OPTICAL RADIATION SPECIAL FEATURES FROM PLASMA OF LOW PRESSURE DISCHARGE INITIATED BY MICROWAVE RADIATION WITH STOCHASTIC JUMPING PHASE

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We study the plasma discharge, initiated by microwave radiation with stochastically jumping phase (MWRSJP) in a coaxial waveguide at the optimal mode of the beam-plasma generator. Present results continue the line of the previous research. In this paper we experimentally examine the optical characteristics of the discharge plasma in a wide range of both an air pressure and microwave radiation power. In general the research aims to develop a new type of sources of optical radiation.

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INTRODUCTION

High-frequency (HF) heating is very important field in connection with fundamental questions of plasma physics and applications. This area of physics is intensively investigated as theoretically and experimentally (for example, see [1 - 3] and references therein). The issues widely discussed in literature are connected with additional plasma heating in tokamaks [1], the nature of accelerated particles in space plasmas, gas discharge physics [2, 3]. Among the problems that attract attention of scientific community is development of sources with solar spectrum. This is utmost important problem from the point of fundamental, as well as practical application, and in this direction interesting achievements is obtained (see, for example [3]). It is worth mentioning that one of the difficulties associated with additional plasma heating in tokamaks is a well-known dependence of the Rutherford cross-section on velocity. As a consequence, the probability of collisions decreases with plasma temperature rising, thus creating obstacles for further plasma heating. Another important challenge in interaction of HF radiation with plasma is a barrier of the radiation penetration into the overdense plasma. To our knowledge, the most part of investigations in this direction are made with help of HF generators of electromagnetic radiation with regular phase. Thus the new opportunities that microwave radiation with jumping phase provides in this area would be very important.

In this paper, we describe results of the theoretical and experimental investigation of the plasma interaction with microwave radiation with jumping phase that obtained with help of the unique beam-plasma generator (BPG) made in KIPT [4]. This study continues research on behaviour of plasma discharge subjected to microwave radiation with stochastically jumping phase (MWRSJP) which started in [5, 6]. The paper is organized as follows. The first section contains introduction and brief review of previous research. In section 2, we consider experimental parameters of MWRSJP obtained from the BPG. The scheme of measurement of various parameters is given and experimental studies of optical radiation from the plasma discharge initiated by MWRSJP are presented. The illustrative simulation re-sults are presented graphically. Concluding remarks fol-low at the end.

It was shown in [7], both theoretically and experimentally, that the phenomenon of anomalous penetration of microwave radiation into plasma, conditions for gas breakdown and maintenance of a microwave gas discharge, and collisionless electron heating in a microwave field are related to jumps of the phase of microwave radiation. In this case, in spite of the absence of pair collisions or synchronism between plasma particles and the propagating electromagnetic field, stochastic microwave fields exchange their energy with charged particles. In such fields, random phase jumps of microwave oscillations play the role of collisions and the average energy acquired by a particle over the field period is proportional to the frequency of phase jumps.

Gas breakdown and maintenance of a discharge in a rarefied gas by a pulsed MWRSJP were studied theoretically and experimentally in [8], as well as propagation of this radiation within the plasma produced in such a way. The conditions for ignition and maintenance of a microwave discharge in air by MWRSJP were found. The pressure range in which the power required for discharge ignition and its maintenance has its minimum was determined [7, 8]. It was shown that, in the interval of pressures that have a level less than optimal (about 50 Pa for argon), the minimum of MWRSJP breakdown power depends weakly on the working gas pressure owing to several reasons. These reasons are efficient collisionless electron heating, weakening of diffusion and, finally, decrease of elastic and inelastic collisional losses. This allows one to extend the domain of discharge existence toward lower pressures. The intensity of collisionless electron heating increases with increasing rate of phase jumps in MWRSJP. There is an optimal phase jump rate at which the rate of gas ionization and, accordingly, the growth rate of the electron and ion densities reach their maximum. The optimal phase jump rate is equal to the ionization frequency at electron energies close to the ionization energy of the working gas.

