Sources of high-power short-pulse UV radiation

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We have studied experimentally the power and time characteristics of a short-pulse radiation of the discharge plasma. The maximum output pulse power density was obtained from a high-pressure volume discharge formed in a planar excilamp with the UV preionization in the discharge gap. At the mixture pressure of several atmospheres the output power density was 5 kW/cm^2 at $\lambda \sim 250$ nm and 3.5 kW/cm^2 at $\lambda \sim 222$ and 308 nm. In a cylindrical excilamp with the internal electrodes, the pulse power of 75 kW was obtained in the Xe–I_2 mixture, and in a similar capacitive discharge KrCl excilamp ($\lambda \sim 222$ nm) it was up to 2.5 kW through the lamp end of 10 cm^2 area. It was shown that the use of a capacitive discharge allows the excilamp service life to be increased.

In recent years the interest in creation of UV lamps excited by a pulsed discharge in rare gases, halogens, and their mixtures has strongly increased.[1–5] Such sources of radiation can receive a wide use in various fields, for example, in microelectronics.

In this paper we consider the amplitude-temporal characteristics of the radiation of KrCl, XeCl, KrF, and XeI excilamps. These lamps have a simple design and are excited by short-pulse discharges of different types. The conditions, at which the output power density and the pulse power in the UV spectral region are maximum, are sought.

1. Experiment

In our experiments we used excilamps of three types: a glow-discharge cylindrical lamp (first type), a high-pressure volume discharge lamp with the UV preionization in the discharge gap (second type), and a capacitive discharge lamp having no electrodes (third type).

The lamps of the first type were made of cylindrical quartz tubes (with the transmittance higher than 80% in the region of 200–300 nm wavelengths). Nickel or stainless steel electrodes were set at the tube ends together with flanges for gas bleeding-in and evacuation.

We also used the lamp of the second type described earlier in Ref. 1. This lamp was pumped by a self-maintained pulsed discharge with the UV preionization. The discharge was formed between a grid electrode 8 cm in diameter and a solid electrode with the diameter varying from 4 to 7 cm. The radiation from the volume discharge escaped from the lamp through the grid electrode and quartz or CaF_2 exit windows of 90–120 mm in diameter. The diameter of the light beam was determined by the size of the area occupied by the volume discharge between the electrodes, as well as the distance from the grid to a screen in which plane measurements were conducted. The beam diameter at the exit from the lamp was roughly 8 cm, and then it increased linearly with the distance from the exit window. To form the volume discharge at a high pressure, we used preionization from spark gaps distributed evenly around the main electrodes.

In the lamp of third type pumped by the capacitive discharge, the radiation was exited through a plane quartz window at the tube end. Inner electrodes were made of aluminum foil tightly pressed to the surface of the quartz tube. The lamp was evacuated and filled with binary mixtures of krypton (xenon) and Cl_2. For convenience the design parameters of the excilamps, parameters of the pump sources and their gas composition are tabulated below.

Two different circuits were used for excitation of the excilamps. The lamps of the first and second types were excited by a generator consisting of a controlled spark gap or thyratron K and an energy storage capacitor C_g. The lamps were connected to it in series (Fig. 1). A TGI1–1000/25 thyratron served a switch in the repetitively pulsed mode. The generator provided the charge voltage U_g up to 30 kV and the pulse repetition frequency up to 100 Hz. The lamp of the third type was excited by a thyristor-magnetic generator, whose detailed description can be found in Ref. 6. The generator provided voltage pulses with the amplitude up to 36 kV and duration from 120 ns to 5 μs. The leading edge duration was variable, and in our experiments it was 3, 0.6, 0.19, and 0.04 μs. Besides, in the latter case an additional resistor R_v or inductance L_v was used to match the generator and the lamp of the third type.

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Table 1. Parameters of excilamps and power supply

Lamp type	Discharge area dimensions: diameter/length, cm	Working mixture, Torr	Voltage pulse repetition frequency, Hz/Charge voltage U_g, kV	C_g, nF/ R_v, kΩ/ L_v, μHn
First	1.5 / 1.5 4.3 / 45	Xe (10) + I_2 Xe (10) + I_2	1 – 50 / 15 1 – 50 / 10	9 / – / –
Second	1.5 – 8 / 1.5 – 2.9	Ne + Kr + Hq l Ne +Xe + HCl	up to 5 / 32	4.4 / – / –
Third	3.8 / 3.6	Kr + Cl_2 Xe + Cl_2	250–1000 / up to 36	0.25 / 0.1–100 / 0.25–40

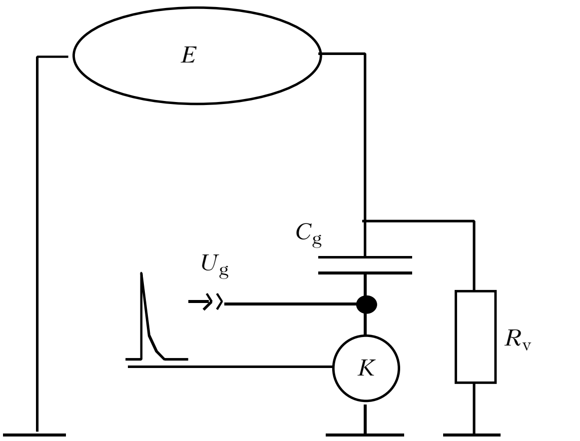

Fig. 1. The circuit of connections of a pulsed power supply to excilamp E: power supply voltage U_g, switch K, energy storage capacitor C_g, elements R_v and L_v for charging C_g and controlling the excitation pulse duration.

