A SPAD based configurable photon counting system

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Abstract: In this work, a single photon avalanche diode (SPAD) based configurable photon counting system is developed. The photon counting system is able to operate in three working modes to enhance the system's different performance characteristics for various use cases (e.g., strong/weak incident light signal, high/low ambient light, long/short distance ranging/sensing). The working modes can be switched digitally by the user or signal processing circuit that makes it possible to add intelligent control logic for switching in real-time between working modes to achieve a stable and optimized performance when it is used under varying working conditions. Performance characteristics of the system operation in each working mode are measured and compared.

Index Terms: Single photon avalanche diode, photon counting system, configurable system, performance optimization.

1. Introduction

Single photon counting technology has been used in a wide range of low light sensing applications such as LIDAR, fluorescence lifetime imaging (FLIM), DNA sequencing and medical imaging [1-5]. The advances in single photon avalanche diodes (SPADs) including low bias voltage, high sensitivity, low cost and compatible with CMOS processing have promoted them as popular detectors for use in photon counting systems. To improve the performance characteristics in SPAD based photon counting systems, researchers have proposed various solutions using digital logic processing methods [6-12]. In [6-8], multi-SPADs/SPAD arrays are used with OR logic to improve the dynamic range and sensitivity of the photon counting system. Researchers aimed to provide faster lifetime measurements and enable the SPADs based counting system's usefulness in applications that require high speed and wide dynamic range such as confocal scanning fluorescence lifetime imaging. In [9], researchers demonstrate an XOR-based dSiPMs which shows improved signal strength, enhanced dynamic range, and linearity with OR-based topologies. In [10] a dual-SPADs are used for the false alarm probability reduction in LIDAR system. Result show that a drastically noise decreasing is achieved because the noise distributed randomly in the time domain is filtered out. In [11-12], multi-SPADs are used with their outputs also processed using AND logic to reduce the noise in the photon counting system. Those designs improve the specific performance characteristics of the photon counting system, however, that is achieved at the expense of other parameters. For example, the use of OR/XOR logic increases the overall dark counts and thus the noises in the system and the use of AND logic reduces the overall detection efficiency of the photon counting system. In addition, the fixed working mode of these systems limits their usefulness under varying incident light intensity and testing environment.

In this work, we propose a configurable photon counting system enables three working modes in the system: Mode 1: all the incident light directed to one SPAD and its output is used for photon counting; Mode 2: incident light is equally split and directed to two SPADs, the outputs of the two SPADs are processed using an “AND gate”, the output of the “AND gate” is used for photon counting; Mode 3: incident light is equally split and directed to two SPADs. For light intensity measurement, outputs of the two SPADs are counted independently and overall counting rate equals the addition of the counting rates from the two outputs. For time correlated single photon counting, the outputs of the two SPADs are processed using an “OR gate”. Performance characteristics in the proposed system are tested and compared under various measurement conditions. This design allows simple digital switching (using signal processing circuitry) between the working modes in the system to optimize its performance for different use cases (e.g. strong/weak incident light signal, high/low ambient, long/short ranging/sensing) and enable the SPADs based counting system to enable its active switching between different working modes to achieve a stable and optimized performance when it is used under varying working conditions (e.g. when the photon counting based instrument is moved from indoor to outdoor, from dark condition to strong ambient condition, etc.).
2. Design Description

Fig. 1 shows the block diagram of the proposed design. Incident light is coupled into a fiber which is connected to a port of an optical switch (ISEELINK 1×2 optical switch, part number: GP-OSW1x2T), port A. The optical switch is digitally controlled to direct the light signal from port A to port B or port C (when the “Digital control” is “01” light signal is from port A to port B, and when the “Digital control” is “10” light signal is from port A to port C). The fiber connected to port B of the optical switch is connected to Fiber coupler 1 (SHUCHUANG fiber coupler, part number: BGSU-100/104-125-22-PI). The light signal transferred in the fiber will be split equally by Fiber coupler 1 with one part directed to APD2 through a Fiber adapter and the other part directed to Fiber coupler 2 (SHUCHUANG fiber coupler, part number: BGSU-100/104-125-22-PI). The Fiber coupler 2 will combine the light signal from Fiber coupler 1 and from the port C of the optical switch and direct it to APD1 through a fiber adapter. APD1 and APD2 used are single photon avalanche diodes (SPADs) with the same structure and size (two SPADs from Laser Component are used in this design, the part number is SAP500-S2). Readout circuits (see Fig. 2, the amplifier used in the circuit is TLV3501 from Texas Instruments, R1, R2, R3, C1 and C2 are set to 10 kΩ, 100 Ω, 4.7 kΩ, 4.7 kΩ, 47 pF and 10 pF respectively) are connected to APD1 and APD2 to convert the avalanche events in the SPADs to TTL signal. The outputs of the readout circuits are connected to OR gate (Texas Instruments, part number: SN74LS32N), AND gate (Texas Instruments, part number: SN74LS08N) and used for photon counting measurements.

