EFFICIENCY COMPUTATION OF CURRENT CONTROLED EXCILAMPS

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Abstract. The coupling between the power supply and a Dielectric Barrier Discharge (DBD) for UV production purposes (excilamp) is a major issue for the design of powerful and efficient UV sources. In order to improve this coupling, new power supply topologies have been developed, based on the current control of the DBD. The aim of this paper is to present the modeling results of such a control on the performances of the excilamp.

1. INTRODUCTION

Dielectric Barrier Discharge (DBD) established in rare gas or rare gas/halogen mixtures (excilamps) are promising sources of high power Ultraviolet or Vacuum Ultraviolet (UV or VUV). Their specific properties such as efficiency, high power and mercury free, make these lamps especially suited for various industrial applications [1]. Previous researches have shown that these sources are especially efficient when supplied in pulsed mode [2], [3], [4], [5], and efficiencies above 60% were reported for DBD in xenon [8]. It was shown that the optimum parameters for supplying these excilamps are voltage pulses of some kilovolts applied at frequencies of some tens of kilohertz (around 100kHz) with a duty ratio about 1%. Unfortunately, these values can hardly be achieved with a high voltage switching topology for the power supply and, most of the time, a step-up transformer is used to generate the high voltage pulses. In this case, the strong coupling between the inductive load of the transformer and the capacitive load of the excilamp leads to a ringing which might affects the efficiency of the system. As a result, the most important issue nowadays for a high efficiency excilamp system is to improve the coupling between the excilamp and the power supply.

In [7] was presented a power supply topology which would improve the UV output control of an excilamp in generating current pulses instead of voltage pulses. The aim of this paper is to evaluate, on a model, the effect of a current source controlled DBD on its UV emission. In a first part, sine wave is considered and in the second part, current pulses are applied in the model.

2. MODEL DESCRIPTION

We have developed a Partial Differential Equation (PDE) based model [9] for a planar double-dielectric layer Xenon excilamp. The plasma is assumed homogeneous and side effects around the electrodes are neglected. The computation is consequently performed in 1D, along the axis of the geometry similar to the one presented in [6]. The thick of the dielectric layers are 2mm, the gas gap is 4mm and the Xenon filling pressure is $5.33 \bullet 10^4$Pa (400Torr). The model solves the drift-diffusion equations for the species considered in the model coupled to Poisson's equation.

A voltage supplied DBD is modeled in imposing a potential on both outer sides of the dielectrics. This leads to two Dirichlet boundary conditions for Poisson's equation. Usually, one side is grounded and the other is held at the voltage chosen for the modeling. A current supplied DBD is modeled in grounding one side of the outer surface of a dielectric and in imposing the electric field, which is proportional to the time integral of the current, on the outer surface of the other dielectric:

$$\vec{E}(x_0,t) = \frac{1}{\varepsilon}\int_0^t \vec{j}(x_0,t)dt \tag{1}$$

where $\vec{E}(x_0,t)$ is the electric field at the outer surface of the dielectric, ε the permittivity of the dielectric and $\vec{j}(x_0,t)$ the current density flowing through the dielectric. This corresponds to a Neumann boundary condition for Poison's equation.

The model relies on the local field approximation and consequently the transport coefficients and source terms depend on the electric field. These coefficients and source terms are computed by Bolsig [11]. Once solved, the model can display the evolution of the plasma species density, as well as the electric field, in time and space.

The mechanism which has the major impact on the development of the discharge is the propagation of the ionization wave, occurring in the neighborhood of the dielectrics in cathode phase. This ionization wave has a strong impact on the current waveform and leads to a massive production of charges, excited species and especially excimers [7]. This is the argument that led to the concept of controlling the current in the DBD in order to achieve a control of the UV flux of the excilamp.

3. SINE WAVE CURRENT CONTROLED EXCILAMP

3.1. Effect of the current frequency

Figure 1 presents the results of the discharge controlled by a sine wave current of 5mA peak at different frequencies.

