Parameter study of RF excited diffusively cooled all-metal slab waveguide CO_2 laser

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Received December 17, 2004

In this paper, we have investigated some parameters of a radio frequency (RF) excited diffusively cooled all-metal slab waveguide CO_2 laser based on the modified Rigrod theory by introducing a waveguide coupling efficiency which designates the coupling between the waveguide and the resonator mirrors. The parameters of the laser small signal gain g_0, saturation intensity I_s, and waveguide coupling efficiency η are studied theoretically and experimentally. In the experiments, three sets of output coupling flat mirrors with the different transitivities were used, and a maximum laser power output of 150 W was obtained from a gas discharge region of 2-mm height, 20-mm width, and 386-mm length coupled with a CASE-I optical waveguide resonator.

OCIS codes: 140.3470, 140.3320, 230.7400.

In 1989, Hall *et al.* first presented the radio frequency (RF) excited diffusively cooled area scaling waveguide CO_2 laser technique[1] using an off-axis unstable optical resonator and a RF gas discharge excited slab hollow waveguide combined with a diffusive cooling technique to obtain a compact high power laser. Because this technique has the advantages of high beam quality and excellent performance over the DC excited glass tube CO_2 laser and fast flow CO_2 laser, it has attracted the attentions of many researchers.

In the past decade, RF excited waveguide CO_2 lasers have been developed from all-ceramic waveguide channel structures to ceramic and metal sandwich waveguide channel structures to all-metal channel structures. In 2004, Xin *et al.* reported a novel RF excited diffusively cooled all-metal waveguide CO_2 laser technique[2], in which the waveguide channel was constructed by two aluminum side walls and two aluminum electrodes. Combining this technique with the off-axis unstable optical resonator, they obtained 127-W laser power from a discharge region dimension of 2 mm (h) × 20 mm (w) × 386 mm (l).

In this paper, the experimental setup is shown in Fig. 1. Laser resonator and gas discharge electrodes are sealed in the aluminum vacuum chamber. M_1 is copper flat feedback mirror, M_2 is ZnSe output coupling flat mirror, which are fixed on the adjusting brackets to align laser resonator. The top and bottom electrodes which construct the all-metal slab waveguide are water-cooled. The gas pressure is monitored with a vacuum gauge, and the laser output power is measured with a laser power meter. The frequency of the RF power supply is fixed at 96 MHz and the RF power output can be tuned from 0 to 1000 W. The gas composition in a mixture of $CO_2 : N_2 : He : Xe = 1 : 1 : 3 : 0.26$ is employed.

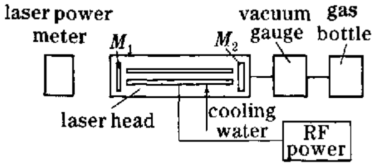

Fig. 1. Schematic diagram of experimental setup.

The laser head structure is shown in Fig. 2. The all-metal slab waveguide channel consists of two aluminum electrodes and two aluminum side walls, the surfaces of the electrodes towards the waveguide are polished to an optical surface to obtain a high reflectivity for the laser wave propagating in the waveguide. The top electrode, the bottom electrode, and the two supporting side walls compose a gas discharge region of the slab waveguide with 2 mm (h) × 20 mm (w) × 386 mm (l). Electric insulation separations are formed between the top electrode and the supporting side walls and between the bearing plate and the supporting side walls, respectively, through a plurality of small ceramic insulation plates with a diameter of 6 mm and a thickness of 0.3 mm along longitudinal direction of the electrode. Eight matching inductors with different periodical values are connected between the top electrode and the bottom electrode longitudinally to achieve the longitudinal uniformity of the RF power disposition[3]. The top electrode is connected with a copper electrode link pin which passes through a vacuum separation insulation bush to connect with the high

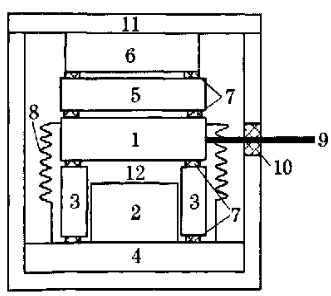

Fig. 2. Schematic diagram of the all-metal slab waveguide laser head. 1: top electrode; 2: bottom electrode; 3: side wall; 4: bearing plate; 5: liner plate; 6: clamp plate; 7: ceramic insulating plate; 8: matching inductor; 9: copper electrode link pin; 10: vacuum separation insulation bush; 11: vacuum box; 12: slab waveguide discharge region.

frequency power supply outside the vacuum chamber. By the use of this structure, when a high frequency electric field is applied between the top electrode and the bottom electrode, a stable gas discharge can be confined in the slab waveguide, no gas discharge phenomenon was found outside the waveguide.

