SOURCES OF PARASITIC LOSSES IN A POWER SUPPLY UNIT OF METAL VAPOR LASERS

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Received December 1, 1997

Results of experimental investigations of the power put by a power supply unit of metal vapor lasers in a commutator and a gas-discharge tube (GDT) are presented. Simple relations are derived that can be used to calculate the plasma capacitance of the commutator and GDT caused by space charges due to plasma polarization as well as the amplitude-temporal parameters of a gas-discharge pulse. The existence of the Pashen pulse-frequency responses (PPFRs) for a periodic-pulse discharge is identified. They are functions of the pulse repetition frequency and the rate of the voltage increase on a gas-discharge gap with all other parameters remaining the same. The enhanced pump power density is found experimentally in the near-electrode zones of the GDT together with the temperature gradient between the electrodes. The latter depends on the gas pressure, voltage, and other parameters.

A typical power supply circuit of a metal vapor laser equipped with systems for measuring the amplitude and average values of the current and voltage U_c on a working capacitor C_w, a high-voltage rectifier U_s, I_s, and along a plasma column in a gas-discharge tube (GDT) of laser[1] was investigated. Measurements were performed with a shunt inductor L_{sh} connected in parallel to a gas-discharge channel. The inductor in the form of a coil made from molybdenum wire (a distributed electrode[2]) was placed inside or outside a discharge channel of the GDT. The circuit without L_{sh} was also investigated.

Figure 1 shows the dependences of the plasma capacitance of the commutator C_{com} on the voltage on the working capacitor U_c for different pulse repetition frequencies f.

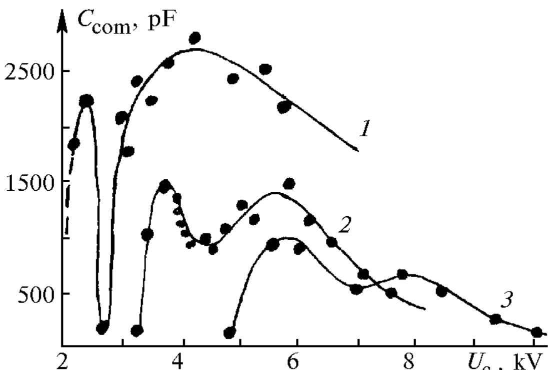

FIG. 1. Dependence of C_{com} on U_c for f = 10 (1), 5 (2), and 3 kHz (3) calculated from EC (6). The GDT aperture was 20 mm, d = 80 cm, P_{Ne} = 200 Torr for the TGI 1000/25 commutator, and C_p = 7920 pF. The external shunt inductivity L_{sh} was connected.

The first maximum in the dependences (see Fig. 1) corresponds to a discharge of the working capacitor through the shunt inductivity L_{sh} when U_c is insufficient for breakdown of the gas-discharge gap of the GDT. For this reason, a long pulse is carried through a thyratron for high Q-factor of the discharge circuit, thereby providing a high level of residual ionization in the commutator. The low voltage and the high level of residual ionization yield a small radius of Debye screening, which increases the plasma capacitance.

The second maximum is observed at the voltage U_c sufficient for breakdown of the gas-discharge gap of GDT. Analogous dependence of C_{com} on U_c with two maxima was also obtained for the distributed electrode.

It should be noted that when the length of the interelectrode gap and the gas pressure increase but the pulse repetition frequencies of C_w and L_{sh} decrease, the dependences of C_{com} on U_c are shifted toward larger U_c.

The volt-ampere characteristic (VAC) of the power supply unit of the laser has discontinuities in the regions of maxima (see Fig. 2) with the subsequent decrease of the average source current or acquires N-shape with negative curvature (curve *1* in Fig. 2).

The characteristics of the heating regime of GDT in the region of nonlinear volt-ampere characteristic of molybdenum distributed cathode is illustrated by curve *2* in Fig. 2.

