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APPLIED PHYSICS

Processes of Development and Relaxation of Plasma Channel in Pulse-Periodic Cesium–Mercury–Xenon Discharge

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Abstract—The work is devoted to the study of thermophysical and radiation processes during the formation of a plasma channel under the passage of a series of current pulses of pulsed-periodic cesium–xenon–mercury discharge. The influence of the auxiliary discharge mode, temperature, and vapor pressure of metals on the development and relaxation of the plasma channel is shown. The spectral characteristics of the passage of each of the current pulses are studied.

Keywords: pulse current, cesium, discharge, plasma, series of pulses, absorption coefficient, radiation spectrum

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Currently, the gas-discharge plasma is still of great practical interest as a source of optical radiation. This is due to the possibility of obtaining conditionally selective radiation in different spectral intervals by selecting plasma-forming media and conditions of the electric power supply of gas-discharge lamps. For example, AC lamps with a sodium vapor discharge are the most efficient light sources [1], and those with a plasma-forming medium based on potassium and rubidium are pump sources for YAG: Nd^{+3} solid-state lasers [2]. The processes of the generation of radiation by the gas-discharge plasma of alkali metals during the passage of alternating and direct currents have been studied in sufficient detail in [1–3].

In the case of a pulsed discharge, the total picture of the plasma state becomes more complicated, since it is supplemented by the time aspect of the development of a discharge in metal vapors. Earlier, the author in [4] studied thermophysical processes occurring during one pulse and eventually leading to the state of the thermal stabilization of parameters at the current maximum (the quasi-stationary stage [5, 6]). The transition to a pulse-periodic structure (Fig. 1) of the current pulse repetition complicates the formation and relaxation processes of the discharge channel even more, since each pulse from the series has different initial plasma states, and, consequently, different energy losses to achieve the quasi-stationary state.

This work is devoted to the study of time dependences of electrical parameters and spectral characteristics of the radiation of flash lamps with a discharge in a cesium–mercury–xenon vapor-gas mixture [7] as a quasi-stationary state and during the development and relaxation of the discharge column during the passage of a series of current pulses.

FEATURES OF THE POWER SUPPLY OF A LAMP WITH A VAPOR DISCHARGE OF A Cs–Hg–Xe MIXTURE

The formation of a current pulse in the plasma channel in different gas-discharge media consists in forced thermal ionization due to the applied electric field using the residual ionization of the discharge volume produced by the preceding pulse.

If the voltage pulse repetition rate is less than a certain value due to the time of the complete plasma ionization relaxation or the gas-discharge lamp operates

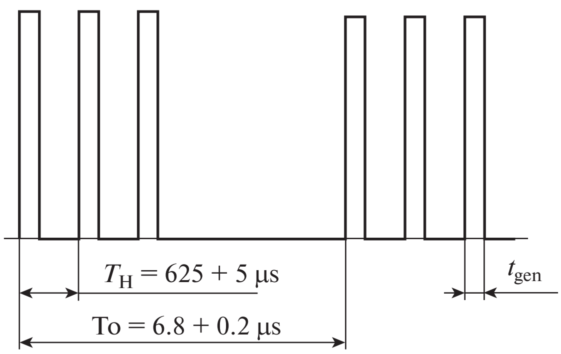

Fig. 1. Pulse-periodic structure of voltage pulses: T_c is carrier frequency period; T_e is the period of the envelope of the pulse repetition rate; t_{gen} is voltage pulse duration.

in the presence of significant pauses (of more than (2–3)t_{gen}, Fig. 1) in the sequence of voltage pulses, then the discharge is quenched. This phenomenon can be avoided by using a constantly burning low-current plasma channel (the auxiliary discharge [8], pilot arc [9]), to which the voltage pulse structure formed by the master generator according to the required law is supplied (Fig. 1).

This technical solution has the following advantages:

1. The amplitude and time stability of each radiation pulse is improved in pulse sources of different purposes [5, 7], since the delay time of the lamp ignition decreases [8].

2. The use of this method of electric power supply is more energy-efficient, since it is necessary to apply the voltage to the lamp of 1.5 times less than that when working without a duty arc [8, 9] in order to obtain identical values of the radiation characteristics.

3. The service life of a discharge lamp increases, since the cathode spot disappears and the sputtering of the electrodes is reduced sharply [8, 9].

The presence of an auxiliary discharge introduces some corrections in the theory of post-breakdown expansion of the electric arc in "cold" inert gases, which were discussed in detail in [5, 8, 9]. In fact, The forced thermal ionization of the plasma-forming medium is implemented in the low-temperature discharge channel already formed by the standby mode under the action of the longitudinal potential gradient.

