



DESIGN AND TESTING OF USER-CONFIGURABLE DRIVING BOARDS OF PULSED XENON LAMPS WITH ADJUSTABLE FLASH DURATION AND BRIGHTNESS FOR CARBON-NANOTUBES PHOTO-INDUCED IGNITION

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ABSTRACT

This paper describes the design and testing of programmable driving boards for turning on Xenon flash lamps, with the aim to photo-ignite Multi-wall carbon nanotubes (MWCNT) with added metal impurities (ferrocene), makers of photo-ignition process. The realized ac powered electronic boards present different features such as variable flash brightness, pulse duration and high flash rate as function of user-adjustable potentiometers or by PC provided command signals. By using the designed PC-configurable boards in the realized experimental setup, the lighting parameters (i.e. pulse energy/power and energy density) for different Xe lamps have been measured and optimized. Varying temporal/luminous parameters of used light sources by means of realized driving boards, different pulse energy and power values were obtained, in order to fully exploit and analyze MWCNTs/ferrocene photo-induced ignition. Finally, employing these boards, the ignition of MWCNT/Ferrocene mixtures has been triggered and investigated.

Keywords: electronic driving boards, xenon flash lamp, carbon nanotubes photo-ignition, IGBT driver.

1. INTRODUCTION

The photo-ignition process of CNTs was observed for the first time accidentally, exposing single wall CNTs to the flash of an ordinary camera (Ajayan *et al.*, 2002). It was found that this photo-effect occurs in air for different types of SWCNTs, prepared with different methodologies and with different percentages of CNTs with respect to the metal catalyst (Fe) contained in them (from 50% to 90%) (Ajayan *et al.*, 2007) (Braidyet. *al.*, 2002) (Tseng *et al.*, 2007) (Sysoev *et al.*, 2011).

The effects of features owned by used triggering Xe light source such as wavelength range selected by suitable optical filters, pulse duration and needed light pulse energy/intensity have been only partially analyzed, finding that a lower pulse energy is needed to trigger the ignition when a shorter flash duration is used (A. Badakhshanet *al.*, 2014) (B. Chehroudi, 2012).

In this context, aim of this work is to design and test different programmable driving boards with the purpose to trigger photo-ignition of CNT enriched with metal impurities by means of Xenon light pulse with proper adjustable parameters.

The realized PC-controlled boards are used to obtain a Xenon light pulse with adjustable features, such as variable flash rate (up to 10Hz), pulse time duration (from 115µs up to 2.41ms) and pulse's energy/intensity. These features can be varied manually by means of potentiometers located on board or interfacing the board with a PC. Finally, varying Xenon light source's parameters, the photo-induced ignition of MWCNTs/ferrocene mixtures was triggered; captured frames of the combustion process show the evolution over time of the ignition phenomenon.

2. CIRCUITAL SCHEMATIC AND OPERATION OF DRIVING BOARD WITH ADJUSTABLE FLASH RATE AND LIGHT PULSE INTENSITY

The circuitual solution, shown in figure 1, powered by ac mains voltage ($V_{RMS}=230V$), does not need a storage capacitor; in fact, the ac input sinusoidal voltage, after being elevated by means of an appropriate circuitual solution, is directly applied on the flash lamp. Driving board's features are adjustable intensity/power and flash rate (up to 10Hz) of light pulse by varying proper variable resistors. Utilizing a square wave with variable frequency [$1 \div 10$]Hz, it is possible to provide the trigger signal thus obtaining the light pulse. The square wave is generated by "variable frequency square wave generator" section, highlighted in green colour in figure 1; it can be also provided by 6.35mm external jack isolating automatically, in this way, the trigger control from "flash rate resistor".

Voltage elevator section (highlighted in red) allows to obtain, as previously cited, an elevation of ac input sinusoidal voltage in order to apply, on the flash lamp, a sine-wave signal whose voltage range is [$325 \div 975$]V and therefore to have the possibility to use lamps which provide higher luminous energy.

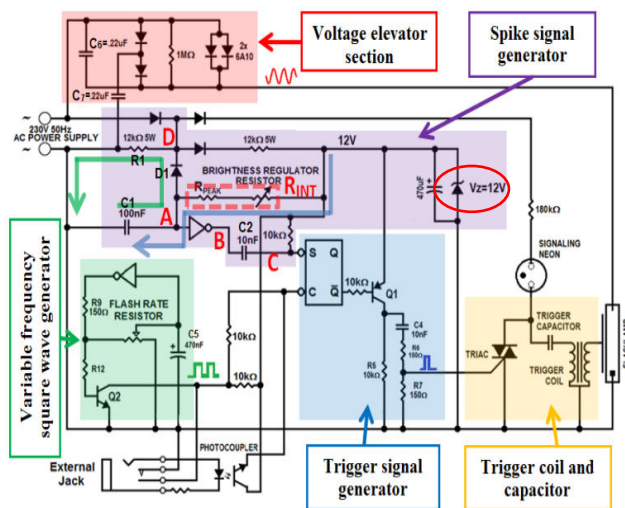


Figure-1. Circuitual scheme of ac-powered designed board for driving Xenon flash lamps with variable flash rate and lamp brightness without a storage capacitor.

