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LED as a low cost single photon source

El LED como fuente de fotones individuales

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Resumen

Las fuentes de fotones individuales usan luz no-agrupada para producir fotones individuales, y en este artículo se describe una aplicación con el diodo emisor de luz (Light Emitting Diode; LED) como una fuente de fotones individuales de bajo costo usando pulsos débiles de luz coherente, el uso correcto de circuitos de radiofrecuencia (RF) para controlar la zona de agotamiento del LED, puede lograr una emisión de pulsos ópticos correspondiente a los pulsos eléctricos en la excitación del LED para generar fotones individuales, sin embargo circuitos tradicionales de conmutación para control de un LED fallan considerablemente cuando el tiempo de conmutación es menor a 10ns provocando una foto emisión no deseada. Este experimento demuestra que un fotón individual puede ser generado por un LED controlado.

Palabras clave: Fotonica Cuántica, fuente de fotones, LED

Abstract

Single photon sources use anti-bunched light to produce single photons, and in this article an application is described. With a light emitter diode (LED) as a low cost single photon source using weak light coherent pulses, the appropriate use of radiofrequency (RF) circuits to control the LED depletion zone, it could achieve an emission of optical pulses appropriate to the electrical pulses in the LED excitation to generate single photons. Nevertheless, the switching circuits for the LED control fail when the time of commutation is under 10ns, which then provokes a non-desired photon emission. This experiment shows that a controlled LED can generate a single photon.

Key Words: Quantum photonics, single photon sources, LED.

1. Introduction

Single photon sources began with the Brown and Twiss experiment [1], who had the purpose of studying the astrophysical properties of space. After Glauber postulated that the correlation functions for coherent fields [2] applied to coherent fields like a laser light, by 1965 it was still believed that light quantum properties followed the electromagnetic classic theory. However when Bell published his theory about inequality [3], finally there was a possibility to prove the Einstein-Poldolsky-Rosen paradox [4] experimentally. This is the moment when the necessity to obtain single photons with anti-bunching light became important.

Clauser in 1974 [5], developed an experiment to obtain single photons based on the transition cascade of calcium atoms. This experiment is considered the first single photon that was sourced successfully. Thus there was a way to demonstrate experimentally Bell's inequality proposed years before. Since this first single photon source, there have been several developments of single photon sources, dividing them in to two types: deterministic and probabilistic [6]. However to understand how a single photon source works, it is necessary to understand the anti-bunching light concept.

In 1977 Kimble observed for the first time an anti-bunching light effect [7] when a single photon could be detected in the transmitter and receiver arms of the Brown and Twiss experiment, this single photon is isolated from other photons by a gap of time, this effect can be mathematically

demonstrated with the second-order correlation function in Eq. (1) [8].

$$g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t) \rangle}{\langle I(t) \rangle^2} \quad (\text{Eq. 1})$$

Where t is time of propagation, τ a delay and I the intensity of the electromagnetic field. When $\tau = 0$ and $g^{(2)}$ is 0, it is considered a perfect anti-bunching light. Also the second-order correlation function can be related with the number of photons at a sample time in the Eq (2) [9].

$$g^{(2)}(\tau) = \frac{\langle n_T(t)n_T(t+\tau) \rangle}{\langle n_T \rangle^2} \quad (\text{Eq. 2})$$

Where T is the photo detection sample time and $\langle n_T \rangle$ is the average count rate per photo detection sample time. This function is illustrated in Figure 1 applied to continuous or pulsing light. When it is continuous, the single photon detection observes Rabi oscillations (Figure 1a) and when it is pulsed, it behaves like the Dirac function (Figure 1b) where each Dirac pulse represents coincidences of optical pulses.

