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High-power UV excilamps excited by a glow discharge

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Abstract

The results on study of light sources based on spontaneous radiation of molecules KrCl* ($\lambda \sim 222$ nm) and XeCl* ($\lambda \sim 308$ nm) excited by a glow discharge are presented. It is demonstrated that additions of light inert gases (He and Ne) lead to increase in emission of radiation power and efficiency in mixtures Kr(Xe)-Cl_2. A high-power cylindrical multi-section excilamp was built and energy, time, and spectrum characteristics have been studied. Average output power obtained in the UV spectral range were 1,9 kW at $\lambda \sim 222$ nm and 1,1 kW at $\lambda \sim 308$ nm with efficiencies with respect to the excitation power of up to 14%.

Keywords: Excilamp; XeCl; KrCl; Glow discharge

1. INTRODUCTION

Today spontaneous radiation light sources based on utilizing of excimer and exciplex molecules radiation are intensively studied and find increasingly wide application in various fields of science and engineering (Obara, 1995; Arnold *et al.*, 1998; Kogelschatz, 2002). These sources were named excilamps (Boichenko *et al.*, 1993*a*) and allow to obtain high efficiencies moderate (10%) of spontaneous radiation on bound-free transitions of molecules R_2^* and RX* (R is an atom of inert gas, X is the atom of halogen) rendering comparatively narrow UV and VUV bands (Rhodes, 1979; Gerasimov *et al.*, 1992). Various methods are used for excilamps excitation: e-beam (Boichenko *et al.*, 1993, 2000), a barrier discharge (Volkova *et al.*, 1984; Kogelschatz & Esrom, 1990; Kogelschatz, 2002; Tarasenko, 2002), a longitudinal pulsed discharge (Gerber *et al.*, 1980; Taylor, 1991), microwave discharge (Kumagai & Obara, 1989*a*, 1989*b*; Hatakeyama *et al.*, 1991; Kumagai & Toyoda, 1991), transverse discharge with UV preionization (Koval *et al.*, 1992; Skakun *et al.*, 1992; Boichenko *et al.*, 1993*a*, 1993*b*; Kuznetsov *et al.*, 1993), and so on. One of the simplest ways to excite excilamps is a stationary glow discharge in a mixture of inert gases with halogens under low-pressure operating mixture. This type of discharge was first applied for excitation of cylindrical excilamps in the papers by Golovitski (1992) and Golovitski and Kan (1993). In a quartz tube, at excitation of krypton and xenon mixture with halogen Cl_2, correspondingly, on molecules of XeCl* and KrCl*, the average values of radiation power of ~ 8 W and efficiency of up to 12% were obtained. In our papers, (Panchenko *et al.*, 1995, 1999*a*; Lomaev *et al.*, 1997, 1998; Tarasenko *et al.*, 1999; Tarasenko, 2001) we reported on creation of coaxial and cylindrical KrCl and XeCl excilamps excited by a stationary glow discharge providing average radiation power in of 100–200 W in the UV spectral range. In more detail, the study of excitation modes by a glow discharge has shown that the maximum efficiencies of excilamps are achieved using excitation pulses of millisecond duration of a specific shape (Panchenko *et al.*, 1997*b*). In the patent by Panchenko *et al.* (1997*a*) it was presented that the maximum emission radiation power values are realized with light inert gases (He, Ne) admixtures to Kr(Xe)-Cl_2.

The aim of this work was to create KrCl ($\lambda \sim 222$ nm) and XeCl ($\lambda \sim 308$ nm) glow discharge excited excilamps with average emission power above 1 kW constructing which is rather simple and cheap emitter excimer radiation with also simple power supply unit.

2. DESIGN OF EXCILAMP AND POWER SUPPLY UNIT

The circuit of excilamp selected after preliminary studies is shown in Figure 1. The set-up consisted of excilamp emitter and power supply units. The emitter consisted of three parallel branches, each including four sections (total 12) representing cylindrical quartz tubes with 2.5-mm-thick walls.

