Quantum Electronics **41** (12) 1093–1097 (2011)

PACS numbers: 42.55.Lt; 42.60.By; 52.80.Pi
DOI: 10.1070/QE2011v041n12ABEH014686

Gas mixture circulation system in lasers using a high-frequency barrier discharge

S.I. Moshkunov, S.V. Nebogatkin, I.E. Rebrov, V.Yu. Khomich, V.Ya. Yamshchikov

Abstract. **Electrohydrodynamic flow in gas for a high-frequency barrier discharge distributed over the surface of a dielectric was investigated. An electric-discharge laser circulation system with a gas flow rate higher than 15 L s^{-1} was proposed.**

Keywords: *electrohydrodynamic flow, barrier discharge, circulation system, electric-discharge lasers.*

1. Introduction

To form high velocity gas media, advantage is traditionally taken of different types of mechanical fans with rotating vanes; these fans, however, have several fundamental drawbacks like outer dimensions, weight, form factor, vibrations, noise, etc., which arise from the presence of elements rotating at a high velocity. In the paths of repetitively pulsed lasers, self-circulation of gas is possible owing to the onset of vibrations; this self-circulation is markedly resonance in character related to the excitation of the eigenfrequencies of an acoustic resonator [1]. An alternative to these systems is offered by electric circulation systems, whose operation relies on the effect of 'electric wind' [2–12], or the electrohydrodynamic (EHD) effect [3–16].

The employment of electric circulation systems in electric-discharge gas lasers has received sufficient attention [4–11]. An advantage of electric circulation over the mechanical one consists in the absence of moving parts and their related failures due to the rotor wear or the thermal and mechanical fatigue of fans. The operation of such a system is absolutely noiseless, does not induce vibrations, is rather efficient, and is also a rather simple and compact device. In this case, the system ptovided a vacuum purity, which is critically important for the environmental protection from aggressive gaseous media in their circulation.

In electric-discharge lasers, use is made of circulation systems in which the EHD flow is produced due to a corona gas discharge [4, 7, 11]. A disadvantage of the corona discharge is the existence of the limiting (up to 3 L s^{-1}) value of gas flow rate [7], which limits the application of such systems in high-power lasers.

Khomich and Yamshchikov [6] proposed the use of a periodic gas discharge across a dielectric barrier instead of a corona discharge. Owing to artificially increased interelectrode capacitance and the tunable frequency of alternating voltage, this discharge is significantly higher in power than the corona discharge. More recently we elaborated a new approach to the production of electric wind based on the use of a high-frequency barrier discharge distributed over the surface of a dielectric [9, 10]. This discharge serves as the source of ions, which drift in the external electric field and transfer the momentum to neutral gas molecules to produce the EHD flow. The discharge area on the dielectric surface may exceed 103 cm^2 [6]. The proposed approach is void of fundamental restrictions on the gas flow rate, which opens up the way to the development of high-power electric circulation systems capable of competing with electromechanical fans.

The aim of our work is to investigate the feasibility of producing EHD flow rates higher than 10 L s^{-1} for the circulation of gas media in electric-discharge lasers.

2. Description of experimental facility

In our experiments use was made of the setup (Fig. 1) described in detail in Refs [9, 10]. The function of charged particle source was fulfilled by the plasma emitter (PE) with a high-frequency barrier discharge induced on it, the discharge being distributed over the dielectric surface. The PE consisted of a 30-cm long dielectric tube (*1*) (Al_2O_3 ceramics) 5 mm in radius, with a copper tube (*2*) inserted inside it, which served as the inner electrode. A 20-cm-long copper gutter (*3*) was the outer electrode. A copper wire (*4*) 0.5 mm in diameter was

