ELSEVIER

15 January 1997

Optics Communications 134 (1997) 145–148

OPTICS COMMUNICATIONS

Discharge and circuit simulation of a plasma cathode TEA HF laser operating with a He/SF_6/C_3H_8 gas mixture

G.N. Tsikrikas, A.A. Serafetinides [1]

National Technical University of Athens, Physics Department, Zografou Campus, Athens 15780, Greece

Received 14 August 1996; accepted 2 September 1996

Abstract

A circuit and discharge simulation is presented for a TEA HF laser operating with a He/SF_6/C_3H_8 gas mixture. A comparison of the simulated discharge voltage, current, resistance and input power with the corresponding experimental results is presented together with a discussion on the factors affecting the simulation accuracy.

PACS: 42.55.E; 42.60.B

1. Introduction

In the last decade there has been an increasing interest on laser sources in the wavelength range around 3 μm mostly for medical applications. This trend revived the interest in HF laser development [1], which together with the Er:YAG laser are the only laser sources in this region. Recently we reported the development of an HF laser with a plasma cathode, which operated with a He/SF_6/C_3H_8 gas mixture [2]. In the present article we report the results of a circuit and discharge simulation for the above laser. Most of the HF laser discharge models that have been previously reported refer to the chain reaction type gas mixture H_2/F_2 [1], with a few exceptions of models based on the SF_6/H_2 [3] and more recently on the Ne/SF_6/H_2 [4] gas mixture. Although the He/SF_6/C_3H_8 gas mixture used in the present work is frequently used in HF lasers, to the best of our knowledge it is the first time that a discharge model based on that mixture is presented.

2. Circuit and discharge simulation

The laser has been described in detail in Ref. [2], so it will be briefly presented here. The equivalent of the laser driving circuit used in the simulation is shown in Fig. 1. It is an LC inversion type circuit with $C_s = C_m = 48$ nF charged at $V_{ch} = -27$ kV. The spark gap switch was modeled as a time varying resistance R_s, of the form $R_s = R_{s0} + R_{s1} \times \exp(-t/\tau)$ and a constant inductance L_s in which the switching loop inductance was incorporated as well. The values that best fitted the experimentally observed waveforms of V_s and i_s were $R_{s0} = 100$ Ω, $R_{s1} = 0.15$ Ω, $\tau = 5$ ns and $L_s = 35$ nH. The main loop inductance L_m was separated in two parts $L_m = L_x + L_h$ where, L_x and L_h are the external and the laser head inductances respectively. In this way it was possible to compare the model predictions with the experimentally accessible voltage V_h external to

---

[1] E-mail: aseraf@central.ntua.gr.

PII S0030-4018(96)00560-3

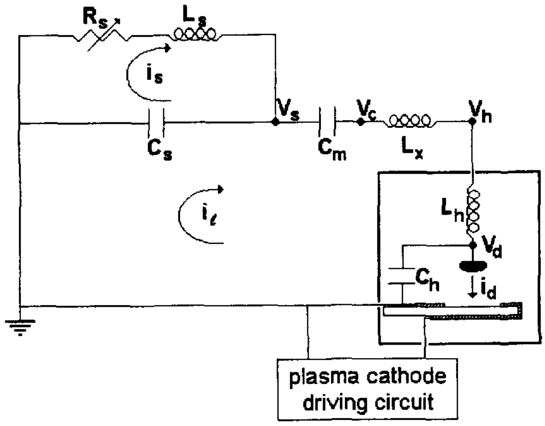

Fig. 1. Equivalent model of the driving circuit and the laser head arrangement.

the laser head. The total inductance L_m was calculated from the main loop self ringing frequency, while L_x and L_h were estimated using the solenoid approximation formula and were found to be $L_\mathrm{m} = 70$ nH with $L_\mathrm{x} = 55$ nH and $L_\mathrm{h} = 15$ nH. However, the best simulation results were obtained for the values $L_\mathrm{m} = 60$ nH with $L_\mathrm{x} = 35$ nH and $L_\mathrm{h} = 25$ nH. The 15% discrepancy in L_m is reasonable, while the quite large difference in the values of L_x and L_h is attributed to their rough estimation with the solenoid approximation. C_h accounts for the laser head stray capacitance. A value of $C_\mathrm{h} = 0.1$ nF was used. The plasma cathode was driven by a separate LC inversion circuit which is not shown in the figure, since it was not explicitly included in the model apart from providing the necessary preionisation. The delay between the firing of the plasma cathode and main discharge circuits was 200 ns. The plasma cathode was assumed able to provide an initial electron density of $n_{\mathrm{e}0} = 10^9$ cm^{-3} although the model results were similar for $n_{\mathrm{e}0}$ values in the range $10^8 < n_{\mathrm{e}0} < 10^{10}$ cm^{-3}.

