External Electrode Fluorescent Lamp (EEFL) Driving Methods

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***Abstract*—External electrode fluorescent lamps (EEFLs) are used as backlight source for large screen size liquid-crystal displays. Since electrodes are outside of the discharge tube, lifetime is enhanced when compared with cold cathode fluorescent lamps. Also, a single inverter can drive multiple EEFL tubes, leading to a compact design, driven by sinusoidal or square waveforms. Luminance can be enhanced by synchronizing the moment of the self-discharge of the dielectric wall charge with voltage rising and falling. This paper presents luminance measurements for different driving alternatives and lamp voltages, showing that EEFLs have an electrical behavior similar to dielectric barrier discharge lamps and light emission similar to the conventional fluorescent lamps. It is also shown that sinusoidal operation is more efficient than square wave operation in the light emission sense for the explored conditions.**

***Index Terms*—Capacitive component, external electrode fluorescent lamp (EEFL), liquid-crystal display (LCD) backlight.**

I. Introduction

THE external electrode fluorescent lamp (EEFL), whose structure is shown in Fig. 1, is typically a linear small diameter (2–3 mm) thin wall (about 0.3 mm) borosilicate glass tube fluorescent lamp. External end-cap copper electrodes are fixed on the external glass surface by a silver paste coating annealed in a furnace at high temperature (just below the glass melting point) [1]. The discharge tube is usually filled with Ar or Ne/Ar Penning mixture with a minuscule amount of mercury at a total pressure in the range between 30 and 100 Torr [1]. The discharge in the EEFL is basically a dielectric barrier discharge (DBD) and the lamp glass plays the role of the dielectric barrier across which the displacement current flows, excited by an alternating electric field. The capacitance of the dielectric layer, which limits the current in the discharge, is determined by its dielectric constant, glass thickness, and electrode area.

EEFLs are used as backlight source for large screen liquid-crystal display (LCD) television sets and monitors as an alternative to cold cathode fluorescent lamps (CCFLs) [1]. Since EEFLs are operated with capacitive coupled electrodes mounted outside of the tube at the glass barrier, no electrode materials are inserted into the discharge space, which gives them an enhanced lifetime compared with CCFLs. Like other DBD lamps, the electrical current in an EEFL does not flow through electrodes; instead, charged particles are alternatively accumulated on the inner surfaces of the glass tube ends.

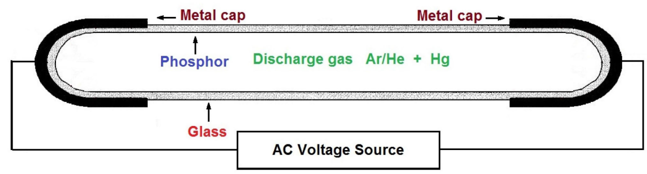

Fig. 1. EEFL basic structure.

The CCFL is traditionally operated by a sine wave obtained from an *LC* inverter, since a square pulse switching inverter requires an external capacitor for the lamp current control. The capacitive coupling effect in EEFLs allows operation with either sine waves or square pulses. Thanks to the current-limiting role of the glass tube, no ballast elements are required and multiple EEFLs can be driven in parallel by a single voltage source inverter, since each EEFL has a small capacitance and operates like a ballast.

Many authors suggest the use of a square wave drive instead of sinusoidal to increase the luminance using the intrinsic dielectric layer capacitance to limit the lamp current [2]–[5]. Additionally, Cho *et al*. [6] recommend an EEFL square wave drive with synchronization of self-discharge of the dielectric wall charge with the voltage rising and falling in order to obtain higher luminous output. However Lee *et al*. [7], based on experimental measurements, conclude that the power efficiency of the sinusoidal wave driving method is better than that of the square wave drive and also that a better efficiency is obtained when self-discharge does not occur in the square wave driving method. Thus, there is apparently no consensus on which kind of driving strategies is better for EEFLs. The purpose of this paper is to present luminance measurements on EEFLs operated at 50 kHz with sinusoidal and pulse driving modes with and without self-discharges.

This paper is organized as follows. Sections II and III discuss in more detail the EEFL structure and the physics of operation. Section IV contains the driver description and some comments on its implementation. Experimental results are shown and discussed in Section V and final considerations are presented in Section VI.

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II. EEFL Lamp Structure

As mentioned before, EEFLs use capacitive-coupled discharges through the external electrode, i.e., dielectric barrier discharges between the external electrode and the plasma inside the tube, where the dielectric layer is the glass itself.

The permittivity of the glass plays a crucial role in EEFLs. Glasses with high dielectric constant K provide high capacitances to the EEFL. Also a high electric field inside the discharge tube can be established, improving discharge efficiency, since the energy dissipation in the glass is proportional to the imaginary part of the complex dielectric constant of the glass capacitor [1].

