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T.-K. Cheng Ken

Lee W. Casperson
Portland State University

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Properties of a coaxial cw CO₂ laser

Ken T.-K. Cheng and Lee W. Casperson

A cw CO₂ laser has been developed in which the active medium is formed by a discharge between coaxial electrodes. The laser gain and saturation properties have been studied as functions of the various device parameters. Over-all efficiency is about the same as for a conventional longitudinal discharge laser, and advantages of the coaxial geometry include low voltage operation, rapid cooling, and rugged construction.

I. Introduction

Continuous-wave gas lasers have traditionally used high-voltage and low-current longitudinal dc discharges to establish a plasma for the required population inversion. Attention has also been directed into the transverse excitation approach to gas lasers in an attempt to reduce the high drive voltage inherent in conventional longitudinal discharge lasers.^{1,2} The transversely excited cw lasers usually use a number of discrete electrodes to produce a glow discharge at low voltage and high current, and the discharge with these short electrode spacings often exhibits an abnormal glow. The advantage of this abnormal glow is that the impedance is positive and the ballast resistor for the discharge becomes unimportant. Unfortunately this type of discharge tends to form arcs. Once an arc is formed, the lasing action is terminated, and this is the main problem which has to be overcome for all transversely excited lasers. A coaxial discharge for the laser gain medium has been successful for pulsed CO₂ lasers,³⁻⁵ and a study of the gain medium of a coaxial discharge for cw CO₂ lasers has been performed.⁶

The purpose of this work has been to develop a coaxial discharge scheme for generating a gain medium and to study the application of this medium to a coaxial cw CO₂ laser oscillator. The coaxial cw discharge shows a number of interesting features. The excitation voltage is low being of the order of 500–1000 V. The discharge exhibits a positive impedance, so that very small or zero ballast resistance can be used. This increases the over-all efficiency. The discharge is also much easier to sustain without arcing than other transverse

geometries. A coaxial cw CO₂ laser has been constructed and investigated, and the properties of this device are discussed in the following sections. After a brief consideration of coaxial discharges, the experimental setup is described in Sec. II. The basic V-I characteristics are reported in Sec. III, and the results of detailed gain measurements are summarized in Sec. IV. The highest gain achieved has been about 200%/m. With the addition of cavity mirrors a laser oscillator is formed, and our oscillator experiments are described in Sec. V.

II. Coaxial Discharge

The general characteristics of gas discharges are highly complex, and in spite of their importance, no exhaustive analysis has been given. Special complications in the present laser studies include the coaxial geometry and the use of a three component laser gas mixture. Nevertheless, a few general comments may be helpful in anticipating the performance of a coaxial laser.

For voltages below the breakdown voltage in a coaxial capacitor, the radial electric field variations are given by⁷

$$E(r) = V/[r \ln(b/a)], \quad (1)$$

where V is the voltage, and a and b are, respectively, the inner and outer radii. This formula illustrates the well-known result that the field may be much higher near the smaller central electrode. In the glow discharge regime Eq. (1) is no longer rigorously valid, but it remains true that the field tends to be stronger near the axis. Within limits the higher field region tends to have a more rapid ionization of the laser gases and a higher population inversion. Thus it is not unreasonable to anticipate that the laser gain would be higher near the axis, although there is an optimum E/N ratio for excitation of the upper laser level.⁸

The authors are with University of California, School of Engineering & Applied Science, Los Angeles, California 90024.

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A glow discharge may actually consist of several different spatial regimes including from cathode to anode the Aston dark space, cathode glow, cathode dark space, negative glow, Faraday dark space, positive column, anode dark space, and anode fall.^{9,10} Of these regions only the glows can have any relevance as laser gain media, and typically only the negative glow and the positive column are large enough and bright enough to have practical interest. Experiments with CO₂ lasers have demonstrated that the highest gain is generally obtained in the positive column.²

The system used for the present studies of the glow discharge and gain and laser oscillator properties is the coaxial electrode scheme shown in Fig. 1. The outer tube of this coaxial device is a 1-in. (2.54-cm) i.d. copper pipe which serves as the anode. Both ends of this pipe are flared in order to reduce field gradients near the edges, and the internal surface is polished to discourage arcing. In the present model, thin Plexiglas spacers are placed on each end to support and to center the cathode. For most of our experiments, the cathode is a 1/8-in. (3.2 mm) o.d. stainless steel tube.

