THz gas discharge in nitrogen as a source of ultraviolet radiation

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Abstract. This work presents the results of investigation of THz gas discharge in inhomogeneous flow of nitrogen. As a source of sub-millimetre radiation we used 40 kW@670 GHz gyrotron created in IAP RAS. It is shown that, despite the tendency of the discharge in electromagnetic wave beams to propagate towards the heating radiation from the breakdown region, in the case of a strongly inhomogeneous gas flow (nitrogen in our case), conditions can be created under which the discharge practically does not propagate and becomes point-like. The features of the glow of a THz discharge in a nitrogen flow in a wide range of background gas pressures are studied. The presence of a powerful afterglow in some bands of the second positive system of nitrogen at high pressures was demonstrated. The prospects of using such a discharge as a source of UV radiation are discussed.

1. Introduction
THz band lying between microwave one and infrared still remains the least studied from the point of view of gas discharge physics and its investigation, that became possible recently due to the creation of the powerful sources of THz radiation – gyrotrons and free-electron lasers [1-5], is in a great interest from the point of view of both fundamental and applied sciences. One of the possible applications of THz gas discharge dense plasma – powerful source of radiation in different bands, mainly from EUV to UV. In this paper features of the glow of a THz discharge in a nitrogen flow in a wide range of background gas pressures are studied. The prospects of using such a discharge as a source of UV radiation are discussed.

2. Discharge in non-uniform gas flow as f point-like source radiation
In [6] it was proposed to use a discharge in an inhomogeneous gas flow of noble gases as a point-like source of vacuum and extreme ultraviolet. The idea is that high-pressure gas (1-5 atm) is fed into a continuously evacuated vacuum discharge chamber through a nozzle of small diameter (about 100 μm). Inhomogeneous gas inlet provides localization of the breakdown conditions for the radiation of the terahertz frequency band only in the region of high gas pressure (hundreds of Torr) near the gas inlet opening. In this case, the discharge, arising under the action of THz radiation, directed into the discharge chamber through the input dielectric window, in the high-pressure region practically does not propagate towards heating radiation, which ensures its localization.

In this paper we extend this idea to the discharge in nitrogen, sustained by powerful terahertz radiation. As is known, in nitrogen there are a lot of intense bands in the so-called second positive
system, which emit in the UV spectral region. Plasma density in the case of a THz discharge can be at the cut off level [7], which for a given frequency range corresponds to \(10^{15}–10^{16}\) cm\(^{-3}\). Thus, a THz discharge in nitrogen can be a rather effective source of UV radiation.

Figure 1. Experimental setup (photo): gyrotron (1), quasioptical converter (2), discharge chamber with a window for optical diagnostics of discharge glowing (3), gas injection system (4), vacuum pumping system (5).

This section discusses the prospects for creating a so-called point-like discharge in nitrogen, sustained by powerful THz gyrotron radiation. As in [8], we used a gyrotron as a radiation source, capable of generating radiation at a frequency of 670 GHz and a power of up to 40 kW in 20 microsecond pulses (1 in figure 1). The radiation, transformed by quasi-optical converter (2) into the form of a Gaussian beam, was focused into a previously evacuated and then nitrogen-filled discharge chamber (3). In the discharge chamber was set an additional focusing parabolic mirror (can be seen on figure 2) with a gas inlet of 150 μm in diameter. Gas was continuously introduced by system (4) into the discharge chamber through this hole under high pressure (4 atm). The background pressure in the discharge chamber was ensured by continuous pumping of gas using the fore-vacuum and (if necessary) turbomolecular pumps (5). Thus, a strongly inhomogeneous pressure profile was formed in the discharge chamber near the gas inlet, in which the discharge was ignited. Figure 2 shows a time-integrated photo of the discharge in the visible range at a background nitrogen pressure of 150 Torr in the chamber. The discharge appeared at the focus of an additional parabolic mirror and then propagated towards the THz heating radiation (from right to left in the photo). In the structure of the discharge glow two regions are clearly visible. One of them is strongly inhomogeneous, elongated along the THz beam and repeating the structure of the field. The second (purplish-blue color) occupies a large area and is much more uniform. The first is a discharge running toward THz radiation during the entire heating pulse, the second is the afterglow at the end of the heating radiation pulse (see below).

Figure 2. Time-integrated photo of a discharge in the visible range at a background nitrogen pressure in the chamber of 150 Torr.

With a decrease in the background gas pressure in the discharge chamber, the discharge shortened and at the pressure of 0.8 Torr almost turned into a point-like one (figure 3). Thus, the possibility of
maintaining a point-like discharge in an inhomogeneous nitrogen flow by powerful radiation of the THz frequency range was demonstrated. The following section is devoted to the characteristics of the glow of a THz discharge in nitrogen.

