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PLASMA OSCILLATIONS AND WAVES

Interaction of Microwave Radiation Undergoing Stochastic Phase Jumps with Plasmas or Gases

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Abstract—New types of beam–plasma devices generating intense stochastic microwave radiation in the interaction of electron beams with hybrid plasma waveguides were developed and put into operation at the National Science Center Kharkov Institute of Physics and Technology (Ukraine). The objective of the paper is to discuss the results of theoretical and experimental studies and numerical simulations of the normal and oblique incidence of linearly polarized electromagnetic waves on an interface between a vacuum and an overcritical plasma. The main results of the reported investigations are as follows: (i) for the parameter values under analysis, the transmission coefficient for microwaves with a stochastically jumping phase is one order of magnitude greater than that for a broadband regular electromagnetic wave with the same spectral density; (ii) the electrons are heated most efficiently by obliquely incident waves with a stochastically jumping phase and, in addition, the electron distribution function has a high-energy tail; and (iii) necessary conditions for gas breakdown and for the initiation of a microwave discharge in stochastic fields in a light source are determined. The anomalously large transmission coefficient for microwaves, the anomalous character of the breakdown conditions, the anomalous behavior of microwave gas discharges, and the anomalous nature of collisionless electron heating, are attributed to stochastic jumps in the phase of microwave radiation. *© 2005 Pleiades Publishing, Inc.*

INTRODUCTION

Litvak and Tokman [1] demonstrated that, because of the classical analogue of the effect of electromagnetically induced transparency in quantum systems, electromagnetic waves in a plasma can pass through the region where they should be absorbed. Faĭnberg *et al.* [2] showed that stochastic electric fields with a finite phase correlation time can efficiently heat particles in a collisionless plasma, so physically the inverse correlation time in the interaction between a particle and an electromagnetic wave has in fact the meaning of an effective collision frequency [2, 3].

The objective of the present paper is to determine the conditions for the effective penetration of microwaves with a stochastically jumping phase into a high-density plasma, to study the collisionless electron heating by it, and to utilize microwaves to initiate microwave discharges in light sources. In Section 1, we discuss the results of theoretical investigations of the normal and oblique incidence of linearly polarized electromagnetic waves on an interface between a vacuum and an overcritical plasma. The electron dynamics is described by the relativistic Vlasov equation for the electron distribution function together with Maxwell's equations for self-consistent electromagnetic fields under the assumption that the ions are immobile. We use the method [4] that not only provides a complete nonlinear kinetic description of the electron dynamics for a plasma of arbitrary density and for electromagnetic waves of arbitrary intensity but also makes it possible to carry out numerical simulations by taking short time steps in comparison to the electron plasma period. We consider how an overcritical plasma is penetrated by three types of waves, namely, a microwave with a stochastically jumping phase, a broadband regular wave with the same spectral density, and a monochromatic wave.

The possible mechanisms whereby electromagnetic waves penetrate through a wave barrier in a plasma are as follows:

(i) linear and nonlinear conversion between different types of waves,

(ii) linear and nonlinear echoes involving van Kampen waves,

(iii) the linear induced transparency of a wave barrier ("beam antennas"),

† Deceased.

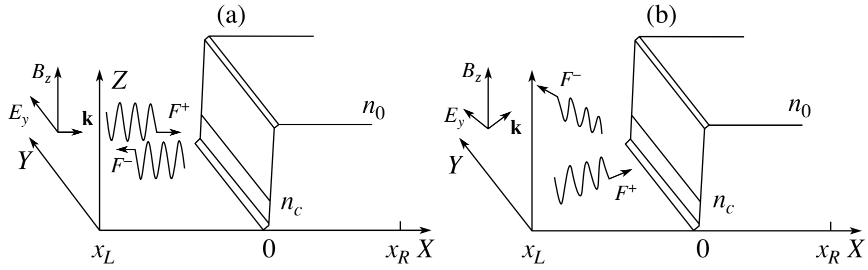

Fig. 1. Schematic representation of the computation region for the cases of (a) a normally and (b) an obliquely incident microwave.

(iv) collisional penetration of a wave into a wave barrier, and

(v) penetration of a wave into a wave barrier due to the jumps in its phase (this penetration mechanism is associated with the fact that the transmission coefficient is proportional to the time derivative of the wave phase, which in turn is determined by the derivative of the electric field)—an effect that is the subject of the present study.

The known mechanisms whereby electromagnetic waves can heat plasma particles are as follows:

(i) resonant absorption due to the synchronism between a wave and a particle (the particle always oscillates in phase with the wave),

(ii) collisional absorption due to the loss of synchronism between a wave and a particle in collisions (as a result, the absorption efficiency is proportional to the ratio of the collision frequency to the wave frequency),

(iii) linear and nonlinear absorption in a nonuniform wave, and

(iv) wave absorption due to the jumps in the phase of the wave when it loses its synchronism with the particle—an effect that was investigated in [2] and is the subject of the present study.

1. THEORETICAL STUDY OF THE NORMAL AND OBLIQUE INCIDENCE OF ELECTROMAGNETIC WAVES ON AN INTERFACE BETWEEN A VACUUM AND A HIGH-DENSITY PLASMA

1.1. Physical Model

Here, we describe the results of investigations of the incidence of three types of electromagnetic waves, namely, a monochromatic wave, a stochastic wave with a finite phase correlation time, and a broadband wave with the same spectral density, from vacuum on a plasma half-space. Numerical simulations were carried out by means of two techniques: a particle-in-cell (PIC) method for solving the Vlasov equation and a method based on a grid splitting scheme (the SUR code). A study of the transmission coefficients for different types of waves showed that a monochromatic wave is reflected from the plasma almost totally (except for its front), whereas a stochastic wave is reflected only slightly due mainly to the penetration of the wave pulses associated with stochastic jumps in the wave phase. In turn, the transmission coefficient for a broadband regular wave having the same spectral density as the wave with a stochastically jumping phase is much less; the reason is that, in this case, the plasma slab simply acts as a filter that transmits waves with the frequencies $\omega > \omega_p$ (where $\omega_p = (4\pi e^2 n_0/m)^{1/2}$ is the electron Langmuir frequency, n_0 is the plasma density, e is an elementary charge, and m is the mass of an electron) and reflects others.

1.2. Formulation of the Problem

Numerical simulations were carried out for a computation region $x_L < x < x_R$ that is shown schematically in Fig. 1. Initially, a uniform electron plasma ($n(x) = n_0\lfloor\theta(x - x_p) - \theta(x - x_R)\rfloor$) with a Maxwellian electron velocity distribution occupies the half-space to the right of the point $x = x_p$. The background plasma ions are assumed to be immobile. The electron plasma density n_0 is above the critical density ($\omega_p > \omega_0$).

Let a plane-polarized electromagnetic wave with the wave vector $\mathbf{k} = (k_x, 0, 0)$ and with the field components $\mathbf{E} = (0, E_y, 0)$ and $\mathbf{B} = (0, 0, B_z)$ be normally incident on the plasma from the left. In vacuum, in a cross section $x = x_L$ that is sufficiently far from the plasma boundary, the field components of a microwave with a stochastically jumping phase are given by the expressions

$$\begin{aligned} E_y^{\text{sp}}(x, t) &= B_z^{\text{sp}}(x, t) \\ &= F_0\cos(\omega_0 t - k_x x + \hat{\varphi}(t)). \end{aligned} \quad (1.1)$$

We consider a stationary Poisson process with the frequency $1/\tau$; specifically, we assume that, over a sufficiently long time interval T, the phase $\tilde{\varphi}$ undergoes, on the average, T/τ jumps. In each jump, the phase randomly takes a value within the interval $[-\pi, \pi)$ with equal probability. The correlation coefficient for such a stochastic process has the form (see, e.g., [3])

$$R(t) = \exp\left(-\frac{|t|}{\tau}\right)\cos\omega_0 t,$$

the spectral density being

$$G(\omega) = \frac{1}{(1/\tau)^2 + (\omega - \omega_0)^2}.$$

We also consider a broadband wave with the same spectral density but with time-independent phases φ^{lr} and time-independent amplitudes F^{lr}:

$$E_y^r(x, t) = B_z^r(x, t) = \sum_l F_0^{lr} \cos(\omega_l t - k_l x + \varphi^{lr}). \quad (1.2)$$

