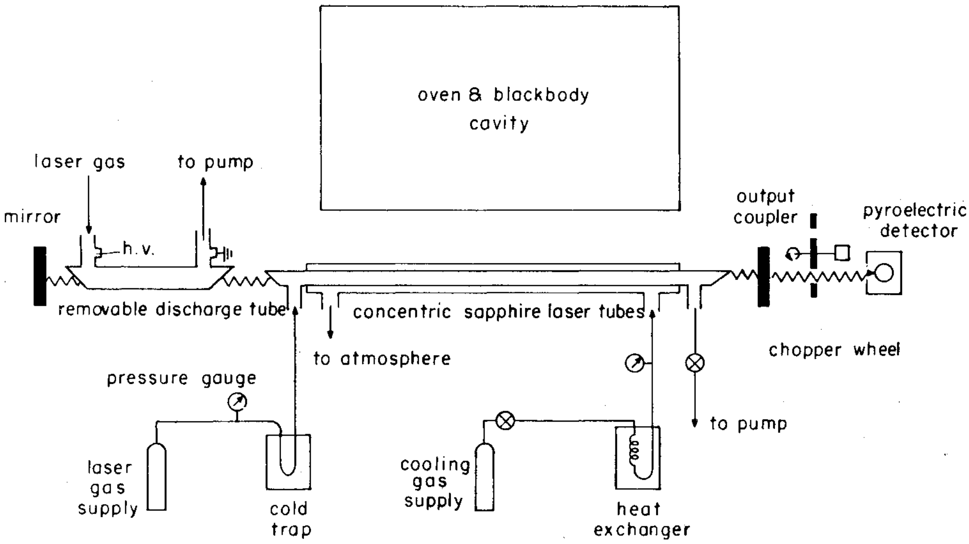

Fig. 3 Experimental setup of the blackbody-pumped CO_2 laser.

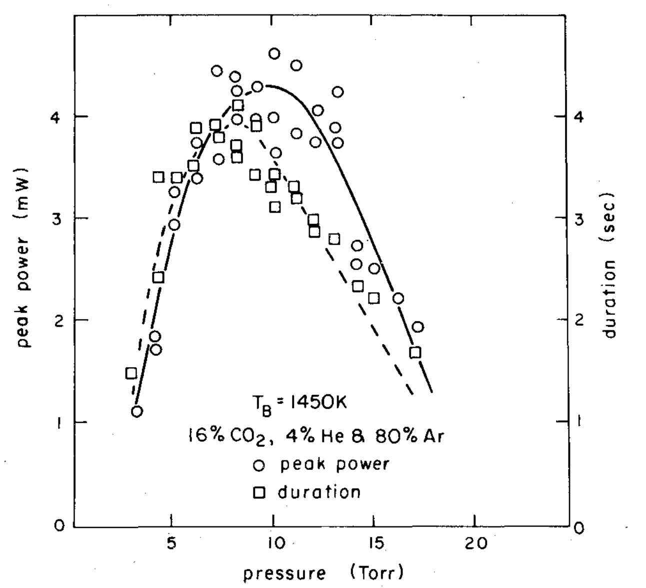

Fig. 4 Nonsteady peak power and laser duration vs pressure for 1.5% output coupling (initial gas temperature 300 K).

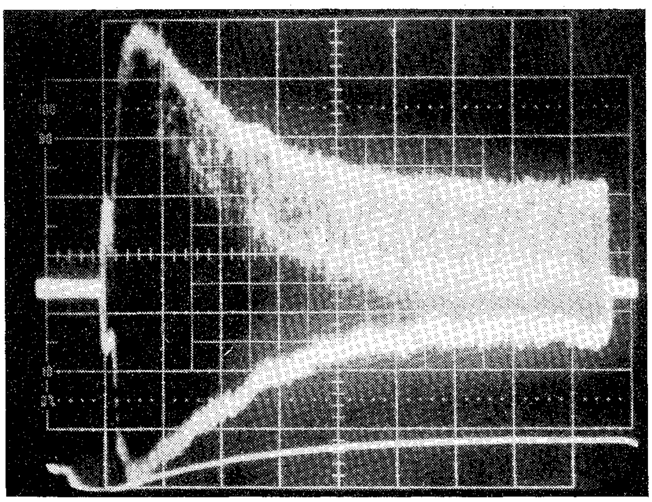

Fig. 5 Typical oscilloscope trace for the cw experiment, 16% CO_2/4% He/80% Ar flowing at 10 Torr: upper trace is the laser signal 1.7 mW/cm and lower trace is chromel-constantan thermocouple 80°C/cm (horizontal axis is 5 s/cm).

The present model is formulated on state concentrations rather than the mode analysis used in Refs. 6 and 9. As is usually done, the CO_2 system is assumed to have only two independent groups of levels: those associated with the asymmetric stretch mode form one group and those associated with the symmetric stretch and the bending modes are combined into the second group.[10] In the simplest form, this system can be modeled as a three-level laser system with the ground state N_0, the lowest symmetric stretch level N_2, and the lowest asymmetric stretch level N_3. Other levels of interest are presumed to have much smaller concentrations of particles and hence can be neglected. If it is necessary to calculate any level that is not explicitly contained in the model, such as the lower laser level, it is done by assuming mode equilibrium within each group. Each group has its own vibrational temperature, T_{v12} and T_{v3}, which can be calculated from the ratios N_2/N_0 and N_3/N_0, assuming Boltzmann equilibrium. The resulting linearized equations are then

$$D\nabla^2\mathfrak{N}_3 - \frac{1}{\tau_8}\mathfrak{N}_3 + S = 0$$

$$D\nabla^2\mathfrak{N}_2 - \frac{1}{\tau_1}\mathfrak{N}_2 + \frac{3}{\tau_8}\mathfrak{N}_3 = 0 \tag{1}$$

