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Miniature UV lamp excited by subnanosecond voltage pulses

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***Abstract*. Energy, time, and spectral characteristics of emission of the second positive system of N_2 molecules in gaseous nitrogen, $Ar-N_2$ mixture, and air are investigated. An FPG-10 generator with voltage pulse FWHM of 200 and 400 ps and matched-load amplitudes of 14 and 6 kV, respectively, is used to excite gases. It is shown that excitation can be performed in two regimes using this generator. In the first regime a diffuse discharge is formed at atmospheric pressure, which opens ways to design miniature nanosecond UV lamps. A diffuse discharge is formed due to the generation of runaway electrons, with the aid of electrodes having a small radius of curvature and voltage pulses with a sharp leading edge. In the second regime an elevated average radiation power is obtained under excitation by a barrier discharge. However, the operating pressure is lower in this case, and the sizes of the emitting region and the UV pulse width significantly increase.**

Keywords: *REPDD excitation, emission from the second positive system of nitrogen, nanosecond UV pulses.*

1. Introduction

Much attention has been given to the development of spontaneous UV and VUV radiation sources, including excilamps (see reviews [1 – 6] and references therein), due to their wide application in different fields of research and technique and the progress in the design of spontaneous radiation sources of different types [6, 7]. However, some practical applications require spontaneous radiation sources with new properties, in particular, miniature sources with emitting-region sizes of $(1-3)\times 1\times 1$ mm and a relatively high (above 1 W) pulsed radiation power. Spontaneous ns-pulsed radiation sources, operating both in the single-pulse and pulse-periodic regimes, are also of great interest. Until now miniature sources have been designed only based on short spark discharges. These sources generate broadband radiation with a pulse width of few hundred nanoseconds or more [7].

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Gas-discharge ns-pulsed radiation sources with a bandwidth of few nanometers can be designed based on runaway-electron preionised diffuse discharge (REPDD) (see [8, 9] and references therein). The diffuse character of this discharge is due to the gap preionisation by runaway electrons, generated near the electrodes with a small radius of curvature and in the gap [10]. To implement REPDD, one has to apply voltage pulses with an amplitude of ~100 kV or more and a short leading edge at the gas-discharge gap.

The properties of light from REPDD in inert-gas halides were investigated in [11]. The discharge was excited using nanosecond voltage pulses with an amplitude up to 150 kV from a RADAN-150 generator [12]. It was shown that the maximum peak power densities of UV radiation (~ 5 kW cm^{-2} with an efficiency of 5 %) were obtained at a discharge gap of 12 mm, inert gas/halogen ratio of 50 : 1, and a pressure of ~ 1 atm. UV pulse widths were in the range 30 – 40 ns and corresponded to the discharge current pulse width. The emitting volume under REPDD excitation in [11] and other studies exceeded 1 cm^3. When exciting a barrier discharge with the same generator, the UV pulse widths for XeCl, KrCl, XeBr, and KrBr excilamps shortened to ~ 4 ns due to the decrease in the current pulse width [13, 14]. The radiation power density decreased to 700 W cm^{-2}, whereas the discharge region increased in volume. To design miniature sources, one has to significantly reduce the emitting region and the generator voltage. However, even under these conditions the working gas pressure should be sufficiently high (close to atmospheric), and the discharge must be diffuse.

The purpose of this study is to analyse the possibility of designing a UV ns-pulsed radiation source with a small emitting region using generator voltage pulses of small (~ 10 kV) amplitude.

2. Experimental setup and measurement technique

Excitation was performed using both a barrier discharge and REPDD. The excitation by a barrier discharge was performed with a one-barrier lamp, composed of a cylindrical flask (high-quality quartz, 18 mm in diameter), filled with nitrogen, air, xenon, or nitrogen – argon mixture. Voltage pulses were applied to a tungsten electrode (wire 1 mm in diameter), placed in the flask, and to a copper foil 1 cm wide, located on the outer surface of the flask. The tungsten electrode was shifted with respect to the central axis of the lamp; the discharge gap was 3 mm wide.

Radiation was extracted through a quartz window, oriented perpendicularly to the discharge axis. The distance from the discharge space to the lamp end face was 15 mm. When exciting REPDD, we used two pointed electrodes, spaced by 1 – 3 mm; most experiments were performed in atmospheric air. The inductance of the switching cable connecting the generator with the electrodes was maintained at minimum.