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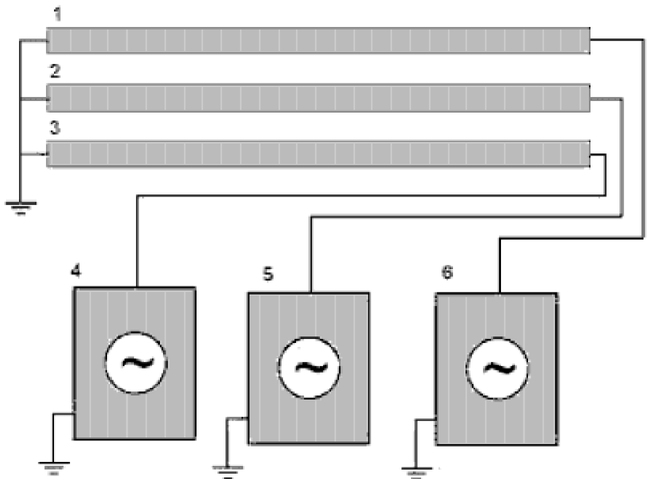

Fig. 1. Block-diagram of connection of excilamp modules to power supply units. *1*, *2*, *3*—excilamp modules; *4*, *5*, *6*—power supply units.

The sizes of one section of the excilamp are as follows: length is about 100 cm, internal diameter is 47 mm (for one branch), and 51 mm (for two other branches). The glass-shape electrodes made of stainless steel were mounted at the edges of each branch or separate section. Short stainless steel pipes connected sections. Vacuum rubbish plates were used for joint packing. Each branch had a separate power supply unit. Every section and every branch could be operated independently. The excilamp was air-cooled. Every section and every branch could be operated independently. The excilamp was air-cooled. Each power supply consisting of a transformer and a voltage regulator produced a sinusoidal voltage of commercial frequency (50 Hz) with amplitude of up to 20 kV (smoothly controled) and power of up to 7 kW. This design of the emitter and the power supply units probably offers the simplest variant ensuring an average emission radiation power of 1 kW and above.

When constructing excilamp, a separate section was taken and studied carefully. Quartz tube length was varied from 60 to 180 cm, and internal diameter changed from 24 to 60 mm. Different cooling-systems were used. In a number of cases, an additional quartz tube was placed internally with the main cylindrical tube and operating mixture. Water-cooling was realized by flowing water of 5–10°C inside the additional quartz tube. Based on preliminary experiments, air-cooling was selected. Replacing air cooling system by a water jacket does decrease excilamp sizes (the length of coaxial excilamp discharge tube was 60 cm and the average emission radiation power reached 200 W) but essentially complicates emitter design.

The emission radiation power was measured by a calibrated FEK-22 SPU photodetector sequentially moved along each branch of the excilamp. For several sections the distribution of emission radiation power was either examined in all directions in the plane perpendicular to the tube axis. The lamp current and voltage pulses and output emission intensity were measured by current probes, voltage dividers, FEK-22SPU, and TDS-224 oscilloscope. The glow discharge was photographed using a digital camera. The working gas mixtures of krypton or xenon with molecular chlorine and (in the experiments with admixtures) helium were prepared immediately inside the emitter tubes of excilamp.

3. RESULTS AND DISCUSSION

Characteristics of radiation of one section and one branch of excilamp. As we noted earlier, we have separately tested one section and one branch of excilamp using cylindrical tubes with various diameters. A sine alternating voltage was applied to tubes from a commercial network transformer (50 Hz). Figure 2 shows the plots of emission radiation power, current and voltage taken for one branch, as well as calculated curve of excitation power. It is seen that the emission radiation pulses concord by duration to current pulses and excitation power, and their amplitude does not depend on polarity of voltage and current pulses. The breakdown occurs within every voltage pulse half-period, and at decreasing of voltage the discharge current decreases up to zero, then it is discontinued, and there is a delay before the

