PLASMA CAPACITANCE AND INDUCTANCE MEASUREMENTS IN PULSED GAS LASER DISCHARGE TUBES

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PA.CS : 42.60

ABSTRACT

The plasma capacitance and inductance in pulsed gas laser discharge tubes are measured with a new plasma impedance matching technique. It gives information about plasma parameters by analysing the stimulated radiation pulse characteristics.

INTRODUCTION

The plasma characteristics in gas lasers are of fundamental importance for a better understanding of the corresponding population inversion mechanisms. Parameters like electron density (n_e) and temperature (T_e) are important tools for a complete knowledge of the stimulated emission generation. A simple example of that is the modification in electron energy due to the presence of H_2 and the corresponding modification in laser emission of a N_2-H_2 hollow cathode laser [1].

Gas lasers operating in a direct current (DC) excitation regime allow plasma characteristics be measured in a simple way, for example with the help of Langmuir probes [2], to obtain electron temperature (T_e) and density (n_e).

The importance of this kind of plasma plus laser analysis has been recently stressed in the case of CO_2 lasers [3-4]. The application of unstable glow discharges has allowed the laser efficiency to increase up to almost the maximum expected limit.

In the case of lasers excited in the pulsed regime, the situation is not so simple. As the excitation discharge is a typical transient one, Langmuir probes are not appropriate. This problem becomes even more serious in the case of the so called self-terminated laser systems. This kind of lasers is characterized by the effective lifetime value of the upper laser level being lower than the corresponding one of the lower laser level. Then, the corresponding (main) condition for laser operation is the application of excitation pulses with rise-time ideally much lower than the effective life-time of the laser upper level. Only in that situation the inversion population regime is attained.

Recently [5-6], matching processes involving spark- gap and laser channel plasmas in gas lasers have been reported. At matching condition, the laser emission presents a minimum in laser pulsedwidth and a maximum in peak-power.

The present work follows results of Refs. [5,6], to obtain the plasma capacitance (C_p) and inductance (L_p) of the laser discharge tube in a self-terminated pulsed gas laser (N_2 TE, 2' 0-0 transition band, 337.1 nm wavelength emission). Since the data is obtained from the analysis of laser emission characteristics, the plasma does not suffer any probe insertions.

EXPERIMENTAL SET-UP

The method has been tested with the help of a N_2 UV laser (2' 0-0 transition band, 337.1 nm wavelength emission), with waveguide characteristics [7]. Figure 1 presents the corresponding excitation circuit, with a capacitive transfer configuration. The discharge channel was determined by two metallic plates (electrodes) and two teflon plates. We define d as interelectrodic distance and d' the thickness of the discharge channel. The laser discharge tube is 30 cm long.

The all possible set of combinations between C and C' have been tested. C values varied from 0.6 up to 12.0 nF and C' from 0.6 up to 10.0 nF. The coupling inductance (L_{ext}) had 3.2, 5.5 and 12.0 μH values.

The vacuum system was an Edwards E2M2 rotary pump, manometers and a commercial grade N_2 reservoir. The laser discharge tube has two sub-chambers to assure a regular gas flux and a equilibrium pressure condition inside the discharge chamber.

The interelectrodic distance (d) was kept constant at a 5 mm value. The thickness between teflon plates was varied in the 0.1 - 0.8 mm range, being 0.5 mm the most used value.

The spark-gap design followed a new design recently reported [8], giving ultra-high frequency excitation pulses.

The detection system consists of a ITL 1850 vacuum photodiode and a 7104 Tektronix oscilloscope with a 7A29 Tektronix vertical unit. The system allows to assure a temporal resolution limit lower than 0.35 ns.

Voltage pulses are observed with a help of a capacitive voltage divider.

The data were analyzed with the help of a Tektronix DCS01 digitizing camera system.

