Design and performance of a sealed CO₂ laser for industrial applications

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Abstract. A large amount of materials processing is done using an industrial CO₂ laser operating in the mid-infrared (IR) spectrum. Their high efficiency and tremendous power output have made them one of the most commonly known transition wavelength at 10,6 microns facilitates laser cutting, drilling and marking of a wide variety of materials in the electronics and medical industries. Because lasers are feedback systems, many of their design parameters strongly interact with one another, and arriving at an optimum design requires a really thorough understanding of just how they interact. We report the construction of a sealed CO₂ gas discharge laser with a glass laser tube design as well as clear acrylic housing makes this an excellent demonstrational tool. Sealed operation was characterized in mode, power, warm-up and stability over a long time. The results indicate a good operation, optimum wavelength, powers and beam quality will remove material more efficiently in effective industrial applications.

1. Introduction

The CO₂ laser’s most commonly known transition wavelength at 10,6 microns facilitates laser cutting, drilling and marking of a wide variety of materials in the electronics and medical industries, [7]. Important innovations to be made in commercial CO₂ laser technology, particularly in the low and medium power ranges. The reason why this work was undertaken the strong dependence of the parameters of the resonator and the condition that a ray launched inside the resonator parallel to the optical axis remains inside the resonator, directly with the output power. The laser was designed and constructed out of glass and is contained in an acrylic casing so that all of its functioning components can be observed. The laser simply plugs into a standard A/C outlet and more than 100 Watts of coherent, monochromatic laser radiation is produced, enough to burn paper and wood. From a Metaxial Method, we report the calculations for an optical resonator and the prediction of the output power, for an industrial CO₂ laser at 10.6 microns, with more than 100 Watts of coherent and monochromatic laser radiation that combine high reliability and low operating cost.
2. The laser resonator

The function of an optical resonator is to ensure that the light waves generated have the required shape and spacing. We assume a cylindrical laser amplifier, in particular a gas discharge tube. Let us now consider figure 1, which illustrates the arrangement of a typical laser resonator, [4].

![Figure 1. Typical laser resonator](image)

A laser amplifier of length \( L \) is placed between two end reflectors spaced a distance \( b \) apart. Since the laser amplifier is equivalent to a plane-parallel plate, the translation matrix representing the gap between the two mirrors will contain the reduced thickness,

\[
T = (b - L) + \frac{L}{n} = b - \frac{(n - 1)}{n} L
\]  

(1)

We are interested in the shape of the waves. The initial ray which arrives at RP1 in the +z-direction after emerging from the amplifier,

\[
\begin{bmatrix}
y_1 \\ V_1
\end{bmatrix}
\]

(2)

And a portion of this is reflected by the output mirror the travels back through the amplifier to the left-hand mirror and the returns, again through the amplifier, to the output mirror.

If the reference plane RP2 so as to coincide with to RP1, we can write the transfer matrix \( M \) connecting this pair of reference planes representing a single round trip through the resonator. Using \( P_1 \) and \( P_2 \) for to denote the powers of the two end-mirrors, we have

\[
\begin{bmatrix}
y_2 \\ V_2
\end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -P_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -P_2 & 1 \end{bmatrix} \begin{bmatrix} y_1 \\ V_1
\end{bmatrix} = \begin{bmatrix} 1 - P_1 T - 2 P_2 T + P_1 P_2 T^2 & T(2 - P_1 T) \\ -P_1 - P_2 + P_1 P_2 T & 1 - P_1 T \end{bmatrix} \begin{bmatrix} y_1 \\ V_1
\end{bmatrix}
\]

(3)

In order to represent the effect of \( N \) successive round trips through the resonator. We consider a resonator composed by two spherical mirrors \( M_1 \) and \( M_2 \), (See figure 2).
We will use coordinated $r$ and field amplitude $U_1$ in $M_1$ and coordinated $s$ and amplitude $U_2$ in $M_2$. We will consider the wave that travels from $M_1$ to $M_2$ after the reflection in $M_1$ and before the reflection in $M_2$. From Metaxial Method, $[3]$, using $R_1'$ and $R_2'$, the transfer field is:

$$
\left( R_1', R_2', D, r, s, U_1, U_2 \right) \rightarrow \left( \alpha_1, \varepsilon_1, \rho_1, \sigma_1, V_1, V_2 \right)
$$

(4)

