A RATE EQUATION MODEL
OF A
HYBRID CW-TEA CO₂ LASER

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ABSTRACT

A theoretical model of a hybrid CW-TEA CO₂ laser is presented which, in agreement with preliminary experiments, predicts single mode performance of the hybrid laser system when the CW section is maintained above threshold. Such a single mode laser pulse is required for proposed coherent laser scattering plasma diagnostics.

Introduction

Operation of a laser in more than one longitudinal or transverse mode results in temporal modulation of the laser output since different modes oscillate at different frequencies. Mode beating can limit coherent scattering experiments when the scattered frequency shift is comparable to the beat frequency between modes. This report describes a theoretical model of a hybrid CW-TEA CO₂ laser which predicts the shape, energy content, and mode purity of the laser pulse as a function of operating conditions.

Efforts to produce a predominantly single mode pulse from a TEA CO₂ laser have included use of an intracavity SF₆ absorption cell [1], an intracavity CW gain cell [1], the hybrid CW-TEA CO₂ laser configuration [2,3] (Fig. 1), and injection of radiation into the optical cavity by an external laser [4]. The distinction made here between an "intercavity CW gain cell" and the "hybrid CW-TEA laser" is that in the hybrid laser, the CW section can have sufficient gain to lase by itself.

For an optical cavity characterized by a length L and mirrors with radii of curvature R_1 and R_2 , the frequencies of the passive cavity resonances are given by:

$$f(n,m,q) = \frac{c}{2L} \left\{ q + \frac{1+n+m}{\pi} \cos^{-1} \left[\left(1 - \frac{L}{R_1}\right) \left(1 - \frac{L}{R_2}\right) \right]^{\frac{1}{2}} \right\} \quad (1)$$

where n and m are transverse mode numbers, and q is the longitudinal mode number. For our optical cavity ($L = 3.0$ m, $R_1 = 20$ m, $R_2 = \infty$ m)

the spacing between longitudinal modes is 50 MHz and the spacing between the modes TEM_{00q} and TEM_{01q} is 6.3 MHz.

The width of the gain profile for a CO_2 laser transition receives contributions from doppler broadening: $\Delta f_d = 55$ MHz for $T = 300$ °K, and collision broadening: $\Delta f_c = 4.5$ MHz torr⁻¹ [5]. The width of the gain profile at atmospheric pressure is dominated by collision broadening: $\Delta f_{atm} = 3.4$ GHz. Since this width is large compared to the spacing between longitudinal modes, a CO_2 laser operating at atmospheric pressure will oscillate on a number of longitudinal modes simultaneously, resulting in modulation of the output pulse at the beat frequencies between the modes. For a CW CO_2 laser operating at about 4 torr, the width of the gain profile is $\Delta f_{CW} = 75$ MHz. Since this width is comparable to the spacing between longitudinal modes, oscillation on a single longitudinal mode is possible (Fig. 2).

Presence of the CW section in the same optical cavity with the TEA section can influence buildup of a TEA pulse in two ways. If the CW section is operated below threshold, the longitudinal modes receiving the benefit of gain in the CW section build up faster than those that don't, and can dominate the output pulse. If the CW section is operated above threshold on a single longitudinal mode, then when the TEA section is fired, radiation in this mode has an enormous head start in intensity over radiation in other modes. (Radiation in these other modes start from the spontaneous emission level of about 10^{-14} Watts). Since the radiation builds up exponentially for

some time, radiation in the CW mode builds up and depletes the gain in both CW and TEA sections before the other modes build up to an appreciable level. The result is a single longitudinal mode pulse. Transverse mode selection is accomplished by means of intracavity apertures.

Details of the Model

The theoretical analysis is based on a rate equation approach similar to that described by C. B. Moore, et al., [6], and J. Gilbert, et al., [7]. Figure 3 shows some of the low lying vibrational states of CO₂ and N₂. The vibrational state of CO₂ is labeled by the triplet of numbers (nmp). The number of vibrational quanta in the symmetric stretch is n, the number in the bending mode is m, and the number in the asymmetric stretch is p.

At atmospheric pressure, the mean time between collisions is roughly 10⁻⁸ sec. Transfer of rotational energy in molecular collisions is very efficient: equilibrium among the rotational states associated with each vibrational level of CO₂ is established in about one collision time [5]. Since rotational relaxation is so rapid, it is assumed in the model that the rotational states remain in equilibrium throughout the history of the laser pulse.