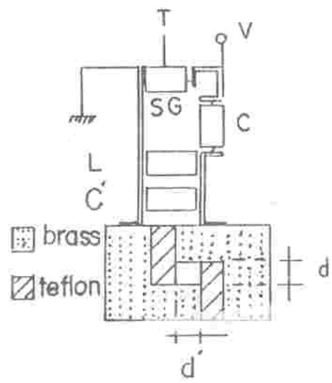
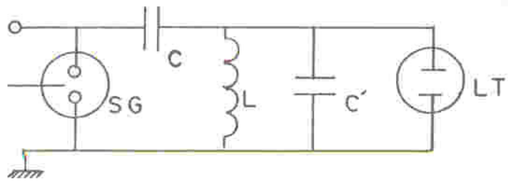


Figure 1.- Laser circuit. Modifying d and d' it is possible to change discharge channel dimensions.

IMPEDANCE MATCHING

The dielectric properties of the plasma are such that it carries an impedance. This is particularly important in plasmas between electrodes [9-12]. The equivalent circuit of this plasma impedance is a tank circuit. To show the importance of plasma impedance, we carry out a sequence of circuit analysis to identify the role of each section of the equivalent circuit of Figure 1, now presented in Figure 2. On it, we are including the C" preionization capacitor, not present in Figure 1, to give rise to a more general analisis. It is obvious from the circuit that a rigorous analysis is a non linear problem that includes plasma equations to determine the time dependent plasma parameters. Instead of solving this complicated self-consistent problem, we assume constant C_s and L_s whose values are inferred from experimental results that we will come to in the following sections. Then, for fixed storage capacitance and charging voltage, C_s and L_s are basically functions of L. Furthermore, we neglect all resistive elements since we are interested primarily in the eigenfrequencies.



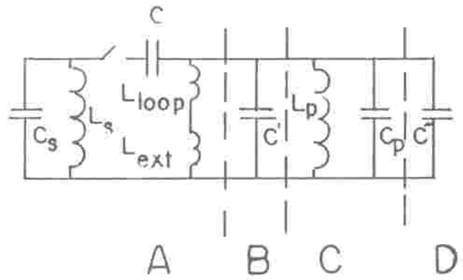


Figure 2.- Equivalent electric circuit including the spark-gap (C_s, L_s) and laser channel (C_p, L_p) plasma impedances, without (section C) and with (section D) preionization.

Taking a Laplace transform of the circuit equations of Figure 2, section A, and considering $L_s << L$, $C_s \cong C$, the time asymptotic behavior is described by the two frequencies:

$$\omega \cong (L\ C)^{-1/2} \qquad (1)$$

$$\omega_s \cong (L_s\ C_s)^{-1/2} \qquad (2)$$

where $L = L_{ext} + L_{loop}$. If the spark-gap is considered to be an ideal switch, the frequency is given by (1). Experimentally, when only section A is used, the recorded signal shows an oscillation about two orders of magnitude higher which we attribute to the spark-gap impedance, (2). The high frequency solution ω_s can be controlled by the circuit inductance L since it affects C_s.

Next, when the circuit is extended to section B, the frequencies are slightly modifyed as follows:

$$\omega \cong [\ L\ (\ C + C'\ )\ ]^{-1/2} \qquad (3)$$

$$\omega_s \cong [\ L_s\ (\ C + C_s\ )\ ]^{-1/2} \qquad (4)$$

The corresponding experimental analysis shows a reduction in high frequency components that is compatible with (4).

Finally, we add the laser discharge channel, and if we neglect the time delay between the breakdown of the spark-gap plasma and the laser channel plasma, the frequencies are:

$$\omega_x \cong [\ L_x\ (\ C + C_x\ )]^{-1/2} \qquad (5)$$

$$\omega_s \cong [\ L_s\ (\ C + C_s\ )]^{-1/2} \qquad (6)$$

where $L_x^{-1} = L^{-1} + L_p^{-1}$, $C_x = C' + C_p$ and C_p and L_p are the impedance of the laser channel plasma. As in the spark-gap plasma C_p and L_p are functions of the laser channel plasma density, which is sensitive to having or not having preionization, sections C and D. Consequently, they are implicit functions of C", d' and gas pressure. The two frequencies ω_x and ω_s can now be comparable with each other.

