A regulated high negative voltage generator for single-photon avalanche photodiodes

Shijie Deng and Liam Lewis
Centre for Advanced Photonics & Process Analysis,
Cork Institute of Technology and Tyndall National Institute,
Cork, Ireland
shijie.deng@cit.ie, liam.lewis@cit.ie

Alan P. Morrison
Department of Electrical and Electronic Engineering
University College Cork,
Cork Ireland
a.morrison@ucc.ie

***Abstract*—In this work, a regulated high negative voltage generator for biasing single-photon avalanche photodiodes (SPAD) was developed. The circuit provides up to -70 V from a positive voltage source. This circuit allows users to control the negative output voltage using a positive voltage rail, thus eliminating the need for a negative voltage rail for the negative voltage control. This approach simplifies the overall control of the output voltage and facilitates integration in a miniaturized single photon counting system. The testing on a fabricated PCB of this circuit shows that the voltage can be accurately controlled up to -70 V with ripples of less than 80 mV. A SPAD based experimental setup was also built and the experimental results show that the circuit is able to maintain a stable bias voltage for a planar SPAD at both low and high counting rates.**

Keywords—negative voltage generator; negative voltage regulator; single photon avalanche photodiode.

I. Introduction

Negative voltage is required for many applications such as double-ended amplifiers [1], LCD/OLED display [2-3] and Non-volatile Memories [4]. In some single-photon avalanche photodiode (SPAD) applications, the negative voltage required could be from minus tens of volts to minus hundreds of volts [5-7] depending on the type of SPAD used. Typically, the bias solution for generating these high negative voltage is to use bench top power supplies which are bulky and expensive. There are some IC based circuits that can provide negative supply voltage from – 5V to – 40V [8-10]. These circuits, however, require a negative voltage rail for the regulation of the output. This leads to extra cost and board space for a miniaturized system which typically has only positive voltage supply rail.

In this work, we developed a regulated high negative voltage generator for biasing single photon avalanche photodiodes. The circuit sources from a positive supply rail and is able to provide regulated high negative voltage of up to -70V. With the voltage regulator in the circuit, the negative output voltage can be controlled using positive voltages. This eliminates the need for a negative voltage rail for the negative voltage control, simplifies the overall control of the output voltage and facilitates integration in a miniaturized single photon counting system. A printed circuit board (PCB) of the circuit was fabricated and tested. The experimental results show that the circuit can provide a precisely regulated negative output voltage of up to -70V with ripples of less than 80 mV. Testing of the circuit in a SPAD based experimental setup show that the circuit is able to maintain a stable biasing voltage for the SPAD's at both low and high counting rates.

II. Circuit Description

Fig. 1 shows the schematic of the developed regulated negative voltage generator which consists of two main parts: (i) An inverting buck–boost converter which provides the high negative voltage for the output. (ii) An output voltage regulator which is used to control the voltage for the output.

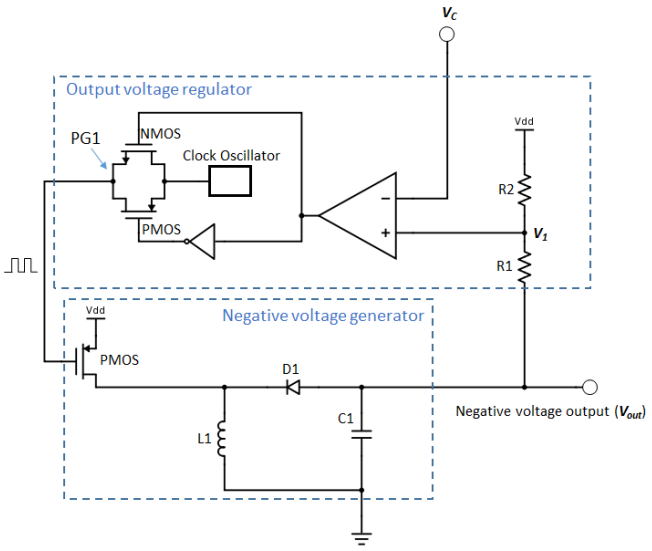


Fig. 1. Schematic of the controlled negative voltage generator developed.

