Scalable multiplexed detector system for high-rate telecom-band single-photon detection

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We present an actively multiplexed photon-counting detection system at telecom wavelengths that overcomes the difficulties of photon-counting at high rates. We find that for gated detectors, the heretofore unconsidered deadtime associated with the detector gate is a critical parameter, that limits the overall scalability of the scheme to just a few detectors. We propose and implement a new scheme that overcomes this problem and restores full scalability that allows an order of magnitude improvement with systems with as few as 4 detectors. When using just two multiplexed detectors, our experimental results show a 5× improvement over a single detector and a greater than 2× improvement over multiplexed schemes that do not consider gate deadtime. © *2009 American Institute of Physics.* [doi:10.1063/1.3247907]

Single-photon technology is of growing importance as interest in quantum communication and computation intensifies.[1,2] A major limiting factor in developing quantum key distribution at telecom wavelengths is efficient and low error single-photon detection.[3,4] Because of growing demands for higher-rate secret key distribution, the single-photon detector (SPD) development community is focused on improving relevant properties of detectors. Among these are detection efficiency (DE),[2,5,6] detector timing jitter,[7] and detector deadtime.[8] Unfortunately, one cannot optimize one property alone, as SPD properties can be interrelated. For example, it is often the case that reducing deadtime increases afterpulsing (the subsequent refiring of a detector not caused by a new input photon). Therefore, the goal is to reduce deadtime, while other important characteristics are kept constant (or improved). To do this we use active multiplexing to significantly improve single-photon detection.[9,10] Our initial efforts proved that a generic active multiplexing algorithm compares favorably to all passive detector arrangements.[11–13]

Deadtime, i.e., the "recovery" time after photon detection when a detector cannot register another photon, is a characteristic common to most SPDs. Deadtime is the major factor impeding higher photon-counting rates, especially at telecom wavelengths. For infrared avalanche SPDs (SPADs), the largest deadtime contributions come from (i) deadtime due to carrier trapping in the active avalanche region of the detector that requires long times before the detector can be reactivated (relative to Si SPADs) and (ii) electronics processing deadtime, or gate deadtime that requires recovery, even when no detection occurred. Active infrared detector arrangements that do not optimize gate deadtime yield significantly lower maximum detection rates. Additionally, their performance quickly saturates with the number of detectors. This fundamental limitation requires us to create a new photon-counting arrangement that restores a truly scalable design. This new multiplexed detector arrangement enables more than an order of magnitude detection rate improvement with just 4 SPADs compared with known active multiplexing arrangements. We demonstrated a 5 times increase in detection rates as compared with conventional InGaAs SPADs, while keeping deadtime at the same level.

The actively multiplexed detector arrangement uses an array of N photon-counting detectors connected via a 1-by-N optical switch. A switch control circuit tracks the history of events, such as detector gate pulses and detections, and routes subsequent incoming pulses to a detector that is ready. This arrangement saturates at a significantly higher detection rate than N times the detection rate of an individual detector, and its performance is better than that of any passively multiplexed detector arrangement of N detectors (i.e., a "detector/beamsplitter tree"). We compare performances of several switching algorithms with this system.

To compare SPD arrangements, we define deadtime fraction (DTF) as the ratio of time spent by the detector arrangement in its "dead" state τ_{dead} to the total measurement time τ_{total}: $\mathrm{DTF}=\tau_{dead}/\tau_{total}$. This definition does not depend on the particular realization of a photon-counting scheme. High DTF is particularly detrimental for quantum communication applications, where each detection must be independent of others. For precision measurement applications, deadtime is also detrimental, as it increases the nonlinearity of detection, etc. For comparison, we chose a DTF level ($\mathrm{DTF}=10\%$) as our benchmark. When reducing deadtime, it is also important to pay attention to a related effect—afterpulsing. In fact, along with deadtime reduction, it is possible to improve detection characteristics such as dark counts and afterpulsing probability with an actively multiplexed system relative to those of a passive beamsplitter/detector tree.[9–13]

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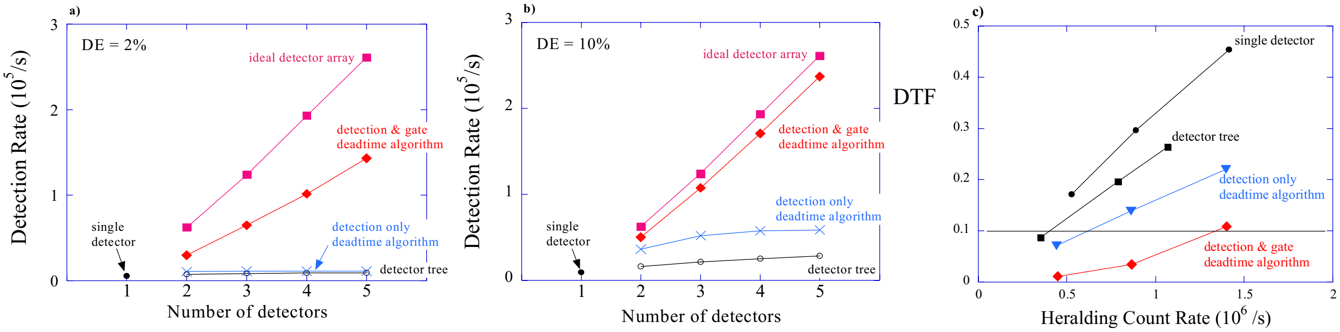

