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Improved implementation and modeling of deadtime reduction in an actively multiplexed detection system

G. Brida[a], I.P. Degiovanni[a*], V. Schettini[a], S.V. Polyakov[b,c] and A. Migdall[b,c]

[a]*Istituto Nazionale di Ricerca Metrologica, Turin, Italy;* [b]*Optical Technology Division, National Institute of Standards and Technology, Gaithersburg, MD, USA;* [c]*Joint Quantum Institute, University of Maryland, MD, USA*

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We have presented a scheme to allow photon counting at higher rates than is otherwise possible with existing photon-counting detectors and detection systems. This is done by multiplexing a pool of detectors in a way that greatly suppresses the effect of the deadtimes of the individual detectors. In our previous work we demonstrated the advantage of this approach over simply trying to improve the deadtime of an individual detector or using the type of passively switched system that can be implemented with group of detectors and a tree of beamsplitters. Here, we present an extension of the theoretical modeling of our actively multiplexed scheme to include effects that arise solely from the use of detectors that require gating. We see that such detectors exhibit a deadtime associated with their gate circuitry, independent of whether the detector fires or not, that should be treated separately from the deadtime due to an actual photodetection. In addition, we present experimental results made with an improved switch control system and shorter gate deadtime demonstrating an approximate twofold effective deadtime improvement over our previous demonstration.

Keywords: fast fiber switch; InGaAs single-photon avalanche detector (SPAD); multiplexing; parametric down-conversion; photon counting

1. Introduction

The interest in single-photon technology is growing as quantum communication and computation efforts intensify. These applications place especially difficult design requirements on the detection of single photons [1,2]. Quantum key distribution (QKD) is currently significantly limited by detector characteristics such as detection efficiency, dark count rate, timing jitter and deadtime [3,4] and thus would particularly benefit from improved detectors. Due to demands for higher-rate secret key production, the quantum information community is presently engaged in a number of efforts aimed at improving detectors for QKD, including improving detector efficiency [2,5,6], reducing detector timing jitter [7] and reducing detector deadtime [8]. Moreover, with the exponential growth of non-classical photon production rates, the need is increasing for better photon-counting detection. The major factor impeding the detection rate is deadtime. However, one cannot just focus on this parameter alone, as often shorter deadtimes are associated with higher after-pulsing probabilities. Addressing the need for counting at high rates by reducing deadtime, while other characteristics of a single-photon counting device are kept constant or improved, is our aim here.

The idea here relies on the well-established principle of multiplexing many individual, but imperfect, components into a system that operates with significantly better characteristics. The method of active multiplexing single-photon detectors is getting more feasible thanks to the current attempts to integrate detectors in microchip arrays [9–11].

Reducing the effects of deadtime is the most direct way to achieve higher detection rates. Deadtime is typically defined as the time a photon-counting detector needs to recover after it registers a photon and is ready to register another one. This recovery time may be due to the physical properties of the detector and/or the pulse processing electronics. In photomultiplier tubes (PMTs) for example, the detector deadtime is almost negligible, so the electronics ultimately sets the deadtime. In single-photon avalanche photodiodes (SPADs), however, because of the avalanche effect combined with carrier trapping in the detection region, the detector deadtime dominates. Indeed, in a SPAD, the avalanche must be quenched and the carriers removed from the detection zone before the detector is ready for another photon, resulting in a deadtime in the range of few tens of nanoseconds to about tens of microseconds. The rate of carrier removal depends on the concentration of defects and

*Corresponding author. Email: i.degiovanni@inrim.it

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impurities of the semiconductor structure and is process dependent. Our approach deals with this problem by using fast processing electronics to reduce the effect of these detector non-idealities. We believe that this is a much easier route to faster counting than to push for significant improvements in individual SPADs by efforts such as reducing trap concentrations. In addition, it should be possible to build our multidetector system with associated electronics integrated together on the same chip.

The acceptable peak rate of detection for a photon counting solution is application specific. Obviously, the higher the count rate, the longer the time the detection system is *dead*, or unable to detect a new event. Therefore, the higher the count rate, the larger the nonlinearity of detection. We define the deadtime fraction (DTF) as the ratio of missed- to incident-events. Alternately, in the case of a time-independent Poissonian continuous-wave (cw) source, it may be defined as the fraction of the time the detector spends in its recovery state (where it is effectively blind to incoming photons) to the total elapsed time. Furthermore, we assume $\mathrm{DTF} = 10\%$ to be a reasonable limit for most detection applications.