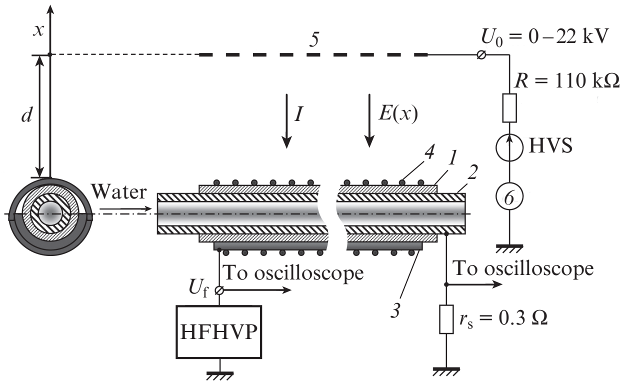

Figure 1. Schematic representation of the experimental facility: (*1*) dielectric Al_2O_3 ceramic tube; (*2*) copper tube (inner electrode); (*3*) copper gutter (outer electrode); (*4*) copper wire; (*5*) metal grid with a transmittance $\sigma = 0.7$; (*6*) microammeter.

S.I. Moshkunov, S.V. Nebogatkin, I.E. Rebrov, V.Yu. Khomich, V.Ya. Yamshchikov Institute of Electrophysics and Electric Power, Russian Academy of Sciences, Dvortsovaya Naberezhnaya 18, 191186 St. Petersburg, Russia; e-mail: rc@iperas.nw.ru

Received 28 June 2011; revision received 12 October 2011
Kvantovaya Elektronika **41** (12) 1093–1097 (2011)
Translated by E.N. Ragozin

coiled around the dielectric tube and the copper gutter, the coil pitch was equal to 5 mm.

An alternating voltage $U_f = 5-12$ kV was applied to the outer electrodes of the plasma emitter, and the inner electrode was grounded via a current shunt r_s. In this case, on the outer surface of the dielectric tube there emerged a barrier discharge plasma layer. The heat released in the operation of the PE was removed by water flowing through the tube (*2*).

Above the PE was a metal grid (*5*) with a transmittance $\sigma = 0.7$, which served as an ion beam collector. The separation d between the collector and the emitter was varied. A constant voltage $U_0 = 0-22$ kV of positive polarity from a high-voltage source (HVS) was applied to the grid via a limiting resistance R = 110 kΩ. Electrons were extracted from the barrier discharge plasma under the action of external field $E(x)$ and formed negative ions by way of three-body attachment to oxygen molecules [17]. The ion motion towards the grid produced the EHD flow. The current I emerging in this case was recorded by a microammeter (*6*).

To feed the plasma emitter, use was made of a specially developed high-frequency high-voltage pulse generator (HFHVPG) based on a half-bridge circuit loaded on the electrodes of the PE. The generator features the employment of a high-voltage semiconductor commutator proposed in Ref. [18]. The HFHVPG was made using all-solid-state electronics [19, 20]. Formed at the HFHVPG output were quasi-rectangular pulses of positive polarity with a variable voltage amplitude ($U_f = 0-122$), a duration $t_p \approx 7$ μs, a repetition rate f = 10–25 kHz, and a high-frequency component at the voltage pulse edge.

The voltage U_f was measured with a Tektronix P6015A high-voltage probe and the barrier discharge current I_f was measured with a low-inductance ohmic shunt $r_s = 0.3$ Ω. The oscilloscope traces of the voltage and the current were recorded with a LeCroy WaveSurfer 432 oscilloscope.

Figure 2 shows typical oscilloscope traces of the voltage and current of the plasma emitter. The barrier discharge current starts at the front and droop of high-voltage pulses.

The velocity characteristics of the electrohydrodynamic flow were monitored using an ATT-1004 heat-loss anemometer. The measurements were carried out ~5 cm downstream of the grid collector.

