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Measurements of the small-signal gain and saturation intensity for a cw CO_2 laser using an intracavity loss element

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***Abstract*. A new scheme with an intra-cavity loss element for small-signal gain measurement at two main wavelengths of a tunable gas flow longitudinally excited CO_2 laser is presented. By inserting a ZnSe stack polariser into the cavity, the critical condition for the laser is obtained. The small-signal gain and saturation intensity are calculated using the Rigrod formula. The small-signal gain measurement was performed for different gas pressures and different input electric powers. Under the same experimental conditions, the values of the saturation intensities were calculated from the output power and the measured small-signal gains. The advantage of this method is that no probe laser system is required. The results agree with experimental data obtained earlier by the conventional oscillator – amplifier method.**

Keywords: *tunable CO_2 laser, small-signal gain, saturation intensity, intracavity losses.*

1. Introduction

The small-signal gain α_0 and saturation intensity I_s are two most important parameters in the calculations of the laser output power and design [1]. These parameters can be measured at the line center ν_0 of a single-longitudinal-mode laser, the result of measurements being dependent on the broadening [2]. For CO_2 lasers operating at a normal pressure of about 10 Torr, the homogenous line broadening dominates for vibration – rotational transitions from the upper (001) level to the lower (02^00, 10^00) levels [3, 4]. In this paper, the theoretical analysis based on the assumption of the homogenous line broadening was performed for the line center. The linear small-signal gain α_0 has been experimentally studied by the oscillator – amplifier method for an untunable CO_2 laser [5 – 7] at different wavelengths [8, 9] and for a TEA CO_2 laser [10, 11]. In this classical method, reduction of the probe laser beam diameter causes diffraction of the beam. The method proposed in our paper doe not use a probe beam from an auxiliary laser, and therefore, errors related to the instability of the auxiliary laser are eliminated.

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2. Theoretical estimates

The gain at the central frequency ν_0 of the homogeneous line in an optical resonator per transit of length l in the active medium is:

$$G = \frac{I(l)}{I(0)} = \exp\left[\frac{\alpha_0 l}{1 + I(0)/I_s}\right], \tag{1}$$

where, $I(0)$ and $I(l)$ are the input and output intensities, respectively. Consider an optical oscillator containing an active medium as an amplifier and a variable loss element (Fig. 1). The self-oscillation condition for such an oscillator can be written as

$$r_2 t_1^2 (1 - L_0)^2 \exp(2\alpha l) = 1, \quad t_1 = 1 - L_1, \tag{2}$$

where L_0 is the loss due to diffraction from the cell windows; L_1 and t_1 are the loss and transmission coefficient of the loss element, respectively; and r_2 is the output mirror reflectivity. Here, α is:

$$\alpha = \alpha_0 \left[1 + \frac{I(0)}{I_s}\right]^{-1}. \tag{3}$$

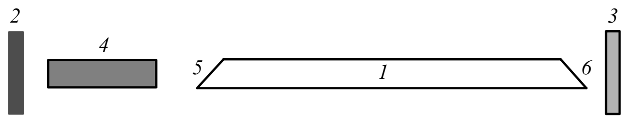

Figure 1. Optical oscillator containing an active amplifying medium and an intracavity variable loss element (polariser): (*1*) active medium; (*2, 3*) mirrors; (*4*) polariser; (*5, 6*) windows of a cell with an active medium.

By increasing the loss inside the cavity and achieving the critical condition, when $I(0) \ll I_s$, we obtain $\alpha = \alpha_0$. Then Eqn (2) takes the form:

$$r_2 t_1^2 (1 - L_0)^2 \exp(2\alpha_0 l) = 1,$$
$$\alpha_0 = \frac{-\ln\left[r_2 t_1^2 (1 - L_0)^2\right]}{2l}. \tag{4}$$

The small-signal gain can be determined for different operation conditions from (4), when the coefficients t_1 and r_2 are known. Then, by measuring the output intensity I_{out} for each lasing regime, we can obtain the saturation intensity from the Rigrod formula. This formula in the general form including all intracavity losses can be written as [12]:

$$I_{out} = t_{w2} t_2 I_s \left[\alpha_0 l - \frac{1}{2} \ln \left(\frac{1}{t_{w2}^2 t_{w1}^2 t_{1m}^2 r_1 r_2} \right) \right] \times \left\{ \left[1 - \left(t_{w1}^2 t_{w2}^2 t_{1m}^2 r_1 r_2 \right)^{1/2} \right] \left[1 + \left(\frac{r_2 t_{w2}^2}{r_1 t_{1m}^2 t_{w1}^2} \right)^{1/2} \right] \right\}^{-1}, \quad (5)$$

