Design considerations of a Class I CO_2 Laser

Output power of a typical Class I CO_2 laser operating in an optimized condition with respect to gas ratio, pressure, and tube current may be calculated if design data on the optical cavity and laser tube are known. This section presents a set of equations that may be used to determine approximate maximum output power of a Class I CO_2 laser. The equations are based in part on experimental observation and are presented without a theoretical development. An example problem is included to illustrate use of the equations.

Design Equations

The following can be used to determine output power of a CO_2 laser:

$$P(W) = \frac{8.36\,[(1-\ell)^{1/2}T]\{aL_a + 1n[(1-\ell)(1-\ell-T)]^{1/2}\}}{\{(1-\ell)^{1/2} + (1-\ell-T)^{1/2}\} \times \{1-[(1-\ell)(1-\ell-T)]^{1/2}\}} \quad \text{...(1)}$$

$$\ell_d = e^{-\left(\frac{2r^2}{w_s^2}\right)} \quad \text{... (2)}$$

$$w_f^4 = \left(\frac{\lambda}{\pi}\right)^2 L_c(R - L_c) \quad \text{...(3)}$$

$$w_s^4 = \left(\frac{\lambda R}{\pi}\right)^2 \left[\left(\frac{R}{L_c}\right) - 1\right]^{-1} \quad \text{... (4)}$$

$$\ell_d = e^{-\frac{2\pi r^2}{R\lambda}\left(\frac{R}{L_c} - 1\right)^{1/2}} \quad \text{... (5)}$$

$$\alpha = (0.0822\text{ cm}^{-1} - 0.0026\,D\text{ cm}^{-2}) \quad \text{... (6)}$$

P = Output power of laser in watts (Equation 1).

l = Total cavity loss.

T = Fractional transmission of output coupler.

a = Gain coefficient (Equation 6).

L_a = Active length (length of discharge providing gain), in centimeters.

l_d = Diffraction loss of beam passing through an aperture (Equations 2 and 5).

r = Radius of cavity-limiting aperture.

W = Watts of power.

w = Spot size (radius to $\frac{1}{e^2}$ points) of beam at aperture.

w_f = Spot size (radius to $\frac{1}{e^2}$ points) of beam on flat mirror (Equation 3).

w_s = Spot size (radius to $\frac{1}{e^2}$) of beam on spherical mirror Equation 4).

R = Radius of curvature of spherical mirror, in meters.

L_c = Cavity length (distance between mirror surfaces), in meters.

D = Tube diameter, in centimeters.

λ= Laser wavelength.

Equation 1 gives the power of the laser during optimum operation if active length, gain coefficient, loss, and transmission of the output coupler are known. Transmission of the output coupler and the active length may be obtained from system data sheets or can be measured. The gain coefficient is given by Equation 6 in cm^{-1} where tube diameter D is measured in cm. Loss is calculated using either Equations 2 or 5 as described below.

Equation 2 gives the diffraction loss of a Gaussian laser beam of radius w when it passes through an aperture with a radius r. In this case the radius r is the radius of the cavity aperture, when is located near the spherical mirror, and beam radius w is defined as the spot size of the beam on that mirror.

Size of the Gaussian laser beam inside the optical cavity depends upon curvature and separation of the mirrors and the wavelength of the light. Size of the aperture does not affect size of the beam for any given laser mode. It determines only the loss for that mode. Equations 3 and 4 give spot sizes of the TEM_{00} mode on the flat and spherical mirrors for a long-radius hemispherical cavity.

Equation 5 is the result of substituting the value for w_s from Equation 4 into the expression for diffraction loss in Equation 2. Thus, Equation 5 gives the diffraction loss for any long-radius hemispherical laser cavity with its limiting aperture near the spherical mirror. This is usually the case, because the beam has its maximum diameter on the spherical mirror.

In CO_2 lasers the limiting aperture is usually the bore of the laser tube. Decreasing the bore increases gain because of more efficient gas cooling, but it also increases diffraction loss. Larger-diameter tubes also tend to support higher-order TEM modes. In most Class I CO_2 lasers tube diameter is chosen to give a loss of 2% to 15% for TEM_{00}, depending on laser size. If optics of the system are clean, undamaged, and aligned properly, total loss l usually may be assumed to be equal to the diffraction loss l_d. If damaged optics or additional optical components are present, the loss they introduce must be added to the diffraction loss.

