



Improve and Study the Pulse Shape of TEA-CO₂ Laser

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Abstract:

This paper presents a theoretical model based on the laser rate equations to describe pulsed CO₂ laser characteristics. The dependence of laser output power and pulse shape on several parameters such as gas pressures ratio, gas temperature, reflectivity of the output mirror have been investigated. This model can provide a theoretical basis for the design and analysis of TEA CO₂ lasers.

Keywords: CO₂ laser, pulsed laser beam, kinetic modelling, reflectivity of the output mirror, numerical solution, laser rate equations.

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INTRODUCTION

The word laser means light amplification by stimulated emission of radiation, and it is an electro-optical device that produces a coherent beam [1]. It works to amplify the narrow and dense beam with a quality of coherent light. The laser has many uses at the present time and is widely used in the industry for cutting and punching in metals. Communication and in medicine (for surgery) [2]. And the dominant laser systems in the commercial industry are CO₂ laser systems, which have wide uses and in various industrial applications [3]. And one of the most famous types of gas lasers in the CO₂ laser system, which is operated by or through a gas-filled tube (vacuum tube) and produces light. (Electric operation). This device consists of an ejection tube, which consists of mirrors, one of which is fully reflective and the other allows the passage of some light. far infrared from the spectrum. The nitrogen in the gaseous mixture has an important role, which is when the N₂ molecules in the gaseous mixture are stimulated by an electric current (ie it gains energy) [4], and the role of N₂ is to maintain excited states for a long period of time without discharging energy in the form of

light (photons with high energy vibrations), as well as Excitation of CO₂ molecules, in which reverse rehabilitation is achieved [5], the state in which the system is considered to be the most excited state. In addition to this, the CO₂ gas laser is one of the most efficient partial lasers after the CO₂ laser, and an operational efficiency machine in gas systems that operate in continuous mode (Cw-mode), where the operational efficiency reaches 30%, while the system that arrives in the pulsed mode has an efficiency of about 10%. The CO₂ laser has the longest wavelength (10.6 μm) and the longest wavelength (9.6 μm) located in the infrared region [5].

THEORETICAL BACKGROUND

As it is well known, pulsed CO₂ lasers are excited by creating a glow discharge in a gas mixture of CO₂:N₂:He. The creation of the glow discharge takes place by interaction of the electrical circuit with the laser gas mixture. The discharge plasma resistance changes during the process of excitation and is a function of the electrical excitation circuit and the gas mixture. Figure (1) is a schematic diagram of the energy levels of a pulsed CO₂ laser in which the main



processes of relaxation and excitation considered in this work [6],

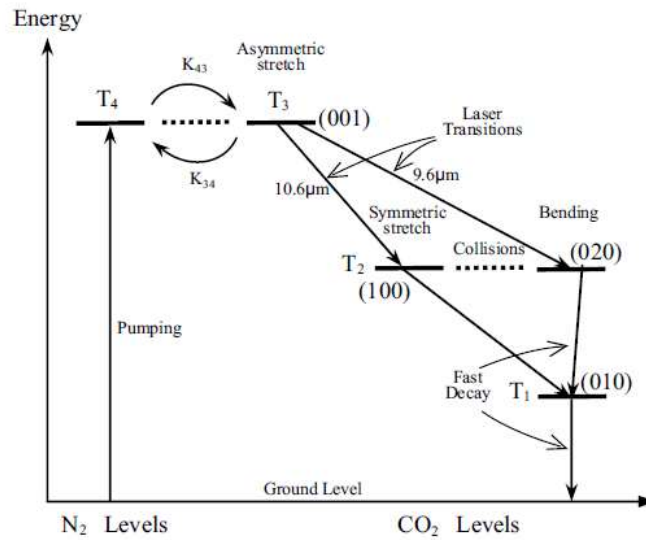


Figure 1: Energy levels diagram of the CO₂ laser [6].

are shown. The following six assumptions were used for derivation of equations representative of a CO₂:N₂:He pulsed laser system:

