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A source of powerful nanosecond pulses of vacuum ultraviolet radiation based on a high-current volume discharge in xenon

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A radiation source in the wavelength range from < 70 to 400 nm with a pulse duration of ~ 1 ns and a power of 350 MW based on a high-voltage volume discharge in xenon at a pressure of 2 atm is proposed. The discharge with a duration of ~ 1 ns with a current of ~ 50 kA, a voltage of 100 kV, and a pulse repetition rate of 0.1–2.0 Hz was excited in a low-inductance discharge chamber by injecting a plasma jet of an auxiliary low-power volume discharge in xenon (110 kV, 5 kA, 250 ps), which in turn was initiated by applying a voltage pulse to the discharge gap from a small-sized picosecond Tesla generator.

Keywords: nanosecond high-voltage discharge, VUV–UV radiation spectrum, picosecond Tesla pulser, sapphire luminescence.

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Nanosecond discharges in dense gases have been studied extensively for several decades due to the high relevance of the associated physical phenomena and their practical significance. Specifically, these studies provided the data needed to construct high-power pulsed sources of spontaneous vacuum ultraviolet (VUV) radiation [1,2] and systems for optical pumping of laser media [3]. In addition, they have certain applications in rapid combustion of gas mixtures and aerodynamics [4].

Research into fast processes stimulates the design of sources of high-power VUV–UV radiation of a (sub)nanosecond duration. The developed sources based on fast high-voltage discharges in inert gases emit VUV pulses driven by excimer transitions of xenon in a wavelength band around 172 nm [5]. The minimum radiation pulse duration achieved was several tens of nanoseconds and decreased with increasing pressure; however, even at a pressure of 12 atm and a discharge pulse duration of 2 ns, the radiation pulse duration was 8 ns [5]. Therefore, the construction of a high-power VUV radiation source with a pulse duration $\leqslant 1$ ns is a relevant task. In addition, the design of a broadband radiation source operating within the VUV–UV spectral range is of interest for a number of applications. The present study addresses these needs.

We have already constructed a small-sized picosecond high-voltage generator, where a high efficiency of volume discharge emission in the VUV–UV range was achieved in a low-inductance discharge chamber at a gas pressure of 0.1–3 atm with various gas media (Ar, Xe, N_2, He, H_2, etc.) [6]. The radiation power of a volume discharge in xenon at a pressure of 1 atm within the VUV–UV spectral range was as high as 12 MW in these studies. In subsequent experiments, a high-voltage pulsed generator supporting a volume discharge in xenon with an extremely short duration (~ 200 ps) and a high rate of current rise (approximately $5 \cdot 10^{13}$ A/s) was developed. A radiation pulse with a quasi-thermal spectrum within the range of 110–400 nm and a power of 60 MW (i. e., an energy of approximately 10 mJ at a total energy release in the discharge of 300 mJ) was recorded in these experiments [7].

Continuing this research, we propose here a significantly higher-power source of broadband VUV–UV radiation with a pulse duration on the order of a nanosecond. This discharge was initiated by the auxiliary generator of low-power picosecond pulses described above. Various techniques were used to examine the discharge radiation parameters within a wide spectral range. Note that an in-depth study of the electrical discharge parameters is beyond the scope of the present work.

The source is driven by the discharge of capacitor C_1 that is initiated by a trigatron circuit with a Tesla generator pulse with voltage shaper *3* (Fig. 1). The parameters of a picosecond initiating pulse measured in accordance with the procedure detailed in [8] are as follows: voltage, 110 kV; current, 5 kA; duration, 250 ps. Low-inductance metal-ceramic high-voltage discharge capacitor $C_1 = 3400$ pF with an operating voltage of 100 kV is designed in such a way that one of its plates is connected to a tungsten electrode of the main discharger and the other plate is connected coaxially to the copper body of the discharge chamber through a support damping high-voltage insulator. The picosecond initiating spark gap is a single coaxial low-inductance unit (Fig. 1) consisting of a trigatron discharge chamber, a capacitive shaper, a matching line operating in the traveling wave mode, and a small-sized high-voltage Tesla generator [7].