Generators of two types were used for excitation. A high-voltage unipolar FPG-10 generator (FID GmbH) operated at the maximum pulse repetition frequency $f =$ 1 kHz and formed voltage pulses with FWHM $\tau \sim 200$ and ~ 400 ps and amplitudes $U = 14$ and 6 kV, respectively, on a matched load. The generator was connected by a coaxial cable ~ 1 m long with the discharge gap electrodes. Figure 1 shows the oscillograms of voltage pulses on a matched load, which correspond to two regimes of FPG-10 operation. The other generator formed voltage pulses with FWHM $\tau \sim 1$ μs and amplitude $U = 6$ kV; previously we used it to excite one- and two-barrier excilamps [5]. Here, this generator operated at a pulse repetition frequency $f = 1$ kHz.

The radiation power density was measured at the lamp end face by a calibrated Hamamatsu photodetector, which contained an H8025-222 photohead and a C8026 measuring unit. The time profiles of the radiation pulses were recorded by a FEK 22 SPU vacuum photodiode and a fast Photek PD025 Low Noise S20 photodiode on Tektronix DPO 70604 (band 6 GHz) and Tektronix TDS 224 (100 MHz) oscilloscopes. The discharge emission spectra in the range of 200 – 600 nm were recorded with a StelarNet EPP2000-C25 spectrometer.

We investigated the radiation pulse widths, the sizes of the emitting region, and the pulsed and average radiation powers as functions of the voltage pulse parameters, discharge gap geometry, and the gas composition and properties.

3. Experimental results and discussion

Preliminary investigations were performed on a lamp connected to a vacuum system, with excitation by a barrier discharge. All other factors being equal, two-barrier lamps require higher generator voltages than one-barrier excilamps. Since our purpose was to reduce the generator voltage and increase the working pressure, the experiments were carried out on a one-barrier lamp with a tungsten point cathode. The presence of a metal electrode inside a lamp limits the application of halogen-containing working mixtures; therefore, we used nitrogen, nitrogen – argon mixtures, air, and xenon.

The dependences of the discharge power density in nitrogen and $Ar - N_2$ mixtures of different composition on gas pressure at FPG-10 pulse amplitudes of 14 and 6 kV are shown in Fig. 2. As in [15], the highest power densities were obtained in nitrogen – argon mixtures. In these media the electron energy is transferred to lower Ar levels and then from metastable Ar levels to the $C^3\Pi_u$ level of the nitrogen molecule; therefore, the partial argon pressure in optimal mixtures significantly exceeds the partial nitrogen pressure. In both FPG-10 operation regimes the maximum power density was obtained for the $Ar : N_2 =$ 200 : 1 mixture; under excitation by pulses with $U = 14$ kV