1. All of the vibrational-rotational transitions are homogeneously pressure broadened due to high gas pressure.
2. No molecular dissociation occurred in the CO₂ content of gas mixture.
3. The gas pressure in the discharge tube is constant in time.
4. Stimulated emission only occurs for the 10P(19) line due to the
5. (001)→(100) transition.
6. Due to fast intra-mode V-V relaxation, the initial equilibrium Boltzmann's population distribution of CO₂ molecules among the vibrational levels, N_{ijk} , is given by [7]:

$$N_{ijk} = N_{CO_2} P^i s^j r^k (1 - P)(1 - s)^2 (1 - r) \quad (1)$$

N_{CO_2} is defined as the total density of carbon dioxide (CO₂) molecules at the ground level, and (p, s, r) is defined by the following cases,

$$P = \exp\left(-\frac{hv_1}{K.T}\right), \quad S = \exp\left(-\frac{hv_2}{K.T}\right), \quad r = \exp\left(-\frac{hv_3}{K.T}\right) \quad (2)$$

It defines (v_1, v_2 , and v_3), respectively, are the frequencies of the different vibration patterns of the CO₂ molecule, and determines the first equilibrium of the Boltzmann and N₂ molecular distributions, and is determined by,

$$n_{N_2} = N_{N_2} \exp\left(-\frac{hv_4}{K.T}\right) \cdot \left[1 - \exp\left(-\frac{hv_4}{K.T}\right)\right] \quad (3)$$

$N_{N_2} = P_{N_2}/K.T$ is defined as the total density of nitrogen molecules at the ground level.

v_4 is the frequency of the vibration patterns of the excited N₂ particles [7,8],

$$\frac{dN_3}{dt} = (X_3 N_e + K_{43} N_4) N_{CO_2} - K_{34} N_{N_2} N_3 - N_3 \left[\frac{1}{\tau_{32}} + \frac{1}{\tau_{31}} \right] - \left[N_3 \cdot P(J) - \left[\frac{2J+1}{2J+3} \right] \cdot P(J+1) \cdot N_2 \right] \frac{\sigma \cdot I_v}{hv} \quad (4)$$

$$\frac{dN_2}{dt} = X_2 N_e N_{CO_2} + \left[N_3 \cdot P(J) - \left[\frac{2J+1}{2J+3} \right] \cdot P(J+1) \cdot N_2 \right] \frac{\sigma \cdot I_v}{hv} + \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} \quad (5)$$

$$\frac{dN_1}{dt} = X_1 N_e N_{CO_2} + \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{10}} \quad (6)$$

And

$$\frac{dN_4}{dt} = (X_4 N_e + K_{43} N_3) N_{N_2} = K_{43} N_4 N_{CO_2} \quad (7)$$

Whereas, N_1, N_2, N_3 , and N_4 is defined as the numerical density of the carbon dioxide molecules in the laser levels and the numerical density of the N₂ molecules in the vibrational state.



K_{43} and K_{34} are defined as the resonant energy transfer rate constants between the excited levels of nitrogen (N_2) and the molecules in the upper level of the laser.

X_1 , X_2 , and X_3 define the signal rate coefficients for the first, second and third level of CO_2 molecules, respectively, and X_4 : is the coefficient of the excitation rate of nitrogen molecules (N_2) from the ground state to the high oscillation state. σ : is the induced cross-section of the laser transmission from (001) \rightarrow (100) and is defined by the relationship

$$\sigma = \frac{\lambda_c^2}{4\pi^2 \tau_s \Delta V_L} (\lambda_c = 10.6 \mu m) \quad (8)$$

Where λ is the wavelength of the CO_2 laser ((in the center of the spectral line)) T_s spontaneous emission time, and τ_{ij} is relaxation time of the CO_2 molecule in the i to j level [7, 9, 10],

$$\tau_{10}^{-1} = 1.4 \times 10^4 (0.46 P_{N_2} + P_{CO_2} + 0.46 P_{He}) S^{-1} \quad (9)$$

$$\tau_{32}^{-1} = 100 (8 P_{N_2} + 6 P_{He} + 27 P_{CO_2}) S^{-1} \quad (10)$$

$$\tau_{34}^{-1} = (110 P_{N_2} + 85 P_{He} + 365 P_{CO_2}) S^{-1} \quad (11)$$

$$\tau_{20}^{-1} = (40 P_{N_2} + 4000 P_{He} + 200 P_{CO_2}) S^{-1} \quad (12)$$

$$K_{43} = 1.7 \times 10^3 P_{N_2} S^{-1} \text{ and } K_{34} = 1.9 \times 10^3 P_{CO_2} S^{-1} \quad (13)$$

