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Once again on the role of UV illumination in non-chain electric-discharge HF(DF) lasers

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Abstract. **The influence of UV illumination of a discharge gap on the stability and homogeneity of a volume self-sustained discharge (VSD) in working mixtures (SF_6 with hydrocarbons) of a non-chain HF laser is studied in broad ranges of the discharge-current duration and the energy deposition. It is shown that the UV illumination in lasers with the cathode area $S \leqslant 300$ cm^2 and in lasers with the current-pulse duration $T \leqslant 150$ ns stabilises the delay time and the voltage amplitude of the electric breakdown of the gap and leads to the levelling (due to photoeffect) of the VSD current density distribution over the cathode surface. The volume preionisation of the working mixture of a non-chain HF laser by UV radiation is impossible because of strong absorption of this radiation by SF_6. There is no need in UV illumination in wide-aperture, large-volume lasers when small-scale (~ 50 μm) inhomogeneities are present on the cathode surface.**

Keywords: *non-chain HF(DF) laser, volume self-sustained discharge, preionisation, UV illumination.*

1. Introduction

The main problem in the development of high-power non-chain HF(DF) lasers with a chemical reaction initiated by a volume self-sustained discharge (VSD), as for other gas lasers operating at medium and high gas pressures, is the production of the VSD itself. To initiate the VSD in dense gases, a number of basic conditions should be fulfilled [1]. First, it is necessary to perform preionisation of a gas (for example, by an electron beam, UV radiation or soft X-rays) for producing the initial electron concentration in the gas volume required for the development of electron avalanches when a high-voltage pulse is applied to a discharge gap. Second, during the VSD initiation in a laser medium, it is necessary to provide a homogeneous electric field in the discharge gap for uniform excitation of the active medium. These requirements should be strictly fulfilled in most gas lasers (CO_2, N_2O, excimer lasers) because the VSD stability, the output energy, and the lasing efficiency depend on the preionisation level.

The analysis of papers devoted to non-chain electric-discharge HF(DF) lasers reveals one special feature of these lasers: despite different experimental conditions, types and power of preionisation sources used in experiments (X-rays, UV radiation, barrier discharge), the results obtained by different authors were close. For example, the authors of papers [2, 3] obtained the same output energy for the HF lasers equal to 11 J, although no preionisation was used in Ref. [3], while in Ref. [2] preionisation was performed by a high-power X-ray pulse emitted by a high-current creeping discharge. Note that the efficiency of the laser studied in Ref. [3] was higher by a factor of 1.9 than that in Ref. [2]. This suggests that the role of preionisation in non-chain HF(DF) lasers is not so important as in other gas lasers.

Indeed, a self-sustained discharge in working mixtures of a non-chain HF(DF) laser (mixtures of SF_6 with hydrogen- and deuterium-containing substances) substantially differs from discharges in other, less electronegative gases [4 – 7]. It can develop as the VSD in the absence of preionisation (as the self-initiated volume discharge [6]). The volume V of an active medium in Refs [4 – 7] was varied from 0.05 to 60 L, the cathode surface was $S = 12 - 2000$ cm^2, the interelectrode distance was $d = 2 - 27$ cm, and the partial pressure of SF_6 in the mixture was $p_{SF_6} \leqslant 120$ Torr. The presence of small-scale (~ 50 μm) inhomogeneities on the cathode surface, which appeared, for example, after cathode sandblasting, proved to be the necessary and sufficient condition for the initiation of a volume discharge both in a homogeneous electric field and in gaps with the high edge enhancement of an electric field. Preionisation performed by different methods had little effect on the VSD stability and the output parameters of the laser. However, the authors of some papers, including recent papers [8 – 11], found that the VSD stability and the output energy of the HF laser were increased due to preionisation of the laser medium both by soft X-rays [11] and UV radiation [8 – 10].

In this connection we decided to consider again the role of preionisation in non-chain electric-discharge HF lasers. For this purpose, we studied the influence of UV illumination on the VSD stability and homogeneity in working mixtures of the HF laser in broad ranges of the discharge-current duration and the energy deposition. We also analysed the results of Ref. [11], where the active medium of the HF laser was preionised by soft X-rays.

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2. Experimental setup

Figure 1 shows the scheme of the setup for studying the VSD. The discharge was ignited in the SF_6: $C_2H_6 = 10 : 1$ mixture at the pressure $p = 33$ Torr and the interelectrode distance $d = 4$ cm between a disc cathode of diameter 6 cm, which was rounded off over the perimeter of radius 1 cm and sandblasted, and a grid anode behind which four parallel spark gaps were located for UV illuminating the discharge gap. The capacitances of capacitors used in the setup were $C_1 = 4 - 15$ nF and $C_2 = 680$ pF (capacitor C_2 consisted of four 170-pF capacitors, each of them being discharged in its own spark gap).