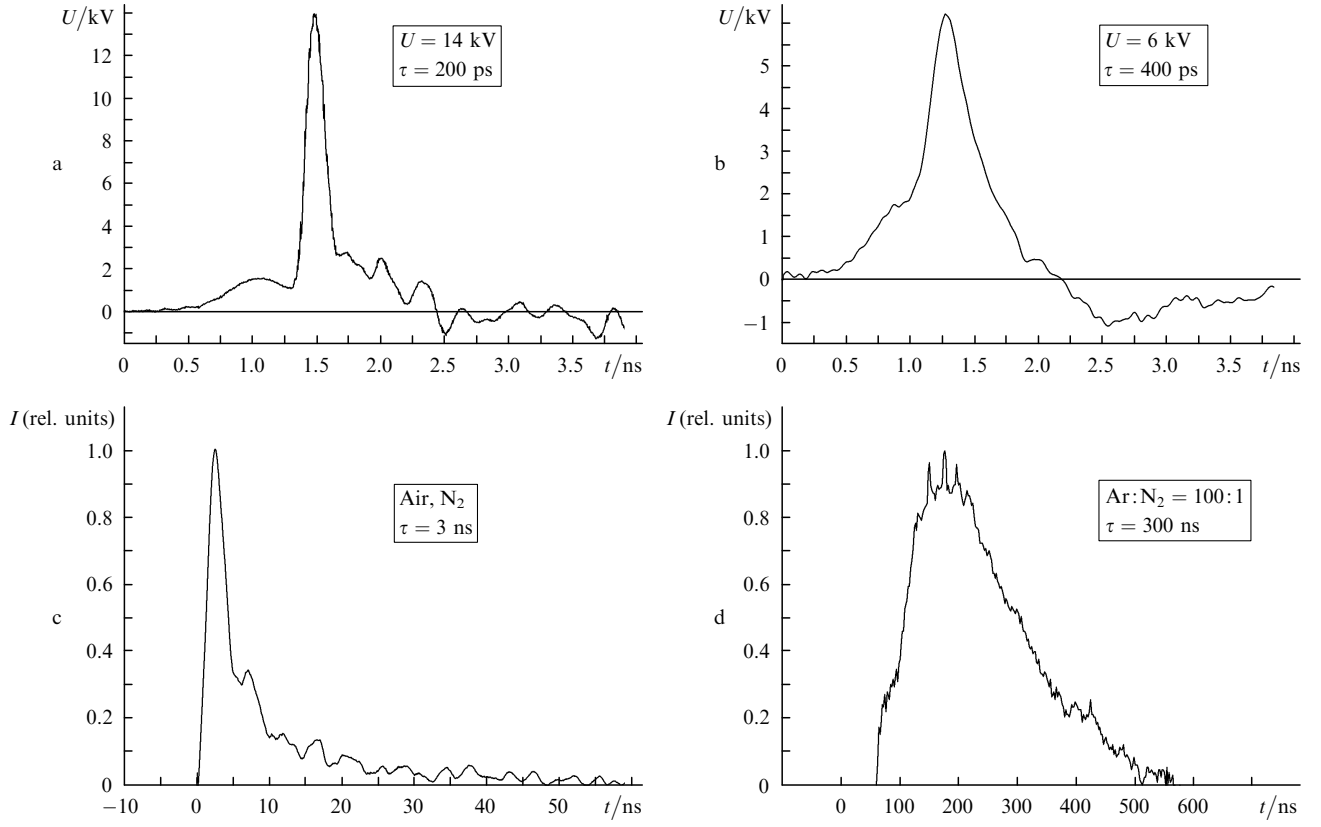

Figure 1. Oscillograms of (a, b) voltage pulses from FPG-10 generator with amplitudes of (a) 14 and (b) 6 kV and (c, d) radiation pulses from discharges in (c) air at atmospheric pressure and (d) $Ar : N_2 = 100 : 1$ mixture at a pressure $p = 180$ Torr.

and $\tau \sim 200$ ps power peaks were observed at lower pressures in comparison with the excitation by pulses with $U = 6$ kV and $\tau \sim 400$ ps. Note that in the first excitation regime we also observed the second peak in the dependence $P(p)$ at pressures close to $p = 130$ Torr (Fig. 2). This can be related to the effect of the voltage pulse width and amplitude on the discharge formation. It can be seen in Fig. 2 that an increase in the pulse amplitude by a factor of 2.3 leads to an almost proportional increase in the power density. At pressures above 100 or 300 Torr in Ar–N_2 mixtures with different component ratios the discharge was contracted or ceased to ignite. The radiation obtained with air and nitrogen as working media had approximately the same characteristics.

