

# Role of Heated Gas Self-Absorption on CW CO<sub>2</sub> Laser System Output

Oday A. Hammadi <sup>1</sup>, Najem A.K. Al-Rubaiey <sup>2</sup>, Dayah N. Raouf <sup>3</sup>, Salah N. Abdullah <sup>4</sup>

<sup>1</sup> Department of Physics, College of Education, Al-Iraqia University, Baghdad, IRAQ

<sup>2</sup> Department of Oil Technology, University of Technology, Baghdad, IRAQ

<sup>3</sup> Department of Applied Sciences, University of Technology, Baghdad, IRAQ

<sup>4</sup> Commission of Atomic Energy, Ministry of Science and Technology, Baghdad, IRAQ

## Abstract

In this research, the effect of self-absorption by the active medium molecules on the output power of a continuous-wave carbon dioxide laser at low pressures was studied. The effect of the discharge current, output mirror transmittance, and total gas pressure on the laser output power was discussed. It was observed that self-absorption depends on the concentration of carbon dioxide molecules, the output mirror transmittance of the optical resonator, and the discharge current used, and that there is a threshold value for both the transmittance and the discharge current at which absorption significantly affects the output power.

**Keywords:** CO<sub>2</sub> laser; Self-absorption effect; Laser design; Output optimization

**Received:** 22 October 2024; **Revised:** 25 November; **Accepted:** 16 December; **Published:** 1 January 2025

## 1. Introduction

The output power of CO<sub>2</sub> lasers is affected by changes occurring in the optical cavity of the laser system, such as scattering losses, absorption losses at the mirror surfaces, diffraction losses, in addition to absorption losses by gas molecules that heat up without being excited [1]. Unexcited CO<sub>2</sub> gas molecules inside the continuous-wave laser chamber have a significantly negative effect on the output power [2]. This effect is attributed to fluctuations in the cavity losses resulting from thermal convection generated by self-absorption of radiation by the gas that heats up without being electrically excited inside the chamber [3].

The instability in losses occurs at a certain threshold level of the laser output power, and this threshold is determined by the initial state of the temperature change resulting from the rapid increase in the absorption coefficient of CO<sub>2</sub> molecules with increasing gas temperature [4]. After this threshold, the laser output power decreases due to the increasing cavity losses caused by the self-absorption of hot CO<sub>2</sub> molecules [5].

The gain coefficient  $g(v_0)$  of the active medium at the center of the laser's produced transition band is given as follows [2]:

$$\alpha_0 = \frac{\lambda^2}{8\pi\tau_{sp}} g(v_0) \left( N_2 - \frac{g_2}{g_1} N_1 \right) \quad (1)$$

where  $\lambda$  is the wavelength,  $\tau_{sp}$  is the spontaneous emission lifetime,  $N_1$  and  $N_2$  are the population

values in the lower and upper laser levels, respectively,  $g_1$  and  $g_2$  are the degeneracy values for each of the levels, and  $g(v_0)$  is the normalized gain function, given as follows [4]:

$$g(v_0) = \frac{1}{8\pi\Delta\nu} \quad (2)$$

where  $\Delta\nu$  is the homogeneous spectral line width (MHz), which is a function of the gas pressure inside the chamber ( $p$ ) and its temperature ( $T$ ), and is given as follows [3]:

$$\Delta\nu = 7.58[X(CO_2) + 0.73(N_2) + 0.6(He)]p\sqrt{\frac{300}{T}} \quad (3)$$

The homogeneous spectral line width of the laser beam is directly related to the absorption coefficient of the active medium for the resulting wavelength. The absorption coefficient  $a_{v_0}(J)$  at the central frequency ( $v_0$ ) of the P(20) transition is given as follows [3]:

$$a_{v_0}(J) = YX [(2J-1)/(2J+1)](F^{(100)} - F^{(001)})N \quad (4)$$

where  $Y = \lambda^2/[4\pi^2\Delta\nu\tau_{sp}]$ ,  $X$  is the mole fraction of CO<sub>2</sub> gas in the gas mixture,  $N$  is the total density of gas molecules,  $J$  is the rotational quantum number, and  $F(lmn)$  is the fractional population of the vibrational level ( $lmn$ ) with rotational quantum number  $J$

Also, the spectral line width is related to the population inversion achieved during operation through its dependence on the gas temperature, which determines this value, as follows [4]:

$$N = N_0 \exp(-\Delta E/K_B T) \quad (5)$$

Several published studies have investigated the absorption of the gas medium for the 10.6  $\mu\text{m}$  band of the CO<sub>2</sub> laser [6-12]. These studies

included investigating the dependence of the absorption coefficient of pure CO<sub>2</sub> gas and the absorption coefficient of the CO<sub>2</sub>:N<sub>2</sub>:He gas mixture on both the total gas pressure [13,14] and its temperature [15]. The absorption spectrum of the CO<sub>2</sub> laser gas medium was represented by a homogeneous function at a total gas pressure of 10 Torr at the central frequency ( $\nu_0$ ) of the band, as in Eq. (4) [3].