Together with a wave undergoing stochastic phase jumps and a broadband wave, we consider a regular monochromatic wave with the electromagnetic field components

$$E_y^{mf}(x, t) = B_z^{mf}(x, t) = F_0 \cos(\omega_0 t - k_x x + \varphi_0). \quad (1.3)$$

1.3. Basic Equations and Numerical Methods

The electron dynamics is described by the Vlasov equation for the electron distribution function $f(t, x, p_x, p_y)$:

$$\frac{\partial f}{\partial t} + V_x \frac{\partial f}{\partial x} - e\left[E_x + \frac{V_y}{c} B_z\right] \frac{\partial f}{\partial p_x} - e\left[E_y - \frac{V_x}{c} B_z\right] \frac{\partial f}{\partial p_y} = 0. \quad (1.4)$$

In one-dimensional geometry, the longitudinal electric field E_x can be determined from the Gauss formula,

$$E_x = E_x\big|_{x = x_L} + 4\pi \int_{x_L}^{x} \rho(\xi) d\xi. \quad (1.5)$$

In planar geometry, Maxwell's equations for the electromagnetic field,

$$\frac{1}{c}\frac{\partial E_y}{\partial t} + \frac{\partial B_z}{\partial x} = -\frac{4\pi}{c} j_y,$$

$$\frac{1}{c}\frac{\partial B_z}{\partial t} + \frac{\partial E_y}{\partial x} = 0,$$

can be decoupled by introducing the auxiliary fields $F^{\pm} = E_y \pm B_z$:

$$\left(\frac{1}{c}\frac{\partial}{\partial t} \pm \frac{\partial}{\partial x}\right) F^{\pm} = -\frac{4\pi}{c} j_y, \quad (1.6)$$

where the charge density and the transverse current density are given by the expressions

$$\rho = e\left(n_0 - \int f(x, \mathbf{p}) d\mathbf{p}\right),$$
$$j_y = -e \int V_y(x) f(x, \mathbf{p}) d\mathbf{p}. \quad (1.7)$$

The boundary conditions for the longitudinal electric field and the transverse auxiliary fields have the form

$$E_x\big|_{x = x_L} = 0, \quad F^+\big|_{x = x_L} = F(t), \quad -F^-\big|_{x = x_R} = 0, \quad (1.8)$$

where the function $F(t)$ is given by expression (1.1), (1.2), or (1.3).

The above equations were solved numerically using the SUR code [4–6].

1.4. Simulation Results

Numerical simulations of a normally incident electromagnetic wave were carried out for the following parameter values: $V_y^{\text{osc}} = 3V_T$, $\omega_0 = 0.5\omega_p$, $\tau = 40/\omega_p$, and $x_L = -1000\lambda_D$, $x_R = 1000\lambda_D$ (here, V_T is the electron thermal velocity and λ_D is the Debye length). The total run time of the code is $T = 5000/\omega_p$. The numerical results are illustrated in Figs. 2–4. The transmission coefficient for a wave is defined as the ratio of the electromagnetic wave energy at the point $x = x_R$ (i.e., the energy that has passed through the plasma) to the energy of the incident wave at the point $x = x_L$ (with allowance for the corresponding time shift).

The incident electromagnetic wave is mostly reflected from the plasma slab, without having any significant effect on the plasma electrons. The longitudinal fields in the plasma are weak (two to four orders of magnitude weaker than the transverse fields). During the run time of the code ($500/\omega_p$), the longitudinal energy of the electrons (as well as their temperature) changes by no more than 1%. The electron distribution function remains nearly Maxwellian, but a small fraction of the electrons (about 10^{-4}) are accelerated in both directions from the plasma boundary.

A monochromatic wave is reflected from the plasma almost totally (except for its front). A stochastic wave is reflected to a lesser extent due mainly to the penetration of the wave pulses associated with stochastic jumps in the wave phase. The transmission coefficient for a broadband wave with the same spectral density as that of a wave undergoing stochastic phase jumps is one order of magnitude less because, in this case, the plasma slab simply acts as a filter that transmits waves with the frequencies $\omega > \omega_p$ and reflects others.

The oblique incidence of an electromagnetic wave was simulated for the same parameter values as those for the normal incidence, the only difference being in the length of the time interval, $T = 2500/\omega_p$. In this case, the electromagnetic wave incident on the plasma has a strong impact on the electron dynamics, especially at large angles of incidence. The longitudinal electric fields in the plasma are close in strength to the transverse fields. The longitudinal energy of the electrons and their temperature increase severalfold. The electron

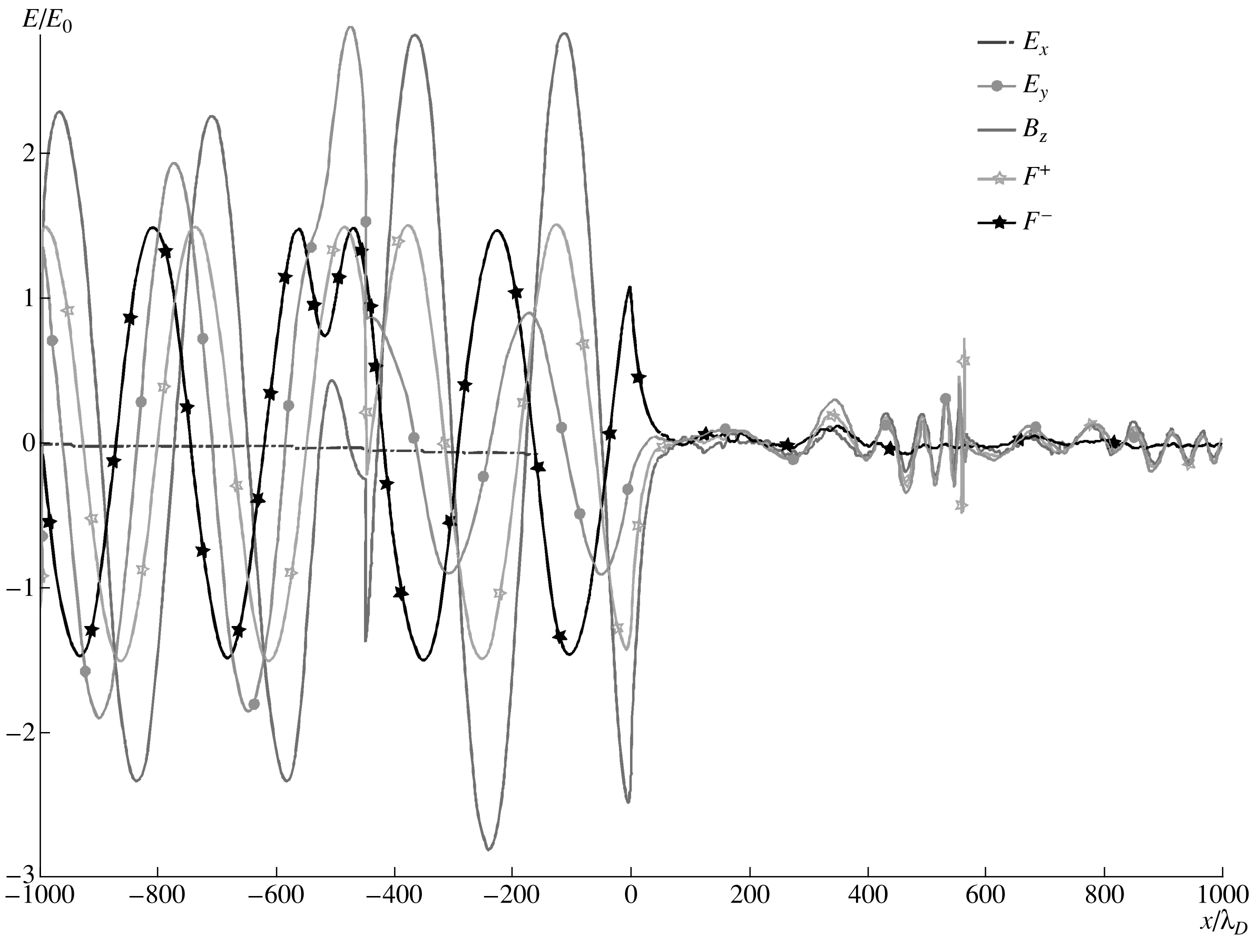

Fig. 2. Spatial profiles of the amplitudes of the incident (F^+) and reflected (F^-) waves and of the components of the transmitted wave (E_x, E_y, B_z) for the case of a microwave with a stochastically jumping phase. The plasma boundary is at $x = 0$.

distribution function becomes non-Maxwellian: it has a tail of accelerated electrons. The energy of the incident transverse wave is partially converted into the energy of the longitudinal wave and partially into the electron energy.