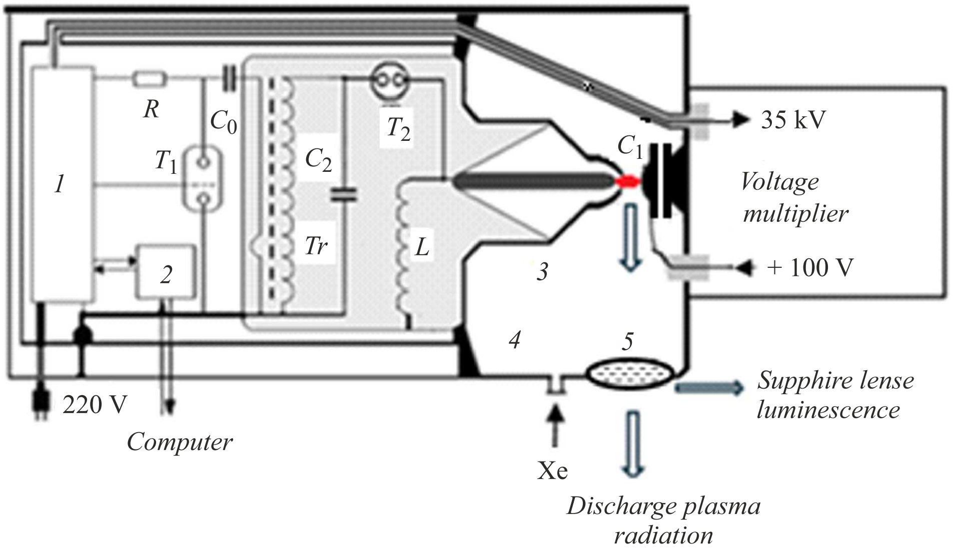

Figure 1. Diagram of the experiment. *1* — High-voltage pulsed power supply, *2* — microcontroller, *3* — capacitive shaper with a Tesla generator of the initiating picosecond discharge, *4* — low-inductance main discharge chamber, and *5* — sapphire lens.

The capacitance C_1 is charged by a high-voltage pulse power supply via a special coaxial line with a built-in distributed charging resistance. This coaxial line design has its own capacitance for effective suppression of electromagnetic interference. Pulsed power supply *1* (400 W) is controlled by a microprocessor *2*. When the charging C_1 capacitor voltage reaches the operating value (100 kV, measured by a two-stage resistive attenuator), the microcontroller issues a command for the startup system of spark gap T_1 of the Tesla generator, and a picosecond pulsed plasma torch formed by the latter ensures the initiation of a high-power main volume gas discharge. A discharge plasma jet bridging a 12-mm-wide discharge gap is in the focus of sapphire lens *5* with a diameter of 3 cm and a focal length of 8 cm. The amplitude of the main discharge current was estimated at 50 kA based on the discharge circuit characteristics and the discharge pulse duration.

VUV−UV radiation of a volume discharge was examined at a xenon pressure of 2 atm in the coaxial discharge chamber through the single-crystal sapphire window (lens made of high-purity Al_2O_3 with an impurity content $< 10^{-7}$ wt.%). The kinetics and spectrum of optical radiation were recorded by a VUV−UV spectrometer that combined a VMS-1 vacuum monochromator, a FEU-142 photomultiplier tube, an S1722-O1 (Hamamatsu) $p{-}i{-}n$ photodiode with the window removed, and a Tektronix TDS3032B oscilloscope. The temporal resolution of the spectrometer was close to 1 ns. The VUV−UV radiation intensity integrated over the spectrum was measured using a FDUK-1UVSKM calibrated $p{-}i{-}n$ photodiode (spectral range $\Delta\lambda = 0.12{-}650$ nm; temporal resolution $\tau \approx 1$ ns).

The VUV−UV spectrum of intense flashes with a duration (full width at half maximum) close to 1 ns (see the inset in Fig. 2) was measured in the spectral range of 140−450 nm. The left boundary of the spectrum is set by the fundamental absorption of the lens material and the spectral sensitivity of standard equipment (Figs. 2 and 3). Taking into account the results of analysis performed in [6,7], we may state that radiation with a spectrum close to a thermal one, the intensity of which is maximized in the VUV range and decreases with increasing wavelength (Fig. 2), is dominant in the VUV−UV emission spectrum of discharge plasma.

In addition to discharge plasma emission, fast ($\tau \sim 1$ ns) $2pO^{2-}$ valence photoluminescence (PL) of the sapphire lens excited by VUV−UV radiation of the discharge (Fig. 3) was recorded in the experiment in a band with a maximum at a wavelength of 390 nm. The PL spectrum was recorded at an angle of 90° to the optical axis of the lens in order to avoid exposing the detector to discharge plasma emission.

It is known that $2pO^{2-}$ PL in the band with wavelengths around 390 nm in sapphire crystals is excited by femtosecond laser pulses [8]. To determine the spectral composition of radiation exciting $2pO^{2-}$ PL, we examined a sample of the original lens material under the influence of fourth harmonic radiation of a tunable femtosecond TIF-50 4ω:Ti:Al_2O_3 laser with a pulse duration of 50 fs, spectral range $\Delta\lambda = 200{-}215$ nm, and a power density of 0.03−1.5 GW/cm^2, which was adjusted using a standard quartz two-lens telescope by varying the laser beam diameter within the range of 0.1−1 mm. It was found that the $2pO^{2-}$ PL intensity has a cubic dependence on power density of excitation laser pulses (see the inset in Fig. 3), which is indicative of the three-photon PL excitation mode.

This implies that the short-wavelength boundary of the spectrum of radiation exciting $2pO^2$ PL in the 390 nm band is at $\lambda \leqslant 67$ nm; i.e., photon energy $h\nu > 18$ eV. Thus, the emission spectrum of this gas-discharge plasma source lies within the spectral range from < 70 to 400 nm.