$P(J)$ is defined as the ratio of the number of molecules in the spin plane to the ratio in the vibration plane.

$$P(J) = \left[\frac{hBc}{kT} \right] (2J + 1) \exp \left[- \frac{hcB J(J + 1)}{KT} \right] \quad (14)$$

Where B is defined as the constant of rotation, K Boltzmann's constant, J the spin quantum number, c speed of light, T is temperature of the gas, h is Planck's constant and ν is the laser frequency, I_v : Cavity field strength, $\Delta \nu_L$: the lumen width, defined by the relationship [7],

$$\Delta \nu_L = \sum_i \frac{(N_i Q_i)}{\pi} \left[\frac{8KT}{\pi \mu_i} \right]^{\frac{1}{2}} \quad (15)$$

$$\mu_i = \frac{M_{CO_2} M_i}{M_{CO_2} + M_i} \quad (16)$$

is the reducing mass of carbon dioxide in the molecule ($i=CO_2, N_2, He$), N_i is i^{th} partial density, Q_i is collision section between CO_2 and the i^{th} molecule Shows the time evolution of the cavity field density [7],

$$\frac{dI_v}{dt} = \left[N_3 \cdot P(J) - \left[\frac{2J + 1}{2J + 3} \right] N_2 \cdot P(J + 1) \right] \sigma \cdot I_v \cdot c + D N_3 - \frac{I_v}{\tau_c} \quad (17)$$

D is the spontaneous emission rate and defined $D = \tau_s^{-1}$, τ_c : is the lifetime of the photon in the cavity

$$\tau_c = - \frac{2L}{C \ln R_{out}} \frac{1 - R_{out}}{1 - R_{out} - K_{loss}} \quad (18)$$

L is length of the resonator, R_{out} is the reflection coefficient of the output mirror, K_{loss} is loss factor, The laser output power can be found by I_v ,

$$P_{out} = - \frac{A}{2} \cdot \frac{1 - R_{out} - K_{loss}}{1 - R_{out}} (\ln R_{out}) I_v \quad (19)$$

A : The reflective area of the storage mirror, and γ_0 is coefficient of obtaining a weak signal from the laser. It can be calculated using the following relationship [11],

$$\gamma_0 = \sigma \Delta N = \sigma \left[N_3 P(3) - \left[\frac{2J + 1}{2J + 3} \right] \cdot P(J + 1) \cdot N_2 \right] \dots \dots \quad (17)$$

RESULTS AND DISCUSSION

In this study, the equations for the time ratios of CO_2 lasers (equations 4, 5, 6, 7, 17) have been solved by a numerical analysis method called the Range-Kota method, where the equations for the time ratios are considered simultaneous differential equations of the first degree, and they have been written A computer program using Matlab 2021 to perform the calculations of the four-level laser pulse, where

the numerical density of CO_2 gas molecules ($N_1, N_2, N_3,$ and N_4) and the intensity of the outgoing laser pulse (I_v) was calculated, then the output power was calculated according to equation (17) and The physical constants and parameters listed in Table (1), which are very important for solving the equations of time ratios for the laser pulse, have been taken into consideration:



Table 1: Physical constants used in solving laser pulse time ratio equations.

