Picosecond high-current discharge pumping of gaseous media emitting VUV-UV

V I Baryshnikov\textsuperscript{1} and V L Paperny\textsuperscript{2,3}

\textsuperscript{1}Irkutsk State Railway University, Irkutsk, 664074, Russia
\textsuperscript{2}Irkutsk State University, Irkutsk, 664003, Russia
\textsuperscript{3}E-mail: paperny@math.isu.runnet.ru

Abstract. The possibility of creating small picosecond lasers in the VUV-UV spectral range by pumping by a high-current volume discharge of gaseous media (Xe and N\textsubscript{2}) at a pressure of 1-3 atm is investigated. Generation of picosecond (200 ps) powerful (1.2 MW) pulses at a wavelength of 337 nm at an N\textsubscript{2} pressure of 1–3 atm has been achieved. Based on studies of high-current volume picosecond discharges in xenon, using VUV-UV spectroscopy, the presence of short-lived absorption of VUV radiation by discharge plasma was observed. A mechanism for the suppression of the formation of Xe\textsubscript{2} dimers due to thermal effects at the stage of recombination of electrons with Xe\textsuperscript{+} ions at a plasma temperature of 10^7 K with a pulsed pump of 200 ps duration was suggested.

1. Introduction

Generators of high-power VUV-UV volume optical nanosecond flares in gaseous media with pressure (1-3 atm) have been developed as promising small-sized amplifiers of femtosecond laser pulses in the UV-VUV range [1-5]. In these devices, the volume discharge mode is achieved by pre-ionization of the gas in the working volume using a high-current nanosecond beam of an electron accelerator, which works synchronously with a generator of powerful electric pulses. This method is quite effective, but, at the same time, in powerful systems it has an accompanying bremsstrahlung X-ray radiation. Radiation shielding complicates the design and degrades the electrical parameters of a powerful nanosecond VUV-UV generator.

To eliminate this drawback, a design has been developed in which a powerful three-stage Marx generator of nanosecond pulses with parameters: 300 kV, 50 J, 1 ns operates synchronously on a gas Xe chamber with a pressure of 1-3 atm with an auxiliary discharge of low power, with a duration of 100 ps, a voltage of up to 300 kV, a pulse energy of 0.3 J [5]. In this case, a small-sized picosecond high-voltage generator effectively provides the ignition of a volume discharge in a gas chamber coaxially connected to a powerful nanosecond three-stage Marx generator. This nanosecond VUV-UV generator of a volume discharge was also used to pump solid-state crystalline media of tunable lasers [6].

Further studies of the operation of a small-sized picosecond high-voltage generator on a low-inductance chamber at a gas pressure of 0.1-3 atm showed a high radiative efficiency of a volume discharge in the VUV-UV spectral range for various gaseous media (Ar, Xe, N\textsubscript{2}, He, H\textsubscript{2}, etc.) [5, 7]. In these studies, the power of a volume discharge, for example of xenon at a pressure of 1 atm in the VUV-UV range of the spectrum, reaches 12 MW with a pulse duration of 200 ps [7]. The results
obtained in [5, 7] make it possible to consider a powerful volume gas discharge in the indicated gases as an active laser medium.

The present work is aimed at investigating the possibility of achieving a population inversion in quantum systems of gaseous media with 1 atm a pressure of 1 to 3 atm under high-current electric-discharge pumping in order to create small-sized high-power picosecond VUV-UV lasers. and multipass quantum amplifiers.

2. Experimental details

The picosecond gas-discharge generator is a single coaxial low-inductance design (figure 1), consisting of a discharge chamber, a matching line operating in the traveling wave mode, and a small-sized high-current subnanosecond high-voltage generator [8].

The gas discharge chamber consists of a cylindrical-hemispherical brass cathode with a diameter of 9 mm and an anode in the form of a hollow truncated cone. The cathode forms the optimal distribution of the electric field strength in the discharge volume. The matching line is connected to the cathode and to the output of the high-voltage high-current generator spark gap (figure 1).