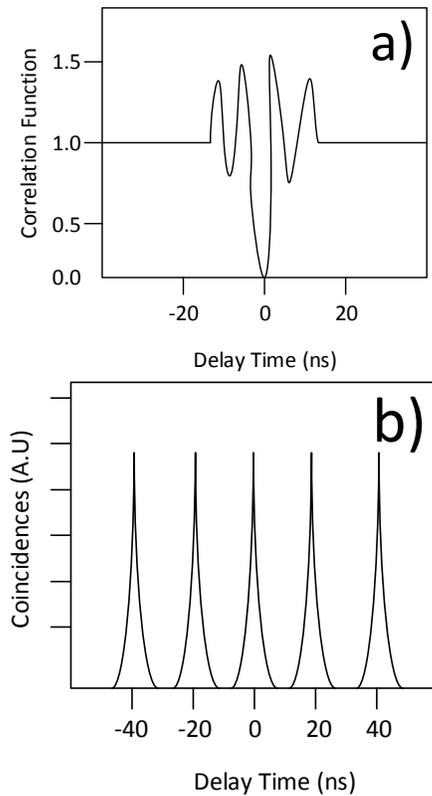


Figure 1. a) Rabi oscillations in a continuous single photon light source, b) coincidences generate by each single photon detector.

The single photon sources can be controlled optically or electrically, although the latter has more applications. The electrical pulses are applied to the LED structure stimulating the minority carriers in the silicon substrate (N and P). This generates photons under demand however when the purpose is to generate single photons with the LED, it is not possible due to the minority carriers combination. It still releases photons until it becomes a non-radiative recombination in a so-called depletion zone.

There are single photon sources with nano-wired LEDs [10], although they are considered as quantum dots due to the special temperature conditions of 10°K (-263°C). Therefore, there is a proposal to control the combination of minority carriers with high-speed response circuits, of which

the advantages are: low cost, compactness and lack of requirement to have special temperatures, i.e. they can work at room temperature.

2. Experimental Procedure

A. Material and Equipment

The LED can have different parameters of excitation such as physical and electrical properties. Therefore, the LED used in this experiment could have some slight difference between another of the same model. Figure 2 illustrates the equivalent circuit of the LED when it is forward bias.

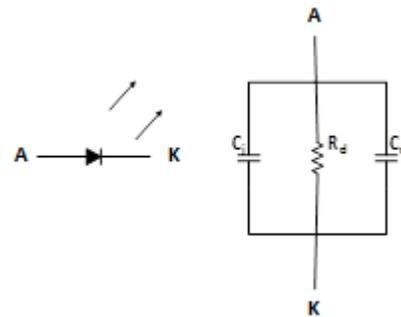


Figure 2. LED equivalent circuit, C_j is the junction capacitance, R_d is the diffusion resistance and C_d is the diffusion capacitance.

The junction capacitance is low and despised, diffusion capacitance is related with the depletion zone. The LED used is a Vishay TLHR4400 with a wavelength (λ) of 625nm.

The single photon detector used is an id100-50-MMF of idQuantique, with a λ response between 360 - 760nm. The optical pulses measurement is realised with a PicoQuant time-correlator PicoHarp300. An optic fibre multi-mode of 100 μm model FG105LCA, to transfer the light to the single photon

detector and an optical power meter model PM100D with its detector SC700C to measure the LED optical power were used both sourced from Thorlabs.

The experiment was mounted in a cage system to avoid problems of alignment between the LED, and the aspheric lens (ACL2520U-DG6), which concentrates the light in the fibre-optic tip to reduce losses. Figure 3 illustrates the scheme and shows a picture of the optical experimental array.

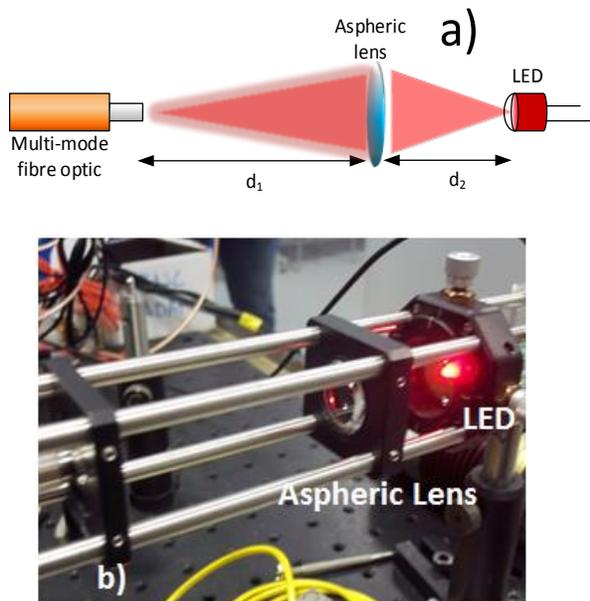


Figure 3. a) Scheme of the optical system, b) Optical experimental array.