Our scheme to improve detection rates takes an array of photon-counting detectors and operates them as a single unit, a detection system. Most importantly, this design involves an intelligent multiplexing, i.e. keeping track of each single SPAD state (*dead* or *alive*), and switches the single photon input to a SPAD that is known to be *alive*. We have shown that this arrangement allows overall photon detection at higher rates than would be possible if the detectors were operated individually (or even in a passive detector tree configuration), while maintaining comparable DTFs.

The theoretical study shows that the proposed scheme is superior to other passive detector arrangements aimed at improving deadtimes. In particular, we compare the proposed arrangement DTFs to those of detector tree arrangements, as well as to the performance of a (hypothetical) single detector with reduced deadtime.

Our first theoretical study considered the simple case of a system with negligible switching time [12], while our subsequent analysis considered the more realistic case of a system with a non-negligible switching time [13]; in this paper we extend further our theoretical modeling by including in our analysis the additional 'deadtime' contributions resulting from when the (heralded) detector is gated, but no detection is registered. We refer to these as empty gate events. In addition to deadtime improvement that leads to higher photon counting rates, in this paper we also discuss and compare other improvement schemes for relevant characteristics such as afterpulsing and dark count rates.

Furthermore, we report on a proof of principle experiment of an actively switched multiplexed single-photon detector system. In this context we present a new circuit designed specifically for our optical switching application, reducing significantly the switching time with respect to the previous version of the multiplexed system [13], as well as with respect to individual detectors with improved deadtimes or simple detector trees. We demonstrate that the best scheme to reduce DTF and increase photon count rates, along with the added bonus of improving the signal to background ratio and reducing afterpulsing, is the active switching arrangement that uses an external logic circuit that remembers the order in which the detectors fired.

2. Detector arrangements

To judge the performance of various arrangements, deadtime improvement alone is not sufficient. Performance has to be weighed together with changes of other important characteristics, such as afterpulsing probability and dark count rate. In this study we consider the following detector arrangements (Figure 1(*b*)) aimed at decreasing deadtime: (i) an *improved detector* (perhaps hypothetical) that has a deadtime N times shorter than a conventional SPAD; (ii) a *tree* of N conventional detectors connected through a series of passive beam splitters; (iii) an actively controlled array of N conventional detectors connected via a 1-by-N optical switch.

The latter detection arrangement relies on the rather obvious fact that, while a detector has a significant deadtime when it does fire, it has no deadtime when it does not fire. (In practice this is not quite true, but as we shall see we now handle this directly.) A switch control circuit monitors which detectors have fired recently and are thus *dead*, and then routes subsequent incoming pulses to a detector that is ready. As we showed in our previous works [12,13], this system allows an arrangement of N detectors to be operated at a significantly higher detection rate than N times the detection rate of an individual detector, while maintaining the same DTF.

To understand the process, consider a time-independent Poisson (cw) input photon source. At first, all detectors are ready to detect a photon. The optical switch is set to direct the first incoming photon to the first detector of the array. Control electronics (Figure 1(*c*)) monitor the output of that detector to determine when it fires. If the detector does fire, the

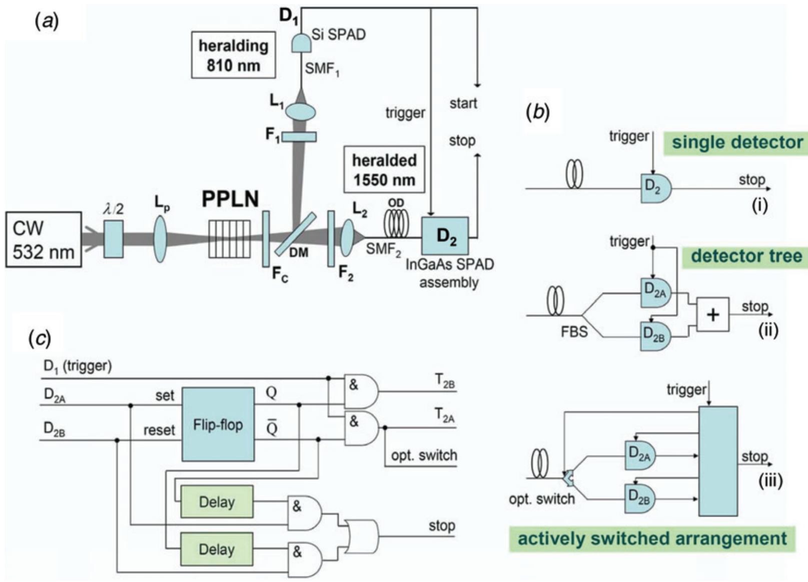

Figure 1. (*a*) Setup for testing different arrangements of InGaAs SPAD assemblies; (*b*) three different InGaAs SPAD assemblies; (*c*) a schematic of electronic logic to actively control InGaAs assemblies and photon routing.

