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Phenomena in a CO_2 discharge plasma during continuous-pulsed excitation

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This paper deals with the phenomena occurring in a CO_2 gas laser plasma during the continuous-pulsed excitation (an experiment with this type of supply has been described in the preceding paper). Dynamics of time changes in both the gas temperature and CO_2 dissociation has been carefully discussed. This discussion made possible the explanation of certain experimental results presented in the preceding paper. The increase of the mean output power (P_m) at the continuous-pulsed (CP) excitation observed with respect to the output power (P_0) at the CW excitation can be explained by the fact that during any current pulse with a few miliseconds duration the CO_2 dissociation degree is not changed.

1. Introduction

An experiment with the continuous-pulse (CP) excitation of a CO_2 gas laser has been described in previous paper [1]. Experimental results, presented there, have been partly explained in the Sec. 5 of this paper. Explanation of the remaining experimental facts requires a detailed analysis of discharge conditions during any current pulse as well as in time between these pulses. Conception of such explanation has been based on the fact that the pulses of the output power observed in the experimental conditions were independent of each other.

Rectangular waveform of the output pulses observed in all the experiments permits us to conclude that new discharge conditions in the CO_2 gas laser plasma were settled in time much shorter than the 2.5 ms duration of the current pulses. These fast changes of discharge conditions occur when any current pulse begins as well as when any current pulse ceases. When any current pulse occurs the following discharge parameters can change:

- electron concentration,
- electron energy distribution and mean value of their energy,
- gas temperature in discharge tube,
- CO_2 dissociation rate and as result both CO_2 and CO concentrations.

Among these four discharge parameters only the last two can be interesting for farther interpretation, because their time constants seem to be comparable with the current pulses duration of 2.5 ms. Time changes of the concentration of electrons and distribution of their energy proceed, however, in microsecond scale [2].

The gas temperature and the CO_2 dissociation are known as fundamental factors limiting the output power of a CO_2 gas laser (e.g., [3, 4]). All elementary collisional processes taking part in the population inverse mechanism in a CO_2 laser depend on the gas temperature. Particularly deexcited processes of the upper laser level are strongly temperature-dependent and cause the life time of this level to fall down when the temperature grows. As a result the population difference decreases and so does the output radiation power. The output power drops practically to zero when the gas temperature approaches 700 K [5].

Second of the mentioned factors, the CO_2 dissociation, occurs after the initiation of the discharge as a result of electron collisions with these molecules. Main dissociation product, carbon monoxide, results in variation of discharge and laser properties (simultaneously formed O_2 in half the quantity of CO may be disregarded because it does not affect significantly the laser level). Carbon monoxide, like nitrogen, takes part in supplying vibrational energy to the upper laser level $(00^01)CO_2$ [6]. Besides, CO molecules share in fast quenching of the first bending level of the CO_2 molecule [7]. The above two processes become more effective with the increasing rate of CO_2 dissociation. When, however, the dissociation increases the number of CO_2 molecules diminishes and consequently the energy transfer from the lower laser level to the relaxing bending mode is slower. That is why a maximum occurs always in dependence of the output power on the degree of CO_2 dissociation [8, 9].

Rapidity changes of each of the two processes occurring in time is very important from point of view of the CP excitation of a CO_2 gas laser. The output peak power as well as waveform of the output pulses depend on dynamics of both the processes. It is obvious that certain reduction of the heating effect can be expected when duration of any single exciting pulse is less than thermal response time of the laser medium. Similarly, certain decrease of CO_2 dissociation rate can be expected when duration of the output power pulses is shorter than a characteristic time to achieve an equilibrium state to the CO_2 and CO concentrations.

Below, time-dependence of the gas temperature and CO_2 dissociation dynamics have been discussed (Sec. 2 and 3). Based on this discussion, the phenomena in the CO_2-mix plasma during the CP excitation have been analysed in Sec. 4. The problem of the mean output power at the CP excitation has been analysed in Sec. 5.

