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On the Opto-Voltaic Measurements in CO and CO_2 Lasers

K. M. Abramski*, J. van Spijker, and W. J. Witteman

Department of Applied Physics, Twente University of Technology, Enschede,
The Netherlands

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Abstract. We observed and compared the opto-voltaic signals in CO and CO_2 lasers. The signals are obtained capacitively from the water cooling jacket as a low voltage source not influencing the current circuit. We observed from measurement that the output power and the so-called optovoltaic input power have a distinct relationship depending on laser current and cavity parameters. It will be shown that opto-voltaic detection is a very sensitive method especially for CO lasers.

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The phenomenon of static resistance fluctuation in a cw laser discharge due to the intra-cavity coherent radiation is well-known as opto-voltaic or opto-galvanic effect [1]. It was used succesfully for stabilizing a single line CO_2 laser with high accuracy [1, 2], the alignment of a laser cavity [3], and the detection of radiation [4] in CO_2 lasers.

In general, the resistance fluctuations of the discharge due to laser-action in a current stabilized or ballast resistor regime results in fluctuations of the power that is dissipated in the discharge, and hence in temperature variations of the plasma and the discharge tube.

We shall analyze and compare the opto-voltaic effects in CO and CO_2 lasers having intra cavity modulation.

It will be shown that the potential of the cooling water jacket which is capacitively coupled to the plasma is equal to half the maximum opto-voltaic value of the discharge.

1. The Opto-Voltaic Effect

The relative changes of static resistance of the laser tube due to changes of stimulated emission inside the laser cavity can be expressed in terms of relative changes of the tube voltage U_L (or longitudinal electric field) and the discharge current I:

$$\frac{\Delta R_S}{R_S} = \frac{\Delta U_L}{U_L} - \frac{\Delta I}{I}. \tag{1}$$

We shall consider the discharge laser tube as a nonlinear resistance with parametrical change of its voltage-current characteristic by the coherent radiation in the discharge tube.

The operating current and voltage on the characteristic are determined by the voltage E_a of the power supply and the serial balast resistor R_b, which value must be larger than the absolute value of the negative dynamic resistance of discharge tube (Fig. 1).

The operating values of U_{L_0} and I_0 changes with the radiation power along the working-line determined by balast resistor R_b and supply voltage E_a:

$$U_{L0} = E_a - R_b I_0 . \tag{2}$$

It is seen from Fig. 1 that the displacement along this line involves the change of discharge voltage ΔU_L, and simultaneously the change of discharge current ΔI.

The impedance of the discharge tube, however, increases with the produced radiation. This means that the variation of the discharge voltage ΔU_L, called opto-voltaic effect, is in phase with the variation of the radiation power P, and simultaneously the variation ΔI, called opto-galvanic effect, is in opposite phase.

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* Permanent address: Institute of Telecommunication and Acoustics, Technical University of Wroclaw, Poland

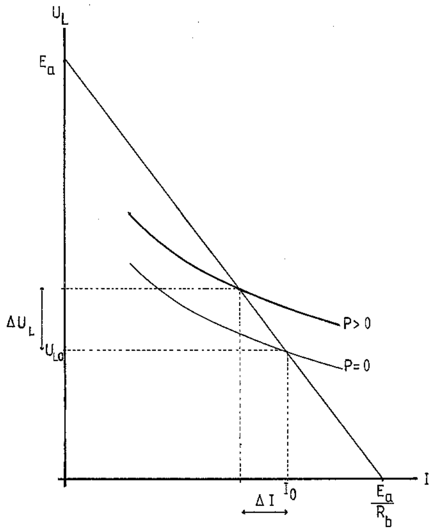

Fig. 1. Illustration of voltage-current characteristic of laser tube parametrically changed by the power of radiation inside cavity

The opto-galvanic signal is usually measured over a probe resistor connected in series between cathode and earth.