control switches the next incoming light pulse to the next detector. If the detector does not fire, then the switch state remains unchanged. The process repeats with the input always directed to the available live detector that fired the longest time ago. At high count rates many of the detectors may fire within a short period of time and be *dead*, but, as long as the first detector recovers to its live state before the last detector fires, the whole arrangement will still be live and ready to register an incoming photon. The reason to choose the detector that did not fire for the longest time is that, in a typical SPAD, afterpulsing probability is inversely related to the time the detector was inactive; hence the overall arrangement will have a reduced afterpulsing rate. Only when all detectors have fired within one deadtime of each other will the system be *dead*. This scheme would allow for optimum use of an array of detectors where each detector may have a different deadtime.

3. Theory of operation: DTF

The theoretical treatment of the intelligent multiplexing arrangement is best understood by starting with the ideal case where electronic switching delay is negligible as compared to the SPAD's deadtime. In practice, however, this is not the case, because switching can take a sizable fraction of deadtime (from 1% to 10%). Also, another non-ideality is that some SPADs, especially those that operate at telecom wavelengths, require gating. After such a gate is received, these detectors are unable to accept another gate for some time (i.e. they are effectively *dead*) even if they did not fire. Even though the fraction of time when a SPAD cannot accept another gate is small (~0.5–5% of the deadtime), the number of gate events is usually many times (10 or more) larger than the photon detection events. Therefore, their effect can be significant.

So, let us introduce the different kinds of deadtimes that are present in our gated and switched detection system: T_d is the nominal deadtime of a single detector due to detection of a heralded photon; T_0, the empty gate event deadtime, is the time interval when a detector on the heralded channel is busy after being gated by a heralding pulse but no photon was detected. In the presence of a switch, we also have to consider the switching time T_s, which is the time the switch control circuit takes to redirect the incoming photon to the next detector after a heralded detection. In analogy with the previous paper [13], we introduce an overall *effective* deadtime $\mathcal{T}_{d(N)}$ of our detection system with N detectors. $\mathcal{T}_{d(N)}$ obviously depends on the different deadtime contributions T_0, T_d, T_s and on the heralding rate λ.

In our previous experiment we estimated, from the experimental data, the DTF using the heuristic formula [13]

$$\mathrm{DTF} = \lambda_{\mathrm{registered}} \mathcal{T}_{d(N)} + \lambda_0 T_0, \qquad (1)$$

where $\lambda_{\mathrm{registered}}$ is now the overall rate of counts registered by our detection system, and λ_0 is the rate of empty gate events.

For a hypothetical improved detector with a deadtime N times shorter than a conventional SPAD and for the case of a tree of N conventional detectors connected through a series of passive beam splitters, the effective deadtime has the explicit expression $\mathcal{T}_{d(N)} = T_d/N$ [12,13]. The evaluation of $\mathcal{T}_{d(N)}$ in the case of the actively multiplexed detection system shown next is the main result of the theoretical model.

This model considers a scheme based on a cw (Poissonian) heralded single photon source, and a gated detection system. The heralding signals are Poissonian distributed according to $P(n) = (\lambda T)^n \times \exp^{-\lambda T}/n!$, where λ is the rate of the heralding signals and T is the measurement time. These heralding signals are used to gate the detection system. In the absence of heralded channel deadtime effects, the number of heralding counts will be equal to the number of gate counts. Furthermore, we assume that our detection system presents a non-unit quantum efficiency; thus, for each gate count, it observes the heralded event with only the probability ξ (a detailed model for ξ is presented in Appendix 1).

In the ideal case, i.e. all deadtimes = 0, the probability of having m heralded counts given n gate counts is $B(m|n,\xi) = n!/[m!(n-m)!]\xi^m(1-\xi)^{n-m}$; thus the probability of having m heralded counts is $P_{hd}(m) = (\xi\lambda T)^m \exp^{-\xi\lambda T}/m!$. The probability of having k gate counts that will not produce heralded counts (an empty gate event) given n gate counts is $B(k|n, 1-\xi) = n!/[k!(n-k)!](1-\xi)^k\xi^{n-k}$; thus the probability of having k empty gate events is $P_0(k) = [(1-\xi)\lambda T]^k \exp^{-(1-\xi)\lambda T}/k!$.