The voltage elevator section can be modified in order to get two different voltage ranges of the sinusoidal signal applied on flash lamp ($[325 \div 975]$ V or $[0 \div 650]$ V). In Figure-2, two different circuitual topologies, to perform a double voltage shifter (topology highlighted in red in Figure-2a) or a single voltage shifter, are shown.

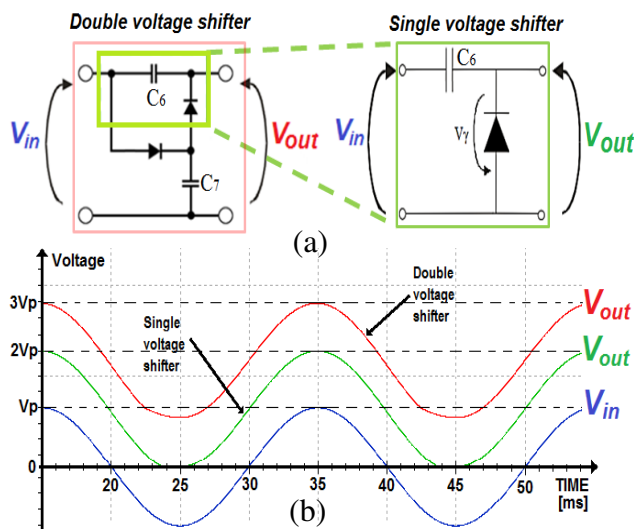


Figure-2. Voltage elevator section: double voltage shifter, on the left side, which performs an elevation of the ac input sinusoidal voltage in the range $[325 \div 975]$ V and single voltage shifter, on the right side, that provides an elevation of the input signal in the range $[0 \div 650]$ V (a). Graph with the sine-wave signals obtained by using the two different circuitual topologies: input sinusoidal voltage with peak voltage value $V_P = 325$ V (blue curve), single voltage shifter with peak value equal to $2V_P$ (green curve) and double voltage shifter with peak value equal to $3V_P$ (red curve).

The circuitual section highlighted in purple provides a pulsed signal to set input of the latch suitable to generate the trigger signal, and regulates, by means of the “brightness regulator resistor” R_{INT} (R_{PEAK} in series with potentiometer in red rectangle), the luminous intensity/power of flash lamp. Intensity regulation is obtained through a RC circuit and a logical NOT gate. The NOT threshold levels are $V_{IHmin} = 2/3V_Z$ and $V_{ILmax} = 1/3V_Z$ (where V_Z is the voltage value, 12V, fixed by Zener diode in red circle). The operation circuit is the following:

- During the positive values of the ac input signal, the diode D_1 is reverse biased and the capacitor C_1 is charged through the resistor R_{INT} , to 12V according to the time constant $\tau = R_{INT} C_1$ (blue path in figure 1). When node A reaches V_{IHmin} , the output of the NOT gate commutes, bringing its output voltage to 0V (node B) producing, in this way, on node C (the latch input), for a very short time, a negative spike. This negative spike and so trigger pulse that enables the flash, occur after a time interval Δt (trigger delay time) that depends on time constant $\tau = R_{INT} \cdot C_1$.

In this way, by changing the resistor R_{INT} , it is possible to delay (or anticipate) the instant (and thus the voltage value to apply for the light pulse) in which the discharge phase through the lamp, once the trigger signal is provided, starts.

The negative spike is always synchronized with the ac 50Hz power voltage for two reasons: 1) the instant in which C_1 starts charging is exactly when the ac sinusoidal input becomes positive; 2) from this moment on, the time needed to the RC circuit to charge C_1 up to the value V_{IHmin} is fixed by R_{INT} .

- During the negative values of the ac input signal, voltage on node D drops down to a low value close to 0V, causing the discharging of the capacity C_1 through the resistor R_1 (green path in figure 1). Consequently, once the voltage on node A drops down to V_{ILmax} , the NOT gate commutes again towards V_Z , causing a positive spike on node C but totally irrelevant.

The trigger signal generator section is highlighted in blue; the negative spike signal is applied on the SET input of latch and a square wave on CLEAR input. The high level of square wave, this last provided by the square wave generator section or by external jack if connected, determines on inverted latch output, when negative spike on SET input occurs, a low pulsed signal that enables the pnp BJT (for Xenon lamp triggering).

The block highlighted in orange is responsible for providing the trigger signal in order to ionize the gas inside the lamp. When the trigger signal occurs, the trigger capacitor discharges on the primary of the transformer (trigger coil), producing on the secondary of transformer a high pulsed voltage value of the order of kV; in this way, a strong ionization of gas contained in the Xenon lamp is obtained.