An important issue related to lifetime of EEFLs is the so-called pinhole formation in the glass tube near or beneath the external electrode. A pinhole is a small hole formed on the glass surface, caused by punctual heat concentration due to large current. This occurs whenever a high voltage above a threshold value is applied to the lamp and the electrode temperature approaches approximately 200 °C [1]. Tubes made of alkaline free alumino-silicate glasses have a high dielectric constant ($K \approx 6$) and low dielectric loss tanδ ($\delta \approx 8 \times 10^{-4}$), where tan$\delta$ is the tangent of the angle between the capacitor complex impedance vector and the negative reactive axis (a measure of dielectric loss). The weak dependence of tanδ on the temperature makes them more resistant against pinhole formation. CCFLs and EEFLs currently found in LCD television sets are made of the conventional borosilicate glass with a lower dielectric constant ($K \approx$ 4.9–5.3) and higher dielectric losses ($\delta \approx$ 2.3–2.4 $\times$ 10^{-3}). The pinhole formation in these lamps occurs only above 15 W, which is far above their nominal operating condition [1], [8], [9].

The external electrode may be formed by inserting a metal cap on a pretreated glass surface, or by laminating a metal tape or foil over the glass surface. Beneath the tape, a conductive resin is attached. Alternatively, the electrode can be obtained by dipping the end of the lamp tube into a metal paste, for example, silver paste consisting of silver powder and a binder material. Higher quality electrodes are produced by metal–glass melt bonding, resulting in higher capacitance [1].

The electrode length plays an important role because it influences luminance and efficiency when a square pulse drives the lamp. Experimental investigations showed that luminance and lamp efficiency increase with the electrode length but saturate at an electrode length between 3 and 4 cm [9], [10].

III. EEFL Lamp Operation Principle

In the conventional CCFLs driven by the sinusoidal voltage, a physical discharge current flows through the metal electrode inside the tube. In EEFLs, the discharge current flows by the movement of the wall charges inside the glass tube. The plasma current does not flow through electrodes; instead, charged particles are alternatively accumulated on each end of the inner surface of the glass tube. EEFLs can be driven by both square and sinusoidal voltage waveforms. The square pulse driving is explained in the following subsections.

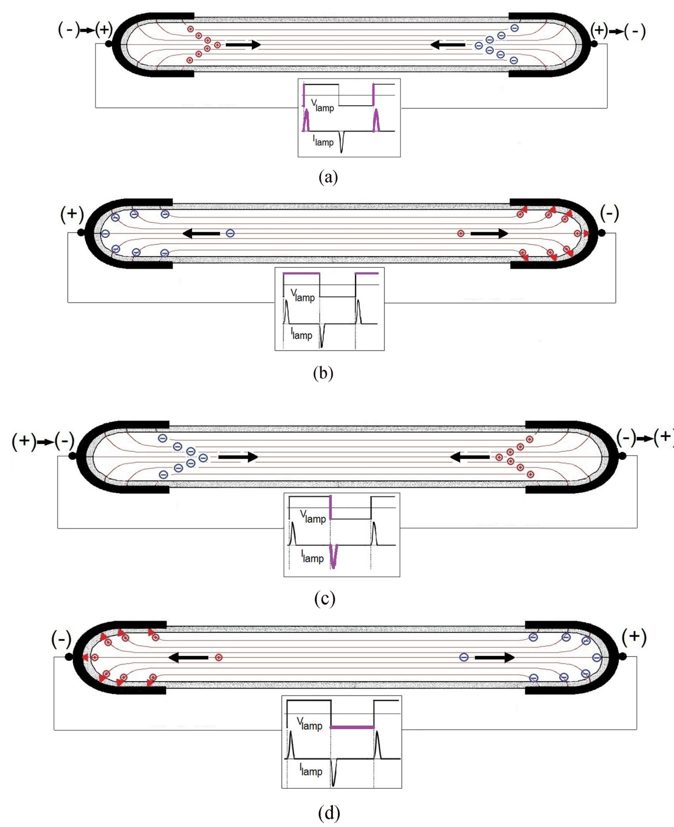

Fig. 2. Schematic drawings of electric field lines and wall charge distribution in an EEFL driven by a square wave without intervals of zero voltage. (a) Rising voltage. (b) Positive sustaining voltage. (c) Falling voltage. (d) Negative sustaining voltage.