We note that in our previous paper [13] $\mathcal{T}_{d(N)}$ was evaluated with $T_0 = 0$. In that case, i.e. with empty gate events not introducing any deadtime effect, the probability that the detection of the Nth heralded count occurs in the time interval $[t; t+\mathrm{d}t]$ is [13]

$$f_N(t, \mathcal{T}_{d(N)}) = \frac{(\xi\lambda)^{N-1}[t-(N-1)\mathcal{T}_{d(N)}]^{N-2}}{(N-2)!} \times e^{-\xi\lambda[t-(N-1)\mathcal{T}_{d(N)}]}\theta[t-(N-1)\mathcal{T}_{d(N)}]\mathrm{d}t, \tag{2}$$

which is a modified Gamma function and θ is the Heaviside step function with $\theta(x) = 1$ for $x > 0$ and 0 otherwise. The total time between the first and the Nth heralded count during which the detection system is *alive* is $[t-(N-1)\mathcal{T}_{d(N)}]$; thus the mean number of empty gate events in this time interval is $\mu_t = (1-\xi)\lambda[t-(N-1)\mathcal{T}_{d(N)}]$.

In the case $T_0 \neq 0$, each empty gate count in the time interval $[t-(N-1)\mathcal{T}_{d(N)}]$ presents an associated deadtime T_0, and thus the mean number of empty gate counts is reduced to

$$\mu_t = \frac{(1-\xi)\lambda[t-(N-1)\mathcal{T}_{d(N)}]}{1+(1-\xi)\lambda T_0}. \tag{3}$$

This term introduces a further deadtime effect. On average we have an additional deadtime contribution of $\mu_t T_0$. Thus, the total time interval during which the detection system is *alive* between the first and the Nth heralded count becomes

$$t-(N-1)\mathcal{T}_{d(N)} - \mu_t T_0 = \frac{(1-\xi)\lambda[t-(N-1)\mathcal{T}_{d(N)}]}{1+(1-\xi)\lambda T_0}. \tag{4}$$

This comes from substituting $[t-(N-1)\mathcal{T}_{d(N)}]$ for $[t-(N-1)\mathcal{T}_{d(N)}]/[1+(1-\xi)\lambda T_0]$ into Equation (2). Moreover, by regrouping, we are able to re-write the probability of detecting the Nth heralded count in the time interval $[t; t+\mathrm{d}t]$ as

$$f_N(t, \mathcal{T}_{d(N)}) = \left[\frac{\xi\lambda}{1+(1-\xi)\lambda T_0}\right]^{N-1} \frac{[t-(N-1)\mathcal{T}_{d(N)}]^{N-2}}{(N-2)!} \times \exp\left[-\frac{\xi\lambda}{1+(1-\xi)\lambda T_0}[t-(N-1)\mathcal{T}_{d(N)}]\right] \times \theta[t-(N-1)\mathcal{T}_{d(N)}]\mathrm{d}t. \tag{5}$$

Starting from $f_N(t, \mathcal{T}_{d(N)})$, and following the development of [13], we get the effective deadtime for N detectors $\mathcal{T}_{d(N)}$ by solving

$$\mathcal{T}_{d(N)} = p_{a,N}(\mathcal{T}_{d(N)})T_s + p_{b,N}(\mathcal{T}_{d(N)})(T_d - E_{b,N}(\mathcal{T}_{d(N)})), \tag{6}$$

where

$$p_{a,N}(\mathcal{T}_{d(N)}) = \int_{T_d-T_s}^{+\infty} f_N(\Delta t, \mathcal{T}_{d(N)})\mathrm{d}\Delta t, \tag{7}$$

$$p_{b,N}(\mathcal{T}_{d(N)}) = \int_0^{T_d-T_s} f_N(\Delta t, \mathcal{T}_{d(N)})\mathrm{d}\Delta t, \tag{8}$$

and

$$E_{b,N}(\mathcal{T}_{d(N)}) = \frac{\int_0^{T_d-T_s}\Delta t f_N(\Delta t, \mathcal{T}_{d(N)})\mathrm{d}\Delta t}{\int_0^{T_d-T_s} f_N(\Delta t, \mathcal{T}_{d(N)})\mathrm{d}\Delta t}. \tag{9}$$