A first-order approximation of the static current-voltage characteristic of the discharge can be obtained by an expansion in power series in the neighbourhood of the point: $I=I_0$, $P=0$. We obtain:

$$U_L(I,P)=U_L(I_0,P=0)+\frac{\partial U_L(I,P)}{\partial I}(I-I_0)+\frac{\partial U_L(I,P)}{\partial P}P \tag{3}$$

or

$$U_L(I,P)=E_b-R_dI+\alpha P, \tag{3}$$

where $R_d=-\frac{\partial U_L}{\partial I}$ for $P=0$ and $I=I_0$ is the dynamic resistance, $E_b=U_{L0}-R_dI_0$, $\alpha=\frac{\partial U_L}{\partial P}$ for $P=0$ and $I=I_0$.

The opto-galvanic and opto-voltaic signals can be found from (2 and 3) as a function of power:

$$\Delta U_L=\frac{\alpha R_b \Delta P}{R_b-R_d}, \tag{4}$$

$$\Delta I=\frac{\alpha \Delta P}{R_b-R_d}. \tag{5}$$

The relative change of the impendance becomes

$$\frac{\Delta R}{R}=\left(\frac{\alpha R_b}{E_bR_b-E_aR_d}+\frac{\alpha}{E_a-E_b}\right)\Delta P. \tag{6}$$

In the case of current stabilization only the opto-voltaic effect is present. This kind of operation is useful for determining the static voltage-current characteristics of the laser discharge. Voltage stabilization of the discharge is impossible due to the negative dynamic resistance.

2. The Potential of the Water Jacket

It is interesting to make an analysis of voltage drop $U(x)$ along the laser tube, which can be considered as a positive column of a glow discharge. Figure 2 shows the simple models for two typical cases:

a) the laser tube is connected only to the supply voltage through the ballast resistor R_b (Fig. 2a) and

b) when it is connected from cathode side to a current stabilizer (Fig. 2b). In the second case the current stabilizer can be treated as a current-controlled source.

In both cases the change of voltage as function of distance along the discharge axis due to internal radiation power $E_{ov}(x,P)$ is given by

$$E_{ov}(x,P)=U(x,P=0)-U(x,P). \tag{7}$$

In the set-up from Fig. 2a it is seen that the largest opto-voltaic effect is obtained near the balast resistor

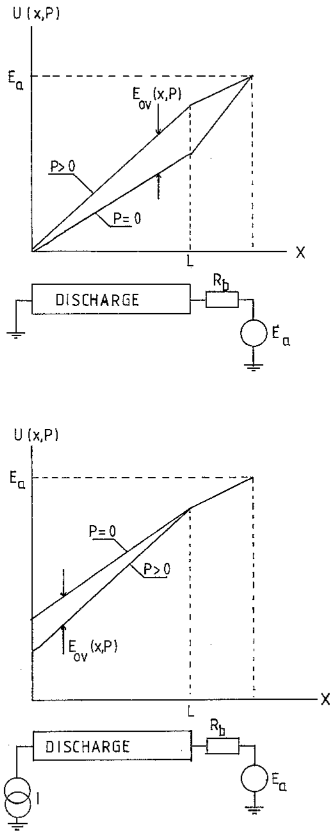

Fig. 2a and b. Voltage drop $U_L(x,P)$ along the laser tube for two typical cases of operation: (a) discharge tube with balast resistor, and (b) additional application of current stabilizer