A. Square Pulse Driving Without Intervals of Zero Voltage

The main discharge in EEFLs is illustrated by the schematic drawings of Fig. 2, showing electric field lines and wall charge distribution in a lamp driven by a square wave without intervals of zero voltage. The main-discharge starts when the driving voltage of the square pulse is high enough to trigger the discharge and a pulse shaped current flows when the polarity of the applied voltage changes. The dielectric barriers of the glass tube restrict its amplitude. Accumulated wall charges around the electrode position on the internal surface of the glass tube move to the opposite electrode side where they accumulate again [see Fig. 2(a) and (c)]. During the sustaining pulse period, the applied voltage is constant [see Fig. 2(b) and (d)] and the discharge current vanishes due to the electric balance between the externally applied field and the self-field from the wall charges. In this condition, the induced wall voltage is equal to the applied voltage.

The wall voltage resulting from the wall charges starts a new discharge after the square voltage falls. When the polarity of the external field is inverted, the wall charges are reversed and the current flows in the opposite direction.

The glow discharge induced in the EEFL is sustained by the creation of the charged particles due to ionization collisions in the discharge and by the secondary electron emissions due to the colliding ions onto the inner glass wall underneath the

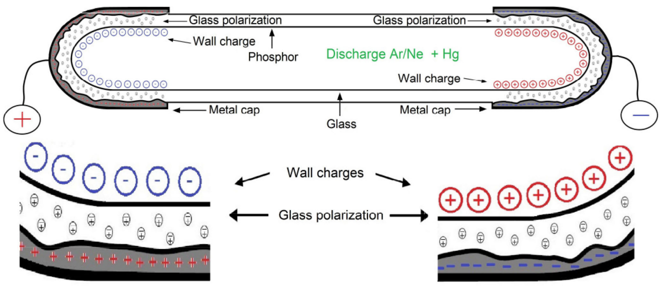

Fig. 3. EEFL main-discharge—Schematic drawings of wall charge distribution when driven by a square wave without intervals of zero voltage.

electrodes. The UV light is generated in the glow discharge by electronic impact excitation of mercury atoms [1].

The schematic drawing in Fig. 3 shows a snapshot of the wall charge distribution during the sustaining pulse period.

B. Square Pulse Driving With Intervals of Zero Voltage

In addition to the main discharge, there is a self-discharge that occurs whenever there is a period of zero voltage between polarity changes of the applied voltage as shown in Fig. 4. When the voltage reaches zero [see Fig. 4(c) and (f)], the self-discharge occurs due to the reversed wall voltage electric field. The self-discharge current flows in the lamp without contribution of the external supply source.

The EEFL's two external electrodes behave as a capacitor and the gas plasma has an electrically high conductive characteristic and behaves as a resistor. Therefore, it is assumed that the electric equivalent model of the EEFL is a resistor in series with two capacitors [11]. The capacitance of each electrode is about 40 pF and the lamp resistance is in the order of 50–200 kΩ [12], [13].

IV. Experimental Setup

The push–pull resonant inverter shown in Fig. 5 was used to drive the EEFL with a sinusoidal waveform. The transformer magnetizing inductance and the association of the tank capacitance Cp and the reflected lamp capacitance impose the resonance frequency.

The input voltage is between 20 and 30 V and the transformer has a turns ratio of 1:25. The frequency is fine tuned by adjusting the transformer air gap and the tank capacitance. This is a scheme also used for other DBD lamp applications [14], [15].

The two-stage full-bridge inverter shown in Fig. 6 is used to implement the two-level and three-level square wave drivers. The high-voltage pulses are directly applied to the lamp and two stages are used to reduce the voltage stress to the switches. The switches were implemented using the high-voltage IGBT IXGF25N250 for capacitor discharge applications. The dc input voltages are adjustable between 500 and 800 V. The resistors at bridge outputs are used to discharge the switch capacitance in the three-level mode to produce a zero-voltage level and induce self-discharge. Gate resistors and additional gate source capacitances are necessary to block high frequency oscillations in the megahertz range due to driver coupling [16].