In order to illustrate the practical importance of the situation under examination, we present characteristic waveforms of stochastic signals in actual beam–plasma generators [7–9].

From Fig. 5 we can see that stochastic jumps in the phase of the signal occur very frequently (after each two to three periods or even more often).

2. EXPERIMENTAL INVESTIGATION OF THE PASSAGE OF STOCHASTIC ELECTROMAGNETIC RADIATION THROUGH A HIGH-DENSITY PLASMA

The passage of stochastic electromagnetic radiation from a broadband generator [10] through a plasma was investigated experimentally on the device [11] whose block diagram is illustrated in Fig. 6. The plasma in cavity *2* was created by M-571 magnetron *1* with a controlled output power ($W \leq 2.5$ kW), operating at a frequency of $f = 2.475$ GHz.

The working gas (deuterium) was puffed into and pumped out of cavity *2* through pipes *3* and *4*. The mirror magnetic field (whose longitudinal profile is shown in Fig. 6a) was produced by solenoids *5*, positioned at the ends of cavity *2*.

It should be noted that, although the experimental investigations were carried out under conditions different from those analyzed theoretically in Section 1 (the experiments were performed with a short plasma cavity, rather than with a semi-infinite plasma, and with a nonzero external magnetic field), an important point, as will be clear later, is that they justified the main conclusion of Section 1 that microwaves with a stochastically jumping phase can penetrate far deeper into the plasma than a broadband wave with the same spectral density. Preliminary experimental results were reported in [12].

A signal from G4-76A generator *6* of regular waves or from broadband generator *7* of microwaves with a stochastically jumping phase was fed through coaxial

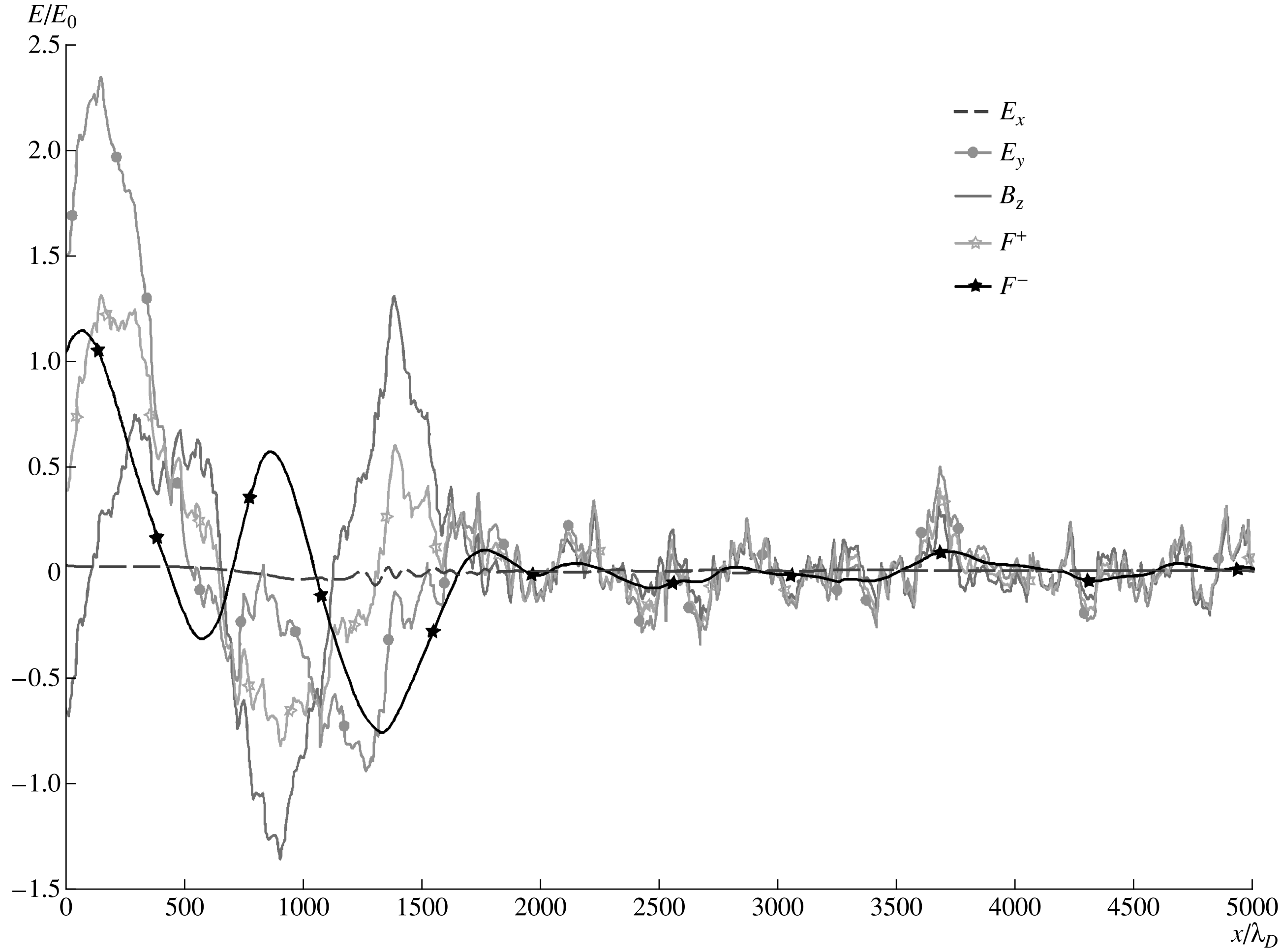

Fig. 3. Spatial profiles of the intensities of the incident (F^+) and reflected (F^-) waves and of the electromagnetic field components of the transmitted wave (E_x, E_y, B_z). The plasma boundary is at $x/\lambda_D = 1500$. The wave phase undergoes regular jumps after each time interval of length $\tau = 40/\omega_p$.

T-connector *8* and É6-32 ferrite isolator *9* and then through coaxial line *10* to emitting probe *11*, placed at the device axis. The signal that had passed through plasma-filled cavity *2* was received by probe *12* and was fed through É6-32 ferrite isolator *13* and coaxial T-connector *14* to S4-60 spectrum analyzer *15* or to S7-19 oscilloscope *16*. Ferrite isolators *9* and *13* served to suppress the signal from magnetron *1*. The emitting and receiving probes of length $l = 100$ mm and diameter $d = 1$ mm were the end portions of the central conductors of an RK-2 coaxial cable. They were protected from contact with the plasma by ceramic tubes with an outer diameter of 4 mm. In experiments, the position of the emitting probe was fixed, the distance between its end and the end of the cavity being 45 mm. The cavity was a stainless-steel cylindrical chamber with a diameter of $D = 50$ cm and length of $L = 50$ cm. At both ends, the main cavity was equipped with beyond-cutoff (for the electromagnetic waves under investigation) auxiliary cavities.