FIG. 1. (Color online) (a) Detection rates for various detector arrangements at DTF=10%, DE=2% (matching our experiment); (b) same, DE=10% (hypothetical); (c) measured DTF vs the heralding (D_1) count rate for a single detector, a detector tree, and two multiplexed detectors arrays: one based on detection only deadtime algorithm of Refs. 11–13 and one based on the detection and gate deadtime algorithm specific for infrared SPADS. Horizontal line is the benchmark level (DTF=10%).

To apply this analysis to any real single-photon detection arrangement, all deadtime properties must be considered together. Specifically, InGaAs infrared SPADs have long detection deadtimes (10 μs) resulting from the avalanche process, as well as having a high level of dark counts. Because of these high dark count rates, they are usually operated in a gated mode, which has its own recovery issues. When a single photon is expected, a gate pulse turns the detector on for 1 to 100 ns. To adequately describe these effects, we have to consider the following times:

(a) T_d detection deadtime, the photon detection-related deadtime (i.e., time after an avalanche that the detector remains off. This includes avalanche quench times and any additional hold-off times);
(b) T_s switching deadtime, the time for the multiplexing electronics and optical switch to process a detection event; and
(c) T_g gate deadtime, the shortest time between two gate events that can be processed by the detector electronics.

Typically, any subsequent gate pulses are rejected for 100 ns after a first gate pulse is received by the electronics. This process increases the overall deadtime, even when no photon detection occurred. This effect is significant for InGaAs SPADs, which suffer from low DE, as it is comparable to the conventional detection deadtime, because the contribution of T_g scales with 1/DE (because as DE decreases, gate pulses are less likely to produce a count even if a photon was incident).

Monte Carlo simulations include the above deadtime contributions to model performance of different detector arrangements. We use parameters matching our experimental setup: $T_d=10$ μs, $T_s=0.01T_d$, $T_g=0.02T_d$, and DE$\approx$0.02. Simulations show that the performance of both the passive detector assembly and algorithm based on detection deadtime reduction only[9–13] are significantly worse than that of the ideal multiplexed detector with $T_g=T_s=0$ (see Fig. 1). The old deadtime reduction algorithm quickly saturates as the number of detectors used increases, limiting the utility of the entire scheme.

To reduce the contribution of the trigger deadtime to the total system deadtime, we present a new switching algorithm specifically for gated SPADs. This algorithm sends the first photon toward the first detector, the second toward the second detector in the array and so on. It also keeps track of the status of detectors in the array and "skips" any detector that has recently fired and is therefore inactive. This optimally reduces effects of both the gate deadtime and the detection deadtime and simultaneously reduces the effect of T_s because the algorithm does not "wait" for the detector's response before making a decision. We find that this switching algorithm solves the saturation problem, and eliminates the limit to the number of detectors that can be used fruitfully. Our calculation shows that regardless of DE, the scaling is comparable to that of the ideal detector assembly ($T_g=T_s=0$), see Fig. 1(b) (while without the gate deadtime algorithm scaling is not possible). Figures 1(a) and 1(b) allow a direct comparison with other methods. For instance, by using $N=8$ and improved, commercially available low-noise fast switches in a truly scalable switching setup, one can match the count rates of Ref. 14, while improving the DE, dark count rate and afterpulsing probability.

We implemented both algorithms as firmware code in a field programmable gate array (FPGA). The original switching algorithm [Fig. 2(b)] tracks the order in which detectors