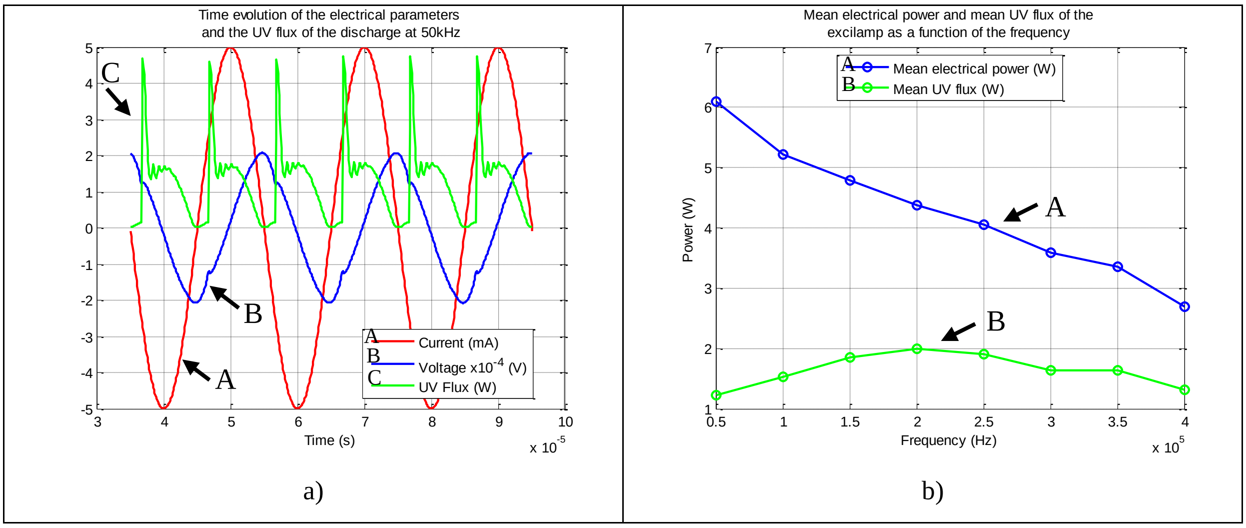

FIGURE 1. a) Time evolution of the current, voltage drop and UV flux of the excilamp at 50kHz. b) Mean electrical power and mean UV flux of the excilamp as a function of the current frequency.

When the current flows in the DBD, at steady state, it increases the voltage drop in the cathode sheath until this voltage achieves the value for the ionization wave to occur. This leads to a strong formation of excimers and consequently, a high peak in the UV emission of the discharge. Then, if the current is maintained, the ionization wave is sustained and produces excimers.

This can be observed on figure 1a), where the UV peak occurs suddenly, some microseconds after the zero crossing of the current. Then, after this peak, the current is still important and the UV emission has the same shape as the current. In this phase, the current is significantly controlling the UV output.

When the frequency increases, the repetition rate of the UV pulses increases. But, in the same time, the duration of the current-sustained UV emission phase decreases, leaving the UV peak due to the ionization wave as the most part of the total UV output. These antagonist effects lead anyway to an increase in the mean UV output of the excilamp until 200kHz. Above this frequency, the current half period if too short to generate a significant electric field in the cathode sheath and the ionization wave is weak or even does not occur at each half period. The mean UV output falls consequently. As it can be seen on figure 1b), the mean UV flux of the excilamp has thus a maximum around 200kHz. Nevertheless, the efficiency is monotonically increasing and a good compromise between UV flux and efficiency is achieved for a frequency between 200kHz and 250kHz.

3.2. Effect of the current amplitude

Figure 2 presents the results obtained for current amplitudes of 1mA, 2.5mA, 5mA, 10mA and 15mA. The effect of an increase of the amplitude is an increase of the efficiency of the excilamp, especially at high frequencies.

