Avalanche Photodiode with Amplitude Modulated Sine Gating

Leonardo Rocha Bomfim, Jorge Fredericson de Macedo Costa da Silva e Fábio Alencar Mendonça

***Abstract* — In this work the model of an avalanche photodiode for QKD in the so-called Geiger mode operating with an amplitude modulated sine gating is analyzed and simulated. It is shown that the use of this type of gating can reduce the magnitude of the avalanches and hence the population of charge carriers trapped in deep levels traps, thereby reducing the afterpulsing effect (P_{ap}) and the dark count rate (DCR).**

***Key-words* —single-photon avalanche detectors, sine gating, amplitude modulation.**

I. Introduction

In the quantum key distribution (QKD) based on the optical fiber links, it is important to develop the single-photon detectors (SPDs) at the telecommunication wavelength with high quantum efficiency and low dark counts rates (low noise) [1]. In practical use, a SPD is required to operate with a high repetition rate. Single-photon avalanche diodes (SPADs) are among the best single-photon detectors not only for their good performance, but also for their easier implementation in practical and reliable systems when compared to other solutions, such as cryogenic cooled detectors.

The main bottleneck of SPADs is the afterpulsing effect. It refers to avalanches triggered by carriers correlated to the previous avalanches (due to the arrival of a photon or not) and it happens with probability P_{ap}. During an avalanche event, some charge carriers are trapped in deep levels traps and then released, with lifetimes that can be as long as tens or hundreds of microseconds, thus triggering new avalanches that increase the detector noise. For most applications is crucial reducing it to a low level. Afterpulsing effect can be reduced either at the device level, by reducing the number of deep level traps, thanks to better fabrication processes, or at the circuit level, by reducing the number of charge carriers flowing during each avalanche pulse [5]. One way is reducing the quantity of charge carriers during the avalanche process or shortening the lifetime of trapped carriers can decrease P_{ap}. According [], for a single-photon detector system, P_{ap} is related to multiple conditions, which can be roughly modeled as

$$P_{ap} \propto \left(C_D + C_S\right) \times \int_0^{\delta} V_{ex}\left(t\right) dt \times e^{-\tau_d/\tau}, \qquad (1)$$

where C_D is the diode capacitance, C_S is the parasitic capacitance of circuit including the lead capacitance of device, δ is the avalanche duration time, τ_d is the hold-off time and τ is the lifetime of detrapping carriers. From the above equation, the approaches to reduce P_{ap} include: (1) minimizing C_S; (2) limiting δ; (3) lowering $V_{ex}(t)$; (4) increasing τ_d; and (5) decreasing τ by increasing the operation temperature. However, these approaches also have consequent disadvantages. For instance, approach (1) and approach (2) can effectively reduce avalanche charge quantity, but the technical challenge is to extract weak avalanches from background noise. Approach (3) decreases PDE. Approach (4) limits the maximum count rate. Approach (5) increases DCR. The main idea of our work is reduce $V_{ex}(t)$ by amplitude modulation of the sinusoidal gating without reducing photon detection efficiency (PDE).

In many applications that the APD is used to detect single-photons, it usually is operated in the so-called Geiger mode. In this mode, the reverse bias voltage of the APD (V_B) is larger than the breakdown voltage (V_{br}). When a photon is absorbed, an electron-hole pair of electrical carriers is created. One carrier is injected into the depletion zone of multiplication layer and may initiate a self-sustaining avalanche due the impact ionization mechanism at high electric field (on the order of 10^5 $V.cm^{-1}$). The avalanche current reaches a macroscopic steady state within a buildup time on the order of a few hundred picoseconds. Thus, it is necessary a circuitry to quench the avalanches, such as, passively, actively and gated quenching or a combination of them. In the QKD systems, synchronous single-photon detection is required, being gated quenching more appropriate. In such schemes, since the arrival time of the optical pulses with single photons is known, it is turned on only at this time. Thus, the voltage on the APD is maintained over the breakdown voltage (V_{br}) only during a short time (τ_g) during which an avalanche may occur. These periods are separated by disuse time windows (τ_d), in which the voltage V_{APD} is maintained below V_{br}, over the voltage V_B, when the avalanche cannot occur. In Figure 1 is shown this operation principle.