R_b of the laser tube. In the case of Fig. 2b the opto-voltaic effect is largest near the current stabilizer.
We measure $E_{ov}(x, P=0)$. It is clear that these two techniques give different values for the opto-voltaic signal in both amplitude and phase.
In the following we consider internal chopping of the radiation. The signal $E_{ov}(x, P)$ is then a modulated part of plasma potential and it is linearly distributed along the tube (Fig. 2b). For current stabilization the total ballast resistance is $R_b + R_s$, R_s is the dynamic resistance of the stabilizer which is much larger then R_d. With this condition (4) becomes

$$\Delta U_L = \alpha \Delta P$$

and thus

$$E_{ov}(x \cdot P) = \alpha P \frac{(L-x)}{L}. \tag{8}$$

The extra power Q that is delivered to the discharge, the so called opto-voltaic input due to laser action is then given by

$$Q = E_{ov}(x=0, P) \cdot I. \tag{9}$$

For efficient molecular lasers such as CO_2 and CO the discharge tube is surrounded by a water jacket. In this way the plasma is capacitively coupled to the water jacket. The initial linear distribution of the polarization charges due to $E_{ov}(x, P)$ will equilibrate over the water jacket because of its conductivity. For an usual quartz tube laser construction the capacity over the quartz wall can be estimated as 6 pF/cm and the resistance through the cooling water is 1.5 kΩ/cm. For a one-meter tube the corresponding equilibrium time τ is about 9×10^{-5} s. With this time constant the potential of the water jacket reaches a maximum amplitude $\bar{E}_{ov} = 0.5\, E_{ov}(x=0, P)$. This value can experimentally be observed and turns out to be appropriate in a range of typical chopper modulation frequencies.

3. Mechanism of the Opto-Voltaic Effect

Many of the microscopic effects in a laser discharge have been elucidated by Smith and co-workers [1] by considering the gas laser as a positive column of a glow discharge. The current in such a discharge tube with radius R can be expressed by

$$I = 2\pi e \int_0^R n_e(r) U_e(r) r dr, \tag{10}$$

where $n_e(r)$ is the electron density and $U_e(r)$ the drift velocity as a function of the radial distance from the axis.

The drift velocity is given by

$$U_e = E \cdot \mu_e \tag{11}$$

where E is the field strength in axial direction, and μ_e is the electron mobility. The impedance of the discharge tube is then given by

$$z = \frac{L}{2\pi e \int_0^R \mu_e n_e r dr}.$$

In the positive column there is a balancing of energy that electrons gain from the electric field and the energy they lose by collisions. Both the mobility and electron density increase with higher electron energies. In a molecular discharge there is also a balancing of energy between the molecular excitation and electron cooling. The energy transfer flow to the molecules depends on the molecular transition losses such as spontaneous decay, molecular relaxations and stimulated emission. In the presence of laser action there is thus a larger cooling effect on the electrons and this on its turn decreases both μ_e and n_e.

4. Experiments

We have investigated the opto-voltaic effect in cw CO and CO_2 lasers. For both lasers we used similar sealed off discharge tubes of which the schematic diagram is presented in Fig. 3.
The laser tube used in the experiments was made of fused quartz with a discharge length of 100 cm and internal diameter of 6 mm. It was filled with an optimal mixture of CO(2.5), N_2(1.2), He(30.5), Xe(2.3) [Torr] [5]. It was closed with an output dielectric flat mirror M_1 (during the experiments we used several reflectivities) on one side and with a ZnSe Brewster window at the other. We used a full-reflection concave mirror M_2 with radius of curvature 3000 mm for multiline operation.
The length of the laser resonator was 135 cm.
The balast resistor was connected in series with the laser tube. The current stabilizer with a high internal dynamic resistance (200 MΩ) and a wide frequency