Fig. 1. Block diagram of the proposed design

Fig. 2. Schematic of SPAD’s readout circuit.

Three modes in the photon counting system can be digitally configured in the system: Mode 1, “Digital control” of the optical switch is set to “10” (pin 10 and pin 1 of the optical switch are set to V+ (3V or 5V) and GND, respectively) that makes all the incident light directed to APD1 and Out 1 in the system is selected for photon counting; Mode 2, “Digital control” of the optical switch is set to “01” (pin 1 and pin 10 of the optical switch are set to V+ and GND, respectively) that makes all the incident light equally split and directed to APD1 and APD2, the outputs of the readout circuits are connected to an “AND gate”. Out 2 in the system is selected for low noise mode; Mode 3, “Digital control” of the optical switch is set to “01” (pin 1 and pin 10 of the optical switch are set to V+ and GND, respectively) that makes the incident light equally split and directed to APD1 and APD2. When it’s used for light intensity measurement, the pulses from the outputs of the readout circuits are counted independently and the overall count rate equals to the addition of the count rates from the two outputs. The two outputs from the readout circuits are connected to an “OR gate” for the time correlated single photon counting measurement.
3. Experiment results

Fig. 3 shows the oscilloscope traces on the outputs of the two SPADs’ readouts circuits, the OR gate and the AND gate. As can be seen, anytime when the SPAD outputs an avalanche pulse, the OR gate outputs one pulse, and only when the two SPADs output pulses at the same time the AND logic outputs one pulse.

![Oscilloscope traces](image)

Fig. 3. Oscilloscope traces on the outputs from SPADs readouts circuits, the OR gate and the AND gate.

Fig. 4 shows the experimental results of the dark count rates of system for different excess bias values (the bias voltage above the breakdown voltage of the SPADs). Results show that the system produces the highest dark count rates in Mode 3 which is caused by the accumulation of the two SPADs’ dark count rates. Results also show that in Mode 2, the system delivers the lowest dark count rate which is about 90% lower than that in Mode 1 and Mode 3. This is because the random distribution of the noise counts are filtered by the AND logic. For light intensity measurement application, the noise would be mainly contributed by the dark count rate and the afterpulsing. Since the both the light signal and noise are uniformly distributed, the AND logic would result in a reduction of both signal and noise.

For TCSPC or LIADR system, the noise (false counts) would be the combination of dart count rate, afterpulsing and ambient or background caused count rate. In these applications, in the time domain, the statistical distribution of the returned photons and the noise is different. The noise is uniformly distributed but the returned photons are time related to the pulsed laser. In this case, the noise related detection probability of a single SPAD on the i-th time bin can be expressed as [10, 11]:

$$P_D(i) = e^{(-N_{PE}(i-1)\tau_{bin})} \times \left[1 - e^{(-N_{PE}\tau_{bin})}\right]$$

(1)

Where NPE is the combination of the background noise and dark count and $\tau_{bin}$ is the time duration of a time-bin. When take the AND logic into account, the expression of the noise in the system become:

$$P_{noise} = \sum_{i=1}^{N} P_{D1}(i) \times P_{D2}(i)$$

(2)

Where PD1 and PD2 are the noise related detection probability of APD1 and APD2, respectively. This is a simplified equation. By taking parameters such as the pulsed laser energy, SPAD’s afterpulsing possibility and the APD’s output pulse width into account would give a more accurate description on the noise model.
In Fig. 5, the output count rates of the system for different incident light intensities is demonstrated. In the experiment, the SPADs are biased at the excess bias voltage of 3 V and a 650 nm laser is used with attenuation filters to alter its intensity. Results show that in Mode 2, the system shows a better dynamic range and linearity, but it delivers the lowest detection efficiency as the “AND” logic also decreases the probability of the system detecting photon related avalanche events. Results also show that in Mode 3, the system gives higher count rate as the overall dead time of the system in the mode is reduced by using two SPADs and the missed photon counts decrease.
To evaluate and compare the performances of the system in different modes when used in time correlated single photon counting applications, the experimental setup shown in Fig. 6 was built. In the setup, a 650nm pulsed laser (ALPHALAS, part number: PLDD-50M. PICOPower-LD-660-50) is used to provide the pulsed light signal to the system and the time delay between the laser synchronized pulse signal and the pulses of the photon counting system's output is measured using a time-to-digital converter (SIMINICS, part number: FT1010).

