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Light emission properties of a discharge induced in a gas flow by terahertz waves in the vacuum and extreme ultraviolet range

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Introduction

Research activity on the discharge, sustained by powerful radiation of the terahertz frequency range, has been actively conducted at the Institute of Applied Physics for a number of years [1-4]. Such a discharge is a new object of the plasma physics, and its investigations are of both fundamental and applied interest. This paper presents the results of experimental studies of the terahertz discharge plasma emission in the VUV spectral range (112 - 180 nm) and EUV spectral range (12 - 17 nm). The discharge was induced in a nonuniform gas flow (Ar, Kr, Xe) under the action of a focused beam of terahertz waves.

Experimental Setups

The experiments were carried out at two different facilities (see the block diagram in Fig. 1). The sources of terahertz radiation were gyrotrons. One gyrotron operated in a pulsed mode (setup № 1, frequency 0.67 THz, pulse duration 20 μs, power 40 kW, intensity in the beam focus 16 MW/cm^2 (for a detailed description of the setup, see [3 - 5])), another gyrotron operated in a CW mode (setup №2, frequency 0.263 THz, power 1 kW, intensity in the beam focus 15 kW/cm^2).

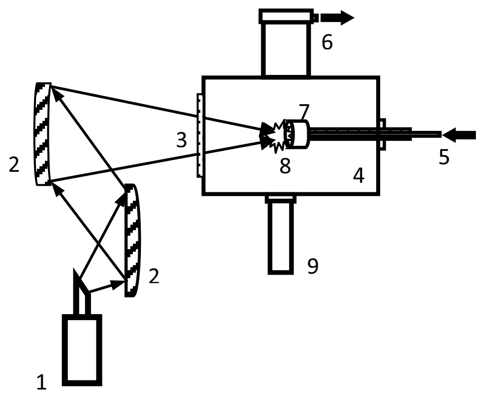

Fig. 1. Block diagram of experimental facilities. 1 – gyrotron, 2 – quasi-optical beamline, 3 – THz vacuum window of the discharge chamber, 4 – discharge chamber, 5 – working gas supply system, 6 – vacuum pumping system, 7 – nonuniform gas flow formation unit, 8 – discharge plasma, 9 – VUV photoelectron multiplier or EUV solid state detector with set of suitable filters.

The discharge was ignited in a nonuniform gas flow (Ar, Kr, Xe) under the action of a focused beam of terahertz waves. The gas flow was formed by injecting gas into the discharge chamber through a small-diameter hole (80 μm) under the pressure up to several atmospheres. An absolutely calibrated photoelectron multiplier (PMT) and a semiconductor detector in combination with a set of appropriate filters were used to measure the VUV (spectral range 112 - 180 nm) and EUV (spectral range 12 - 17 nm) emission of plasma.

Experimental Results

The performed experiments showed that the maximum power of the VUV and EUV radiation was observed in a point-like discharge with characteristic dimensions of about 1 mm [2 - 4]. In Fig. 2 for an example, a photo of such a point-like discharge realized on the above-described setup №2 with a CW mode of the gyrotron operating is given. It should be noted that earlier at the setup №1 we have already performed measurements of the VUV emission power of the point-like discharge. In particular, in the spectral range 112 - 180 nm a value of the order of 10 kW was obtained in argon [3, 4].

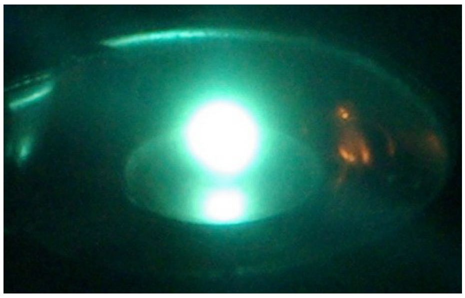

Fig. 2. A time-integrated photo of the emission of the point-like discharge plasma in a nonuniform flow of xenon in the visible spectral range. Setup № 2, the background pressure in the discharge chamber is $4 \cdot 10^{-3}$ Torr, the terahertz radiation is propagated from top to bottom.

Analysis of the experimental data showed that the most promising in terms of generation of both vacuum and extreme ultraviolet is a point-like discharge in the xenon flow. Xenon multiply charged ions emit a lot of intense lines in the VUV and EUV spectral ranges [6], in particular, in the area of 13.5 nm, which is of interest for high-resolution microlithography.