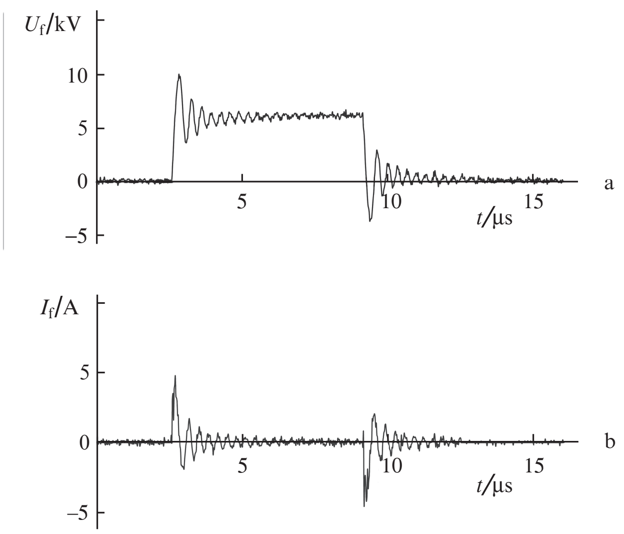

Figure 2. Typical oscilloscope traces of the voltage U_f (a) and current I_f (b) of the plasma emitter.

3. Calculated dependences of electrohydrodynamic flow characteristics

To analyse experiments, we give several computational characteristics of the EHD flow. In Refs [6, 9, 10] we proposed a one-dimensional model describing the ion beam drifting in the external electric field – between a plane-parallel emitter and an ion collector. This model corresponds to the design of a plasma emitter with a dielectric tube of infinite radius (see Fig. 1). Assuming steady-state conditions, we derived the distributions of the electric field intensity $E(x)$, the ion density $n(x)$, and the ion current density j. For $x > 0$, their approximate expressions are of the following form:

$$E(x) = \frac{3}{2} E_0 \sqrt{\frac{x}{d}}, \quad (1)$$

$$n(x) = \frac{3}{4} \frac{\varepsilon_0 E_0}{ed} \sqrt{\frac{d}{x}}, \quad (2)$$

$$j = \frac{9}{8} \frac{\mu \varepsilon_0 E_0^2}{d}, \quad (3)$$

where μ is the ion mobility; $E_0 = U_0/d$ is the average field intensity in the gap; U_0 is the collector bias voltage; d is the separation between the emitter and the collector; e is the electron charge; and ε_0 is the electric constant.

The dependence of the current I on the collector voltage U_0 is described by the expression

$$I = Sj = \frac{9}{8} \frac{S \mu \varepsilon_0 U_0^2}{d^3}, \quad (4)$$

where S is the effective area of the ion emitter.

The force caused by the action of the electric field $E(x)$ on the spatial ion charge $n(x)$ produces a pressure gradient in the gas [3, 12]:

$$\frac{dp}{dx} = n(x) e E(x) = \frac{j}{\mu}. \quad (5)$$

By substituting expression (3) in formula (5), it is possible to determine the pressure of electric forces at the grid collector:

$$p = \frac{1}{\mu} \int_0^d j dx = \frac{9}{8} \varepsilon_0 E_0^2; \quad (6)$$

the value of p at the grid may also be represented as

$$p = \rho V^2, \quad (7)$$

where ρ is the gas density in the interelectrode gap and V is the velocity of the gas flow. We equate expressions (6) and (7) to find

$$V = \sqrt{\frac{9}{8} \frac{\varepsilon_0}{\rho}} E_0. \quad (8)$$

Assuming that $\rho = 1.2928$ kg m^{-3}, for the air at room conditions [21] we obtain

$$V \approx 0.28 E_0, \quad (9)$$

where V is expressed in m s^{-1} and E_0 in kV cm^{-1}.

4. Experimental results

In our experiments we investigated the effect of plasma emitter supply regime (of the voltage amplitude, the duration and frequency of the pulses from the solid-state generator) on the characteristics of the high-frequency barrier discharge and the ion beam current as well as on the velocity and the spatial velocity profile of the electrohydrodynamic flow in the ambient air.

Figure 3 shows the characteristic photographs of the plasma glow of the barrier discharge on the surface of the dielectric tube of the plasma emitter for different values of U_f and f. The ignition voltage of the barrier discharge, whereby a faintly glowing plasma layer appeared on the PE, was equal to 4 kV. One can see that the surface occupied by the discharge plasma and hence the effective area S of ion emission increase progressively with U_f and f.