Where D is the diffusion coefficient assumed to be independent of vibrational excitation. In this form, the unknown number densities are measured relative to the spatially constant equilibrium values N_0^*, N_2^*, and N_3^*, i.e.,

$$\mathfrak{N}_3(r) = N_3(r) - N_3^*, \quad \mathfrak{N}_2(r) = N_2(r) - N_2^*$$

$$\mathfrak{N}_0(r) = N_0(r) - N_0^* \tag{2}$$

The state conditions as well as the relative concentrations are functions of radius only. The appropriate boundary conditions are symmetry on the centerline and a balance between diffusion and the kinetic flux at the wall,[11] i.e.,

$$\nabla\mathfrak{N}_3(0) = 0 \qquad -D\nabla\mathfrak{N}_3(R_w) = \frac{\eta'\bar{c}}{4}\mathfrak{N}_3(R_w)$$

$$\nabla\mathfrak{N}_2(0) = 0 \qquad -D\nabla\mathfrak{N}_2(R_w) = \frac{\eta'\bar{c}}{4}\mathfrak{N}_2(R_w) \tag{3}$$

where $\bar{c}$ is the mean molecular speed and $\eta' = \eta/(1-\eta/2)$ is assumed to be the same for both states since other in-

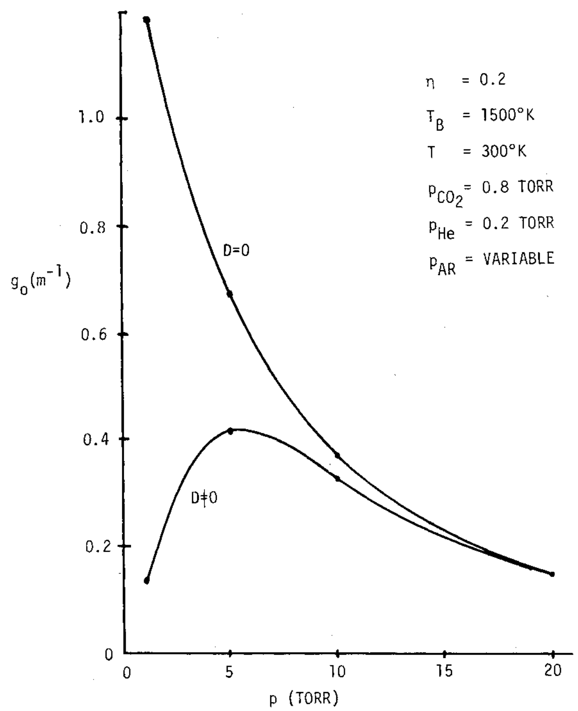

Fig. 6 Calculated small signal gain on centerline with and without diffusion assuming an optically thin laser medium.

formation is lacking. Neglecting the energy differences between the P and R branches in the 4.3 μm region, the source term S is approximated as

$$S = (0.85/\tau_{4.3} Q_v)\,[\mathfrak{N}_3(T_B) - \mathfrak{N}_3] \tag{4}$$

where $\tau_{4.3}$ is the radiative lifetime of the band (2.5 ms) and T_B the blackbody temperature. Also

$$\mathfrak{N}_3(T_B) = N_3(T_B) - N_3^* = \frac{N}{Q_v}\left[\exp\left(\frac{-\theta_3}{T_B}\right) - \exp\left(\frac{-\theta_3}{T}\right)\right] \tag{5}$$

which can be calculated except for a slight variation in the partition function[9] Q_v that depends implicitly on N_3 and N_2.

Since Q_v is only weakly dependent on radius, $\mathfrak{N}_3(T_B)$ is almost spatially constant, which is consistent with the assumption that the gas is optically thin. These equations were solved using a second-order finite difference method with false boundary conditions.[12] Initially, Q_v is taken as 1 and $\mathfrak{N}_3$ and $\mathfrak{N}_2$ are calculated. Then Q_v is adjusted to account for the Boltzmann distribution of energy. Using these values and subsequent estimates for Q_v, the solution is iterated until the variation in Q_v is less than 0.001. The final values of Q_v and T_{v12} are used to calculate the lower laser level population so that the small signal gain can be calculated. In Fig. 6 the gain obtained with this diffusion model ($D \neq 0$) is compared to the results with the diffusion coefficient set equal to zero. With diffusion the predicted small signal gain at low pressures is greatly reduced, whereas at pressures over 10 Torr the diffusion effects are minimal.

Remarks

The experiment described here has proved that pumping of gas lasers by a blackbody cavity is possible and a continuous-wave output of ~4.5 mW was obtained. A simple model assuming an optically thin gas has been developed to calculate the small signal gain for this blackbody-pumped CO_2 laser and the trends predicted by it seem to qualitatively match the experimental results. However, calculations show that the peak absorption coefficient of the CO_2 gas is $\mathcal{O}(20\ \text{cm}^{-1})$ for the conditions of the experiments, indicating that the assumption of an optically thin gas is not very appropriate. It appears that modeling should include representations of the optical depth associated with the pumping radiation and the axial temperature distribution of the laser gas. A more complete understanding of the physics involved in the weakly blackbody-pumped laser is still needed. Experiments optimizing the gain at 10.6 μm and the output power are ongoing.

Acknowledgments

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