In Figure-3, the realized board is shown with properly indicated the different circuitual sections.

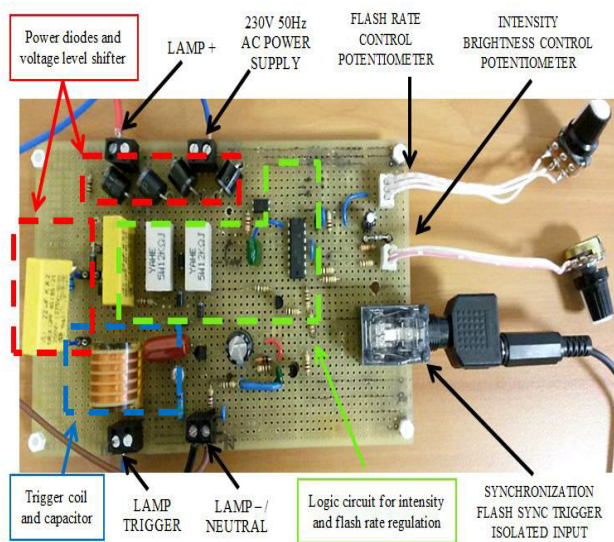


Figure-3. Image of the realized driving board, connected to PC, with indication of the different circuitual sections.

The realized driving board can be used to drive different types of lamps adopting the following changes/adjustments (performed on board by means of jumpers): the already discussed single or double level shifter and R_{PEAK} value that determines the minimum possible trigger delay (when the potentiometer value is equal to $0\ \Omega$) capturing in this way different values of ac voltage applied on flash lamp. R_{PEAK} resistor can be changed to obtain different maximum power values of driving board ($R_{PEAK} = 43\text{k}\Omega$ for piloting 1500W Xe lamps or $72\text{k}\Omega$ for 750W power Xe lamps). Finally the C_6 capacitor value ($0.22\mu\text{F}$) can be replaced with a different capacity (in our case $47\mu\text{F}$), in order to modify slightly the luminous energy emitted by Xenon lamps.

The curves reported in Figure-4 clarify the energies involved during the light pulse generation. The ac input sinusoidal voltage with single voltage shifter ($v_{in} + V_p$, red curve) is applied on the flash lamp; when trigger occurs, C_6 capacitor (charged to voltage value V_p) is quickly discharged over the lamp, until reaching the voltage value v_{in} (orange curve).

The total energy is obtained as sum of the stored energy contribution of C_6 equal to $\frac{1}{2}(C_6 V_p^2)$, shown in green in Figure-4, and energy provided from v_{in} (shown in blue). For potentiometer values higher than $18\text{k}\Omega$ (i.e. $R_{INT} \geq 90\text{k}\Omega$ for $R_{PEAK} = 72\text{k}\Omega$), the v_{in} captured value is already below the lamp's threshold value (approximately 100V). Therefore in this case, the energy supplied to the lamp is given by the only contribution of the energy stored on C_6 ; for $C_6 = 0.22\mu\text{F}$, this contribution is practically negligible, whereas for $C_6 = 47\mu\text{F}$ this energy contribution is significant.

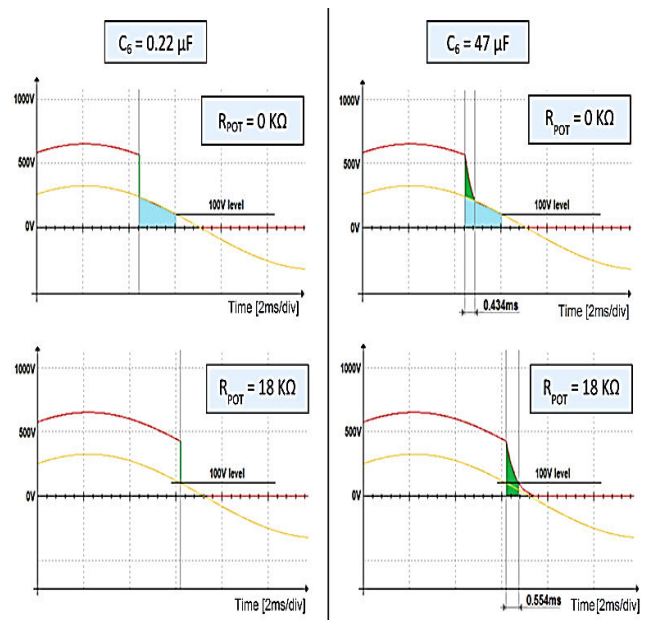


Figure-4. Analysis of involved energies using two different capacity values for C_6 ($0.22\mu\text{F}$ and $47\mu\text{F}$), varying the potentiometer value. Stored energy on C_6 does not concur to total energy if $C_6 = 0.22\mu\text{F}$ being its contribution negligible. On the contrary, when $C_6 = 47\mu\text{F}$, related stored energy is significant especially for potentiometer values higher than $18\text{k}\Omega$. Orange curve is ac input sinusoidal voltage (v_{in}) and red curve the ac input sinusoidal voltage elevated by single shifter ($v_{in} + V_p$).