In the present work, the effect of high power pulsed decimeter MWRSJP action on a plasma, produced in a coaxial waveguide filled with a rarefied gas, is investigated with use of the above mentioned BPG [4], which was upgraded for the given experimental conditions. The goal of this work is to study the special features of low pressure discharge initiated by MWRSJP und also optical radiation spectra. For interpretation of the experimental results on the ignition and maintenance of a microwave discharge in air obtained with MWRSJP BPG, a numerical code has been developed. This code allows simulating the process of gas ionization by electrons heated in the MWRSJP field and studying the behaviour of plasma particles in such a field.

1. EXPERIMENTAL STUDIES

1.1. MWRSJP PARAMETERS OBTAINED FROM THE BPG, AND THE SCHEME OF THEIR MEASUREMENTS

We study MWRSJP parameters and optical radiation characteristics from the plasma discharge of induced by MWRSJP in a gas (air for the present case), taken at low pressure. To conduct experiments, a coaxial waveguide with axial vacuum pumping is connected to the BPG. Coaxial waveguide filled with gas with impedance of about 75 Ohms and a length of 1000 mm is made of brass pipes with inner diameter of 45 mm and external diameter of 50 mm (Fig. 1).

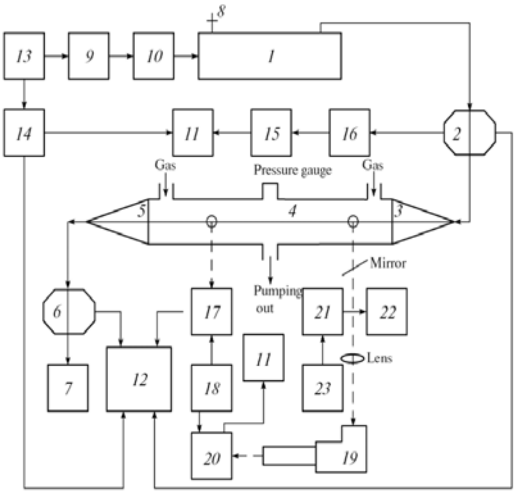


Fig. 1. Block diagram of measurement of BPG and plasma principal parameters

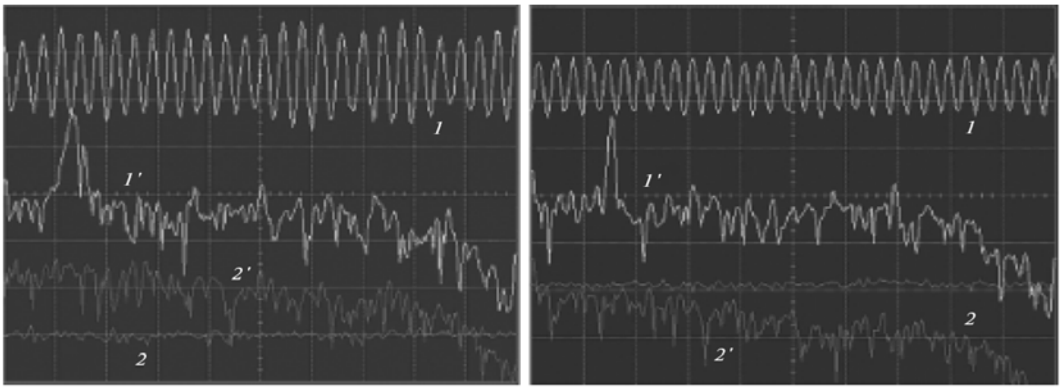
The central conductor is a brass rod diameter of 12 mm. At the ends of the coaxial waveguide, tapered flanges provide the joining of coaxial transitions. In the middle of the coaxial waveguide a tube is installed to pump gas or gas mixtures, which also mounted a thermocouple tube to monitor the pressure of the gas. Admission process of gases or gas mixtures is carried out with sufficient precision using the second inlet valve through diametrically located holes 2 mm in diameter that are situated at both ends of the coaxial waveguide. Tubes for the introduction of diagnostic probes are located along the length of the coaxial waveguide. The first tube is located at 60 mm from the input microwave power of stochastic electromagnetic waves; the second one is placed at a distance of 260 mm and a third – at 840 mm. During the working process, such arrangement of instruments allows us to have controlled diagnostic probes of a spatial distribution, as well as to monitor parameters of the microwave discharge along throughout the waveguide length. This provides more detailed information about processes that take place inside the waveguide. The block diagram shown in Fig. 1 schematically represents measurements of the main parameters of the BPG and of the plasma, which is produced in the coaxial waveguide. Stochastic microwave oscillations generated by the BPG (1) were supplied from the output of the slow-wave structure through a broadband directional coupler (2) and 75-Ω conical coaxial junction (3) to the input of the coaxial waveguide (4) and then, through a conical coaxial junction (5) and coupler (6), were fed to an IBM-2 high power gauge (7).

