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Ionization wave in air under the action of powerful radiation of the terahertz frequency range

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Abstract. Sub-terahertz and terahertz frequency ranges remain the least studied from the point of view of gas discharge physics. Investigation of terahertz gas discharge, sustained by the powerful focused beams of the electromagnetic radiation, has become possible recently due to the development of the powerful sources in this range (FELs and gyrotrons) and is of interest both from a fundamental research and from possible applications. This work presents the results of the studies of the discharge propagation under the action of the focused beam of sub-terahertz (250 GHz) gyrotron. The discharge propagation velocity towards electromagnetic radiation was measured in air in the wide pressure range (0.01 − 1 atm). The focusing system provided the size of the focal spot of (2−3)·λ, which ensured the investigation of discharge phenomena in a wide pressure range. The optical glow of the discharge was recorded with the help of a speed camera. The discharge appeared in the focal spot spread towards heating radiation into the area with the field intensity much less than one in the focal spot. Velocity of the discharge propagation was measured by using photos from speed camera with small exposure (down to 20 ns). It was demonstrated that discharge velocity increase along with pressure decrease and drops with electric field decrease as it moves away from the focal spot.

Keywords: terahertz radiation, gas discharge, discharge propagation

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Материалы конференции
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Волна ионизации в воздухе под действием мощного излучения терагерцового диапазона частот

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Аннотация. В работе представлены результаты исследований распространения разряда под действием сфокусированного пучка субтерагерцового (250 ГГц) гиротрона. Скорость распространения разряда навстречу электромагнитному излучению измерялась в воздухе в широком диапазоне давлений (0.01–1 атм). Система фокусировки обеспечивала размер фокального пятна (2–3)·λ, что обеспечивало исследование разрядных явлений в широком диапазоне давлений. Оптическое свечение разряда фиксировалось с помощью камеры контроля скорости. Разряд возникал в фокальном пятне, распространяясь навстречу греющему излучению в область с напряженностью поля, много меньшей, чем в фокальном пятне. Скорость распространения разряда измерялась по фотографиям с камеры контроля скорости с малой экспозицией (до 20 нс). Показано, что скорость разряда увеличивается с уменьшением давления, а падение электрического поля уменьшается по мере его удаления от фокального пятна.

Ключевые слова: терагерцовое излучение, газовый разряд, распространение разряда

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Introduction

This work is devoted to an experimental study of the propagation of a gas discharge in focused beams of electromagnetic waves of the sub-terahertz band. The discharge propagation in the wave fields is quite well studied at optical and microwave frequencies. It was observed in one of the very first works devoted to the laser spark in gases [1]. It was found that the propagation of the discharge has much in common with the combustion process [2]. As indicated in work 2, the physical reason for this analogy is rooted in the similar nature of the temperature dependence of the main factors that determine the rate of energy release in matter in both cases – the rate of a chemical reaction during combustion and the degree of gas ionization in discharge phenomena. At sufficiently large values of the fields, the propagation, as a rule, has a detonation character. In the case when the field in the beam is less than the breakdown field (when the initial plasma is created by an external source), the discharge can propagate according to the slow combustion principle [2]: thermal ionization of the gas occurs, and heat transfer from the discharge front occurs due to thermal conductivity.

Studies of the propagation of a discharge sustained by microwave radiation were carried out mainly in air [3–7], as a rule, at atmospheric pressure. Interest in this type of discharge, as a rule, was associated with the creation of various microwave plasmatrons [8], and with the fight against parasitic breakdowns in waveguides [3]. In the course of these studies, a number of important features of the discharge propagation were noted in comparison with a laser spark. In particular, the important role of ultraviolet radiation through the discharge front was shown in [5]. Under the action of this radiation ahead of the discharge front (compared to the plasma behind the discharge front) a so-called plasma halo of rarefied density is formed, in which a significant absorption of microwave radiation is possible. At not too high intensities of the incident microwave radiation, this leads to sufficiently strong heating of the gas and its thermal ionization. Thus, the thermal ionization of the gas ahead of the discharge front is maintained not due to thermal conductivity, as in the case of slow combustion [2], but due to the absorption of microwave radiation in the halo. In this case, the discharge propagation velocity is proportional to the incident microwave radiation flux. The discharge propagation has an equilibrium character; the discharge glow repeats the gas temperature distribution. With an increase in the flux of incident microwave radiation, the nature of the discharge propagation becomes non-equilibrium [4]. The structure of the discharge glow repeats the distribution of the electric field strength. In this case, gas heating in the halo leads to a decrease in the breakdown field and the appearance of an independent breakdown ahead of the discharge front. The discharge propagation velocity, as shown by measurements [4], is proportional to the square of the incident microwave radiation flux. It should be noted that interest in the propagation of microwave discharges in air has not weakened so far [9].