where I_{out} is the output power; t_{1m} is the maximum transmission of the loss element; r_1 and r_2 are mirror reflectivities; t_{w1} and t_{w2} are the transmission coefficients of cell windows; $t_2 = 1 - r_2$ is the transmission coefficient of the output mirror. By assuming that the diameter of the beam passing through the windows does not change, which implies that $t_{w1} = t_{w2} = 1 - L_0$, we can obtain I_s from (5) in the form:

$$I_s = I_{out} \left\{ 1 - (1 - L_0)^2 \left(t_{1m}^2 r_1 r_2 \right)^{1/2} \left[1 + \left(\frac{r_2}{r_1 t_{1m}^2} \right)^{1/2} \right] \right. \times \left. \left\{ \left[\alpha_0 l - \frac{1}{2} \ln \left[\frac{1}{(1 - L_0)^4 t_{1m}^2 r_1 r_2} \right] \right] (1 - L_0) t_2 \right\}^{-1} \right. . \quad (6)$$

3. Experimental

The experimental setup is shown schematically in Fig. 2. A gas-discharge CO_2 Laser Pyrex tube of length 58 cm, inner diameter 9 mm, the output NaCl window at the Brewster angle, and a pair of tungsten electrodes spaced by 50 cm were used for the gain measurements. A circulated water jacket cooling system was used and water temperature was controlled and set at 27 °C during the experiment. The output flat germanium-coated mirror with the transmission coefficient 90 % and a gold-coated 100-line mm^{-1} ruled grating with the reflection coefficient of 98 % at 10.6 μm with an electric motor controller formed the laser cavity. A CO_2 laser spectrum analyser (Optical Engineering, Inc.) was used for the wavelength measurements.

The pressure of the working gas mixture could be varied in the range of 0 – 40 Torr but the optimum pressure of about 20 Torr was kept constant during the experiments. A Field Master Coherent power meter (with an LM-200 XL HTD head) was used to measure the absolute laser output power. The calibrated ZnSe polariser was used to introduce intracavity losses. The maximum transmission of the poliriser was measured by using a stable 10-W sealed cw CO_2 laser.

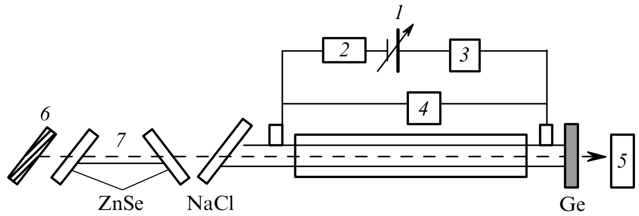

Figure 2. Scheme of the experiment setup used for gain measurements: (*1*) high-voltage power supply; (*2*) resistance; (*3*) milliampermeter; (*4*) kilovoltmeter; (*5*) power meter; (*6*) diffraction grating; (*7*) polariser.

4. Results

Because one window of the laser cell was set at a Brewster angle, the laser beam passing through this window was linearly polarised. The poliriser introducing intracavity losses consisted of two ZnSe plates set at the Brewster angle for 10.6 μm. This stack polariser could be rotated around the horizontal axis with accuracy of ±1°, thereby reducing the output power. The transmission coefficient of the poliriser can be written as

$$t_1^2 = t_{am}^2 t_w = t_{am}^2 \cos^3\theta, \quad (7)$$

where t_{am} is the maximum transmission coefficient of the polariser; θ is its rotation angle; $t_w = \cos^3\theta$. The value of the t_{am} was measured by placing the polariser in front of the laser. By rotating the polariser, the maximum power transmitted through it was obtained. The ratio of this power to the power in front of the polariser was 0.97. To calculate the absolute value of α_0, the value of l_0 is required. By writing the self-excitation condition for two different transmission coefficients of the output mirror (60 % and 80 %), we obtain from (2):

$$0.6\left[1 - (L_1 + L_0)^2\right] t_w = 0.8\left[1 - \left(L_1' + L_0\right)^2\right] t_w', \quad (8)$$

where $L_1 = 1 - t_{am} \cos\theta$ and $t_w = \cos\theta$. In this formula, the primes refer to the self-excitation condition with the 80 % transmission mirror. By using values of t_{am} and polariser angle θ at the self-excitation threshold for both CO_2 laser wavelengths (9.6 μm and 10.6 μm), we calculated the value of $L_0 = 0.06$, which shows that the loss at the cavity windows is negligible.