In this paper, we theoretically and experimentally studied some parameters of the RF excited diffusively cooled all-metal slab waveguide CO_2 laser based on the Rigrod theory[4] and the characteristics of waveguide lasers. A waveguide coupling efficiency η is introduced into the Rigrod equation[4] to designate the coupling between the waveguide end aperture and the resonator mirrors. And the laser small signal gain g_0 and saturation intensity I_s also are researched. A CASE-I waveguide resonator[5] was employed, three sets of ZnSe output coupling flat mirrors with the different transitivities and a copper flat reflector were used to obtain the three groups of the experimental data.

According to Rigrod theory[4], the medium gain is

$$g(z) = \frac{1}{\beta_+} \times \frac{\partial \beta_+}{\partial z} = -\frac{1}{\beta_-} \times \frac{\partial \beta_-}{\partial z} = \frac{g_0}{1 + \beta_+ + \beta_-}, \quad (1)$$

$$\beta_+ \times \beta_- = C, \quad (2)$$

$$\begin{aligned} r_1 &= 1 - a_1 - t_1, \\ r_2 &= 1 - a_2 - t_2, \end{aligned} \quad (3)$$

where $\beta_\pm = \frac{I_\pm}{I_s}$, I_s stands for the saturation intensity, I_+ and I_- designate the laser intensities along positive direction and negative direction, respectively, g_0 represents the small signal gain of the laser medium, C is a constant, r_1 and r_2 are the reflectivities of the resonator mirrors, t_1 and t_2 are the transitivities of the resonator mirrors, and a_1 and a_2 are the dissipative losses of the resonator mirrors.

For the boundary condition of the above, we can write

$$\begin{aligned} \beta_2 \times r_2 &= \beta_3, \\ \beta_4 \times r_1 &= \beta_1, \end{aligned} \quad (4)$$

where β_2 and β_3 (β_4 and β_1) designate the beam parameters at the resonator feedback (output) mirror before and after reflection, respectively.

In our experiments, the waveguide gain medium is employed, a waveguide coupling effect must be taken into account, and η should be introduced into Eq. (4), which can be rewritten as

$$\begin{aligned} \beta_2 \times r_2 \times \eta_2 &= \beta_3, \\ \beta_4 \times r_1 \times \eta_1 &= \beta_1, \end{aligned} \quad (5)$$

where η_1 and η_2 represent the coupling efficiencies between the waveguide end and the resonator output mirror M_1 and between the waveguide end and the resonator feedback mirror M_2, respectively.

From Eqs. (2) and (5), we can get

$$\frac{\beta_2}{\beta_4} = \left(\frac{r_1 \times \eta_1}{r_2 \times \eta_2}\right)^{\frac{1}{2}}. \quad (6)$$

From Eqs. (1) and (2), for the positive direction beam, we obtain

$$\frac{1}{\beta_+} \times \frac{\partial \beta_+}{\partial z} = \frac{g_0}{1 + \beta_+ + \frac{C}{\beta_+}}, \quad (7)$$

$$g_0 \times L = \ln\left(\frac{\beta_2}{\beta_1}\right) + \beta_2 - \beta_1 - C \times \left(\frac{1}{\beta_2} - \frac{1}{\beta_1}\right). \quad (8)$$

The same result for the negative direction beam is

$$g_0 \times L = \ln\left(\frac{\beta_4}{\beta_3}\right) + \beta_4 - \beta_3 - C \times \left(\frac{1}{\beta_4} - \frac{1}{\beta_3}\right). \quad (9)$$

Thus,

$$I_2 = \frac{(r_1 \times \eta_1)^{\frac{1}{2}}}{[(r_1 \times \eta_1)^{\frac{1}{2}} + (r_2 \times \eta_2)^{\frac{1}{2}}] \times [1 - (r_1 \times \eta_1 \times r_2 \times \eta_2)^{\frac{1}{2}}]} \times [g_0 \times L + \ln(r_1 \times \eta_1 \times r_2 \times \eta_2)^{\frac{1}{2}}] \times I_s. \quad (10)$$

In our experiments, a_1 and a_2 are very small, so it could be ignored, thus $r_1 = 0.99$, $r_2 = 1 - t_2$. η is a function of the separation between resonator mirror and the waveguide end, and the separation at both ends of the waveguide are the same, so $\eta_1 = \eta_2 = \eta$, therefore, we have

$$\begin{aligned} P &= I_2 \times t_2 \times A \\ &= A \times t_2 \times \frac{(r_1)^{\frac{1}{2}}}{[(r_1)^{\frac{1}{2}} + (r_2)^{\frac{1}{2}}] \times [1 - (r_1 \times \eta^2 \times r_2)^{\frac{1}{2}}]} \\ &\quad \times [g_0 \times L + \ln(r_1 \times \eta^2 \times r_2)^{\frac{1}{2}}] \times I_s, \end{aligned} \quad (11)$$

where A is the transverse area of the laser beam, and P is the laser output power.