Self-absorption by the hot gas can affect the oscillation line because the absorption coefficient  $a_{\nu_0}(J)$ , which depends on the rotational quantum number ( $J$ ), is primarily affected by the gas temperature. The value of ( $J$ ) at which the maximum value of the absorption coefficient  $a_{\nu_0}(J)$  is obtained increases with the gas temperature. At temperatures above 400 K, the absorption coefficient  $a_{\nu_0}(J)$  is an increasing function of the rotational quantum number  $J$  for the range  $J < 20$ . Therefore, the absorption loss due to self-absorption is also a function of  $J$  and increases with it for the same range.

In this research, the effect of self-absorption by the active medium molecules on the output power characteristics of a locally manufactured, low-pressure CW CO<sub>2</sub> laser was discussed.

## 2. Experimental Part

A CO<sub>2</sub> laser system operating in continuous-wave mode with longitudinal electrical discharge and axial gas flow at a relatively low pressure was used [16-18]. The length of the electric discharge tube used was 110 cm with an inner diameter of 0.8 cm. The length of the connecting tube used to isolate the front mirror from the electric discharge region to protect it from damage was 10 cm with the same diameter as the electric discharge tube. The optical resonator length was 126 cm when the connecting tube was not used, while it was 144 cm when the connecting tube was used. The resonator used was of the hemispherical type, consisting of two mirrors: a gold-coated metallic rear mirror with total reflectivity and a radius of curvature of 5 m. Four different plane mirrors (each used separately) were used as the front mirror: two made of ZnSe with total reflectivities of 40% and 60%, respectively, and two made of germanium (Ge) with total reflectivities of 40% and 80%. A premixed gas mixture of CO<sub>2</sub>:N<sub>2</sub>:He with proportions of 10:6:84 was used.

## 3. Results and Discussion

The operating results of the continuous-wave CO<sub>2</sub> laser system shown in Fig. (1) and

previously used [13] were adopted. These included measuring the laser output power as a function of the electric discharge current for different values of the total gas pressure, as well as measuring the output power as a function of the total gas pressure for different values of the discharge current.

In this research, the system was operated using the intermediate connecting tube, as shown in Fig. (2). In this case, the electric discharge chamber is divided into three distinct regions – as shown in the figure – which are: the region where the gas is electrically excited without being cooled (Region C) at both ends of the chamber, the region where the gas is electrically excited and cooled by the gas flow (Region B) at one end of the chamber, and the active region of the chamber (Region A). In Region C, self-absorption of radiation inside the chamber causes gas heating, and the losses resulting from self-absorption are negligible in the other regions where the gas flow works to limit the heating process.

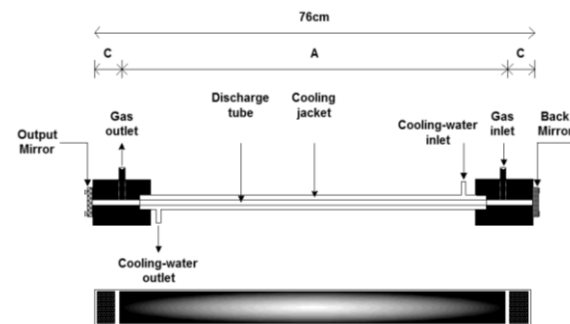


Fig. (1) Schematic diagram of the CW CO<sub>2</sub> laser system and the electric discharge regions in the case of not using a connecting tube

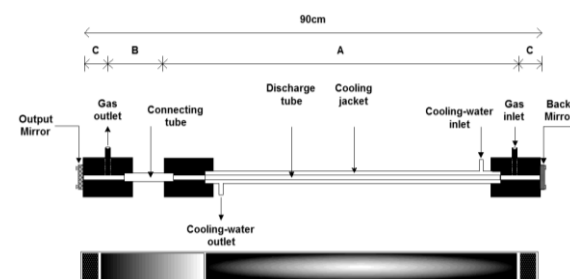


Fig. (2) Schematic diagram of the CW CO<sub>2</sub> laser system and the electric discharge regions in the case of using a connecting tube

The laser output power of the laser system was measured as a function of the discharge current for different values of the total gas pressure inside the chamber, as shown in Fig.

