NUCLEAR RADIATION ENHANCEMENT OF CO₂ LASER PERFORMANCE

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Abstract

The effect of nuclear radiation on the operation of electrically excited CO₂ lasers is discussed. Three types of experiments and results are presented: (1) low-pressure CW laser; (2) low-pressure pulsed laser; and (3) high-pressure TEA pulsed laser.

Introduction

The authors and others¹⁻³ have reviewed earlier attempts to use energetic ions from neutron induced nuclear reactions to pump and/or enhance gas lasers performance. The present paper describes recent studies of the enhancement of CO₂ laser operation carried out at the University of Illinois.

The possibility of improved CO₂ laser operation was first suggested by Andriakhin, et.al.⁴ who showed an increased output when an electrically excited laser was bombarded by a proton beam from an accelerator. Later other⁵ observed small changes with quite small radiation inputs. Ganley et.al.⁶ first reported sizable changes when a low-pressure DC excited CO₂ laser with a boron lined discharge tube was irradiated by neutrons from a nuclear reactor. Additional low-pressure results are described here along with high-pressure and pulsed studies.

The population inversion in electrically excited gas lasers is produced, either directly or indirectly, by electron collisions with the atoms or molecules of the gas. Thus, the pumping process depends on the electron density and, because of the energy dependent collision cross sections, on the electron energy distribution function. Unfortunately, the electron energy distribution cannot be arbitrarily controlled. Its shape is determined by the various collision cross sections, and also by the requirement that each electron be reproduced in its lifetime. The performance of many existing laser systems could be improved if part of these requirements be relaxed. One possible way to do this is through the use of an external or auxiliary source of ionization.

The experiments described here are an attempt to study the effects on an external source of ionization on various types of CO₂ laser discharges. It is shown that when the discharge conditions are properly chosen, an increase in laser output is obtained, and this is attributed to a partial control over the electron density and energy distribution functions.

A wide variety of conditions have been examined. Experiments have been performed with low-pressure (5 to 20 Torr) longitudinal discharges for both continuous and pulsed current conditions. High-

pressure (100 to 760 Torr) transversely pulsed discharges (TEA design) have also been studied.

The external ionization was produced by the α -particles emitted from neutron irradiation of a boron coating. In the low-pressure discharges, the boron (90% enriched ¹⁰B) was coated on the inside wall of the discharge tube, while in the high-pressure discharges, the boron was placed on the anode. In the presence of a flux of thermal neutrons, high energy particles are produced by the reaction:

Nuclear particles escaping from the coating pass into the discharge region and act as an independent ionization and excitation source. Although our experiments have used reaction (1) for this purpose, it could probably be fulfilled equally well by other nuclear reactions or by an electron beam, an X-ray source, or a γ -source.

In the low-pressure D.C. discharges, the 10.6 μ gain has been observed to increase over a wide range of pressures and currents as a result of the external ionization source. Corresponding increases in the output from an operating CW laser have been observed. Increases have also been produced in pulsed discharges (high and low pressure), but no study has been made of the changes in the gain of these discharges.

It is believed that the external ionization has two main effects on the discharges studied. First, there appears to be a tailoring of the electron energy distribution toward optimum laser pumping. Second, the uniformity of the discharges is improved. The former effect appears to be dominant in the D.C. discharges--an opinion which is born out by the results of the gain experiments. Since no gain experiments have been performed on the pulsed discharges, it is not possible to say which of the two effects is dominate.

Low Pressure D.C. Discharges

Figure 1 shows the details of the electrical discharge tube used to study the effects of an external ionization source on the operation of a low pressure, continuous wave CO₂ laser. A quartz tube was used for maximum neutron transmission. With the exception of the region one centimeter from the electrodes, the inside of the tube was coated with a thin (2-10 μ), rather non-uniform layer of ¹⁰B. The aluminum mirror mounts served as connecting points for the anode and cathode leads and the current to the discharge was controlled by an external circuit. Water cooling was employed to minimize gas heating effects. A mixture of He, N₂, and CO₂ (8:1:1) was slowly flowed through the tube at pressures ranging

from 5 to 20 Torr.