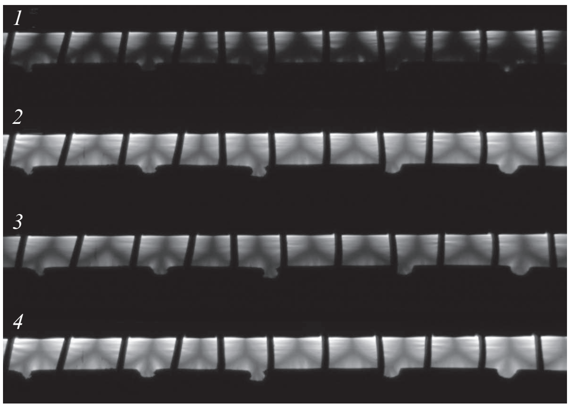

Figure 3. Photographs of the barrier discharge plasma glow on the surface of the ion emitter for $U_f = 6$ kV, $f = 20$ kHz (*1*), $U_f = 10$ kV, $f = 20$ kHz (*2*), $U_f = 10$ kV, $f = 10$ kHz (*3*), and $U_f = 10$ kV, $f = 25$ kHz (*4*).

Figure 4 displays the experimental dependences of the average ion beam current I on the collector voltage U_0 for an invariable collector–emitter separation $d = 18$ mm and different values of U_f and f. The current I rises proportionally to U_0^2, which is consistent with formula (4). The growth of $I = jS$ with increase in U_f and f is obviously due to the corresponding increase in S.

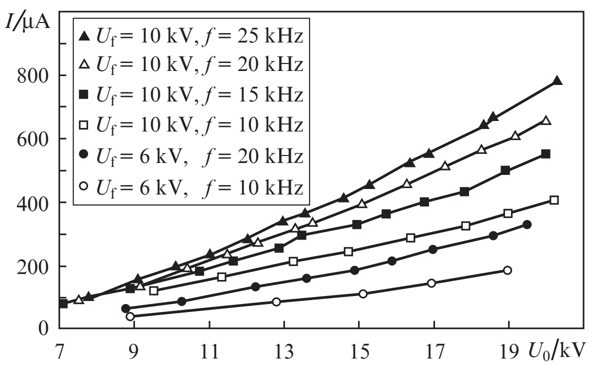

Figure 4. Experimental dependences of the ion beam current I on the collector voltage U_0 for $d = 18$ mm and different values of U_f and f.

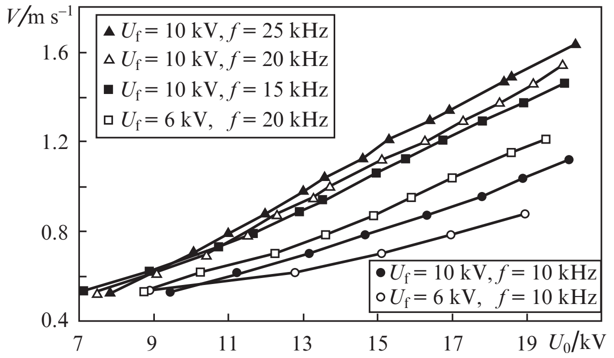

Figure 5. Experimental dependences of the air flow velocity V on U_0 for $d = 18$ mm and different values of U_f and f.

Figure 5 depicts the measured dependences of the EHD flow velocity V on the voltage U_0 for the same experimental conditions as in Fig. 4. It is evident that the magnitude of V also rises with increasing U_0, U_f, and f; however, unlike the ion current, the flow velocity is directly proportional to U_0 [4, 9].

The profiles of the air flow velocity distribution in the plane perpendicular to the flow are plotted in Fig. 6. The transverse profile of V is somewhat asymmetric about the PE tube axis. Obviously, this asymmetry is due to the influence of the measuring sensor on the flow velocity vector.

In the case depicted in Fig. 6, for $U_0 = 20$ kV the gas flow rate W in the transverse section with $V = 1$ m s^{-1} is equal to about 4 L s^{-1}, which is higher than the limiting value attained with the use of a corona discharge and a voltage of 30 kV [7].