The parameter C_{com} was calculated from the experimentally measured U_c, I_s, U_s, f (pulse repetition frequency), and C_w as follows.

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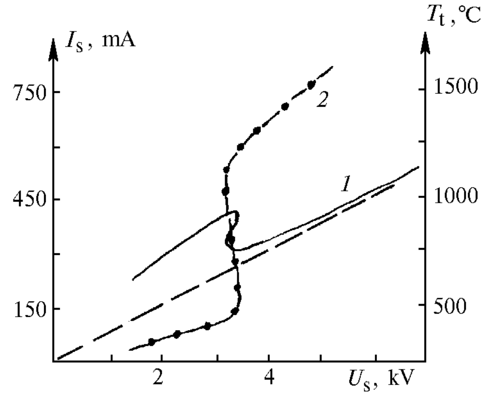

FIG. 2. Volt-ampere characteristic and temperature dependence of GDT and source operation. The GDT parameters are the same as in Fig. 1. The distributed molybdenum electrode in the form of a coil with a resistance of the cold coil of 0.2 Ω *was placed inside the GDT. Here,* $f = 3$ kHz, *curve 1 is for the VAC of the power supply unit, and curve 2 illustrates the dependence of the active volume temperature of the GDT on* U_s.

In case of resonance charging of C_w through the storage inductor of the source $L_{ch} \gg L_{sh}$ we have

$$U_c = 2\ U_s - \Delta U_c, \tag{1}$$

where ΔU_c is the residual voltage on the working capacitor after its discharge through the commutator and the entire discharge circuit.

When we consider only the working capacity C_w, the source current can be calculated by the formula

$$I_w = (U_c - \Delta U_c)\ C_w\ f. \tag{2}$$

From Eq. (1), we have

$$\Delta U_c = 2\ U_s - U_c. \tag{3}$$

By substituting Eq. (3) into Eq. (2) and accounting for the true measured source current, we determine the current increment ΔI_{com} due to charging of the plasma capacitor of the commutator C_{com}, that is charged in parallel with the working capacitor C_w, hence

$$\Delta I_{com} = I_s - I_w. \tag{4}$$

By substituting Eq. (2) into Eq. (4) and considering that $C_\Sigma = C_w + C_{com}$, where C_Σ is the total capacitance of C_w and C_{com} charged in parallel, we derive

$$C_{com} = \Delta I_{com}/[(U_c - \Delta U_c)\ f], \tag{5}$$

from which the plasma capacitance of the commutator is calculated based on the formula

$$C_{com} = I_s/[2\ (U_c - U_s)\ f] - C_w. \tag{6}$$

The results of these investigations allowed me to conclude the following:

1. When the working capacitor is charged at high pulse repetition frequencies in the gas-discharge commutator and GDT (in their near-electrode zones), plasma capacitance is formed in the process of longitudinal polarization of the plasma column whose value may reach the same order of magnitude as the rated value of the working capacity. At the same time, the plasma column of the GDT acquires the potential whose sign coincides with that of a high-voltage unearthed electrode (positive in our case) due to transverse polarization.

A discharge of the plasma capacitor engenders currents that flow through the GDT gap between the pulses and thereby decrease the efficiency of pumping of the active laser volume.

2. When the thyratron is triggered, the energy stored in the plasma capacitor of the commutator is absorbed in its volume thereby decreasing the efficiency of the power supply unit of the laser relative to the energy put in the GDT.

In the initial stage of the working capacitor discharge, plasma capacitors and the GDT plasma column in the near-electrode zones of the GDT are charged in the external field caused by the plasma polarization (in this case, their potential with respect to the earthed electrode is negative).

Charging of the plasma capacitors in the near-electrode zones of the GDT in the process of longitudinal plasma polarization significantly decreases the amplitude of voltage on the gas-discharge gap and decreases the energy put in the main volume of the GDT. In this case, the laser pumping efficiency also decreases.