The density of the plasma created in the cavity by the magnetron could be varied from 10^9 to 10^10 cm^{-3} by varying the magnetron power. The dependence of the plasma density on the magnetron current at a working gas pressure of $p = 5 \times 10^{-5}$ torr is shown in Fig. 7.

We also investigated how the plasma density depends on the working gas pressure and found that this dependence was far weaker than that on the magnetron current. This is why we varied the plasma density in the cavity at a constant gas pressure only by varying the magnetron current.

The signals from a G4-76A generator or from a generator of stochastic radiation (the amplitude–frequency characteristics of these signals are shown in Figs. 8–12) were fed to the cavity through an emitting probe *11* installed in a fixed position. The signal that had passed through the plasma was received by probe *12*, which could be installed in one of the four fixed positions within the cavity, and then was fed to the spectrum analyzer. Since there was a small number of eigenmodes of

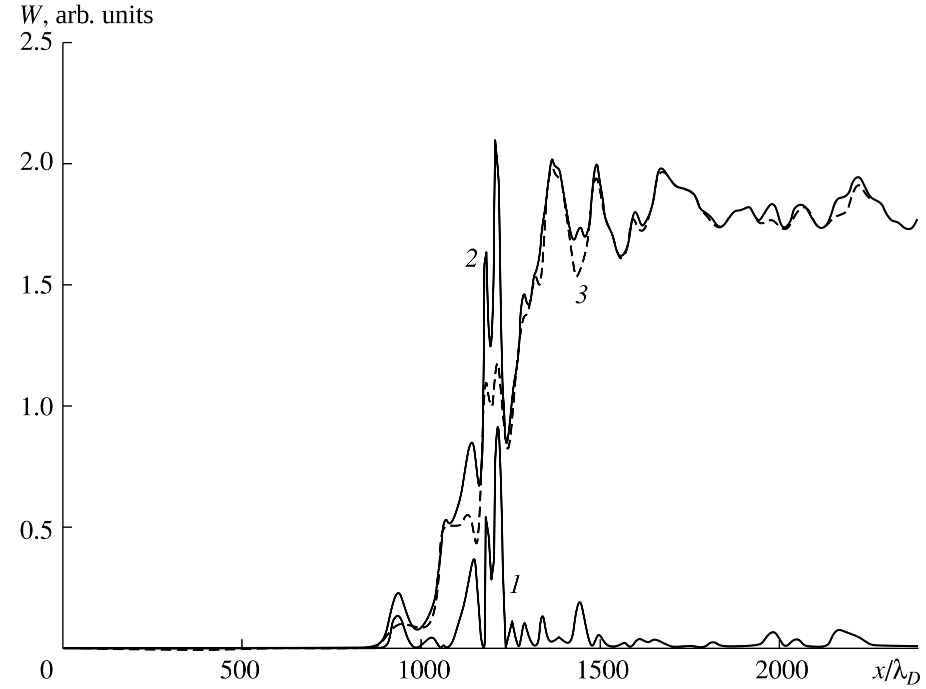

Fig. 4. Spatial profiles of the energy of the longitudinal field of the regular radiation (W, curve *1*), stochastic radiation (W_s, curve *2*), and radiation whose phase undergoes regular jumps after each time interval of length τ (W_τ, curve *3*).

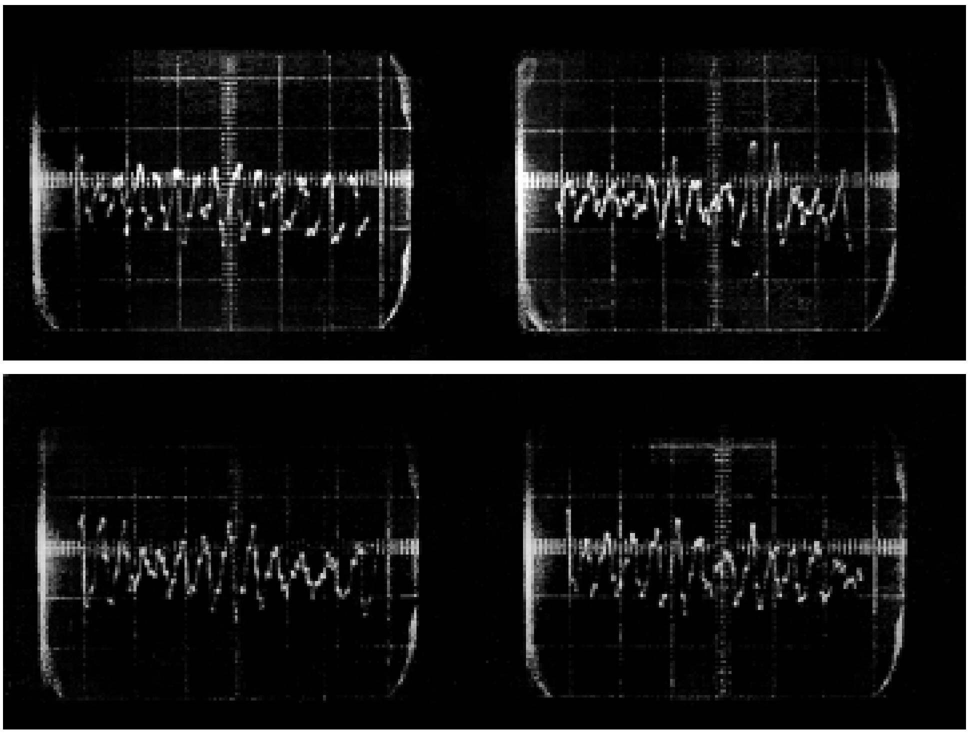

Fig. 5. Microwave signal with a stochastically jumping phase from a beam–plasma generator.

the plasma waveguide with frequencies below 1 GHz, it was expedient to identify them by choosing such four positions of the probe that corresponded to the nodes or antinodes of these eigenmodes.

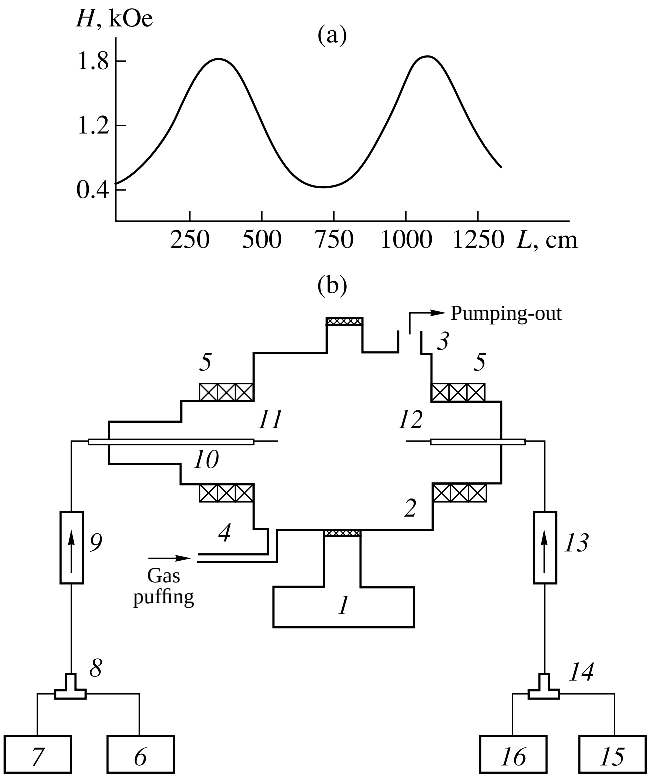

Fig. 6. (a) Longitudinal magnetic field profile in the experimental setup for investigating the passage of stochastic electromagnetic radiation through a plasma and (b) block diagram of the experimental setup: (*1*) magnetron, (*2*) cavity, (*3*) pumping-out, (*4*) gas puffing, (*5*) solenoids, (*6*) G4-76A generator, (*7*) generator of broadband stochastic radiation, (*8*, *14*) T-connectors, (*9*, *13*) ferrite isolators, (*10*) coaxial line, (*11*) emitting probe, (*12*) receiving probe, (*15*) S4-60 spectrum analyzer, and (*16*) S7-19 oscilloscope.