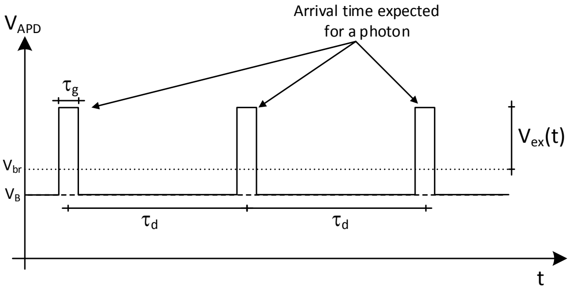

Fig. 1. Gated quenching operation principle.

Leonardo Rocha Bomfim, Programa de Pós-Graduação em Engenharia de Telecomunicações, Departamento de Telemática, IFCE – Campus Fortaleza, Fortaleza-CE, Brazil, E-mail: leo.rbomfim@gmail.com .

Jorge Fredericson de Macedo Costa da Silva, Programa de Pós-Graduação em Engenharia de Telecomunicações, IFCE – Campus Fortaleza, Departamento de Telemática, Fortaleza-CE, Brazil e IFCE-Campus Tauá, Tauá-CE, Brazil. E-mail: jorge.fredericson@gdeste.ifce.edu.br .

Fábio Alencar Mendonça, Programa de Pós-Graduação em Engenharia de Telecomunicações, IFCE – Campus Fortaleza, Departamento de Telemática, Fortaleza-CE, Brazil, e-mail: fabioalencar@ifce.edu.br .

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A general quenching gated circuit is shown in figure 2-a. The voltage V_{OUT} is used to detect an avalanche pulse when it happens in the APD. When it is powered by rectangular gate pulse with fast transition at the edges, there is a narrow pulse due to the internal photodiode capacitances. The comparison level must be greater than the peak value of this pulse, otherwise, the detector will show a false count. However, the faster the transition, the higher the peak value of the pulse, hence, for rapid photon detectors that operate in the microwave range, rectangular gate pulses (similar to that in Figure 1) are not appropriate. To overcome this disadvantage, it was proposed the use of a sinusoidal gate instead of the rectangular gate pulses and since sinusoidal waves have softer transitions, the narrow pulse due internal capacitance is shorter [3,4,6]. In Figure 2 is shown the sinusoidal gated quenching operation principle.

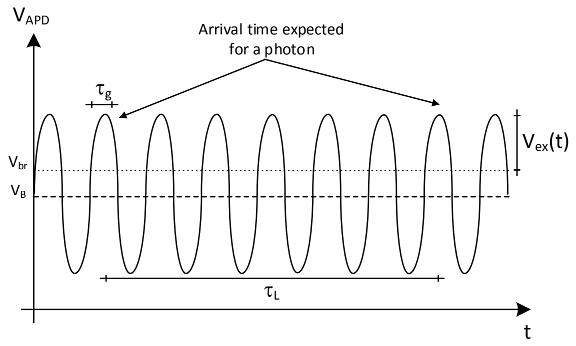

Fig. 2. Sinusoidal gated quenching operation principle.

In the sinusoidal gated quenching, the gating signal has a constant amplitude with frequency $f_g=1/(2\tau_g)$. The disuse time (τ_d) is equal to τ_g. The frequency $f_L=1/\tau_L$ is defined as transmission rate of the single-photon source used in the QKD scenario. One can notice that during the time τ_L, there are interval times in which APD is over V_{br}. Thus, avalanches can happen even without the arrival of a photon, contributing to the afterpulsing effect and dark count rates.

In this work, our goal is to show how amplitude modulation of a sinusoidal signal, used in gated quenching circuits of APDs working as single-photon detector operating in the Geiger mode, can reduce the number of charge carriers flowing during an avalanche pulse and, hence, the afterpulsing effect. This work is outlined as follows: in Section II the AC model for a gated quenching circuit is reviewed and circuit analytical expressions are shown; in Section III, simulations' results for the gated quenching circuit when powered by sine gating with constant and modulated amplitude are shown; at last, the conclusions are presented in Section IV.

II. QUENCHING GATED CIRCUIT IN AC REGIME

The gated quenching circuit in the AC model is shown in figure 3-b [2]. In the AC model, the avalanche photodiode is represented by its internal resistance and capacitance, R_D and C_D, C_S represents the capacitance due to the terminals and the packing and the switch CH simulate the occurrence of an avalanche, which is closed (opened) when an avalanche is (not) present. C_G is the coupling capacitor, R_{OUT} is a load resistor where the avalanche is detected, R_L limits the current flowing through the APD.