Near resonant vibration-vibration energy sharing of the type:

is responsible for rapid equilibration among the levels in the

(n00) manifold. Similar processes establish equilibrium within the (0m0) and (00p) manifolds. In addition, the processes:

tightly couple the (n00) and (0m0) manifolds (M is any molecule in the gas mix). The equilibration time between the (n00) and (0m0) manifolds is about 3×10^{-7} sec. [5]. In the model, it is assumed that the entire set of levels (nm0) remain in equilibrium throughout the history of the laser pulse. This is not a very good assumption since the observed width of the gain switched peak of the laser pulse is about 4×10^{-7} sec. It is also assumed that the set of levels (00p) remain in equilibrium. Collisional coupling of the (00p) manifold with the (nm0) manifold is considerably slower than the processes (2) and (3). This circumstance permits a substantial population inversion to be maintained for some time. It is assumed that depletion of the population in the (nm0) manifold to ground state CO_2 occurs only by collisional vibration $\rightarrow$ translation energy transfer from the (010) level (this level has the fastest V $\rightarrow$ T rate).

The relevant kinetic processes in the TEA section are:

A. Vibrational energy transfer

B. Electron impact

C. Radiative transitions

The CW section influences buildup of the radiation field by providing some gain over a narrow frequency bandwidth, and if operated above threshold, by establishing an initial level of radiation far above the level of spontaneous emission. Saturation of the CW gain by the TEA pulse depends on the pressure in the CW section. For pressures ≥ 5 torr, the CW gain profile can be taken to be homogeneously broadened [5].

Saturation of a homogeneously broadened gain profile is given by:

$$\gamma(v) = \frac{\gamma_0(v)}{1 + I/I_s(v)} \quad (12)$$

where $\gamma_0(v)$ is the unsaturated gain, I is the intensity of the radiation field, and $I_s(v)$ is the saturation intensity [8].

The time evolution of the populations of ground state CO_2 , the (nm0) and (00p) vibrational manifolds of CO_2 , ground state and vibrationally excited N_2 , and the intensity of the radiation field is described by the set of rate equations presented below. Provision is made for two distinct modes of the radiation

field which compete with each other for the available gain in the TEA and CW sections. Since the width of the TEA gain profile is large compared to the spacing between adjacent longitudinal or transverse modes, it is assumed that both modes of the radiation field experience the same TEA section gain. However, the two modes may have different losses, different CW gain, different initial values, etc. Rapid modulation of the radiation field due to beating between the modes and all mode locking phenomena are ignored (these phenomena require a more sophisticated theoretical treatment than the rate equation approach). In the rate equations, the following notation is used:

- n_1 = number of particles cm^{-3} in $\text{CO}_2(000)$
- n_2 = number of particles cm^{-3} in $\text{CO}_2(010)$
- n_3 = number of particles cm^{-3} in $\text{CO}_2(00p)$
- n_4 = number of particles cm^{-3} in $\text{N}_2(v \geq 1)$
- n_5 = number of particles cm^{-3} in $\text{N}_2(v=0)$
- ϕ_1 = number of photons cm^{-3} of mode 1 inside the cavity
- ϕ_2 = number of photons cm^{-3} of mode 2 inside the cavity
- n_e = number of electrons cm^{-3} in the TEA discharge
- c_{ij} = rate to go from n_i to n_j by bimolecular collisions
- e_{ij} = rate to go from n_i to n_j by electron impact
- r_{ij} = rate to go from n_i to n_j by a stimulated radiative transition
- r_0, r'_0 = decay rate of photons from the cavity (modes 1,2)
- $w_{\text{spont}}, w'_{\text{spont}}$ = rate of spontaneous emission into modes 1,2
- $g_{\text{CW}}, g'_{\text{CW}}$ = CW section gain for modes 1,2
- $\phi_{\text{sat}}, \phi'_{\text{sat}}$ = CW gain saturation constant for modes 1,2
- f_{2b} = fraction of n_2 in the (010) level