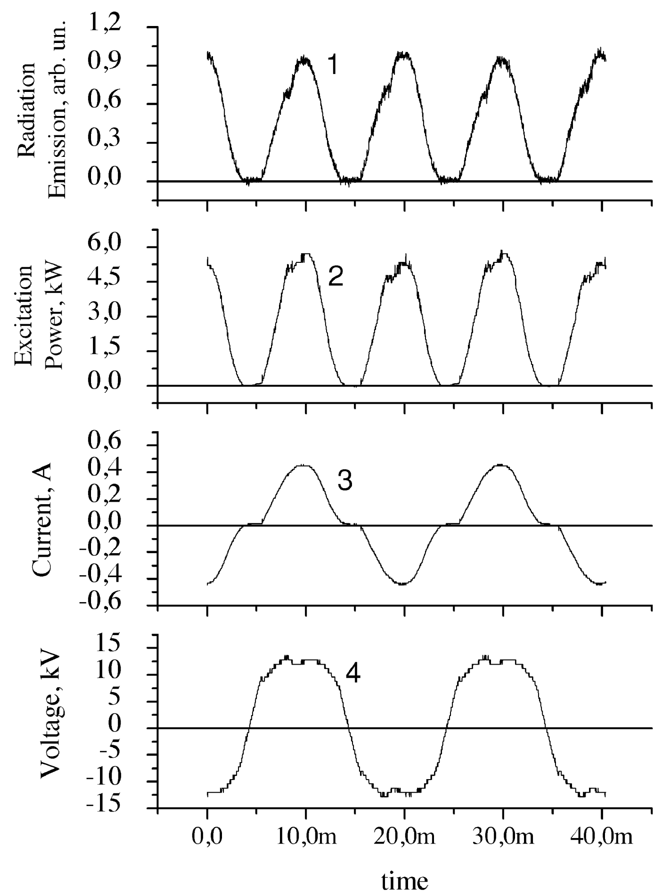

Fig. 2. Oscillograms of emission radiation (*1*), current (*3*), voltage (*4*) and calculated curve of excitation power (*2*) of $KrCl_2$ excilamp excited by glow discharge (one branch).

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next breakdown of working mixture. The main results of energy characteristics of excilamp are:

1. When using long air-cooled tubes (~2 m and above) the higher values of emission radiation power are achieved in the case with the internal tube diameter of ~50 mm.
2. Maximum emission radiation efficiencies (up to ~20% on KrCl* molecules and up to ~15% on XeCl* molecules) are reached at a relatively small discharge average current of ~0.05 A. Discharge current increasing (in these experiments of up to 0.4 A) through one branch leads to an increase in average emission radiation power, but the efficiency with respect to excitation power decreases (Figs. 3 and 4).
3. Helium admixture results in an essential increase in average emission radiation power and efficiency both on KrCl* and XeCl* molecules (Figs. 3–5). And the increase of average emission radiation power is more appreciable with the higher excitation power. The reason for such an effect is probably connected with high thermal conductivity of helium.
4. Replacement of air-cooling system by a water jacket leads to increase in specific emission radiation power hence the design of the discharge tube becomes complicated. Water-cooled coaxial excilamps are described in Panchenko *et al.* (1995) and Lomaev *et al.* (1997).
5. With discharge tubes of smaller diameters the optimal pressure of working mixture and operating voltage increase.
6. Increase in the length of discharge tube results in increase of the total emission radiation efficiency due to relative loss saving in the near-cathode and near-anode discharge areas.