The transverse polarization of the plasma column, to the contrary, increases to a certain degree the energy put in the GDT due to the fact that the discharge of the transverse plasma capacitor occurs in the main volume of the active GDT zone rather than near its ends, as in the first case.

Taking into account the polarization of residual ionization of the GDT gas[1] and the fact that the plasma conductance and current increase predominantly in the trailing edge of the GDT voltage pulse starting from its amplitude U_t after passage of the first ionization waves,[1] the resultant plasma capacitance C_t can be calculated from the simple formula

$$U_c\ C_w = U_t\ (C_t + C_w), \tag{7}$$

from which we derive

$$C_t = C_w\ (U_c/U_t - 1). \tag{8}$$

If the plasma conductance starts to increase (in the breakdown stage of the discharge) when the GDT voltage increases, the parameter U_t in Eqs. (7) and (8) can be found from the waveforms of the GDT current and voltage pulses recorded simultaneously with an oscilloscope. It is determined for the moment when slow rate of current increase is changed by its fast increase. This moment is determined from the waveform of the current pulse. In other words, in general U_t is the value of the GDT voltage at the start of the discharge stage or at the end of the stage of discharge delay, that is, at the moment of gas-discharge gap breakdown under the action of high strength of the electric field formed by spatial charges near the emitting surface of the cathode when re-charging (ionization) waves pass through the gas-discharge gap.[1]

Measurements of the temperature with thermocouples (see Fig. 3) showed that the energy losses on the electrodes and the temperature gradient between the cathode and anode increase as the buffer gas pressure decreases and the gas-discharge pulse repetition frequency increases with all other parameters remaining the same. In so doing, the portion of the pump energy spent in the near-electrode zones increases by ~ 10%. This result also follows from Eq. (8), because the exponential decrease of U_t/U_c with the decrease of the gas pressure and the increase of the pulse repetition frequency and voltage U_c was experimentally established. The remainder of the energy put in the GDT is spent mainly in its volume in the process of passage of the re-charging (ionization) waves and in the stage of discharge when the current emitted from the cathode largely exceeds the current produced by volume charges in the near-electrode zones of the polarized plasma column.[1] To measure the temperature characteristics, the GDT was equipped with a heater in the form of a cold coil made of tungsten-rhenium wire wound round the external wall of the ceramic tube with a resistance of 0.4 Ω and a special heater.