By inverting the Laplace transform, the voltage across the laser channel is

$$V(t) = V(0)\ .\ \{\ (C\ C_s) / [\ (\ C_s + C\ )\ (\ C_x + C\ )\ ]\ .\ 1 / (\omega_x^2 - \omega_s^2)$$

$$.\{\ [\ (L_s\ C_s)^{-1} - \omega_s^2]\ \cos \omega_s t - [\ (\ L_s\ C_s\ )^{-1} - \omega_x^2]\ \cos \omega_x t\} \qquad (7)$$

with ω_s and ω_x defined by (5) and (6). When the laser channel impedance is such that

$$\omega_x^2 = \omega_s^2 \qquad (8)$$

by varying the gas pressure, the voltage reaches a maximum and (7) reduces to

$$V_x\ (t) = V_x\ (0)\ .\ \cos \omega_x t \qquad (9)$$

with $V_x\ (0) = V\ (0)\ .\ (C\ C_s\ ) / [\ (\ C_s + C\ )\ (\ C_x + C\ )]$ (10)

and the energy transfer to the laser channel is

$$E_x\ (t) = E_x\ (0)\ .\ \cos^2 \omega_x t \qquad (11)$$

with

$$E_x\ (0) = (1/2)\ .\ C\ V(0)^2\ .\ [\ C_s / (C_s + C\ )]^2\ .\ [\ (\ C\ C_x\ ) / (\ C_x + C\ )^2\ ] \qquad (12)$$

It is clear that E_x (0) is a function of C_x and by diferentiating with respect to C_x, we can readily show that $E_x(0)$ has a peak at $C_x = C$, for

$$\partial E_x(0) / \partial C_x\ \Big|_{C_x = C} = 0 \qquad (13)$$

RESULTS AND DISCUSSIONS

After these previous considerations, let us have a look at the laser pulsewidth as a function of pressure. The results of Figure 3 show a significant narrowing of the laser pulse from 3.0 to 1.5 ns. This confronts the general concept that the pulsewidth reduces gradually and monotonically as a function of pressure according to the known lifetime of $C^3\ \Pi_u$ level as mentioned, for example, in reference [13]. The voltage measurement across the discharge channel shows a corresponding maximum at the same pressure. It is important to note that at a 330 mbar pressure value we have, simultaneously, the maximum laser output, channel voltage and minimum pulsewidth. Also, we have to stress that this situation corresponds to the impedance matching between the spark-gap and discharge channel plasmas

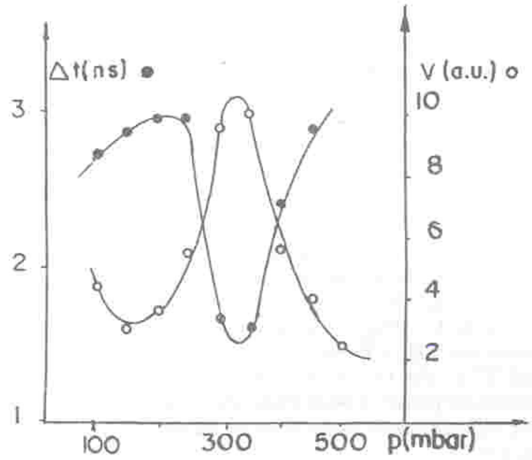


Figure 3.- Excitation voltage and laser pulsewidth behaviors as a function of pressure, with C = 5.1 nF, C' = 6.1 nF, L_{ext} = 3.2 μH, V = 15 kV.

Now we keep constant nitrogen pressure values and look for the C, C' relations that allow results of the type showed in Figure 3. The corresponding results are presented in Figure 4 for 150 mbar and different C values. We observe pairs of C, C' values giving a minimum Δt_{laser} value, and maximum laser peak power output.

From Eq. (13) and having in mind the condition $C = C_x = C' + C_p$ we see that the minimum Δt_{laser} condition corresponds to the $C = C' + C_p$ situation. Then, from Figure 4 results C_p values can be deduced. A summary of this results is shown in Figure 5 for the $p(N_2)$ = 150 mbar situation. We observe how C_p value behaves as a function of applied energy, having in mind that V = 15 kV excitation voltage value was kept constant. Then, applied energy values correspond to a C (nF) variation.