There are two circuits used for this experiment: the operational amplifier THS3202 from Texas instruments with its respective evaluation board and an LED switching driver with a current booster. The transistor used in the driver is a BFG 198 UHF transistor from NXP semiconductors and BC847 with MMBTA42LT1G for the current booster.

The electric signals are recorded by a

storage oscilloscope from Keysight model DSOS404A and the electrical pulses are generated with a pulse generator from Agilent model 81130A.

B. Circuits simulation

The circuit analysis is developed through a simulation with the most realistic conditions using Multisim 12.0 from National Semiconductors with electrical pulses of 2ns duration as the middle point of the times used to excite the LED. Afterwards the simulation results are compared with the experimental results.

C. Experimental method

The first step previous to any optical measurement is a light concentration from the LED to the fibre-optic tip thus reducing possible losses, the adjustment of the aspherical lens to a certain distance of 24.5mm from the LED and 104.2mm from the optical fibre. These are obtained empirically or they can be calculated by the Eq. (3).

$$\frac{1}{f} = \frac{1}{d_1} + \frac{1}{d_2} \quad (\text{Eq. 3})$$

Where f is the focal length (Thorlabs specified this information), d_1 is the distance from the LED and d_2 is the distance to the optical fibre. The frequency of repetition for the electrical pulses is 10MHz and the duration times used are 1ns, 2ns and 5ns.

The schematic diagram of the THS3202 evaluation circuit (Figure 4a), is provided by Texas instruments [11]. Only the channel 2 is used due to the gain of 1 because at

commutation times of 2ns and 1ns, more voltage and current are necessary for the LED excitation. The input of the pulses is connected to the non-inverter input and 1V in the inverters input to adjust the offset level in the output signal. This offset level would stop the minority carrier in the depletion zone.

The diagram schematic of the LED driver with a current booster is illustrated in Figure 4b.

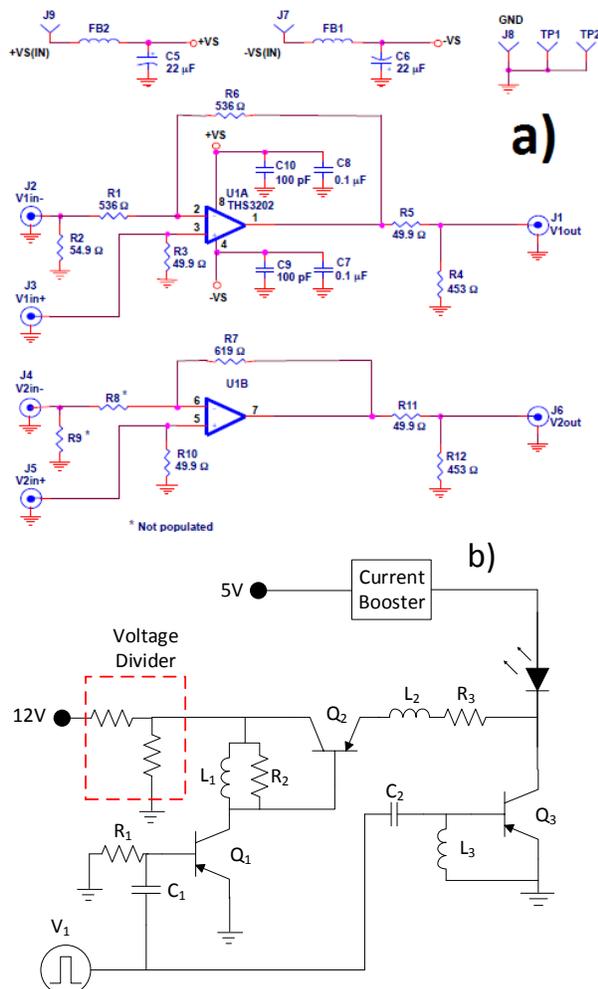


Figure 4. Diagram schematic of: a) THS3202 evaluation circuit and b) The LED driver.

This circuit uses two voltage sources: the first is 5V for the LED reference in its anode and the second is 12V as a reverse

pulse to stop the recombination in the depletion zone. The current booster is used to increase the current through the LED without changing the 5V.

