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SELECTION OF MODELING CRITERIA IN THE DEVELOPMENT OF SYSTEMS FOR EXCITATION OF THE ACTIVE MEDIUM FOR GAS-DISCHARGE LASERS

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It is shown that an algorithm for selection of modeling criteria that lies in isolating the most general features of the objects studied can lead to such investigational methods as methods of dimensional theory and similarity theory. Similarity relations for electrodeless gas discharges are given that are obtained based on the above algorithm. A design technique is presented for a system for excitation of the active medium for CO_2 *lasers with pumping by a non-self-maintained discharge and preionization by an electrodeless pulsed discharge.*

In [1], consideration is given to general approaches to the selection of modeling criteria in the study of electronic systems that are based on the construction of an appropriate model that adequately represents basic properties of studied objects by isolating their most general features. It is noted that the set M of properties of objects of a certain class (of a group of devices, for example, for the same purpose) that are taken into account by the modeling criterion should be equal to the intersection of the sets M_i of properties of these objects:

$$M = M_1 \cap M_2 \cap \ ... \cap M_i \cap ... \cap M_k \,. \tag{1}$$

For a subclass of objects (of a group of same-class objects unified by a more particular feature, for example, the physical effects used in them), the most informative modeling criterion should take account of the set N of properties defined by the expression

$$N = (N_1 \cap N_2 \cap ... \cap N_j \cap ... \cap N_p) \setminus M \,, \tag{2}$$

where N_j is the set of properties of the j-th object of the given subclass, and M is defined by expression (1) for the class into which this subclass enters. The approach of [1] permits isolation of the necessary and sufficient features of the objects of a certain class, which produced positive results in various investigational series, including the development of laser systems for atmospheric probing by continuous frequency-modulated optical signals [2], the development of a new class of highly efficient radio electronic devices for voltage transformation [3, 4], and a comparative analysis of the methods of preionization of gas mixtures by an electrodeless pulsed discharge [6]. The above examples indicate universality of the algorithm for selection of modeling criteria [1], which is supported by the efficiency of its use not only in the study of optical and radio electronic systems but also in other fields of knowledge, specifically, in philology and linguistics – in compiling dictionaries of a new type, namely, phonetic bilingual dictionaries [7, 8] – and in the field of patent science – in identifying new classes of objects of industrial property (dictionaries) [8].

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Below we consider in more detail similarity relations for electrodeless gas discharges [9] that are obtained based on the algorithm for selection of modeling criteria [1] and permit use of the results of model experiments and numerical calculations in the development of real devices. Questions are discussed as to the application of similarity relations to setting up engineering techniques for designing systems for excitation of the active medium for gas-discharge lasers. A technique for designing systems for pumping of CO_2 lasers with a non-self-maintained discharge and preionization by an electrodeless pulsed discharge is presented.

Selection of Modeling Criteria in Determination of Similarity Relations for Electrodeless Gas Discharges. Electrodeless gas discharges are of practical importance, for example, in laser engineering. Among them is a high-frequency capacitive discharge [10], which is used for producing the active medium for gas lasers [11], and an electrodeless pulsed discharge [10, 12], which is used in systems for preionization of the active medium for gas lasers and provides an efficiency (15–20%) of the preionization system that is close to the maximum possible in the region of low and medium pressures of the working mixture (several torr – tens of torr (mm Hg)) [5, 6]. The concept of the efficiency of the preionization system that was formulated in [5] based on the algorithm for selection of the modeling criteria (1) [1] is defined by the expression

$$\eta = n_e I / w \,, \tag{3}$$

and is equal to the product

$$\eta = \eta_{p.s}\, \eta_g\, \eta_{act}\, \eta_f \,. \tag{4}$$

Here, n_e is the density of free electrons formed in the discharge volume under the action of the ionizer and I is the ionization potential of molecules of the working gas. Regardless of the ionizer type, the efficiency of formation of electrons η_f is expressed by the relation [5]

$$\eta_f = n_e I / W \,. \tag{5}$$

Electrodeless gas discharges are excited in dielectric discharge chambers whose electrodes are separated from the discharge volume by either a dielectric layer [5, 6, 10, 13] or weakly conducting near-electrode layers of the space charge [11, 13]. The characteristics of electrodeless discharges depend on both the parameters of the dielectric discharge chamber and its operating mode (the applied voltage, the pressure of the working mixture, and the predominant mechanisms of formation and destruction of charged particles in the discharge plasma), and in each specific case their determination needs separate investigations that take into account the nonlinearity and nonstationarity of the properties of the plasma formed [5, 6, 10–13].