The small-signal gain α_0 calculated from (3) for the 9.6-μm and 10.6-μm wavelengths for three different gas mixtures is shown in Fig. 3. The gain saturation intensities calculated from (5) under the same conditions are presented in Fig. 4. Note that due to the axial distribution of the small-signal gain [13], the average value of the small-signal gain

$$\bar{\alpha}_0 = \frac{1}{l} \int_0^l \alpha_0(z) \mathrm{d}z \quad (9)$$

is measured in fact.

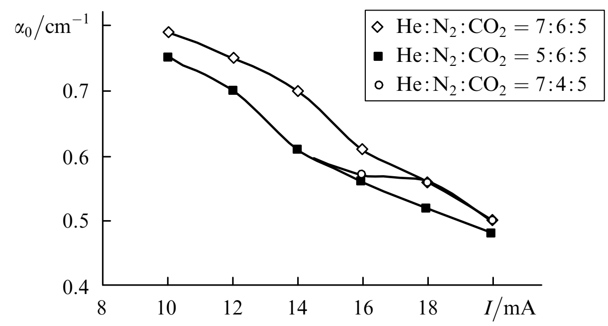

Figure 3. Dependence of the small-signal gain α_0 on the discharge current I for three different gas mixtures ($\lambda = 9.6$ μm).

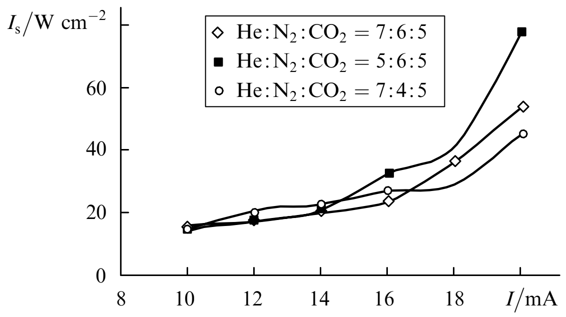

Figure 4. Dependence of the saturation intensity I_s on the discharge current for three different gas mixtures ($\lambda = 9.6$ μm).

The intensity of the output power P_{out} was calculated from the expression

$$I_{out} = \frac{P_{out}}{\pi d_2^2}, \qquad (10)$$

where the beam diameter d_2 at the output mirror calculated taking into account the Gaussian distribution of the beam intensity in a stable cavity is 2.3 mm. The experimental values of α_0 and I_s obtained under different conditions are presented in Figs 3–6. These results agree with the data obtained by the standard method [5–9, 13]. Therefore, the method described above can be used for quick estimates of α_0 and I_s [14].

5. Conclusions

A new method for small-signal gain measurement in a cw CO_2 laser has been proposed. The gain and saturation intensity of the laser for different gas mixtures and input powers were calculated. It was shown that with increasing the input electric-discharge power, the small-signal gain decreases, whereas the saturation intensity increases.

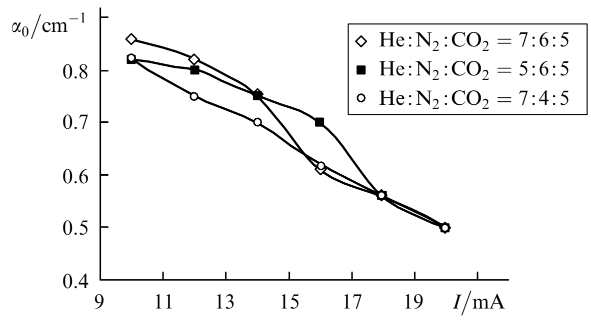

Figure 5. Dependence of the small-signal gain α_0 on the discharge current I for three different gas mixtures ($\lambda = 10.6$ μm).

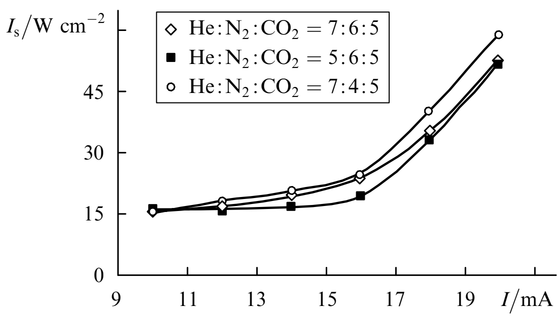

Figure 6. Dependence of the saturation intensity I_s on the discharge current for three different gas mixtures ($\lambda = 10.6$ μm).

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