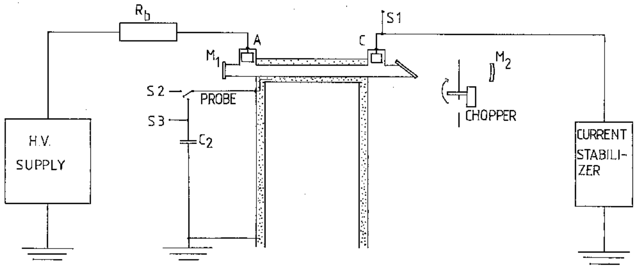

Fig. 3. Schematic diagram of experimental system

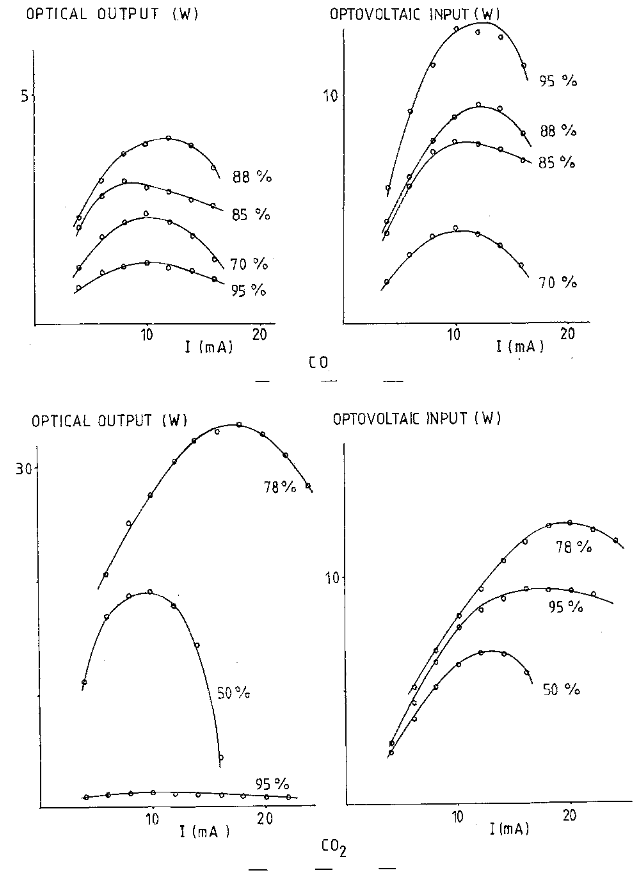

Fig. 4. Optical output and opto-voltaic input as a function of discharge current for several reflectivities of the outcoupling mirror. (notice the difference of the power scales)

range of stabilization (6 kHz) was connected to the cathode of the laser tube.

The chopping of the power occurred by means of mechanical chopper with a frequency of 100 Hz. The changes of the cathode voltage were measured by means of high impedance probe.

The CO_2 laser tube used was also made of fused quartz with a discharge length of 130 cm and an internal diameter of 9 mm. It was filled with a mixture of CO_2(2.5), N_2(3.5), He(13.6), and Xe(0.4) [Torr].

The output dielectric mirror was flat (during the experiments we used several reflectivities) and we used an AR coated Ge flat in front of a full reflection curved mirror ($R = 4000$ mm).

The electric circuit was the same as with the CO laser.

We measured the opto-voltaic signal $E_{ov}(x=0, P)$ at the cathode and obtained the opto-voltaic input power Q in accordance with (9).

The optical output was simultaneously measured with a Coherent Radiation (Model 201) power meter.

In Fig. 4 the opto-voltaic input and optical output powers are shown as a function of discharge current with the reflectivity of the output mirror as parameter.

From these figure one can observe that for a given reflectivity optical output P and opto-voltaic Q are correlated. It is seen that the ratios Q/P calculated for each system do not vary considerably except for the high reflectivity of 95%. Comparing the observation for CO and CO_2 we mention that the optical power generation in CO laser causes extra heating of the discharge, whereas for the CO_2 laser we find that for optimum reflectivities the stimulated emission extraction causes cooling of the discharge.

One might expect that the large ratio of Q and P at 95% reflectivity is due to large internal radiation losses. At such low outcoupling the internal losses are relatively large. The detected radiation is then only a small part of the stimulated emission.