Figure 1. Details of the low-pressure CO₂ laser.

The experiments consisted of inserting the discharge tube into the beam port of a Triga Reactor and positioning it adjacent to the reactor core. When the reactor power was increased, neutrons produced in the core were absorbed in the boron coating and high-energy ions were produced by reaction (1). Energetic ions produced in this way pass through the discharge volume, causing ionization and excitation which is independent of the main discharge conditions.

Figure 2. Schematic of the gain experiment.

To explore the effects of this external ionization, two types of experiments were performed: a "gain experiment" and a "laser monitoring experiment". The setup for the gain experiment is shown in Figure 2. The output of a CO₂ reference laser was directed onto a sodium chloride beam splitter. Part of the beam was reflected into a reference detector, D1, and part passed through the beam splitter and into the boron coated discharge tube. After passing through this tube, the laser light was reflected back out toward the beam splitter by a gold-coated spherical mirror. At the beam splitter, part of this light from the discharge tube was reflected onto the output detector, D2. Since the beam entering D2 made a double pass through the discharge tube, the magnitude of the signal from D2 was dependent on the optical gain of the medium in the discharge tube as well as on the intensity of the light coming from the reference laser. The output

from D1 depended only on the intensity of the light from the reference laser. Thus, by comparing the relative magnitude of the signals from the two detectors, it was possible to determine the percentage increase (gain) of the laser light passing through the discharge tube.

To interpret these experiments, it was necessary to record the detector outputs for three different situations. First, the outputs were recorded with the tube filled with gas but with the discharge off. The corresponding detector outputs were denoted $I_0(D1)$ and $I_0(D2)$. Next, the signals from the detectors were recorded with the discharge on. The signal D2 under these conditions, $I_E(D2)$, was much larger than $I_0(D2)$ because of the gain introduced in the discharge tube. (The signal from D1, $I_E(D1)$, was essentially the same as $I_0(D1)$). Finally, signals were recorded as the discharge was subjected to the nuclear radiation. Under appropriate conditions this led to an increased gain, i.e. an increased signal from D2, $I_N(D2)$. The signal from D1, $I_N(D1)$, was again unchanged.

The various signals obtained are related in the following manner:

$$I_0(D2) = KI_0(D1) \quad (1)$$

where K is a constant scaling factor which accounts for the raw light levels reaching the two detectors and for different detector sensitivities. With the discharge on (radiation off) the signals become:

$$I_E(D2) = KI_E(D1) e^{+2\alpha_E L} \quad (2)$$

where α_E is the gain coefficient of the electrically excited discharge and L is the length of the discharge region.

When the radiation is turned on, we obtain:

$$I_N(D2) = KI_N(D1) e^{+2\alpha_N L} \quad (3)$$

where α_N is the gain coefficient of the irradiated discharge. These equations may be solved for the gain coefficients with the following results:

$$\alpha_E = \frac{1}{2L} \ln \frac{I_E(D2) I_0(D1)}{I_E(D1) I_0(D2)} \quad (4)$$

$$\alpha_N = \frac{1}{2L} \ln \frac{I_N(D2) I_0(D1)}{I_N(D1) I_0(D2)} \quad (5)$$

The change in the gain coefficient, $\Delta\alpha = \alpha_N - \alpha_E$, is given by the relation:

$$\Delta\alpha = \frac{1}{2L} \ln \frac{I_N(D2) I_E(D1)}{I_N(D1) I_E(D2)} \quad (6)$$

The gain coefficients are directly proportional to the population inversion in the medium and therefore $\Delta\alpha$ gives a measure of the relative change in population inversion which is produced as result of the external ionization.

The pressure range from 5 to 20 Torr has been explored for values of discharge current from 5 to 45 ma. The value of Δa is plotted as a function of discharge current for various pressures in Figure 3.

Figure 3. Change in gain of a CO₂ discharge for neutron irradiation flux of $\sim 5 \times 10^{14}$ n/cm²/sec.