The transistor Q_2 enters in the saturation region when there is no stimulation from the source input V_1 and the cut-off region is activated with the presence of stimulation, Q_1 controls the operation of the cut-off-saturation in Q_2 synchronized with Q_1 , Q_3 is the LED switching driver; when in the cut-off region the LED cathode is polarized with 12V, although that voltage can be adjusted by a voltage divider.

The LC circuits in the Q_2 and Q_3 base terminals have the function of filters and impedance coupling. The RL circuit in Q_1 has the function of polarizing the transistor in DC and AC, this circuit is based in the high speed optical communication [12]. The time resolution in the time-correlator is adjusted to 512ps with threshold levels of 150mV to discriminate possible noise.

D. Control measurement of optical pulses

Previous to testing the circuits, the LED is directly connected to the pulse generator to know the depletion zone effects on the electrical pulse stimulation with the widths times proposed (1ns, 2ns and 5ns). Figure 5 and 6 illustrate the electrical and optical pulses respectively.

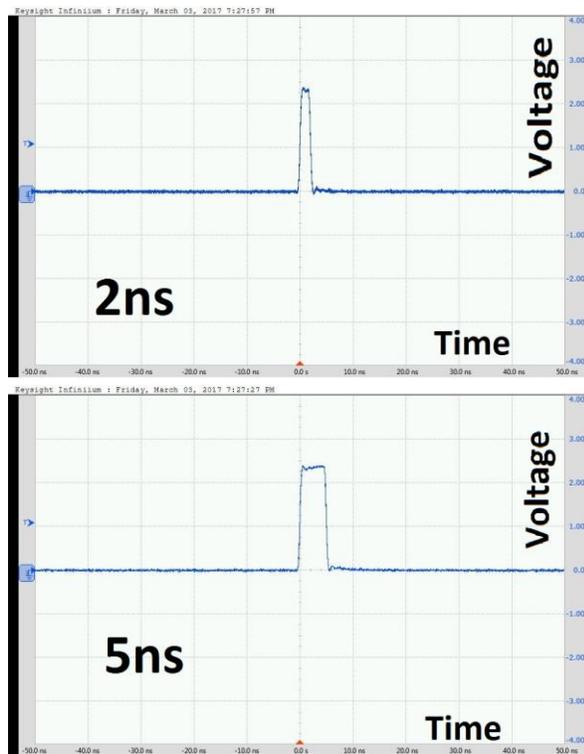


Figure 5. Electrical pulses obtained from the oscilloscope. Scales: 1V/div and 10ns/div.

generate any photon, and between the optical pulses that correspond to 2ns and 5ns. There is an attenuation, due to the time of electric pulse, stimulations need to be amplified for a suitable photon radiation, Table 1 shows the results of the optical measurements.

Table 1. Comparison between pulses.

Electrical pulse	Optical pulse
1nS	No emission
2nS	6.656ns
5nS	8.192ns

Therefore the time in the depletion zone is around 4ns.

3. Discussion

A. Simulation Results

The result of the THS3202 evaluation circuit is promising because the current in the output signal is adjusted to the input signal, although the output voltage signal is low and has a longer duration but the simulator indicates there is an emission from the LED.

The LED driver enhances the output signal voltage and the current is high, this could be possible for Q₃ switching. Figure 7 illustrates the results of the simulation for both circuits.

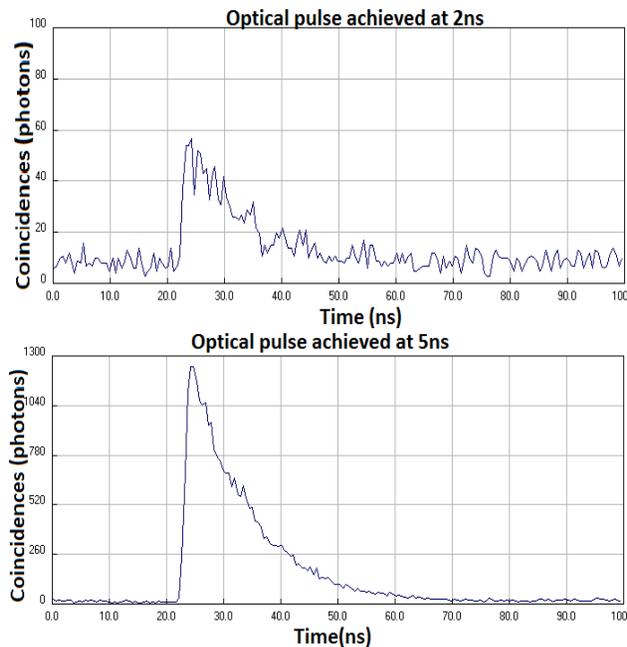


Figure 6. Optical pulse measurements registered with the time-correlator.