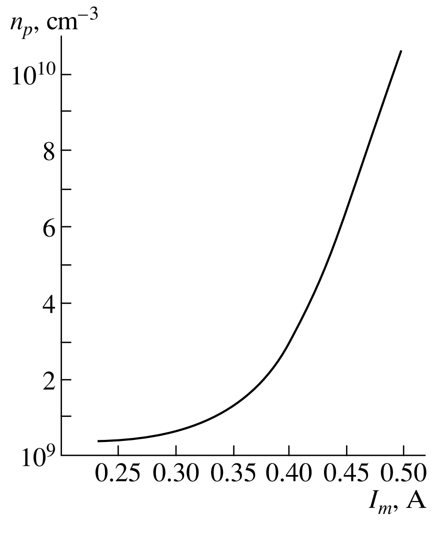

Fig. 7. Plasma density vs. magnetron current.

2.1. Results and Discussion

Let us analyze the structure of a stochastic signal from a broadband generator after it has passed through the plasma. The corresponding results obtained for a low-density plasma ($n_p \approx 10^9$ cm^{-3}) and a high density plasma ($n_p \approx 5 \times 10^9$ cm^{-3}) are presented in Figs. 9–11. It can be seen that the signals that arrive at the receiving probe at different positions have different amplitude–frequency characteristics. Note that the conditions of our experiments correspond to a magnetized plasma, because the electron gyrofrequency ω_{He} exceeds the electron Langmuir frequency, $\omega_{He}^2 \gg \omega_p^2$.

It is known that, in this case, the eigenmodes of the system under discussion exist in two different frequency ranges. These are the ranges of working frequencies ω above the cutoff frequency $\omega_{\text{cut}} = \sqrt{\omega_p^2 + c^2 k_\perp^2}$ (where $k_\perp = 2.4/R$, with R being the cavity radius) and below the electron Langmuir frequency ω_p. The range of frequencies of up to 1 GHz, which was investigated in our experiments, overlaps with both of them. In this frequency range, the number of eigenmodes of the plasma cavity is small. However, the waveforms of the signals show the presence of many unnatural waves that are attributed to the small cavity length and the short distance between probes *11* and *12* (the amplitude of the waves excited by probe *11* cannot decrease substantially over such a short distance). The maximum in the amplitude of the transmitted stochastic signal in the high-frequency range at a frequency of f_{1a} = 800 MHz (Fig. 10a) corresponds to the first radial harmonic with a longitudinal field structure such that there are two minima at the cavity ends and one maximum at the center of the cavity. Note that, in Fig. 10, the signal amplitude at this frequency is somewhat lower than its maximum value, because the receiving probe is displaced from the center of the cavity (the case in which the receiving probe is placed just at the center of the cavity is presented in Fig. 11). The maxima in the amplitude of the stochastic signal in the high-frequency range at a frequency of f_{2a} = 950 MHz (Figs. 9a, 9c) correspond to the first radial harmonic with a longitudinal field structure such that the longitudinal wavelength is equal to the cavity length, i.e., the field has a maximum and a minimum within the cavity and vanishes at the center of the cavity and at its ends. We can see from Fig. 11 that the signal amplitude at this frequency is minimum at the center of the cavity (that it is minimum rather than zero stems from the fact that the probe is extended rather than pointlike) because the amplitude of the mode in question is maximum at distances from the cavity ends that are equal to one-quarter of the cavity length. The next eigenmode of the cavity corresponds to the first radial harmonic with a longitudinal field structure such that the cavity length is equal to 1.5 longitudinal wavelengths, i.e., the field has three extremes within the cavity and is zero at the cavity ends

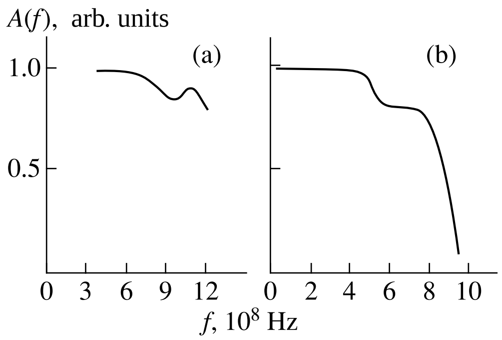

Fig. 8. Amplitude–frequency characteristics of the signals from (a) the G4-76A generator and (b) the generator of stochastic radiation.

and between the extreme points. However, even in the absence of plasma, the frequency of this eigenmode is higher than 1 GHz, i.e., is beyond the frequency range under investigation. A further increase in the magnetron current results in a corresponding increase in the plasma density and, accordingly, in the frequencies f_1 and f_2, which thus turn out to be above the working range of frequencies. Recall that, first, in the low-frequency range, the eigenmodes of the cavity can propagate within it only when it is filled by a plasma of corresponding density, and, second, the existence of unnatural waves is a consequence of the small geometric dimensions of the cavity and the short distance between the probes. These two remarks refer in full measure to both stochastic and regular signals.

Let us analyze the passage of a regular signal through the cavity, compare the results obtained with those for microwaves with a stochastically jumping phase, and examine the degree to which they agree with the theoretical results presented in the first part of this paper (see also [6]). Figure 12 shows the amplitude–frequency characteristic of a regular signal that has passed through the cavity (a) without a plasma, (b) with a low-density plasma ($n_p \approx 5 \times 10^9$ cm^{-3}), and (c) with a high-density plasma ($n_p \approx 10^9$ cm^{-3}). From Fig. 12a we can see that, in the absence of plasma, regular signals at frequencies higher than 400 MHz pass through the cavity; in this case, the cutoff frequency is equal to 478 MHz, which corresponds to the critical wavelength ($\lambda_{cr} = 2.62R$) for the E_{01} mode. It is also seen that the peaks corresponding to the eigenmodes of the cavity are pronounced only slightly. In order for the transmitted signals from an incident regular wave and from an incident wave with a stochastically jumping phase to have the same amplitude, the amplitude of the former should be one to two orders of magnitude larger than that of the latter. This provides evidence for a low efficiency of the excitation of waves in the cavity by a regular signal, on the one hand, and for a lack of selectivity between eigenmodes and unnatural waves during the passage of a regular signal, on the other hand.

2.2. Conclusions

Our experimental investigations of the excitation of regular and stochastic electromagnetic waves in plasmas of different densities and their passage through a cavity allow us to draw the following conclusions:

(i) A regular wave excites a cavity less efficiently than does a wave with a stochastically jumping phase (in order for the transmitted signals from an incident

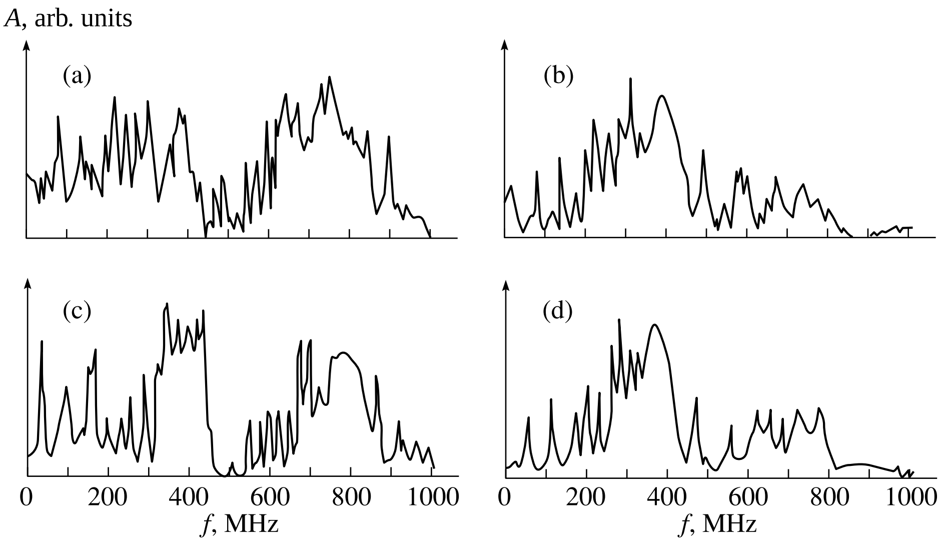

Fig. 9. Frequency spectrum of a stochastic signal that has passed through a plasma of density $n_p \approx$ (a, c) 5×10^9 and (b, d) 10^{10} cm^{-3}. The distance between the emitting and receiving probes is (a, b) 14.0 and (c, d) 33.5 cm.