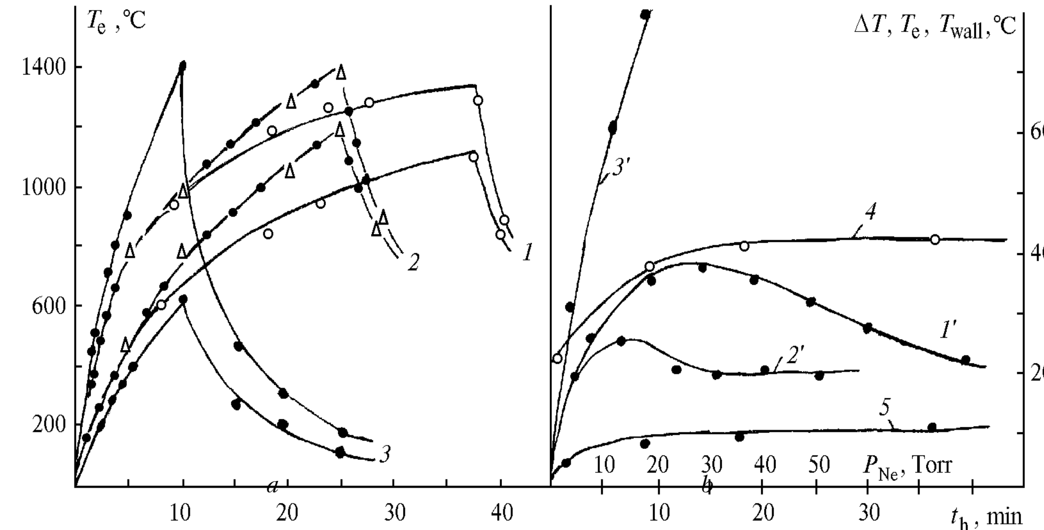

FIG. 3. Temperature dependences of operation of the GDT with an aperture of 20 mm *and* d = 80 cm; *a) curves 1–3 illustrate the dependences of the electrode temperatures* (T_e) *on the time of heating* (t_h) *of the GDT by a pulse-periodic discharge (upper curves are for the cathode and lower curves are for the anode); the temperature decrease corresponds to cooling of the electrodes after termination of the discharge; b) curves 1′–3′ illustrate the dependences of the temperature gradient between the electrodes* (ΔT) *on the time of heating* (t_h) *of the GDT by the pulse-periodic discharge, and curves 4 and 5 illustrate the dependences of the electrode temperature* (T_e) *and the temperature of the external wall* (T_{wall}) *of the Cuartz housing with a thermal insulator made of zirconium dioxide on the neon pressure* (P_{Ne}) *when the ceramic tube was heated up to* 1000°q *by a special heater with a heating element. The parameters of the GDT pump system in case of pulse-periodic discharge are the following:* f = 15.4 kHz, I_s = 500 mA; C_w = 1566 *(2, 2′), and* 2350 pF *(1, 1′ 3, and 3′);* P_{Ne} = 3 *(3, 3′) and* 35 Torr *(1, 1′, 2, and 2′);* P_s = 1.85 *(3, 3′),* 2 *(1, 1′), and* 3 kW *(2, 2′);* U_s = 4.1 *(1, 1′),* 6 *(2, 2′), and* 3.7 kV *(3, 3′).*

From the preceding it follows that to provide more uniform distribution of energy put in the GDT and to decrease the relative losses, the ratio of the electrode area at the ends of the active volume to the working area of the internal GDT surface should be decreased through the corresponding increase of the length of the gas-discharge gap, the increase of the GDT aperture, the decrease of the area of the working electrodes at the ends of the GDT, the use of the distributed electrode[2] closing the entire gas-discharge gap of the GDT and providing more uniform emission of the electrons and therefore energy put in the discharge plasma over the entire length of the active laser volume, and sectionalization of the working volume of the GDT.[5]

The Blumlein circuit that allows one to provide the constant rate of the voltage increase in the gas-discharge gap of the GDT dU_t/dt irrespective of the initial conditions of the discharge[3] was also used in our experiments. In so doing, the working capacitors in the Blumlein circuit had capacitance 400 pF, the GDT diameter was 10 mm, the length of the gas-discharge gap was 300 mm, the pulse repetition frequency was 7.7 kHz, and the voltage on the power supply unit was $U_s = 5$ kV.

Figure 4 shows the dependences of the average current that flows through the power supply unit I_s (curve *1*) and of the voltage decay time on the gas-discharge gap of the GDT (τ_f) (curve *2*) on the pressure of neon (P_{Ne}).

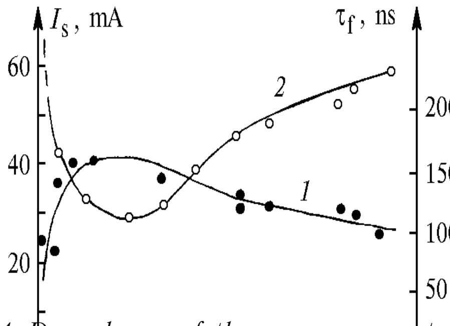

FIG. 4. Dependences of the average current I_s (curve 1) and the voltage decay time τ_f of the GDT (curve 2) on P_{Ne}. Blumlein circuit.

The results of these experiments have shown that for high repetition frequencies with all other parameters remaining the same the dependence of the pump pulse edge duration on the buffer gas pressure is pronounced only for pressures at which the pump pulse duration is minimum. As to the dependence of the average current flowing through the power supply unit on the buffer gas pressure, it reaches its maximum at a certain value of the buffer gas pressure. In this case, the values of pressure at which the average current and the duration of the pump pulse edge reach their maxima practically coincide.