For operating in the regime of narrow-band signal generation the input of the BPG slow-wave structure was attached to a shorting plug (8). The oscilloscopes (11, 12) and the submodulator (9) and modulator (10) of the high voltage supplied to the cathode of the BPG electron gun were triggered synchronously by using a timing unit (13). A time-delay circuit (14) was used to vary the instant of triggering the oscilloscopes with respect to the beginning of the high voltage pulse. This allowed us to observe the shape of the generated signal at different instants after the beginning of the electron beam pulse. A detector head (15) and D2-13 variable resistive-capacitive attenuator (16) connected to the secondary line of the coupler (2) were used to measure the envelope of microwave oscillations and the waveforms of the electron beam pulse. The temporal realizations and spectral characteristics of MWRSJP at the input and output of the coaxial waveguide were studied using an HP Agilent Infinium four-channel broadband (2.25 GHz) oscilloscope (12). A PEM-29 photomultiplier (17) powered from a VSV-2 high-voltage stabilized rectifier (18) was used to measure the integral intensity of optical radiation from the plasma. An ISP-51 three-prism glass spectrograph (19) and PEM-106 photomultiplier (20) were used for optical spectroscopy of the discharge in the coaxial waveguide.

Ignition of the discharge does not affect the penetration into dense plasma of MWRSJP what is evidenced by nearly constant amplitude at the entrance to the waveguide (curves 1 in Fig. 2). Because of expenditures of radiation energy on air ionization for the discharge maintenance the MWRSJP amplitude at the output of the coaxial waveguide (see curves 2 in Fig. 2) is essential diminished. It is also important that the MWRSJP local spectrum on the output waveguide significantly changed (see curves 2′ in Fig. 2), a peak associated with the main spectral component of MWRSJP is absent. It should be noted that in the pressure range from P = 30 to P = 2 Pa at a MWRSJP power that conforming to the optimal operating mode of BPG a similar situation is observed.

The optimal operating mode of BPG corresponds to the following parameters: magnetic induction in the interaction range of the beam with slow-wave structure in BPG is B =0.096 T, a high voltage is U_{opt} = 13.2 kV, the current electron gun is I_b= 3…5 A, high-voltage pulse is 160 μs, MWRSJP power is W = 36 kW, the pulse repetition frequency is 5 Hz.

The results presented in Fig. 2 shows that, as the spectrum of the micro-wave signal used to initiate and maintain a steady-state discharge is narrowed, the amplitude of the MWRSJP electric field can be decreased by nearly a factor of 2.



a *b*

Fig. 2. Waveforms of MWRSJP at the (1) input and (2) output of the coaxial waveguide, respectively, and local microwave spectra on a logarithmic scale (10 dB/div) at the (1') input and (2') output of the coaxial waveguide, respectively. The gas pressure in the waveguide is P = (a) 2.0 and (b) 30 Pa, respectively. The time scale is 5 ns/div, and the voltage scale is 100 (V·cm⁻¹)/div

However, in order for the pressure range in which breakdown occurs and a steady-state discharge exists to be sufficiently broad, it is necessary that the phase jump frequency be suffi-ciently high (as will be seen below, it should be about one-third of the microwave frequency).