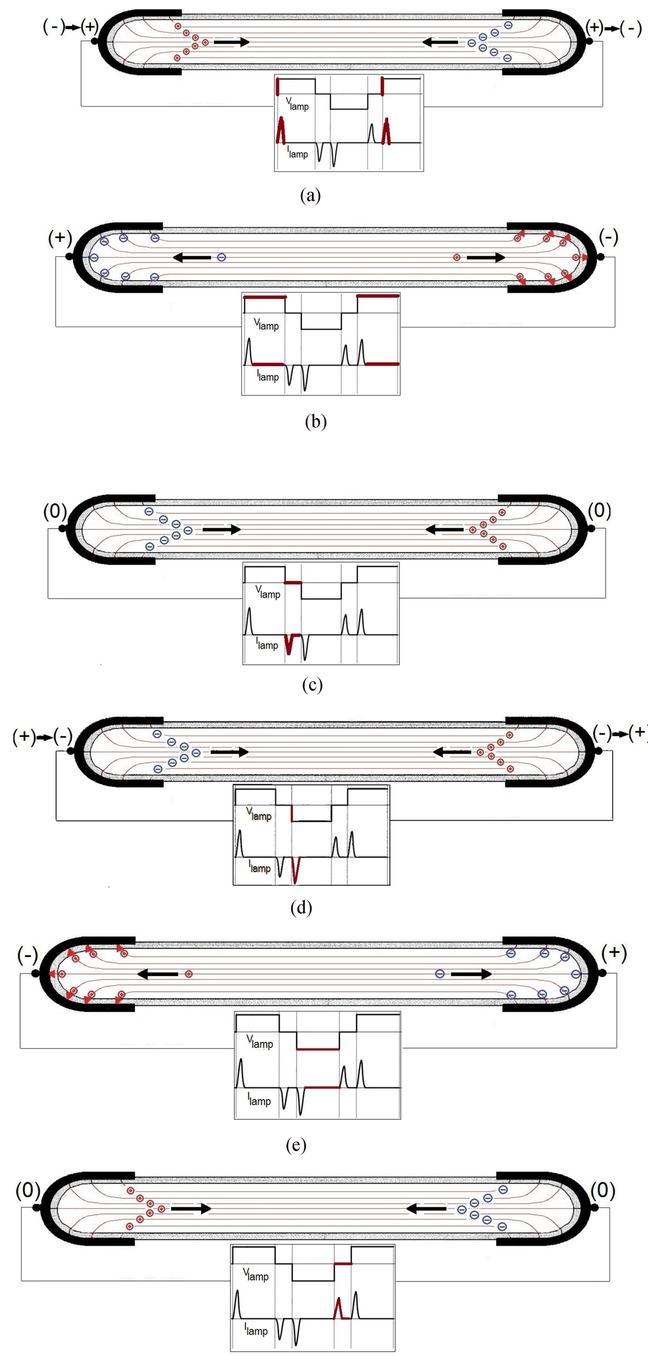

Fig. 4. EEFL main and self-discharge —Schematic drawings of electric field lines and wall charge behavior in an EEFL driven by a square wave with intervals of zero voltage. (a) Main discharge—Rising voltage. (b) Positive sustaining voltage. (c) Self-discharge. (d) Main discharge—Falling voltage. (e) Negative sustaining voltage. (f) Self-discharge.

V. Experimental Results

Lamp voltage and current measurements were made using a digital oscilloscope (Tektronix TDS2014) with a high-voltage differential probe (Tektronix P5200) and a current probe (Tektronix P6302). The ac component of the optical signal was measured using a calibrated silicon photocell. Luminance measurements were carried out with a J17 Tektronix photometer.

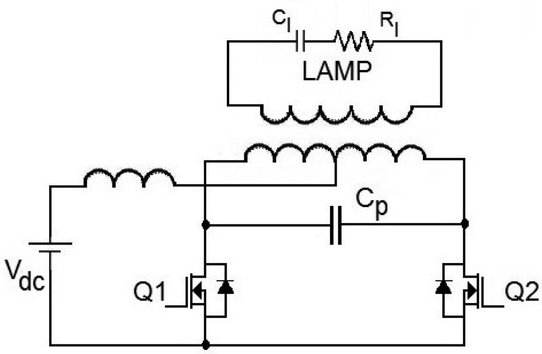

Fig. 5. EEFL sinusoidal wave driving circuit.

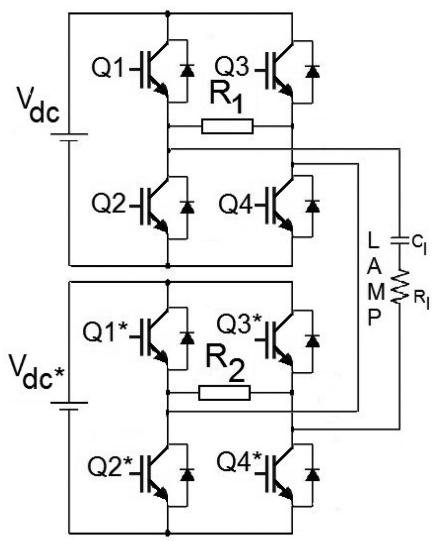

Fig. 6. EEFL square wave driving circuit.