From Eq. (11), for a waveguide laser with a defined output beam radius and gain length, if three sets of output coupling flat mirrors with the different transitivities are used, we can obtain three groups of equations with three undefined parameters, η, I_s, and g_0, which can be obtained by solving these equations.

In the experiments, the gain length of the all-metal slab waveguide laser was 386 mm, the slab waveguide cross section was 2 mm (h) × 20 mm (w), the transitivities of three sets of ZnSe output flat mirrors were 19%, 17.3%, and 10%, respectively. A copper flat mirror whose reflectivity was 99% was used to compose a CASE-I optical resonator with the ZnSe output flat mirror. For each set of the CASE-I resonator, we obtained a group of the output laser power data under the condition of gas pressure ranging from 5.4 to 12.66 kPa, and input RF power ranging from 400 to 950 W.

Based on the experimental data and the theoretical analysis, we have found that for our waveguide laser resonator, η was approximate 1.0, which is because that η is the function of separation between resonator mirror and the waveguide end, the smaller the separation is, the higher the η will be, the separation between waveguide end and resonator mirror is only 12 mm, the coupling coefficient is close to unit.

Figure 3 is I_s against the gas pressures. It has shown that I_s increases only as the gas pressure goes up, it is not affected with increasing or decreasing the RF input power. This is because that I_s is a function of the gain medium homogeneous broadening line width, which is a function of gas pressure. The experimental results have shown that I_s for the all-metal slab waveguide CO_2 laser is in the range of 300—1300 W/cm^2 corresponding to the gas pressure range of 5.4—13 kPa. Typically, when the gas pressure is 12 kPa, I_s is 1200 W/cm^2, which is much larger than that for the DC excited glass tube CO_2 lasers. It suggests that the technique of all-metal slab waveguide CO_2 lasers have the potential in kilowatts lasers.

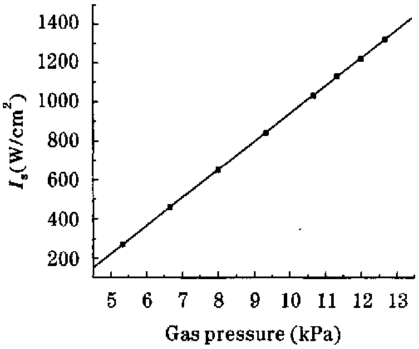

Fig. 3. Saturation intensity against gas pressures.

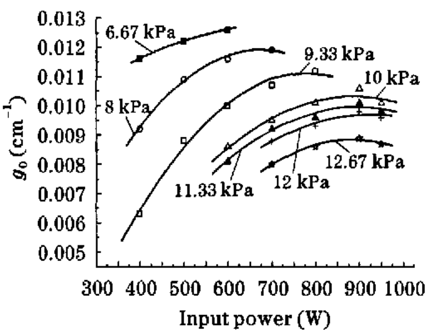

Fig. 4. Small signal gain against RF input power for the different gas pressures.

Figure 4 shows g_0 against RF input power for the different gas pressures. It shows that g_0 goes up, reaches a maximum and then goes down with the increase of the RF input power. In the RF discharge excited gas laser, for a certain value of gas pressure, as the RF input power increases, the plasma density increases, and the exciting probability of laser upper level increases, therefore g_0 increases, but as the RF input power further increases, the absorption power of plasma increases, which lead to the increase of gas temperature, g_0 will decrease. It means that for a certain value of gas pressure, laser output power will reach a maximum value as the RF input power increases.

In this paper, we theoretically analyzed and experimentally studied some parameters of the new type of RF excited all-metal slab waveguide CO_2laser. The results have shown that the saturation intensity I_s for the all-metal slab waveguide CO_2 laser can reach to 1200 W/cm^2, and small signal gain g_0 can be 1%/cm. It shows that this technique has the potential to be employed in kilowatts lasers.

This work was supported by the National Natural Sciences Foundation of China under Grant No. 60178002.
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刊名： 中国光学快报（英文版）ISTIC EI SCI
英文刊名： CHINESE OPTICS OF LETTERS
年，卷(期)： 2005,3(6)

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