Parameter	Value	Unit
h	6.626×10^{-27}	erg.s
c	2.998×10^{10}	cm/s
λ	10.6	μm
J	19	---
L	60	cm
τ_s	5	s
B	0.4	cm ⁻¹
A	1	mm ²
K_{loss}	0.001	---

1. Laser pulse in different mixing ratios

The output power of the CO₂ laser was calculated with different mixing ratios of gases, which are 1:1:1, 1:1:2, 1:2:4, 1:3:3 and 2:1:1 for each of the CO₂ gas. And nitrogen gas N₂ and helium gas He, respectively (CO₂:N₂:He), as a function of the pulse time, which is estimated at (3 μs) as in Figure (2):

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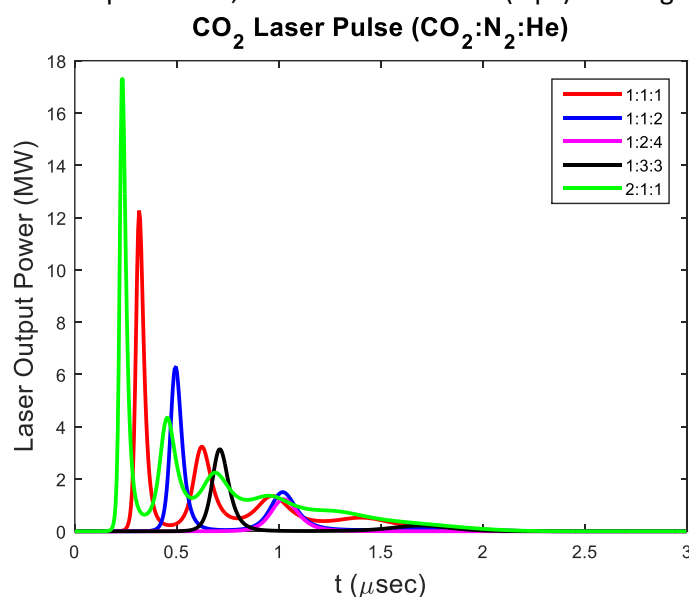


Figure 2: CO₂ laser pulse with different ratios for the CO₂:N₂:He gas mixture at a temperature of T=300 K and with a reflectivity coefficient R_{out}=0.68.

Figure (2) represents the relationship between the output power and the pulse shape time of the CO₂ laser, where the red curve represents the mixing ratio of 1:1:1, the blue curve represents the mixing ratio of 1:3:3, the green curve represents the mixing ratio of 2:1:1 and the black curve the mixing ratio of 1:2:2 and the curve in pink is the mixing ratio of 1:2:4. We note that the greatest peak of the output power curve increases with the increase in the proportion of CO₂ gas in

the mixture, but the high proportion of CO₂ gas leads to the instability of the pulse as we note in curve 2:1:1 ratio (curved in green). We also note that increasing the ratios of the rest of the gases gives the laser pulse great stability, but it leads to a decrease in the maximum value of the output power, a delay in the growth of the pulse, an increase in its width, and a decrease in the maximum gain coefficient, as we note in Table (2).



Table 2 : It includes the greatest power, growth time, greatest gain coefficient, and pulse width in CO₂ gas laser with different ratios of the gas mixture CO₂: N₂: He at temperature T=300 K and with reflectivity coefficient R_{out}=0.68.

CO ₂ :N ₂ :He	P_{max} (MW)	t_{max} (μ s)	γ_0^{max} (cm^{-1})	FWHM (ns)
1:1:1	12.27	0.32	0.0064	45
1:1:2	6.29	0.50	0.0052	65
1:2:4	1.23	1.03	0.0040	153
1:3:3	3.14	0.71	0.0045	94
2:1:1	17.31	0.23	0.0076	36

2. Laser pulse for different reflectivity values

The output laser power of CO₂ gas was calculated for the different reflectivity values represented by 0.95, 0.85, 0.80, 0.75, 0.65 for each of CO₂ gas, N₂ gas and He gas (1:1:2), respectively.