The electric pulse with a time of 1ns is not registered because there is not enough excitation between the minority carriers to

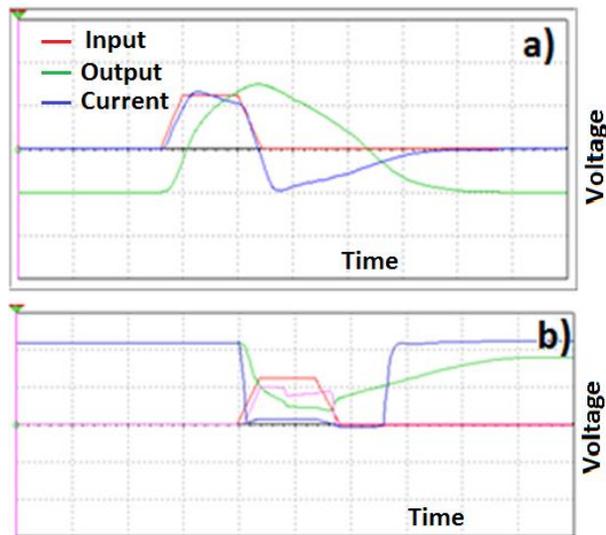


Figure 7. Graphic results obtained with the simulator oscilloscope: a) THS3202 evaluation circuit, b) LED driver.

Scales: a) 1V/div and 2ns/div.

b) 2V/div and 2ns/div.

The input signal is represented with the red curve with 2V/div for both circuits. In Figure 7a the blue signal represents the current with 50mA/div and the green signal is the voltage in the output signal with 1V/div. In Figure 7b, the blue signal represents the transition between the cut-off and saturation region with 2V/div, the green signal represents the falling voltage in the cathode with 5V/div, and the pink signal represents the circulation current. The time division for both graphs is 2ns/div.

B. Experimental Results of circuits

The THS3202 has an *excellent output signal*, better than the simulation although there is a slight attenuation that limits a photon emission. Figure 8 illustrates the signals observed.

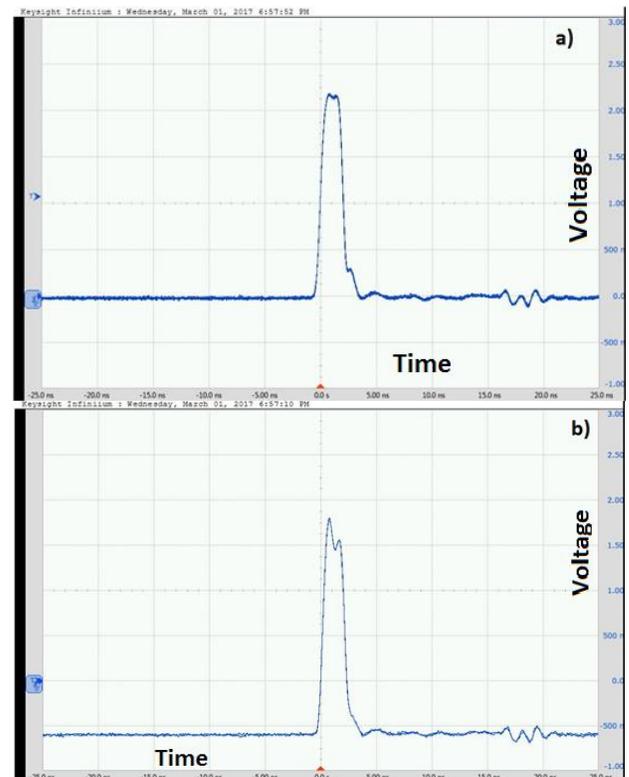


Figure 8. Signals obtained experimentally with the THS3202 evaluation circuit: a) input signal, b) output signal.