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This work is devoted to the study of the propagation of a discharge in air, supported by radiation in the sub-terahertz frequency range, in a wide range of gas pressures. The sub-terahertz and terahertz frequency ranges lie between the microwave and optical ranges. The study of discharge phenomena in this range has become possible relatively recently due to significant progress in the creation of powerful sources of radiation in the sub-terahertz and terahertz ranges—gyrotrons and free electron lasers [10–14].

Experimental setup

A pulsed gyrotron [13] (1 in Fig. 1) generating radiation at a frequency of 250 GHz with a power of up to 250 kW was used as a source of heating radiation. The pulse duration could vary in the range of 20-40 microseconds. The gyrotron radiation was directed into a vacuum discharge chamber using a system of quasi-optical mirrors and focused into a spot with a diameter close to two wavelengths. Maximum power density was 3.5 MW/cm^2, which corresponds to the rms electric field density of 35 kV/cm.

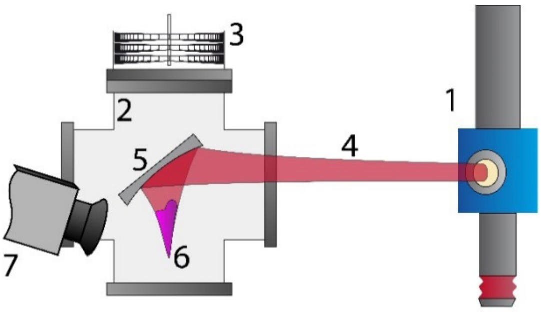

Fig. 1. Scheme of the 250 GHz experimental setup. gyrotron *1*, vacuum chamber *2*, turbomolecular pump *3*, THz beam *4*, focusing mirror *5*, beam waist/discharge plasma *6*, video camera *7*

The discharge glow could be observed through the optical flange of the discharge chamber. The discharge propagation was studied using the Nanogate-24 high-speed camera. The minimum possible frame duration for this camera is 20 ns. During this time, the plasma, at propagation velocities characteristic for this type of the discharge, could move only on a few millimeters or less, so we can assume that the plasma was static during one frame. Numerous photographs were taken with varying delays between the onset of the discharge and the shutter of the camera to calculate the propagation velocity at each point in the propagation path. The discharge propagation speed can be easily calculated as the distance divided by the time between adjacent frames.

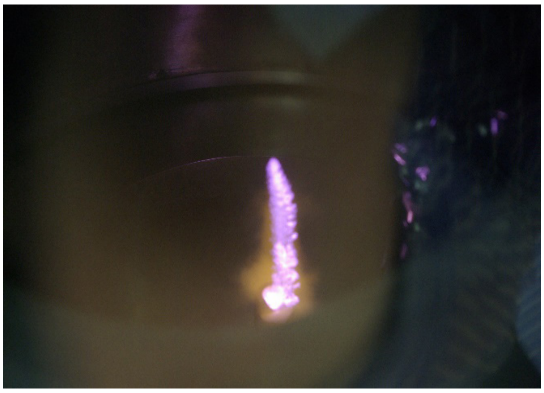

Fig. 2. Photo of the 250 GHz discharge in the air.
Gas pressure is 0.7 atm, gyrotron power is 250 kW

Experimental results

The discharge appeared at the beam waist and propagated towards heating radiation. From the Fig. 2 one can see the time-integrated photo of the discharge in air. The gyrotron beam power was of 250 kW, gas pressure was 0.7 atm. THz radiation spreads from the top to the bottom. It can be seen that the structure of the discharge repeats the structure of the electric field, which means the non-uniform character of the discharge propagation. Orange halo around the main part of the discharge corresponds to the first positive system of nitrogen which excited by the ultraviolet radiation from the main discharge.

Fig. 3 shows a series of photographs of a discharge in air at the pressure of 1 Torr, taken by a high-speed camera with different delays between the moment of ignition of the discharge and the start of the camera. The delay difference between frames is close to 1 microsecond.