In the presence of deadtimes ($T_d \neq 0; T_s \neq 0; T_0 \neq 0$) only a subensemble of heralding events is accepted by the detection system, corresponding to the time interval during which the system is not dead. In the following we refer to these accepted heralding events as gate counts. M is the mean number of gate counts in the time interval T. Each gate count produces a heralded count with a probability ξ, and an empty gate count with probability $1-\xi$. The mean number of heralded counts is ξM, and after each heralded count an effective deadtime $\mathcal{T}_{d(N)}$ occurs ($\lambda\mathcal{T}_{d(N)}$ heralding counts are, on average, missed during each effective dead time $\lambda\mathcal{T}_{d(N)}$). The mean number of empty gate events is $(1-\xi)M$, and after each such event the detection system is busy (*dead*) for a time T_0, during which, on average, λT_0 heralding counts are missed. Therefore, we can write the mean number of heralding counts λT as

$$\begin{aligned}\lambda T &= M[\xi(1+\lambda\mathcal{T}_{d(N)})+(1-\xi)(1+\lambda T_0)]\\ &= M[1+\xi\lambda\mathcal{T}_{d(N)}+(1-\xi)\lambda T_0]. \qquad (10)\end{aligned}$$

Thus, the mean number of gate counts in terms of heralding counts is

$$M=\frac{\lambda T}{1+\xi\lambda\mathcal{T}_{d(N)}+(1-\xi)\lambda T_0}. \qquad (11)$$

We define the DTF of our photon counting detection system as the ratio of the lost count rate over the total count rate in the absence of deadtime:

$$\mathrm{DTF}=1-\frac{M}{\lambda T}. \qquad (12)$$

Substituting Equation (11) into Equation (12) we obtain

$$\mathrm{DTF}=\frac{\xi\lambda\mathcal{T}_{d(N)}}{1+\xi\lambda\mathcal{T}_{d(N)}+(1-\xi)\lambda T_0}+\frac{(1-\xi)\lambda T_0}{1+\xi\lambda\mathcal{T}_{d(N)}+(1-\xi)\lambda T_0}. \qquad (13)$$

To match theory to the experiment, we note that the DTF formula Equation (13) adds the effect of empty gate counts to the traditional deadtime effect considered in the previous paper [13]. In fact, the theoretical analysis leading to Equation (13) provides a rigorous theoretical justification of the heuristic model for DTF in Equation (1) used in [13]. Figure 2 shows that the incident photon rate for DTF = 10% (a reasonable limit for most detector applications) is significantly reduced for all arrangements when $T_0 \neq 0$. Clearly, empty-gate deadtime should be minimized.

4. Theory of operation: dark counts and afterpulses

While we have so far limited our discussion to improving DTF, there are, however, other important features of the detector arrangements that should be characterized. First, we consider dark counts. For the purpose of quantitative analysis we assume a *standard* SPAD with a dark count rate of unity. We further assume that all SPADs have the same dark count rate. In reality dark count rates may vary significantly from

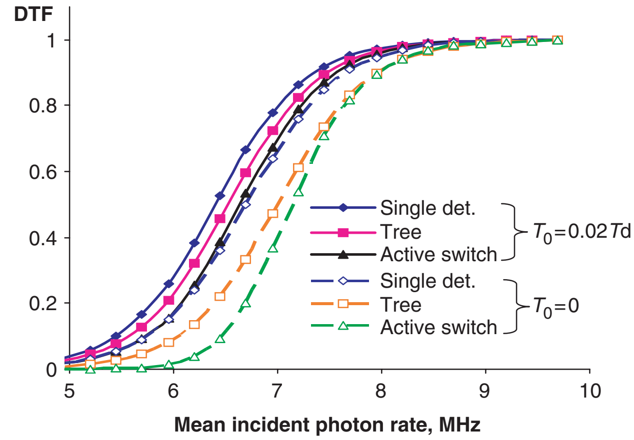

Figure 2. Effect of non-zero empty-gate deadtime on DTF for various detector arrangements of one and two detectors. Diamonds: single detectors; squares: tree arrangements; triangles: actively switched arrangements; open markers: $T_0 = 0$; filled markers: trigger deadtime $T_0 = 0.02T_d$. (The color version of this figure is included in the online version of the journal.)