Let us now analyze the measured characteristics of MWRSJP at the input and output of the coaxial waveguide in the optimal BPG mode. The oscillograms shown in Fig. 2 were processed by the method of correlation analysis, and the frequency spectra, the time dependence of the phase of microwave oscillations, and self-correlation functions were determined. It was shown that gas breakdown takes place only after the electric field amplitude of MWRSJP reaches a certain critical value, which depends on the gas pressure. The instant of discharge ignition can be easily determined from the abrupt decrease in the amplitude of the microwave signal at the output of the coaxial waveguide to almost zero. It can also be seen that the electric field amplitude required to maintain a steady-state discharge is one order of magnitude lower than that required for breakdown. From Fig. 2 it can be seen that, MWRSJP amplitude at the waveguide outlet is reduced substantially (more than an order of magnitude) due to the development of the discharge and also the discharge ignition and maintenance lead at the waveguide outlet to a strong damping of the spectral components, which are corresponded to the maximum range of input signal into the waveguide.

Let us now consider the conditions for breakdown in air by microwave radiation from the BPG described in [4]. In optimal regime at narrowband signal of this generator the working frequency is 500 MHz, the mean rate of the phase jumps being $\nu_{jp} = 2\times10^{8}$ s^{-1}. It is important to keep in mind that, when the electron energy increases from zero to the ionization energy I_{air}, the cross section for elastic collisions of electrons with air atoms and molecules 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 air 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 inelastic 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.

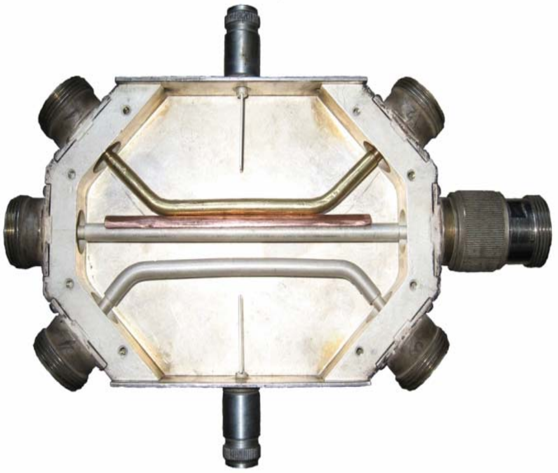


Fig. 3. The general view of the coupler (6) internal structure

To determine the dependence of the threshold power, required for ignition of the discharge in a coaxial waveguide, on the pressure of working gas, BPG has worked in the mode of generating the maximum output power level of narrow-band signal in which the generation of microwave radiation with a maximum frequency of phase jumps occurs. In this case part of the power with the help of a broadband directional coupler with variable coupling (Fig. 3) was supplied to analyezed gas-filled coaxial waveguide. The rest of the power assigned to the matched load. Such a method of regulating the power delivered to the coaxial waveguide for ignition of the discharge allows conserving the permanent parameters of microwave radiation. In particular, this concerns the mean rate of the phase jumps and the energy spectrum density of MWRSJP, because in this situation BPG works in the same mode.

In Fig. 3 the general view of the coupler (6) internal structure is shown.

While conducting experiments, to determine the dependence of the threshold power on the gas pressure, the left center coax transition coupler was connected to BPG, the lower left coax transition joined the coaxial waveguide, the right central and the lower coaxial transitions were connected to the load. By changing the bond between the central and the lower shoulders of the coupler through the use of different linked curved shoulders, we adjusted the peak power coming into the coaxial waveguide from 6 to 28 kW. Fig. 6 shows the dependence of peak power required for the discharge ignition in the air that filled coaxial waveguide on its pressure.