Both electrodes are cooled by flowing water. Without such cooling, the discharge at high currents tends to form intense restricted hot spots which finally turn into arcs. Besides reducing the arc transition instability, cooling also enhances the gain and power by reducing the gas temperature of the active medium. To further prevent arcing at the ends of the discharge, glass tubes are slipped over each end of the cathode. A Pyrex pipe is connected to each edge of the anode to define the gas volume and also to discourage the discharge from forming at the anode edges for low pressure operation. For visual observations and gain measurements, the coaxial discharge is equipped with salt windows. In the laser oscillator studies, internal mirrors are employed.

A power supply of 5 kV–1.3 A is used for sustaining the discharge. Although the discharge has a positive impedance, a ballast resistor of about 500 Ω is used to protect the power supply from damaging by sudden arcs caused mainly by defects on the cathode. The flow rate for all gas mixtures is kept constant at about 5 SCFH.

III. V-I Characteristics

Numerous experiments have been performed to determine how the characteristics of the coaxial laser depend on the many physical parameters of this device. This section includes a summary of the experiments concerning the V-I characteristics of the discharge. When the pressure is raised above 1 Torr, the cathode glow, negative glow, and the Faraday dark space tend to shrink toward the cathode, and the positive column and anode dark space fill the rest of the volume. If the pressure decreases below 1 Torr, the negative glow and cathode glow extend their boundaries at the expense of the positive column. Below 0.2 Torr, the positive column disappears entirely, and the negative glow fills the region between the concentric electrodes. A transition

Fig. 1. Coaxial amplifier configuration (not to scale).

Fig. 2. Discharge voltage as a function of current for various gas mixtures.

from glow to arc occurs inevitably if the pressure is increased to more than about 30 Torr.

Figure 2 shows the effects of pressure on the V-I characteristic for the typical gas mixture 13.5:3:1 of He, N₂, and CO₂ at pressures of 4 Torr and 8 Torr. We find that it requires less voltage to maintain a given current at the higher pressures. The reason is that the potential of cathode fall V_c varies as j/p^2 (current density/pressure²),¹¹ which means V_c decreases with increasing p at a constant value of current after the cathode is covered by glow.

The effect of gas ratio on the V-I curves can also be inferred from Fig. 2. We observe that the mixture 13.5:3:1 of He, N₂, and CO₂ has the best discharge characteristics in terms of lower sustaining voltage. It is clear that most portions of these curves show a positive impedance, which reduces the need for ballast resistance.

Fig. 3. Influence of cathode material on the V-I characteristics of a coaxial discharge.

When the cathode material has a lower work function, a lower voltage is required to start and to maintain the discharge. Figure 3 shows the differences between the V-I curves for aluminum, copper, and stainless steel cathodes. Aluminum has the lowest work function and possesses the lowest breakdown and sustaining voltages. However, this material has been found to deteriorate gradually and forms a hard insulating deposit on the cathode surface. Stainless steel is chosen for the final cathode design. Varying the anode material has not led to significant changes in the V-I characteristics.

IV. Gain Measurements

The amplifier used for the investigation of the gain has been described, and a sketch of the over-all experimental setup is shown in Fig. 4. The gain measurements were performed by the standard procedure. The CO₂ probe laser used in the gain measurements consists of a 1-cm diam 80-cm long water-cooled sealed-off discharge tube with salt windows at the Brewster angle on each end. This discharge tube is placed between a flat germanium mirror with an 80% reflectivity and a 2-m gold coated curved mirror, forming a 1-m resonator cavity. A 13.5:3:1 mixture of He, N₂, and CO₂ is used in the discharge tube at a total pressure of 20 Torr and a discharge current of 10–20 mA at 7–10 kV. The probe laser operates in the fundamental TEM₀₀ mode at 10.6 μ m, and the higher order transverse modes are eliminated by an aperture. The laser output power is controlled by the applied current.

Due to the invisibility of the 10.6- μ m probe beam, a He-Ne laser is used to align the setup. By adjusting mirrors M1, M2, M3, and M4 in Fig. 4 and using reflections from the salt windows S₁ and S₂ on the ends of the amplifier, the two laser beams can be made to propagate collinearly through the amplifier parallel to its axis. The beam is focused at the center point of the amplifier with a beam diameter of about 2 mm by a $f = 1$ -m gold mirror. The beam is scanned across the amplifier by horizontal movement of the amplifier support stages.