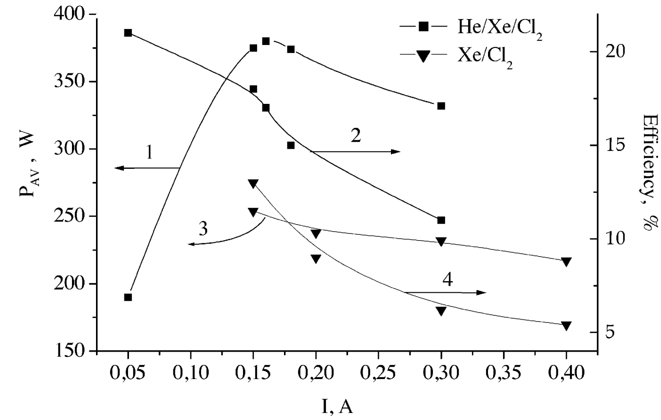

Fig. 4. Dependences of average power and efficiency of radiation of excilamp versus discharge current at excitation of working gas mixtures He:Xe:Cl_2 = 2:5:1 with total pressure of 0.2 Torr (*1*, *2*); Xe:Cl_2 = 5:1 with total pressure of 0.3 Torr (*3*, *4*). Length of branch is 4 m, internal diameter of tube is 51 mm.

Characteristics of excilamp's emission radiation. Based on the above described results, an excilamp was built. It is shown in the working mode in Figure 6 (the excilamp's design is illustrated in Fig. 1). Figure 7 presents the results of excilamp's testing as a whole and of separate branches in the mixture of He/Kr/Cl_2. The plots of emission radiation power versus discharge current for each separate branch of KrCl excilamp, and for the whole excilamp emitter are shown in Figure 7. Analogous dependences take place for the working gas mixture He/Xe/Cl_2. The higher radiation power values were achieved with quartz tubes internal diameter of 51 mm. When testing one separate emitter branch consisting of of four sections, an average emission radiation power was about 0.7 kW at 222 nm with efficiency of ~12% with respect to excitation power (for 51-mm internal diameter tubes). Three branches operating simultaneously produced an average emission radiation power of 1.9 kW with effi-

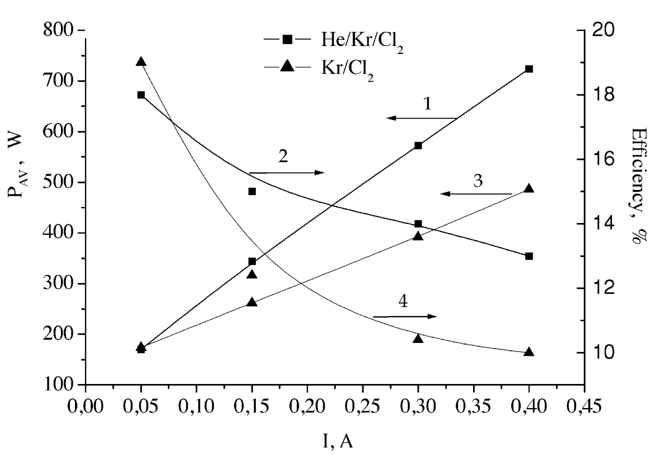

Fig. 3. Dependences of average power and efficiency of radiation of excilamp versus discharge current at excitation of working gas mixtures He:Kr:Cl_2 = 2:5:1 with total pressure of 0.3 Torr (*1*, *2*); Kr:Cl_2 = 5:1 with total pressure of 0.4 Torr (3, *4*). Length of branch is 4 m, internal diameter of tube is 51 mm.

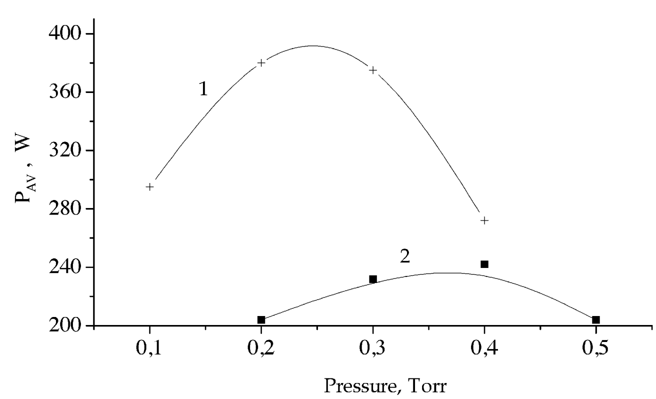

Fig. 5. Dependences of average power of excilamp emission on the total pressure of working mixtures He:Xe:Cl_2 = 2:5:1 (*1*); Xe:Cl_2 = 5:1 (*2*). Length of branch is 4 m, internal diameter of tube is 51 mm.

