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Effect of Gas Mixture on the Output Characteristics of a CW CO_2 Laser

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Abstract: In this work, the effect of partial amounts of gases in gas mixture of a CW CO_2 laser on the output power was investigated. Also their effect on the condition determining the glow-discharge self-sustaining required for pumping the active medium was studied. Two fit relations were derived to predict the output laser power and the electric field to unit pressure ratio as functions to the partial amounts of gases. Results presented in this work could be used fruitfully to determine some of the optimum operational conditions of glow-discharge low-power CW CO_2 lasers.

Introduction

After the invention of the CO_2 laser in 1964 by Patel [1], it was soon recognized that this type of laser had great possibilities. It could be produced with 30% efficiency and it was relatively simple to construct and could be scaled to large dimensions. The reason that lasers are such versatile tools for delivering optical energy is the principle of stimulated emission of radiation. Gas discharge pumping is extensively used in CO_2 laser systems as a result of its high efficiency. The voltage across the laser medium accelerates the electrons those collide with and excite the atoms or molecules in the medium, exchanging some of their initial energy. This results in slower secondary electrons. In turn, these electrons also excite the atoms and molecules and such process can be up to 90% efficient.

The glow discharge is used widely to pump CO_2:N_2:He mixture lasers and that used for pumping CW CO_2 laser has steady time-dependent characteristics. This discharge is referred as “self-sustained” glow discharge. In general, the self-sustained glow-discharge CO_2 lasers are simple in technology and construction, low in cost compared to other types of CO_2 lasers [2]. Despite, full description of the homogeneous self-sustained glow discharge in these lasers has not established yet.

The discharges can be divided into self-sustained and electron-beam sustained discharges. Self-sustained discharges are used in most moderately sized systems because of their simplicity. The process of glow-discharge formation is divided into two related and consequent stages. In the first stage, discharge initiating or beginning stage, both electric field and gas ionization rate are too high and the plasma conductivity increases extremely. In this stage, the discharge current density and input energy are low. The second stage is energy-entrance stage in which the electric field in discharge column is nearly equal to a constant value while the current density reaches its maximum. These two stages are related and the spatial uniformity of glow discharge is determined by gas-ionization homogeneity and applied electric field during the first stage. This uniformity hardly affects the energy entrance during the second stage of discharge [3].

In order to sustain and develop the glow discharge of CO_2:N_2:He mixture laser, the following two principal conditions should be fulfilled [4]:

$$n_0 \geq \left\{ \frac{3(\alpha - \gamma) eE}{32 W_k} \right\}^{3/2} \quad (1)$$

$$E_1(d) = \frac{2en_0}{\alpha - \gamma} \exp[(\alpha - \gamma)d] \geq E \quad (2)$$

where n_o is discharge electron density, α is Townsend ionization coefficient which is a function of gas-particle density and mixture, γ is electron-loss coefficient due to electron-ion recombination, e is electron charge, E is applied electric field, d is the spacing between electrodes, E_1 is the electric field near anode and W_k is mean kinetic energy of electrons. Satisfying these conditions ensures spatial homogeneity to the self-sustained glow discharge. However, the optimum ratio of gases in the mixture is usually found empirically by varying the partial amounts of gases in the mixture during operation [5-6].

A fit treatment to the two conditions above was presented [3] in which the first one requires the consistent (or internal) electric field to be higher than that applied prior the discharge column reaches anode. While the second one requires the formed discharge-series to attach each other just before the first condition is satisfied.

Electron loss includes three processes as following:

1. electron diffusion and transport out of discharge volume.
2. positive ion-electron recombination, and
3. attachment and detachment between electron and neutral atom.

Self-sustained, steady or quasi-steady discharge operation requires that ionization balance the entire loss of electrons resulting from attachment [7]. In large CO_2 laser systems, the first process could be neglected and the third process is the dominant when gas mixture contains relatively large amount of CO_2 molecules.

The aim of this work is to present a description and understanding to the process leading to the formation of self- sustained glow discharge as well as to determine the conditions required to develop discharge, hence increase output laser power, for different gas mixtures used in CW CO_2 lasers.

Experiment

An axial-flow longitudinal-discharge CW CO_2 laser system was used [8]. The discharge tube was 80 cm in length and 0.8 cm in diameter surrounded by a water-jacket tube of same length and 3 cm diameter. Discharge electrodes were made of stainless steel as a cylinder of 10 cm in length and 8 cm in diameter. The electrode has a 3 cm hole on the face the discharge tube mount through, and a 1cm hole at the opposite face allowing the output beam to exit.