The discharge voltage and current were both monitored during these experiments. These parameters are of importance because, with the aid of positive column theory, they can be interpreted in terms of average electron energy and electron density. When this is done it is possible to infer the variation of the gain as a function of electron density. As was stated earlier, the discharge parameters of importance are electron density and energy distribution. Unfortunately, because of the flow rates used, the gas temperature is also a variable and hence it is not possible to evaluate the absolute change in pumping rate corresponding to various values of current.

The details of the laser monitoring experiment are shown in Figure 4. The discharge tube employed earlier in the gain experiments was used, but with the sodium chloride window replaced by a suitable mirror. The output of this laser was then monitored under many of the same conditions which were studied in the gain experiments.

The results of the laser experiments cannot be as easily interpreted as the results of the gain experiments since it is difficult to distinguish laser mode switching and/or transition jumping from the desired 10.6 μ enhancement. The results of a typical run are shown in Figure 5, and it can be seen that the laser output follows the same trend as the laser gain. This was the case for all pressures and currents studied. This correlation

implies that the increased output is, indeed, due to an increased gain on the 10.6 μ line.

Figure 4. Schematic of the laser experiment.

Figure 5. Changes in laser output due to the neutron irradiation.

To explain the results of the low-pressure experiments is a difficult task because of the large number of interdependent variables (for example, gas temperature and current). However, a few general conclusions can be drawn on the basis of this data.

First, it appears that the effect of nuclear irradiation must be a catalytic one. Calculations show that the power supplied by the nuclear source is negligible (<1%) when compared to that supplied by the electric field. Indeed, the nuclear power deposited in the gas is even smaller than the change in laser power shown in Fig. 5 at $I = 40$ ma. Thus, direct nuclear pumping can be ruled out for this case.

On the other hand, the calculated nuclear power is comparable to that part of the electrical power that is utilized to keep the discharge alive. This is emphasized in Fig. 6 where an energy flow diagram for the CO₂ laser is shown. In a normal positive column, a very small fraction of the input energy goes into the ionization path, but it is all important. Even though most of energy passes through the

paths of W_1 and W_2 , the distribution of the electrons must be such that the "loop gain" of the ionization path, W_3 , equals 1.

Figure 6. Energy flow diagram of a CO_2 laser.

The introduction of the external ionization source relaxes this requirement allowing the electron energy distribution to assume a form more closely dictated by the cross sections of the reactions of paths W_1 and W_2 ; apparently, this latter distribution is better suited for pumping the laser levels.

This explanation is in qualitative agreement with the variation in gain (Fig. 3) or laser output (Fig. 5) vs. current; namely, the decrease in gain at low currents, the increase at moderate currents, and no change at higher currents.

At low currents, the nuclear induced ionization is much more than required to maintain the discharge at a constant current and constant average energy. Thus, the longitudinal electric field drops to compensate for the external source. If the average energy drops too low, there are few electrons able to pump the laser levels⁶ and the laser output decreases.

At moderate currents, the nuclear induced ionization appears to be more nearly matched to that required to maintain the discharge current at a given electric field. In this region, the longitudinal field is not appreciably reduced by the external ionization. Since the longitudinal field is a good measure of the drift velocity of the electrons and their average energy, the latter have not changed. Furthermore, since the current is held constant, the electron density has not increased appreciably. Thus it appears that the shape of electron energy distribution has changed

as discussed above such that the laser levels are pumped more efficiently.

At high currents, the nuclear ionization is much smaller than that caused by the electrical source, hence the electron distribution is determined by requirements of paths 1, 2, and 3 of Fig. 6 and very little change in gain or laser output is observed.

In summary, then, for a given set of conditions (pressure, current, and gas mix), there is optimum value of external ionization rate which enhances the laser output.

Pulsed Discharges

The effect of external ionization on pulsed CO_2 laser operation has also been investigated. Nuclear radiation was found to increase the size of the laser output pulse and lower the voltage threshold required to produce lasing in both low and high pressure discharges.