Fig. 3 shows the oscillogram of the VUV signal from the PMT obtained at setup №1 in the xenon flow. It is necessary to pay attention to the intense afterglow, the duration of which exceeds the duration of the terahertz pulse by several tens of times (it should be noted in the same way that an extremely long afterglow was observed earlier in other rare gases, in particular, in Ar [3, 4]). In addition, the intensity of the VUV radiation increased during the entire terahertz pulse. Hence it can be concluded that an increase in the gyrotron pulse duration should lead to a shift the emission spectrum of the discharge into the shorter-wave region. Probably, this should also lead to an increase in the intensity of the extreme ultraviolet.

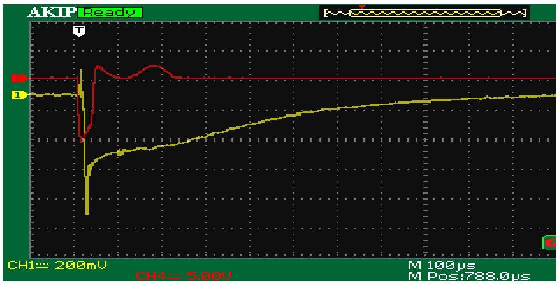

Fig. 3. Dynamics of the emission of a point-like discharge in the xenon flow in the VUV spectral region (the oscillogram of the signal from the PMT at a background pressure of $5 \cdot 10^{-3}$ Torr, lower waveform, setup №1). The upper waveform is a high-voltage pulse at the gyrotron cathode, the duration of which is approximately equal to the THz pulse duration.

According to experiments, the pressure of the gas injected into the discharge chamber has a significant effect on the plasma characteristics [5], and, consequently, on the generation of VUV and EUV emission. Fig. 4 shows the dependence of the VUV power of the plasma of a point-like discharge in the xenon flow on the pressure in the gas inlet system, obtained at setup № 2 at a maximum power of THz radiation of 1 kW. It should be noted that at the same time the vacuum evacuation rate (up to 2000 l/s) provided a low background pressure in the discharge chamber, and as a consequence, the maintenance of the point-like mode of the discharge. As can be seen from the Fig. 4, the power of the vacuum ultraviolet emitted by the plasma increases with increasing gas pressure in the gas-supply system.

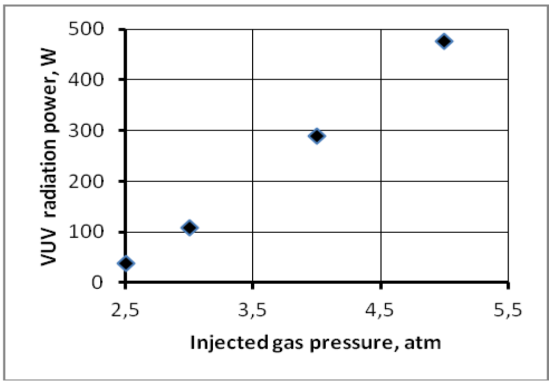

Fig. 4. The dependence of the VUV power emitted by the plasma of a point-like discharge in the xenon flow on the pressure in the gas-supply system (setup №2, power of terahertz radiation is 1 kW).

As for the EUV radiation of the THz discharges described above, the analysis of the signals from the semiconductor detector showed that specific power of the EUV radiation of the plasma in the wavelength range 12-17 nm is 0.1 W/mm^3 for set up №1, and 0.01 W/mm^3 for set up №2.

Conclusion

Thus, the performed experiments showed that the discharge plasma created by focused terahertz radiation in a nonuniform flow of rare gases emits both a vacuum (112 - 180 nm) ultraviolet and extreme ultraviolet (12 - 17 nm). In the conditions described above the power of the VUV radiation is large and reaches several tens of percent of the THz power supplied to the discharge. At the same time, the emitted EUV power is only a portion of a percent of the gyrotron radiation power. In the case of setup №1, an increase in the degree of conversion of THz radiation to an extreme ultraviolet is possible, apparently, by increasing the duration of the terahertz pulse of the gyrotron. Under the conditions of operation of the setup №2, an increase in the conversion degree is possible by increasing the THz radiation power and the pressure in the gas-supply system (in this case, it is necessary to maintain the point-like mode of the discharge, i.e., to keep the background pressure in the discharge chamber at the level of $10^{-2} - 10^{-3}$ Torr). These experiments are planned in the nearest future.

Acknowledgements

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