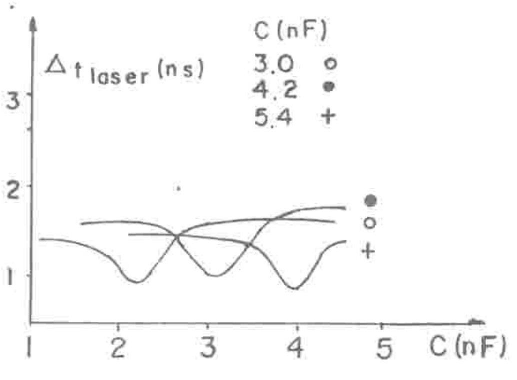


Figure 4.- Typical laser pulsewidth variation as a function of C'values, with C as a parameter, p (mbar) = 150, d = 5 mm and d' = 0.5 mm

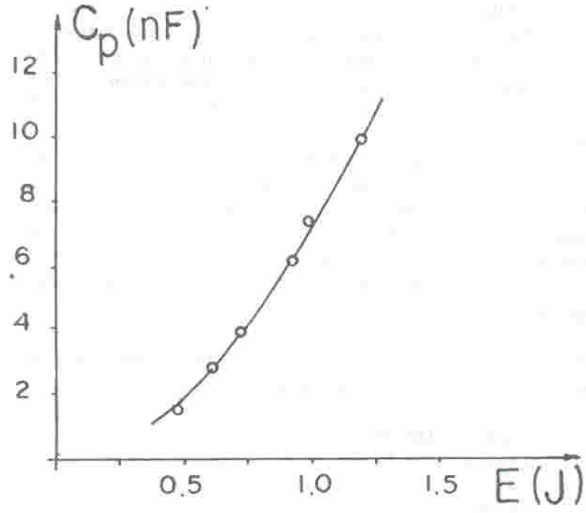


Figure 5.- Plasma capacitance value [C (nF)] behavior as a function of input energy [E (J)].

Knowing the C, C' pairs of values that give the $C = C' + C_p$ at a given pressure, we now look for plasma inductance values (L_p).

With the help of a capacitive voltage divider we measure the excitation voltage period, for the complete set of $C = C' + C_p$ situations. The corresponding value was always around the 40 ns value region. As

$$f = (1/2\pi)\,[\,L_p\,(\,C' + C_p\,)\,]^{-1/2} = (1/2\pi)\,[\,L_p\,C\,]^{-1/2} \quad (14)$$

then, having period values information we now make

$$L_p = (1/C)\,.\,[\,P / 2\pi\,]^{-1/2} \qquad (15)$$

with P = period of the excitation voltage pulse. The corresponding L_p behavior with applied excitation energy is presented in Figure 6.

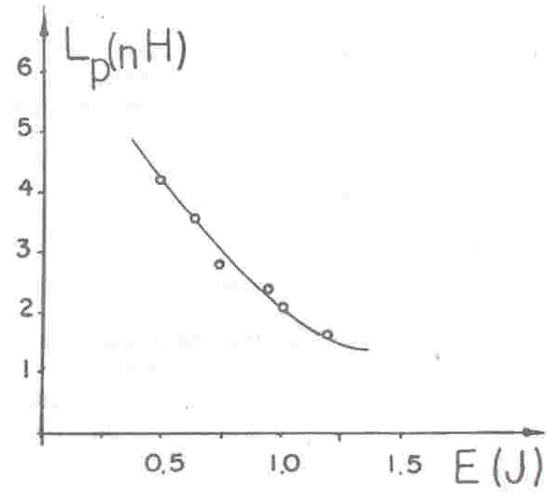


Figure 6.- Plasma inductance value [L_p (nH)] behavior as a function of input energy [E (J)].

CONCLUSION

This work presents a method for the determination of plasma capacitance and inductance values in pulsed gas lasers. Both plasma parameters are shown as a function of applied excitation energy, from the behavior of a N_2 TE UV laser (2^+ system, 0-0 band, 337.1 nm wavelength).

It is important to note that, in authors knowledge, it is the first time this kind of data involving capacitance (C_p) and inductance (L_p) measurements in high frequency excitation pulse regime are presented. Also, measurements are extracted from the discharge channel without introducing any probe or other perturbing element, that is, looking only at laser pulsewidth properties.

At present, theoretical calculations are being made looking for the possibility to extract plasma electron density values (n_e) from capacitance and inductance data.

ACKNOWLEDGMENTS

Authors wish to thank the finantial support of the Financiadora de Estudos e Projetos (FINEP), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ).

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