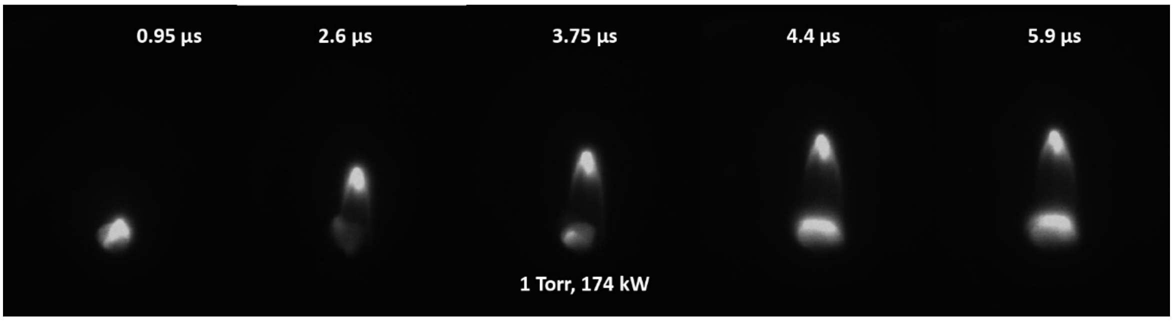

Fig. 3. Series of photographs of a discharge in air at the pressure of 1 Torr, taken by a high-speed camera with different delays between the moment of ignition of the discharge and the start of the camera

Fig. 4 shows the dependence of the discharge front coordinate on time, reconstructed from instantaneous photographs of the discharge. This dependence clearly shows that as the discharge propagates towards the heating radiation, the propagation velocity decreases with a decrease in the field strength in the focused beam. In this case, two characteristic regions of space can be distinguished: with a higher propagation velocity and with a lower one. At present, these two regions of space are associated with the region where the field is higher than the breakdown field (in the absence of plasma), closer to the beam focus, and the region where the field is smaller than the breakdown field, farther from the focus of the heating radiation beam. In the first region, propagation occurs in breakdown fields. In this case, breakdown fields are understood to mean fields sufficient for independent breakdown of the gas in the absence of plasma. In the second area, propagation occurs in pre-breakdown fields. This is most likely related to the fact that the discharge propagation velocity in this region is lower. The same effect was observed in a discharge sustained by a 303 GHz gyrotron in atmospheric pressure air [15].

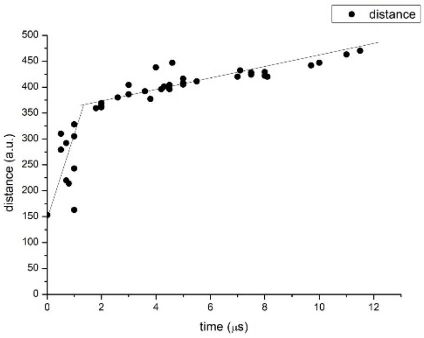

Fig. 4. Dependence of the discharge front coordinate on time. Gas pressure is 95 Torr. Gyrotron power is 215 kW

Fig. 5 shows the dependence of the discharge propagation velocity in the second region on the gas pressure. The pulse power of the gyrotron in this case was 175 kW. It can be seen that the propagation velocity decreases with increasing pressure, from 3.5·105 cm/s to 8·104 cm/s, which is much higher than the speed of sound.

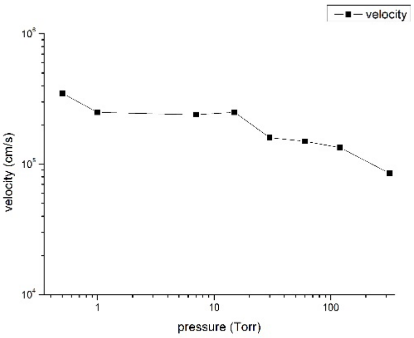

Fig. 5. Dependence of the discharge propagation velocity on the gas pressure.
Gyrotron power is 175 kW

Unfortunately, for the first region (breakdown fields), it was not possible to obtain a reliable dependence of the discharge propagation velocity on pressure, which was due to the difficulty of synchronizing the moment of camera start-up and the moment of discharge occurrence at times less than one microsecond. The fact is that even at optimal gas pressures, the moment of the discharge occurrence floats relative to the time of the beginning of the electromagnetic radiation pulse by a value of the order of one microsecond or more. While the propagation velocity in breakdown fields, as measurements show, is quite high, at the level of 106 cm/s, and the size of the region it does not exceed 2–3 cm. As a result, the discharge runs through the first region just in times of the order of a microsecond. As a result, it was not possible to obtain a statistically reliable dependence of the discharge propagation velocity on the gas pressure in this region.

No reliable dependence of the discharge propagation velocity on the power in the gyrotron radiation pulse was found either. Perhaps this was because the range of available powers (to maintain self-discharge in air) was not too wide: 170–250 kW.

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