Fig. 6. Experimental setup for testing the time response of the system.

Fig. 7 shows the timing responses of the photon counting system in the different working modes. As can be seen in the figure, in Mode 1 (one SPAD is used), the system delivers the lowest timing jitter of around 239 ps. The timing jitters of the system when operated in Mode 2 and Mode 3 are 346 ps and 386 ps respectively (these timing jitters consist of TDC jitters of around 100ps). To improve this timing jitters, the reference voltage in the readout circuit must be carefully adjusted, so that the time differences of the avalanche events detection from the two SPADs can be minimized.

Fig. 7. Timing responses of the photon counting system in different modes.

Fig. 8 shows the timing responses of the system in different working modes when the pulsed laser’s power is reduced to a low level (around 0.3 nW). In the measurement, the interval time is recorded for 3000 laser pulses. Results show that the system operating in Mode 1 gives the best performance with nearly 80% interval times correctly recorded. This is mainly because of its better detection efficiency and lower noise (compared to Mode 3). In comparison, the system operating in Mode 2 delivers the worst performance with only around 30% of the interval times correctly recorded due to its low detection efficiency.
To evaluate the system’s performance for long distance ranging/imaging/sensing, we introduce a delay of 50 µs between the “start signal” to the time interval measuring instrument and the laser pulses. The laser power in this measurement is set to around 50 nW. Fig. 9 shows the results of the system in the three different working modes. As shown in the figure, due to its low noise performance, the system operating in Mode 2 delivers the best performance with nearly 90% of the interval times recorded correctly. Due to the effect of high dark count rates, the system operating in Mode 3 gives the worst performance with only around 26.7% of interval times recorded correctly.

From all the above measurements, it is shown that the system operating in Mode 1 provides the lowest timing jitter and best time interval measuring capability when the incident pulsed laser power is low. This makes it useful for the applications that require high measurement resolution or with very weak incident light signal. In Mode 2, the system shows the best performance in term of noise, dynamic range and time interval measuring capability when the ranging/sensing distance is long. This makes it suitable for applications working in high ambient or background condition (e.g. outdoor). It also a good candidate for applications requiring high dynamic range or accurate linearity for light intensity measurement. However, it shows a poor time interval measuring capability when the incident light is low due to the reduced detection efficiency. In Mode 3, the system shows a better photon counting capability as the dead time and missed photon counts is reduced. It shows a similar performance for measuring the time interval when the incident light is low. This makes it suitable for the application requiring high speed photon counting capability such as in fluorescence lifetime imaging (FLIM). However, it suffers in the time interval measurement when the interval time to be measured is long due to its high dark count rate. These working modes can be switched digitally or automatically through signal processing circuitry to achieve optimized performance in photon counting system for different working conditions.

4. Conclusions

In summary, we have developed a digitally configurable photon counting system. The system uses digitally controlled optical switches and fiber couplers to manage the incident light’s direction. Two SPADs and logic processing circuits are used to achieve three different working modes. The three modes are: Mode 1: all the incident light directed to one SPAD and its output is used for photon counting; Mode 2: incident light equally split and directed to two SPADs, the outputs of the two SPADs are processed using an “AND gate”, the output of the “AND gate” is used for photon counting; Mode 3: incident light...
equally split and directed to two SPADs. For light intensity measurement, outputs of the two SPADs are counted independently and overall counting rate equals the sum of the counting rates from the two outputs. For time correlated single photon counting, the outputs of the two SPADs are processed using an “OR gate”. Performance characteristics of the three working modes are tested and compared under various measurement conditions. This design provides a photon counting solution that allows users to switch the working modes (using signal processing circuitry or digital switches) for the enhancement of specific performance characteristics in the photon counting system for different use cases (e.g. strong/weak incident light signal, high/low ambient, long/short ranging/sensing) for an optimized performance in applications including LiDAR, and photon counting OTDR. It also makes it possible to add intelligent control logic in the photon counting system to enable the active switching between different working modes to achieve a more stable and optimized performance when it is used under varying working conditions.

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