By means of Thorlabs optical power/energy meter and a pyroelectric sensor (ES145C model), the luminous energy emitted from 120J Xe flash lamp was measured varying the brightness regulator resistor value RINT. The experimental tests were performed using two C_6 capacitor values ($0.22\mu\text{F}$ and $47\mu\text{F}$) and the obtained results are shown in Figure-5.

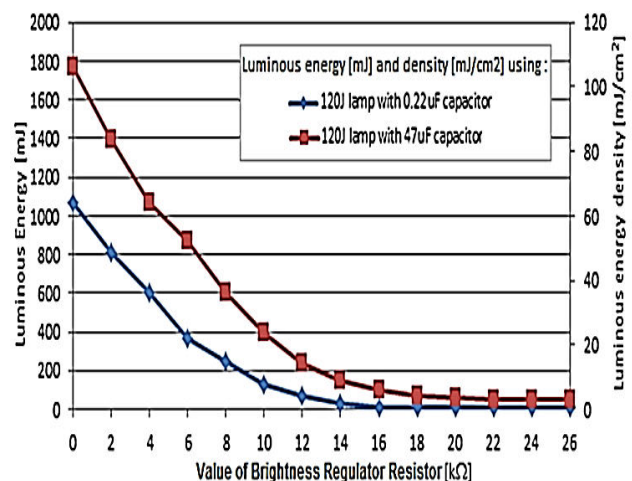


Figure-5. Luminous energy (mJ) and density (mJ/cm^2) as function of RINT resistor for different values of capacitor C_6 , using the 120J Xe flash lamp.



As reported in Figure-5, the red graph, relative to 120J Xe lamp and $C_6 = 47\mu\text{F}$, shows a higher energy than the blue curve obtained by using the same lamp but $C_6 = 0.22\mu\text{F}$. For lower values of the potentiometer, the contribution of stored energy on $C_6 = 47\mu\text{F}$ to the total luminous energy, as shown in Figure-4, is more significant respect to the negligible energy value related to $C_6 = 0.22\mu\text{F}$; instead for $R_{\text{INT}} \geq 18\text{k}\Omega$, the luminous energy is not zero only for $C_6 = 47\mu\text{F}$ due to the stored energy on C_6 capacitor itself.

3. CIRCUITAL SCHEMATIC AND OPERATION OF AC-POWERED DRIVING BOARD WITH ADJUSTABLE LIGHT PULSE TIME DURATION BY USING IGBT SWITCH

The designed driving board is useful when shorter lighting pulses with respect to storage capacitor's discharge time are needed. In a typical flash-lamp at triggering instant, the stored charge on COUT capacitor fully discharges through the lamp, producing the light flash. In order to vary the flash time duration producing shorter light pulses, the adopted circuitual solution uses a device that stops the current flow in the discharging path before the discharge phase ends. This goal is obtained by using a IGBT switch that, located in series to flash lamp, is able to control the light pulse duration opening the current path before that COUT discharge is completed. Also the IGBT device controls trigger pulse required to ionize the Xenon gas inside the flash lamp.

The circuitual solution is powered by the ac mains voltage ($V_{\text{RMS}} = 320\text{--}330\text{V}$); therefore it needs just a simple rectifier to produce proper voltage that will be provided to the COUT storage capacitor. The IGBT-based architecture allows to adjust the flash time duration between $115\mu\text{s}$ and 2.41ms by means of *flash time regulator potentiometer* or PC-provided control signal.

A storage capacitor COUT with selectable value of $141\mu\text{F}$ ($3 \times 47\mu\text{F}$) or $330\mu\text{F}$ ($7 \times 47\mu\text{F}$) can be utilized (as shown in prototype board of Figure-9). 230VRMS power input voltage is used to charge the storage capacitor whereas a DC voltage VIN (from 5V to 15V) is needed to supply the IC NE555 timer. The designed circuitual scheme of the ac powered driving board which employs the IGBT switch (red circle) is reported in Figure-6.

The photoflash capacitor COUT is charged at V_{peak} level equal to $230V_{\text{RMS}} \times \sqrt{2}$. Furthermore, this circuitual typology needs an independent IGBT driver, which block diagram is shown in figure 7, to provide the proper signal at the IGBT gate. The IC IRS4427 driver can supply an output voltage from 6V to 20V. It's composed by a CMOS trigger Schmitt input stage, a pre-driver unit needed to rise the incoming low-voltage signal and the final stage for driving the gates of Q1 and Q2 MOSFET transistors, as shown in Figure-7.