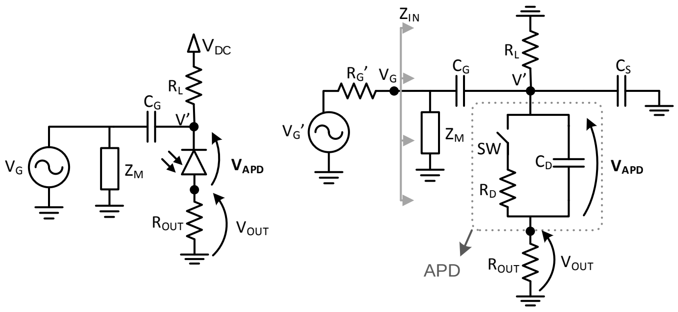

Fig. 3. (a) Gated quenching circuit. (b) AC model.

In circuits of passive quenching, R_L is responsible for the extinction of the avalanche. To reduce the loss of amplitude of V_G, a high value for C_G must be used. When the gate pulse is very large, the avalanche's extinction occurs through R_L. The gate generator is represented by a voltage source V_G' in series with its internal resistance R_G'. The voltage V_G is

$$V_G = V_G'\left(\frac{Z_{ENT}}{R_G + Z_{ENT}}\right). \tag{2}$$

In expression (2), Z_{ENT} is the input impedance

$$Z_{IN} = Z_M//\left\{Z_{CG} + \left[R_L//Z_{CS}//\left(R_S + Z_D\right)\right]\right\}, \tag{3}$$

with Z_M being an impedance placed to match the input impedance of the quenching circuit with the output impedance of the gate source, $Z_{CG}=1/j\omega C_G$, $Z_{CS}=1/j\omega C_S$; and $Z_D=1/j\omega C_D$ is the impedance of the photodiode when there is not avalanche (CH is opened). When an avalanche occurs, $Z_D=R_D//(1/j\omega C_D)$ (CH is closed). Hence, one can derive that

$$V' = V_G \frac{\left[R_L//Z_{CS}//\left(R_{OUT} + Z_D\right)\right]}{\left[R_L//Z_{CS}//\left(R_{OUT} + Z_D\right) + Z_{CG}\right]}, \tag{4}$$

$$V_{OUT} = V' \frac{R_{OUT}}{\left(R_{OUT} + Z_D\right)}, \tag{5}$$

$$V_{APD} = V' - V_{OUT}, \tag{6}$$

with V_{APD} and V_{OUT} being the voltage over the APD and resistance R_{OUT} respectively.

III. SIMULATIONS AND RESULTS

To analyze the behavior of the circuit and the magnitude of the avalanches, simulations for (4)-(6) were performed. There, the voltages V_{APD} and V_{OUT} (with and without avalanches) are shown. The parameters with your values used are in the Table I. We simulated the voltages using two situations: 1) a customary sine gating with constant amplitude of 5V and gating frequency (f_g) of 1GHz; 2) an amplitude modulated sine gating with amplitude modulation index of 100% and frequency of the modulation signal (f_m) with 100MHz. In a hypothetical QKD scenario, the transmission rate of the single-photon source is equals to f_m.

TABELA I. PARAMETERS USED FOR SIMULATE THE AC MODEL GATED QUENCHING CIRCUIT.

parameter	Value
Z_M, R_G and R_{OUT}	50Ω
R_D	1 kΩ
R_L	50kΩ
C_G	100nF
C_D and C_S	0.01pF

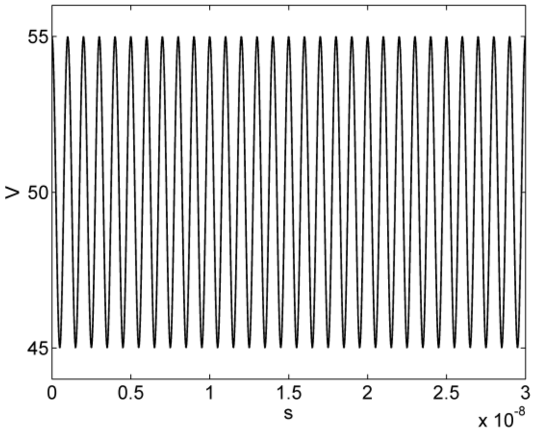

Fig. 4. The voltage over the APD for sine gating with constant amplitude of 5V and gating frequency of 1GHz. V_B=50V.