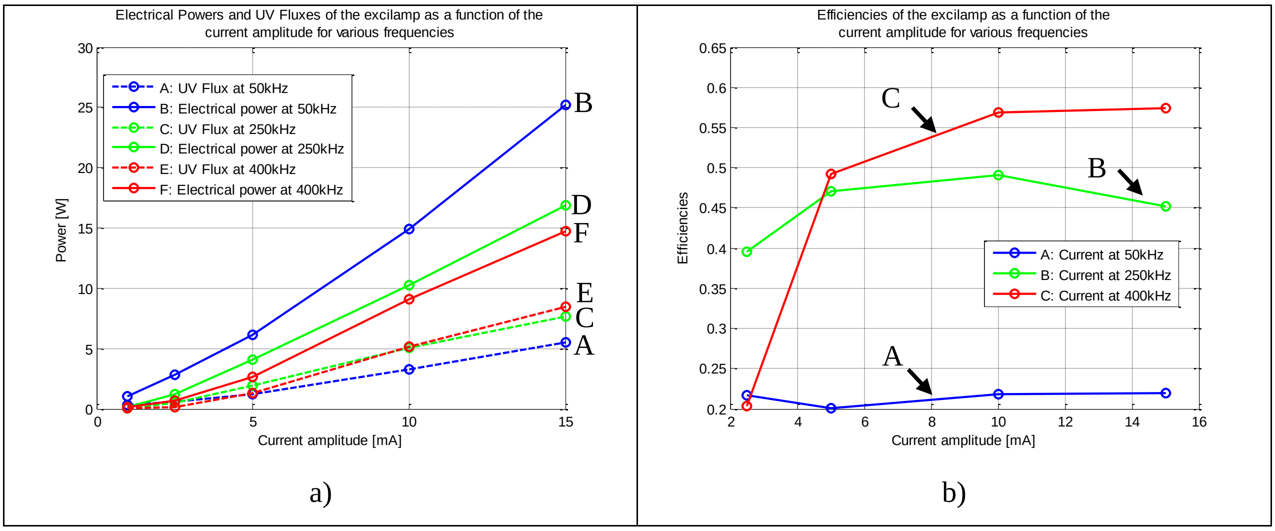

FIGURE 2. a) Electrical power and UV flux of the excilamp versus current amplitude, b) Efficiency of electrical power to UV conversion versus current amplitude.

Efficiencies as high as 57% can then be achieved at 400kHz. The low efficiency obtained at this frequency for low current amplitude is due to the lack of development of the ionization wave, as mentioned previously.

4. PULSED CURRENT CONTROLED EXCILAMP

The power supply topology described in [7] is a pulsed current source. The chosen shape for the current pulses applied to the model corresponds consequently to what would be expected from such a topology: a sudden current rising front followed by a sine wave portion. This last part depends on the coupling of the lamp and the power supply. As a result, it was chosen empirically at 3µs, according to the experimental values from [10]. The junction between the vertical current rising front and the sine wave portion occurs when the current achieves 90% of the maximum current amplitude.

4.1. Effect of the frequency

Figure 3 presents the wave forms of the current, voltage and UV flux in the discharge for different frequencies. Unlike the case of a voltage source, the current source does not change drastically the performances of the excilamp when switching from sine wave to pulsed wave. The UV flux is approximately similar, around 2W, but the electrical power is higher, with a resulting efficiency around 40%, which is lower than the sine wave case.

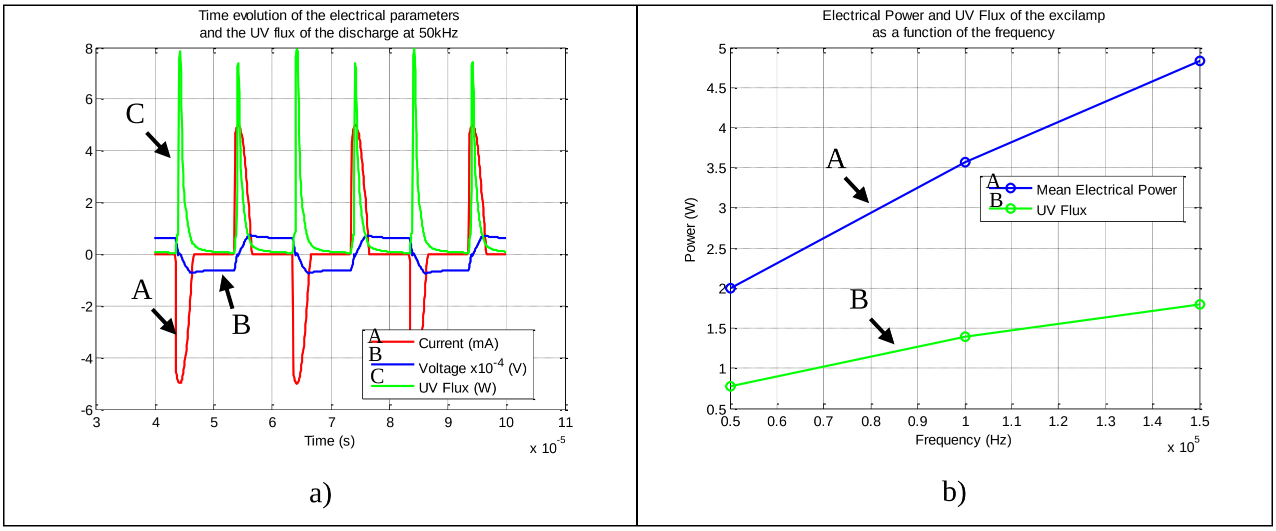

FIGURE 3. a) Time evolution of the current, voltage drop and UV flux of the excilamp at 50kHz. b) Mean electrical power and mean UV flux of the excilamp as a function of the current frequency.

4.2. Effect of the amplitude

The computation was performed with a current amplitude of 1mA, 2.5mA, 5mA, 10mA and 15mA, for frequencies of 50kHz, 100kHz and 150kHz. An increase of the amplitude of the current involves an increase of the UV flux. In the best case, it achieves around 6W which is a value similar to the one obtained in the sine wave form at the same frequency, but the efficiency is drastically lower.