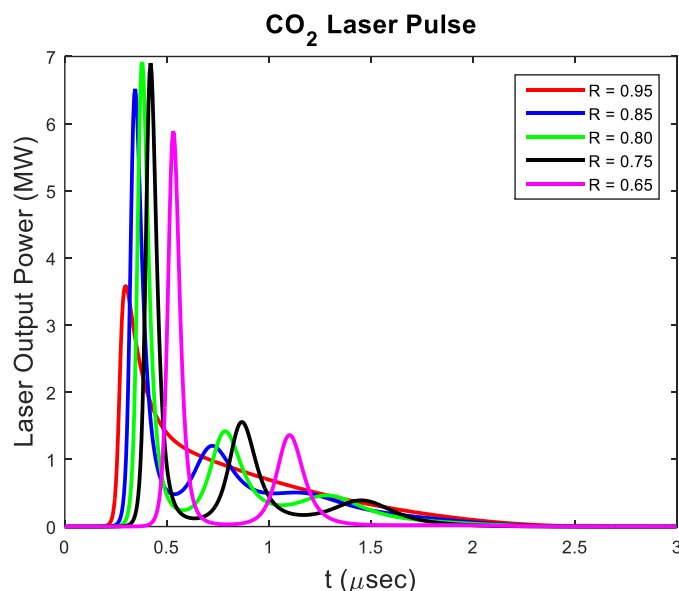


Figure 3 : A CO₂ laser pulse for different R_{out} values at T=300 K and a 1:1:2 mixing ratio.

Figure (3) represents the relationship between the output power and the time of the CO₂ laser pulse for the values of the reflectivity R_{out}, where the curve in red represents the reflectivity ratio in the mirrors with a percentage of 0.95, the curve in green with a reflectivity rate of 0.80, the curve in blue with a percentage of 0.85, the curve in black with a percentage of 0.75 and the curve in pink with a percentage of 0.65, where we note that the

greatest peak of the output power curve is 0.80. An increase in the reflectivity ratio leads to the instability of the outgoing pulse. We notice this in the curve in red, and we also notice an increase in the pulse width, a delay in the growth of the pulse, a decrease in the greatest gain coefficient, and a decrease in the peak of the maximum value of the pulse.

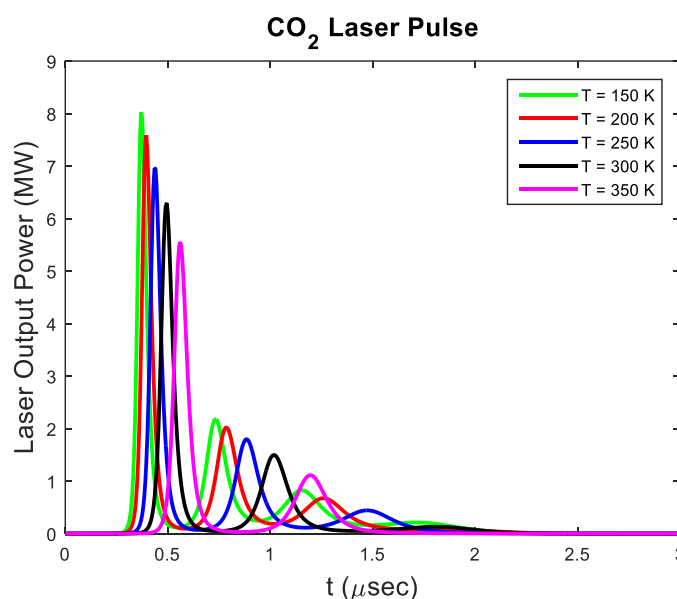


Table 3 : It includes the maximum power, growth time, maximum gain coefficient, and pulse width in CO₂ laser for different values of reflectivity coefficient R_{out} at temperature $T=300$ K and mixing ratio 1:1:2.

R_{out}	P_{max} (MW)	t_{max} (μs)	γ_0^{max} (cm^{-1})	FWHM (ns)
0.95	3.58	0.30	0.0033	162
0.85	6.52	0.35	0.0039	70
0.80	6.92	0.38	0.0042	65
0.75	6.90	0.42	0.0046	63
0.65	5.89	0.53	0.0054	67

3. Laser pulse for different temperatures

The power of the CO₂ laser was calculated at different temperatures of 150, 200, 250, 300 and 350 temperature in Kelvin,



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Figure 4: CO₂ laser pulse for different absolute temperature values with reflectivity coefficient $R_{out}=0.68$ and 1:1:2 mixing ratio.

Figure (4) represents the relationship between the output power and the pulse time of the CO₂ laser for different temperature values. It represents the curve in green with a value of $T=150$ K, the curve in red with a value of $T=200$ K, the curve in blue with a value of $T=250$ K, the curve in black with a value of $T=300$ K, and the curve in pink with a value of $T=350$ K. Where we note that the greatest

peak of the outgoing power curve is with a value $T=150$ K and that the increase in temperature leads to a decrease in the peak of the outgoing power curve as we notice in the red curve, and it also leads to the instability of the outgoing pulse as well as the increase in the pulse width and the delay in growth Pulse and decrease in the maximum gain coefficient.