Figure 5 shows the typical behavior of the VAC of the power supply unit for the discharge circuit.

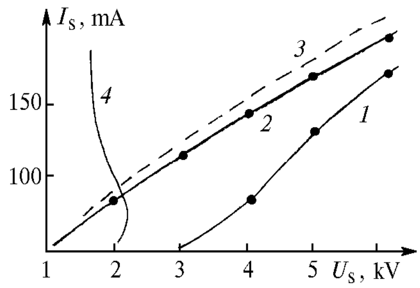

FIG. 5. VAC of the power supply unit for the discharge circuit with the thyratron, working capacitor (C_w), and GDT connected in parallel (without the shunt inductor L_{sh}), that is, $I_s = f(U_{\Sigma s})$ (1); for the discharge circuit in which the GDT was substituted by an ideal conductor having the same inductance and length as GDT – commutation VAC with $I_s = f(U_{com.s})$ (2); and, shifted commutation VAC for the source after switching on the GDT (3). Here, curve 4 is for the loaded VAC of the GDT, that is, $I_s = f(U'_t)$. In the experiments, $C_w = 733$ pF, $f = 12$ kHz, $P{\cdot}d = 1000$ Torr·cm *for d varying between* 10 *and* 70 cm; *the tube diameter was* 22 mm.

The decrease of the slope of commutation VAC with the increase of U_s indicates the increase of the resistance of the commutator and therefore the increase of the portion of the source power absorbed in the commutator. This is confirmed by measurements of the duration of the current pulse flowing through the commutator in the process of recording of the commutation VAC. Namely, the current pulse amplitude and duration increase with the increase of the source voltage U_s. This salient feature is peculiar to gas-discharge devices, including hydrogen thyratron, that operate on the left branch of the Pashen curve. This is also confirmed by the behavior of $\tau_f(p_{Ne})$ in the region of low neon pressures.

It should be noted that after switching on the GDT connected in series, the commutation VAC is shifted toward smaller values of U_s (curve *3* in Fig. 5), which should be taken into account in the determination of the power put in the GDT from its loaded characteristic (see Fig. 5, curve *4*). The average voltage on the GDT is calculated from the formula

$$U'_t = U_{\Sigma s} - U_{com.s} \tag{9}$$

for the given values of I_s. Here, $U_{com.s}$ is determined from the shifted VAC (curve *3* in Fig. 5). The power put in the GDT (p_t) is calculated from the formula

$$P_t = U'_t\, I_s. \tag{10}$$

An analysis of these data allowed me to obtain the empirical dependences that can be used to calculate the discharge current pulse duration at haft-maximum τ_p and its amplitude I_p for gas pressures p and lengths of the gas-discharge gaps d corresponding to the working pressures in the GDT (for the right branch of the Pashen curve). These dependences directly relate the inductance L, the capacitance C of the discharge circuit, and the pulse repetition frequency f for $f > 1/\tau_{pl}$ (where τ_{pl} is the recombination time of the plasma in the GDT):

$$\tau_p = K_1\sqrt{LC} + K_2\,(Pd)/(U_c\,f), \tag{11}$$

$$I_p = K_3\,U_c\sqrt{C/L} - K_4\,(Pd)/(U_c\,f). \tag{12}$$

Here, K_1 and K_2 are the empirical coefficients that depend mainly on the design and type of the commutator and K_3 and K_4 are the empirical coefficients that depend on the design of the GDT and the gas. Thus, for the TGI 1000/25 thyratron for $f > 5$ kHz and $U_c > U_{br}$ (the voltage of breakdown of the gas-discharge gap), Eqs. (11) and (12) transform into the formulas

$$\tau_p = 2.2\sqrt{LC} + Pd/(U_c\,f), \tag{13}$$

$$I_p = 0.6\,U_c\sqrt{C/L} - Pd/(U_c\,f), \tag{14}$$

where τ_p is measured in ns, I_p in A, p in Torr, L in μH, C in pF, d in cm, U_c in kV, and f in kHz. The error of calculations by Eqs. (13) and (14) does not exceed 10%.