From Fig. 4 (curves 1, 2) it can be seen that, the peak power levels from 6 to 28 kW MWRSJP discharge is ignited stably at a pressure of gas (air) ranging from 1.5 to 3990 Pa. This result clearly demonstrates the advantages of the discharge, supported by microwave with stochastic jumps in the phase compared with the microwave discharge in the fields of regular waves.

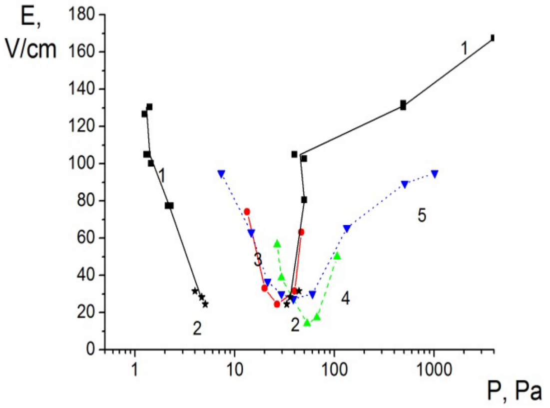


*Fig. 4. Dependences for breakdown electric field strength of a microwave narrowband signals with a stochastically jumping phase versus a pressure for air in the optimal BPG mode (curves 1 – ■; 2 – *), in the non-optimal BPG mode: for air (curve 3 – •), argon (curve 4 – ▲), helium (curve 5 – ▼), respectively*

Thus we have the opportunity to create a discharge at a pressure of almost two orders of magnitude lower than the pressure that is necessary for the fulfillment of the condition of minimum capacity of the discharge ignition by regular microwave radiation. Namely, (see [20]) for $\nu_{col} \approx \omega$ (where ν_{col} is the frequency of binary collisions, as well ω is the frequency of microwave radiation), effectiveness of such a discharge is much higher because of the small contribution of energy loss on unnecessary elastic and inelastic collisions when working at low pressures. For comparison, dependence of microwave radiation power required for the discharge ignition in air (curve 3), argon (curve 4) and helium (curve 5), which are filled the coaxial waveguide, on its pressure, obtained while working in the non-optimal BPG mode is given. It is seen that the pressure range in which it is possible the ignition of the discharge is much narrower than under the optimal BPG mode functioning. This is due to a significant difference in mean rates of the phase jumps in these modes of BPG.

Using the delay device (14), the time for start of the oscilloscope can be modified within the length of high-voltage pulse. This circumstance allows us to observe the shape of the generated signal at a different time moments starting from the very begin of the electron beam current pulse. Features MWRSJP at the inlet and outlet of the coaxial waveguide are studied using the four-channel broadband (2.25 GHz) oscilloscope (12) HP Agilent Infinium Oscilloscope. In the next part we present the results of experimental studies of optical characteristics of plasma discharge. Preliminary results of an optical characteristic studies presented in [8].

1.2. EXPERIMENTAL STUDIES OF OPTICAL RADIATION FROM THE PLASMA DISCHARGE INITIATED BY MWRSJP

Optical characteristics of plasma discharge initiated by MWRSJP in coaxial waveguide are examined in the conditions of BPG operation in the optimal mode in air for a wide pressure range, in which the discharge is ignited and maintained stably. For spectroscopic studies of the discharge in the visible spectrum a monochromator (19) MDR-1 is used. With help of the lens, the radiation from the discharge is focused onto the entrance slit (slit width is 0.01 mm) of the spectrograph. By the output gap with width of 0.015 mm the spectrograph is attached to the photoelectron multiplier (20) of type PEM-106. The photomultiplier PEM-106 has high spectral sensitivity in the wavelength range from 350 to 550 nm. Within zone from 550 nm to 1000 nm the sensitivity is less that will lead to distortion of the discharge optical spectra which are observed on oscilloscope (11). This fact should be taken into account when the wave forms of the emission spectra are analyzed. The signal from the photomultiplier PEM-106 was fed to the digital (2 GB/s) oscilloscope (11) Le Croy Wave Jet 324 with a frequency band of 200 MHz. The ISP-51 spectrograph was calibrated using the spectral lines of a PRK-2M mercury lamp (21) and the Balmer hydrogen lines emitted by a Geissler tube (22). The mercury lamp and the Geissler tube were powered from an OU-1 lighting unit (23).

