Optical Characteristics of the Plasma of a Nanosecond Atmospheric-Pressure Volume Discharge in a Nonuniform Electric Field

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Abstract—Optical characteristics of the plasma of nanosecond volume discharges in air, nitrogen, krypton, argon, neon, and Ar/N\textsubscript{2} and Ar/Xe mixtures at elevated pressures are investigated. The discharges are excited in a gap with a cathode of small curvature radius. The waveforms and spectra of plasma emission from discharges in different gases in the 230- to 600-nm spectral range are measured. Optical generation in an Ar/Xe mixture is achieved at an active length of 1.5 cm. A comparison is performed of the spectral characteristics of the emission from nitrogen, krypton, argon, and neon excited by a volume discharge in a nonuniform electric field, by a nanosecond electron beam, and by a pulsed volume discharge in a uniform electric field at a high initial voltage. © 2004 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

Volume discharges in atomic and molecular gases at elevated pressures are usually excited by preionizing the discharge gap with a source of ionizing radiation [1]. The plasma of volume discharges is widely used in pulsed lasers [2]. It is well known [3, 4] that an atmospheric-pressure volume discharge in a nonuniform electric field can also be excited without preionization, by applying a nanosecond voltage pulse with a steep front (fractions of a nanosecond) to the discharge gap. In [5, 6], X-ray emission from nanosecond atmospheric-pressure discharges in air [5] and helium [6] was observed in a system with a point cathode and plain anode. Later, accelerated electron beams with energies from several tens to hundreds of kiloelectronvolts were observed under similar conditions [4, 7–12].

In systems with a cathode of small curvature radius, pulsed nanosecond volume discharges excited in atomic and molecular gases at elevated pressures in a nonuniform electric field have unique features and find wide application. In particular, such discharges are used for preionization in lasers pumped by a self-sustained discharge at an elevated pressure [13, 14] and for the generation of electron beams in gas diodes [9–12].

In [15], this type of volume discharge in nitrogen was used to create a UV radiation source with a short pulse duration (below 3 ns), and a total (into a solid angle of 4\pi) emission power of \(-10\) kW in the wavelength range of 340–400 nm (the second positive system of nitrogen) was achieved. However, the estimated efficiency of this source, which was obtained by us from the waveforms of the current and voltage presented in [15], turned out to be very low. The efficiency of converting the excitation power into spontaneous emission of the second positive system of nitrogen (\(^{A}P_{2} \rightarrow ^{B}P_{2}\) transitions) is lower than 0.01\%, i.e., more than one order of magnitude lower than the efficiency of an electric-discharge nitrogen laser [16], usually radiating at a single wavelength of 337.1 nm. It is well known that the total (into a solid angle of 4\pi) efficiency of spontaneous radiation sources is usually higher than the laser efficiency. Thus, the power and efficiency of the spontaneous emission of the second positive system of nitrogen in a pulsed source [17], excited by a transverse discharge with UV preionization, is more than one order of magnitude higher than the efficiency of the gas-discharge source described in [15].

The aim of this study was to investigate the optical characteristics of the plasma of a nanosecond volume discharge excited in a nonuniform electric field in air, nitrogen, krypton, argon, neon, and Ar/Xe and Ar/N\textsubscript{2} mixtures at elevated pressures and to compare the experimental data with the known optical characteristics of the plasma generated by a nanosecond electron beam [18–20], by a self-sustained discharge with UV preionization [18, 20], and by an RF discharge [21] with a duration from a few nanoseconds to a few tens of nanoseconds.

2. EXPERIMENTAL FACILITY AND TECHNIQUE

In experiments, we used two RADAN generators of nanosecond voltage pulses (see [22, 23] for details). The first generator (RADAN-303) with a wave resistance of 45 \(\Omega\) generated 50- to 170-kV pulses at a matched load (the open-circuit voltage was up to 340 kV). The full width at half-maximum (FWHM) of
The voltage pulses was ~5 ns, the voltage rise time being ~1 ns [22]. The voltage across the discharge gap could be varied smoothly by varying the length of the main spark gap.

A second generator (RADAN-220) with a wave resistance of 20 Ω generated voltage pulses with an amplitude of up to 220 kV across the discharge gap. The FWHM of the voltage pulses was ~2 ns, the voltage rise time being ~0.3 ns [23]. The design of the gas diode was the same for both generators [24] (Fig. 1). As in most studies devoted to the generation of X rays and fast electrons in gas diodes, we used a plane anode and a cathode with a small curvature radius; this ensured an additional amplification of the field near the cathode. For both generators, we usually used a cathode shaped as a 6-mm-diameter tube made of a 50-μm steel foil. The tube was mounted on a metal rod of the same diameter. The plane anode, through which the electron beam produced in the gas diode was output [9–12, 24], was made of either a 45-μm AlBe foil or a grid with an optical transmittance of 20–70%. The distance between the cathode and anode was varied from 13 to 20 mm. When measuring the waveforms and spectra of plasma emission and photographing the discharge in the transverse direction to the cathode axis, the gas diode was extended by 3 cm toward the foil, which was also displaced by 3 cm. For this purpose, the cathode holder and the casing of the gas diode were lengthened and diagnostic holes were made in the side wall of the latter. In some experiments, the discharge gap was placed inside a gas chamber with windows or mirrors; this allowed us to pump out the gas and to vary the composition and pressure of the working gas in the gap.

To measure signals from capacitive voltage dividers, collectors, and shunts, we used a TDS-684B oscilloscope with a bandwidth of 1 GHz and time resolution of 5 GS/s (five spots per 1 ns) or a TDS-334 oscilloscope with a bandwidth of 0.3 GHz and time resolution of 2.5 GS/s (five spots per 2 ns). The discharge glow was photographed with a digital camera. The emission spectra were recorded on the RF-3 film with the help of an ISP-30 spectrograph.

### 3. EXPERIMENTAL RESULTS

The observations of the discharge glow and the measurements of the emission spectra, the discharge current, and the voltage pulses across the gas diode show the following:

Over a wide range of experimental conditions, a volume discharge in the form of diffuse cones or jets is excited between the anode and the sharp edge of the tubular cathode (Fig. 2). It can be seen that an atmospheric-pressure discharge is volume in character; bright spots are usually observed only near the cathode. When the length of the discharge gap was decreased, a point cathode was used, or the pressure was varied, we observed individual channels against the background of a diffuse discharge (Fig. 2b) and hot spots at both the cathode and the anode. Under nonoptimal conditions...