By experimental specification of \( C_0 \), \( U_1 \) and adjustment of the capacities of the discharge circuit \((C_1 \text{ and } C_2)\), a high-current volume discharge mode was achieved in air at atmospheric pressure [5] and in gaseous media at a pressure of 0.1-3.0 atm [7].

Timing pulse is formed from the high-voltage pulse of a picosecond generator by means of a built-in capacitive attenuator. In the transverse pumping mode of a high-current volume discharge placed in an optical confocal cavity (figure 1), the VUV-UV radiation of \( \text{N}_2 \) and \( \text{Xe} \) gaseous media at a pressure of 1-3 atm was studied. A tunable resonator with a length of 3.0-6.0 cm was formed by spherical mirrors with a radius of 6 cm: for the \( \text{N}_2 \) medium, dielectric mirrors \( M_1 \) (reflection coefficient \( R = 99.5\% \)) and \( M_2 \) \((R = 60\%)\) were used; for the \( \text{Xe} \) medium, mirrors with aluminum films deposited on polished sapphire plates: \( M_1 \) \((R = 96\%)\) and \( M_2 \) \((R = 60\%)\) were used.

**Figure1.** Schematic diagram of the experimental setup: (1) high-voltage power supply, (2) microcontroller, (3) picosecond high-voltage Tesla-Marx generator, (4) discharge chamber, (5) cathode, (6) anode, (7) plasma jet (speculative), (8) holder for a light filter, (9) \textit{pin}-diode, (10) electronic unit for \textit{pin}-diode.
The emission spectrum of the gas discharge in the wavelength range 110–430 nm was measured through a LiF window at an angle of 60° to the axis of the optical resonator, using a VMS-1 vacuum monochromator with PMT-142 photomultipliers (spectral sensitivity range $\Delta \lambda = 100-340$ nm, time resolution $\tau = 1$ ns) and PMT-31ELU-FM ($\Delta \lambda = 180–700$ nm; time resolution $\tau = 0.1$ ns).

The radiation intensity in a wide spectral range was recorded perpendicular to the cavity axis with a SPD-1UVHC photodiode ($\Delta \lambda = 0.12–650$ nm, $\tau \approx 1$ ns) and a Tektronix TDS3032B oscilloscope with a time resolution of about 1 ns (figure 1). With the help of this photodiode with a known spectral sensitivity, an additional calibration of the equipment for spectral measurements was carried out.

The time-integrated image of the discharge in the UV range ($\lambda = 320–420$ nm) was recorded through a LiF window using a SDU-285 CCD matrix with a special lens and an UFS-1 filter.

The spectra of laser UV radiation were measured with an ASP-100M 170–1100 nm spectrometer (spectral resolution 1 nm), and the radiation pulse parameters were recorded with an FEK-15KM high-speed photocell and a Tektronix TDS-6604B oscilloscope with a full resolution of 50 ps.

To study the spectral and kinetic parameters of optical pulses passing through a VUV-UV volume gas discharge ("pump-probe experiment"), we used the radiation of the fourth harmonic of a tunable (170-225 nm) femtosecond (50 fs) Ti: Al$_2$O$_3$ laser with a three-channel mirror unit providing a pulse repetition rate of 320 MHz. In this series of experiments, laser pulses were recorded through MgF$_2$ windows (in place of cavity mirrors) using PMT-142 photomultiplier, which was connected to a Tektronix TDS3032B oscilloscope. In this case, the oscilloscope was triggered through a delay generator, which was triggered by a pulse to turn on the thyatron of the high-voltage generator. It was shown that the probe laser pulse at wavelength $\lambda = 170$ nm decreased significantly when passing the discharge Xe plasma. This means that the inverse population of the levels is not achieved under the given experimental conditions, and the probe laser beam is substantially absorbed by the dense discharge plasma.

In a gas medium N$_2$ at a pressure of 0.1-3.0 atm and pumped by a transverse high-current volume discharge placed in an optical confocal cavity, laser radiation was generated at a wavelength of 337 nm. The measured duration of the UV laser pulse is $\sim 200$ ps (figure 2). The pulsed power of laser radiation reaches 1.2 MW and is practically independent of the gas pressure. In this case, the pulsed radiation power observed from the output window perpendicular to the cavity axis (figure 1) is $\sim 15$ MW and also weakly depends on the gas pressure.

