J.Basrah Researches (Sciences) Vol. 33. No.3. 1 -7 SEP.(2007)

Radio Frequency Breakdown in Partial Z-Fold Waveguide CO_2 Laser

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ISSN –1817 –2695

(Received 11/2/2007, Accepted 27/5/2007)

Abstract:

The detailed mathematical model for the evolution of uniformly distributed voltage in RF-excited partial Z-fold CO_2 waveguide laser with common elec- trodes excited by a same RF source is discussed. In the experiment, we studied the voltage distribution along the electrodes. The length of the partial Z-fold channel is 3x460 mm (long channel) and that of the single channel is 460 mm.

Keywords: Waveguide CO_2 laser, RF discharge, Partial Z-fold, Two channels

Introduction:

The CO_2 laser discharge can be excited by dc, high frequency (10 KHz-3 MHz), radio frequency (13-1500 MHz) and microwave (2.45GHz). The first CO_2 laser was excited by a dc discharge. Nowadays, CO_2 lasers are still excited by a dc discharge because the low cost of dc high-voltage generators microwave generators has also moderate prices[1], but CO_2 lasers excited by microwaves do not reach the power densities of dc and RF excited lasers, most of the CO_2 lasers operated today use the RF excitation, which presents many advantages over the dc excitation, for example, the avoidance of anodes and cathodes, which eliminates the associated gas chemistry problem at the cathode and the occurrence of a stable discharge at higher discharge pressures.

Observation and measurements on RF discharges at an intermediate pressure reveal a considerable variation close to the electrode boundaries in the direction of the applied field of visible light emission, internal electric field and electron energies. Notably the electric field and electron energy are usually higher, closer to the boundaries in the so called striation zones. The encroachment, at low RF discharge and pressure, of the striation zones on the central gain region or positive column-like portion of the discharge is known to be detrimental to CO_2 laser operation which is favoured by low electron energies [2]. The purpose of the present work is to develop new analytic model for the radio frequency breakdown in partial Z-fold waveguide CO_2 laser with common electrodes and excited by a same RF source.

Laser design

The laser is designed around a metal ceramic sandwich waveguide, which has a 2.25x2.25 mm^2 cross-section, as illustrated in figure(1). The laser structure has two channels, partial Z-fold channel and single channel. The two channels are excited by the same RF source and placed within a water–cooled stainless vacuum housing, which incorporate a RF feed through to enable power to be transmitted to the waveguide. The distance of two channels is 20 mm. The partial Z-fold channel is 3x460 mm in length and the single one is 460 mm. Case I waveguide resonator with a flat total reflector and a flat output mirror is used for the single channel. For reducing coupling losses for the EH_{11} mode and easy to insert a modulator crystal and other optical elements into the resonator, we designed equivalent Case III waveguide resonator for partial Z-fold channel. Two total reflector laser mirrors are placed 5mm away from the ends of the two waveguides. Another two total reflectors are at the elbow parts of Z-fold. A flat

ZnSe window is placed 5mm away from the front of the partial Z-fold waveguide. A ZnSe lens and a output mirror, which are closed as soon as possible, are equivalent to concave mirrors as Case III waveguide resonator for partial Z-fold channel. The four total reflectors, a ZnSe window and a flat output mirror are attached to the vacuum housing with mounts sealed by "O" ring, which permitted angular adjustments along the two orthogonal axes. The laser output directions from the two channels are opposite.

RF Breakdown Theory

In electrically breaking down the gases, it is required that the velocity of producing new ionized particles should surpass or be equal to the velocity of particle losses during the various deionizing processes. The deionizing processes of charged particles in the conducting gases includes the combination of positive and negative charged particles, absorption of electrons and diffusion of charged particles. In some occasion, when the absorption and combination can be ignored, the diffusion of charged particles becomes the main factor of losses. That is the basic idea of Browns theory of microwave breakdown and diffusion and also the core of the breakdown mechanism of diffusion control [3].

Because the variation of electron density with time evolution is the difference between production rate and diffusion rate, therefore [4].

$$\frac{\partial n_e}{\partial t} = D_e \nabla^2 (n_e) + v_i n_e \qquad \text{..(1)}$$

where, n_e is the electron concentration, D_e is the diffusion coefficient, $v_i n_e$ is the number of electrons newly produced as a result of the collision between electron and gas in unit volume and during unit time interval.

