Voltage Multiplication and Single-Photon Detection using a Red LED

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(Dated: March 14, 2025)

This experiment explores the Cockcroft-Walton voltage multiplier and its application in biasing LEDs for use as Single Photon Avalanche Detectors (SPADs). The study also investigates pulse detection using an Arduino and discriminator circuits. We present measurements of voltage multiplication, single-photon avalanche characteristics, and pulse counting rates for different conditions. Additionally, the role of a discriminator circuit in processing detected pulses and converting them into digital signals is examined.

INTRODUCTION

The Cockcroft-Walton voltage multiplier is a circuit used for generating high DC voltages from a lower AC source. It consists of a cascade of capacitors and diodes, effectively multiplying the peak AC input voltage by some factor, depending on the number of "stages" the circuit has. This method of voltage amplification is particularly useful for applications requiring high voltages without bulky transformers.

A secondary focus of this experiment is the characterization of red LEDs as inefficient Single Photon Avalanche Detectors (SPADs). When reverse biased at sufficiently high voltages, certain red LEDs can exhibit an avalanche effect, where a single photon can trigger a cascade of charge carriers (electrons and holes). This phenomenon allows for the detection of single-photon events and can be analyzed through pulse characterization techniques.

In order to filter out these pulses, we use a discriminator, which converts analog input pulses (continuous voltage signals with varying amplitude) from the SPAD into digital pulses (binary signals that are either "high" or "low") by comparing them to a set threshold voltage. This ensures that only significant pulses are counted by the Arduino.

EXPERIMENTAL SETUP

The setup includes a three-stage Cockcroft-Walton voltage multiplier circuit, an LED in reverse bias for avalanche detection, and an Arduino UNO R3 SMD [1] for pulse counting. The voltage multiplier is constructed using $1\mu F$ capacitors and 1N4005 Rectifier diodes [2], providing the necessary high voltage for biasing the LED. The detected pulses from the LED are analyzed using a Keysight DSOX1204G oscilloscope [3] and further processed using a discriminator circuit built around an LM293P comparator [4]. The discriminator ensures that only pulses above a specific voltage threshold are converted into digital signals, which are then counted by the Arduino.

Uncertainties for DC voltage measurements were calculated based on the Keysight 34461A multimeter specifications [5].

RESULTS AND DISCUSSION

Cockcroft-Walton Voltage Multiplier

We began by constructing the Cockcroft-Walton voltage multiplier circuit consisting of three stages, whose intended functionality was to multiply the input voltage by close to a factor of 3. We then verified its performance by measuring the output at different stages..

R-1: Cockcroft-Walton Voltage Multiplier Circuit

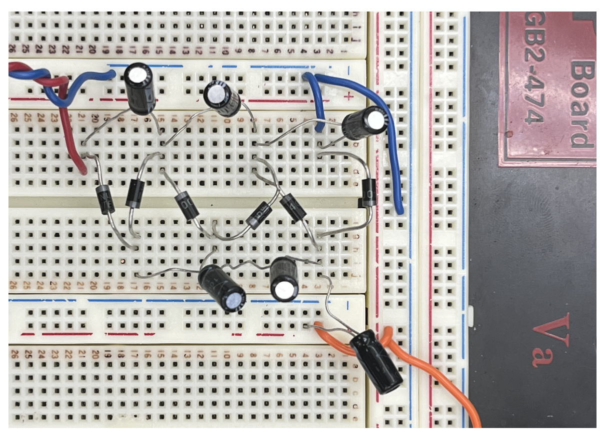

FIG. 1. Cockcroft-Walton voltage multiplier circuit constructed on a breadboard.

Figure 1 shows the expected zig-zag wiring pattern for a multi-stage voltage multiplier, allowing for effective DC voltage multiplication.

To verify that the circuit was functioning correctly, we measured the output at three different stages of the multiplier:

- The first and second stages showed sine wave outputs, confirming that the capacitors were properly charging and discharging.

- The final stage provided a stable DC output, indicating successful voltage multiplication.