2. Time-dependence of the gas temperature

Theoretical calculations which have been presented in paper [10] throw some light on dynamics of changes of the gas temperature. These calculations have been made for gas temperature changes in the positive column of an He rich mixture discharge. If in a time interval between $t = 0$ and $t = t_1$ certain constant in time source of gas heating is active, then the gas temperature T_g changes vs. time as follows:

$$T_g(r, t) = T_{\mathrm{wall}} + A \exp\left(-\frac{t-t_1}{t_r}\right)\left[1-\exp\left(-\frac{t}{t_r}\right)\right]$$

where: A – function of r/R_0 and electrical input power,
R_0 – radius of discharge tube,
$t_r = \dfrac{R_0^2}{(2{:}405)^2 a}$ – time constant of the transient processes,
$a = \lambda/\varrho c$ – thermal diffusivity (λ – thermal conductivity, ϱ – density, c – specific heat).

The above equation is also valid for periodic gas heating, provided that duration of the supply pulses t_1, and the interval between them are much greater than the time constant t_r. It seems that this equation is fulfilled in conditions of the described experiment, because the observed output pulses were of rectangular waveform. Calculations of the t_r based on above pattern have confirmed this supposition. Necessary data for these calculations have been taken from papers [11, 12]. The gas temperature in the experimental conditions has been estimated by the method described in paper [13]. The calculated values of the T_g and t_r are presented in Tables 1 and 2, respectively.

Table 1. Estimated values of the gas temperature T_g [K] for different discharge parameters used in the experiment

DC discharge current [mA]		2.5	5	10	15	20	25
	8	340	380	450	500	540	580
Total mixture pressure [hPa]	10.6	–	400	470	530	570	620
	13.3	–	410	490	550	600	640
	16	–	420	510	570	630	670

Table 2. Calculated values of the t_r [ms] for different discharge conditions in the mixture CO_2 N_2 : He = 1 : 1 : 4

Gas temperature T_g [K]		400	500	600
	8	0.34	0.24	0.17
Total mixture pressure [hPa]	10.6	0,45	0.31	0.23
	13.3	0.56	0.39	0.29
	16	0.59	0.47	0.35

From both tables it results generally that the values of the t_r time constant are below 0.5 ms for almost all the total gas pressures and all DC current used in the experiment. It is at least five times less than the current pulse duration of 2.5 ms. Similar values of the t_r can be read out from the experiments described in papers [14, 15]. Thus, in first approximation, it can be assumed that the changes in time of the gas temperature imitated the changes of the discharge current observed in the experiment with the CP excitation.

3. Dissociation dynamics

Contrary to the relatively fast changes of gas temperature the time t_d, needed for the CO_2 dissociation to become stationary, is greater. This time varies within a wide range of 0.1 s to a few and more seconds depending on the discharge tube diameter, gas mixture composition, gas flow rate, total gas pressure and discharge current (e.g., [9, 16–19]). For example, LOTKOVA et al. [16] have measured CO_2 concentration vs. discharge operating time in tubes of different diameters. The time t_d ranged from 0.1 s for a 3 mm tube to 15 s for a 34 mm tube.

Particularly much information referring to the CO_2 dissociation dynamics can be obtained from the measurement of the extent of the CO_2 dissociation vs. gas flow rate. By altering this rate in a wide range one can find such a characteristic value of the rate above which the CO_2 dissociation is excluded. SIEMSEN et al. [4] have stated that the dissociation effects dominate the dynamics of the discharge when gas flow rate is not sufficiently fast to ensure gas residence time in the discharge less than 0.1 s (experiment has been performed with a 1.15 cm ID amplifier tube). Similarly, WIEGAND et al. [2] have noticed that the fractional dissociation of CO_2 on a milisecond time scale is more than one order of magnitude below the 0.1–0.7 values typical of slow-flow or sealed laser discharge.