**Figure 3.** Time-integrated photo of a discharge in the visible range at a background nitrogen pressure in the chamber of 0.8 Torr.

### 3. Features of the THz discharge glow in an inhomogeneous nitrogen flow

The dynamics of the discharge glow was studied using various filters and a SOL Instruments MS 5204i monochromator-spectrograph. The detector in all cases was the “Photon” photomultiplier, capable of detecting radiation in the range of 250–650 nm. A diffraction grating of 1200 lines/mm with an operating range of 270–800 nm and a blaze wavelength of 400 nm was used as a dispersion element in the monochromator. The radiation from the discharge passed through the optical flange of the discharge chamber made of quartz and was focused using a quartz lens onto a fiber attached to the entrance slit of the monochromator. In this case, the discharge image was projected onto the fiber input from the region corresponding to the focus of the parabolic mirror (can be seen on figure 2).

Figures 4 and 5 shows the waveforms of the signal from the photomultiplier attached to the output of the monochromator in the case when it was tuned to the wavelengths of 391.4 nm and 394.3 nm, respectively. The first of them corresponds to the 0-0 band of the first negative nitrogen system, and the second to the edge of the 2-5 band of the second positive nitrogen system. Based on the fact that the peak corresponding to the $N_2^+$ ion is substantially larger than the peak corresponding to the neutral $N_2$ molecule, a fairly high electron temperature can be judged (at the level of 3-5 eV [9]).

**Figure 4.** Waveform of the photomultiplier signal for a wavelength of 391.4 nm. The background gas pressure is 230 torr. **Figure 5.** Waveform of the photomultiplier signal for a wavelength of 394.3 nm. The background gas pressure is 230 torr.

The experiments studying the dynamics of the glowing of the discharge plasma demonstrated that at relatively high pressures (over 50 Torr), a long (with a duration of about 1–1.5 ms) afterglow exists after the end of the terahertz pulse, and the afterglow intensity can exceed the intensity of the plasma glowing during the pulse significantly, by several times (see figure 6, curve 2). At pressures below 50 Torr, the afterglow duration turns to be significantly shorter being about 100 µs. In this case, the dynamics of the afterglow turns to be significantly different as well, specifically, the photomultiplier signal decreases monotonically (see curve 1 in figure 6).
Spectroscopic studies with the use of optical filters showed that the long afterglow lies in the UV spectral range, i.e., in the range from approximately 250 to 400 nm, where intense radiation of the second positive system of nitrogen (C^3Π_u → B^3Π_g) is possible. The study of the spatio-temporal dynamics of the discharge glow using a fast camera showed that the long afterglow corresponds to the uniform purple region in figure 2, which appears only 100 microseconds after the end of the gyrotron pulse. A shorter afterglow lies in a considerably wider spectra region, approximately from 250 to 650 nm. Deeper studies using the MS 5204i monochromator demonstrated that long nonmonotonic glowing is produced by the vibrational bands 0-1 (λ = 357.7 nm), 4-7 (λ = 385.8 nm) and 3-7 (λ = 414.2 nm) of the second positive system of nitrogen. At the same time, radiation of the vibrational bands 0-0 (λ = 337.1 nm), 1-2 (λ = 353.7 nm) and 0-4 (λ = 434.4 nm) does not produce an afterglow that is that long. However, basing on certain reactions, one can make the following assumptions. Under certain conditions, long-living nitrogen metastables in the A^3Σ_u^+ state are produced efficiently in the nitrogen discharge and its afterglow as a result of certain processes (e.g., such as N_2 (X^1Σ_g^-) + e → N_2 (A^3Σ_u^+) + e) and other processes. As a result of reactions with participation of these metastables, specifically, in the reaction N_2 (A^3Σ_u^+) + N_2 (A^3Σ_u^+) → N_2 (C^3Π_u) + N_2 (X^1Σ_g^-) the electron level C^3Π_u is populated, and its luminescence results in a long afterglow. However, detailed explanation of the observed dynamics of the discharge plasma glowing requires further investigation. Especially the fact that long afterglow observed only in certain vibrational bands of the second positive system.

Thus, it can be concluded that the THz discharge in a nitrogen flow can be a rather effective source of UV radiation. It is shown that modes are possible when this source is a point-like source. Under some conditions, radiation modes are possible in the form of a long afterglow with duration of up to 1 millisecond, which significantly exceeds the duration of the THz heating pulse.

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