Furthermore, when the Wave Gen was set to a $10V_{pp}$ sine wave, we recorded a DC output of approximately 26.5748 ± 0.0008V, which is in agreement with the expected value of an output greater than 25V. This confirmed that the Cockcroft-Walton multiplier was effectively stepping up the input AC voltage, and ensured that the next circuits we constructed would be fed the correct input from this multiplier.

R-2: Measured DC Output at 5V WaveGen Amplitude

The multimeter recorded a DC output voltage is 12.2843 ± 0.0006V DC, confirming that the Cockcroft-Walton voltage multiplier was successfully stepping up the input voltage from the waveform generator. We expected that the DC output would be approximately two to three times the peak input voltage, depending on component efficiency and losses, and in this case we achieved multiplication by a factor of about 2.46.

Single-Photon Avalanches

In this exercise, we investigated the operation of a red LED in reverse bias as an inefficient Single Photon Avalanche Detector (SPAD). By applying a sufficiently high bias voltage, we expected to observe small pulses caused by single-photon events. As the bias voltage was increased, these pulses transitioned into broader, more continuous avalanches due to increased carrier multiplication.

R-3: Bias Voltage for Nice Pulses

At the moment we were able to resolve "nice" pulses on the scope, multimeter recorded a voltage of 21.3271 ± 0.0007V DC. This suggests that the system reaches optimal conditions for generating clean pulses when the bias voltage is set around this value. We also observed that small adjustments in voltage significantly affected pulse clarity, as noted in the lab manual.

R-4: Oscilloscope Capture of a Nice Pulse

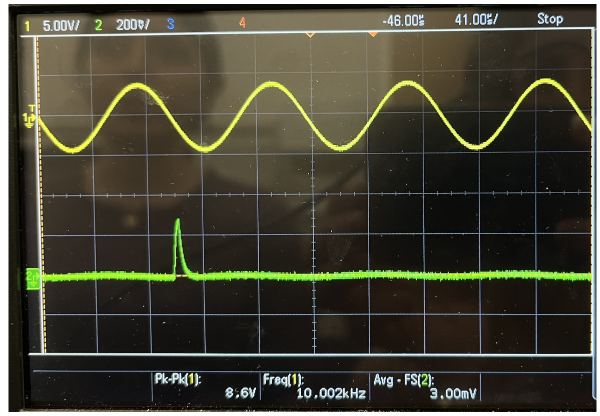

FIG. 2. Oscilloscope capture of a single-photon avalanche pulse.

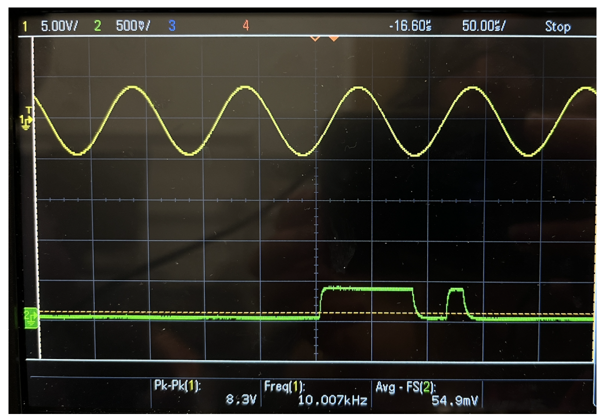

FIG. 3. Oscilloscope capture of multiple-photon avalanching.

Upon increasing the bias voltage slightly, the pulses transitioned from isolated single-photon avalanches to multiple-photon avalanches, as expected. This behavior aligns with theoretical expectations, where increasing the voltage enhances carrier multiplication and leads to broader, continuous, or multipulsing avalanche effects.

Analog Pulse Counting

In this exercise, we connected the output signal V_{sig} from the LED to an Arduino analog pin and measure the pulse rate over time. By analyzing the output on the serial monitor, we measured the frequency of detected pulses when the LED was uncovered versus covered. Upon covering the LED, we expected the pulse rate to drop to zero since photon absorption is responsible for triggering the avalanche pulses.