A. Negative voltage generator

An inverting buck–boost converter is used as the negative voltage generator. It consists of a pulse controlled metal oxide semiconductor field effect transistor (MOSFET) which is connected to an inductor and a diode. The inductor acts as an energy reservoir providing power when the MOSFET switches

off. When the MOSFET is closed, the diode is reverse biased and current builds up through the inductor. When the MOSFET is open the inductor will reverse its polarity in order to maintain the peak switch current. Thus, the diode will be forward biased, and the energy stored in the inductance will be transferred to the capacitor. Since the voltage at the "top end" of the inductor is negative with respect to ground, the output voltage across the capacitor will become negative.

B. Output voltage regulator

The schematic of the output voltage regulator can be seen in Fig. 1. It consists of a clock oscillator, an amplifier, a pass-gate (PG1), an inverter and two resistors (R1, R2). In the regulator, the pass-gate is connected between the clock oscillator and the gate of the MOSFET in the voltage generator and controlled by the output of the operational amplifier. R1 and R2 are potential dividers used to limit the input voltage range at node V_1. V_1 is connected to the non-inverting input (+) of Amplifier. In order to regulate the negative output voltage (V_{out}) using positive voltage, one end of R2 is connected to Vdd and the value of R1 is set to around 15 times of the R2's value. This makes V1 positive for the negative output voltage up to -75V. The regulation of the negative output voltage is as follows: if V1 is less than the control voltage, V_c, the output of the amplifier is "0". The pass-gate PG1 is turned off to block the clock to the negative voltage generator, the amplitude of the negative voltage is decreased and V1 is increased. If V1 exceeds V_c, the amplifier generates an output voltage and the pass-gate will be turned on. Clock pulses will be transmitted to the negative voltage generator which makes the amplitude of the negative output charge up and V1 will decrease. In this way, V1 can be set equal to V_c and the output voltage V_{out} can be calculated as follows:

$$V_{out} = -\frac{R1}{R2}V_{dd} + \left(\frac{R1}{R2} + 1\right)V_c \quad (1)$$

As can be seen from the equation, when R1 and R2 are determined, the negative output voltage, V_{out} of the circuit can be regulated linearly by the control voltage V_c. In this design, we set R1 = 15×R2, which makes V_{out} = -15×Vdd + 16×V_c.

III. Experimental Results

A printed circuit board of the design was fabricated and assembled using discrete components, see Fig. 2. In the circuit, the clock oscillator used is DS1099 (2.046 KHz version), the amplifier is TLE 2021IP and the diode (D1) is 1N4148. The PMOS and NMOS transistors are ZVP3306F and ZVN3306F respectively. The inductor (L1) is set to 47 mH and the capacitor (C1) is set to 1.5 µF. The resistors R1 and R2 are 1500 kΩ and 100 kΩ respectively. Vdd is set to 5 V.

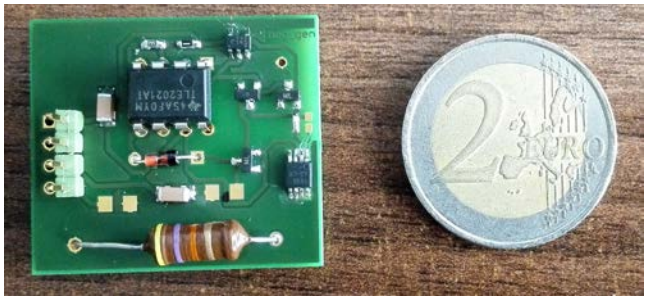


Fig. 2 Fabricated PCB of the circuit designed

Fig. 3(a) and Fig. 3(b) show the oscilloscope traces when the negative output voltage is regulated at -25V and -65 V respectively.