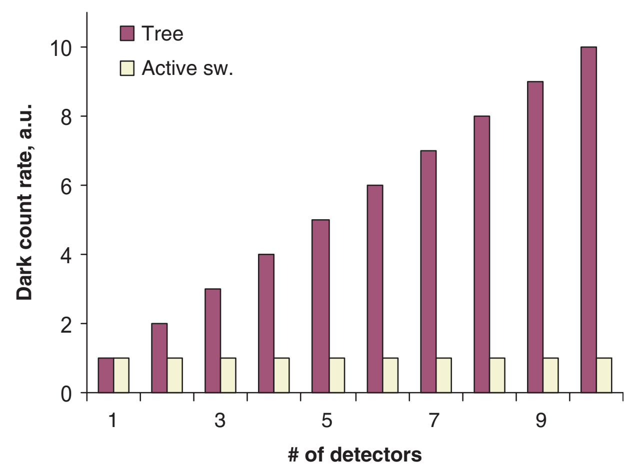

Figure 3. Dark count rate for various multidetector arrangements in units of the dark count rate of a single conventional detector. (The color version of this figure is included in the online version of the journal.)

detector to detector, and this can ultimately affect the design of multidetector arrangements, but here we ignore this for simplicity. The theoretical scaling of dark count rate with a number of detectors is presented in Figure 3. It is clear that an active switching arrangement is better than a tree configuration for any number of detectors $N > 1$.

Now we estimate the afterpulsing probability. To do so, we start from the fact that the afterpulsing probability in SPADs is related to the probability of trapping free carriers in the active detection zone. If a free carrier survives until the SPAD bias is raised

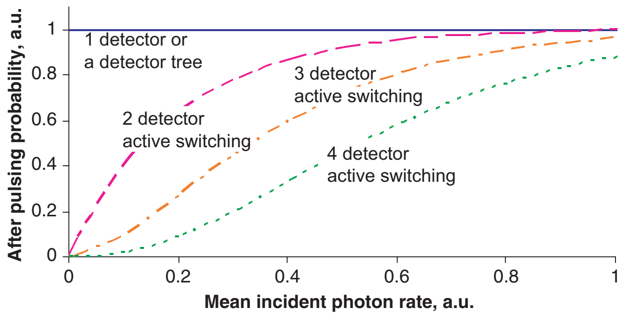

Figure 4. Afterpulsing probability rate for an active switching multidetector arrangement with two (dashed line), three (dotted-dashed line) and four detectors (dotted line), and for a single detector or a tree arrangement (solid). (The color version of this figure is included in the online version of the journal.)

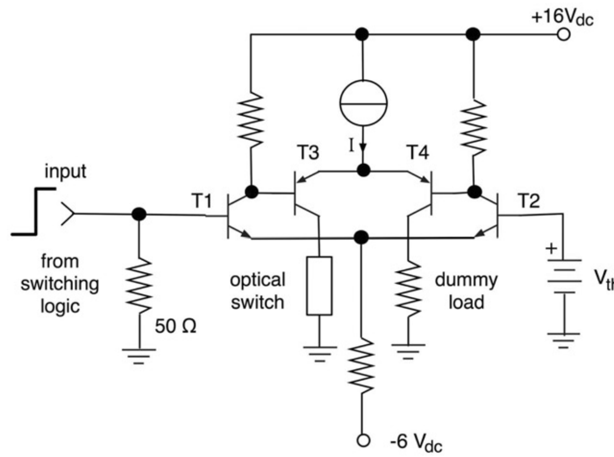

Figure 5. Optical switch electrical driver schematic.

above breakdown again, it will start another avalanche and produce an afterpulse. It has been shown numerous times that the probability for this to happen decreases exponentially with SPAD deadtime [14]. In general, the afterpulse probability of the multidetector scheme will be reduced because each detector will have a longer rest time before it is reactivated.

For the following, we assume negligible afterpulse probability for the cases when the system has at least one live detector. We can calculate the probability for this to happen assuming, as usual, Poisson incoming photon statistics. For a two-detector arrangement, the probability to receive one (or more) detectable photons during a deadtime of a single detector T_d is $P(n \geq 1) = 1 - \exp(-\lambda' T_d)$, where λ' is the rate of the incoming detectable photons. At this stage, the assembly will switch to the first detector immediately after its deadtime is over; thus it will afterpulse with its regular probability. For more than two detectors one writes

$$P(n \geq N-1) = 1 - \exp(-\lambda' T_d) \sum_{i=0}^{N-2} \frac{(\lambda' T)^i}{i!}. \quad (14)$$

One sees from this formula and Figure 4 that the afterpulse probability in the multidetector arrangement will always be lower than that of a single detector or a detector tree and will depend on a count rate. (There is no such advantage for a detector tree as in that case all afterpulses are counted.) This dependence (in units of afterpulse probability of a single SPAD) is presented in Figure 4. Thus, the treatment presented supports the conclusion that active switching arrangements are superior to all other detection arrangements studied and provide better (or equal) DTFs, afterpulsing probabilities and dark count rates than a single SPAD.