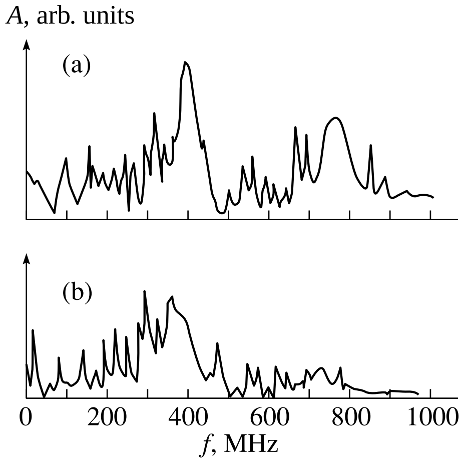

Fig. 10. Frequency spectrum of a stochastic signal that has passed through a plasma of density $n_p \approx$ (a) 5×10^9 and (b) 10^{10} cm^{-3}. The distance between the emitting and receiving probes is 27.0 cm.

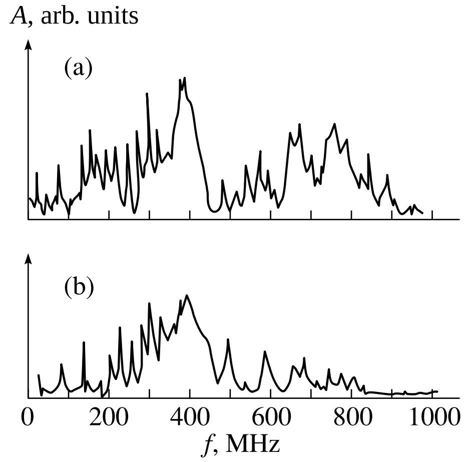

Fig. 11. Frequency spectrum of a stochastic signal that has passed through a plasma of density $n_p \approx$ (a) 5×10^9 and (b) 10^{10} cm^{-3}. The distance between the emitting and receiving probes is 20.6 cm.

regular wave and from an incident wave with a stochastically jumping phase to have the same amplitude, the amplitude of the former should be one to two orders of magnitude larger than that of the latter).

(ii) As a regular monochromatic signal excites a cavity and passes through it, the selectivity between eigenmodes and unnatural waves is lacking.

The results of our experimental investigations are in satisfactory qualitative agreement with the theoretical predictions.

3. MICROWAVE DISCHARGE INITIATED BY WAVES WITH A STOCHASTICALLY JUMPING PHASE AND ITS APPLICATION

In 1992, specialists from the Fusion System Corporation (Maryland) designed a highly efficient light source operating in the quasi-solar spectral region and based on an electrodeless microwave gas discharge in a sulfur-containing tube [13]. The continuous (molecular) spectrum of high-power optical radiation from a sulfur-containing lamp resembles that of the Sun, but with depressed levels of IR and UV radiation. In October 1994, the Fusion Lighting Company, Inc. (Washington, D.C.) demonstrated two efficient light systems, which attracted the attention of experts and potential consumers to new light sources, the development of which has been perceived as a very important technological breakthrough immediately before the XXI century. The first light sources based on a sulfur-containing tube were pumped by two 1.7-kW magnetrons operating in the frequency range from 915 to 2450 MHz. The best results achieved in 1996 were as follows: the light flux from a lamp was 480 km, and the light-output efficiency was 95 lm/W.
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The physical mechanism underlying the operation of sulfur-based lamps is the emission of photons in quantum transitions between the energy states of evaporated sulfur molecules that are excited or ionized by a

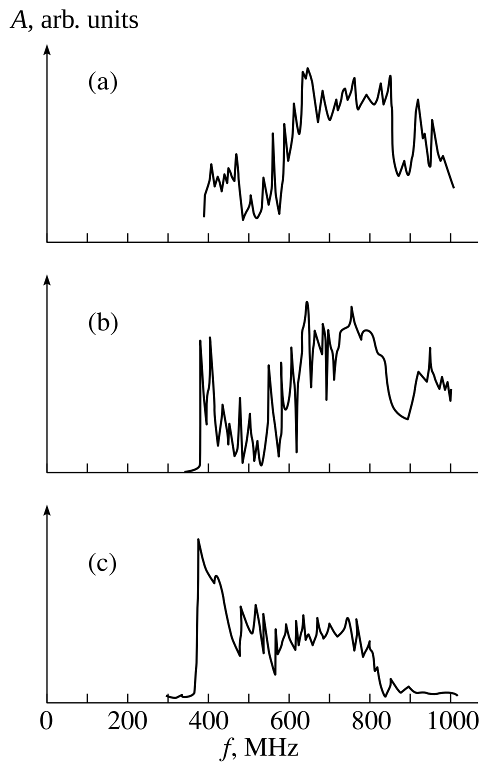

Fig. 12. Frequency spectrum of a regular signal that has passed through a cavity (a) without a plasma ($n_p = 0$) and with a plasma of density $n_p \approx$ (b) 5×10^9 and (c) 10^{10} cm^{-3}. The distance between the emitting and receiving probes is 33.5 cm.

microwave discharge within a small volume bounded by a spherical quartz shell.

The conversion of the microwave (pump) energy is into optical radiation proceeds as follows: Just after the amplitude of the electric component of the microwave field in the cavity (in the region where the sulfur lamp is placed) increases to a breakdown value, a microwave discharge is initiated in a buffer gas (argon) saturated with sulfur vapor (initially, sulfur is in a solid state). In this stage, the lamp radiates not a continuous spectrum but rather individual spectral lines corresponding to typical energy transitions in argon and sulfur atoms, including pronounced IR and UV lines. As the microwave energy is absorbed by a low-pressure discharge and as the number of ionization events increases, the plasma density increases and the bombardment of the inner shell surface (which has been coated with sulfur in the course of previous discharges) by the charge particles (primarily, by the electrons, which are the most mobile charge carriers) intensifies. During the bombardment by the charge particles (which move mainly along the microwave electric field), the shell is rapidly heated, the sulfur is partially evaporated, and the pressure increases. This process consists of two steps: the melting of different polymorphic forms of sulfur (the melting points being 112.8 and 119.3°C) and their complete evaporation (the boiling point being T_{boil} = 444.6°C); as a result, the concentration of sulfur molecules within the shell becomes fairly high. In a stable plasma operating mode (a high-power discharge), the spectrum of the resulting optical light has a molecular character: it reflects transitions between numerous energy levels, including the rotational and vibrational degrees of freedom of the molecules, and thereby is quasi-continuous. The emission spectrum possesses this property at different microwave powers and different initial amounts of sulfur in a lamp of a given size.

The main problems associated with microwave pumping are as follows (see, e.g., [14]):

(i) To choose the power of a microwave signal and its shape (continuous or amplitude-modulated).

(ii) To design a microwave transmission line from a microwave source (generator) to a load (electrodeless lamp), to construct a transmitter (whose operating regime should depend on the mode of microwave radiation), and to provide an appropriate topography of the microwave field in the region where it interacts with the working substance of the lamp (just after the generator is switched on and in the plasma operating mode).

(iii) To maintain the stable operation of the microwave generator loaded by the lamp, whose parameters change substantially during the development of a microwave discharge (from the switching on of the generator up to the beginning of the steady-state plasma operating mode).