The resonator configured was a hemispherical including two mirrors, the back one was a gold-coated copper mirror of 10 m radius of curvature and perfect reflectivity (~99.96%). The front one was a plane ZnSe mirror of 3 cm in diameter and 60% reflectivity. Also, a centered - hole plane brass mirror of 5 cm in diameter and 79.5% reflectivity was used. In the latter case, the end of discharge tube was sealed with a 2 cm-diameter ZnSe window and the spacing between the window and front mirror was 5 cm.

Ten gas mixtures with different CO_2, N_2 and He amounts were used to determine the conditions needed for optimum operation. Amounts of gases were varied throughout using a gas-mixer of three inlets and one-outlet to the discharge tube. The flow rate of the two–stage rotary pump used was 150 lit/min. Chiller used for cooling was able to keep the temperature of discharge tube at 10 °C.

A DC power supply of 6 kV and 150 mA was constructed to be used in this work. A sensitive Rofin-Sinar powermeter of scale (0.1-1000) W was used to measure the output laser power. The maximum output laser power was 50 W.

Fig. (1) shows the schematic diagram of the system used in this work.

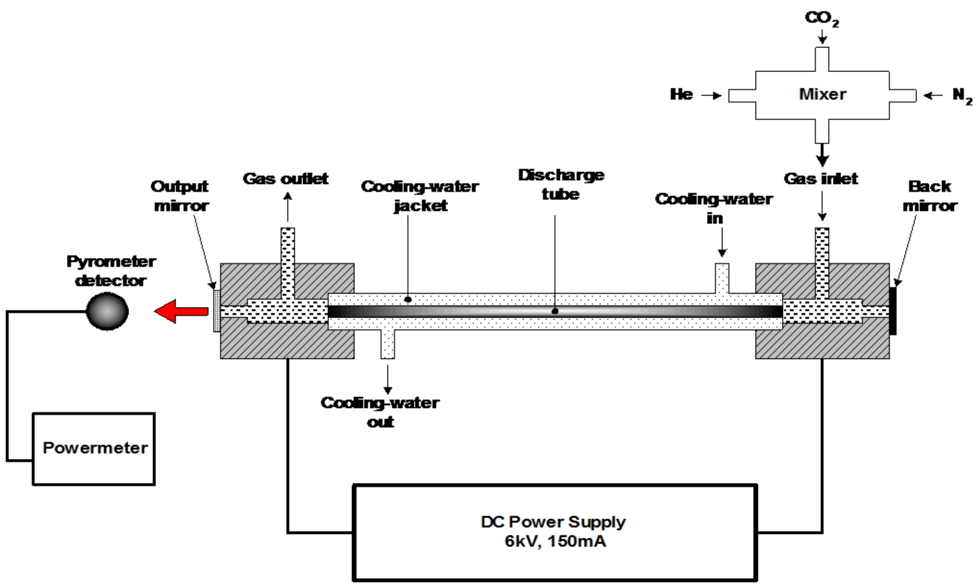

Fig. 1: Schematic diagram of the CW CO_2 laser of this work

Mathematical Treatment

In order to derive a relation predicting a power obtained from a certain gas mixture (CO_2:N_2:He), let us assume a power series as follows:

$$Y = a_o + a_1X + a_2X^2 + a_3X^3 + a_4X^4 + ... + a_iX^i \quad (3)$$

where Y corresponds to laser power, X corresponds to partial amount of the gas, and a_o, a_1, a_2, ... are the numerical parameters of the power series. The deviation (d_i) in data can be determined as:

$$d_i = Y_{data} - Y_{eq} = Y_i - (a_o + a_1X + a_2X^2 + a_3X^3 + a_4X^4 +.... + a_iX^I) \quad (4)$$

To get only positive part of the above equation, let Q = $\Sigma\, d_i^2$, then:

$$Q = \Sigma\, Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4X^4 - ..... - a_iX^i)^2 \quad (5)$$

Differentiating with respect to each parameter,

$$dQ/da_o = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^I)\ (-1) = 0$$
$$dQ/da_1 = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^i)(-X_I) = 0$$
$$dQ/da_2 = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^i)(-X_i^2) = 0$$
$$dQ/da_3 = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^i)(-X_i^3) = 0 \quad (6)$$
$$dQ/da_4 = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^i)(-X_i^4) = 0$$
$$dQ/da_I = \Sigma\, 2(Y_i - a_o - a_1X - a_2X^2 - a_3X^3 - a_4 X^4 - ....- a_iX^i)(-X_i^i) = 0$$

For M data (points), from i= 1 to M, one can get the set of equations:

$$a_o\, M + a_1\, \Sigma\, X_i + a_2\, \Sigma\, X_i^2 = \Sigma\, Y_i \quad (7a)$$

$$a_o\, \Sigma\, X_i + a_1\, \Sigma\, X_i^2 + a_2\, \Sigma\, X_i^3 = \Sigma\, X_i\, Y_I \quad (7b)$$

$$a_o\, \Sigma\, X_i^2 + a_1\, \Sigma\, X_i^3 + a_2\, \Sigma\, X_i^4 = \Sigma\, X_i^2\, Y_i \quad (7c)$$