(3). It is clear that the output power increases with increasing discharge current, which represents the amount of electrical power transferred to the active gas medium. This increase continues until the electric discharge reaches its maximum stability, at which the maximum laser output power is obtained. After this limit, the laser output power begins to decrease despite the continued increase in pumping power transferred to the active medium. This decrease is attributed to the increase in the amount of heat generated by the electric discharge resulting from the increase in the discharge current ( $PH=I_d^2.R$ ), where PH is the generated thermal power,  $I_d$  is the discharge current, and R is the impedance of the gas medium.

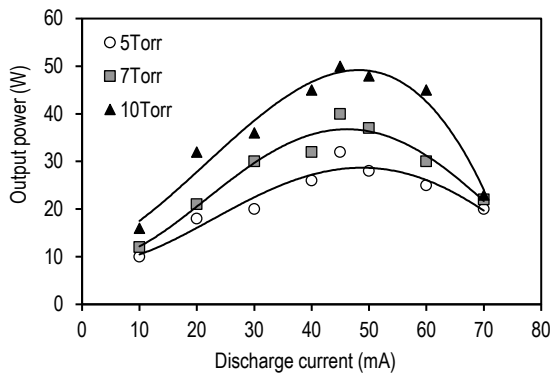


Fig. (3) Variation of laser output power with electric discharge current for different values of gas pressure inside the laser chamber

The behavior of the laser output power as a function of the discharge current and total gas pressure was similar to that obtained in the case of operating the system without using the connecting tube [15-17], with a slight difference in the optimal value of the discharge current. This similarity between the two cases shows that increasing the gas pressure inside the laser chamber (or any of the components of the gas mixture) leads to an increase in the laser output power. However, this continuous increase in the total gas pressure – at the optimal value of the discharge current – will inevitably lead to an increase in the spectral line width and thus an increase in the absorption coefficient of the gas mixture ( $a_v$ ) and a decrease in the gain coefficient ( $\alpha_v$ ) according to equations (1) and (2). Also, reducing the gas temperature strengthens the population inversion condition in the laser levels, and although this leads to an increase in the spectral line width and thus a decrease in the gain coefficient, it

simultaneously works to reduce the value of the absorption coefficient of the gas mixture.

To determine the optimal value of the electric discharge current for the conditions of this work, the laser output power was measured as a function of the total gas pressure inside the chamber for more closely spaced values of the discharge current (40, 45, 50 mA). According to Fig. (4), the optimal value of the discharge current is close to 45 mA, at which the maximum laser output power was obtained.

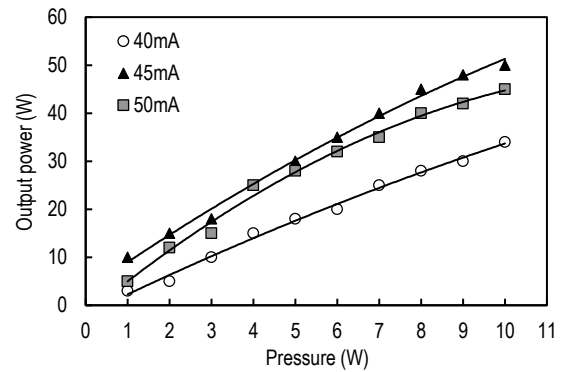


Fig. (4) Variation of laser output power with gas pressure for different values of the electric discharge current (40, 45, 50mA)

Figure (5) shows the change in laser output power as a function of the discharge current for different values of the CO<sub>2</sub> gas proportion in the gas mixture (8, 10, 15%). It is observed that the laser output power is significantly affected by changing the amount of CO<sub>2</sub> gas. Since the absorption coefficient of the CO<sub>2</sub>:N<sub>2</sub>:He gas mixture is proportional to the amount of CO<sub>2</sub> in the mixture, it can be said that the threshold for absorption losses resulting from self-absorption by the active medium molecules may be affected by the mole fraction of CO<sub>2</sub> in the gas mixture.

If the losses inside the laser chamber are zero, the laser efficiency at a certain value of the discharge current depends on the gas pressure because both the laser output power and the input discharge power are proportional to the gas pressure. However, laser systems in general, and CO<sub>2</sub> lasers in particular, must contain a certain amount of losses inside the chamber. The rate of increase in the overall laser efficiency, assuming the presence of losses inside the chamber due to self-absorption by the active medium molecules, is less compared to the case of no such losses, as shown in Fig. (6).