The circuit behavior is described by the following set of equations:

$$\mathrm{d}i_\mathrm{s}/\mathrm{d}t = (V_\mathrm{s} - i_\mathrm{s} R_\mathrm{s})/L_\mathrm{s}, \tag{1}$$

$$\mathrm{d}V_\mathrm{s}/\mathrm{d}t = (i\mathrm{L} - i_\mathrm{s})/C_\mathrm{s}, \tag{2}$$

$$\mathrm{d}V_\mathrm{m}/\mathrm{d}t = -i\mathrm{L}/C_\mathrm{m}, \quad \text{where } V_\mathrm{m} = V_\mathrm{s} - V_\mathrm{c}, \tag{3}$$

$$\mathrm{d}i\mathrm{L}/\mathrm{d}t = (V_\mathrm{d} - V_\mathrm{c})/L_\mathrm{m} \quad \text{where } L_\mathrm{m} = L_\mathrm{x} + L_\mathrm{h}, \tag{4}$$

$$\mathrm{d}V_\mathrm{d}/\mathrm{d}t = (i_\mathrm{d} - i\mathrm{L})/C_\mathrm{h}. \tag{5}$$

The above set of equations is accompanied by the expression for the discharge current i_d,

$$i_\mathrm{d} = e v_\mathrm{d} n_\mathrm{e} S, \tag{6}$$

and the electron number density n_e rate equation

$$\mathrm{d}n_\mathrm{e}/\mathrm{d}t = (k_\mathrm{i} - k_\mathrm{a}) N n_\mathrm{e}, \tag{7}$$

where v_d, k_i and k_a are the electron drift velocity, the ionization and attachment rates respectively, while the other symbols e, S and N have their usual meaning.

A model calculation of the transport coefficients for the gas mixture of He/SF$_6$/C$_3$H$_8$ at atmospheric pressure has been reported recently in Ref. [5]. The authors kindly provided us with the necessary data for the transport coefficients. The experimental results were obtained with an SF$_6$ concentration of 2.2% and a ratio of SF$_6$ to C$_3$H$_8$ of 10. However the transport coefficients calculation for this mixture composition predicted a much higher steady state reduced electric field value $(E/N)^*$ than was experimentally observed. Since the value of $(E/N)^*$ is the most important discharge parameter, we chose to use the set of transport coefficients that corresponds to an SF$_6$ concentration of 1.5% at the same ratio of SF$_6$ to C$_3$H$_8$ of 10, which has a value of $(E/N)^*$ close to the one obtained experimentally. This discrepancy may be due to error in the calibration factor of the SF$_6$ flow meter and also partly to the fact that the laser kinetics were not included in the model of Ref. [5] for calculating the transport coefficients i.e. account was not taken of the decrease in the concentration of SF$_6$ and C$_3$H$_8$ molecules due to the various chemical reactions generating HF molecules, as well as the influence of the generated species on the electron energy distribution.

Thus for the chosen mixture composition of He/SF$_6$/C$_3$H$_8$ of 98.5/1.5/0.15 at 1 atm total pressure the transport coefficients data were best fitted for the reduced electric field region of interest as:

$$v_\mathrm{d} = 1.787 \varepsilon_\mathrm{n}^{1.107} \times 10^4 \text{ m/s}, \tag{8}$$

$$k_\mathrm{i} = 0.043 \exp(-0.017/\varepsilon_\mathrm{n}) \varepsilon_\mathrm{n}^{2.951} \times 10^{-17} \text{ m}^3/\text{s}, \tag{9}$$

$$k_\mathrm{a} = 1.880 \exp(-0.177 \varepsilon_\mathrm{n}) + 0.487 \times 10^{-17} \text{ m}^3/\text{s}, \tag{10}$$

where ε_n is the reduced discharge electric field $\varepsilon_n = E/N = V_d/gN \times 10^{-20}$ V m^2. The discharge cross section was $S = 38$ cm $\times$ 1 cm $= 38$ cm^2 and the discharge gap was $g = 2.8$ cm.

The above set of equations was solved with the ODE solution package PSI [6].

3. Results and discussion

In Fig. 2 are shown the experimentally obtained waveforms for the discharge voltage and current measured externally to the laser head, V_h and i_L respectively and the corresponding simulation results. The simulated actual discharge current i_d had minor differences from i_L, for laser head capacitance values $C_h < 0.2$ nF. As can be seen in the figure the time characteristics are well simulated. The simulated peak current i_{pk} value is 12% lower than the experimental one, $i_{pk} = 14$ kA and 15.8 kA respectively and there is also a small time difference of 5 ns at peak current onset. The remaining voltage after the cessation of the discharge is well predicted being 6.2 kV and 5.2 kV for the experiment and simulation respectively.