The MWRSJP power was input via the conical coaxial junction in the waveguide pumped out to a pressure of 1.33 Pa. In certain ranges of the gas pressure, gas composition, and microwave power, a discharge was ignited in the coaxial waveguide.

Remark, that in the consequent Figs. 5-8, which presents radiation spectra from the low-pressure discharge, the real dependence of the spectral sensitivity of the photomultiplier is taken into account, and for the simplicity of comparison the same arbitrary units are used. For the necessary observations, apertures were drilled with a diameter 2.5 mm on the lateral surface of the coaxial waveguide in the area of the curved quartz optical window. On the one hand, these apertures provide properly output of the light radiation from a coaxial waveguide and, on the other hand, they prevent output of the microwave radiation from the discharge region. It is seen that the discharge radiation intensity decreases along the waveguide.

In Figs. 5-8 the dependence of optical radiation from the discharge on air pressure is compared at the conditions when a stable regime of the gas discharge is held at the MWRSJP power that correspond the optimal BPG mode. It should be noted that the discharge color depends on the working gas pressure and the microwave power input in the waveguide.

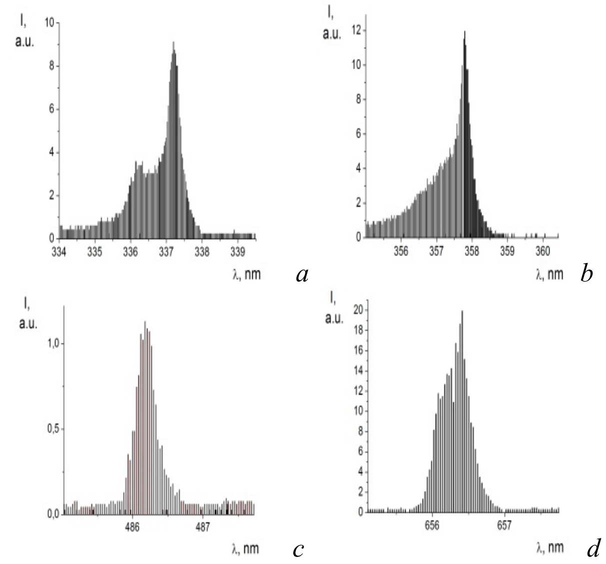


Fig. 5. The emission spectra of discharges in air for a wavelength of 337 nm (a), for a wavelength of 357 nm (b), for a wavelength of 486 nm (c), for a wavelength of 656.3 nm (d) at a pressure P = 28 Pa and the MWRSJP power 18 kW