Hence, the solution of these equations is:

$$Y = a_o + a_1 X + a_2 X^2 \quad (8)$$

Equation (8) could be estimated for each gas in the mixture as

$P_1 = a_o + a_1 A + a_2 A^2$ for CO_2
$P_2 = b_o + b_1 B + b_2 B^2$ for N_2
$P_3 = c_o + c_1 C + c_2 C^2$ for He

Then,

$$P_{Total} = 1/3 (P_1 + P_2 + P_3) = 1/3 \{(a_o + a_1 A + a_2 A^2) + (b_o + b_1 B + b_2 B^2) + (c_o + c_1 C + c_2 C^2)\} = 1/3 \{(a_o + b_o + c_o) + (a_1 A + b_1 B + c_1 C) + (a_2 A^2 + b_2 B^2 + c_2 C^2)\} \quad (9)$$

Results and Discussion

Table (1) indicates gas mixtures used in this work. The laser system was operated and the output laser power was measured as a function to gas pressure at different values of discharge current. Fig. (2) indicates that power increases as the total gas pressure does and Fig. (3) represents the variation of output power with discharge current for different gas pressures. As could be seen, the optimum value of discharge current was 45 mA at which maximum output laser power was obtained. It was shown that output power trends to stability at pressures close to 10 Torr that represented a steady point even with increasing pressure more. Increasing operation total gas pressure requires higher applied voltage (>6 kV) when the discharge current is kept at a constant value (45 mA). This is limited by the maximum electrical power could be supplied.

Data presented were used to derive a fit formula determining the obtainable power from a certain gas mixture. The derived relation is as below:

$$P=3\ [11a+ (b/3)+ 31c- 25a^2- 4b^2- 23c^2- 9.65] \quad (10)$$

where *a*, *b* and *c* are the percentage (%) partial amounts of CO_2, N_2 and He, respectively, in gas mixture at a total pressure of 10 Torr. Eq. (10) explained high approximation between values calculated according to fit formula and those obtained experimentally. Fig. (4) indicates variation of output laser power as the amount of CO_2 varies for the two cases of interpolated and experimental values. According to fit formula to output laser power for different gas mixture, gas composition and total gas pressure are chosen in a combination manner between these two parameters to obtain maximum power.

Table (1) The gas mixtures used in this work

Exp. no.	CO_2 (%)	N_2 (%)	He (%)	P (W)
1	5	13	82	1
2	8.5	12.5	79	18
3	10	6	84	36
4	13.5	14	72.5	32
5	15	15	70	48
6	18.5	13	68.5	35
7	21.5	14	64.5	39
8	27.5	12.5	60	50
9	34	11.5	54.5	20
10	38	11	50	4

The maximum energy is transferred from the power supply to discharge volume at the critical damping condition of the electrical circuit. Critical damping condition is satisfied when the conductivity of discharge plasma equals to inversion of the impedance of power-supply circuit. This is held when the stationary electric field (E_S) is equal to a half of that applied (E), i.e., $E=2E_S$.

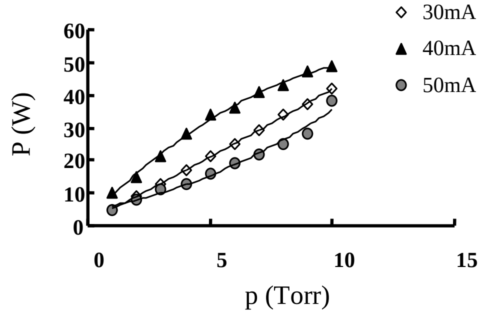

Fig. 2: Output laser power *vs.* total gas pressure for 15:15:70 mixture

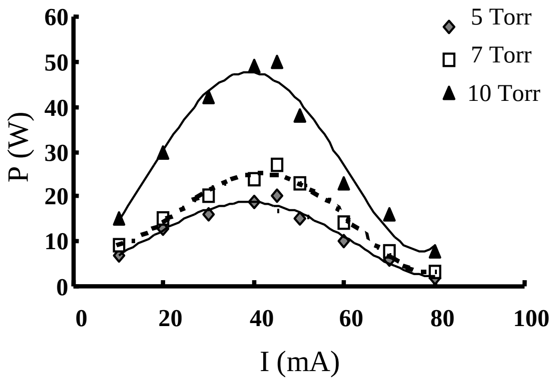

Fig. 3: Output laser power *vs.* discharge current for different total gas pressures