$D$ is the distance among mirrors $M_1$ and $M_2$. Then, the round trip is,

$$
V'_1(\rho_2) = e^{i\alpha_2(\cos \alpha_2 + \varepsilon_2 \sin \alpha_2)}F_{\alpha_2}[V'_2](\rho_2)
$$

(5)

The resonator is stable if the field transfer is expressed by a transformed fractional of Fourier, whose order is real. Therefore, the condition of stability will be:

$$
\cot^2 \alpha_1 = \frac{(R_1' - L)(L + R_2)}{L(L - R_1' + R_2)} = \frac{(R_1' - L)(L - R_2)}{L(L - R_1' - R_2)} \geq 0
$$

(6)

Keeping in mind that the $L(L - R_1' - R_2') = -(R_1' - L)(L - R_2') - R_1'R_2'$, $\alpha_1$ is real if,

$$
0 \leq \left(1 - \frac{L}{R_1'} \right) \left(1 - \frac{L}{R_2'} \right) \leq 1
$$

(7)

In the fundamental mode of a stable resonator, the amplitude of the field in each spherical segment of the mirror $M_\alpha$, is proportional to

$$
e^{-\eta r^2} = e^{\left(\frac{-r^2}{\omega^2}\right)}
$$

(8)

With,

$$
\omega = \sqrt{\frac{\lambda \varepsilon_1 R_1'}{\pi \cos \alpha + \varepsilon_1 \sin \alpha}}
$$

(9)
From this expression, it is possible to obtain the following parameters:

The spot sizes on each mirror,

\[
\omega_1 = \frac{\lambda^2 R^2 L}{\pi^2 (R_1^2 - L)} \quad \text{(10)}
\]
\[
\omega_2 = \frac{\lambda^2 L (L - R_1^2)}{\pi^2} \quad \text{(11)}
\]

The location of the minimum waist,

\[
D_0 = \frac{L (L - R_2^3)}{2L - R_1^2 - R_2^2} = \frac{R_1^3}{1 + \frac{1}{\varepsilon_1^3}} \quad \text{(12)}
\]

And the radius of the minimum waist,

\[
\omega_0 = \frac{\lambda}{\sqrt{\pi}} \sqrt{|D_0 (R_1^2 - D_0)|} \quad \text{(13)}
\]

For this particular design, the results are:

Radius of curvature,

\[
R = \frac{2B}{(D - A)} = \frac{2(1.8)}{0.8 - 0.8} = \infty \quad \text{(14)}
\]

Beam radius,

\[
W = \left(\frac{\lambda B}{\pi \sin \theta}\right)^{\frac{1}{2}} = \left(\frac{(10.6)10^{-6}(1.8)}{\pi(0.602)}\right)^{\frac{1}{2}} = 3.2 \text{mm} \quad \text{(15)}
\]

Location of neck, to the left of reference plane,

\[
z = \frac{(A - D)}{2C} = \frac{0.8 - 0.8}{2(-0.2)} = 0 \text{ m} \quad \text{(16)}
\]

Neck radius,

\[
W_0 = \left(-\frac{\lambda \sin \theta}{\pi C}\right)^{\frac{1}{2}} = \left(-\frac{(10.6)10^{-6}(0.602)}{\pi(-0.2)}\right)^{\frac{1}{2}} = 3.2 \text{mm} \quad \text{(17)}
\]

Confocal beam parameter

\[
z_0 = \frac{\pi W_0^2}{\lambda} = \frac{\pi (3.2)10^{-3}}{(10.6)10^{-6}} = 3.03 \text{ m} \quad \text{(18)}
\]

at this point, it will have increased its spot radius to,

\[
\sqrt{2W_0} = 2.53 \text{ mm} \quad \text{(19)}
\]

and the radius of curvature of the wavefronts will be,

\[
R = 2z_0 = 6.06 \text{ m} \quad \text{(20)}
\]
Far-field semi-angle,

\[ \Theta = \frac{\lambda}{2\pi V_0} = \frac{10.6 \times 10^{-6}}{\pi(3.2 \times 10^{-3})} = 1.05 \text{ mrad} \]  

(21)

3. Design and construction

3.1 The Laser Tube

The laser has a sealed cavity which contains a mix of Carbon dioxide, Nitrogen and Helium. The pressure of the Carbon Dioxide is of 3/760 atmospheres, the quantity of CO2 and Nitrogen are equal, while the Helium quantity is seven times more. The cavity length was conveniently calculated to 1650mm, this cavity has a plane mirror output and a highly reflector mirror of 1960mm of curvature radium, a central cylinder of 10mm of diameter, which is concentric to a extern cylinder of 80mm diameter; through this extern cylinder flows the deionized water, which acts as a cavity cooling. The DC discharge type with attached ballast tank for long life, [6,8]. The silver-copper cathode design was used to reduce the amount of gas consumption by sputter pumping. Construction of the laser was kept simple to reduce expense and excessive consumption of time. The laser is constructed of Pyrex, see figure 4. This design includes a condensation system of the active medium, keeping it in a liquid state when the laser is off; this makes its life time bigger compared with other sealed laser systems which keep their active medium in a gaseous state.