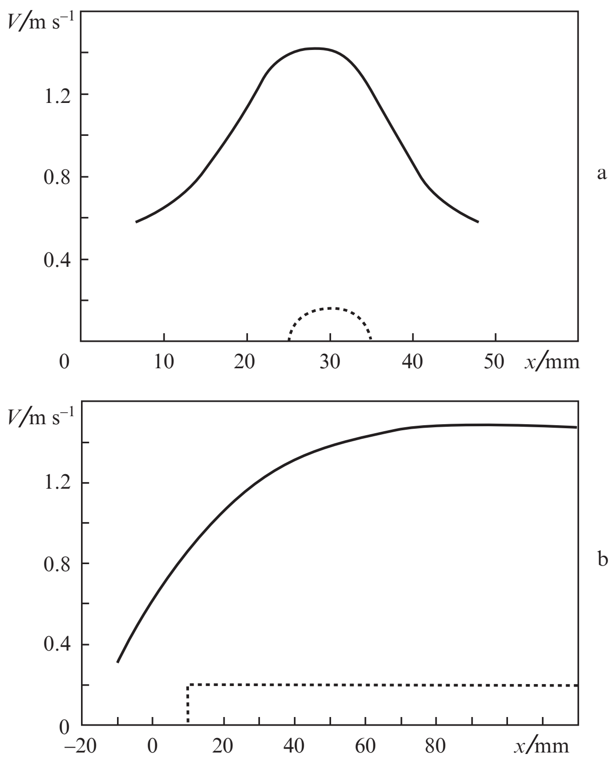

Figure 6. Velocity distribution profiles in the plane perpendicular to the air flow (for $U_f = 10$ kV, $f = 15$ kHz, and $d = 18$ mm) across (a) and along (b) the PE tube. The dashed lines show the tube profiles.

In the case of a barrier discharge, use is made of electrodes with a substantially gentler curvature at their edges, their erosion is insignificant in comparison with the erosion of corona-forming electrodes. This is an important quality for their application in technological lasers with a service life exceeding 10^9 pulses.

Figure 7 shows the experimental dependences of V on the magnitude of $E_0 = U_0/d$ for three values of d. They fit into a common curve quite well, which is consistent with formula (9). However, the slope $V/E_0 \approx 0.14$ m cm s^{-1} kV^{-1} of these experimental dependences is approximately two times lower than the calculated value 0.28 m cm s^{-1} kV^{-1} [see formula (9)]. This is supposedly attributable to the approximate assumptions that the ion beam geometry is planar and that the ion current density j is independent of the ion density $n(0)$ at the PE surface and is time-independent, as well as attributable to the neglect of the air viscosity.

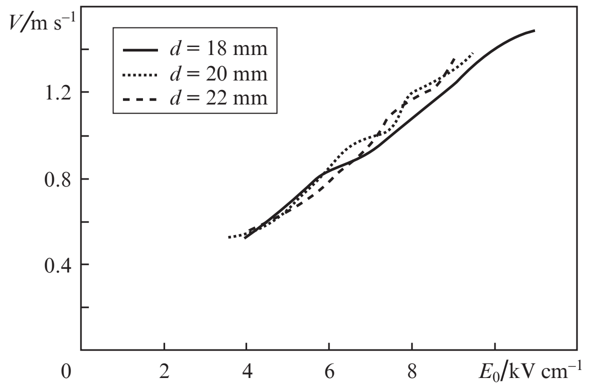

Figure 7. Experimental dependences of the velocity V on the average electric field intensity $E_0 = U_0/d$ for different d and $U_f = 10$ kV, $f = 15$ kHz.

5. Prototype of the device for the circulation of gas mixtures in electric-discharge lasers

The most important factor which controls the highest pulse repetition rate of an electric-discharge laser is the velocity V_d of the working gas mixture in the discharge gap of the laser. The circulation velocity in its turn is determined by the gas flow rate provided by the circulation system:

$$W = V_d S_d = V_d hl, \tag{10}$$

where S_d is the flow section area; h is the interelectrode gap; and l is the discharge length. We estimate the gas flow rate and the flow velocity in the circulation system of a CL-5000 excimer laser, which is commercially available from the Russian company OptoSistemy [22].