In accordance with the algorithm for selection of modeling criteria [1], the most general feature of dielectric discharge chambers is the presence of dielectric walls that separate the gas volume from the external electrodes. Here, the equivalent scheme of the chamber [12] contains the parallel-connected capacitance of the gas gap C and the nonlinear nonstationary conductivity of the gas gap $G(u, t)$, which are series-connected to the capacitance of the dielectric walls C_d.

When only ionization of the mixture molecules by electron impact (the characteristic mode of systems of preionization by an electrodeless pulsed discharge [12]) is taken into account, it is shown [9] that in the general case of uniform and nonuniform electric fields acting in the gas volume, geometrically similar discharge chambers the coordinates of whose one-to-one points (for the first and second chambers) are related as follows are equivalent in their specific characteristics:

$$x_2 = \alpha x_1 \,, \quad y_2 = \alpha y_1 \,, \quad z_2 = \alpha z_1 \,, \quad \alpha = \text{const} \,. \tag{6}$$

The analysis is performed here in the most general case of electric fields of any arbitrary configuration that are written for the compared chambers with account for expression (6) in the form

$$E_1\,(x, y, z) = f\,(\alpha x, \alpha y, \alpha z)\ ; \quad E_2\,(x, y, z) = f\,(x, y, z)\ . \tag{7}$$

Here, the electron concentrations n_e, the current densities j, and the dissipated powers P_j at the one-to-one points (6) of the compared chambers are the same. The specific energy contributions are also the same (for the operating mode with energy storage in the capacitance of the dielectric walls of the discharge chamber [12]):

$$W_{d1}/V_1 = W_{d2}/V_2\ , \tag{8}$$

where W_{d1} and W_{d2} are the energies of the electric field stored in the dielectric regions of the compared chambers, and V_1 and V_2 are the volumes of the gas regions of the chambers. Simultaneously, the condition of identity of the time characteristics is fulfilled [9]:

$$C_1/G_1\,(t) = C_2/G_2\,(t)\ ; \quad C_{d1}/G_1\,(t) = G_{d2}/G_2\,(t)\ , \tag{9}$$

since for the geometrically similar chambers (6) the following relations hold [9]:

$$C_2 = \alpha C_1\ ; \quad C_{d2} = \alpha C_{d1}\ ; \quad G_2\,(t) = \alpha G_1\,(t)\ . \tag{10}$$

Subsequently, successive use of the algorithm for selection of modeling criteria (2) for the subclass of objects [1] in the analysis of processes in the dielectric chamber permitted [9] allowance for the following factors: 1) variation of the pressure of the working mixture in the discharge chamber, 2) attachment (and detachment) of electrons to electronegative molecules (which is characteristic of the working mixture of CO_2 and CO lasers), 3) electron diffusion to the walls of the discharge chamber, 4) processes on the surface of the dielectric (or the electrodes in the absence of a dielectric) that are essential to the high-current combustion mode of a high-frequency capacitive discharge [14]: electron emission by the action of bombardment by positive ions and photoemission by the action of optical radiation of the discharge with allowance for radiation absorption in the plasma, 5) the effect of discharge electrons on the plasma permittivity, 6) the effect of the near-electrode layers of the space discharge, 7) the effect of the parameters of the external discharge circuit.

It is shown [9] that in the general case of the nonuniform electric fields (7), electrodeless gas discharges in the geometrically similar discharge chambers (6) are similar at a constant product of the gas pressure p by the discharge gap d

$$pd = \text{const}\ . \tag{11}$$

For such discharges, the following quantities are invariant with change in the geometric parameters of the chamber and the gas pressure: the ratio of the density of the currents traversing the chamber elements j and the density of the electrons formed in the discharge n_e to the pressure of the working mixture p squared and the product of the characteristic times τ of the processes in the plasma of an electrodeless gas discharge and the pressure of the gas mixture

$$j/p^2 = \text{const}\ ; \quad n_e/p^2 = \text{const}\ ; \quad \tau p = \text{const}\ , \tag{12}$$

and also the efficiency of the preionization system η of (3).