$f_{2\ell}$ = fraction of n_2 in the lower laser level: $(100), J=J_\ell$

f_3 = fraction of n_3 in the (001) level

f_{3u} = fraction of n_3 in the upper laser level: $(001), J=J_u$

f_4 = fraction of n_4 in $N_2(v=1)$

With reference to the set of kinetic processes considered, the following set of rate equations obtains:

$$\begin{aligned} \dot{n}_1 = & - \left\{ \sum_M C_{12}^M n_M \right\} n_1 + \left\{ \sum_M C_{21}^M n_M \right\} f_{2b} n_2 - C_{43} f_4 n_4 n_1 + C_{34} f_3 n_3 n_5 \\ & - \left\{ (e_{12} + e_{13}) n_1 - e_{21} n_2 - e_{31} n_3 \right\} n_e \end{aligned} \quad (13)$$

$$\begin{aligned} \dot{n}_2 = & \left\{ \sum_M C_{12}^M n_M \right\} n_1 - \left\{ \sum_M C_{21}^M n_M \right\} f_{2b} n_2 + \left\{ \sum_M C_{32}^M n_M \right\} n_3 - \left\{ \sum_M C_{23}^M n_M \right\} n_2 \\ & + \left[e_{12} n_1 - e_{21} n_2 \right] n_e + (\Phi_1 + \Phi_2) \left\{ r_{32} f_{3u} n_3 - r_{23} f_{2\ell} n_2 \right\} \end{aligned} \quad (14)$$

$$\begin{aligned} \dot{n}_3 = & \left\{ \sum_M C_{32}^M n_M \right\} n_2 + \left\{ \sum_M C_{23}^M n_M \right\} n_2 + \left[e_{13} n_1 - e_{31} n_3 \right] n_e \\ & + C_{43} f_4 n_4 n_1 - C_{34} f_3 n_3 n_5 - (\Phi_1 + \Phi_2) \left\{ r_{32} f_{3u} n_3 - r_{23} f_{2\ell} n_2 \right\} \end{aligned} \quad (15)$$

$$\dot{n}_4 = - C_{43} f_4 n_4 n_1 + C_{34} f_3 n_3 n_5 + [e_{54} n_5 - e_{45} n_4] n_e \quad (16)$$

$$\dot{n}_5 = - \dot{n}_4 \quad (17)$$

$$\begin{aligned} \dot{\phi}_1 = & -r_o \phi_1 + \phi_1 \left\{ r_{32} f_{3u} n_3 - r_{23} f_{2l} n_2 \right\} + f_{3u} n_3 w_{\text{spont}} \\ & + \frac{g_{cw} \phi_1}{1 + (\phi_1 + \phi_2) / \phi_{\text{sat}}} \end{aligned} \quad (18)$$

$$\begin{aligned} \dot{\phi}_2 = & -r_o' \phi_2 + \phi_2 \left\{ r_{32} f_{3u} n_3 - r_{23} f_{2l} n_2 \right\} + f_{3u} n_3 w_{\text{spont}}' \\ & + \frac{g_{cw}' \phi_2}{1 + (\phi_1 + \phi_2) / \phi_{\text{sat}}'} \end{aligned} \quad (19)$$

In terms such as $\left\{ \sum_M C_{12}^M n_M \right\}$, the sum is over the molecular species in the gas mix: n_M is the particle density cm^{-3} of molecule M in the gas mix. The gas mix is assumed to consist of CO_2 , N_2 , and He. Helium enters the rate equations only in the bimolecular collision terms $\left\{ \sum_M C_{ij}^M n_M \right\}$.

Rates for some of the bimolecular collision and electron impact processes are presented in Tables 1 and 2. Reverse rates for the bimolecular collision processes are determined by imposing $\dot{n}_i = 0$ ($i = 1, \dots, 5$) when $n_e = 0$, and $\phi_1 = \phi_2 = 0$. To complete the electron impact data, it is assumed that $e_{ij} = e_{ji}$. The fractions f_{2b} , f_{2l} , f_3 , f_{3u} , and f_4 , and initial values for the populations n_i ($i = 1, \dots, 5$) are determined from equilibrium statistical mechanics in the Appendix. For simplicity, it is assumed that the fractions remain constant in time.