Scales: 500mV/div and 5ns/div.

The LED driver has similar results in its simulation, although it is possible to observe a slight noise without affecting the stimulation. The main difference observed in the LED with the circuits, is that there is no limitation of photon emission by the LED driver. This is due to the current booster supplying the necessary current that the THS3202 cannot supply. Figure 9 illustrates the signals observed.



Figure 9. Signals obtained experimentally with the LED drive: a) Q2 commutation signal, b) Cathode falling voltage.

Scales: 5V/div and 10ns/div.

The measurement of current on the output signals is not possible to be observed with an oscilloscope without a current probe or a shut resistance, unfortunately the current probe was not available during the experiment and the shut resistance would affect the electrical pulses on the circuits, the best way to estimate the amount of current circulating through the LED is with an estimation of the quantum efficiency of the LED.

Although the manufacturer does not provide this information, it is possible to calculate the power conversion efficiency with a measurement of the optical power of the LED and the application of Eq (4).

$$\eta = \frac{P_o}{P_I} \quad (\text{Eq. 4})$$

This is the power conversion efficiency that is the ratio between the optical power emitted and the electrical power applied. This data should *be taken carefully* because there are other factors that must be taken in to consideration such as the injection efficiency, internal quantum efficiency and

the extraction efficiency. The efficiency of the SC700C is near to 75% and it is included in the measurement of the power meter.

C. Experimental results of optical pulses

The measurements of the optical pulses with the THS3202 board proved that current limitation affects the photon emission, although the optical pulse duration matched with the electrical pulses. Figure 10 illustrates the optical pulse measurements with the THS3202 evaluation board.

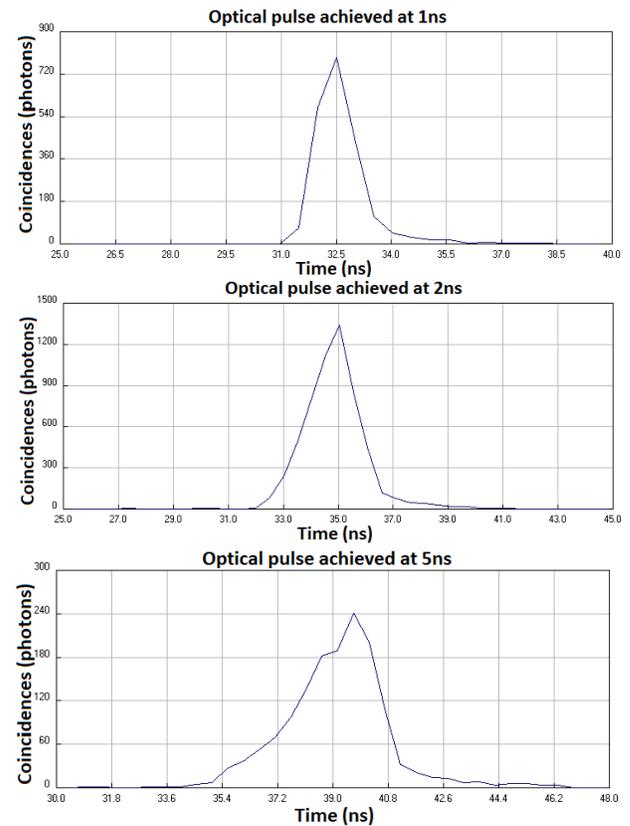


Figure 10. LED optical pulse measurements with the THS3203 evaluation board.

In the measurement of the optical pulses with the LED driver, it was necessary to attenuate the light, reducing the current until it reaches a count rate of $2e4$ counts per

second, to avoid saturating the single-photon detector. Figure 11 illustrates the optical pulses measured.