5. Detection of Opto-Voltaic Signal in the Water Cooling-Jacket

In accordance with the mechanism presented in Sect. 2 we detected the opto-voltaic signal in the water-jacket by putting a needle-shaped probe in the electrically

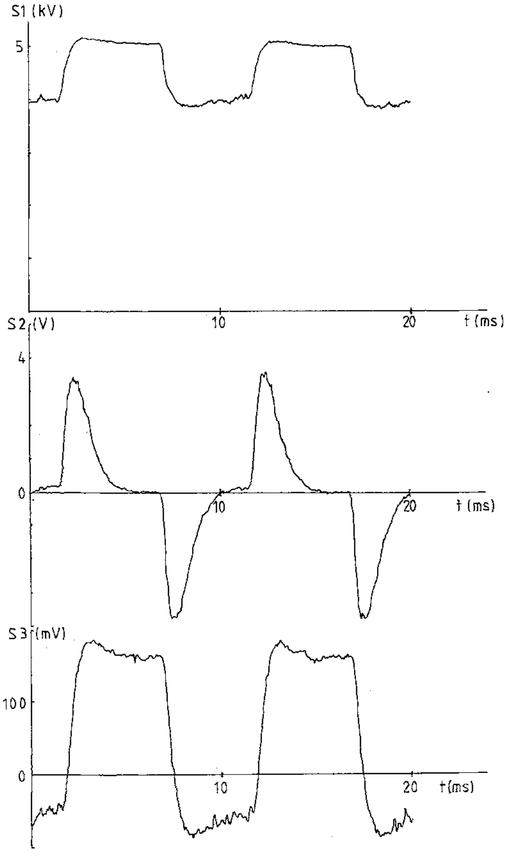

Fig. 5. Oscillograms of the opto-voltaic signals due to intracavity chopping obtained at the points indicated in Fig. 3 (CO laser)

nonconducting water tube. The signals measured on both ends of the water cooling tube (i.e., from input and output of water stream) are equal in agreement with the analysis of Sect. 1, i.e. the potential of the water jacket balances with the time constant τ. The signal measured directly in the water-jacket is the response to a nearly rectangular opto-voltaic signal in the integrating circuit RC_1, where R is the resistance of water to the earth and C_1 is the capacity between the discharge and the water-jacket. For the reproduction of the shape of the opto-voltaic signal we used a capacitor $C_2 = 2.2\,\mu\text{F}$ (Fig. 3). In this way we effectively constructed a capacitive voltage divider (because the resistance of the water between the needle-probe and earth was much higher than the reactance of the C_2 capacitor) consisting of the capacity C_1 between the plasma and the water jacket and C_2 between the water jacket and earth.

In Fig. 5 the oscillograms of signals S_1, S_2, and S_3 (Fig. 3) are shown. We observe that S_1 and S_3 have the same shape and the relative amplitudes are in agreement with the ratio of the capacitive divider.

6. Conclusions

There are several possibilities of photodetectorless detection of laser action in molecular lasers such as spontaneous side-light detection [6], pressure detection and opto-galvanic or opto-voltaic detection. Generally opto-voltaic detection is done by means of a high impedance probe on the cathode or anode depending on the supply regime. In this paper we have shown that the opto-voltaic signal can also be obtained capacitively from the water jacket with a simple needle probe.

The advantage of this method is its high sensitivity and the separation of the high voltage circuit. Because of its sensitivity it may be used succesfully for frequency stabilization. Furthermore we have shown that opto-voltaic input is correlated with the optical output and that for each system the ratio does not vary substantial with cavity parameters and discharge current, except the case of low outcoupling with relatively high internal losses.

As a consequence the presence of laser action can heat or cool the laser plasma, depending on whether the opto-voltaic input is greater or less than the optical output. The most remarkable difference between these two systems is the fact that for CO the stimulated emission is accompanied with additional heating, whereas for CO_2 the stimulated emission results to extra cooling of the plasma. The ratio of the opto-voltaic input to the laser output is for CO systems about 2.5 and for CO_2 only 0.3. This means that the opto-voltaic detection is especially for CO lasers a very sensitive and attractive detection technique.

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