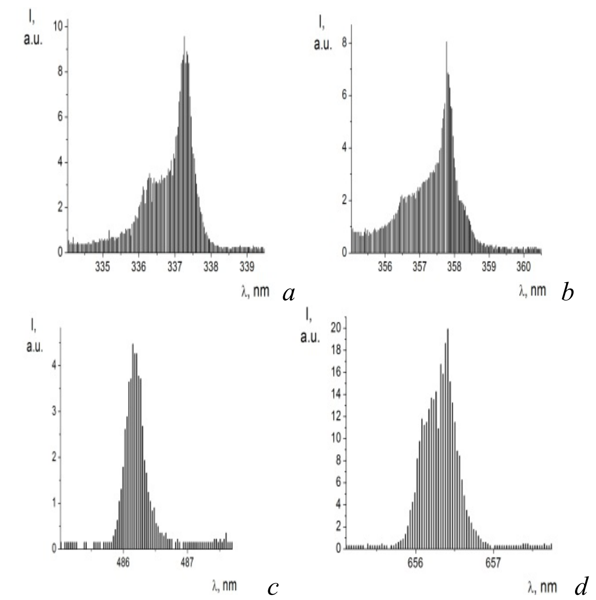


Fig. 6. The emission spectra of discharges in air for a wavelength of 337 nm (a), for a wavelength of 357 nm (b), for a wavelength of 486 nm (c) for a wavelength of 656.3 nm (d) at a pressure P = 4.8 Pa and the MWRSJP power 18 kW

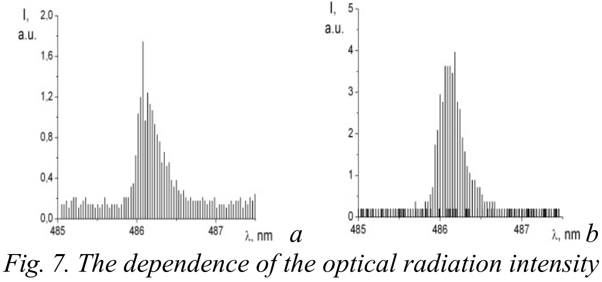


Fig. 7. The dependence of the optical radiation intensity in air vs power for a wavelength of 337,2 nm at P = 4 Pa at the MWRSJP power 5 kW (a) and 16 kW (b)

Figs. 5-7 show that the spectrum of optical radiation intensities of optical radiation for four specific wave lengths) from the discharge depends strongly on the pressure of the working gas (air) and MWRSJP power in a coaxial waveguide. In particular, within the lower range of air pressure, the optical radiation from the discharge is pronouncedly enriched with shorter wavelengths. In this way, if value of pressure is P_1 = 28 Pa then spectrum is depleted at the wavelengths shorter than 600 nm, i.e. red radiation prevails, see Fig. 5. At the same time, when the pressure is reduced nearly an order of magnitude, see Fig. 6 a spectrum becomes significantly enriched with short wavelengths, i.e. blue light prevails. Further Fig. 7 represent the experimental studies of the dependence of the optical radiation intensity in air versus a power for a wavelength of 337,2 nm at P=4 Pa and the MWRSJP power 5 kW (a) and 16 kW (b). It can see that the optical radiation intensity increase at magnify of MWRSJP peak power.

One can observe that the optical emission starts with a delay relatively to the beginning of current pulse however, duration of the optical emission exceeds the duration of the high voltage pulse. From Fig. 8 it is seen that the discharge plasma optical emission is sufficiently stable in time.

Thus, relying on the quantitative indicators of the electric field intensity, frequency MWRSJP and frequency of phase jumps, etc., the prospect of creating a source of light radiation of low power (100 W) is implemented. It is based on the consideration of a stochastic microwave discharge with high efficience at low pressure of working gas.

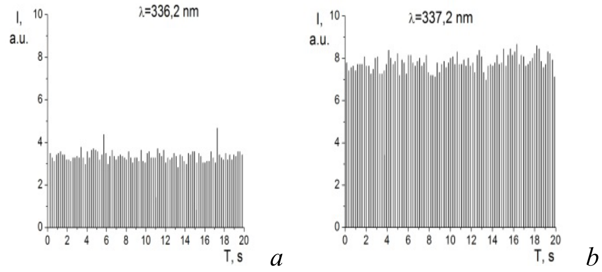


Fig. 8. The dependence of the optical radiation intensity versus time for a wavelength of 336 nm (a) and a wavelength of 337,2 nm (b) at air pressure P = 4.8 Pa and the MWRSJP power W = 18 kW

CONCLUSIONS

At the stage of discharge in the coaxial waveguide, the discharge becomes nonuniform along its length due to the strong absorption of MWRSJP. The electric field amplitude decreases by more than one order when approaching to the waveguide exit.