(iv) To prevent undesirable microwave emission at the pump frequency f_w and its harmonics ($2f_w$, …, $5f_w$, …, nf_w) into the surrounding space (if only the optical light is to be intended for use) and to ensure environmental safety and electromagnetic compatibility, a closely related task being to find compromise between the optical transparency of the wall of the microwave cavity (in which microwave fields interact with the plasma) and undesirable microwave emission.

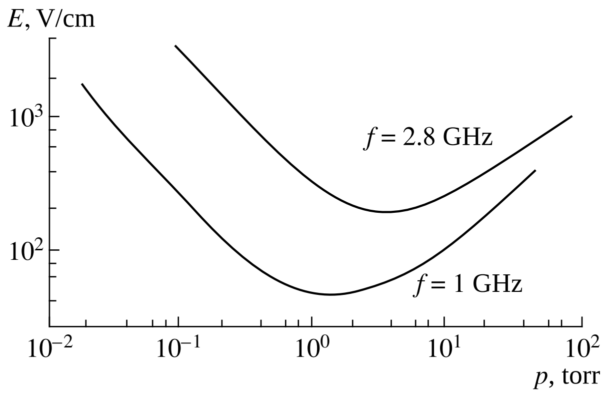

Fig. 13. Thresholds for microwave breakdown of argon (borrowed from [16]).

The underlying problem is that of choosing the microwave field frequency so as to satisfy the requirement that the input microwave power be minimum. In order to determine the working microwave frequency, it is necessary to compare three parameters: the diameter of the shell Λ ($\Lambda \approx$ 1–2 cm), the electron mean free path l, and the electron oscillation amplitude A. Discharges in argon that evaporate sulfur (which is an electronegative element) can be initiated only when the electrons will oscillate within a quartz shell, i.e., when $A < \Lambda/2$. The capture of electrons by sulfur molecules can only be balanced by intense ionization. The amplitude of the electron oscillations in a microwave field is equal to

$$A = \frac{eE_0}{m\omega\sqrt{\omega^2 + \nu_c^2}}, \tag{3.1}$$

where ν_c is the collision frequency, E_0 is the microwave field amplitude, and ω is the oscillation frequency. For $\nu_c \gg \omega$, the desired inequality is satisfied when $2eE_0/(m\nu_c\omega\Lambda) < 1$. This indicates that the boundary frequency depends on the diameter of the quartz shell, the pressure within it, and the microwave (or RF) field intensity. It is known (see, e.g., [15]) that, for all gases, the dependence of the threshold field for gas breakdown on the pressure has a minimum that separates two branches (Fig. 13). Along the left branch, the threshold field decreases with increasing pressure and the situation is as follows: the higher the field frequency and the smaller the discharge chamber, the stronger the threshold field. Along the right branch, the threshold field increases with increasing pressure and its dependence on the size of the discharge chamber and on the microwave field frequency becomes increasingly less pronounced; in the limit of high pressures, this dependence is negligibly weak and the right branches at any size of the discharge chamber and any microwave field frequency asymptotically approach a single branch.

All these results can be qualitatively explained by reference to an elementary analysis of the rate at which an electron gains energy in an alternating electric field and by using the criterion for breakdown. The ionization rate is primarily determined by the time during which the energy of an electron increases to a level slightly above the ionization energy of a gas (hereafter, we are interested in argon), I_{Ar} = 15.76 eV. In order to estimate the threshold for breakdown, we first consider discharges in argon at low pressures. In this case, the electron diffusion is very rapid and the diffusive electron losses are large. To balance them, it is necessary that the ionization rate be high, i.e., the electromagnetic field be strong. In strong fields, however, elastic collisions play an insignificant role in electron energy losses. The electron energy does not exceed I_{Ar} because an electron with such a high energy immediately losses it in ionization events. Consequently, only a limited fraction of energy is transferred from an electron to an atom per elastic collision, $(\Delta\varepsilon_{el})_{max} \approx (2m/M)I_{Ar}$. As for the amount of energy $\Delta\varepsilon_E$ gained by an electron in collisions in an alternating electric field, it is proportional to E_0^2; so, for sufficiently strong fields required to balance large diffusive losses, we have $\Delta\varepsilon_E \gg (\Delta\varepsilon_{el})_{max}$. Ignoring the energy losses in elastic collisions and assuming that the elastic collision frequency is much lower than the electromagnetic field frequency ($\nu_c \ll \omega$), we find that, in the limit of low pressures, the ionization rate in argon is approximately equal to

$$\nu_i(E_0) = \left(\frac{d\varepsilon}{dt}\right)_E \frac{1}{I_{Ar}} = \frac{e^2 E_0^2 \nu_p}{m\omega^2 I_{Ar}}, \qquad (3.2)$$

where ν_p is the transport collision frequency. In accordance with the criterion for steady breakdown, we have $\nu_i(E_0) = \nu_D = D/\Lambda^2$ (where ν_D is the collision frequency corresponding to the diffusion of electrons from a region with a characteristic size Λ and D is the diffusion coefficient). Consequently, for low pressures, the rms threshold field is equal to

$$E_{tr} = \left(\frac{Dm\omega^2 I_{Ar}}{e^2\Lambda^2\nu_p}\right)^{1/2}. \qquad (3.3)$$

For regular microwave radiation, the threshold field just obtained is directly proportional to the frequency and is inversely proportional to the gas density (pressure) and the size of the discharge region, in complete agreement with the known experimental data (see, e.g., [15]). For a field frequency of f = 1 GHz, the minimum threshold field for breakdown, E_0 = 60 V/cm, corresponds to an argon pressure of nearly 133 Pa. It should be noted that the microwave range is preferable from the standpoint of minimizing the breakdown field. It is, however, inexpedient to further increase the field frequency because the electron mean free path satisfies the relationship $A\omega$. Indeed, for low pressures, we have $A \propto 1/\omega^2$, so the electron mean free path decreases with frequency. It is clear that the discharge should be initiated over the entire volume within the shell. This can be done when the penetration depth δ of the microwave field into the plasma is comparable to the shell radius Λ. The depth to which microwaves penetrate into a conducting plasma is equal to $\delta = c/\sqrt{2\pi\sigma\omega} \geq \Lambda$, where σ is the plasma conductivity.

An important task is to determine the power of a microwave generator that is required to initiate a discharge in a buffer gas and then to maintain it in a plasma after the evaporation and ionization of sulfur.

Recall that, for microwave discharges in regular electromagnetic fields, the threshold field is minimum when the collision frequency is equal to the electromagnetic field frequency (see, e.g., [15]). Thus, at a frequency of $f \approx 3.0$ GHz, the minimum threshold field for breakdown of Ar at a pressure of about 650 Pa is 500 V/cm. Such field strengths can be achieved in a cavity in which one of the walls is transparent to light. In the situation under analysis, the electric field amplitude E_Q is proportional to $\sqrt{100P(W)Q}$, where $P(W)$ is the generator power in watts, and Q is the quality factor of the cavity. It follows from this that, for Q = 100, the microwave power should be 25 W. The effective amplitude of the alternating electric field, E_{eff}, which should exceed the threshold field E_{th}, is smaller than E_0:

$$E_{eff} = \frac{E_0}{\sqrt{2}} \frac{\nu_c}{\sqrt{\nu_c^2 + \omega^2}}. \qquad (3.4)$$

Hence, in order to excite a plasma by regular microwaves, the power of the generator should be about 100 W.

In the present paper, we propose to initiate microwave discharges in argon containing sulfur vapor by microwaves with a stochastically jumping phase. The advantages of this method are as follows:

(i) such microwaves are capable of initiating discharges at lower gas pressures because the jumping phase slows electron diffusion,

(ii) the jumps in the phase ensure that the collisionless electron heating is not accompanied by energy losses in elastic and inelastic collisions, and

(iii) a uniform microwave discharge is easy to initiate because microwaves with a stochastically jumping phase can deeper penetrate into an overcritical plasma.