In the case of uniform electric fields acting in the discharge chamber, the similarity (12) is exhibited [9] by electrodeless discharges at a constant ratio of the capacitance of the dielectric walls of the chamber to the capacitance of the gas gap

$$C_d/C = \text{const}\ . \tag{13}$$

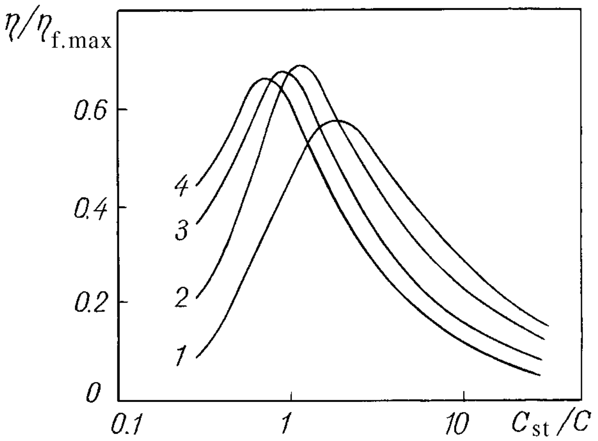

Fig. 1. Efficiency of the preionization system as a function of the ratio of the capacitance of the storage element to the capacitance of the gas gap: 1) u_0 = 1.1; 2) 2.1; 3) 3.0; 4) 4.0.

Such chambers with a uniform distribution of the electric field find wide practical use, since they provide high uniformity of excitation of the active medium of the laser [6, 12, 15].

The similarity conditions (12) are also satisfied by systems of preionization by an electrodeless pulsed discharge at the same ratio of the capacitance of the storage element C_{st} to the capacitance of the gas gap of the discharge chamber

$$C_{st}/C = \text{const}\,. \tag{14}$$

It is possible to use directly the capacitance of the dielectric walls C_d of the discharge chamber [12] or a separate reservoir capacitor [6, 15] as the energy storage element C_{st}.

The similarity of the characteristics of electrodeless discharges (12) is provided when the following requirements on the parameters of the external discharge circuit are fulfilled [9]: with change in the chamber dimensions (6) (and a constant gas pressure), the inductance L and the active resistance R of the external discharge circuit should vary in inverse proportion to these dimensions. With a pressure variation (and constant chamber dimensions), R should vary in inverse proportion to the pressure and L should vary in inverse proportion to the pressure squared. With a simultaneous change in the chamber dimensions and the pressure (but such that pd = const), R should remain constant and L should vary in inverse proportion to the pressure.

Designing of Systems for Excitation of the Active Medium for Gas-Discharge Lasers. The similarity relations for electrodeless gas discharges [9] supplement previously known similarity relations for electrode gas discharges [16] and make it possible to use results of model experiments and numerical calculations in the development of real devices, thus laying the foundation for setting up engineering techniques for designing of systems for excitation of the active medium for gas-discharge lasers. Here, an opportunity is provided to represent results for the characteristics of electrodeless gas discharges in a universal generalized form that is independent of the specific parameters of the discharge chamber and the pressure of the working mixture. Thus, Fig. 1 plots the efficiency of the preionization system as a function of the ratio of the capacitance of the storage element C_{st} to the capacitance of the gas gap C based on the results of experimental investigations and numerical calculations for characteristics of systems for preionization by an electrodeless pulsed discharge with a uniform distribution of the electric field in the gas gap [6].

The quantity u_0 is the voltage of the discharge of the storage element normalized on the basis of the optimum value of the reduced voltage of the electric field $(E/p)_{opt}$ in the plasma of the gas discharge at

TABLE 1. Optimum Values of the Reduced Strength of the Electric Field $(E/p)_{opt}$ in a Gas-Discharge Plasma and the Attained Efficiencies of Formation of Electron-Ion Pairs $\eta_{f.max}$ of (5) for Various Gas Mixtures

Composition of the working gas mixture	$(E/p)_{opt}$, V·cm^{-1}·torr^{-1}	$\eta_{f.max}$, %
He	53	32
$CO_2 : N_2 : He = 1 : 1 : 8$	98	32
$CO_2 : N_2 : He = 1 : 7 : 30$	115	27
$CO_2 : N_2 : He = 1 : 2 : 7$	124	26
$CO_2 : N_2 : He = 1 : 2 : 3$	195	25
CO_2	250	23
N_2	373	21.5

which the maximum efficiency of formation of electron-ion pairs $\eta_{f.max}$ (5) for the working mixture is attained [5]:

$$u_0 = [U_0/(pd)]/(E/p)_{opt} . \tag{15}$$

Values of $(E/p)_{opt}$ and $\eta_{f.max}$ [5] for various gas mixtures are given in Table 1.

Using the similarity relations [9] it is possible to obtain compact expressions for the characteristics of electrodeless gas discharges that contain maximum information. Thus, the relation connecting the efficiency of the preionization system η of (3) and the maximum electron concentration $n_{e.max}$ that is set up in the discharge chamber by the action of a high-voltage pulse [6] takes the following form:

$$n_{e.max} = 0.5\,(C_{st}/C)\,u_0^2\,\eta\varepsilon_0\,p^2\,(E/p)_{opt}^2/I\,, \tag{16}$$

where I is the ionization potential of the most easily ionizable components of the working mixture. It should be noted that the quantity $0.5(C_{st}/C)u_0^2$ is the energy stored by the storage element expressed in dimensionless units. Each expression of type (16) describes a whole set of operating characteristics.