The rate of spontaneous emission into a mode is:

$$w_{\text{spont}} = \frac{F}{t_{\text{spont}}} \quad (20)$$

where F is the fraction of photons radiated into the angular aperture of a mode in the frequency bandwidth of a cavity resonance, and t_{spont} is the spontaneous emission lifetime. The fraction

$$F = \frac{\theta^2}{2} g(\nu) \delta\nu \quad (21)$$

where θ is the half angle of divergence of the laser mode pattern

$$\theta = \left(\frac{\lambda}{\pi} \right)^{\frac{1}{2}} \left[L(R_C - L) \right]^{-\frac{1}{2}} \quad (22)$$

and $g(\nu) \delta\nu$ is the probability that the emitted frequency ν lies within the width of a cavity resonance ($\delta\nu$). The width of a cavity resonance is related to the decay rate r_0 of photons from the cavity and is given by:

$$\delta\nu = \frac{r_0}{2\pi} = \frac{c}{4\pi L} \ln \left[\frac{1}{R(1-\ell)^2} \right] \quad (23)$$

where L is the length of the optical cavity, R is the reflectivity of the output coupler, and ℓ is the diffraction and scattering loss per pass. The lineshape function $g(\nu)$ for the

TEA section is lorentzian:

$$g(\nu) = \frac{\Delta\nu_c}{2\pi[(\nu-\nu_0)^2 + (\Delta\nu_c/2)^2]} \quad (24)$$

with $\Delta\nu_c \approx 3.4$ GHz at atmospheric pressure. The spontaneous emission lifetime $t_{\text{spont}} = 4.7$ sec [5]. The rate of stimulated emission of a frequency ν per unit photon density is

$$r_{32} = \frac{c^3}{8\pi\nu^2 t_{\text{spont}}} g(\nu) \quad (25)$$

By detailed balance, the rate of induced absorption per unit photon density is

$$r_{23} = \frac{(2j_3 + 1)}{(2j_2 + 1)} r_{32} \quad (26)$$

where j_3 and j_2 are the rotational quantum numbers for the upper and lower laser levels respectively. The CW saturation intensity I_{sat} is estimated to be 20 Watts cm^{-2} [9]. This completes the list of rates needed to solve the rate equations.

The radiation field appears in the rate equations as the photon density at some point in the active medium. The intensity of the output pulse is related to the photon density inside the cavity by:

$$I(r) = \frac{c}{2L} \ln\left[\frac{1}{R}\right] \int_0^{L_{\text{active}}} dz \, h\nu\Phi(r,z) \quad (27)$$

The output intensity is the energy density of the radiation field integrated over the length of the active medium times the rate of energy loss due to transmission thru the output coupler.

Actually, the photon density at time t influences the output intensity at a later time, but the error made using Eq. (27) will

be small if the photon density changes little in one round trip time. To obtain the power in the output pulse, the intensity is assumed to have a particular radial dependence (TEM_{00} or TEM_{01}). The output power is:

$$P = \int_0^{\infty} I(r) 2\pi r dr . \quad (28)$$

To obtain an estimate of the electron density in the TEA discharge as a function of time, the discharge current was measured with a Pearson 410 current transformer. The current pulse was found to consist of a triangle shaped pulse with a full width of 0.5 μ sec. The electron density pulse used in the model is assumed to be triangular in shape with a full width of 0.5 μ sec. The value of the peak electron density was adjusted to reproduce the observed time delay between the current pulse and the laser pulse.

The rate equations are integrated numerically by a Runge-Kutta technique: IBM scientific subroutine package RKGS.

Results and Discussion

A typical TEA laser pulse develops in the following way: see Figs. 4 and 5.

- A. Electron impact collisions during the current pulse vibrationally excite the upper and lower laser levels of CO_2 creating a population inversion. N_2 present in the gas mix is also vibrationally excited by electron impact.

- B. In the tail of the current pulse, the radiation field builds up and the degree of population inversion increases due to pumping of the upper laser level by excited N_2 .
- C. The radiation field builds up to a level sufficient to deplete the population inversion by stimulated emission. This results in the gain switched peak.
- D. Continued pumping of the upper laser level of CO_2 by excited N_2 re-established some gain in the medium, producing the N_2 tail of the laser pulse. The extent of the N_2 tail depends on the relative amount of N_2 in the gas mix (CO_2/N_2), and on the rate of loss of radiation from the cavity.