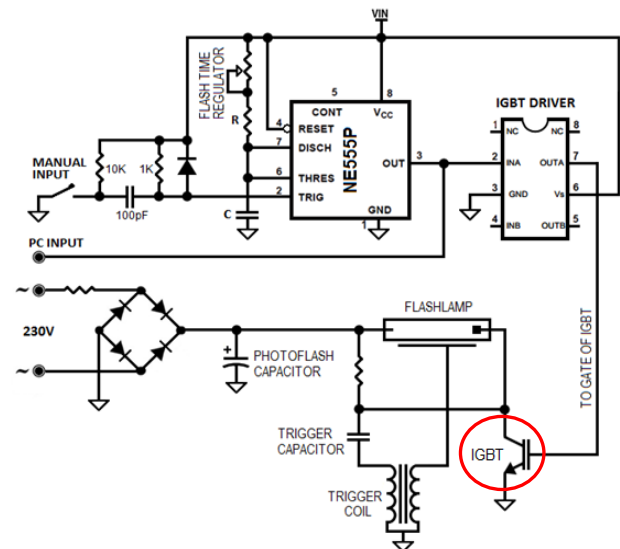


Figure-6. Circuitual scheme of IGBT-based designed board.

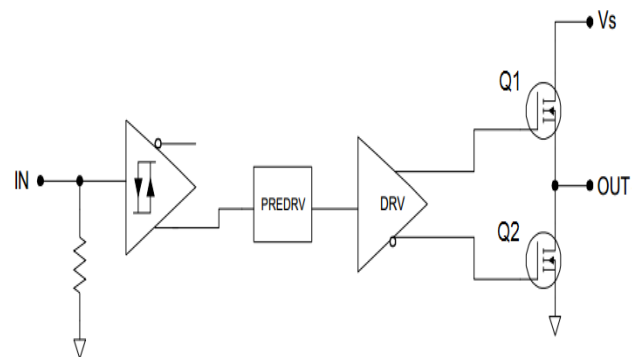


Figure-7. Block diagram of used IGBT driver IRS4427.

A fundamental block is the timing circuit based on IC NE555 timer. This latter is used in monostable configuration in order to produce a high logic signal (5V) of the desired time duration. The time duration of output high pulse can be lengthened or shortened as function of the specific application by adjusting R_{TOT} (sum of R and *flash time regulator potentiometer* R_{POT}).

NE555 input signal is normally high and output signal normally low; when a small negative pulse (lower than $V_{\text{CC}}/3$) is applied to the input, the output goes high with a pulse width T , the required time to charge C to $(2/3)V_{\text{CC}}$, given by:

$$T = \ln 3 \cdot RC = 1.1 \cdot RC$$

Based on this formula, R_{TOT} (sum of $R = 1\text{k}\Omega$ and $R_{\text{POT}} = 20\text{k}\Omega$) and C (100nF) values are chosen obtaining a flash time duration from $115\mu\text{s}$ ($R_{\text{POT}} = 0\Omega$) up to 2.41ms ($R_{\text{POT}} = 20\text{k}\Omega$), as function of R_{POT} value. These durations are calculated in order to be shorter than the free capacitor discharge usually in the range $[2\div 10]\text{ms}$ depending on the COUT storage capacitor value.

In the monostable configuration, the negative trigger pulse applied to NE555 input has to be shorter than desired time duration of NE555 output pulse. This means that a negative input pulse shorter than minimum output



duration ($115\mu\text{s}$) is needed; this is obtained by using the following circuit solution of Figure-8.

Furthermore a protection diode D_1 has been used to remove potentially dangerous positive spikes, otherwise created when positive going transition of input pulse occurs.

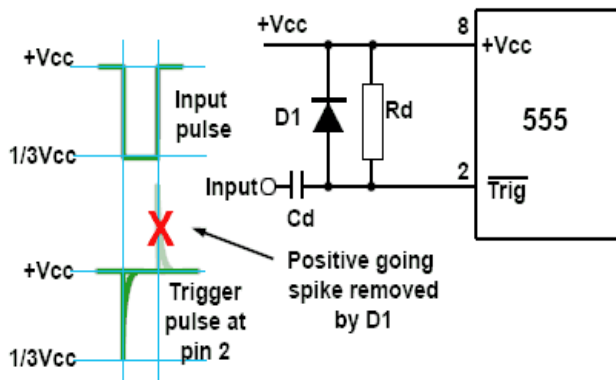


Figure-8. Circuitual solution to produce a negative input spike (shorter than $115\mu\text{s}$) to obtain output triggering signal with proper time duration set by R_{TOT} and C values.

Following the realized driving board is reported in Figure-9 with the different circuitual sections highlighted; on the board, three IGBT switches were mounted to support the very high current value that flows during discharge phase in the flash lamp and IGBT devices connected in series.