After passing through the 10-in. (25.4-cm) active medium of the amplifier, the probe beam is detected by a power meter. Readings of the power meter are taken with the discharge off and on for various radial positions, gas mixtures, pressures, and discharge currents. Saturation is not observed with increasing probe laser power up to about 0.2 W, which implies a power density of 6.5 W/cm² at the beam waist. This is well below the reported saturation intensity of 20–100 W/cm².¹² The laser power, used for all the gain measurements, is controlled to about 100 mW. The dependence of gain on pressure, current, gas mixture, and radial position is summarized below. Values for the saturation parameter have also been obtained.

A. Gain Dependence on Pressure

From Fig. 5, we notice an increase of gain with increasing pressure for several gas mixtures. With the increase of pressure, the concentrations of the active CO₂ molecules are increasing as well. One of these curves also shows some indication of a decrease in gain after the pressure passes about 5 Torr. Such a decrease is to be expected eventually due to the increase of temperature with pressure in the positive column.¹³ For most of our experiments, the discharge is operated at about 5 Torr. At higher pressure, the discharge tends to contract to the cathode surface.

Fig. 4. Gain measurement setup.

Fig. 5. Gain as a function of pressure at a current of 300 mA.

Fig. 6. Gain as a function of current at a pressure of 5 Torr.

Fig. 7. Gain as a function of He/CO₂ ratio at a pressure of 5 Torr.

Fig. 8. Gain as a function of N₂/CO₂ ratio at a pressure of 5 Torr.

B. Gain Dependence on Current

From Fig. 6, we observe that the gain increases with increasing current at lower values of current. The reason is that with the increases of current, the electron concentration grows, and, consequently, the pumping rate and the population inversion of the laser level are growing as well. However, further increases of the current density result in an increase in the gas temperature. Then the population inversion decreases, so that a decrease in gain with increase of current is observed. In addition, at higher gas temperatures, the CO₂ may dissociate into CO and O₂ molecules, which also decreases the gain.¹⁴

C. Gain Dependence on Gas Mixture Ratio

Gain measurements have been made for several different gas mixtures. A flow rate of 5 SCFH is used during all the experiments. The highest gain is about 200%/m for the mixture of 4:1:1 at 5 Torr with a current of 0.25 A as shown in Fig. 6. The gains are higher at lower He/CO₂ ratios as shown in Fig. 7. The limitation for operating the laser in these lower He/CO₂ ratios is the instability of the discharge and arcing. The best choice of mixture is 13.4:3:1 of He:N₂:CO₂ due to its more stable discharge and higher gain. The gain has its peak when the ratios of N₂/CO₂ = 1 and He/CO₂ = 4 as shown in Fig. 8. Also we observe that the gain is insensitive to the N₂/CO₂ ratio when the ratio of He/CO₂ ≥ 8.

D. Radial Gain Profile

The investigation by Wiegand *et al.* showed, experimentally and theoretically, that the radial small signal gain profile was dependent on the discharge current.¹⁵ Typical radial profiles across the amplifier diameter are measured and are shown in Fig. 9 as a function of current. The peaks of the gain lie between 2.5 mm and 3.5

Fig. 9. Gain profiles for the gas mixture ratio 13.5:3:1 at 4 Torr.

mm from the cathode, and the radial gain profiles show the dependence on the discharge currents. The occurrence of such maxima is reasonable considering that the E/N ratio has an optimum value.

E. Saturation Parameter

Besides the gain coefficient, it is essential for power calculations to have some estimate of the saturation intensity of a laser medium. The details of the saturation process depend to some extent on whether homogeneous or inhomogeneous line broadening is dominant. At pressures of about 5 Torr, the CO_2 laser is technically a mixed case, but the saturation characteristics are still very close to those for pure homogeneous broadening. Thus it is sufficient here to consider the familiar intensity equation

$$\frac{dI}{dz} = \frac{g_0 I}{1 + sI}, \quad (2)$$

where g_0 is the small signal gain coefficient and $s = 1/I_s$ is a saturation parameter.