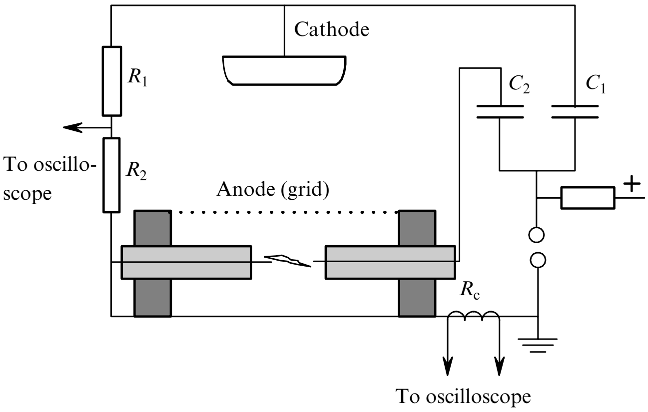


Figure 1. Scheme of the setup for VSD studying.

The capacitor C_2 was not used when the VSD was ignited without UV illumination. In these experiments, high-voltage leads of spark gaps for illumination were grounded. The current and voltage across the VSD were controlled with a Rogowski coil R_c and a R_1/R_2 voltage divider, respectively. The discharge homogeneity (the degree of the overlap of diffusion channels determined by the surface density of cathode spots) was estimated from photographs of the discharge gap. The VSD stability in the case of UV illumination and without it was characterised by the dependence of the limiting energy $W_{\text{lim}} = C_1U^2/2$ accumulated in the capacitors, at which the VSD still did not transform to a spark, on the circuit parameter $T = \pi(LC_1)^{1/2}$ determining the discharge-current duration, where U is the voltage across C_1 and L is the circuit inductance. The higher W_{lim} for the specified T, the better the VSD stability.

3. Experimental results

Figure 2 shows the dependences W_{lim} on the circuit parameter T obtained with UV illumination and without it. The limiting energy weakly depends on illumination over the entire range of the VSD current duration. Figure 3 demonstrates the photographs of emission of the cathode region of the discharge, which were obtained for different values of T and the energy W_{in} supplied to the plasma in the presence and absence of UV illumination. The emission was photographed so that diffusion channels (attached to cathode spots) that were less bright than cathode spots were not detected. The surface density of cathode spots characterises the degree of overlap of the channels attached to them and eventually the VSD homogeneity. One can see from Fig. 3 that, when the discharge current duration is long enough, $T = 260 - 270$ ns, the density of cathode spots and the uniformity of their distribution over the cathode surface are almost independent of UV illumination. Both in the presence and absence of UV illumination, the total number of spots and their density increase with the energy deposited into plasma, in accordance with our earlier results [6, 7]. In the case of a short discharge, for $T = 130$ ns (Figs 3a, b), in the absence of illumination, the region in which bright spots are observed occupies only a part of the cathode surface. This also agrees with our result [6] and is explained by a finite velocity of the discharge propagation (recall that we deal in this case with a self-initiated volume discharge [6]) perpendicular to the electric field after the initial breakdown of the discharge gap without illumination in the region of edge enhancement of the field.

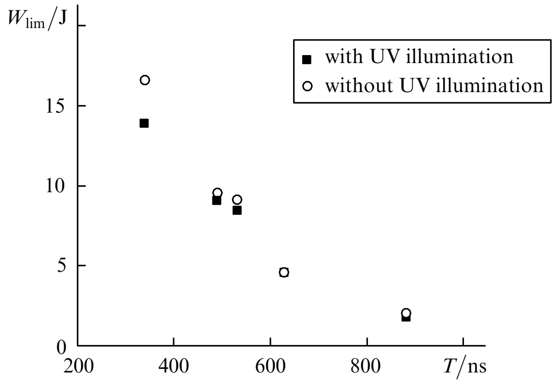


Figure 2. Dependences of W_{lim} on T in the presence (■) and absence (○) of UV illumination.

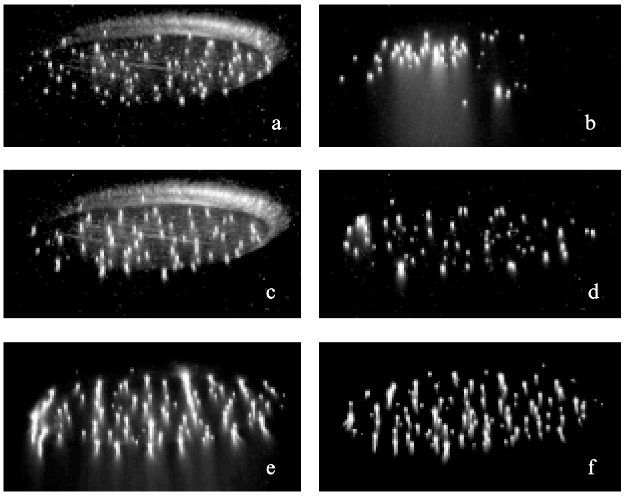


Figure 3. Photographs of emission of the cathode region of the discharge with UV illumination (a, c, e) and without it (b, d, f) for $W_{\text{in}} = 1.4$ J and $T = 130$ ns (a, b), $W_{\text{in}} = 1.4$ J and $T = 270$ ns (c, d), and $W_{\text{in}} = 10$ J and $T = 260$ ns (e, f).