R-5: Analog Pulse Counting Results

The measured pulse rate was 364 counts/second with the LED uncovered and 1.28 counts/second when covered. This confirms that the detected pulses are primarily caused by photon interactions, as the rate drops significantly when external light is blocked. However, the nonzero pulse rate when covered suggests that either the LED was not perfectly shielded from ambient light, or that perhaps, low-level thermal and electronic noise contributed to occasional false counts.

Discriminators & Cockcroft-Walton Tweak

Here, we implemented a discriminator circuit using an LM293P comparator. The discriminator converts analog pulses from the SPAD into digital pulses by applying a threshold voltage. Additionally, a modification to the Cockcroft-Walton circuit was explored, adding a bleed resistor to improve voltage stability.

R-6: Waveforms of Discriminator Output

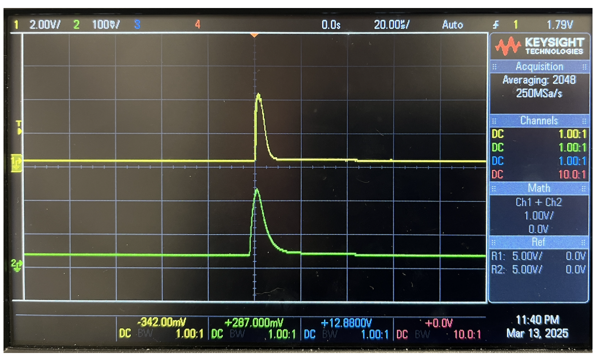

FIG. 4. Oscilloscope capture of pulse signals used for pulse counting analysis.

The oscilloscope capture confirms that the discriminator effectively converts analog pulses into sharp, well-defined digital pulses.

R-7: Pulse Counting Results

The measured pulse rate when the LED was uncovered was 83.89 counts per second. When the LED was covered, the pulse rate dropped to zero, confirming that the pulses are photon-induced and not caused by noise.

To ensure a fair comparison with the results from R5, we used a bias voltage of 21.8600 ± 0.0007V, approximately the same voltage used in R5, which was initially determined in R3. However, our results contradict the lab manual's suggestion that the digital counting method should detect more pulses than the analog method. Instead, our measurements indicate a lower pulse rate in the digital count.

One key difference between our measurements for R5 and R7 is that, in the process of debugging, we adjusted the potentiometer values in the discriminator circuit before performing the digital count. This likely altered the threshold voltage, causing some pulses that were counted in the analog method to be ignored in the digital method.

To investigate this further, one could systematically adjust the potentiometer and observe how the pulse rate changes, providing a clearer understanding of how the threshold setting affects detection efficiency.

R-8: Circuit Setup

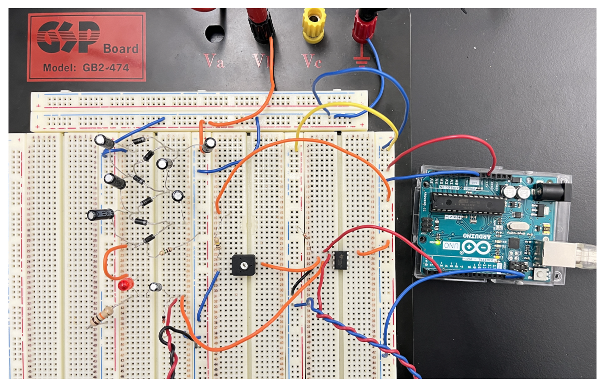

FIG. 5. Final circuit implementation on the breadboard, including the Cockcroft-Walton voltage multiplier, SPAD, discriminator, and Arduino interface.

The circuit was successfully assembled, integrating all components required for voltage multiplication, single-photon avalanche detection, pulse discrimination, and counting using the Arduino.

CONCLUSION

This experiment demonstrated the successful implementation of a Cockcroft-Walton voltage multiplier and its application in biasing an LED for SPAD operation. We verified the expected voltage multiplication and characterized the avalanche behavior of a reverse-biased LED, observing single-photon pulses. Additionally, we investigated pulse counting methods and found that digital counting resulted in a lower detected pulse rate than analog counting, likely due to discriminator threshold adjustments.

Acknowledgements

These experiments were performed in collaboration with Sanai Nezafat.

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