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Discharge in a Nonhomogeneous Gas Flow Sustained by Powerful Novosibirsk Free Electron Laser Emission as a Point-Like Source of Vacuum Ultraviolet Radiation

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Abstract—We consider the prospect of development a point-like source of vacuum ultraviolet radiation based on a plasma discharge sustained by terahertz radiation from Novosibirsk free electron laser.

Keywords: gas discharge, terahertz radiation, vacuum ultraviolet light source

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INTRODUCTION

The study of a gas discharge in quasi-optical beams of powerful electromagnetic radiation in the terahertz frequency range is attractive for a large number of both fundamental and applied research. The study of this discharge became possible only recently due to the development of unique and reliable sources of high-power radiation in this range, namely, terahertz free electron lasers and gyrotrons [1–4].

One of the promising applications of the terahertz discharge is the use of its dense plasma as an intense source of radiation, primarily ultraviolet (UV), vacuum ultraviolet (VUV), and extreme ultraviolet (EUV) radiation. This work is devoted to an analysis of the prospects for such sources and a review of the results of experiments on the development of a point-like source of vacuum ultraviolet radiation based on a discharge in an inhomogeneous gas flow sustained by high-power radiation from a terahertz free electron laser.

A point-like source of EUV radiation is one of the key elements of modern high-resolution projection lithography systems. The EUV source must emit hundreds of watts in the range of 13.5 nm ± 1% from a region of less than 1 mm [5]. At the same time, plasma containing multiply charged tin ions is widely used to generate extreme ultraviolet radiation [5]. There are several methods for creating and maintaining a tin plasma, such as powerful laser discharges, microwave discharges, various types of pinches, etc. [5]. Modern EUV sources with a wavelength of 13.5 nm are based on multiply charged tin plasma produced by a powerful pulsed CO_2 laser. The laser beam is focused on specially made tin drops with a size of tens of micrometers. However, these sources are not yet free from shortcomings [6].

It is worth noting that high-resolution projection lithography based on shorter wavelengths, i.e. 11.2 nm [7] and 6.7 nm [8], can further increase EUV output efficiency and is being actively discussed. Efficient optical systems based on multilayer normal-incidence Bragg mirrors that provide filtering and the formation of a parallel or converging EUV beam for all wavelengths mentioned above have already been developed. Multilayer Mo/Si mirrors reflect 73% of radiation in the range of 13.5 nm ± 1% [9], Ru/Be mirrors reflect 78% of radiation in the range of 11.2 ± 1% [10], and La/B mirrors reflect 60% for radiation of 6.7 nm ± 1%. [9, 11]. It should be noted that the emission efficiency of Xe ions in the range of 11.2 nm ± 1% is comparable to the emission efficiency of tin in 13.5 nm ± 1% [10]. In this sense, it can be said that the plasma of multiply charged xenon ions can become a good alternative to the discharge in tin, which is currently considered as the basis of the EUV point source [7]. Moreover, in the case of a gas discharge, there will be no problems with contamination of multilayer X-ray optics.

Thus, the creation of an efficient EUV source that meets the requirements of high-resolution lithography is an urgent and important task.

THE IDEA OF CREATING A POINT-LIKE DISCHARGE IN A NON-UNIFORM GAS FLOW AND ITS APPROBATION

The idea of localizing the discharge is implemented by maintaining a highly inhomogeneous gas pressure profile. High-pressure gas (at a level of one bar and higher in the inlet line) is admitted into the evacuated discharge volume through a small-diameter hole. By controlling the rate of inlet and pumping out, the value of the background gas pressure in the discharge volume can be maintained at a low level (10^{-2} Torr or less). As a result, the discharge, ignited in the high-pressure region, where the density of neutrals satisfies the breakdown condition for a given electric field, practically does not propagate towards the heating radiation. The dimensions of the plasma are determined by the distribution of the gas density in the flow created by the nozzle. The nozzle geometry and pressure drop can be chosen such that the size of the emitting area is less than 1 mm.