For excimer mixtures, the gas replacement coefficient K in the discharge gap should not be less than four:

$$K = \frac{V_d}{wf}, \tag{11}$$

where w is the discharge width.

The CL-5000 laser possesses the following parameters: $h = 1.2$ cm, $l = 25$ cm, $w \approx 0.3$ cm, $S_d = 30$ cm^2, and the highest pulse repetition rate is equal to 300 Hz [21, 22]; in this case, $W \geqslant 11$ L s^{-1}.

In the circulation system considered above, $V \sim E_0$ and therefore the highest velocity V_{max} of the air flow at the surface of the grid collector is limited by the maximum value E_0^{max} defined by the breakdown intensity E_{br} of the field between the PE and the collector. In the working mixture F_2:Ar:Ne = 10:150:4500 mbar typical for ArF lasers, the weight-average density $\langle\rho\rangle \approx 0.933$ kg m^{-3} [21] and $E_{br} \approx$ 10 kV cm^{-1} [20]. The field $E(x)$ is highest at the collector, i.e. for $x = d$ [see expression (1)]. By assuming that $E(d) = E_b$, we thereby obtain an estimate for the electric strength: $E_0^{max} = \frac{2}{3}E_{br} = 6.7$ kV cm^{-1}, and from formula (9) we obtain $V_{max} \approx$ 1.6 m s^{-1}, which is close to the velocity achieved in the atmospheric air.

According to the results of experiments of Refs [9, 10], the magnitude of W increases proportionally to the number of PE tubes due to the increase in S. To obtain $W \geqslant 11$ L s^{-1}, the PE design should therefore include no less than three tubes similar to that considered above.

Figure 8 displays a device with three tubular emitters made of metal ceramics, which is intended for the circulation of gas mixtures in electric-discharge lasers. This device may be built in the discharge chamber instead of fan propeller. In its operation in the air, the flow rate was higher than 15 L s^{-1}, which corresponds to a circulation rate $V_d = W/S_d \approx 5$ m s^{-1} in the discharge gap.

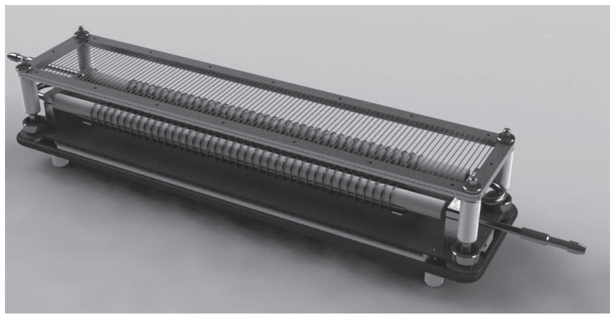

Figure 8. EHD device.

6. Conclusions

We have investigated the electrohydrodynamic air flow produced in the ion emission from the plasma of a high-frequency barrier discharge. The flow velocity was shown to be proportional to the intensity of the electric field between the ion emitter and collector. To feed the plasma emitter of ions, for the first time advantage was taken of an all-solid-state generator of pulses with a voltage $U_f = 0-12$ kV, a tunable pulse repetition rate $f = 10-25$ kHz, and a pulse duration $t_p = 7$ μs. It was experimentally determined that raising the voltage and frequency of plasma emitter feeding results in an increase in ion emission area as well as in a growth in ion current and air flow velocity. A circulation system with a gas flow rate of 15 L s^{-1} and a flow velocity higher than 1.6 m s^{-1} was proposed for electric-discharge lasers.

References

1. Baranov V.Yu., Niz'ev V.G., Pigul'skii S.V., Tolstov V.F. *Zh. Eksp. Teor. Fiz.*, **2** (8), 478 (1980).
2. Stuetzer O.M. *J. Appl. Phys.*, **30** (7), 984 (1959).