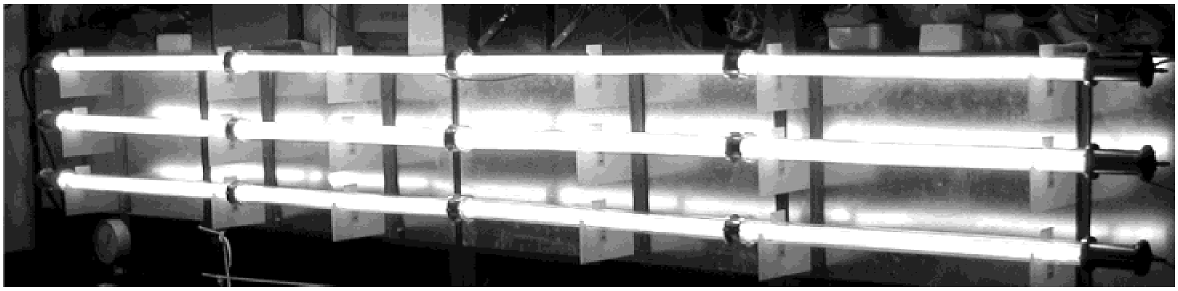

Fig. 6. Excilamp's appearance in operating mode.

ciency above 10%. It should be noted that the high-power excilamp operation is accompanied by formation of ozone and nitrogen oxides in large concentrations, which requires taking measures for laboratory personnel protection.

When krypton was replaced by xenon, the breakdown voltage and resistance of the gas discharge plasma increased and emission radiation power decreased at a comparatively low current, 0.15 A, Figure 4. For this reason, the maximum average power of emission from XeCl* molecules was ~1.1 kW, which is lower when compared with power values for KrCl* molecules, Figure 7. The average emission radiation power of one emitter branch was ~0.4 kW with 51-mm internal diameter quartz tubes, and ~0.3 kW with 47-mm tubes.

For both binary and ternary gas mixtures, a maximum pumping efficiency was observed at small discharge currents and amounted to ~20% for KrCl and XeCl excilamps. The working pressures of the gas mixture in this excilamp were lower as compared to those ones used in the papers by Panchenko *et al.* (1995) and Lomaev *et al.* (1997). That is explained by the larger cross sections of the discharge area and the lower voltages of power supply per unit length of the emitter. When the discharge current density was increased, the maximum average powers of emission for both exciplex molecules were observed in ternary mixtures with helium admixture. The optimal contents of helium were 20–30%. The obtained parameters are not limiting and can be increased by using supply units of higher power and voltage, by increasing pressure of working gas mixture, as well as by improving cooling regime of quartz tubes and electrodes. It should be noted that that the cathode and anode potential drop was observed only at the ends of separate branches (in the terminal emitter sections). The central sections of the excilamp exhibited only a positive glow discharge column resulting in increase of emission radiation efficiency. The three excilamp branches turned on in series can give an increase in power and efficiency of about 15% providing that the voltage applied to excilamp were three times higher.