The integral of Eq. (2) for a laser amplifier of length l can be written

$$\ln \frac{I_{\text{out}}}{I_{\text{in}}} = -\frac{I_{\text{out}} - I_{\text{in}}}{I_s} + g_0 l. \quad (3)$$

From this equation, it is clear that the saturation intensity of an amplifier can be obtained from the slope of a plot of $\ln(I_{\text{out}}/I_{\text{in}})$ vs $(I_{\text{out}} - I_{\text{in}})$. Typical results for the coaxial laser amplifier are shown in Fig. 10, and one finds from these examples that the saturation intensities are about 46 W/cm^2 , 75 W/cm^2 , and 58 W/cm^2 for currents of 200 mA, 300 mA, and 500 mA, respectively, and the gas mixture 13.5:3:1 at 4-Torr pressure. The ordinate intercepts in Fig. 10 show that the small signal gain increases with discharge current as expected.

V. Coaxial Laser Oscillator

Continuous wave gas lasers have traditionally used high-voltage low-current dc discharges to establish a plasma gain medium. In our case, CO_2 cw lasing has been achieved using as the active medium a plasma formed by a low-voltage discharge within a coaxial electrode configuration. The amplifier which has been described in the last few sections is turned into a laser oscillator by placing it between two mirrors. One of these mirrors is a 98% reflectivity germanium flat used as the output coupler, the other is a 2-m gold-coated concave mirror, and the cavity length is 1.2 m. The optical cavity is established on one side of the coaxial discharge, and the beam diameters on the flat and gold mirrors are calculated to be 3.6 mm and 6 mm, respectively. The laser medium is coupled to only one tenth of the total gain volume, and the laser output is about 200 mW. Much higher outputs should be possible with a suitable annular resonator design.⁴ Efficiency would also be improved with a lower reflectivity optimized coupling mirror.

The dominant transverse modes of oscillation are observed to be $\text{TEM}_{0,0}$, $\text{TEM}_{1,0}$, and $\text{TEM}_{2,0}$, and the individual modes can be selected by means of apertures.

The other higher order modes are not observed due to the limited space between electrodes. In order to avoid the inevitable losses caused by Brewster windows, an intracavity resonator has been employed. Alignment is performed with a He-Ne laser, and this alignment is reoptimized after every measurement in our radial power scans.

A typical plot of the laser output power as a function of distance from the cathode is included in Fig. 11. Not surprisingly, this radial power profile is similar in shape to the radial gain profiles, which have been presented in Fig. 9. A linear relationship between the output intensity I_0 and the gain would be expected from the familiar theoretical formula

$$I_0 = \frac{TI_s}{2} \left[\frac{2g_0 l}{(1 - R_1) + (1 - R_2) + 2\gamma l} - 1 \right], \quad (4)$$

where T is the transmission of the coupling mirror, R_1 and R_2 are the mirror reflectivities, and γ is a distrib-

Fig. 10. Saturation parameters for the gas mixture ratio 13.5:3:1 at 4 Torr. Intensity is measured in W/cm^2 .

Fig. 11. Radial power profile for the gas mixture ratio 13.5:3:1 at 2.5 Torr and 1.2 A.

Fig. 12. Laser power as a function of current for the gas mixture ratio 13.5:13:1 at 2 Torr, 2.5 Torr, and 3 Torr.

uted loss coefficient. The first factor of two on the right-hand side of this equation results from attributing the saturation to the sum of the right and left traveling intensities.

Some plots of output power vs current and pressure are given in Fig. 12. It may be observed that these plots do not follow the linear relationship in Eq. (4) due to the nonlinear gain-current relationship and the nonconstant discharge geometry. The lowest oscillation threshold is obtained at the lower pressures where the gain region spreads farthest from the cathode.

VI. Conclusion

We have reported a coaxial discharge configuration for a cw CO₂ laser. The excitation voltage is low, of the order of 500–1000 V, eliminating the usual high voltage power supply and making the laser more attractive for practical applications. The discharge has a high gain and is stable, which makes it a good candidate for moderate power lasers. Due to the positive impedance of the discharge, very small or zero ballast resistance can be used, which increases the over-all efficiency. The wall cooling of the gas mixture is relatively efficient, and the whole laser system is rigid because of the metallic electrodes. This same discharge geometry should also be applicable to many other laser media. Annular

resonators would usually provide the best coupling efficiency. For IR and far IR lasers, however, it should also be possible to obtain oscillation in the familiar plane-wave coaxial waveguide modes.

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