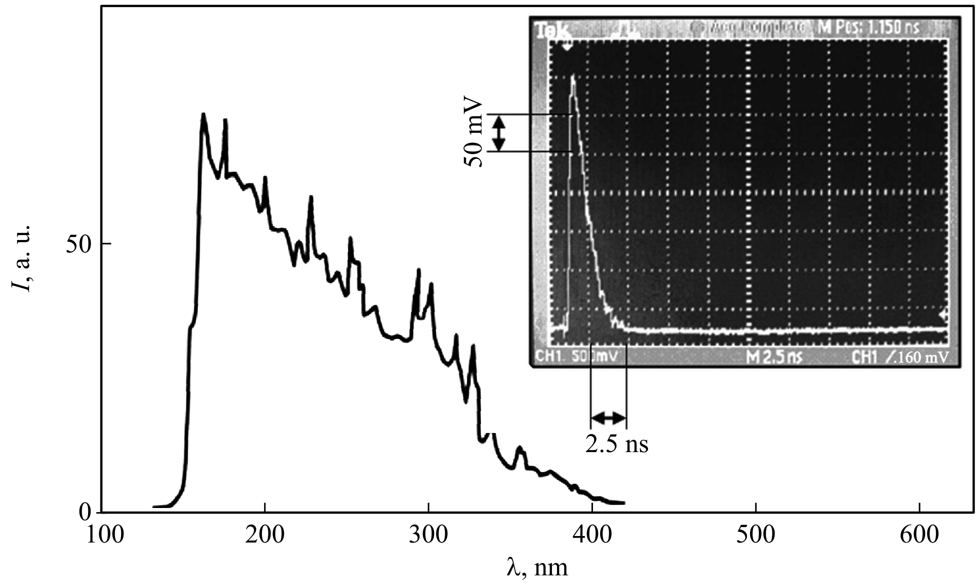

Figure 2. Xenon emission spectrum from the discharge gap recorded through the sapphire window at a xenon pressure of 2 atm. The inset shows the oscilloscope record of radiation at a wavelength of 190 nm.

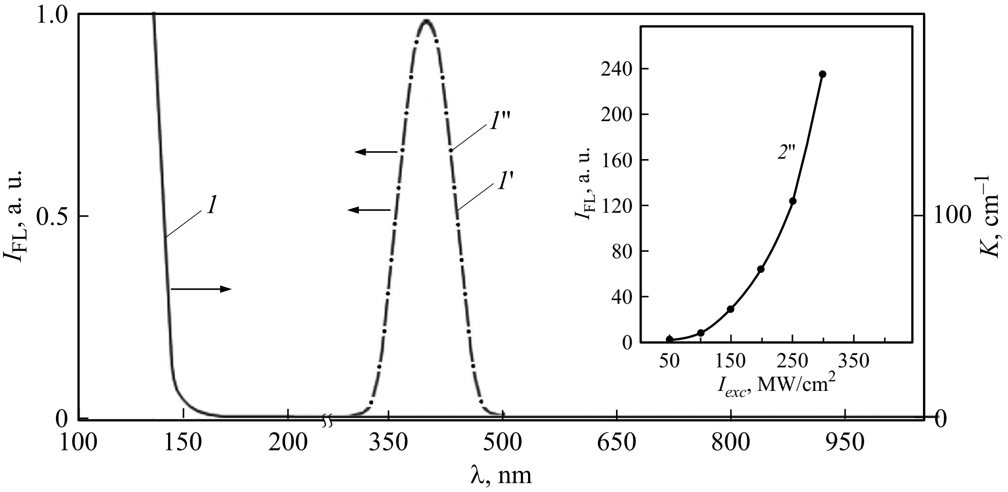

Figure 3. Absorption (*1*) and PL (*1′* and *1″*) spectra of the sapphire crystal. *1′* — PL spectrum excited by VUV pulses of the studied discharge; *1″* — PL spectrum excited by fourth harmonic pulses of a 4ω:Ti:Al$_2$O$_3$ laser. *2″* — Dependence of the PL intensity on the intensity of excitation radiation.

Measurements of the VUV–UV radiation intensity of the volume discharge were performed next using the FDUK-1UVSKM $p{-}i{-}n$ photodiode in two modes: with an open window, when emission is recorded within the entire photodiode sensitivity range (0.12–650 nm), and with a window covered by a UFS-1 light filter, which transmits radiation within the spectral range of 210–420 nm. These measurements revealed that only a small fraction of discharge radiation (approximately $\sim 1/8$ of the total intensity) lies within the wavelength range of 210–420 nm. Therefore, the major part of radiation has $\lambda < 200$ nm (i. e., lies in the VUV region). The total power of VUV–UV radiation in the spectral region of 0.12–650 nm reaches 350 MW.

Thus, a VUV–UV radiation source operating within the wavelength range from < 70 to 400 nm with a pulse duration of ~ 1 nm and a power of 350 MW based on a high-voltage volume discharge was proposed. The discharge was ignited in xenon at a pressure of 2 atm with the following parameters: current, ~ 50 kA; voltage, 100 kV; pulse repetition rate, 0.1–2.0 Hz.

Conflict of interest

The authors declare that they have no conflict of interest.

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