For $f \leq 1/\tau_{pl}$ (the regime of single pulses) the formulas for calculating τ_p and I_p have the forms of Eqs. (11) and (12), but without f in the denominators. For the left branch of the Pashen curve (in the region of small values of Pd, see above), τ_p decreases with the increase of Pd and increases with the increase of U_c. In this case, I_p also increases.

Starting from the preceding, results of Ref. 4, and additional experimental data, it may be concluded that:

– the gas-discharge pulse duration and the breakdown voltage of the gas-discharge gap of the GDT are correlated with Pd;

– a reason for the occurrence of the minimum voltage decay time (see curve *2* in Fig. 4) is the existence of the conditions in this region at which the conductance of the gas-discharge gap reaches its maximum due to gas ionization (the maximum amplification coefficient α is referred to as the Townsend coefficient);

– for pulse-periodic discharge and high pulse repetition frequencies, in the same manner as for single pulse regime,[4] there exist the pulse-frequency Pashen responses (PFPRs) that differ as functions of the pulse repetition frequencies and the rate of voltage increase on the gas-discharge gap of the GDT with all other factors remaining the same;

– the breakdown voltage of the gas-discharge gap increases and the parameter $(Pd)_{min}$ of the PFPR increases with the increase of the pulse repetition frequency.

CONCLUSION

As a result of the work done, the dependences of the plasma capacitance, formed in the process of plasma polarization by volume charges, on the initial conditions of pulse-periodic discharge in the gas-discharge circuit with more than one gas-discharge gap (the GDT, the commutator) have been identified.

The simple relations have been derived that can be used to calculate the plasma capacitance of the commutator and the GDT using the minimum number of experimental parameters.

It has been established experimentally that the amount of heat removed from the active volume increases with the increase of the gas (neon) pressure. It saturates at neon pressures 60–100 Torr (see curves *4* and *5* in Fig. 3*b*). As a consequence, the temperature gradient between the cathode and anode of the GDT first increases under the effect of pulse-periodic discharge, then decreases as the main volume heats up and the gas is excluded toward the electrodes (see curves *4′* and *5′* in Fig. 3*b*), and saturates at a constant with further heating of the GDT.

It also has been found experimentally that when the GDT heats up at U_c = const, the amplitude of the GDT voltage (U_t) increases. This is a consequence of the increase of the gas density in the near-electrode zones due to gas exclusion from the internal part of the GDT located between the electrodes and the decrease of the resultant plasma capacitance of the GDT (C_t) [see Eq. (8)].

The simple procedure has been developed for calculating the energy put in the elements of the system of pulse-periodic discharge excitation at high pulse repetition frequencies (including the GDT and the gas-discharge commutator) from the average values of the voltage and current of the high-voltage power supply unit.

It has been established that the waveforms of the pulse discharge and breakdown voltage in the gas-discharge gap are correlated with the initial conditions of the discharge (including the value of the parameter Pd), that is, the pulse–frequency Pashen responses have been identified.

The formulas have been derived for calculating the amplitude–temporal parameters of the pulse-periodic discharge used for pumping of metal-vapor lasers.

It should be emphasized that the plasma capacitance of the commutator C_{com} is determined by the current increment ΔI_{com} [see Eqs. (5) and (6)]. In so doing, ΔI_{com} is a sum of the components caused by polarization, ionization, and recombination processes that occur in the near-electrode and near-wall zones of the gas-discharge gap as well of the component of the discharge current of the high-voltage rectifier capacitance through the storage inductance and the commutator during the time of triggering of the working capacitor energy C_w through the GDT. The determination of the contributions from the above-indicated components for various discharge conditions, including the GDT, is the subject of future investigations.

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