A discharge excited in argon heats the quartz shell, leading to the evaporation of sulfur and producing a sulfur-containing argon plasma. The luminescence of argon is then followed by the light emissions from the polymorphous sulfur, whose spectral properties have much in common with those of solar radiation. The pressure of sulfur vapor is determined by the amount of sulfur within the quartz shell. Usually, sulfur concentrations of about 2–5 mg/cm^3 are sufficient.

The field required to maintain a discharge in a plasma is far weaker than that needed for gas breakdown. The amplitude E_d of the maintaining field is related to the plasma electron temperature by the relationships

$$\sqrt{\frac{k_B T_e}{I_{\mathrm{Ar}}}}\exp\left(\frac{I_{\mathrm{Ar}}}{k_B T_e}\right) = \mathrm{const}(pR)^2 = 1.27\times10^7 c_T^2 (pR)^2, \quad (3.5)$$

$$E_d = \frac{m}{e}\sqrt{\frac{3k_B T_e}{M}(\omega^2+\nu_c^2)},$$

where R is the radius of the discharge channel and M is the atomic mass of the gas. The value of the constant c_T depends on the sort of gas; for instance, for argon, we have $c_T = 4–10^2$. The channel radius is $R \sim 1$ cm; therefore, for a pressure of nearly 100 Pa, the electron temperature (which decreases with increasing pressure) is equal to $T_e = 3 \times 10^4$ K. Let us substitute this value of T_e into the expression for E_d.

For $\nu_c \ll \omega$, the maintaining field amplitude E_d is equal to

$$E_d = \frac{m\omega}{e}\sqrt{\frac{3k_B T_e}{M}} = \frac{2\pi mc^2}{e\lambda}\sqrt{\frac{3k_B T_e}{Mc^2}}. \quad (3.6)$$

For molecular sulfur (Mc^2 = 50 GeV), we have $E_d \sim$ 0.4 V/cm. The field E_d increases with ν_c and reaches a level of 1–2 V/cm when ν_c becomes higher than ω. It should be taken into account, however, that the electron temperature T_e decreases with increasing ν_c. Note also that formula (3.6) is valid only for elastic collisions. To maintain a discharge in a plasma in which inelastic collisions play an important role, the field E_d should be raised by approximately one order of magnitude.

Let us now consider the conditions for breakdown in argon by microwave radiation from the generator described in [9]. The working frequency of this generator is 400 MHz, the mean rate of the phase jumps being $\nu_{jp} = 2 \times 10^8$ s^{-1}. It is important to keep in mind that, when the electron energy increases from zero to the ionization energy I_{Ar}, the cross section for elastic collisions of electrons with argon atoms varies greatly (by a factor of about 30), being at its maximum several times larger than the ionization cross section corresponding to electron energies of 15–20 eV. This makes it possible to initiate discharges in argon by microwaves with a stochastically jumping phase at pressures as low as 4 Pa. In this case, the mean rate of phase jumps is equal to the maximum elastic collision frequency, which corresponds to electron energies close to the ionization energy. Operation under such conditions is advantageous in that, first, no energy is lost in elastic collisions, and second, due to the jumps in the phase, the electron diffusion remains insignificant and the electromagnetic energy is efficiently transferred to electrons. Considering the effective rate of the phase jumps as the transport collision frequency ν_p and substituting it into expression (3.3), we find that, in the case at hand, the required threshold field does not exceed 50 V/cm, which agrees well with the results of preliminary experiments on determining the threshold electric field of microwave radiation with a stochastically jumping phase.

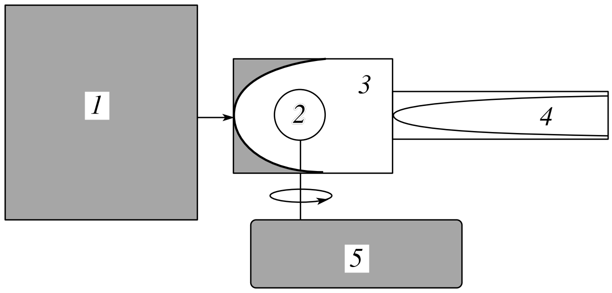

Fig. 14. Block diagram of a microwave-discharge-based light source: (*1*) power supply unit, high-power microwave generator, and matching system; (*2*) quartz shell filled with an Ar–S gas mixture; (*3*) microwave cavity and light output system; (4) lightguides; and (5) system for rotation and forced cooling of the quartz shell.

We thus have estimated the electric field required to initiate and maintain a discharge in a shell containing an Ar–S mixture.

Our numerical simulations and preliminary experiments shows that, in order to initiate a microwave discharge at a frequency of 450 MHz in argon at a pressure of 4 Pa, the microwave electric field strength should be about 50 V/cm, whereas sulfur vapor can be excited by an electric field of 25 V/cm, which can easily be achieved with an input power of several hundred watts, even without using discharge chambers equipped with microwave cavities. With the use of such chambers, it is possible to substantially reduce the generator power. The block diagram of a microwave-discharge-based source of visible light is shown in Fig. 14 (which is borrowed from [16]).

In a sulfur-based light system (SLS) demonstrated by the Fusion Lighting Company, Inc., the shell is placed within a chamber that is opaque to microwaves but is transparent to visible light. The working microwave frequency of this system, 450 ± 50 MHz, is consistent with standards adopted for industrial, scientific, and medical applications. With the version of the light system proposed by the company, it becomes possible to design compact low-power SLSs, in addition to the already existing traditional SLSs with output powers in the kilowatts range [13, 14, 16], which are usually based on 2450 ± 50-MHz magnetrons. The systems for rotation and forced cooling of the shell ensure such thermal regime that does not destroy the quartz shell filled with an Ar–S gas mixture. Inside the microwave chamber, the shell rotates at a rate of 600 rpm. Technologically, the engineering design of the device in question should ensure maximum light yields from a cavity utilizing harmless microwave radiation consistent with the adopted standards. Experts from the Fusion Lighting Company, Inc., propose to fabricate cavities from grids and additional mesh screens. An important role in the system proposed by the company is played by a parabolic reflector and a prism lightguide. The practical role of the parabolic reflector is to ensure that light is emitted into a hollow prismatic lightguide. The shell is inserted into the cavity positioned at the focus of the parabolic reflector. A specially devised array of lightguides serves as an efficient means to transmit light to consumers. This technology makes it possible to use lightguides whose surfaces partially reflect light and partially transmit it to form a required distribution of the output light intensity. The parameters of the lightguides are as follows: they are acrylic, and their walls are as thick as 3 mm, the outer diameter and length being 250 mm and 28 m, respectively.

Such light sources make it possible to obtain considerable (multifold) energy saving, while simultaneously increasing the level of illumination. They are demonstrated in the American Museum of Astronautics.

4. CONCLUSIONS

New types of beam–plasma generators of intense stochastic microwave radiation were developed and put into operation at the National Science Center Kharkov Institute of Physics and Technology (Ukraine). In the present paper, we have discussed the results of theoretical and experimental studies and numerical simulations of the normal and oblique incidence of linearly polarized electromagnetic waves on an interface between a vacuum and an overcritical plasma. The main results of our investigations are as follows: (i) for the parameter values under consideration, the transmission coefficient for microwaves with a stochastically jumping phase is found to be one order of magnitude greater than that for a broadband wave with the same spectral density; (ii) the electrons are shown to be heated most efficiently by obliquely incident waves with a stochastically jumping phase and, in addition, the electron distribution function has a high-energy tail; and (iii) necessary conditions for gas breakdown and for the maintenance of a microwave discharge in stochastic fields in a light source have been determined. The anomalously large transmission coefficient for microwaves, the anomalous character of the breakdown conditions, the anomalous behavior of microwave gas discharges, and the anomalous nature of collisionless electron heating have been attributed to stochastic jumps in the phase of microwave radiation.

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