Regardless of what rapidly changing processes of elementary interactions of atoms, ions, electrons, and photons occur during the formation of the discharge channel, it is more important to know the reasons leading to the termination of the growth of the resulting thermal ionization of the gas. The peak current itself determines the pulse response of the lamp radiation. It is advisable to use power sources for lamps with rectangular voltage pulses supplied to the lamp (Fig. 1) in order to study the radiation characteristics in the low-temperature plasma [4, 6]. Such facilities make it possible to study not only ionization and relaxation processes at the pulse fronts, but also the quasi-stationary plasma at the pulse "plateau". In this case, it is necessary that the duration of the voltage pulse be less than the characteristic time of the energy transfer by diffusion and thermal conductivity. This is required for the predominance of bulk relaxation processes over exchange with a wall bounding it, e.g., ambipolar diffusion. According to [6], the diffusion time for a length of 1 cm is 10^{-2}–10^{-3} s. Therefore, the duration of the current pulse for a lamp with a discharge channel with the diameter of 10 mm should not exceed 5×10^{-3}–5×10^{-4} s. This estimate gives an upper limit of the voltage pulse duration for the bulk relaxation processes.

A special power source for a gas-discharge lamp, in which a stabilized voltage from the converter was supplied to the auxiliary discharge of the lamp when the transistor switch was opened for the pulse duration of $t_{gen.}$ (see Fig. 1), was used to carry out the spectral and electrical studies, the same as in [4].

The operation of the lamp in the electrical circuit is determined by the following parameters: the composition and amount of plasma-forming components (cesium, mercury), the pilot arc current, loop inductance and active resistance. In our studies, the parameters of the electrical circuit were as follows: the voltage on the capacitor of 120 V, inductance of 8 μH, active resistance of the circuit of 0.026 Ohm, pilot arc current of 1.1 A, and the electric power of up to 1.5 kW was controlled by changing the duration t_{gen} of the master oscillator. The studied lamp had the following design characteristics: the radius of the discharge gap of $R = 0.55$ cm and the length of $L = 3.5$ cm, the cesium and mercury content in the discharge was 1.3 and 2.0 mg, the pressure of the starting gas (xenon) in the cold state was 70 mm Hg. The electric mode was implemented in the form of a series of three pulses with pulse repetition rates in the series and the series themselves, determined by the T_c, T_e, and t_{gen} values (Fig. 1).

FORMATION OF A HIGH-CURRENT COLUMN OF THE PULSE-PERIODIC Cs–Hg–Xe DISCHARGE

Figure 2 shows an oscillogram of the current pulses of a series of three pulses at an electric power of a gas-discharge lamp of 1500 W.

The highest current value in the series at a given voltage of 120 V on the capacitor is reached only in the third pulse and its amplitude significantly exceeds the maximum value of the first pulse. This is due to the fact that the initial state of the discharge gap before the first and last pulses differs significantly. If the third current pulse passes through a sufficiently developed channel prepared by the two previous pulses, then the

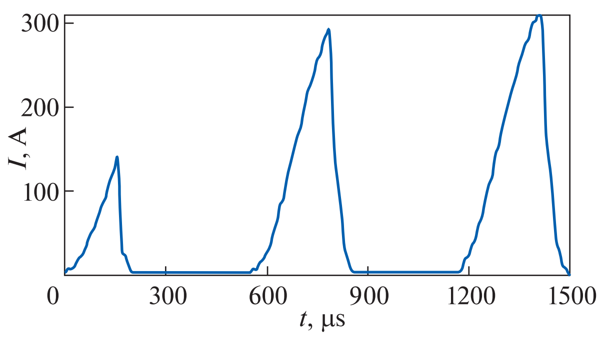

Fig. 2. Oscillogram of a series of three current pulses.

discharge gap is relaxed to the state of the duty arc at the beginning of the series.

The current fall at the back edge of each pulse occurs due to relaxation of the plasma channel charges during 60–90 μs. After the passage of the first pulse, the resistance has time to recover to 10 Ohm, then another pulse follows, and the resistance of the column begins to fall again. As a result, the plasma channel resistance is recovered from the highly conductive state (0.2–0.4 Ohm) to 70 Ohm after the end of the series, which entails the increase in the voltage drop across the discharge gap to 75 V. The nonlinear current dependence of the resistance of the discharge column is manifested in this behavior of the electrical parameters and the latter is also affected by the thermal inertia of the plasma.