When there happen to be a balance between the gain and loss of the charged particles, that is, when $\frac{\partial n_e}{\partial t} = 0$, the breakdown condition can be written as:

$$D_e \nabla^2 n_e + v_i n_e = 0 \qquad \text{……………………… …..(2)}$$

This is the Brown's breakdown criterion. In one dimensional uniform electric field, the diffusion coefficient of electron D_e, can be taken as a constant, therefore

$$D_e \frac{d^2 n_e}{dx^2} + v_i n_e = 0 \qquad \text{………………………….(3)}$$

As mentioned above, v_i ,the frequency of the ionized collision of the electron,is a function of the electric field intensity.

$$v_i = \alpha V_D = \alpha \mu_e E \qquad \text{………………………..….(4)}$$

in which α is the 1st Thomson Coefficient of the ionization caused by the collision between electrons and atom, V_D , is the electron drift velocity, and μ_e is the electron drift rate. Similarity, the ionization coefficient, we introduce one more coefficient, ξ , the frequency offset ionization coefficient.

$$\xi = \frac{v_i}{D_e E^2} \qquad \text{...……………………..(5)}$$

ξ stands for the number of ionization produced by collisions in unit time interval caused by E, the electric field during the electron heat diffusion. Because the electron density is a function of time and space, we can suppose here

$$n_e(x,t) = n_e(x)e^{-t/T} \qquad \text{……………………...…(6)}$$

Substituting equation (6) into equation (3), one gets

$$\frac{v_i}{D_e} n_e + \frac{d^2 n_e}{dx^2} = 0 \qquad \text{………………………..... (7)}$$

in which n_e is no longer a time function.

If the space distribution of the electron density between the parallel-plate electrodes is a (*sine*) wave with a maximum of electron density at the center and zero electron density at both of the electrodes (common electrodes), then

$$n_e = n_o \sin\left(\pi \frac{x}{d}\right) \qquad \text{……………..………..…(8)}$$

Substituting equation(8) and equation(5) into equation(7), yields

$$E_c^2 = \left(\frac{\pi}{d}\right)^2 \frac{1}{\xi} \qquad \text{………..……………..…(9)}$$

which is the high-frequency breakdown electric field between parallel-plate electrodes. Here the electric field along the length of d is regarded uniformly. Comparing equation (5) and equation (9), one gets

$$\left(\frac{\pi}{d}\right)^2 = \frac{v_i}{D_e} = \frac{1}{\Lambda^2} \qquad \text{…………..………………… (10)}$$

which is another form of the solution of the equation (7). Λ is defined as the feature diffusion length. The above result is attained on condition of equilibrium of number of electron.

To model the discharge plasma, we consider the motion of an electron cloud in an oscillatory electric field of angular frequency ω, in gaseous medium without boundaries. Electronic motion can be described by the equation [5] .

$$m\frac{dV_D}{dt} + mV_D v_m = eE_0 e^{j\omega t} \qquad \text{…………………………..(11)}$$

Where m and e are the electron mass and charge respectively, v_m is the electron collision frequency.

Where [6][7],

$$V_D = \left(\frac{e}{m}\right)\frac{1}{v_m + i\omega}E \qquad \text{………………………….. (12)}$$

and the current density is [8],

$$j_e = n_e e V_D = \frac{n_e e^2}{m(v_m + i\omega)}E \qquad \text{…………………………….(13)}$$

On the basis of the above derived relation the following discussion is to point out the relation between the breakdown condition and the equilibrium of energy. The power supplied by the electric field of each unit discharging is $p = j_e.E$. We can get from equation (13) ,

$$p = \frac{n_e e^2}{m(v_m + i\omega)} E.E = \frac{n_e e^2}{m(v_m + i\omega)} E_0^2 e^{i2\omega t} \qquad \text{…..…………………..(14)}$$

the average actual power of one period is

$$p_c = \frac{n_e e^2 E_0^2}{m} \cdot \frac{v_m}{v_m^2 + \omega^2} \qquad \text{……..……………..…..(15)}$$

which is the average power obtained by all the n_e number of electrons existing in the gas.