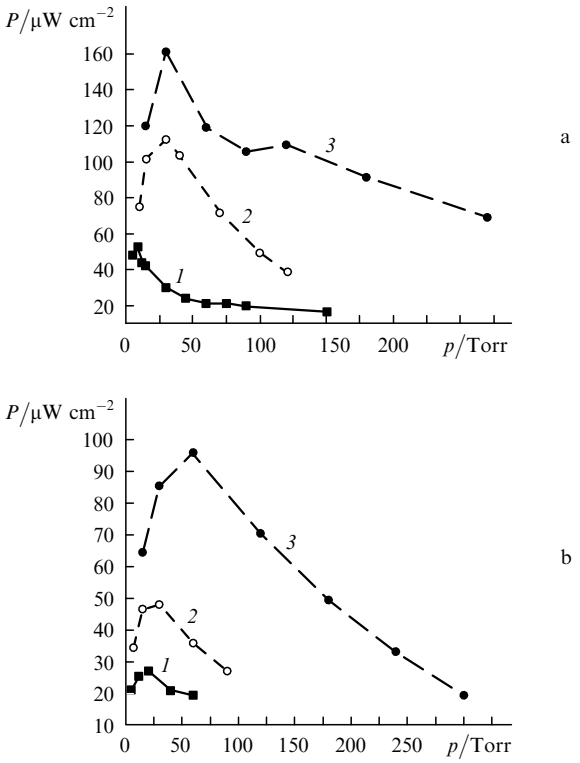

Figure 2. Dependences of the radiation power density for an N_2 barrier-discharge lamp on the working mixture pressure for (*1*) nitrogen and (*2*, *3*) Ar:N_2 mixtures with concentration ratios of (*2*) 10:1 and (*3*) 200:1 under excitation by voltage pulses with amplitudes $U =$ (a) 14 and (b) 6 kV.

The application of the second generator with a voltage pulse FWHM $\tau = 1$ μs made it possible to increase the average radiation power; however, the pulse width increased as well. Each voltage pulse generated two radiation pulses on its leading and trailing edge [5]. The average radiation powers P of the N_2 lamp at $U = 6$ kV and $f = 1$ kHz were 3.2 and 13 mW for the first and second generators, respectively. With an increase in U to 14 kV and reduction of τ to 200 ps the average UV power in the Ar–N_2 mixture was 5.8 mW.

The radiation pulse width τ for the barrier discharge was least ($\sim$ 200 ns) for air and nitrogen working media (Fig. 3); however, it significantly exceeded the FPG-10 pulse width. In the case of nitrogen, the radiation pulse width decreased with increasing pressure to 30 Torr and then somewhat

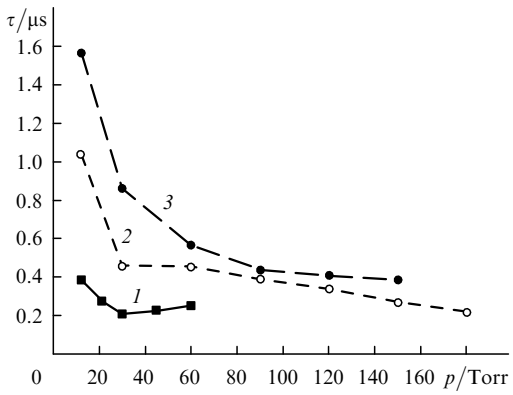

Figure 3. Dependences of the FWHM of N_2 barrier-discharge lamp pulses on the working mixture pressure for (*1*) pure nitrogen and (*2*, *3*) Ar:N_2 mixtures with concentration ratios of (*2*) 100:1 and (*3*) 200:1.

increased. This can also be related to the change in the discharge characteristics. In the Ar:N_2 = 100:1 mixture at a pressure of 180 Torr the radiation pulse width for the N_2 lamp was 300 ns. Thus, the narrowing of the voltage pulse with an amplitude of ~ 10 kV to several hundreds of picoseconds did not allow us to obtain a nanosecond radiation pulse in the barrier-discharge lamp.

The reason is in the relatively low pressures corresponding to diffuse discharge formation in the lamp. In addition, at low operating pressures the discharge region significantly increases in volume; thus, miniature emitters cannot be designed. A diffuse cloud covers the side wall of the tip, and its width exceeds that of the second (copper) electrode. In the case of xenon excitation the gap broke at a pressure below 10 Torr, as a result of which the emission efficiency of xenon dimers near 172 nm was very low.

The shortest radiation pulses were obtained with the FPG-10 generator under REPDD excitation. It was found that a diffuse discharge is formed when 6- and 14-kV pulses are applied between two metal pointed electrodes in air and nitrogen at atmospheric pressure. At a discharge gap of ~ 3 mm the luminous cylindrical column has a diameter of ~ 1 mm (Fig. 4). Voltage pulses with $U = 14$ kV and $\tau =$ 200 ps were applied to the gap. The bands of the second positive system of nitrogen (Fig. 5, dashed curve) dominate in the REPDD emission spectrum. A radiation pulse for REPDD excitation in atmospheric air is shown in Fig. 1c. The REPDD pulse FWHM was 3 ns, and the emission peak power into a solid angle of 4π was 1.7 W. A reduction of the interelectrode distance led to discharge contraction and a decrease in the radiation power of the second positive system of nitrogen. However, even at an interelectrode distance of ~ 1 mm the gap breakdown began with the formation of a volume discharge stage, which then passed to the spark stage. The dynamics of the volume stage–spark stage transition during REPDD formation was investigated in [16]. When the discharge gap is small, the emission spectrum contains bands of the second positive system of nitrogen and a broadband continuum in the range of 200–600 nm (Fig. 5, solid line), which is characteristic of spark discharge. The formation of diffuse discharge at atmospheric pressure in the absence of preliminary gap ionisation is due to the generation of runaway electrons, and the use of voltage pulses with a leading edge width of several hundred picoseconds increases their generation efficiency [8–10].