TABLE I
LAMP DIMENSIONS

LENGTH (MM)		DIAMETER (MM)	
OVERALL	ELECTRODE	OUTER	INNER
310	20	2.6	2.0
250	12	2.6	2.0
125	10	2.6	2.0

Luminance measurement accuracy is $\pm$100 cd/m^2 and power measurement accuracy is $\pm$400 mW.

The EEFLs are house made using devices from JKL Components. CCFLs discharge tubes of 0.3-mm-thick borosilicate glass and 2.6 mm outer diameter were used. The external electrodes are made of six turns of 0.06-mm-thick copper foil wound around the tube and fixed on the glass surface by a conductive silver acrylic resin coating with a sheet resistance of 0.015 Ω/sq (ohms per square). The electrode length is approximately 3 cm. Table I shows lamp dimensions.

Fig. 7 shows lamp voltage (trace 1) and current (trace 2) profiles and the optical probe signal (trace 3) measured in a

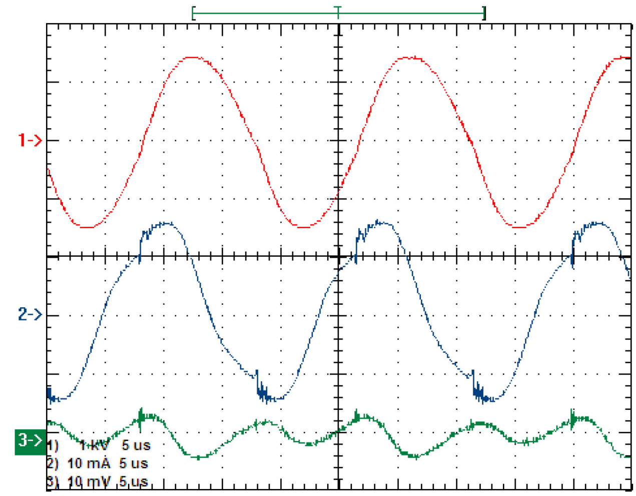

Fig. 7. 310-mm EEFL operated at 52.5 kHz with a $1.5 - \mathrm{k}V_p$ sine wave voltage(1), current(2), and the ac optical probe signal (3).

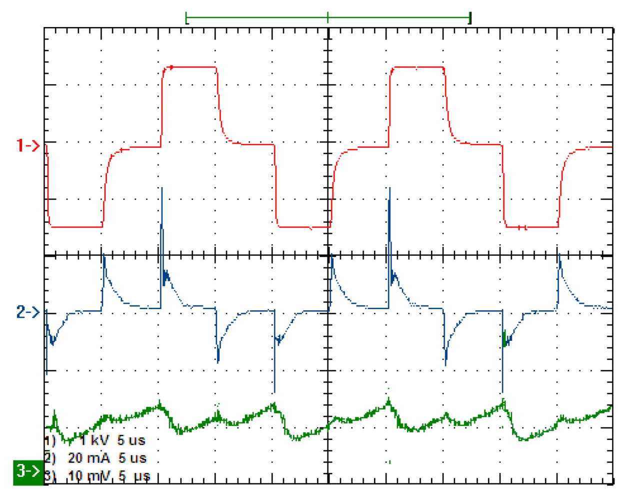

Fig. 8. 310-mm EEFL operated with at 50 kHz $1.5 - \mathrm{k}V_p$ square wave (duty ratio 50%) voltage(1), current(2), and the ac optical probe signal (3).

310-mm-long EEFL driven by a sine wave with a 1.5-kV peak value and 52.5-kHz frequency. The current and the optical signals corresponding to the rising and falling parts of the sine wave voltage represent the main discharge.

Fig. 8 shows lamp voltage (trace 1), current (trace 2) profiles, and the optical probe signal (trace 3) measured in the EEFL driven by a 1.5-kV square pulse of 50 kHz and duty ratio of 50%.

The current and optical signal corresponding to the rising and falling edges of positive voltage pulses represent the main- and self-discharges respectively, which are also shown in the corresponding transitions of the negative polarity pulses. The optical intensity corresponding to the self-discharge is slightly weaker than that corresponding to the main discharge.