Under high gas pressure, $v_m > \frac{\omega}{2\pi}$, therefore,

$$P_c = \frac{n_e e^2 E_o^2}{m v_m} \qquad \text{………..…...……..………(16)}$$

the average energy that one electron gets from collision each time is,

$$\frac{P_c}{n_e v_m} = \frac{e^2 E_o^2}{m v_m^2} \qquad \text{………..……………..(17)}$$

If the average electron energy is $\frac{1}{2}mv^2$, the energy that the electron obtains from the electric field will be lost after its elastic collision against gas atom. If each time the percentage of the average loss of electron energy due to collision is $\frac{2m}{M}$ (M is the mass of the gas molecule), the average loss of energy of electrons each time due to collision is $\frac{1}{2}mv^2.\frac{2m}{M} = \frac{m^2v^2}{M}$. Viewing from the aspect of energy equi1ibrium, the energy of electron obtains must be equal to that it loses. Therefore, we can get from equation (17).

$$E_c = v_m \left(\frac{m^3 v^2}{e^2 M} \right)^{\frac{1}{2}} \qquad \text{…………….…………..(18)}$$

under given conditions, because $\left(\frac{m^3 v^2}{e^2 M} \right)^{\frac{1}{2}}$ is a constant , v_m and E_c are both directly proportional to gas pressure P. This relationship in high-gas pressure microwave discharge has been proved by a lot of experiment facts.Under low gas pressure, $v_m < \frac{\omega}{2\pi}$ from equation (15), we can get the power that each electron obtains from the electric field

$$\frac{p_c}{n_e} = \frac{e^2 E_0^2 v_m}{m\omega^2} \qquad \text{……………….……………(19)}$$

Suppose under optimistic conditions, all electrons, if the collision that causes ionization is only against gas atoms, then, one can suppose that the input power is equal to the ionizing power since, the ionizing power is ,

$$P = eV_i v_i \qquad \text{………………………..……….} \ (20)$$

Where V_i , is the ionizing potential of the gas atom. From equation (19) and equation (20), we can get

$$E_c^2 = \frac{m\omega^2 V_i v_i}{e v_m} \qquad \text{………………………………..}(21)$$

If we substitute $D_e = \frac{1}{3}\bar{\lambda}\bar{v}$ into equation (10), we can get

$$v_i = \frac{\bar{\lambda}\bar{v}}{3\Lambda^2} = \frac{\bar{v}^2}{3\Lambda^2 v_m} \qquad \text{…………………….…………..}(22)$$

Therefore,

$$E_c = \frac{\omega}{\Lambda v_m}\left(\frac{m\bar{v}^2}{3e}V_i\right)^{\frac{1}{2}} \qquad \text{…………………………………} \ (23)$$

Results and Discussion

In our new structure, the laser head is fed by a power (0-300W) and frequency (80 MHz) controllable RF transmitter and it is matched to $50\,\Omega$ by network based on a tunable strip line(see figure(1)) .Ten parallel inductors are placed across the electrodes to form a resonant transmission line at 80MHz . The network was chosen in order to minimize the power losses due to stray resistances and to avoid the meantime voltage differences along the longitudinal direction of the waveguide. In this way, we can assume with confidence that the RF power, measured at the RF source by a bird through line directional power meter, is completely delivered to the discharge. The quantities inside the parentheses on the right hand side of the equation (23) are the physical constants of gases and electron. E_c is inversely proportional to gas pressure P as the v_m (under low gas pressure) is directly proportional to the gas pressure also under certain gas pressure and in certain distance between electrodes, E_b increases linearly with ω.Figure (2)shows the experimental results of the voltage distribution along the electrodes with the shunt inductors and the position of the inductors along the electrodes .figure(3) indicates the theoretically calculated results of E_c of partial Z- fold RF excited waveguide CO_2 laser under high and low pressure with the laser' s operating conditions as follows: the gap between the upper and lower electrodes, 2.25mm; the proportion of the mixed gases, CO_2:N_2:He:1:1:3; and the frequency of the RF electric power source, 80MHz.