A CW section operated below threshold has very little effect on the shape of the laser pulse; the pulse will develop a little bit earlier due to the extra little bit of gain (compare Fig. 5 and Fig. 6). If the CW section is operated above threshold, the laser pulse appears much earlier (see Fig. 7). With the CW section above threshold, the radiation field starts out with a power on the order of Watts rather than from the spontaneous emission level of about 10^{-14} Watts. Consequently, the time that it takes for the radiation field to grow by about 14 orders of magnitude is "saved", and the gain switched peak appears earlier. During the period between the current pulse and the development of the gain switched peak, the amount of population inversion is increasing in time due to N_2 pumping. Since the gain switched

peak appears earlier, the radiation field experiences less gain when the CW section is above threshold than it would if the CW section were below threshold. The result of this is to produce less of a gain switched peak and more of a N_2 tail when the CW section is above threshold (compare Fig. 5 and Fig. 7). The energy in the laser pulse remains about the same.

Use of a CW section operated below threshold is not very good for longitudinal mode selection. A simulation of the most optimistic case - the 'dominant' longitudinal mode at line center of the CW gain profile (Fig. 2) - indicates a mode purity of about 1 part in 200. That is, the intensity in longitudinal modes adjacent to the mode at CW line center is about 0.5% of the intensity of the dominant longitudinal mode.

If the CW section is operated above threshold on a single longitudinal mode, then the mode purity is quite good - roughly 1 part in 10^{14} . This is due to the fact that radiation in the longitudinal mode above threshold builds up and depletes the available gain in both the TEA and CW sections before the radiation in other modes (which must start from the spontaneous emission level) can build up to an appreciable level. Simulations giving competing modes an equal amount of CW gain and a weaker form of CW gain saturation still led to mode purities on the order of 1 part in 10^{14} . If more than one longitudinal mode is above threshold on the CW gain profile, then a multimode TEA pulse results.

Competition between radial modes is similar. If the TEM_{00} mode is the only radial mode above threshold in the CW section, then the radial mode purity of the TEA pulse is quite good (about 1 part in 10^{16}). Discrimination against the TEM_{01} mode and higher order modes is due to diffraction losses imposed by intracavity apertures [10]. As the aperture is reduced, the TEM_{01} mode suffers more loss than the TEM_{00} mode and consequently leaks out of the cavity faster. When the aperture is sufficiently reduced, only the TEM_{00} mode is above threshold. Then the competing higher order modes have to start from the spontaneous emission level in addition to suffering greater cavity losses than the TEM_{00} mode. The threshold condition can thus ensure radial mode purity.

Conclusion

A rate equation model of a hybrid CW-TEA CO_2 laser has been presented which is in substantial agreement with experiment in terms of pulse shapes and energies. The model predicts that the CW section may be used very effectively for both longitudinal and radial mode selection as long as only one longitudinal and radial mode is above CW threshold. When this condition is met, a single longitudinal, single transverse mode TEA pulse results.

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APPENDIX

The fractions to be calculated are:

f_{2b} = fraction of $\text{CO}_2(\text{nmo})$ in (010)

$f_{2\ell}$ = fraction of $\text{CO}_2(\text{nmo})$ in (100), $J = J_\ell$

f_3 = fraction of $\text{CO}_2(\text{oop})$ in (001)

f_{3u} = fraction of $\text{CO}_2(\text{oop})$ in (001), $J = J_u$

f_4 = fraction of $\text{N}_2(\nu \geq 1)$ in $\text{N}_2(\nu = 1)$

The energies associated with the vibrational modes of CO_2 are: [5]

$E_1 = 0.167 \text{ eV}$ symmetric stretch

$E_2 = 0.083 \text{ eV}$ bending mode

$E_3 = 0.29 \text{ eV}$ asymmetric stretch

$B_\ell = 0.3901 \text{ cm}^{-1}$ rotation const. for lower laser level

$B_u = 0.3871 \text{ cm}^{-1}$ rotation const. for upper laser level

Define:

$$x = e^{-\frac{E_1}{kT}}$$

$$y = e^{-\frac{E_2}{kT}}$$

$$z = e^{-\frac{E_3}{kT}}$$

Form the partition functions:

$$Q_{(\text{nmo})}^{\text{vib.}} = \left\{ \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} (m+1) x^n y^m \right\} - 1$$

$$= \left[\frac{1}{(1-x)(1-y)^2} - 1 \right]$$

$$Q_{(oop)}^{vib} = \sum_{p=1}^{\infty} z^p = \frac{z}{1-z}$$

$$Q_i^{rot} = \sum_{J=0}^{\infty} (2J+1) \exp\left[-\frac{hcB_i J(J+1)}{kT}\right] \approx \frac{kT}{hcB_i}$$