As is seen from [5, 9] and the results presented, the considered algorithm for selection of modeling criteria (1) and (2) [1] can lead to such investigational methods as methods of dimensional theory and similarity theory [17].

As an example of application of the results obtained, we consider the designing of systems for excitation of the active medium for a CO_2 laser with pumping by a non-self-maintained discharge (generally, of direct current [12, 15]) and with preionization by an electrodeless pulsed discharge. In practice use is made of discharge chambers with a uniform distribution of the electric current in the gas volume and a longitudinal non-self-maintained discharge, with preionization by an electrodeless discharge effected transversely [6, 12, 15].

To determine the parameters of the system for excitation of the active medium, we preassign the required power input to the main non-self-maintained discharge P_{main} that is established from calculations of the parameters of the laser cavity, the specific energy input to the plasma of the non-self-maintained discharge P_{sp} that is specified by the cooling mode of the working mixture (of the order of 1 W/cm^3 for chambers with diffusion cooling [18] and 2.5 W/cm^3 and over in the mode with convective cooling [12]), the reduced strength of the electric field of the main discharge $(E/p)_{main}$ that is selected below the threshold of burning of a self-maintained discharge [12], the geometric parameters of the discharge gap of the chamber – the length a, the width b, and the height d, and the pressure p and composition of the working mixture: $CO_2 : N_2 : He = K_{CO_2} : K_{N_2} : K_{He}$.

Then, the voltage of the power source of the main discharge is determined by the expression

$$U_{\text{main}} = (E/p)_{\text{main}} pa + U_c\,, \tag{17}$$

where U_c is the cathode voltage drop specified by the cathode material and the composition of the working mixture (of the order of 140–200 V for aluminum and iron cathodes [19]). The current drawn from the power source of the main discharge is

$$J_{\text{main}} = P_{\text{sp}} V/[(E/p)_{\text{main}}\, pa]\,, \tag{18}$$

where $V = a\ b\ d$. Next, based on the Joule–Lenz law in differential form we determine the specific conductivity of the plasma of a non-self-maintained discharge:

$$\sigma = P_{\text{sp}}/[(E/p)_{\text{main}} p]^2\,, \tag{19}$$

after which we find the average electron concentration $n_{\text{e.av}}$ need for sustaining a non-self-maintained discharge. Here, we use the expression for the specific conductivity of the plasma [19]

$$\sigma = (e^2 n_{\text{e.av}})/(m\nu_{\text{m}})\,, \tag{20}$$

where e and m are respectively the electron charge and mass, and ν_{m} is the frequency of the electron collisions with particles of the working mixture, which characterizes the change in the electron momentum. Here, ν_{m} is taken as the "weighted" value for the components of the working mixture [20]:

$$\nu_{\text{m}} = (K_{\text{CO}_2}\nu_{\text{CO}_2} + K_{\text{N}_2}\nu_{\text{N}_2} + K_{\text{He}}\nu_{\text{He}})/(K_{\text{CO}_2} + K_{\text{N}_2} + K_{\text{He}})\,, \tag{21}$$

with ν_{CO_2}/p = $1.8\cdot10^9$ $\text{sec}^{-1}\cdot\text{torr}^{-1}$, ν_{N_2}/p = $3.5\cdot10^9$ $\text{sec}^{-1}\cdot\text{torr}^{-1}$, and ν_{He}/p = $2.4\cdot10^9$ $\text{sec}^{-1}\cdot\text{torr}^{-1}$ [12].

The primary function of the preionization system lies in maintaining the average electron concentration n_{eav} in the plasma of a non-self-maintained discharge (for the considered continuous operating mode of the laser). It is necessary to preset the interval of repetition of preionization pulses T (from considerations of an acceptable depth of the amplitude modulation of laser radiation). In this case, in calculating the elements of the preionization system, it is necessary to determine the maximum electron density $n_{\text{e.max}}$ needed to maintain $n_{\text{e.av}}$.