Table 4 : It includes the maximum power, growth time, maximum gain factor, and pulse width in CO₂ lasers for different values of absolute temperature and at reflectivity coefficient R_{out} =0.68 and mixing ratio 1:1:2.

T (K)	P_{max} (MW)	t_{max} (μs)	γ_0^{max} (cm^{-1})	FWHM (ns)
150	8.02	0.37	0.0059	51
200	7.58	0.40	0.0057	53
250	6.96	0.44	0.0055	59
300	6.29	0.50	0.0052	65
350	5.55	0.56	0.0049	74

CONCLUSIONS

From the discussion of the results in this study, the following conclusions were reached:

1. The work of the CO₂ laser needs special conditions of mixing ratios, reflectivity and temperature in order to work well and give an excellent laser pulse ability to be used in various industrial and medical fields of application.
2. Increasing the percentage of carbon dioxide CO₂ over the percentage of the rest of the gases will generate a laser pulse of high power, but it is an irregular pulse. When the percentage of the rest of the gases is increased, a regular laser pulse will be generated, but with a low output capacity. For this reason, we find that the best result we reach is by 1:1:1, although there is a 2:1:1 laser pulse that has a higher peak and is higher than the 1:1:1 pulse, but the behavior of this pulse is not uniform, so the best regular laser pulse is 1:1:1.
3. We note that increasing the reflectivity ratio R_{out} in the mirror by a value of 0.95 does not make the number of photons emitted from the laser sufficiently to generate a high-power pulse because when R increases, it does not make the laser output with a high-power pulse, but when R_{out} is low, for example with a value of 0.80 The stimulated reactions are not allowed to be generated by the resonator (photons) and therefore a high-power laser pulse is not emitted, and in light of this we conclude that the best value is at 0.85, which is very suitable for generating a high-power laser pulse.
4. We note that the lower the temperature give the greater the output laser power. We

conclude that the laser, in order to increase its efficiency, is necessary to operate at low temperatures.

References

- [1] Sovelto, O. (1989) Principles of Laser, 3rd edition, Plenum Press (New York), pp.270.
- [2] Charschan, S. S., (1972) Laser In Industry, Western Electric Series.
- [3] Hitz, B., Ewing J. J. and Hecht, J. (2001) Introduction To Laser Technology, 2nd ed., IEEE Press, New York.
- [4] DeMaria, A. J. (1973). Review of CW high-power CO₂ lasers. *Proceedings of the IEEE*, 61(6), 731-748.
- [5] Letokov, V. S., and Ustinov, N. D. (1983) Power Laser and The Their Applications, Harwood Academic Pub., New York.
- [6] Koushki, A. M., Jelvani, S., Silakhori, K., & Saeedi, H. (2011). Kinetic Modelling of a pulsed CO₂ laser. *Lasers in Engineering*, 21(5), 265.
- [7] Thomson, R. M., & Smith, K. (1978). Computer Modelling of Gas Lasers.
- [8] Kumar, M., Khare, J., & Nath, A. K. (2007). Numerical solution of Boltzmann transport equation for TEA CO₂ laser having nitrogen-lean gas mixtures to predict laser characteristics and gas lifetime. *Optics & Laser Technology*, 39(1), 86-93.
- [9] Khosravi, H., Bahrampour, A. R., Bahari, A., Farrahi, R., & Daneshfar, N. (2008). Theoretical study of hybrid TEA-CO₂ lasers. *Optics & Laser Technology*, 40(6), 779-784.
- [10] Al-Hawat, S., & Al-Mutaib, K. (2007). Numerical modeling of a fast-axial-flow CW-CO₂ laser. *Optics & Laser Technology*, 39(3), 610-615.



- [11] Jelvani, S., &Saeedi, H. (2008). Numerical investigation of a fast-axial-flow CW CO₂ laser. *Optics & Laser Technology*, 40(3), 459-465.