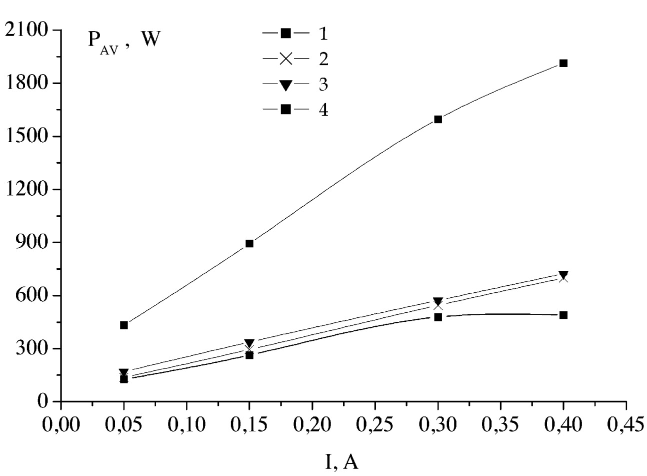

Fig. 7. Dependences of radiation power on discharge current done for separate branches of excilamp with internal radius of tube of 47 mm (*1*), 51 mm (*2*, *3*), total output power of the three excilamp branches (*4*) for He:Kr:Cl_2 = 2:5:1 mixture under the total pressure of 0.3 Torr.

The emission spectrum of the new emitter is typical of the excilamps excited by a glow discharge (Fig. 8). The main emission radiation power (>70%) is concentrated in the B-X band.

In this excilamp, the decay time of emission of radiation power up to the half of the initial value depended on excitation power comprising ~1 min at excitation power maximum. That time could be increased either by more intensive cooling of the excilamp and selecting materials for electrodes and consolidation or using additional buffer volume and slow pumping of the working gas mixture. The last method is widely used in creation of exciplex lasers pumped by electric discharge.

4. CONCLUSIONS

As a result of this study, the data on optimum excitation conditions of KrCl and XeCl excilamps by glow discharge have been obtained. In particular, a considerable increase in average emission radiation power and efficiency has been demonstrated when 20–30% of the helium was added into the working mixture. This increasing effect is observed with high discharge currents.

A high-power cylindrical excilamp was built and characteristics of excilamp at two wavelengths in the UV spectral range have been studied. The average emission radiation power of ~1.9 kW on the molecules KrCl* ($\lambda \sim 222$ nm)

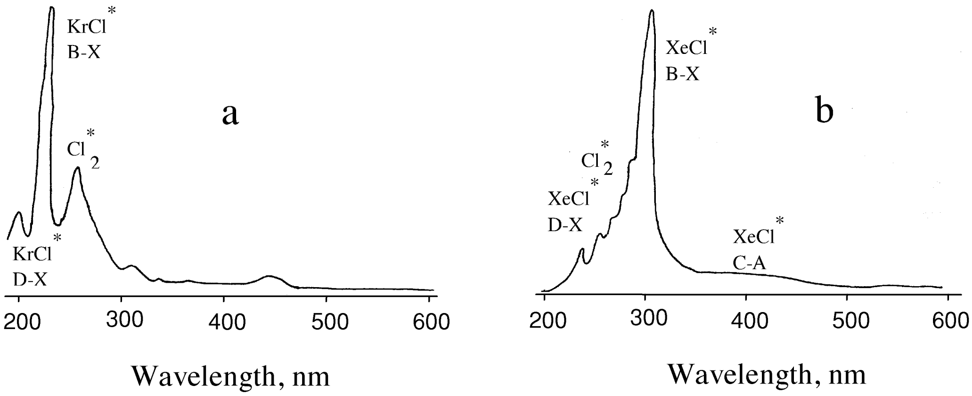

Fig. 8. Emission spectrum of the glow discharge excilamp for the mixtures Kr-Cl_2 (*a*), Xe-Cl_2 (*b*).

and ~1.1 kW on the molecules XeCl* ($\lambda \sim 308$ nm) with efficiency 10% with respect to excitation power have been achieved. With excitation power decrease, the maximal efficiencies of emission radiation were 20%.

This excilamp can be used with other working mixture to obtain a high-power spontaneous emission (~1 kW and above) at transitions of other molecules and atoms, for e.g., XeBr* ($\lambda \sim 282$ nm), XeI* ($\lambda \sim 253$ nm), I ($\lambda = 206$ nm), Br_2 ($\lambda = 291$ nm), Cl_2 ($\lambda = 258$ nm) etc.

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