Fig. 9 shows lamp voltage (trace 1), current (trace 2) profiles, and the optical probe signal (trace 3) measured in the 310-mm EEFL driven by a 1.5-kV square pulse of frequency 50 kHz and

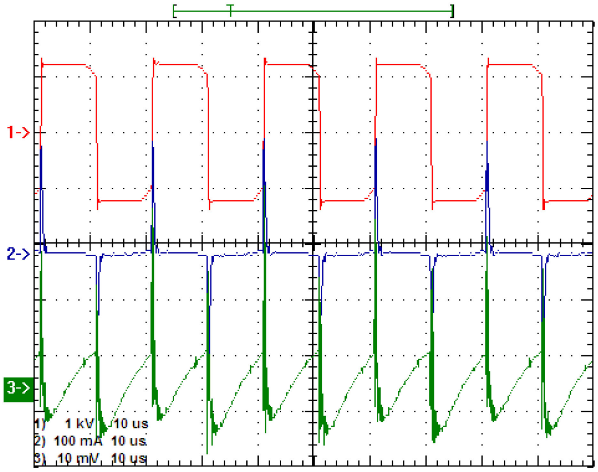

Fig. 9. 310-mm EEFL operated at 50 kHz with a $1.4 - \mathrm{k}V_p$ square wave (duty ratio 100%): voltage(1), current(2), and optical probe signal (3).

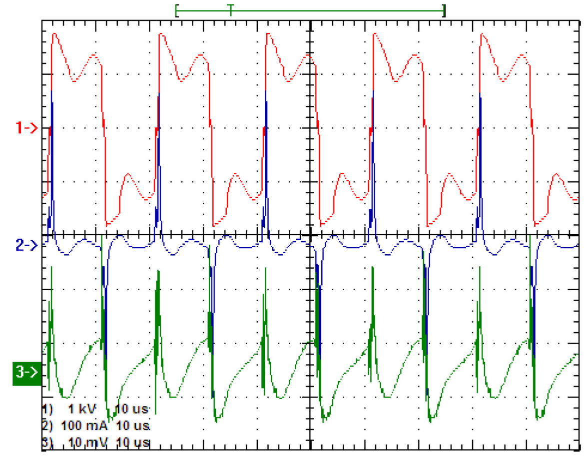

Fig. 11. 310-mm EEFL operated at 50kHz with a $1.4 - \mathrm{k}V_p$ square wave (duty ratio 100%): voltage(1), current(2), and the ac optical probe signal (3) with a 14-mH inductor.

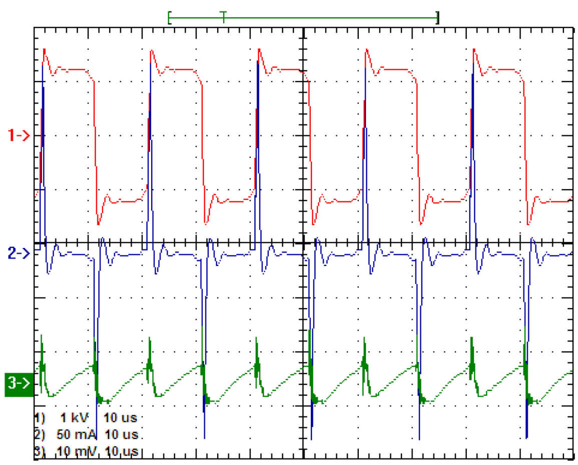

Fig. 10. 310-mm EEFL operated at 50 kHz with a $1.4 - \mathrm{k}V_p$ square wave (duty ratio 100%): voltage(1), current(2), and the ac optical probe signal (3) with a 1.8-mH inductor.

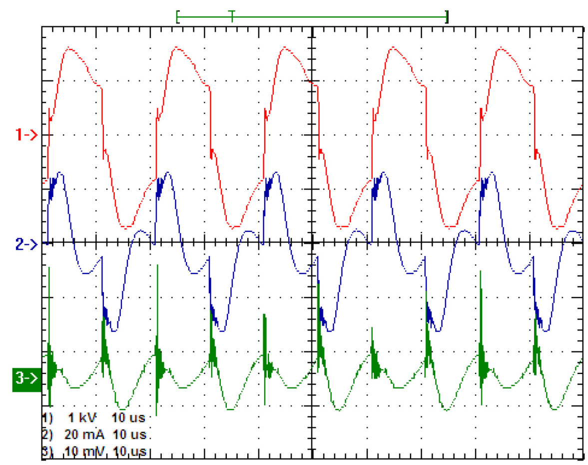

Fig. 12. 310-mm EEFL operated at 50 kHz with a $1.4 - \mathrm{k}V_p$ square wave (duty ratio 100%): voltage(1), current(2), and the ac optical probe signal (3) with an 18-mH inductor.

duty ratio of 100%. The sharp and narrow current pulses at the rising and falling parts of the square wave represent the main discharge of the square wave driving.

Figs. 10–13 show the waveforms for the 310-mm EEFL operated in the same conditions of Fig. 9 but with an inductor of 1.8, 14, 18, and 30 mH, respectively, in series with the lamp. The presence of the inductor enlarges the current pulses. Overshoot can be seen in the lamp voltage and transitions are smoother. One can notice that the current pulse enlargement effect due to an increase in the inductance leads to a more sinusoidal waveform. This is presented here just to illustrate the effect and the inductor inclusion is not necessarily suggested for lamp operation.