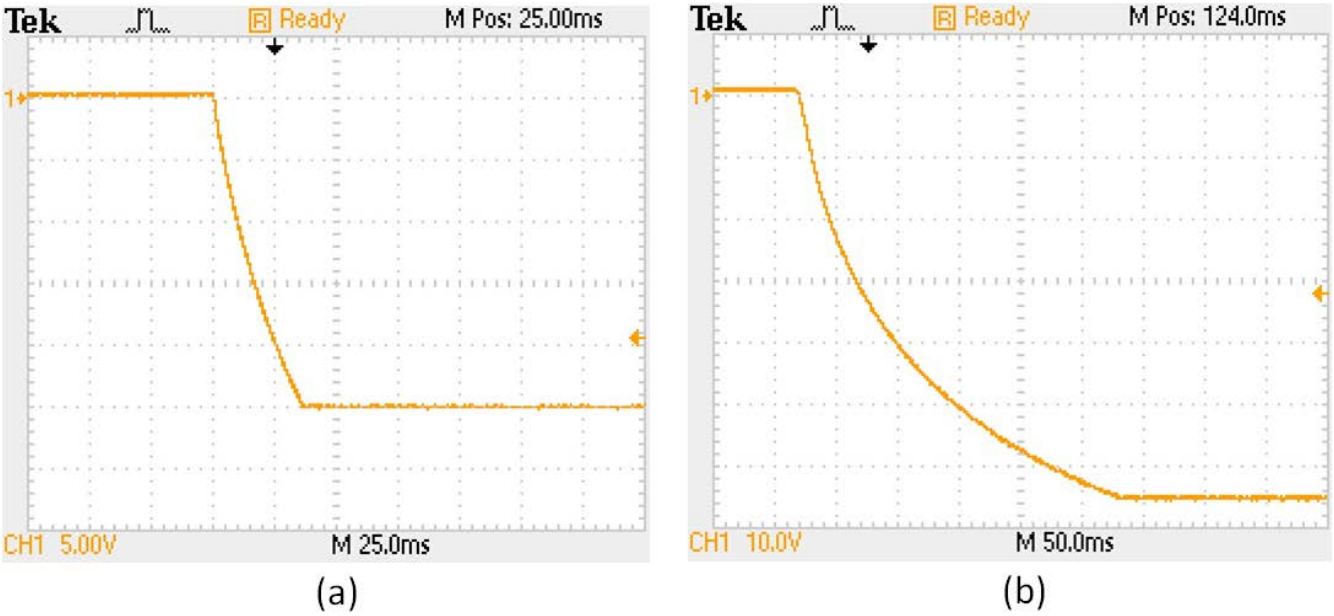


Fig. 3. Oscilloscope traces when the negative output voltage is regulated at (a) -25V and (b) -65 V.

Fig. 4 shows the negative output voltage adjustments for different control voltages. Results show that the negative output voltage can be accurately and linearly regulated up to less than - 70 V using a positive voltage. The peak-peak ripples observed are less than 80 mV

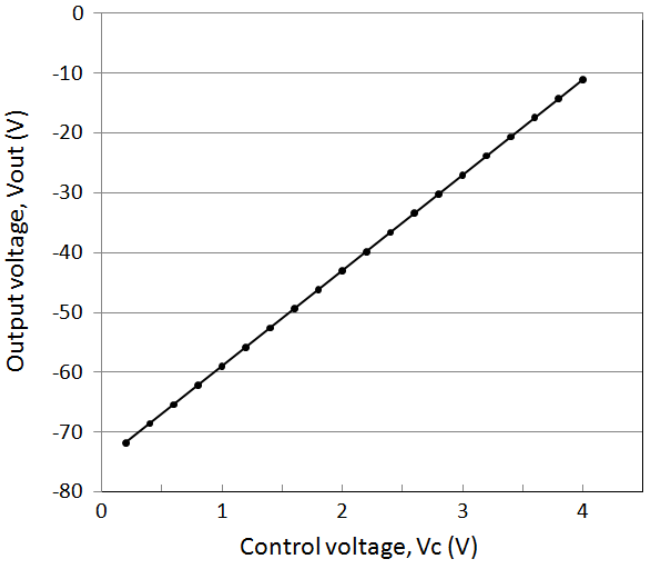


Fig. 4. Negative output voltage adjustments for different control voltages.

An experimental setup was built (see Fig. 5) for testing the developed circuit's use case of biasing a SPAD. In the setup, a planer SPAD previously described [11, 12] was used with the anode connected to the regulated negative voltage generator. A load resistor (R_L) of 100 kΩ was connected between the cathode of the SPAD and 3.3 V. The output of the voltage generator was set to -25 V which sets the bias voltage on the SPAD to around 28.3 V (~2.8 V above the breakdown voltage for this SPAD). A continuous white light source was used to illuminate the SPAD.