Let us now consider the advantage of the THz range. Powerful terahertz radiation makes it possible to maintain a discharge with unique parameters: strongly non-equilibrium plasma with density $N_e > 10^{16}$–10^{17} cm^{-3} [12] and electron temperature T_e at the level of tens of eV; these parameters turn out to be optimal for multiple ionization and excitation of ions. Indeed, heavy neutral particles penetrating the plasma can be ionized to the required charge state (optimal, for example, for EUV radiation of 13.5 nm or 11.2 nm) over a length much less than 1 mm in the case of high plasma density and sufficient electron temperature (tens of eV).

The specified range of plasma density (10^{16}–10^{17} cm^{-3}) is optimal from the point of view of self-absorption of EUV radiation. On the one hand, the radiation power increases with increasing plasma density (as a square in the case when multiply charged ions are excited by direct collision with electrons). In this sense, the transition from the microwave range to THz should indeed lead to an increase in the plasma emissivity [13]. On the other hand, an increase in plasma density will inevitably lead to an increase in its absorption. Calculations show [14] that for radiation in the EUV range, the optimal plasma density is 10^{16}–10^{17} cm^{-3}. Thus, the plasma parameters provided by powerful THz radiation turn out to be optimal for self-consistent generation of EUV radiation.

The possibility of sustaining a point-like discharge in an inhomogeneous gas flow by THz radiation was firstly demonstrated in Ref. 15. The discharge was ignited in a focused 670 GHz beam of a pulsed (20 μs) gyrotron.

The photographs of the discharge presented in [15] showed that the discharge occurred in the focal region and then propagated towards the THz radiation. With a further decrease in the background pressure (less than 0.01 Torr) the discharge occurred in the high-pressure zone and did not penetrate into the region where the gas pressure was at the background level (see Fig. 7 in [15]). The characteristic size of the luminous region in this case was about 1 mm.

Features of the glow of a point-like THz discharge in a gas flow (argon) in the VUV range were studied in [16]. The same 670 GHz gyrotron was used as the source of THz radiation as in the work presented above. At the same time, measurements of the radiation power of a point-like discharge in various wavelength ranges showed that the radiation power in the range of 112–180 nm was at the level of several kW; practically the same power was observed in the range of 180–400 nm, while the THz radiation power was close to 60 kW. These results demonstrated the possibility and promise of creating point-like sources in the EUV range based on a discharge in an inhomogeneous gas flow sustained by powerful terahertz radiation.

As for the features of luminescence in the EUV range required for lithography, they were studied in [17]. In this work, a 250 GHz gyrotron served as a source of THz radiation [2]. To diagnose radiation in the EUV range, a calibrated silicon detector with a set of filters was used [18]. We used a Mo/Zr filter for the range of 13–17 nm and an Al/Si filter for the range of 18–50 nm [19]. Comparison of the radiation power ratios in different wavelength ranges (in the entire range, in 13–17 and 18–50 nm) made it possible to reconstruct the plasma density and temperature.

Comparison of the results of calculations and experiment showed that both in the case of argon and xenon, the plasma density significantly exceeded the cut-off one (2–3 × 10^{16} versus 7 × 10^{14} cm^{-3}), and the electron temperature was at the level of 50 eV.

Thus, the experiments have demonstrated the fact that the concept of a THz discharge in a nonhomogeneous gas flow as a point-like source of extreme ultraviolet radiation is quite viable. However, the conversion efficiency of heating radiation into EUV, demonstrated in [17], was low.