Figs. 14–16 present luminance plots for the three evaluated lamps at different lamp powers for sinusoidal and square waveform excitations with different series inductors.

The measurements show that sinusoidal waveform excitation produces better luminance as compared with square waveform excitation for all lamps evaluated. This should not be understood

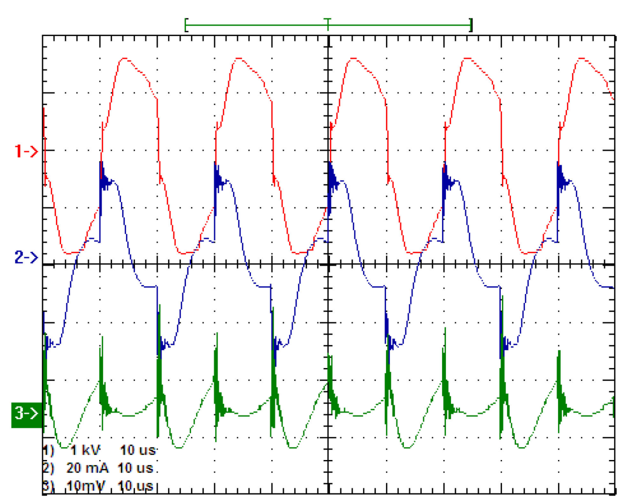

Fig. 13. 310-mm EEFL operated at 50 kHz with a $1.4 - \mathrm{k}V_p$ square wave (duty ratio 100%): (voltage(1), current(2), and the ac optical probe signal (3) with a 30-mH inductor.

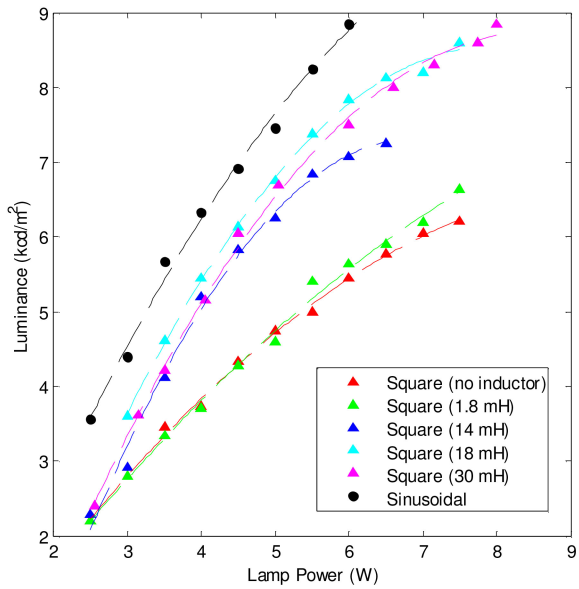

Fig. 14. Luminance measurements for a 310-mm lamp.

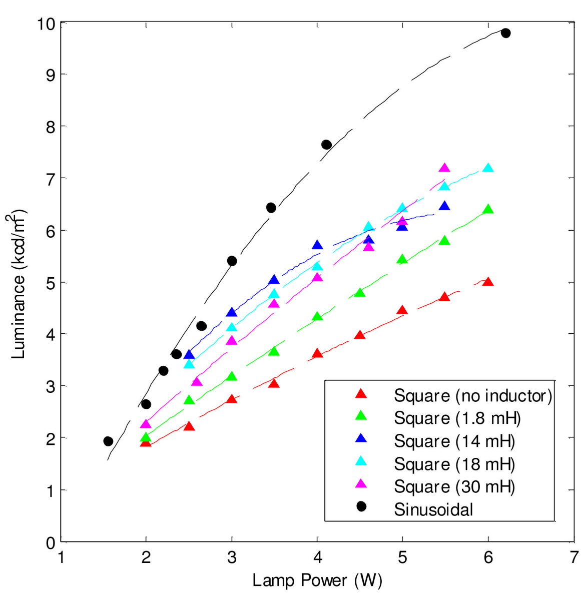

Fig. 15. Luminance measurements for a 250-mm lamp.

as an advantage of sinusoidal operation. In many applications, luminance is not the main objective. For example, Xenon DBD lamps UV emission, a typical application, is much enhanced by square waveform excitation.

In square waveform excitation, there is current only during transition (see Fig. 9), which makes it ideal for the capacitive discharge.

The increased luminance observed for sinusoidal operation is explained by mercury discharge, which requires persistent current to emit radiation. Mercury might not be present depending on the device and application, for instance sterilization by UV emission with Xenon lamps. In that case, square waveform excitation would be a more sensible approach.