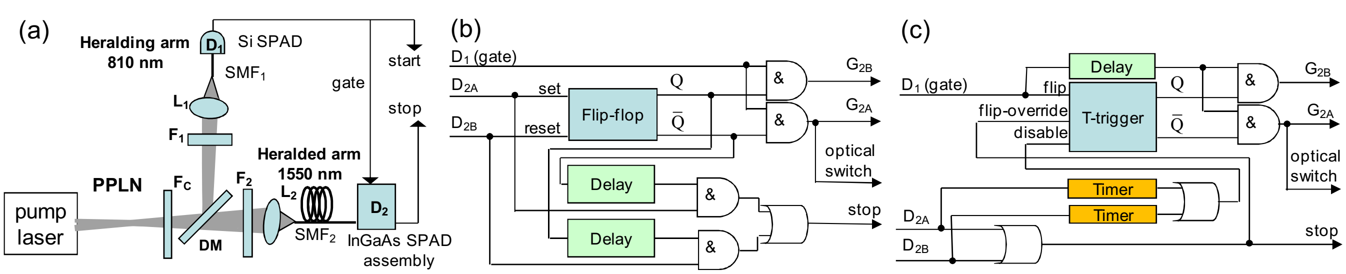

FIG. 2. (Color online) (a) Experimental setup, (b) multiplexing electronics schematic for detection deadtime reduction only, and (c) multiplexing electronics schematics for detection deadtime and gate deadtime reduction.

fired using a memory cell.[11–13]

To implement a new switching algorithm, we track both detection and gate pulse history. We use one memory cell to store the information of which detector was gated last and one memory bit for each detector to store its state (i.e., dead or alive). For our experimental implementation with two detectors, we use a modification of a T-trigger memory cell to store the gate history. A 1-bit T-trigger [Fig. 2(c)] flips its state with each pulse at its "flip" input. We added two more inputs: a "disable" and a "flip-override." If a disable input is asserted, any flip input is ignored. To force the T-trigger to flip even if it is disabled, we introduce a flip-override input. In this way, if no detectors fired (i.e., both of them are ready), each of them receives half of the gate pulses (via T-trigger flips). This gives additional time for detector gate electronics to recover. If the photon detection took place by either of the two detectors, we disable the flipping of the T-trigger, and send gate pulses to the detector that is ready. To track detectors' deadtime, we use timers, one per each detector, implemented as counters. These counters are set to stop counting when a corresponding detector turns back on. A counting timer disables the flip input. When the deadtime ends, the counter stops, enabling the flipping of the T-trigger in the usual order. If both the detectors fire during a time shorter than the detection deadtime, the arrangement is saturated and no detectors can accept a gate. However, the detector that fired first will be ready sooner than the detector that fired second, so we switch active detectors via flip-override input. Both the logic circuits, presented in Fig. 2, are implemented on a FPGA.

We test the performance of the improved multiplexed detector array with the new switching algorithm and gauge its performance against the multiplexed detector array of our previous implementations and a single detector.[9–13] The experiment [Fig. 2(a)] is built around a parametric down-conversion crystal that produces photon pairs at two different frequencies. The photon at 810 nm is detected by a silicon SPAD with a $T_d \approx 50$ ns (negligible compared with the deadtime of the infrared detectors under test). The detection of an 810 nm photon heralds a photon in the signal arm (at 1550 nm), where we tested the different detector arrangements: (i) a single detector, (ii) a passive multiplexed detector arrangement (a detector tree that uses a 50:50 fiber-beamsplitter and two detectors), (iii) a multiplexed detector array with the switching algorithm of Refs. 11–13 that reduces detection deadtime only, and (iv) a multiplexed detector array with the switching algorithm optimized for gated infrared detectors, that reduces both T_d, T_g. The arrangements are built with IdQuantique InGaAs[15,16] detection modules and an EO-Space[17] fast 1×2 switch. In our experiment $T_s < 50$ ns, the only difference between cases (iii) and (iv) is the firmware uploaded to the FPGA board. We see (Fig. 1(c)) that configuration (iv) yields the lowest DTFs. For our chosen threshold of DTF $=10\%$ we see $\approx 5\times$ higher heralding count rate for the improved multiplexed scheme (iv) versus a single detector. The same configuration's performance (iv) compared with the multiplexed detectors array with the previous detection-deadtime-only switching algorithm shows only a $2.1\times$ improvement. Note that these improvement factors were achieved with just two detectors and as we see (Fig. 1(a) and 1(b)), the detection-deadtime-only algorithm yields limited gain from increasing the number of detectors beyond two, while the detector and gate algorithm shows no such limit. Such improvement is made possible by consideration of all deadtime contributions in infrared detectors and tailoring the switching algorithm to mitigate both types of deadtime.

We have presented a truly scalable multiplexed SPAD array for telecom-band gated photon detection that uses a more complete accounting of the deadtime related properties of commercially available single-photon InGaAs detectors. The new algorithm offers significantly better performance and scalability over the old algorithm or other detector arrangements. Our new algorithm with two SPADs improves the maximum count rate achievable by $5\times$, while maintaining a DTF of 10% as compared with a single SPAD, and by $2.1\times$ versus the multiplexed detector array with a switching algorithm that only accounts for T_d and this improvement difference grows with the number of detectors. Also note that together with deadtime, the afterpulse and dark count rates are reduced via these multiplexing schemes.

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