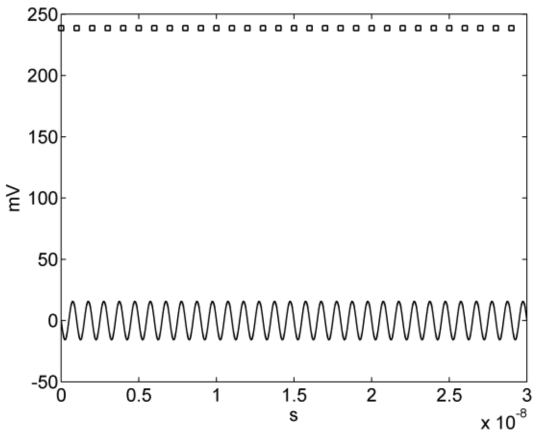

Fig. 5. The output voltage over the resistance R_{OUT} without avalanches (solid line) and the magnitude of the avalanches (squares) when they happen at the maximum peaks of the sine gating with constant amplitude of 5V, gating frequency of 1GHz and V_B=50V.

In the Figures 4 and 6, the voltage over the avalanche photodiode is due to the bias voltage V_B and to the gating signal. In the Figures 3 and 5, there is a soft narrow transition (maximum value closed to 15mV) due to the gating signal when there is not avalanches (SW open in the Figure 3. b) and the magnitude of the avalanches simulated (SW closed) when they happen at the maximum peaks of the gating signal. In both cases, the maximum magnitude value of the avalanches is closed to 250mV. However, it is clear the advantage of using the amplitude modulated sine gating. Considering that the arrival time of the photons emitted by a single-photon source occur simultaneously with the time of maximum peak of the gating, one can notice that, in the other times in which it is not expected a photon, the magnitude of the avalanches suffers a soft and considerable reduction.

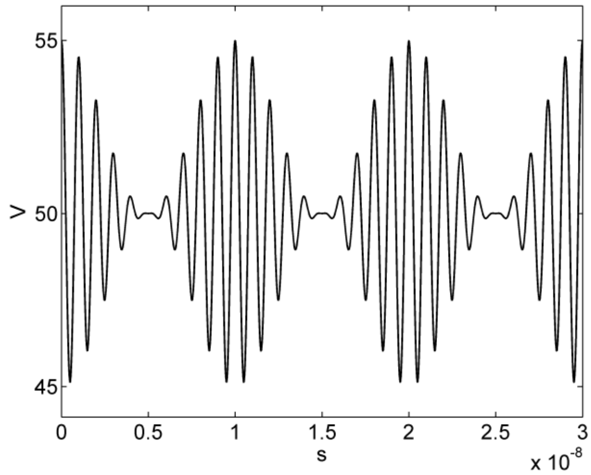

Fig. 6. The voltage over the APD for amplitude modulated sine gating with 100% of modulation index, f_g=1GHz, f_m=100MHz and V_B=50V.

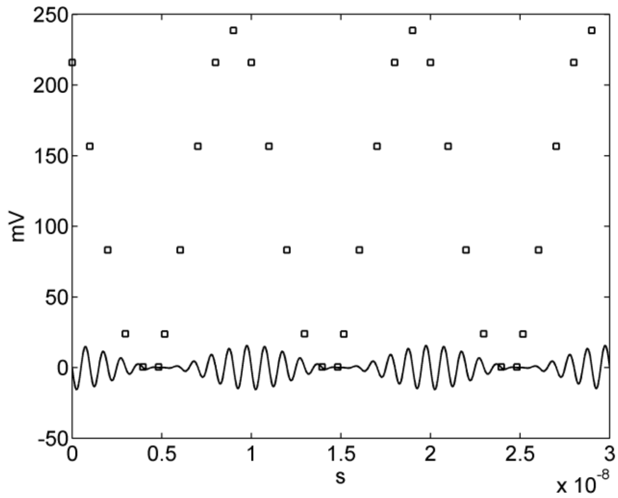

Fig. 7. The output voltage over the resistance R_{OUT} without avalanches (solid line) and the magnitude of the avalanches (squares) when they happen at the maximum peaks of the amplitude modulated sine gating with 100% of modulation index, f_g=1GHz, f_m=100MHz and V_B=50V.

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IV. CONCLUSIONS

This work presented an AC model analysis of an avalanche photodiode operating in Geiger mode with a constant amplitude sine gating and with amplitude modulation. Circuit analytical expressions were found and simulated in both cases. It can be seen that the use an amplitude modulated sine gating reduces the magnitude of the avalanches during interval times in which it is not expected the arrival of photons. In these cases, the number of charge carriers flowing during an avalanche pulse is reduced and, hence, the afterpulsing effect and dark count rate can decrease. It is worth noting that an experimental apparatus must be implemented to reinforce and verify this.

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