Figure 4 shows the dependences of the total number N of spots on the cathode on the energy W_{in} deposited into plasma for the fixed VSD current density ($T = 260 - 270$ ns) obtained in the presence and absence of UV illumination.

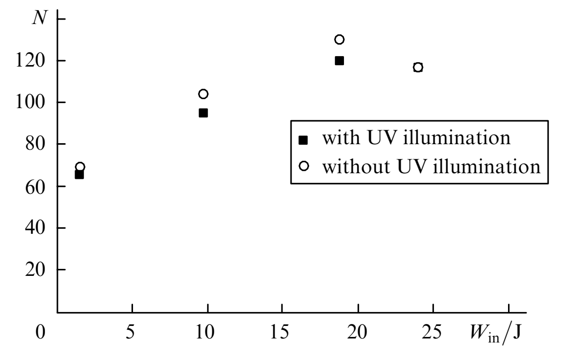


Figure 4. Dependence of the number N of cathode spots on the energy W_{in} deposited into plasma in the presence (■) and absence (○) of UV illumination.

The number of spots increases with the energy deposition and is almost independent of illumination. The decrease in N at high energies is caused by the beginning of the VSD contraction due to the growth of a spark channel from a cathode spot to which the discharge current contracts.

Figure 5 shows the dependence of the total number of spots on the cathode (without illumination) on T for the fixed energy deposition. The parameter N weakly depends on T and decreases at large T due to the beginning of the VSD contraction, as at large energy depositions.

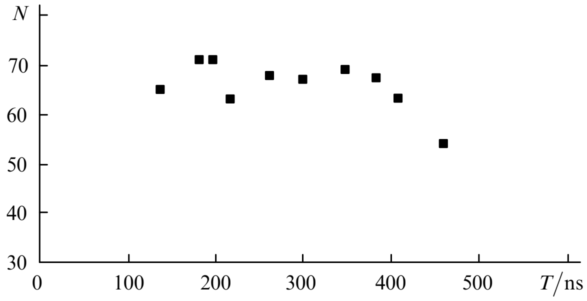


Figure 5. Dependence of the number N of cathode spots on T for the fixed energy deposited into the discharge plasma (without UV illumination).

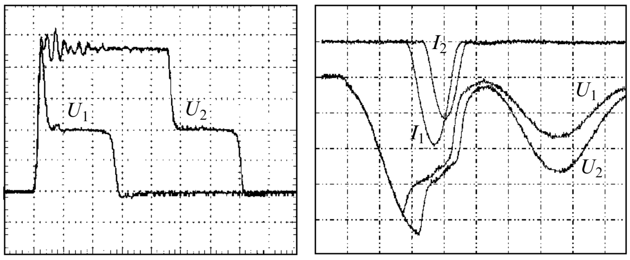
4. Discussion of results

Therefore, UV illumination does not affect substantially the VSD stability and homogeneity in working mixtures of the electric-discharge non-chain HF laser. What is then the reason for the dependence of the output energy of the HF laser on the UV illumination observed in some papers?

Note first of all that UV radiation cannot in principle provide the volume ionisation in wide-aperture non-chain HF(DF) lasers because it is strongly absorbed by SF_6, i.e., in this case the term 'preionisation' cannot be applied in its usual sense [1]. Let us illustrate this by a simple estimate. By using the data on absorption of UV radiation in SF_6 [12], we can readily show that, for the typical partial pressure of SF_6 in the HF laser equal to 60 Torr, the mean free path of a photon of energy ~ 11 eV, which is close to the ionisation potentials of 'heavy' hydrocarbons (hydrogen donors), does not exceed ~ 5 mm. This value is obviously too small to suggest the possibility of UV preionisation even in small HF lasers.

What is in this case, however, the role of UV illumination in HF(DF) lasers? When the photon energy is lower than 5 eV, the UV radiation is very weakly absorbed in SF_6 [12], and the UV illumination of a discharge gap even by a low-current (~ 1 A) spark allows the stabilisation of the electric breakdown of the discharge gap due to photoeffect [13].