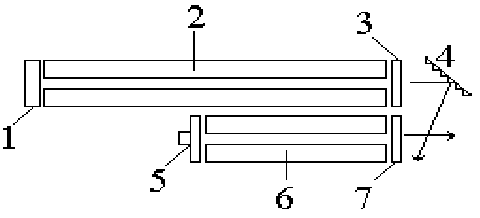

Fig.1.Structure of the laser

1. reflecting mirror ,2.long channel(Z-fold), 3.ZnSe window,4.grating,5.reflecting mirror mounted on PZT ,6. short channel ,7. output mirror

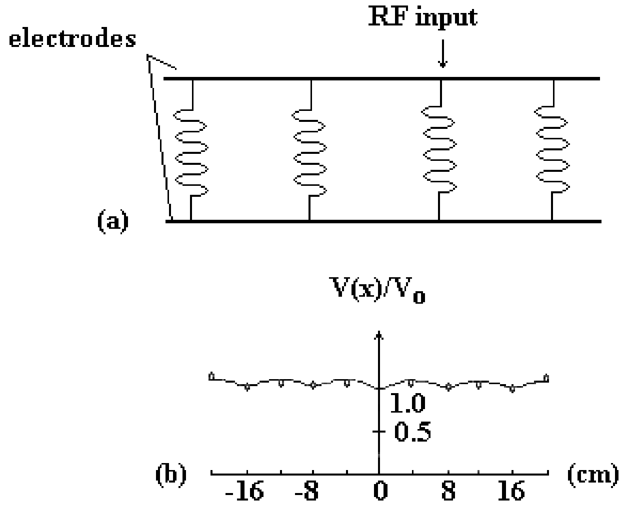

Fig.2. (a) Position of the inductors along the electrodes.

(b) Voltage distribution along the electrodes with the shunt inductors

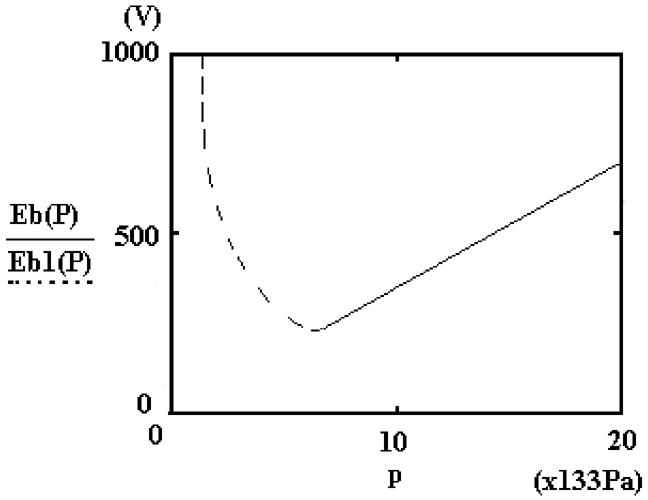

Fig. 3. Fire voltage of partial Z-fold RF- excited waveguide CO_2 laser

Conclusion

The objective of this study was to explore method of obtaining uniform discharge along the length of the two channels (partial Z-fold channel and single channel). In this structure, the waveguide laser utilizes a parallel–resonant distributed–inductance (PRDI) technique to uniformly distribute voltage along the electrodes and hence to uniformly excite the gain medium. With this method a large number of equal-value parallel inductors are uniformly placed from the center of the laser channels to approximate a distributed inductance. The value of the inductance is chosen such that it resonates the capacitance of the waveguide structure at the RF frequency. The main advantages of the laser are a compact structure, small size, easy manufacturing, and lower cost. In addition; the tolerance to misalignment is far greater with the partial waveguide fold reflector than with the general geometry. These advantages can well satisfy the requirements of laser radar and other scientific study.

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أنهيار الغاز في ليزر ثاني أوكسيد الكاربون ذو الحزمه الموجهه المطوي جزئيا على شكل حرف (Z)

حسين علي بدران

الخلاصه:

مناقشة نموذج رياضي تفصيليا لتطوير توزيع الفولتيه بشكل منتظم في ليزر ثاني أوكسيد الكاربون المطوي جزئيا على شكل حرف Z والمحتوي أقطابا كهربائيه مشتركه تتهيج بنفس مصدر التردد الراديوي . عمليا تمت دراسة توزيع الفولتيه على طول الاقطاب حيث كانت طول القناة (الطويله) المطويه على شكل حرف Z 3x460 mm أما القناة المنفرده الاخرى بطول 460 mm .