Taking the above into consideration it can be assumed that in the experiment described in paper [1] the CO_2 concentration remained substantially unaltered by arbitrary current pulse. It means that the degree of CO_2 dissociation at the CP excitation is defined only by initial DC current I_0 and that CO_2 concentration does not alter significantly when a current pulse occurs. The above assumption confirms the fact that at the used repetition rate of the current pulses 200 Hz the output power pulses were of rectangular shape.

4. Phenomena in a CO_2; laser plasma during the CP excitation

The discussion presented in Sec. 2 and 3 makes easy the analysis of phenomena in a CO_2-mix discharge laser operating in the CP excitation conditions. The course of these phenomena depends on the repetition frequency of the supplying current pulses as well as on their duration. To simplify farther discussion, duration of the pulses has been assumed as being equal to one half of pulses repetition period. The undermentioned analysis has been based on the fact that the time t_d in which an equilibrium state for the CO_2 and CO concentration is achieved exceeds considerably the thermal relaxation time t_r of the gas mixture in a CO_2 laser ($t_r \ll t_d$).

At low repetition rate $< 1/2t_d$ duration of the current pulses exceeds the two characteristic time constants t_d and t_r. Therefore, both the gas temperature and the CO_2 dissociation influence the output power in the same degree as the continuous excitation. The closer is repetition rate to $1/2t_d$ the more waveform of the output pulses departs from the rectangular one.

The influence of the CO_2 dissociation on the discharge plasma and the laser action can be considerably diminished when the repetition rate exceeds the $1/2t_d$ several times. However, the heating effect of the laser medium can be reduced when the repetition rate exceeds the value of $1/2t_r$. The output pulses become dependent on each other and their waveform differs considerably from the rectangular one when the repetition rate approaches $1/2t_r$. Thus, for the repetition rate ranging from $1/2t_d$ to $1/2t_r$ only the influence of the CO_2 dissociation on the output power can be diminished. Simultaneous reduction of the CO_2 dissociation rate and the gas heating effect can be obtained for repetition rates higher than $1/2t_r$:

Two other processes must be taken additionally into account when the repetition rate exceeds $1/2t_r$. These processes are resonant energy transfer from vibrationally excited levels of CO and N_2 molecules to the (00^01) level of CO_2. Both the processes have been specified in papers [20, 21] as main factors determining the frequency range of sinusoidal modulation of the output by means of the discharge current. These two resonant processes can influence the sinusoidal modulation effect as well as the pulsed one above the frequencies of 200–400 Hz.

The presented above description of the phenomena in a CO_2 gas laser at the CP excitation is in a good agreement with the experiment described in paper [1]. This description is confirmed by the following experimental facts:

1. Below the repetition rate of 150 Hz the shape of output pulses differed strongly from the rectangular one, it means that duration of the current pulses became comparable with the time constant of t_d for the CO_2 dissociation.

2. For repetition rate ranging from 150 Hz to 250 Hz the output pulses were independent of each other and had rectangular shape, it means that the frequency of 150–250 Hz corresponds to the range of $(1/2t_d)$–$(1/2t_r)$.

3. Above the frequency of 250 Hz, the output pulses were strongly distorted, it means that duration of the current pulses approached the thermal time constant t_r.

4. Above the frequency of 250 Hz the amplitude of the output pulses falls down fast with the repetition frequency of the current pulses, it means that the processes of resonant energy transfer takes place above the repetition rate of $1/2t_r$.

5. Mean output power of a CO_2; laser at the CP excitation

The experiment with the CP excitation described in the previous paper [1] has shown that the mean output power (P_m) of the CO_2 laser exceeds always the output power level (P_0) measured in equivalent conditions of the continuous excitation. A comparison of some CO_2 discharge plasma parameters at both the types of excitation has been given in Table 3 in order to find out which elementary processes are decisive in this respect. This comparison was based on the former discussion (Sec. 2–4) and is true only for the repetition rate of 150–250 Hz (generally, for arbitrary CO_2 laser, it is true for a range $(1/2t_d)$–$(1/2t_r)$.