This is illustrated in Fig. 6a by oscillograms of the voltage across the discharge gap for two discharge pulses, which were recorded for the VSD ignited without illumination on the setup whose electric circuit is shown in Fig. 1. Even when the voltage across the discharge gap was more than twice as large as that in the quasi-stationary phase of the VSD, the difference in the delay times of the electric breakdown for the two pulses in the absence of UV illumination amounted to ~ 450 ns. Figure 6b shows the voltage (U_1, U_2) and current (I_1, I_2) oscillograms for two discharge pulses, which were recorded on the same setup by igniting the VSD (also without illumination) with the help of the Fitch pulsed voltage generator. An increase in the duration of the leading edge of a voltage pulse in the absence of UV illumination leads not only to the time spread but also to the spread in the amplitude of the breakdown voltage of the discharge gap from pulse to pulse. This in turn, unlike the Arkad'ev–Marx pulsed voltage generator or electric circuits with a discharge occurring in a capacitor, is accompanied by a large spread in the VSD current amplitude and, hence, in the energy deposition into a plasma.



a b

Figure 6. Voltage (U_1, U_2) and current (I_1, I_2) (100 ns/div sweep) oscillograms obtained in the absence of UV illumination of the discharge gap for discharges in a capacitor (a) and the Fitch generator (b).

Such a situation is observed in discharge gaps with the cathode area $S \leqslant 300$ cm^2 and the interelectrode distance $d \leqslant 5$ cm, especially in lasers with specially profiled polished electrodes to provide a homogeneous electric field in the discharge gap (recall that in the experiments described above, we used the cathode whose surface was sandblasted to produce small-scale inhomogeneities). The VSD current and voltage instability naturally results in the irreproducibility of the output energy of the HF laser from pulse to pulse. The parameters of the electric breakdown of a discharge gap in such systems can be usually stabilised by illuminating the cathode by a spark [13], which can be located even outside the discharge chamber of the laser (UV illumination through the input window of the laser). When the interelectrode distance and the cathode area are large, or when electrodes with a large edge enhancement of the electric field are used, the problem of stabilisation of the electric-discharge parameters does not exist (see, for example, Ref. [7]).

Therefore, our analysis has shown that the role of UV illumination in non-chain HF(DF) lasers is reduced to the stabilisation of the delay time and the voltage amplitude of the pulsed breakdown of a discharge gap due to photoeffect on the cathode. For $d \geqslant 5$ mm, photoionisation of the medium by radiation cannot in principle provide the initial volume electron concentration required for the VSD ignition because UV radiation is strongly absorbed by SF_6 (another reason preventing preionisation – large photoelectron losses during the electron attachment, is not discussed here).

As mentioned above, for a short duration of the discharge current ($T \leqslant 150$ ns), which is typical for small-volume lasers (with active medium volumes $\sim 100-200$ cm^3 [8–10], in the absence of UV illumination, except the instability of the electric breakdown of the discharge gap, the discharge current density can be distributed nonuniformly over the cathode surface (especially over its length) due to a finite velocity of discharge propagation perpendicular to the electric field after the local initial breakdown [6]. This reduces the output parameters of the HF laser because of the decrease in the active-medium length and the increase in the local energy release. In this case, the levelling of the current density distribution over the cathode length after UV illumination (it is appropriate to arrange UV radiation sources along the cathode) accompanied by an increase in the output energy appears as the result of preionisation of the medium.

In conclusion, we will analyse briefly the results obtained in Ref. [11], where preionisation was performed by soft X-rays in the regime of the so-called photoinitiated discharge [14], in which a radiation source was switched on when the voltage across the discharge gap exceeded the static breakdown voltage. This regime allows us to obtain the initial electron concentration in the discharge gap that is sufficient for the development of a volume discharge because the rate of ionisation multiplication of electrons exceeds the rate of their losses during their attachment to SF_6 molecules. However, to analyse in detail the real factors resulting in the improvement in the VSD stability and the increase in the laser output energy, it is necessary to study the current density distribution over the cathode surface. Indeed, the maximum duration of the current pulse in Ref. [11] did not exceed 155 ns for $d = 2.5$ cm in the discharge gap with a homogeneous electric field. As follows from the above analysis, this could lead in the absence of preionisation to the nonuniform distribution of the energy deposition in the discharge gap along the laser axis.

5. Conclusions

The results of our paper confirm again that UV illumination in HF lasers with the cathode area $S \leqslant 300$ cm^2 and in lasers with the current pulse duration $T \leqslant 150$ ns stabilises, respectively, the delay time and the voltage amplitude of the electric breakdown of the discharge gap and levels off, due to photoeffect, the discharge current density distribution over the cathode surface. There is no need in UV illumination in wide-aperture, large-volume lasers when small-scale (~ 50 μm) inhomogeneities are present on the cathode surface.

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