4.3. Effect of the duty ratio and the pulse width

Table 1 presents the results obtained for different duty ratio and pulse width. The first line displays, as a reference, the value obtained in sine wave form at 50kHz with 5mA of amplitude. The line 2 presents the pulsed wave form considered previously but with a different duty ratio. In this case, it can be seen that the values are quite similar than in the case of a 50% duty ratio (Fig. 3). Despite the values of the UV flux is lower than in the sine wave case, this supply mode is more efficient. The line 3 concerns a pulsed wave form which differs from the ones considered previously by its shorter pulse width (1μs instead of 3μs). In this case, the UV flux is lower but the efficiency achieves a high value (62%). In this case, changing the duty ratio does not affect drastically the powers (line 4 of Table 1).

5. CONCLUSION

A DBD model was used to compute the electrical and radiative parameters of an excilamp. This model was supplied by a sine wave current and it was shown that an optimum frequency could be found, with a maximum UV output, around 2W, and an efficiency around 45%. An increase of the amplitude of the sine wave current increases the UV flux as well as the efficiency. A value of 57% was obtained at 400kHz with an amplitude of 15mA.

The pulsed current mode presents, with 3μs pulse width, a lower performance of the excilamp according to the model. But, the model predicts that a short pulse width significantly increases its efficiency, which then exceeds the best value achieved in sine wave.

The pulsed current mode seems, in these conditions, a promising mode for an efficient coupling of the excilamp and the power supply.

TABLE 1. Electrical Power, UV Flux and Efficiency of the excilamp for different wave forms

Current wave form	Electrical Power [W]	UV Flux [W]	Efficiency [%]
Sine wave, 50kHz, 5mA of current amplitude	6.10	1.22	20
Pulsed wave, 50kHz, 5mA of current amplitude, 3µs of pulse width, 0.5µs of delay between the two pulses of the same period.	1.97	0.78	40
Pulsed wave, 50kHz, 5mA of current amplitude, 1µs of pulse width, 50% of duty cycle	0.77	0.48	62
Pulsed wave, 50kHz, 5mA of current amplitude, 1µs of pulse width, 0.5µs of delay between the two pulses of the same period.	0.72	0.45	64

REFERENCES

Journals

[1] U. Kogelschatz, "Dielectric-barrier Discharges: Their History, Discharge Physics, and Industrial Applications", Plasma Chemistry and Plasma Processing, Vol. 23, No. 1, March 2003

[2] A. Oda, H. Sugawara, Y. Sakai, H. Akashi, "Estimation of the light output power and efficiency of Xe barrier discharge excimer lamps using a one-dimensional fluid model for various voltage waveforms", J. Phys. D: Appl. Phys. 33 (2000), 1507-1513

[3] R.P. Mildren, R.J. Carman, "Enhanced performance of a dielectric barrier discharge lamp using short-pulsed excitation", J. Phys. D: Appl. Phys. 34 (2001), L1-L6

[4] R.P. Mildren, R.J. Carman, I.S. Falconer, "Visible and VUV Emission from a Xenon Dielectric Barrier Discharge Using Pulsed and Sinusoidal Voltage Excitation Waveforms", IEEE transactions on Plasma Scienc, vol. 30, no. 1, February 2002.

[5] R.J. Carman, R.P. Mildren, "Computer modelling of a short-pulse excited dielectric barrier discharge xenon excimer lamp (172nm)", J. Phys. D: Appl. Phys. 36 (2003), 19-33

[6] A. Oda, Y. Sakai, H. Akashi, H. Sugawara, "One-dimensional modelling of low frequency and high-pressure Xe barrier discharges for the design of excimer lamps", J. Phys. D: Appl. Phys. 32 (1999) 2726-2736.

Proceedings

[7] H Piquet, S Bhosle, R Díez, A Toumi, G Zissis, "Innovative power supply concepts for DBD excilamps", Atomic and Molecular Pulsed Lasers VII. Edited by Tarasenko, Victor F. Proceedings of the SPIE, Volume 6938, pp. 693810-693810-14 (2008)

[8] F. Vollkommer, L. Hitzschke, "Dielectric Barrier Discharge", Proc. 8th Symp. on the Science and Technology of light sources (Greifswald) pp 51–60

[9] S. Bhosle, G. Zissis, J.J. Damelincourt, A. Capdevila, "A new approach for boundary conditions in dielectric barrier discharge modeling", Gas Discharge 2006, Xian (China)

[10] R. Díez, H. Piquet, S. Bhosle, J.M. Blaquière, "Current Mode Converter for Dielectric Barrier Discharge Lamp", PESC 2008, IEEE 39thPower Electronics Specialists Conference, 15-19 juin 2008 à Rhodes (Greece) (to be published)

Reports and Theses

[11] "The Siglo Database", CPAT and Kinema Software, 1995.