$$Q_{N_2(v \geq 1)}^{vib} \approx Q_{(oop)}^{vib}$$

In terms of these partition functions, the fractions are:

$$f_{2b} = \frac{2y}{Q_{(nmo)}^{vib}} - \frac{hcB_{\ell} J_{\ell} (J_{\ell} + 1)}{kT}$$

$$f_{2\ell} = \frac{x}{Q_{(nmo)}^{vib}} \frac{(2J_{\ell} + 1) e^{-\frac{hcB_{\ell} J_{\ell} (J_{\ell} + 1)}{kT}}}{Q_{\ell}^{rot}}$$

$$f_3 = \frac{z}{Q_{(oop)}^{vib}} - \frac{hcB_u J_u (J_u + 1)}{kT}$$

$$f_{3u} = \frac{z}{Q_{(oop)}^{vib}} \frac{(2J_u + 1) e^{-\frac{hcB_u J_u (J_u + 1)}{kT}}}{Q_u^{rot}}$$

$$f_4 \approx f_3$$

$T_{(nmo)}^{vib}$	f_{2b}	$f_{2\ell}^{vib}$	$T_{(oop)}^{vib}$	$f_{3u}^{vib} = f_4$	T^{rot}	$f_{2\ell}^{rot \dagger}$	$f_{3u}^{rot \dagger}$
3000°K	0.05	1.9E-2	4000°K	0.57	300°K	3.27E-2	3.38E-2
2000°K	0.12	3.8E-2	3000°K	0.67	400°K	3.10E-2*	3.14E-2*
1000°K	0.37*	7.0E-2*	2000°K	0.81*			
500°K	0.73	5.2E-2	1000°K	0.97			

The * indicates the value assumed in the simulation.

The simulation is not very sensitive to changes in these fractions.

† The rotational fractions are evaluated for the P(20) transition.

Initial conditions:

$$n_2(0) \approx \left\{ 1 - \frac{1}{Q_{(\text{nmo})}^{\text{vib}} + 1} \right\} n_{\text{CO}_2} = 8.1 \times 10^{-2} n_{\text{CO}_2}$$

$$n_3(0) \approx \left\{ 1 - \frac{1}{Q_{(\text{oop})}^{\text{vib}} + 1} \right\} n_{\text{CO}_2} = 1.3 \times 10^{-5} n_{\text{CO}_2}$$

$$n_4(0) \approx 1.3 \times 10^{-5} n_{\text{N}_2}$$

$$n_1(0) \approx 0.92 n_{\text{CO}_2}$$

$$n_5(0) \approx n_{\text{N}_2}$$

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TABLE 1
BIMOLECULAR COLLISION RATES

M	$c_{12}^M (\text{cm}^3 \text{sec}^{-1})$	Ref. #	$c_{32}^M (\text{cm}^3 \text{sec}^{-1})$	Ref. #
CO ₂	5.5×10^{-15}	11	10.9×10^{-15}	6
N ₂	1.1×10^{-15}	11	3.3×10^{-15}	6
He	106×10^{-15}	12	2.6×10^{-15}	6

$$N_2(v=0) + CO_2(001) \xrightarrow{c_{34}} N_2(v=1) + CO_2(000)$$

$$c_{34} = 465 \times 10^{-15} \text{ cm}^3 \text{sec}^{-1} \text{ Ref. 14}$$

TABLE 2
ELECTRON IMPACT EXCITATION RATES (Ref. 13)

$e_{12} (\text{cm}^3 \text{sec}^{-1})$	$e_{13} (\text{cm}^3 \text{sec}^{-1})$	$e_{54} (\text{cm}^3 \text{sec}^{-1})$
3.5×10^{-8}	6.0×10^{-9}	2.0×10^{-8}

HYBRID CW-TEA

Fig. 1. Hybrid CW-TEA CO₂ laser configuration.
 M_1 = output coupler, M_2 = 100% reflecting mirror, A = aperture

Fig. 2. The CW section gain profile.

CO₂ - N₂ VIBRATIONAL STATES

Fig. 3.

TEA SECTION GAIN

Fig. 4.

5a

5b

6a

6b

7a

7b

766003

Figs. 5-7 are for the following operating conditions: The gas mix is 3% CO_2 , 12% N_2 , 85% He; the output coupler is 90% reflecting; the aperture diameter = 1.4 cm. Experimental pulse shapes were recorded with a Molelectron pyroelectric detector.