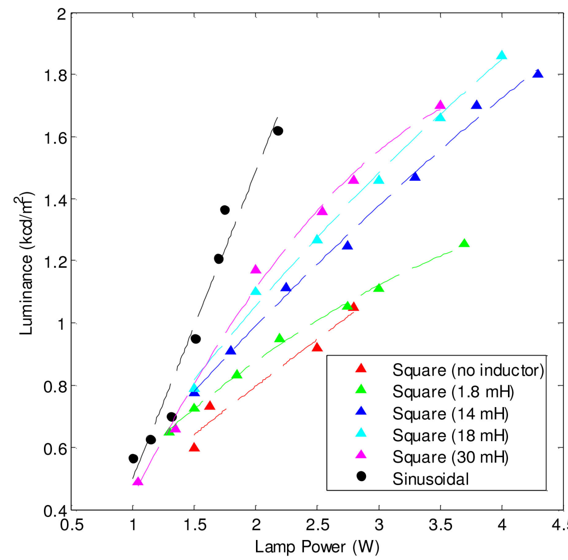

Fig. 16. Luminance measurements for a 125-mm lamp.

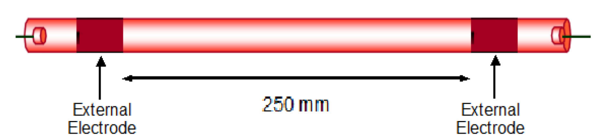

Fig. 17. Schematic diagram of the lamp with receded electrodes.

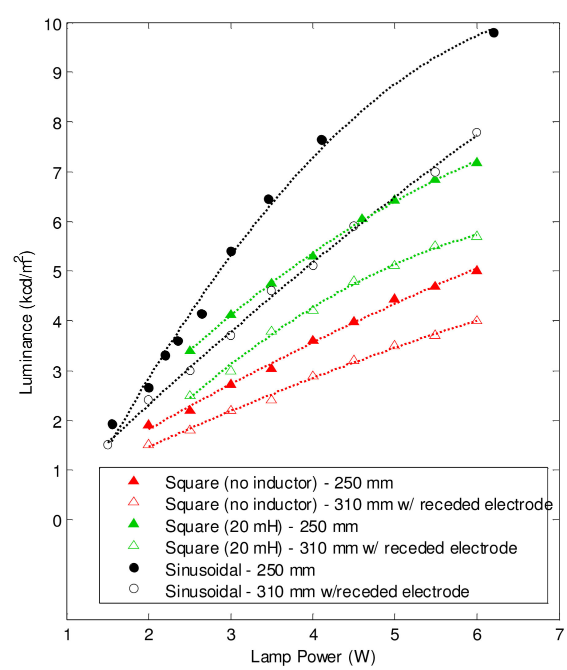

Fig. 18. Electrode displacement comparison.

The original devices employed are CCFLs, containing internal electrodes that might affect lamp behavior, even if not part of the excitation circuit. To check for eventual interferences, measurements for the 310-mm lamp with both electrodes receded by 30 mm were made, as shown in Fig. 17, and compared to their counterparts from the 250-mm lamp.

The results are presented in Fig. 18. Electrode displacement causes a decrease in luminance in the order of 15–20%, but as can be seen from the curves, lamp behavior is very similar. This indicates that the physical processes occurring in the lamp specimens are, for the purpose and scope of this paper, very similar to those occurring in EEFLs.

VI. Final Remarks

EEFLs exhibit an electrical behavior similar to DBD lamps, since they are capacitive discharge devices. From the point of view of light emissions, their behavior is similar to the conventional fluorescent lamps, for light emission occurs whenever there is current circulation in the device.

The measurements confirm these assertions. It was shown that sinusoidal waveform excitation produces better luminance as compared with square waveform excitation for all lamps evaluated, as can be seen in Figs. 14–16.

For square waveform excitation, better luminous efficiency can be achieved with the use of inductors in series with the lamps, as can also be seen in Figs. 14–16. Our conclusions match with those presented in [7], where the authors were only concerned with converter and lamp efficiency. They concluded that for the same lamp luminance, the sinusoidal drive would require a power of 110 W, whereas the square wave driving method would require 180 W.

Electromagnetic interference could also be an issue due to the high-frequency content associated with the square waveforms, and might constitute an interesting research topic.

A previous version of this paper was presented in the 2014 Industrial Applications Society Annual Meeting [17].

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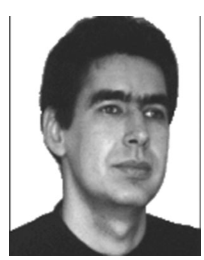

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