![Figure 2. Waveforms of a discharge radiation pulse in nitrogen at a pressure of 3.0 atm.](image)

![Figure 3. Emission spectra discharge in xenon at volume (1) and streamer (2) modes at a pressure of 1 atm. The inset presents the waveform of pulses of volume (1') and streamer discharges (2') at $\lambda = 200$ nm.](image)
In the volume discharge, when the pulse duration is ~ 200 ps, plasma radiation is observed practically only in the VUV-UV spectral range in air, N₂, and Xe at a pressure of 0.1–3.0 atm (figure 3). A different picture occurs when a streamer discharge is formed in the gas chamber at nanosecond duration of the generator pulse (figure 4 (b)). In this case, the spectrum of less intense radiation from the streamer plasma is in the visible range of the spectrum (figure 3). Such a significant difference in the energy, spectral, and kinetic characteristics of the volume and streamer discharges is explained by the volume of the ionized gas.

![Figure 4. Photo of a volume discharge (a) and a streamer discharge in the UV range of the spectrum.](image)

Thus, a discharge streamer has a cross section of (1–3) mm², a large length, and a very small discharge volume. Consequently, the streamer resistance to the discharge current is high, the discharge duration in accordance with the generator output parameters reaches 300 ns, while the discharge power drops sharply. Since the emitting volume of the streamer is small, the unexcited volume of gas effectively absorbs the VUV-UV radiation of the streamer, and its spectrum is observed only in the visible region of the spectrum. On the contrary, in the case of a volume gas discharge with the same length of the interelectrode gap, the discharge emitting area (~ 2 cm²) is several orders of magnitude larger than the emitting area of the streamer, the dynamic resistance of the volume discharge becomes insignificant, the discharge duration drops to less than 1 ns, and its power exceeds the power of the streamer discharge by four orders of magnitude.

The emission spectrum of a volume discharge in xenon has the form of a continuum, against the background of which individual lines are recorded, and lies in the VUV-UV range at λ < 400 nm (figure 3). Since a monotonic rise in intensity is observed in the spectrum of a volume discharge up to the short-wavelength boundary of the registration range (figure 3, curve 1), it is natural to assume that the maximum and the main part of the spectrum lies in the shorter-wavelength range. In [9], based on the results of studies the intensity distribution of VUV-UV radiation of this volume discharge in the range of 0.12–400 nm and fitting by the Planck distribution, it was concluded that the maximum of the reconstructed model spectrum is located at a wavelength of λₘ ≈ 30 nm. Thus, the pulsed temperature of the volume discharge plasma reaches 10⁵ K.

Under our experimental conditions, a weak intensity of the VUV emission lines of Xe₂⁺ dimers is observed with respect to the thermal VUV radiation (figure 3). In accordance with the results [10], it can be assumed that this result may be due to the suppression of the formation of Xe₂⁺ dimers during the process of electron recombination with Xe⁺ ions by thermal destruction on the stage of associatively formed dimers at a non-stationary plasma temperature of 10⁵ K.

3. Conclusions

Thus, the work demonstrates a method for obtaining in gaseous media a high power volume picosecond discharges emitting in the VUV-UV spectral range (110–420 nm). The results, the scheme, and the conditions for achieving the generation of picosecond (200 ps) high-power (1.2 MW) UV
(λ = 337 nm) laser pulses with picosecond high-current electric-discharge pumping of N\textsubscript{2} gaseous media with a pressure of up to 3 atm are presented.

Based on the analysis of experimental data of VUV-UV spectroscopy of high-power volume picosecond discharges in xenon, the presence of short-lived absorption of VUV radiation by plasma has been experimentally established. In addition, a mechanism was considered for the suppression of the process of electrostatic creation of \text{Xe}_2^* dimers due to their thermal destruction even at the stage of electron recombination with \text{Xe}^+ ions during a pulse pumping time of 200 ps at a non-stationary plasma temperature of 10\textsuperscript{5} K.

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