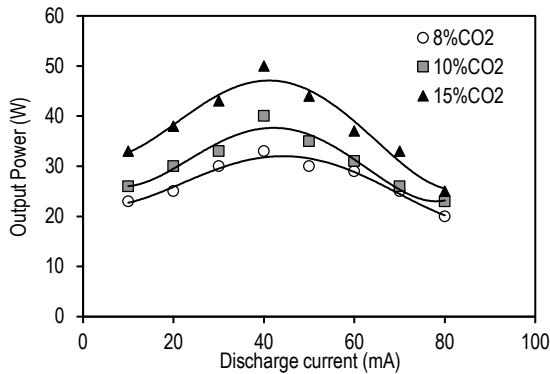


Fig. (5) Variation of laser output power with electric discharge current for different proportions of CO<sub>2</sub> gas in the gas mixture

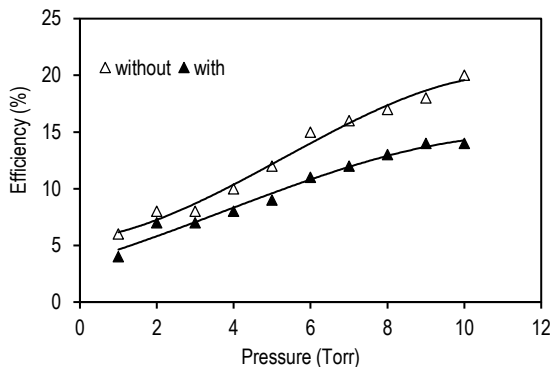


Fig. (6) Variation of the overall laser efficiency with gas pressure in the cases of with and without absorption losses inside the chamber ( $I_d=45\text{mA}$ )

If the gas mixture in regions B and C is cooled more efficiently by increasing the gas flow rate or pumping the constituent gases of the gas mixture pre-cooled, it is possible to neglect the absorption loss in these two regions because the value of the absorption coefficient ( $a_v$ ) will be very small at temperatures lower than room temperature ( $\sim 300\text{K}$ ). Therefore, self-absorption loss can be neglected when studying the laser output power characteristics with increased cooling efficiency of the gas mixture.

#### 4. Conclusion

According to the conditions and results obtained in this research, it can be concluded that

when the optical power absorbed by the active medium is high, the output power characteristics of the laser are significantly affected. Self-absorption by the active medium molecules affects the efficiency of the continuous-wave CO<sub>2</sub> laser system. When operating the laser system according to the previously described characteristics, it is necessary to perform compensation between several operating parameters, the most important of which are the total gas pressure, the mole fractions of the gas mixture components, the discharge current, and the output mirror transmittance, in order to avoid the attenuation caused by self-absorption of the generated laser beam by the active gas medium itself.

#### References

- [1] M. Hishii et al., Appl. Phys. Lett., 36 (1980) 797.
- [2] A. DeMaria, IEEE Proc., 61 (1973) 348.
- [3] A. Robinson and N. Sutton, Appl. Opt., 18 (1979) 378.
- [4] C. Banwell, "Fundamentals of Molecular Spectroscopy", 3<sup>rd</sup> ed., McGraw-Hill (London, 1983), p. 25.
- [5] M. Hishii et al., J. Appl. Phys., 52 (1981) 4953.
- [6] R.A. Markub, O.A. Hammadi and M.A.K. Ahmed, Almustansiriya J. Sci., 12(6) (2001) 307-309.
- [7] T. McCubbin Jr., R. Darone and J. Sorrell, Appl. Phys. Lett., 8 (1966) 118.
- [8] O.A. Hammadi and A.J. Haider, Eng. Technol. J., 20(2) (2001) 612-617.
- [9] E. Gerry and D. Leonard, Appl. Phys. Lett., 8 (1966) 227.
- [10] R. Ely and T. McCubbin Jr., Appl. Opt., 9 (1970) 1230.
- [11] S. Munjee and W. Christiansen, Appl. Opt. 12 (1973) 993.
- [12] R. Leonard, Appl. Opt., 13 (1974) 1920.
- [13] A. Robinson and E. Girczyc, Appl. Opt., 19 (1980) 1969.
- [14] J. Miller, J. Appl. Phys., 49 (1978) 3076.
- [15] A.A. Ibrahim et al., Sci. J. Iraqi Atom. Ener. Comm., 2(2) (2000) 100-106.
- [16] D.N. Raouf, N.A.K. Al-Rubaiey and O.A. Hammadi, Iraqi J. Laser, 1(1) (2003) 1-6.
- [17] O.A. Hammadi, D.N. Raouf and N.A.K. Al-Rubaiey, Eng. Technol. J., 22(1) (2003) 1-8.
- [18] O.A. Hammadi, Iraqi J. Phys., 2(2) (2003) 8-14.