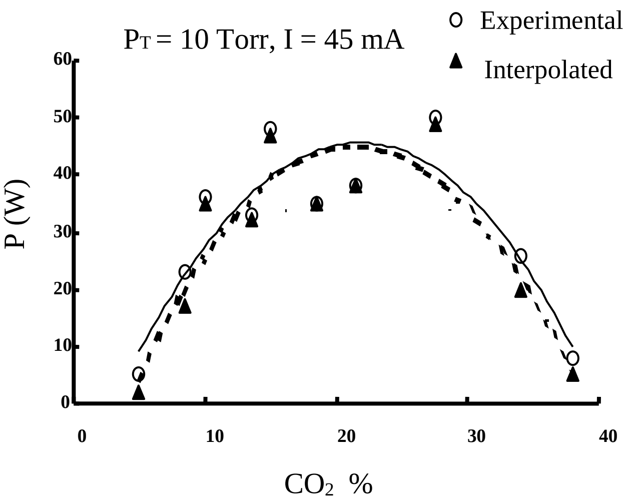

Fig. 4: Output laser power *vs.* CO_2 amount (%) in the mixture

From the results, the stationary electric field to unit pressure (E_S / p) ratio could be deduced. This parameter determines the energy transferred to unit pressure (volume) of gas mixture. Fig. (5) indicates the variation of E_S/p parameter with the partial pressures of CO_2 and N_2. In this figure, decreasing in E_S/p could be noted as the pressure of two gases increase. This behavior justifies need to higher stationary electric field (E_S), hence higher applied electric field (E), to sustain glow discharge in case of increasing CO_2 and N_2 pressure above an optimum operational value. The parameter E_S/p was computed using a numerical approach considering Eq. (10) as:

$$\frac{E_S}{p} = D - FL - \frac{(GAB + H)}{L} \qquad (11)$$

where A and B are the partial pressure (Torr) of CO_2 and N_2, respectively, and

$L = p\,(A+B)$
$H = 8.9 \times 10^{-4}\ kV.cm^{-1}$
$G = F = 1.78 \times 10^{-3}\ kV.cm^{-1}.Torr^{-1}$
$D = 4.7 \times 10^{-3}\ kV.cm^{-1}.Torr^{-1}$

Fig. (5) did not consider ratio of helium gas which appeared in Eq. (10) as term C. the reason is that He gas does not contribute to the electrical pumping of laser energy-levels, so it consumes no amount of supplied energy required for excitation. The energy gap between the ground and first excited levels in He molecule is too high compared to those in CO_2 and N_2 molecule.

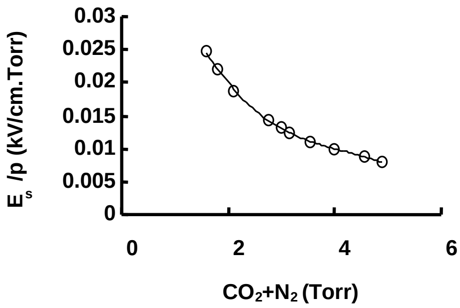

Fig. 5: The E_S/p parameter *vs.* CO_2+N_2 amount (Torr) in the mixture

Conclusions

It could be concluded that certain gas mixture, which is optimum to obtain maximum laser output power, is not necessarily optimum to achieve self-sustained spatially-uniform glow discharge. Two fit formulae were derived and they showed coincident results to those obtained experimentally with acceptable deviation. The mixture (27.5:12.5:60) of gases CO_2:N_2:He, respectively, seems to be the optimum to obtain maximum output laser power regarding to our practical conditions, while the calculations according to the derived numerical formulae stated that the optimum gas mixture for same operational conditions is (21.5:14:64.5). This work is an attempt to establish a requirement to design low-cost CW CO_2 laser.

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تأثير الخليط الغازي على خصائص الخرج لليزر ثنائي أوكسيد الكربون المستمر

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الخلاصة

في هذا البحث، جرى دراسة تأثير النسب الجزئية لمكونات الخليط الغازي على قدرة الخرج لليزر ثنائي أوكسيد الكربون المستمر. كما جرى دراسة تأثيرها على شرط المساندة الذاتية للتفريغ التوهجي المستخدم لضخ الوسط الغازي الفعال. تم اشتقاق علاقتي استكمال رياضي لتخمين مقدار قدرة الخرج الليزري التي يمكن الحصول عليها وكذلك نسبة المجال الكهربائي لوحدة الضغط كدالة للمقادير الجزئية من مكونات الخليط الغازي. يمكن الإفادة من النتائج المقدمة في هذا البحث بشكل جيد لتحديد بعض الظروف التشغيلية المثلى لليزرات ثنائي أوكسيد الكربون المستمرة ذات التفريغ التوهجي والقدرة الواطئة.