5. Optimization of switching time

For our current experiment, we used a specifically designed fast optical switch driver instead of the commercial pulse generator used in [13]. Independent of our verifying experiment, lower switching times allow for higher count rates at the same DTF level. Currently, all the delays in electronic processing must be matched by extra fiber length in the heralded arm (i.e. before an optical switch). Therefore, by reducing electronic processing times one can use shorter optical fiber delay lines, and thus decrease the possibility of drifts, including polarization drifts, as well as increase the overall detection efficiency, and therefore increase the robustness of the assembly. Moreover, one wants the switching time to be less than the shortest possible time between trigger events (in our experimental setup this corresponds to a deadtime of a trigger SPAD that is ≈50 ns) to match the experiment to all theoretical assumptions.

The analysis of the setup used in [13] showed that the longest delay was due to the commercial triggered pulse generator that operated the switch. To reduce this delay, we implemented a fast switch driver capable of producing variable pulse heights. The simplified schematic of the circuit is shown in Figure 5. This driver is realized with two transistor differential stages (T1–T2 and T3–T4). The circuit simply switches the current *I* from the dummy load resistor to the electrical port of the optical switch when the input signal switches from a low to a high level. The main reason for using an emitter-coupled circuit is its switching speed and the capability to easily change the output amplitude by varying the current *I* of a voltage controlled source. In the first prototype the amplitude of the output voltage could be adjusted from 4 V to 6 V and the total propagation delay (including rise-time and settling) was ≃15 ns, which is nearly an order of magnitude shorter than that obtained with the commercial pulse generator used in [13].

This circuit therefore allows for testing in the regime when all trigger pulses can be processed. To further improve the performance of the control electronics, we plan to integrate an field programmable gate array (FPGA) and a driver on a single board. Having an integrated circuit will improve its speed by reducing propagation delays. Secondly, the switching time can be improved if the driver is triggered by a differential, rather than a single-ended transistor–transistor logic (TTL) signal, allowing for optimization of the rise-time of the driver. The development of this integrated board is underway.

6. Experimental results

To test our model we produced correlated photons at 810 nm and 1550 nm via a parametric down conversion obtained by pumping a periodically poled MgO-doped lithium niobate (PPLN) crystal with a cw laser at 532 nm [15]. The visible photons are the heralding channel that triggers the infrared photon's arrival at the InGaAs SPAD assembly-heralded channel (Figure 1(*a*)).

Our experiment compares the DTF as a function of the gate count rate for three detector configurations: a single detector, a detector tree and an actively switched arrangement (Figure 1(*b*)). The latter consists of an optical switch and a logic circuit (Figure 1(*c*)), whose task is to keep track of the order in which detectors have fired and to route the next input to the detector that has had the longest time to recover.

To demonstrate the advantage and the feasibility of active routing of photons, we made a series of DTF measurements at different gate count rates. Figure 6 shows both the previous measurements [13] and the new ones obtained with the optimized optical switch electrical driver, highlighting the decrease in DTF at a fixed trigger count rate for the multiplexed system, allowing operation at higher count rates. This illustrates that reducing trigger deadtime (as suggested by the theory, Figure 2) and improving switching time is very important for DTF reduction. The dramatic decrease in DTF shown in our latest experiment represents (Figure 6 lowest two curves) another important step in optimizing the active switching technology for multiplexed detection systems.

In Figure 7 we show the measured probability of observing an accidental count, i.e. a dark count or an afterpulse, for each gate count for several gate count rates, in three detection system configurations: a single InGaAs SPAD, the detector tree arrangement