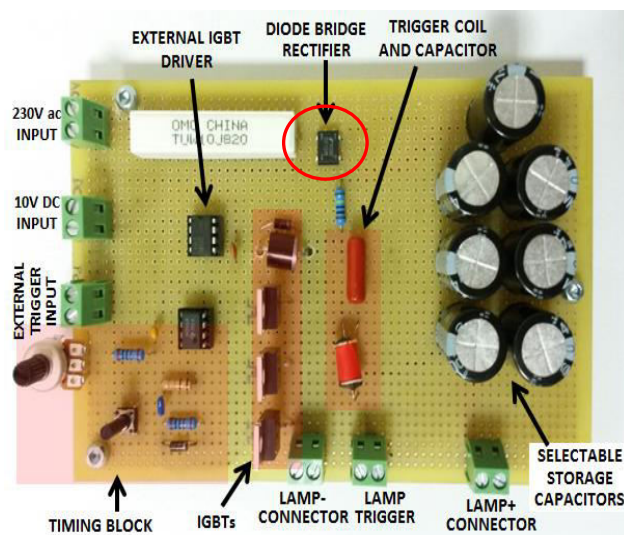


Figure-9. Image of the ac powered IGBT-based driving board with pointed out the different circuitual sections; the storage capacitor is charged by a voltage rectifier (diode bridge in the red circle).

The luminous energy, emitted employing the Xe flash lamp (50J Xe lamp model) was measured using $C_{OUT} = 141\mu\text{F}$ and afterwards $C_{OUT} = 330\mu\text{F}$. Utilizing the greater C_{OUT} value, the whole discharging time is about twice respect to lower C_{OUT} value; similarly, for same

pulse time duration, the final voltage on C_{OUT} storage capacitor, before that IGBT turns off, is greater if higher C_{OUT} value is used due to slower discharging.

In order to perform the experimental tests in the right way, it's important to measure the ac mains voltage applied to the realized driving board since the voltage value stored on the photoflash capacitor C_{OUT} depends on it. The measured voltage value is $226V_{RMS}$ providing a rectified voltage (measured) equal to $315V$ on the storage capacitor.

The graph of the luminous energy values obtained by using $C_{OUT} = 330\mu\text{F}$ (red curve in figure 10) becomes flat when the pulse temporal length is higher than $690\mu\text{s}$ ($R_{POT} = 5k\Omega$, overall resistor $R_{TOT} = 6k\Omega$), while using $C_{OUT} = 141\mu\text{F}$, this behaviour can be observed for pulse time durations higher than $350\mu\text{s}$ ($R_{POT} = 2k\Omega$, overall resistor $R_{TOT} = 3k\Omega$), as shown in the blue curve of Figure-10.

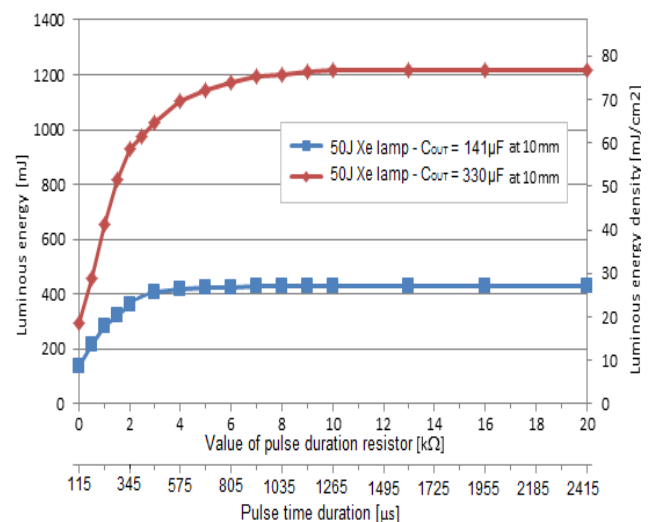


Figure-10. Luminous energy (mJ) and density (mJ/cm^2) as function of pulse time duration in the range $[115\div 2415]\mu\text{s}$ (depending on variable resistor), using a 50J Xe lamp at 10mm from sensor with storage capacitor equal to $141\mu\text{F}$ and $330\mu\text{F}$.

The following table and graph (Figures 11 and 12) show the different luminous energies, for two distance values (10mm and 4mm) between the pyroelectric sensor and the used 50J Xe lamp, measured using $C_{OUT} = 141\mu\text{F}$. As reported in Figure-12, the luminous energy is lower if the distance lamp-sensor is 10mm respect to 4mm.