As noted in [17], the low efficiency of converting heating radiation into EUV (and indeed into radiation in the entire range from EUV to visible) in the case of 250 GHz radiation is due to two factors: the plasma is too dense compared to the cut-off density (about 40 times) [17, 20] and the discharge is too small compared to the waist of the microwave beam. Increasing the nozzle diameter will eventually improve the absorption efficiency at 250 GHz [17], but this spoils the discharge conditions [20]. In the experiments described in [17], no improvement was observed with larger gas inlets. In this regard, the paper [17] proposed a transition to a higher frequency of heating radiation. On the one hand, this will make it possible to reduce the diameter of the wave beam in the waist, and on the other hand, it will increase the cut-off value of plasma density. In particular, it was shown in [12]

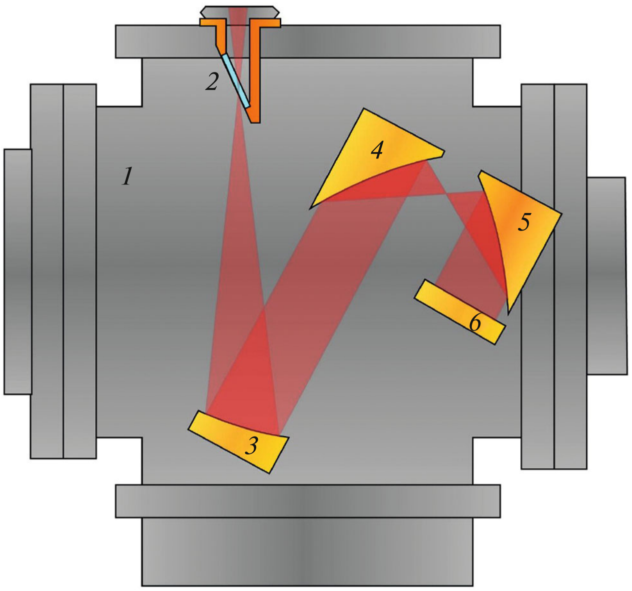

Fig. 1. Optical scheme of the THz laser discharge station.

that in the case of heating at a frequency of 670 GHz, the plasma density is five times higher than the cut-off one, which improves the radiation–plasma matching. In part, this is demonstrated in [16], where it is noted that the part of energy going into the VUV is close to 10%, in contrast to [17]. Unfortunately, the duration of the heating radiation pulse in this case was short, only 20 microseconds, which led to the fact that ions with a charge sufficient for EUV generation appeared only at the very end of the pulse. As a result, despite the increase in the degree of conversion to UV radiation, it is mainly a conversion to vacuum UV radiation, but not EUV. The situation could be corrected by switching to an even shorter wavelength of heating radiation, for example, to radiation with a frequency of 1 THz.

The most powerful source of radiation in this range at present is the Novosibirsk free electron laser. The average radiation power at a frequency of 2.3 THz (130 μm) reaches 500 W. In this case, the radiation itself is a burst of pulses with a duration close to 100 ps, following with a high repetition rate (5.6, 11.2, and 22.4 MHz) [1]. Thus, the power in a single pulse reaches several hundreds of kW.

At present, two institutes (IAP RAS, Nizhny Novgorod and INP SB RAS, Novosibirsk) are conducting experiments to study a discharge sustained by radiation from the Novosibirsk FEL as a point-like source of EUV radiation. Undoubtedly, this FEL is a large-scale installation compared, for example, to gyrotron. Nevertheless, as mentioned above, at present this is the only sufficiently powerful source of radiation in one pulse with a frequency of about 1 THz. In addition, the ongoing research is aimed at demonstrating an increase in the efficiency of the EUV radiation output with an increase in the frequency of heating radiation.

RESULTS OF EXPERIMENTS ON PLASMA CREATION IN A NONHOMOGENEOUS GAS FLOW IN A FOCUSED BEAM OF THE NOVOSIBIRSK FEL RADIATION

An experimental study of a discharge in an inhomogeneous flow of noble gases in a focused beam of electromagnetic radiation from a free electron laser was carried out at one of the specially designed user stations of the Novosibirsk FEL, designed for experimental studies of the THz laser discharge in gases [21]. The discharge was carried out in an evacuated vacuum discharge chamber which can be filled by operating gas to a predetermined pressure. Figure 1 shows the layout of the experimental setup. The Novosibirsk FEL radiation was introduced into the discharge chamber (*1*) through a diamond window (*2*) located at the Brewster angle in the focal waist of the mirror that introduced radiation into the chamber. Further, in the discharge chamber, using an optical system consisting of three parabolic (*3*–*5*) and one flat (*6*) mirrors, the FEL radiation was focused into a spot between mirrors (*4*) and (*5*) with a minimum transverse dimension (width at half height Gaussian beam for 130 μm radiation was about 0.3 mm).