Table 3. Comparison of some discharge plasma parameters of a CO_2 gas laser at the continuouspulsed excitation and continuous excitation, for the same optional total pressure

Type of discharge parameter	Continuous-pulsed excitation: Given parameter in interval between current pulses	Continuous-pulsed excitation: The same given parameter during any current pulse	Continuous excitation
	index 0	index p	index c
Discharge current I	I_0	I_0+I_p	$I_c = I_0+I_p$
Electron concentration N_e	N_{e0}	$N_{ep} > N_{e0}$	$N_{ec} = N_{ep}$
Gas temperature T_g	T_{g0}	$T_{gp} > T_{g0}$	$T_{gc} = T_{gp}$
Degree of CO_2 dissociation D	D_0	$D_p = D_0$	$D_c > D_0$
CO_2 concentration N_m	N_{m0}	$N_{mp} \lesssim N_{m0}$	$N_{mc} < N_{mp}$

Notations: I_0 – given initial current at the CP excitation, I_p – amplitude of any current pulse, N_{e0} – electron concentration corresponding to the given current I_0, N_{ep} – electron concentration corresponding to the current (I_0+I_p), T_{g0} – gas temperature at the given current I_0, D_0 – dissociation rate at the given current I_0, N_{m0} – CO_2 concentration at the given I_0 and dissociation rate D_0, N_{mp} – CO_2 concentration at the current (I_0+I_p), unaltered dissociation rate D_0 and at elevated gas temperature T_{gp}, N_{mc} – CO_2 concentration at DC current (I_0+I_p), dissociation rate $D_c > D_0$ and at elevated gas temperature T_{gc}.

The observed increase of the mean output power at the CP excitation can be attributed to the fact that the CO_2 dissociation rate does not alter during any current pulse. In other words, the CO_2 concentration is the same both in interval between the current pulses and during any current pulse. The value of the rate, as mentioned in Sec. 3, is determined by initial DC current (I_0) at the given total pressure. The CO_2 concentration in the CP excitation exceeds always the one in comparable discharge condition with the continuous excitation. The last conclusion can explain the observed increase of the mean output power at the CP excitation, provided that the dissociation rate at initial discharge current is higher than the optimal rate for the maximum output. This condition seems to be true in the described experiment because the CO_2 laser operated as a sealed one. Fractional dissociation of the CO_2 molecules can reach 0.85 in the no-flow conditions (e.g., [19]). However, the optimal CO_2 dissociation rate for the maximum output power can be as low as 0.1 [9].

The measured dependence of the mean output power P_m on the total pressure can be explained by analysis of CO_2 dissociation extent at different pressures. It is well known that the dissociation rate decreases with the growing total pressure (e.g., [19]). Below the optimum total pressure the output power P_0 and the mean output power P_m increase with the pressure. In both the cases it results, among other, from the drop of the CO_2 dissociation rate.

6. Conclusion

The above described phenomena in a CO_2 laser at the CP excitation are in a good agreement with those described in the previous paper. The fact that this description was based on dynamics of the CO_2 dissociation and the gas heating effect seems to be reasonable. As it results from the discussion, an increase of the mean output power at the CP excitation can be expected solely within the repetition rate ranging from $1/2t_d$ to $1/2t_r$. The method of the continuous-pulsed excitation is particularly suitable for a sealed CO_2 gas laser.

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Явления в плазме CO_2 лазера во время стационарно-импульсной работы

Проведен анализ явлений в плазме лазера на двуокиси углерода во время стационарно-импульсного (С-И) возбуждения. Особенное внимание обращено на расчет динамики как газовой температуры, так и диссоциации. Повышение выходной мощности при С-И возбуждении в состоянии с непрерывным возбуждением можно выяснить тем, что степень диссоциации CO_2 не изменяется во время произвольного токового импульса.