In Fig. 3 is shown the discharge voltage V_d as inferred from the experimentally obtained V_h after subtracting the inductive part $V_d = V_h - L_h\, di_L/dt$ with $L_h = 15$ nH and the corresponding simulated waveform. Also presented is the experimental and simulated variation of the discharge resistance $R_d = V_d/i_L$. The peak V_{pk} and steady state voltage (value at peak current) V_{ss} values, are well predicted, being $V_{pk} = 31.7$ kV and 32.3 kV and $V_{ss} = 24$ kV and 23.4 kV for experiment and simulation respectively. However, the simulation gives a much longer duration for the discharge steady state time phase and a steeper voltage slope at breakdown. In addition, as was mentioned above for V_h, although the remaining voltage after the cessation of the discharge is well predicted, the simulation gives a much stronger oscillatory behavior.

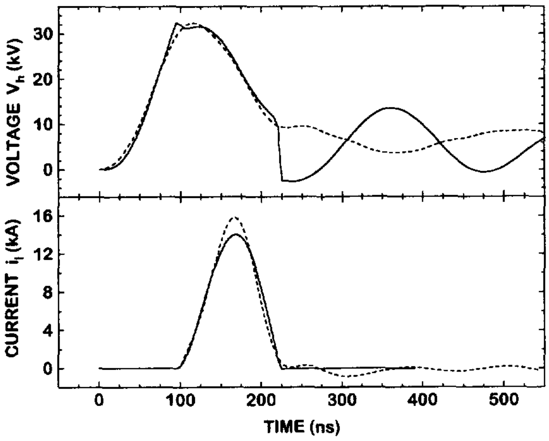

Fig. 2. Voltage and current waveforms external to the laser head V_h and i_L respectively. Solid lines: simulation, dashed: experiment.

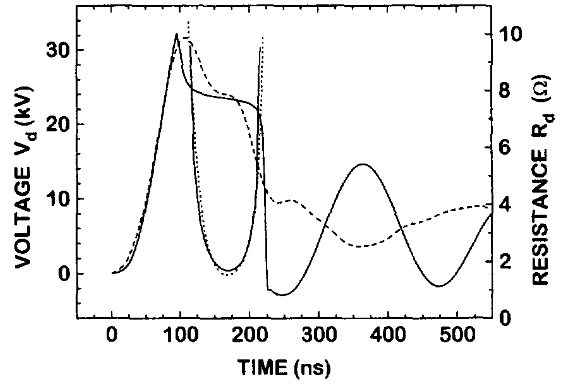

Fig. 3. Discharge voltage V_d and resistance R_d. Solid lines: simulation, dashed: experimental V_d trace, dotted: experimental R_d trace.

A good agreement is obtained for the discharge resistance evolution, the experimental and simulated

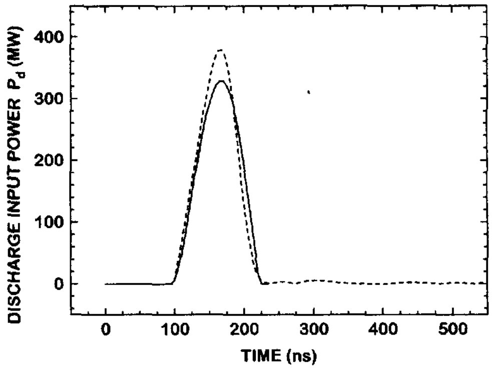

Fig. 4. Discharge input power P_d. Solid lines: simulation, dashed: experiment.

values at peak current being $R_d = 1.52\ \Omega$ and 1.67 Ω respectively.

In Fig. 4 is shown the comparison between the experiment and simulation for the discharge input power $P_d = V_d i_L$. The simulation predicts a 15% lower peak input power value P_{pk} and a 13% longer FWHM $t_{1/2}$, than the corresponding experimental ones. The actual values are $P_{pk} = 379$ MW and 328 MW and $t_{1/2} = 66$ ns and 75 ns respectively.

4. Conclusion

A discharge and circuit simulation of an HF laser operating with a He/SF$_6$/C$_3$H$_8$ gas mixture at atmospheric pressure has been presented. To the best of our knowledge it is the first report of a model based on that mixture. A reasonable agreement between simulation and experiment has been obtained. The differences observed between the experimental and simulated waveforms are mainly attributed to the usual difficulties in the exact simulation of circuit parameters, as well as to the fact that, as was explained in Section 2, in the model used by the authors of Ref. [5] for the calculation of the transport coefficients, the HF laser kinetics were not included.

Acknowledgements

We are obliged to Dr. M.G. Baeva and Prof. P.A. Atanasov, for providing us the data for the transport coefficients of the He/SF$_6$/C$_3$H$_8$ gas mixture.

References

[1] A.V. Eletskii, Sov. Phys. Usp. 24 (1981) 475.

[2] G.N. Tsikrikas, A.A. Serafetinides and A.D. Papayannis, Appl. Phys. B 62 (1996) 357.

[3] J.L. Lyman, Appl. Optics 12 (1973) 2736.

[4] H. Brunet, M. Mabru, J. Rocca Serra and C. Vannier, SPIE 1397 (1990) 273.

[5] M.G. Baeva and P.A. Atanasov, Nuovo Cimento D 17 (1995) 261.

[6] PSI, Interactive Simulation Program, BOZA automatisering, The Netherlands.