The breakdown thresholds of heavy noble gases by FEL radiation were preliminarily measured in a wide pressure range [22]. For the maximum laser power, the minimum breakdown pressures for argon and krypton were 0.4 and 0.2 atm, respectively [22].

The experiments showed that in pure krypton and argon the maximum electron temperature was at the level of 20000 K, as in previous experiments [23]. An increase in the heating radiation power only leads to an increase in the discharge volume.

In order to increase the maximum temperature in the discharge, it was decided to ignite the discharge in a mixture of noble gases and nitrogen. The addition of molecular gas significantly worsens the breakdown conditions, because of which the discharge mainly burns at the focus of the THz beam and does not penetrate the region of lower electric field strengths. This makes it possible to increase the specific energy input into the discharge.

A series of experiments were performed to maintain the discharge in a mixture of heavy noble gases with nitrogen to test the scheme. The temperature in the discharge was determined according to the Ornstein method, from the relative luminosity of the lines of singly charged ions. As a result, in a mixture of noble gases with nitrogen, it was possible to significantly (approximately twice) raise the temperature at the center of the discharge compared with the case of pure gases from 20000 K to 27000–30000 K. Thus, this

Fig. 2. Scheme of gas inlet. (*1–2*) 90° mirrors; (*3*) gas inlet tube.

method of increasing the specific energy input into the plasma discharge proved to be very effective.

Experiments on the ignition of a discharge in a flow of noble gases were carried out in almost the same configuration as the experiments on the breakdown of standing gases. The general scheme of the experiment is shown above in Fig. 1.

The vacuum discharge chamber was preliminarily evacuated to a pressure of about 10^{-5} Torr. The operating gas (argon, krypton) was puffed in through a nozzle of small diameter into the focus region of the THz radiation perpendicular to the direction of radiation propagation (as shown in Fig. 2).

Temperature measurements by the Ornstein method showed that, in contrast to the discharge in a standing gas, the volume average electron temperature for a mixture of noble gases and nitrogen was 45000 K. Thus, in the case of a discharge in a gas flow, it was possible to achieve higher electron temperatures.

In this case, the minimum pressure of the background gas at which it was possible to ignite the discharge was 0.05 bar. Unfortunately, the discharge could not be ignited at lower pressures. It seems that this is because a decrease in the pressure of the background gas led to fact that the jet of gas admitted into the discharge volume was no longer exists: the gas spreads uniformly into a solid angle of 2π. As a result, in the focus region of the THz radiation, the pressure is less than the threshold pressure in terms of breakdown.

CONCLUSIONS

The possibility of igniting and maintaining a point-like discharge in an inhomogeneous flow of heavy noble gases in a focused beam of a THz free electron laser has been demonstrated. In this case, the plasma density reached the cut-off level for a given wavelength (130 μm) and the average electron temperature reached the value of 4 eV. To further increase the electron temperature and improve the yield of vacuum and extreme ultraviolet radiation, it is necessary to switch to lower background gas pressures. To do this, it is necessary to switch to a longitudinal inlet of the working gas with respect to the direction of propagation of the THz radiation. In this case, even with a gas expansion of 2π, it is possible to maintain a sufficiently high gas pressure in the region of the focal waist of the THz beam and facilitate breakdown conditions. Alternatively, in the case of a transverse gas puff, go to the so-called two-stream gas target [24]. In this case, a heavy noble gas is injected through the central nozzle, and lighter helium is injected through the concentric peripheral nozzle. In this case, it is possible to “compress” the heavy gas jet, ensure a slower decrease in gas pressure along the jet axis, and improve the breakdown conditions at the focus of the THz beam.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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