

PACS numbers: 42.55.Ks; 52.80.Mg
DOI: 10.1070/QE2000v030n06ABEH001747

Discharge characteristics in a nonchain HF(DF) laser

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Abstract. It is found that for SF_6 – hydrocarbon (deuterocarbon) mixtures having a composition typical for nonchain HF(DF) lasers, the electric field strength reduced to the partial pressure of SF_6 (p_{SF_6}) in the quasistationary phase of a volume self-sustained discharge $(E/p_{SF_6})_{st} = 92$ V m^{-1} Pa^{-1} is close to the known critical value $(E/p)_{cr} = 89$ V m^{-1} Pa^{-1}, which is specified by the condition that the electron-impact ionisation rate of SF_6 is equal to the rate of electron attachment to SF_6 molecules. This testifies to the decisive role of these two processes and allows the use of the known approximations of the effective ionisation coefficient and the electron drift velocity for pure SF_6 when calculating the discharge characteristics. The oscilloscope traces of voltage and current calculated in this approximation for lasers with apertures ranging from 4 to 27 cm deviated from the experimental data by no more than 10%.

Initiating nonchain HF(DF) lasers on a basis of SF_6 – hydrocarbon (deuterocarbon) mixtures by a volume self-sustained discharge (VSD) makes it possible to obtain substantial output energies with a reasonably high efficiency [1 – 3]. Despite the fact that this initiation method has long been known, the processes occurring in a VSD plasma in the working media of nonchain lasers have not been adequately studied until the present time. In particular, tens of elementary processes are taken into account in calculating VSD characteristics, including the increase in electron losses owing to their attachment to vibrationally excited SF_6 molecules, the gas heating, and the parameters of the external circuit (see, e.g. Refs [4, 5]). However, the calculated oscilloscope traces of voltage and current differ greatly from the experimental ones. This is supposedly related to the inexactness of the data on the rate coefficients for many elementary processes, which in turn does not permit selection of the principal processes that control the VSD characteristics. The aim of this work is to determine the processes whose inclusion would make it possible to attain a good agreement between the calculated and experimental oscillograms.

A clearly defined 'step' is observed in the oscilloscope traces of the VSD voltage in SF_6 and its mixtures with hydrocarbons (deuterocarbons). This step corresponds to the quasi-stationary phase of the VSD during which the voltage across the discharge gap was in fact constant. It is easy to show that, when the voltage varies in this way, the maxima of the VSD current and of the electron concentration coincide in time with a good accuracy; i.e., the quasi-stationary voltage measured from the oscilloscope traces at the time the current reaches a maximum is close to the voltage for which the rates of the electron production and loss in a discharge plasma become equal. Therefore the quasi-stationary voltage is determined by the electron production and loss, and its changes caused by variations in the mixture composition reveal information on the nature of these processes.

We have measured the quasi-stationary voltages of the VSD in SF_6 and its mixtures with hydrocarbons (deuterocarbons) over a wide range of parameters: the mixture pressure $p = 10 - 60$ Torr, the interelectrode gap $d = 2 - 27$ cm, and the energy deposition $W = 20 - 200$ J l^{-1}. The length of the discharge pulse was varied between 200 and 400 ns. These are operating conditions for nonchain HF(DF) lasers with large volumes of the active medium [1 – 3]. In experiments presented here, the VSD was ignited between two disk electrodes: a cathode 6 cm in diameter and an anode 12 cm in diameter, which were perimetrically rounded off with a radius of curvature 1 cm. A capacitor discharged into the gap via a variable inductance. The VSD current and voltage were recorded by using calibrated shunts or Rogowski loops and voltage dividers. The electric signals were recorded with a Tektronix TDS 220 oscilloscope.

Fig. 1 shows the quasi-stationary voltage U_{st} as a function of the parameter $p_{SF_6}d$ for pure SF_6 and for its mixture with C_2H_6 for a ratio of partial component pressures of 10 : 1 (p_{SF_6} is the partial pressure of SF_6 in the mixture). One can see that U_{st} is hardly affected by the addition of C_2H_6 to SF_6; i.e., for mixture compositions typical of HF(DF) lasers, U_{st} is determined primarily by the partial pressure of SF_6. The U_{st} voltage depends linearly on $p_{SF_6}d$. The electric field strength in the quasi-stationary phase derived from Fig. 1 and reduced to the partial SF_6 pressure is $(E/p_{SF_6})_{st} = 92$ V m^{-1} Pa^{-1} (where E is the electric field strength in the VSD column). This value is close to the critical reduced electric field strength for pure SF_6 $(E/p)_{cr} = 89$ V m^{-1} Pa^{-1} known from the literature [6], which is given by the condition that the coefficient of electron attachment to SF_6 molecules be equal to the electron-impact SF_6 ionisation coefficient. For SF_6 mixtures with relatively small (below 20%) additions of hydrocarbons (deuterocarbons), U_{st} is approximated well by the expression $U_{st} = (E/p_{SF_6})_{st} p_{SF_6} d + U_c$, $U_c \approx 800$ V.