R_{POT} [k Ω]	Pulse duration [us]	Stored voltage on capacitor [V]	50J lamp with 141 μ F storage capacitor							
			Distance between lamp and sensor: 10mm				Distance between lamp and sensor: 4mm			
			Mean luminous energy [mJ]	Standard deviation [mJ]	Energy density [mJ/cm ²]	Luminous Power [kW]	Mean luminous energy [mJ]	Standard deviation [mJ]	Energy density [mJ/cm ²]	Luminous Power [kW]
0	115	315	138.5	1.120	8.711	1.204	219.1	1.633	13.780	1.905
0,5	172	315	215.8	1.316	13.572	1.285	346	3.897	21.761	2.060
1	230	315	282.8	1.015	17.786	1.230	453.3	2.633	28.509	1.971
1,5	287	315	324.8	2.879	20.428	1.132	518.4	4.291	32.604	1.806
2	345	315	361	2.260	22.704	1.031	569.3	1.917	35.805	1.627
3	460	315	404.4	2.222	25.434	0.879	634.7	4.502	39.918	1.380
4	575	315	418.4	0.9141	26.314	0.728	659.3	2.202	41.465	1.147
5	690	315	425.8	1.736	26.780	0.617	670.2	4.661	42.151	0.971
6	805	315	425.9	2.322	26.786	0.526	676.2	5.891	42.528	0.836
7	920	315	428.1	1.688	26.925	0.466	674.9	1.403	42.447	0.735
8	1035	315	427.5	1.542	26.887	0.412	678.7	2.706	42.686	0.654
9	1150	315	428	3.221	26.918	0.372	679.6	2.718	42.742	0.590
10	1265	315	428.2	2.251	26.931	0.338	679.7	7.633	42.748	0.536
13	1610	315	428.4	1.226	26.943	0.264	676.6	1.467	42.553	0.418
16	1955	315	427.9	2.699	26.912	0.218	684.5	6.624	43.050	0.349
20	2415	315	428.4	1.575	26.943	0.174	678.5	1.377	42.673	0.275

Figure-11. Luminous energy, density and calculated power by using IGBT-based board with $C_{OUT}=141\mu F$, 50J Xe lamp, 10mm and 4mm distances between light source and pyroelectric sensor, varying flash time duration.

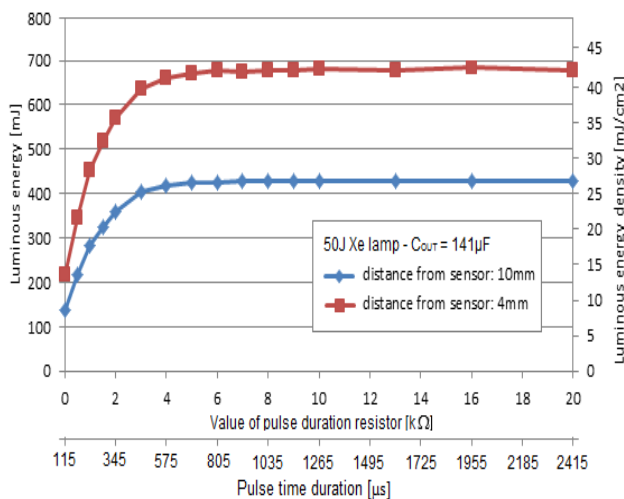


Figure-12. Luminous energy (mJ) and density (mJ/cm²) as function of pulse time duration in the range [115÷2415] μ s using 50J Xe lamp at 10mm or 4mm from light sensor ($C_{OUT}=141\mu F$).

4. MWCNTS/FE PHOTO-IGNITION EXPERIMENTAL TESTS BY USING REALIZED ELECTRONIC DRIVING BOARDS

The carried out experimental tests concerned the photo-induced ignition of MWCNTs/ferrocene mixtures with 75% of ferrocene by weight varying the energy of Xe luminous pulse incident on sample. The weight ratio percentage was chosen according to already published results in which a greater amount of Fe respect to CNTs results in a lower luminous energy required to trigger the

photo-ignition process (Chehroudiet *al.*, 2008) (Badakhshan *et al.*, 2012).

In the photo-ignition test, the realized driving board without a storage capacitor was employed adopting the following settings: single voltage shifter, $C_6 = 0.22\mu F$ and R_{PEAK} (in series with the brightness regulator resistor) equal to 72k Ω . In order to provide to the driving board a single pulse on demand, a comparator PC-interfacing board and a LabVIEW application, suitably developed, were used. The realized experimental setup is shown in Figure-13.

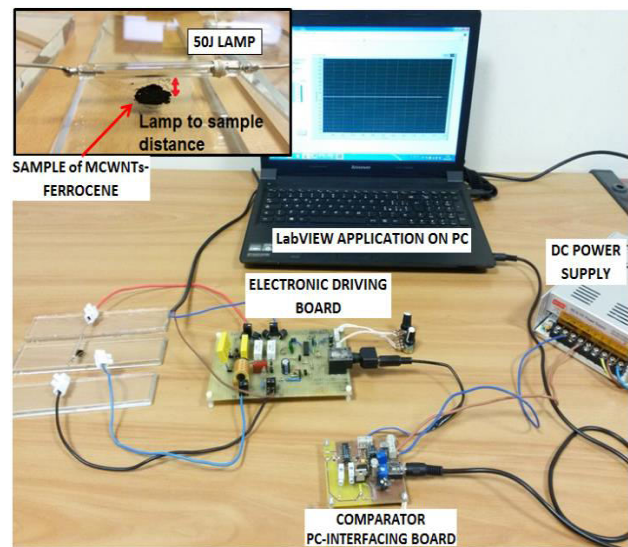


Figure-13. Experimental setup used to perform the photo-ignition of MWCNTs/ferrocene mixture.