The following example illustrates use of Equations 1 through 6 in determination of output power and beam diameter of a CO_2 laser.

Example: A CO2 laser with an active length of 2 m and a cavity length 2.4 m. Tube inner diameter is 12 mm. The output coupler is flat and has a transmission of 20%. The HR mirror has a radius of curvature of 5 m. The only significant loss l in the system is diffraction loss, l_d. Find Output power and diameter of output beam.

<u>Solution:</u>

Given quantities (in appropriate units) are:

L_a = 200 cm

L_c = 2.4 m

D = 1.2 cm

$r = \frac{D}{2} = 6 \times 10^{-3}$ m

$T = 0.20$

$R = 5$ m

From Equation 6, the gain coefficient is

a = (0.0822 cm^{-1} – 0.0026 x D cm^{-2})

a = [(0.0822 cm^{-1}) – (0.0026)(1.2 cm)(cm^{-2})]

a = 0.0791 cm^{-1}

Spot sizes of the beam on the two mirrors are determined using Equations 3 and 4

$$w_f^{\,4} = \left(\frac{\lambda}{\pi}\right)^2 L_c(R - L_c)$$

$$= \left(\frac{10.6 \times 10^{-6}\ \text{m}}{\pi}\right)^2 (2.4\ \text{m})(5\ \text{m} - 2.4\ \text{m})$$

$w_f^{\,4} = 7.104 \times 10^{-11}\ \text{m}^4$

$w_f = 2.90 \times 10^{-3}$ m

$$w_s^{\,4} = \left(\frac{\lambda R}{\pi}\right)^2 \left[\left(\frac{R}{L_c}\right) - 1\right]^{-1}$$

$$= \left[\frac{(10.6 \times 10^{-6}\ \text{m} \times 5\ \text{m})}{\pi}\right]^2 \left[\left(\frac{5\ \text{m}}{2.4\ \text{m}}\right) - 1\right]^{-1}$$

$w_s^{\,4} = 2.6272 \times 10^{-10}\ \text{m}^4$

$w_s = 4.026 \times 10^{-3}$ m

Output beam diameter is twice the spot size on the flat coupler (w_f).

Output beam diameter = 5.8 mm.

The diffraction loss may be calculated using Equation 2.

$l_d = e^{-2r^2/w_s^2}$

$= e^{-}\left[(2)(6 \times 10^{-3}\,\mathrm{m})^2 / (4.026 \times 10^{-3}\,\mathrm{m})^2\right]$

$= e^{-}(4.44)$

$l_d = 0.012 = 1.2\%$

Since the diffraction loss l_d is the only significant loss factor, total l loss may be assumed to be equal to l_d, or 1.2% Equation 1 now may be used to determine laser output power.

$$P = \frac{8.36\,[(1-\ell)^{1/2}\;T]\{\alpha L_a + 1\mathrm{n}\,[(1-\ell)(1-\ell-\mathrm{T})]^{1/2}\}}{\{(1-\ell)^{1/2} + (1-\ell-\mathrm{T})^{1/2}\} \times \{1-[1-\ell)(1-\ell-\mathrm{T})]^{1/2}\}}$$

$(1 - l) = 1 - 0.012 + 0.988$

$(1 - 1 - T) = 1 - 0.012 - 0.20 = 0.788$

$$P = \frac{8.36\,[(0.988)^{1/2}\;(0.20)]\{(0.0791)(200) + 1\mathrm{n}\,[(0.988)(0.788)]^{1/2}\}}{\{(0.988)^{1/2} + (0.788)^{1/2}\} \times \{1-[(0.988)(0.788)]^{1/2}\}}$$

$$= \frac{26.08}{0.221}$$

$P = 117.8$ watts

This laser will have an output beam diameter of 5.8 mm and a maximum output power of 118 W.

H.W.

Use laser parameters given in Example as a specific case to construct graphs showing variation of output power as other parameters are varied. In each case, assume that all parameters are fixed at the value stated in Example except for the parameter specified as variable. Draw a separate graph of output power versus each of the following:

a. Transmission of output coupler varies from 50% to 60%.

b. Tube bore varies from 10 mm to 16 mm.

c. Cavity length varies from 1.5 m to 2.5 m as active length varies from 1.1 m to 2.1 m.