The results of measurements of U_{st} suggest that only the processes of SF_6 ionisation by electron impact and of electron attachment to SF_6 molecules are significant for the VSD under the conditions involved. At the same time, such proc-

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Received 15 October 1999
Kvantovaya Elektronika **30** (6) 483 – 485 (2000)
Translated by E N Ragozin; edited by M N Sapozhnikov

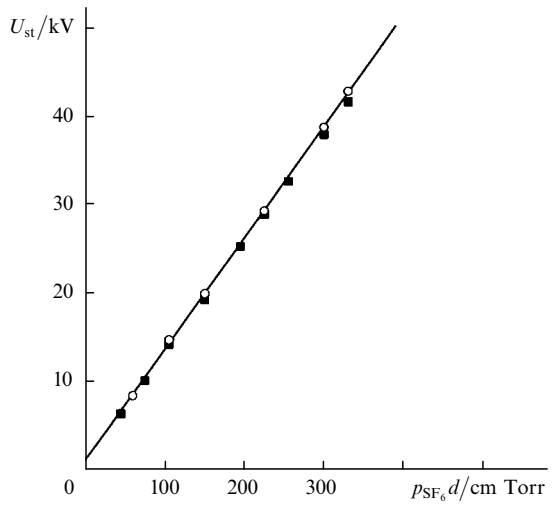

Figure 1. Quasi-stationary voltage U_{st} as a function of the parameter $p_{SF_6}d$ in pure SF_6 (■) and in a mixture of composition $SF_6 : C_2H_6 = 10 : 1$ (○).

esses as stepwise ionisation, the Penning process, electron attachment to the excited SF_6 molecules, and ionisation of impurity molecules can be neglected, at least for an energy deposition not exceeding 200 J l^{-1} and for the VSD current pulse length above 200 ns. In this approximation, the main characteristics of the VSD in the working mixtures of nonchain HF(DF) lasers were calculated by using simple approximations for the effective ionisation coefficient α_{ef} and the electron drift velocity u_e for pure SF_6 taken from Ref. [6]. The electron concentration n_e was determined from the combined solution of the continuity equation for the electron component of the current and the Kirchhoff equations for the electric circuit, as in Ref. [7]. The ion component of the current was disregarded. The initial electron concentration was assumed to be equal to the background value. In the equivalent electric circuit, the discharge gap was represented as a resistive element with resistance $R_d = U/I = U/(en_e u_e S)$, where U is the voltage across the gap, I is the discharge current, e is the electron charge, and S is the cathode surface area.

The validity of the above approximation was verified by the example of a simple discharge circuit whose equivalent electric circuit is shown in Fig. 2a. The capacitor capacitance was $C = 3.9$ nF; the inductance and the resistive losses in the circuit were determined experimentally. The oscilloscope traces of the voltage and the current were recorded for $d = 4$ cm, $S = 12.6$ cm^2, and a 33.5 Torr pressure of the mixture with the composition $SF_6 : C_2H_6 = 10 : 1$. In the calculation, the fact that an ohmic divider measures the sum of potential drops across the gap and the inductance of the electrode current supplied was taken into account. Also shown in Fig. 2a are the experimental and calculated oscilloscope traces of the voltage and current. One can see that the calculated oscilloscope traces agree well with the experimental ones (within 6%).

This model was used for calculating the VSD characteristics in two laser systems with $d = 5$ cm, $p = 67$ Torr and $d = 26.6$ cm, $p = 58$ Torr. The equivalent electric circuits of the two laser systems are shown in Figs 2b, 2c. In both cases the discrepancy between the calculated and experimental oscilloscope traces was within 10%.

Thus, to obtain good agreement between experimental

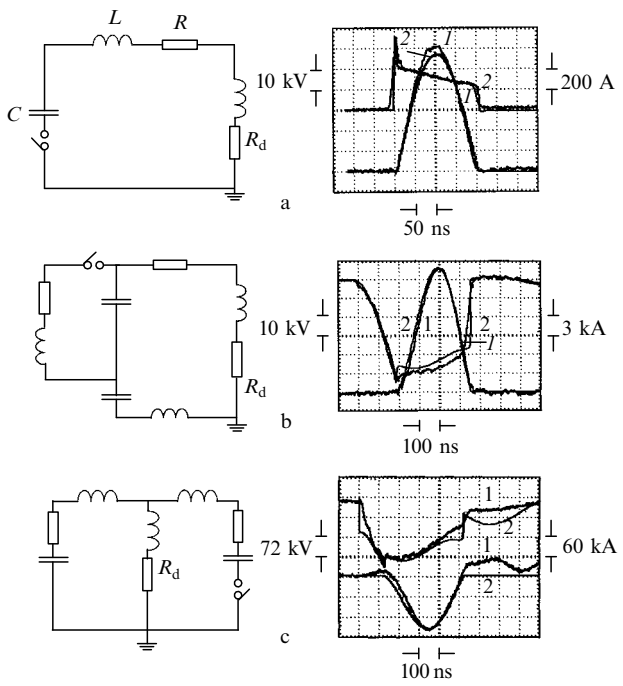

Figure 2. Different equivalent electric circuits of discharge circuits and the corresponding experimental (1) and calculated (2) oscilloscope traces of the voltage (the upper trace) and the current (the lower trace).

and calculated oscilloscope traces of the voltage and the current of the VSD in SF_6 and its mixtures with hydrocarbons (deuterocarbons) under conditions typical of nonchain large-volume HF(DF) lasers (energy deposition below 200 J l^{-1}, current pulses longer that 200 ns), one should take into account only the ionisation of SF_6 by electron impact and the electron attachment to SF_6 molecules. Why, despite the existence of many processes in the discharge plasma, are only these two significant?

This is possibly related to the specific features of the VSD development in SF_6 and its mixtures with hydrocarbons (deuterocarbons). Earlier we considered a mechanism of local current density limitation on reaching some limiting value, which resulted in the increase in the discharge volume during the discharge development with increasing energy introduced into the plasma [1]. As a result, at every instant of time, the discharge current flows primarily through an unexcited gas, resulting in the independence of the voltage across the discharge gap of the accumulation of excited particles in the discharge volume. If the specific energy deposition is raised in some way, e.g. by limiting the discharge volume, it is possible that the dependence of the quasi-stationary voltage on the specific energy deposition would be observable in the oscilloscope traces.

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