The observed phenomenon can be explained by the following arguments. The central axial zone of the plasma-forming medium, which has the lowest electrical resistance, warms up faster at the initial stage during the current pulse. This is manifested in a noticeable difference between the axial temperatures and the average discharge temperature. This effect is especially strong during the passage of the first current pulse, before which the plasma has time to cool down to the state approaching the state of the auxiliary discharge. A narrow near-axial zone, into which the electric power is introduced when the next current pulse is formed, is in such a conducting state. The difference between the axial and average temperatures is the largest for the first pulse [10]. The temperature field is equalized over the radius as the current increases, and cooling down takes place after the end of each pulse. As a result, the third pulse begins under the conditions of the lowest plasma resistance and the highest homogeneity of the temperature field in comparison with the conditions of the two previous pulses. Therefore, as already noted, the current in a given pulse has time to reach noticeably large values (Fig. 2). The axial and average temperatures of the plasma decrease rapidly after a series of three pulses is terminated. However, under the action of the pilot arc current, the central zone is warmed up again, while the bulk of the gas continues to cool. In this case, the conductive zone is reduced in size, but despite this, the overall resistance of the column continues to decrease.

SPECTRAL-TIME CHARACTERISTICS OF THE PULSE-PERIODIC Cs–Hg–Xe DISCHARGE

It follows from the previous section that the temperature profile of the discharge changes with the passage of each current pulse of the series. The pressure in the discharge behaves in accordance with the time course of the average temperature. The pressure rises relatively little (by about 70%), in the first pulse, already in three times in the second pulse, and almost in four times with respect to the initial level of the series in the third pulse. The pressure, the same as the average temperature, slowly relaxes to the level of about 0.1 MPa in the pause between series. This phenomenon affects the absorption coefficient of the plasma and, as a consequence, the spectral characteristics of the radiation of the gas-discharge lamp. The temperature and vapor pressure dependences of the coefficient were considered in detail in [10]. In particular, these factors have the greatest effect on the absorption coefficient in the mid-IR range. For example, when the temperature changes from 2000 to 7000 K (and the populations of the upper levels of the cesium atom increase accordingly), the absorption coefficient changes by almost two orders of magnitude in the range of 3–6 μm.

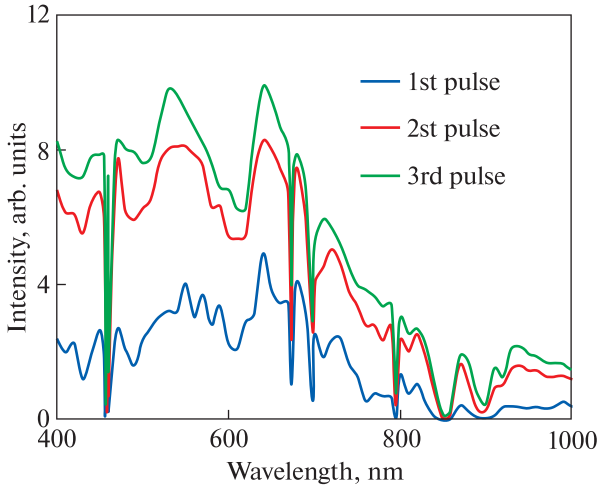

Fig. 3. Emission spectrum of the Cs–Hg–Xe discharge of a series of three current pulses at an electric lamp power of 1500 W.

Thus, the difference can be expected in the emission spectra of the gas-discharge lamp during the passage of each current pulse of the series. Figure 3 shows the spectral characteristics of the Cs–Hg–Xe discharge in the range of 0.4–1.0 μm.

The line component of the spectrum is fully manifested in the radiation of the auxiliary mode before the start of the pulse series, when the plasma is rarefied (about 0.1 MPa). But the ratio of the spectral components changes strongly already during the first pulse during the change in the thermodynamic composition of the plasma and the change in the mechanisms of the radiation formation. As a result, many lines of the emission spectrum of the Cs–Hg–Xe discharge are self-reversed (Fig. 3). This phenomenon is due to the following reasons. According to our calculated estimates [10], the electron density reaches the values of $(0.5–0.9) \times 10^{18}$ cm^{-3} at the end of the third pulse. The electrons are quite uniformly distributed over the channel radius, and the conduction band is on the order of 80% of the inner diameter of the discharge tube. The concentrations of heavy cesium, mercury, and xenon particles increase towards the cold near-wall regions. The increased particle concentration near the walls leads to the inversion of the resonance lines of all elements, and this effect is also observed for nonresonant lines for cesium with its low ionization potential and high absorption coefficients in other lines. For example, the continuous radiation emerging from the hot central region is absorbed by lines in the cold near-wall zone in the region of 0.6–0.9 μm (Fig. 3). This effect is especially noticeable at increasing pressure. The line structure of the spectrum, clearly expressed in the absorption coefficient at low pressures, is strongly smoothed out during the passage of a series of pulses.

CONCLUSIONS

The presented research results are primarily important for understanding the principle of the formation of an interfering signal in optoelectronic systems designed to protect aircraft from guided missiles. In these systems, the effectiveness of countermeasures is determined by the stability of the peak values of radiation pulses and the constancy of the spectral characteristics [7]. On the other hand, the proposed methodology for the formation of a pulse-periodic discharge opens up wide possibilities of using discharge radiation in vapors of a mixture of metals in other optoelectronic systems for civil and special purposes.

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