The design incorporates a laser bore nested in a water cooling jacket, with a feed through the water jacket so that the discharge can go to an external cathode and anode, having the external electrodes lower than the axis of the laser bore reduces the possibility that sputtering or oxidation products at the electrodes will contaminate the optics, [9, 11]. This becomes an important consideration when working with CO2 lasers as intra-cavity power densities, for 50 Watt beam of this laser, measured at about one (1) meter away from the laser head, has a beam diameter of 6 mm =1/4 inch. The area of a 6 mm circle is 28 sq mm. Hence your beam at that position has a power density (called intensity) of 50/28 =1.8 Watt per sq mm (or an intensity of 180 Watt/sq cm), readily causing thermal damage on the surface of an optic should a small piece of contaminant land on it.

A glass vacuum valve is attached for evacuation and filling. Water inlet and outlets are positioned so that air bubbles which from inside the water jacket are ejected as they rise to the top of the tube. Without this design, air buildup inside the jacket would create a radial temperature differential, detuning the resonator and/or thermally poisoning the gain medium, [10, 12].
3.2 Power Supply

The high voltage power supply used is optimized for use in mid-power carbon dioxide and similar laser applications. Of particular significance are the robust and reliable design architecture, and the “superpulsing” capability: maximum pulse currents of up to 60 mA and repetition rates to 2 kHz are available at 100% duty cycle. This Power supplies is switched at a 42 kHz switching frequency for best efficiency and lowest heat generation.

While in operation, all components of the high voltage end of the power supply are floating with respect to building ground. The system has a high power ballast resistance, placed in series with the discharge to limit tube current. The tube current is varied rather crudely, by simply using a variac to adjust input voltage to the power supply.

The RF output voltage could be between 0 and 60KV, which is reached by a control electronic system which receiver an electrical signal of 0-10mADC. For the laser operation in the CW mode a RF voltage is kept fixed at the output, for example, if this is fixed at 45KV an output power of 80W is obtained in the laser, while if it is fixed at the maximum (60KV) an output power of 110W is obtained.
4. Laser Operation

After the laser was assembled and aligned, it was connected to a sink and drain for cooling water. A closed circuit heat exchanger will be built to make the laser self contained. Lasing action is now repeatably attainable. Output power data were taken at varying currents, [12, 13]. Therefore, the peak power obtained was 110 Watts in CW mode. The optimum current was 10 mA. See figure 6.

![Figure 6. Lasing action](image)

The length and brightness of the exiting fluorescence stream was observed to be proportional to the discharge current. A rapid migration of oxygen containing species out of the laser bore makes for a sink of CO2 in the ballast tank and the laser then becomes lean in its lasing medium. If this migration hypothesis is correct, we would expect that the laser power should last longer upon initial turn on if dissociation products are allowed to come to equilibrium between laser bore and ballast tank. This is indeed the case. After repeatedly turning on the laser then allowing diffusion time, performed over a period of a couple days, power does begin to remain consistent at turn on. The maximum power attainable does improve after several days of turning the laser on and off and allowing it to sit. Ultimately, a laser power of 100 Watts (44 Watts/meter) has been achieve this way, with relatively stable output power lasting for over and hours worth of operation.

5. Concluding remarks

The original objective of to calculate the optical resonator and the fraction of the output power for an industrial CO2 laser was accomplished with good results. This work fact with a brief development of the optics Metaxial method, allows to optimize the design of the cavity laser and to choose from a range of options according to the components offered by the suppliers. The general idea is building an industrial CO2 laser with appropriate characteristics of wavelength, power, coherent and monochromatic laser radiation, according to the industrial application, where it is possible combine high reliability and low operating cost. Actually, we work in the design of a scanner laser conformed by perpendicular mirrors of high reflexion to 10,6 microns. These mirrors are coupled on galvo motors, which will be regulated in their phase from a pc. This system will allow carrying out different industrial applications.

6. References

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