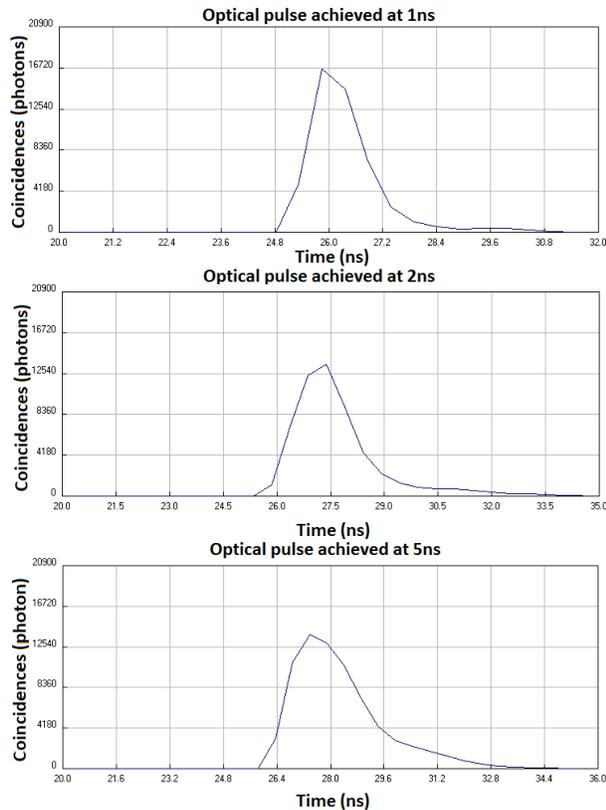


Figure 11. Optical pulse measurements with LED driver.

In Table 2, there is a comparison between electrical and optical pulses of the circuits used and the correspondent photon count rate (counts per second).

Table 2. General time comparison.

Electrical pulses	THS3202		LED Driver	
	Optical	C. Rate	Optical	C. Rate
1nS	1.536ns	6.37e2	1.024ns	7.27e3
2nS	2.048ns	7.22e2	2.048ns	8.30e3
5nS	5.560ns	1.95e3	5.560ns	1.19e4

Some optical results can be slightly different as some of the pulses have a shift in time. This is due to the jitter effect in the single-photon detector.

D. Comparison with other single photon sources.

Although both circuits have acceptable emission times, the LED driver presents better results in the photon emission. Thus with the purposes of comparing it with other single photon sources, it is necessary to estimate the $g^{(2)}$ of the LED driver with the best time emission (1ns), using Eq. (2) that is a developing of the Eq. (1) with count rates.

The quantum efficiency is estimated with the power rate conversion in the Eq. (4). Table 3 shows a comparison with other single photon sources.

Table 3. Single-photon source comparison.

Source	λ (nm)	η	$g^{(2)}$	Temp ($^{\circ}$ K)
Faint laser	Visible-IR	1	1	300
Quantum Dots (GaN)	340-750	-	0.4	200
Single Atoms	Atomic Line	0.05	0.06	≈ 0
LED Driver	≈ 630	≈ 0.34	≈ 0.25	300

The values obtained are considered approximate. It is necessary to have a deep analysis of the physical properties of the LED, e.g. quantum efficiency, responsivity, and with the use of Brown and Twiss experiment that determines if the LED is a deterministic or probabilistic source because it was not in the scope of research of research of this paper. However the results achieve acceptable values.

4. Conclusions

The research and application of quantum optics has brought a revolutionary innovation in areas where electronics ruled during the XX century and quarter of this century, the traditional computing began with vacuum valves and afterwards they were replaced by solid-state semiconductors, now the quantum photonics start to complement them [13].

Quantum computing uses solid-state single-photon emitters [14, 15, 16], thus the information is encoded and processed in the quantum states of single-photons, although the quantum dots are used to generate single-photons, they construction and working requirements make them exclusive for scientific and research purposes [17].

New research has established a Silicon-Carbide LED that works as a quantum dot under room conditions [18], however this device is still expensive. Therefore in this research, a method was used to replicate a semi-coherence light using weak light pulses with a common LED.

The electronic solution proposed to stop the non-radiative recombination released optical pulses with similarities to other single photon sources, hence the reason why the weak coherence light pulses are suitable to produce anti-bunching light [19].

The results obtained from the circuits presented a pulsed light with a low number of photons, this photon emission is similar to a single photon source emission and hence, the LED is an option for possible quantum applications, especially for quantum communication [20]. The LED responses on

external trigger demand to emit a low number of photons but it is necessary to characterize the light pulses to determine what type of single photon source corresponds, deterministic or probabilistic. *Recently the University of Bristol has analysed the use of the LED in commercial applications with the Quantum Key Distribution (QKD) [21] and there are PhD theses [22, 23] with LED applications that have been approved.*

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