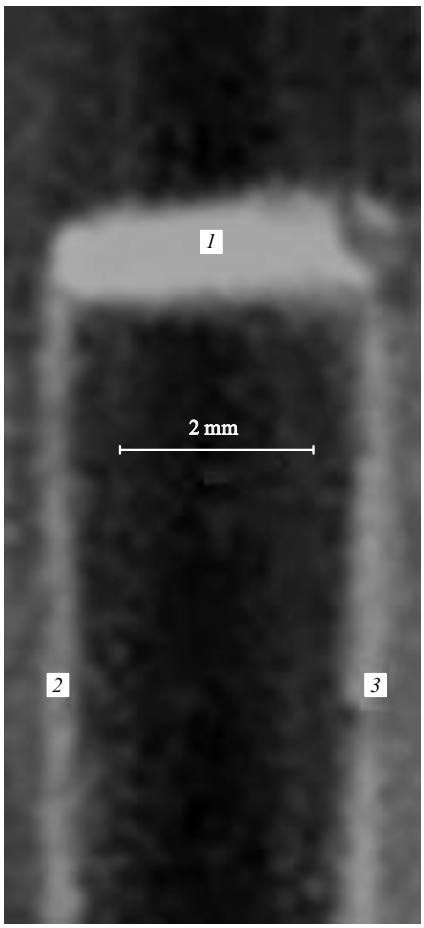

Figure 4. Photograph of a discharge (*1*) burning in air at atmospheric pressure between high-voltage and grounded electrodes [(*2*) and (*3*), respectively].

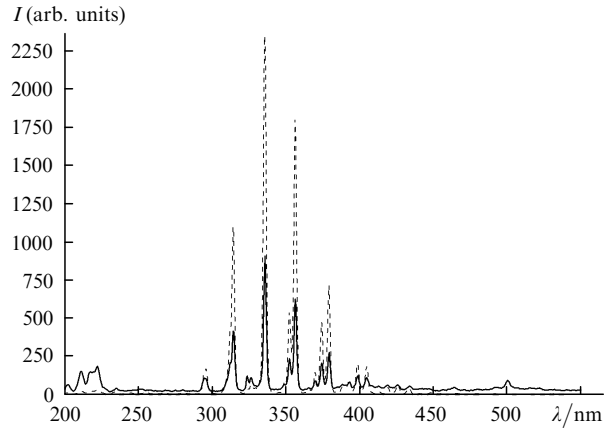

Figure 5. Emission spectra of (dashed line) volume and (solid line) spark discharges between two point electrodes.

4. Conclusions

The time, energy, and spectral characteristics of the discharges excited in nitrogen, $Ar-N_2$ mixtures, xenon, and air at atmospheric pressure by voltage pulses with $U = 6$ and 14 kV and $\tau = 200$ and 400 ps were experimentally investigated. At $U = 6$ and 14 kV the shortest radiation pulses ($\tau = 3$ ns) were obtained in air and nitrogen at atmospheric pressure as a result of REPDD initiation between electrodes with a small radius of curvature. The miniature UV lamp with REPDD excitation, having a cylindrical emitting region 1–3 mm long and ~ 1 mm in diameter, was developed. When using a barrier discharge and the same generator, the highest powers were obtained at pressures below 70 Torr, and the radiation pulse widths in air, nitrogen, $Ar-N_2$ mixtures, and xenon were few hundred nanoseconds (Fig. 1d). A compact sealed-off barrier-discharge lamp, emitting in the second positive system of nitrogen, was designed. It is shown that the maximum efficiencies and powers of UV radiation in this system under excitation by voltage pulses with a width of few hundred picoseconds are lower than under excitation by $\sim$ 1-μs pulses with the same amplitude.

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