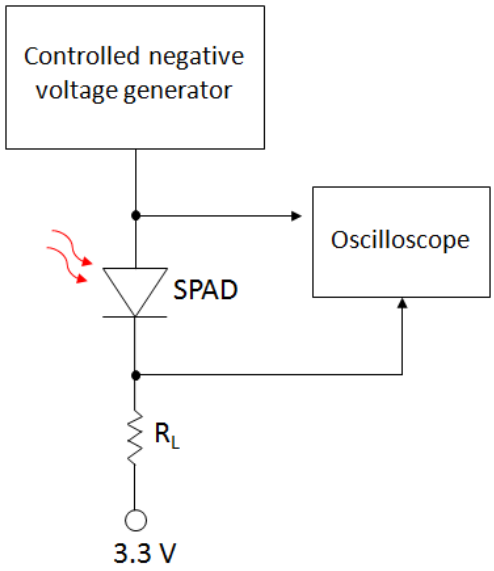
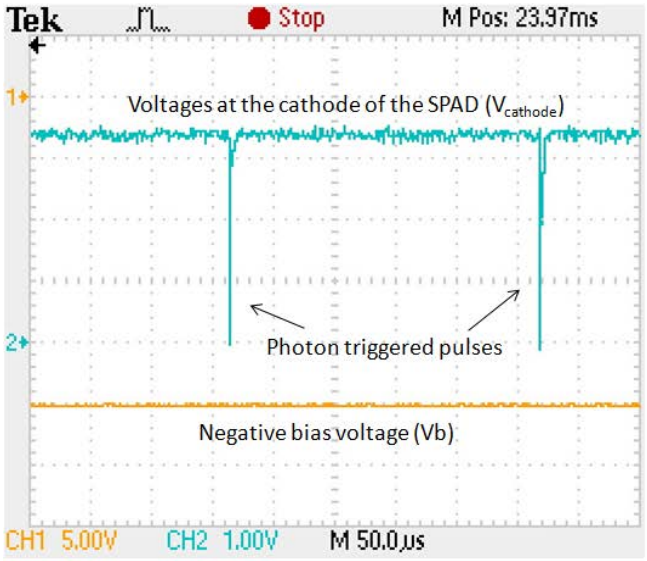
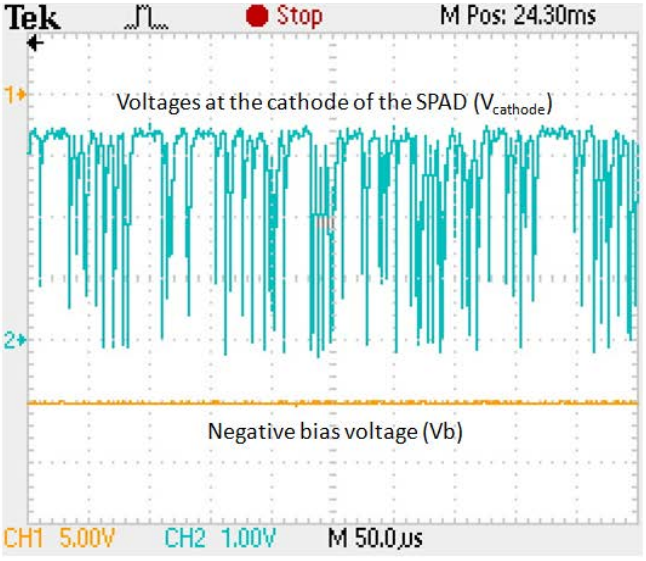


Fig. 5 Experimental setup for testing the developed circuit's use case of biasing a single photon avalanche photodiode.

Fig. 6(a) shows the oscilloscope traces of the voltages at the cathode of the SPAD ($V_{cathode}$) and the negative bias



(a)



(b)

Fig. 6. Oscilloscope traces of the voltages at the cathode ($V_{cathode}$) of the SPAD (photon counting pulses) and the negative bias voltage (Vb) for (a) low photon counting rate and (b) high photon counting rate.

voltage (Vb) from the regulated voltage generator when the photon counting rate is low. Fig. 6(b) shows the oscilloscope traces of $V_{cathode}$ and Vb when the photon counting rate is high. The results show that in both cases that the regulated negative voltage generator is able to maintain a stable output voltage for biasing the SPAD.

IV. Conclusion

In this paper, a regulated high negative voltage generator for biasing single photon avalanche photodiode (SPAD) was described. In the circuit, an inverting buck–boost converter was used as the voltage generator. A specially designed negative voltage regulator was used to control the negative output voltage using positive voltages. This eliminates the need for a negative voltage rail for the negative voltage control, simplifies the overall control of the output voltage and facilitates integration in a miniaturized single photon counting system. A printed circuit board of the circuit was fabricated, assembled and tested. The experimental results show that the circuit can provide a controlled negative output voltage of up to -70V with less than 80 mV ripple. A SPAD based experimental setup was also built for testing the circuit's ability to bias a planar SPAD. Results show that the circuit is able to maintain a stable biasing voltage for both the low and high counting rate cases.

Acknowledgment

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