Low-Pressure

Pulse low-pressure discharges were studied by applying current pulses to the discharge tube shown in Figure 1. The gas mix, flow rate, and pressures were the same as in the D.C. experiments. The current pulse was obtained by discharging a (0.015 μf) capacitor through the laser tube with a thyatron pulser. A 4-5A current pulse of roughly 10 μsec was obtained, and it was found that the laser output was delayed from the current pulse by about 75 μsec . This time lag is not completely understood, but it could be due to the transfer time associated with N_2 pumping of CO_2 or alternately it may be indicative of dissociation of CO_2 and lasing upon recombination.⁹

The effects of the nuclear ionization source on the output of the laser are shown in Figure 7. The first photograph (a) shows a series of laser pulses taken with no external ionization. The laser was pulsed at intervals of 0.8 seconds, starting with the top trace. The second photograph, (b) shows the results of the same pulsing operation, with the same discharge conditions, for various levels of nuclear radiation. Fig. 7 (c) shows the radiation levels at the times of the laser pulses in 7(b). The dots correspond to the times at which the laser was pulsed. Notice that even at very low levels of incident radiation, the favorable effects on laser output are quite pronounced. As the radiation level increases, the laser power also increases. Increased outputs as large as 10 X are observed, however, a point is eventually reached where the radiation effect tends to saturate. Also, notice that in addition to increasing the output of the laser, the external ionization causes the laser pulse to follow the current pulse much more closely. The explanation of these results cannot be given at this time. A combination of effects may be involved--better pumping efficiency, larger active volume, and increased uniformity of the discharge.

High-Pressure (TEA Laser)

The results obtained in experiments with a high-pressure, transversely pulsed discharge (Fig. 8) are

qualitatively the same as those discussed above for the low-pressure pulsed discharge. The laser used here is of the conventional linear TEA design except for several minor modifications. The anode was coated with boron to provide the external radiation source. Also, fairly large (10K) resistors were employed and they were potted in silicone compound to prevent spurious internal arcing which might be enhanced by the reactor radiation.

for clarity). A maximum enhancement of a factor of 2 or 3X is observed.

Figure 8. Construction of TEA laser.

Figure 7. Effect of nuclear radiation on a pulsed CO_2 laser; (a) neutron flux equals zero, (b) Laser output for corresponding neutron flux shown in (c) Counting from the top, each trace in (b) corresponds to a dot in (c).

Figure 9 shows typical increases in output power which can be achieved by irradiating the discharge volume. A raster display was employed so that each laser pulse (separated by 1 sec, traces inverted) appears as a separate trace. The first pulse at the top corresponds to the start of the reactor pulse (see 7(c) and the 6th pulse corresponds to the peak reactor power. The laser pulses were displaced to the right in time by the raster

Figure 9. Output of a 1/2 atmosphere TEA laser for neutron level corresponding to Fig. 7(c) (see text). (a) During reactor pulse as in Fig. 7(c). (b) After reactor pulse.

The peak output of the TEA laser used here was of order of 10 KW. It is hoped that the effect observed here can be scaled-up to higher power

systems; however, this depends on the detailed mechanism responsible for the change and considerable more study is required to identify this. Theoretically the added radiation should provide a more uniform discharge and prevent formation of the "white arcs" that plague TEA lasers. Simultaneously, some tailoring of the electron energy distribution may occur and improve the pumping efficiency. However, the possibilities of mode jumping, transition switches, internal gas lens effects, etc. cannot be ruled out as contributing to these early results.

It should be noted that in both the low and high pressure pulsed discharges, the presence of the external ionization source makes it possible to achieve lasing at higher pressures for a given breakdown voltage. This is, in itself, an important result in light of the attempts now being made to pump CO₂ lasers pressures above 1 Atm where breakdown with obtainable power supplies becomes a problem.

This work was supported by grant AT(11-1) 2007 AEC Research Division. Continued support by the Illinois TRIGA reactor staff is gratefully acknowledged.

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