During the maintenance of MWRSJP discharge in the waveguide, gas ionization leads to almost complete decay in the spectrum of the output signal from the coaxial waveguide of the main spectral components of the input microwave signal.

With the distance increasing from the input of MWRSJP into the coaxial waveguide, the discharge optical radiation intensity decreases significantly, becoming inhomogeneous.

With air pressure decreasing, the optical radiation from the discharge becomes more reach with shorter-wavelength. Thus, if at the pressure of 20 Pa, the radiation has red colour, then at pressure of 2 Pa the radiation becomes blue.

MWRSJP and discharge optical radiation are observed in time almost throughout the pulse duration of electron beam current in BPG.

When the frequency of MWRSJP signal and the frequency of phase jumps are those as observed in the conducted investigations, there is enough to have the magnitude of electric field equals to 50 V/cm, for the creation and maintainence of the discharge in air.

Thus, based on the quantitative indicators, such as the electric field intensity, frequencies of MWRSJP and phase jumps it can be expected the following. The prospective creation of an efficient light radiation source of low power (100 W) in a wide range of air pressure, in which the discharge is ignited and maintained stably, becomes a reality. The main task of future experimental and theoretical research is to optimize the gas mixture for the discharge of quasi-solar optical spectrum.

The results might also be of some use in connection with additional plasma heating in nuclear fusion devices due the fact that, the electron heating by microwave radiation with jumping phase is collisionless. Thus the heating efficiency by MWRSJP does not decreas when the temperature increases, whereas the usual heating by the regular radiation is to be collisional and becomes less and less efficient at increasing temperature. Moreover, instead of pulse working regime of BPG, the constant working regime which is important for tokamak plasma, in principle may be elaborated.

The developing of a new type of the high efficiency sources of optical radiation with quasi solar spectrum would make a fundamental breakthrough in lighting technology.

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ОСОБЕННОСТИ ОПТИЧЕСКОГО ИЗЛУЧЕНИЯ ИЗ ПЛАЗМЫ РАЗРЯДА НИЗКОГО ДАВЛЕНИЯ, ИНИЦИИРОВАНОГО МИКРОВОЛНОВЫМ ИЗЛУЧЕНИЕМ СО СТОХАСТИЧЕСКИ ПРЫГАЮЩЕЙ ФАЗОЙ

В.И. Карась, А.Ф. Алисов, О.В. Болотов, В.И. Голота, И.В. Карась, А.М. Егоров, А.Г. Загородний, И.А. Загребельный, И.Ф. Потапенко

Изучается плазма разряда, инициируемого микроволновым излучением, со стохастически прыгающей фазой в коаксиальном волноводе в оптимальном режиме пучково-плазменного генератора. Представленные результаты являются продолжением ранее проведенных исследований. Экспериментально исследовались оптические характеристики разрядной плазмы в широкой области давлений воздуха и мощности микроволнового излучения. Цель исследования – развитие нового типа источника оптического излучения.

ОСОБЛИВОСТІ ОПТИЧНОГО ВИПРОМІНЮВАННЯ З ПЛАЗМИ РОЗРЯДУ НИЗЬКОГО ТИСКУ, ІНІЦІЙОВАНОГО МІКРОХВИЛЬОВИМ ВИПРОМІНЕННЯМ ЗІ СТОХАСТИЧНО СТРИБКОВОЮ ФАЗОЮ

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Вивчається плазма розряду, ініційованого мікрохвильовим випромінюванням, зі стохастично стрибковою фазою в коаксіальному хвилеводі в оптимальному режимі пучково-плазмового генератора. Наведені результати є продовженням раніше проведених досліджень. Експериментально досліджувались оптичні характеристики розрядної плазми в широкій області тисків повітря та потужності мікрохвильового випромінювання. Метою дослідження є розвиток нового типу джерела оптичного випромінювання.