3. Robinson M. *Transaction AIEE Commun. Electron.*, **80**, 143 (1961).
4. Gorkin S.B., Kozlov B.A., Solov'ev V.I. *Izv. Ross. Akad. Nauk, Ser. Fiz.*, **58** (2), 42 (1994).
5. Shuaibov A.K. *Zh. Tekh. Fiz.*, **68** (9), 84 (1998).
6. Khomich V.Yu., Yamshchikov V.A. *Formirovanie elektricheskogo vetra s pomoshch'yu vysokochastotnogo bar'ernogo razryada* (Electric Wind Formation Using a High-Frequency Barrier Discharge.) Preprint of TsNPIPE RAN (Moscow: RIIS FIAN, 2003).
7. Kozlov B.A., Solov'ev V.I. *Zh. Tekh. Fiz.*, **77** (7), 70 (2007).
8. Kozlov B.A., Solov'ev V.I. *Zh. Tekh. Fiz.*, **76** (7), 1 (2006).
9. Nebogatkin S.V., Khasaya R.R., Khomich V.Yu., Yamshchikov V.A. *Prikl. Fiz.*, **4**, 111 (2009).
10. Mikolutskii S.I., Nebogatkin S.V., Khasaya R.R., Khomich V.Yu., Yamshchikov V.A. *Moshchnyi istochnik elektricheskogo vetra na osnove vysokochastotnogo bar'ernogo razryada v gaze* (High-Power Source of Electric Wind Based on a High-Frequency Barrier Gas Discharge.) Preprint IEE RAN (St.Petersburg, IEE RAN, 2009).
11. Treshalov A., Lissovski A., Chikeev E. *Proc SPIE Int. Soc. Opt. Eng.*, **253**, 4747 (2002).
12. http://zhurnal.ape.relarn.ru/articles/2005/227.pdf.
13. Reece Roth J., Xin Dai. *Abstr. 44th AIAA Aerospace Sci. Meeting and Exhibit* (Nevada, USA, 2006) p. 1.
14. Yang F., Jewell-Larsen N.E., Brown D.L., Pendergrass K., Parker D.A., Krichtafovitch I.A., Mamishev A.V. *Abstr. 13th Intern. Symp. High Voltage Eng.* (Rotterdam, Netherland, 2003) p. 1.
15. Karpov S.V., Krichtafovitch I.A. *Proc. COMSOL Multiphysics Conf.* (Boston, USA, 2005) p. 399.
16. Jewell-Larsen N.E., Karpov S.V., Krichtafovitch I.A., Jayanty V., Hsu C.P., Mamishev A.V. *Proc. ESA Annual Meeting Electrostatics* (Albuquerque, USA, 2008) E1, p. 1.
17. Akishev Yu.S., Grushin M.E., Kochetov I.V., Napartovich A.P., Pan'kin M.V., Trushkin N.I. *Fiz. Plazmy*, **26** (2), 172 (2000).
18. Ivanov E.V., Moshkunov S.I., Khomich V.Yu. *Generator vysokovol'tnykh nanosekundnykh impul'sov na osnove bipolyarnykh tranzistorov s izolirovannym zatvorom* (Generator of High-Voltage Nanosecond Pulses Based on Bipolar Transistors with an Insulated Gate.) Preprint IPEF RAN (Moscow, IPEF RAN, 2004).
19. Gryaznov O.V., Ivanov E.V., Malashin M.V., Moshkunov S.I., Khomich V.Yu. *Prikl. Fiz.*, **5**, 32 (2008).
20. Vartapetov S.K., Gryaznov O.V., Malashin M.V., Moshkunov S.I., et al. *Kvantovaya Elektron.*, **39** (8), 714 (2009) [*Quantum Electron.*, **39** (8), 714 (2009)].
21. Kikoin I.K. (Ed.) *Tablitsy fizicheskikh velichin. Spravochnik* (Tables of Physical Quantities. Reference Book) (Moscow: Atomizdat, 1976).
22. http://www.optosystems.ru.