The predominant mechanism of electron destruction in the gas-discharge plasma (in the case of CO_2 and CO lasers) is attachment to electronegative molecules [12]. This mechanism is characterized by the attachment frequency ν_{a} and leads to an exponential decrease in the electron density after the action of a preionization pulse with the time constant $1/\nu_{\text{a}}$ has terminated. For working mixtures of CO_2 lasers with strengths of the electric field corresponding to a non-self-maintained mode of discharge burning, the value of ν_{a}/p is $3.3\cdot10^4\ x_{\text{CO}_2}$ $\text{sec}^{-1}\cdot\text{torr}^{-1}$ [12], where x_{CO_2} is the fraction of carbon dioxide in the working mixture. The expression that relates the maximum electron density to the average one under these conditions and permits determination of $n_{\text{e.max}}$ is of the form

$$n_{\text{e.av}} = [n_{\text{e.max}}/(T\nu_{\text{a}})]\,[1 - \exp\,(-\,T\nu_{\text{a}})]\,. \tag{22}$$

The selection of the scheme of the preionization system (with energy storage in the capacitance of the dielectric walls of the chamber or with an individual reservoir capacitor) is primarily governed by the mode of cooling of the working mixture. The scheme with energy storage in the capacitance of the chamber walls is applicable to lasers with rapid pumping of the gas [12]. The thickness of the chamber walls is chosen such that the capacitance of the storage element is optimum by the criterion of maximum efficiency. The scheme with an individual reservoir capacitor [15] finds wider use in practice. It is also applicable to lasers with diffusion cooling of the working mixture [6, 8]. The dielectric thickness should be minimum here, providing only fulfillment of the conditions of electric strength.

The optimum capacitance of the reservoir capacitor C_{st} is determined as follows. From the presented plots for the dependence $\eta(C_{st}/C)/\eta_{f.max}$ (see Fig. 1), the value of $\eta_{f.max}$ (see Table 1), and relation (16) we find the optimum value $(C_{st}/C)_{opt}$ and the charge voltage of the storage element u_0 expressed in dimensionless units (15) for which maximum efficiency is ensured and the needed electron density $n_{e.max}$ is attained. Then, the capacitance of the storage element is obtained

$$C_{st} = C\,(C_{st}/C)_{opt}\,, \tag{23}$$

where $C = \varepsilon_0 ab/d$ is the equivalent capacitance of the gas gap. The charge voltage of the storage element is determined from expression (15):

$$U_0 = u_0 pd\,(E/p)_{opt}\,. \tag{24}$$

The power that is consumed from the power source by the preionization system is determined by the relation

$$P_{ion} = 0.5 C_{st} U_0^2 F\,, \tag{25}$$

where $F = 1/T$ is the interval of repetition of preionization pulses.

The remaining components of the preionization system – the power source and the system for startup of the generator of high-voltage pulses – are standard radio engineering devices.

CONCLUSIONS

1. An algorithm for selection of modeling criteria that consists in isolation of the most general features of the objects studied can lead to such investigational methods as methods of dimensional theory and similarity theory.

2. Similarity relations for electrodeless gas discharges that are obtained based on an algorithm for selection of modeling criteria that consists in isolation of the most general features of the objects studied provide an opportunity to represent results for the characteristics of electrodeless gas discharges in a universal generalized form that is independent of the specific parameters of the discharge chamber and the pressure of the working mixture, permit use of the results of model experiments and numerical calculations in the development of real devices, and lay the foundation for setting up engineering techniques for designing of systems for excitation of the active medium for gas discharge lasers using electrodeless discharges.

NOTATION

n_e, electron density; $n_{e.max}$ and $n_{e.av}$, maximum and average electron concentrations; w, energy consumed by the ionizer from the external source per unit volume of the working mixture; η, efficiency of the preionization system; $\eta_{p.s}$, efficiency of the power-supply source of the generator of ionizing action; η_g, efficiency of the generator of ionizing action; η_{act}, efficiency of the system for transfer of ionizing action from the generator to the working volume; η_f, fraction of the energy of ionizing action spent directly on formation of electron-ion pairs; η_{max}, maximum efficiency of formation of electron-ion pairs; W, specific energy input to the plasma from the preionization source; $G(u, t)$, conductivity of the gas gap; u, voltage drop on the gas gap; t, time; C, capacitance of the gas gap; x_i, y_i, z_i, space coordinates; α, constant; E, electric-field strength; j, current density; P_j, power released at a given point; W_d, electric-field energy stored in the dielectric region of the discharge chamber; V, volume of the gas region of the chamber; p, gas pressure; τ, characteristic time of the processes in the plasma; ε_0, electric constant; K_{CO_2}, K_{N_2}, and K_{He}, fractions of CO_2, N_2, and He in the working mixture; U_{main}, voltage of the power source of the main discharge; ν_a, frequency of electron attachment; x_{CO_2}, fraction of carbon dioxide in the working mixture; $(C_{st}/C)_{opt}$, optimum ratio of the capacitance of the storage element to the capacitance of the gas gap; P_{ion}, power consumed by the preionization system.

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