Current and voltage were measured by an ohmic shunt and voltage divider, whose signals came to an S8–17 double-beam oscilloscope. The mean and pulse output power in a given wavelength range were measured with a FEK–22 SPU vacuum photodiode with the known spectral sensitivity in the visible and UV spectral regions. The signal from the photodiode came to a pulsed voltmeter or the S8–17 oscilloscope.

Working mixtures were prepared directly in the lamp, which was filled in turn with halogen (Cl_2, HCl), rare gas (Xe, Kr), and a buffer gas (Ne, He).

2. Results and discussion

Earlier, in Ref. 5, we have studied the discharge in mixtures of Xe with the iodine vapor. In this case the emission spectrum contained the bands of I_2* and XeI* molecules in the spectral region roughly from 250 to 350 nm. We studied the amplitude-temporal characteristics of the pulsed longitudinal discharge in cylindrical excilamps, whose discharge volumes differed significantly: 2.6 and 653 cm^3. Under conditions that are optimal, from the viewpoint of the maximum efficiency, we have obtained the pulse power of 2.5 and 75 kW, respectively, for the lamps of the first and second types. The energy per pulse was $0.3 \cdot 10^{-3}$ and $7.5 \cdot 10^{-3}$ J with the efficiency of $3 \cdot 10^{-2}$ and 3%. From this it follows that although longitudinal-discharge and small-volume excilamps provide high output power density as compared with the large-volume excilamps, their efficiency turned out to be far lower than the efficiency of large-volume excilamps. This is explained by the fact that as the pump power increases, the emission efficiency of exciplex molecules decreases. Besides, a lamp with a large electrode gap can be more readily matched with a capacitive generator. Note that in the described cases the discharge contraction in a lamp occurred as the energy deposition and (or) pressure increased. In this connection it is interesting to obtain a high pulse power in a volume discharge with the use of the UV preionization. For this purpose the lamp of the second type was used.

The shape of the discharge in this lamp depended on the diameter of the solid electrode and the pressure of mixture components (to the highest degree, on the Xe(Kr) and hydrogen chloride pressure and, to a lower degree, on the pressure of the buffer gas Ne). The pulse power increased as the electrode gap and the electrode diameter increased (at unchanged U_g and C_g). The optimal mixtures from the viewpoint of maximum output power corresponded to those used in similar XeCl, KrF, and KrCl lasers. At the mixture pressure of several atmospheres the output power density was 5 kW/cm^2 at λ ~ 250 nm and 3.5 kW/cm^2 at λ ~ 222 and 308 nm. The discharge contraction (Fig. 2) decreased the UV radiation output and, besides, led to electrode destruction with time.

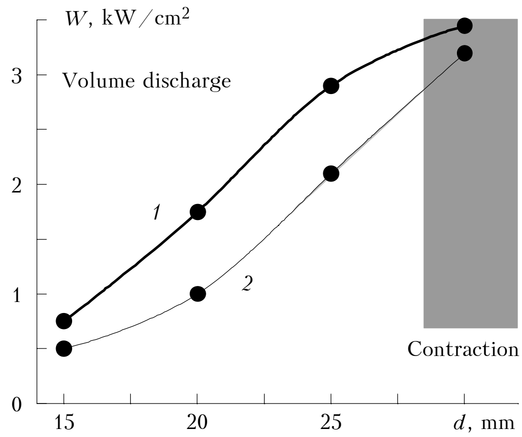

Fig. 2. Pulse power vs. electrode gap size in a lamp of the second type with the UV preionization. Mixture Ne:Kr:HCl = 3 atm:50 Torr:3 Torr. Solid electrode is 40 mm (a lamp of the first type) and 75 mm (a lamp of the second type) in diameter. Charge voltage U_g = 36 kV, energy storage capacitor C_g = 4.2 nF.

The lifetime of a working mixture with chlorine in excilamps can be increased by using lamps without electrodes, similar to the excilamp of the third type, to obtain the pulsed discharge. For tests we took binary mixtures at the total pressure up to 2 Torr. The shape of the radiation pulse from the capacitive discharge excilamps strongly depended on the resistance and inductance of the elements connected in parallel with the lamp. For example, we varied the resistance R_v (see Fig. 1) from 100 kΩ to 100 Ω. The pulse shape in this case transformed from multipeak, which is traditional for capacitive discharge lamps, to a single-peaked. Simultaneously, the pulse power dropped down. This result can be explained, in particular, by the fact that voltage oscillations arise across the lamp at large R_v because of the capacitive character of the load.

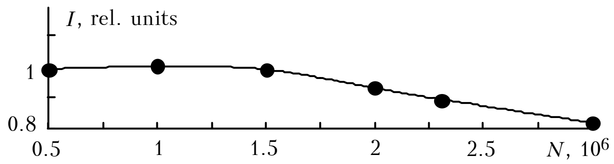

Fig. 3. Output intensity of capacitive discharge XeCl excilamp vs. the number of pulses in the mixture $Kr:Cl_2$ = 25:1 at the total pressure of 2 Torr.

In the mixtures optimal from the viewpoint of the maximum output power ($Kr/Cl_2 = 25/1$) and at the total pressure ~ 0.2 Torr, the pulse power through the lamp end (end area about 10 cm^2) was 2.5 kW. If we assume that the light flux is not limited by lamp elements (electrode, scattering at the places where quartz tubes are sealed to the plane end) and estimate the UV radiation in the angle of 4π, then its value is about 15 kW.

A distinguishing feature of the capacitive discharge excilamps is long operation in the quasi-sealed-off mode as compared with the lamps of the first and second types. For example, in Ref. 3 it was reported that after about 10^4 pulses the intensity of a XeCl excilamp decreased by one third. At the same time, in our experiments (see Fig. 3) the intensity remained almost unchanged after ~ 10^6 pulses.

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