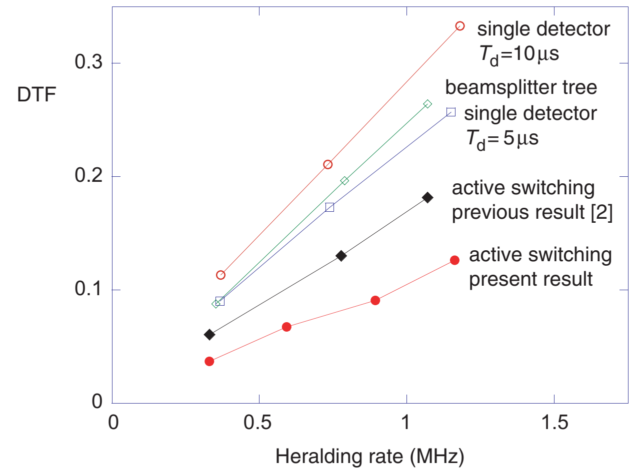

Figure 6. DTF versus the overall gate rate for different detection arrangements. Both the previous data [13] for a single detector, detector tree and multiplexed system (four upper curves), and the data obtained with the multiplexed system with the improved optical switch driver (lowest curve) are shown. (The color version of this figure is included in the online version of the journal.)

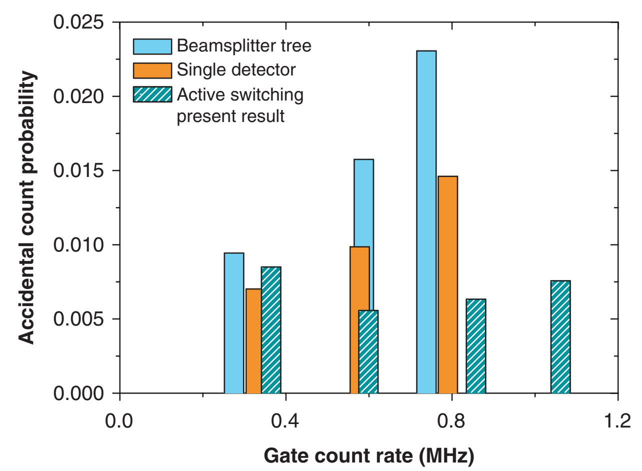

Figure 7. Probability of observing an accidental count for each gate count versus gate count rate for the three detection system configurations. (The color version of this figure is included in the online version of the journal.)

with two InGaAs SPADs, and the multiplexed system with two InGaAs SPADs. In all configurations the InGaAs deadtime was $T_d = 10\,\mu s$. As expected from the analysis in Section 4, the multiplexed detection systems reduce by about half the total probability of accidental counts with respect to the beamsplitter tree arrangement.

7. Conclusion

We have presented the current state of our theoretical and experimental efforts in support of an intelligent management of detector deadtime by use of multiplexed detectors. We have expanded our theoretical treatment to include non-zero switching and empty gate count deadtime, as well as the usual detector deadtimes to better account for physical properties of real-world detectors. We have shown the superiority of the intelligent management scheme not only in reducing the DTF, the main goal of this study, but also in reducing afterpulse rates and keeping dark count rates independent of the number of detectors used. Furthermore, we have shown an improvement in the DTF reduction of our proof of principle multiplexed system realized with the new optical switch electrical driver over our previous experiment [13].

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Appendix 1

We model the probability ξ of observing a heralded count given a gate count following the scheme explained in [15]. In the *heralded single-photon source* schemes based on parametric down conversion, such as the one we used in our experiment, it is well known that a heralded count can be a *true* heralded count – due to a photon of the same pair as the photon in the heralding channel – or it can be an *accidental* heralded count – due to a photon belonging to another pair. We model ξ to verify whether the multiplexed detection system experimentally allows a reduction of *accidental* heralded counts.

A simple model for the measurement can be

$$\xi = p_{dc}(1-\pi_{w,I}\pi_{w,II}) + (1-p_{dc})[(1-\pi_{w,I}) + \pi_{w,I}\eta + \pi_{w,I}(1-\eta)(1-\pi_{w,II})], \tag{15}$$

where p_{dc} is the probability that the gate count comes from a *dark count* on the heralding channel, $\pi_{w,I/II}$ is the probability to have zero accidental heralded counts in the first/second part of the total measurement time window w (we assume that the correlated photons arrive exactly at $w/2$), and η is the total detection efficiency of the detection system including coupling and optical losses and detector detection efficiency. Thus, the first term of Equation (15) accounts for the heralded counts in the full window w but coming from dark heralding counts, and the second group is due to true heralding counts. Within this group the first term is the probability that, even if the heralding detector clicks for a photon of a pair, the heralded detector clicks for an accidental event in the first half of w; the second term is the probability that the heralded detector does not fire in the first half of w but it clicks for the correlated photon; finally the third term is the probability that the heralded detector does not fire in the first half of w and does not fire for the correlated photon, but fires for an accidental event in the second half of the coincidence window.