The used driving board was triggered by a 5V pulsed signal provided by PC through the realized interfacing board. The sample was placed 4mm far from the Xenon flash-lamp.

The luminous energy emitted by the 50J Xe flash lamp was measured with a distance lamp-sensor of 4mm and then, each time, the pyroelectric sensor was replaced with the MWCNTs/ferrocene mixture preserving the same distance lamp-sample, to perform the ignition test (as shown in Figure-14).

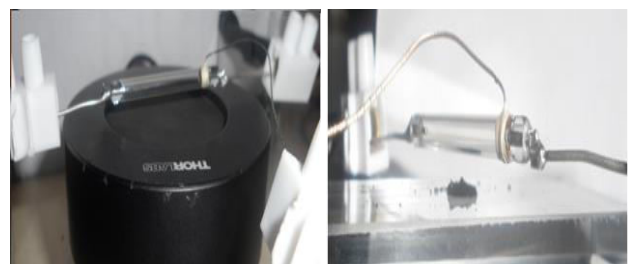


Figure-14. Xe lamp on the sensor at the distance of 4mm to measure the luminous energy (a) and Xe lamp on the mixture at the same distance (4mm).

Changing R_{INT} , through the potentiometer relative to intensity brightness control (see Figures 1 and 3), we



modified the energy emitted by the lamp starting with the lower energy, first delivered on the sensor and then on the mixture, piloting a single pulse by PC. In this way, we increased the pulse energy until the ignition phenomenon was observed, replacing the mixture not ignited, each time, with a new one.

In the following frames, the evolution over time of the combustion process is shown with indication of the time intervals during the combustion itself.

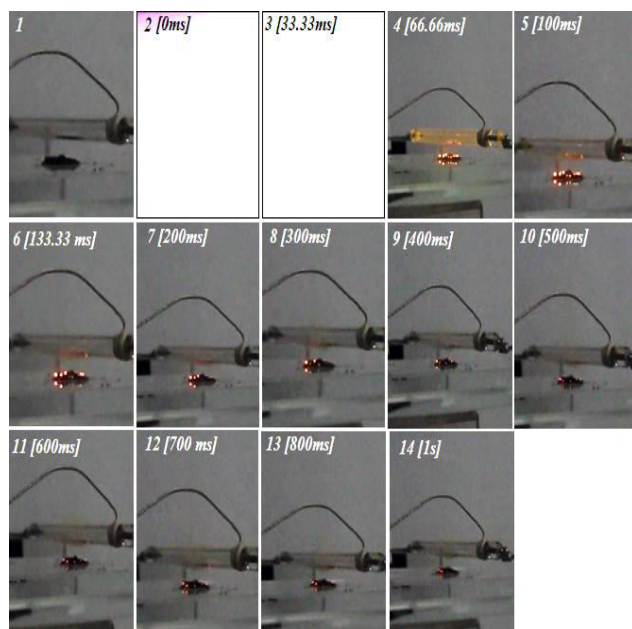


Figure-15. Frames of combustion process taken during ignition phenomenon.

It is clearly visible in the fourth frame (at 66.66 ms), soon after the light pulse, the ignition of the MWCNTs/ferrocene mixture triggered by the Xe lamp which appears still in orange colour. The photo-induced ignition was obtained by irradiating the sample with a measured luminous energy density equal or greater than about $85\text{mJ}/\text{cm}^2$.

5. CONCLUSIONS

In this research work, different programmable driving boards were designed, realized and tested to obtain a Xenon light pulse with different characteristics in order to photo-ignite MWCNTs/ferrocene mixture by varying the Xe light source's parameters.

Each driving board presents different features such as variable flash rate, pulse's energy/intensity and time duration adjustable by user through potentiometers located on the electronic boards. The triggering signal can be provided manually through a push-button placed on boards, or by a LabVIEW application installed on PC and a PC-interfacing board to provide the single triggering pulse on demand.

The realized boards were employed to perform the photo-induced ignition tests of MWCNTs/ferrocene mixture varying the energy of Xe luminous pulse incident

on sample obtaining in this way the combustion trigger and the minimum energy at which it occurs. Frames of the combustion process were taken during the ignition phenomenon highlighting that the photo-ignition occurs soon after the light pulse and continues for about one or few seconds affecting the entire mixture sample.

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