Improved photon-counting detector performance by intelligent management of detector deadtime

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ABSTRACT

We discuss the difficulties of photon-counting at extremely high rates and introduce a scheme for a photon-counting detection system that addresses these difficulties. The method uses an array of *N* detectors and a 1-by-*N* optical switch with a control circuit to direct input light to live detectors. We compare performance of our system to other, passive detection systems and show that our detection system can handle incident photon rates higher than otherwise possible by suppressing the effects of detector deadtime. To support this claim, we present results of theoretical analysis and a proof-of-concept experiment. In particular, both calculations and the experiment prove that a group of intelligently managed *N* detectors provides an improvement in operation rate that can exceed the improvement that would be obtained by either a single detector with deadtime reduced by 1/*N*, even if it were feasible to produce a single detector with such a large improvement in deadtime, or a passive beamsplitter tree system with *N* detectors. In addition to deadtime reduction, our scheme reduces afterpulsing as well as background counts (such as dark counts). We conclude that an intelligent active management of a group of *N* detectors is the best arrangement of photon-counting detectors to handle high photon rates, an important technological challenge for fast developing quantum metrology and quantum key distribution applications.

Keywords: photon counting, detector, down-conversion, correlated photons, statistical methods

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. Because of 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 can not just focus on this parameter alone, as often shorter deadtimes are associated with higher afterpulsing 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 discussed 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 important task on a way to achieve higher detection rates. Deadtime is 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) 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

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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 a range of few tens of nanoseconds to about tens of microseconds. The rate of carrier removal depends on the concentration of defects and 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 detectors nonidealities. We believe that this is a much easier route to faster counting than to push for significant improvements in individual detectors by 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 time the detection system spends "dead", or unable to detect a new event. Therefore, the higher the count rate, the larger is the nonlinearity of detection. We define 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. Further, we assume 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 show 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. In addition to deadtime improvement that leads to higher photon counting rates, we discuss and compare other improvement schemes for relevant characteristics such as afterpulsing and dark count rates. In this theoretical study, we consider a simple case when the switching time is negligible short comparing to an individual SPADs deadtime, and then more complex case when the two times are comparable.

We report on a proof of principle experiment of an actively switched, multiplexed single-photon detector system and prove its advantage over individual detectors with improved deadtimes or simple detector trees experimentally. We show experimentally that the most advantageous 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, the deadtime improvement alone is not sufficient, but has to be weighted with changes of other important characteristics, such as afterpulsing probability and dark count rate. In this study we consider the following detector arrangements aimed at decreasing the deadtime. (a) An 'improved detector' (sometimes hypothetical) that has a deadtime N times shorter than a conventional SPAD. (b) A 'tree' of N conventional detectors connected through a series of passive beam splitters. (c) An actively controlled array of N conventional detectors connected via a 1-by-N optical switch (Fig. 1).

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. 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 work [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 pulse to the first detector of the array. Control electronics monitor the output of that detector to determine when it fires. If the detector does fire, the control switches the next 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 in a short period of time and be 'dead', but as long as the first detector recovers to its live state before the last detector triggers, 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 would allow for optimum use of an array of detectors where each detector may have a different deadtime.

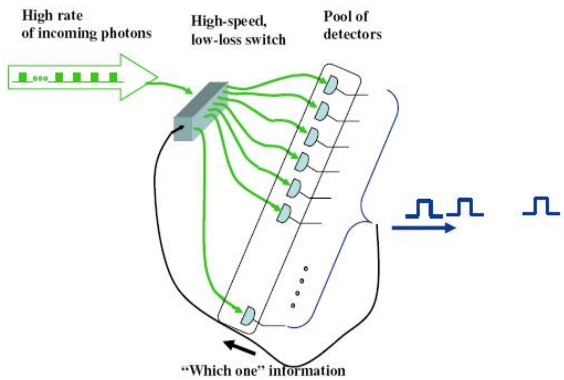

Fig. 1. Schematics of intelligent management of the deadtime.

3. THEORY OF OPERATION

The theoretical treatment of the intelligent multiplexing arrangement is best understood when starts with an ideal case when electronic switching delay is negligible as compared to the SPADs deadtime. Realistically, however, this is not the case, because switching can take a sizable fraction of deadtime (from a 1% to 10%). Also, some SPADs, especially these that operate at telecom wavelength require triggering. After such trigger is received, these detectors are unable to accept another trigger for some time (i.e. are effectively dead) even though they did not fire. Even though the fraction of time then SPAD can not accept another trigger is small (on the order of 0.5%-5% of the deadtime), the number of trigger events is usually many (10 or more) times larger than there are photon detection events. Therefore, their effect can be significant.

Our analytical calculations for the first two cases have been previously presented, so here we only briefly describe key definitions and results [12, 13]. The DTF of a generic photon counting detector is defined as the ratio of the lost count rate over the total count rate in the absence of deadtime:

$$\mathrm{DTF}=\frac{\lambda\text{-}\lambda_{\mathrm{registred}}}{\lambda}=1-\frac{1}{1+\lambda T_{\mathrm{d}}},$$

where $\lambda_{\mathrm{registred}}$ is a count rate registered by a real detector, λ is the count rate of a hypothetical detector with no deadtime (assuming Poissonian statistics), T_{d} is the deadtime of the SPAD. We generalize this definition to an arrangement of N photon counting detectors. The advantage of this definition is that it does not depend on a particular realization of a photon counting arrangement and therefore allows a fair intra-comparison of somewhat dissimilar devices.

For the most idealized case [12, 13], the DTF of an intelligently multiplexed arrangement shows a significant improvement over the other contenders (Fig. 2). It is striking that decreasing the deadtime of a single SPAD 10 times, which would be a very significant advance for SPAD technology, increases the incident photon rate at which DTF reaches 10% by the same factor as the active multiplexed arrangement with only 3 conventional SPADs!

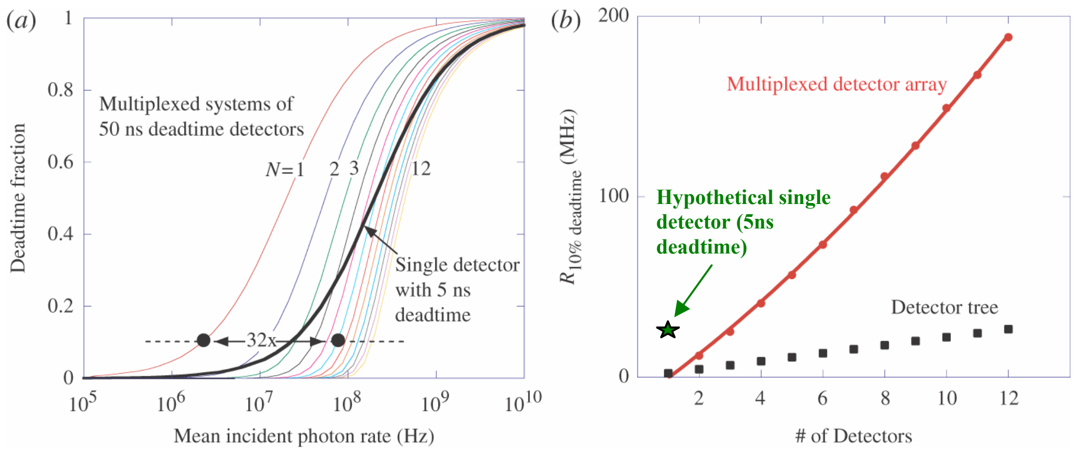

Fig. 2. Comparison of DTFs of an active detector arrangement with N conventional detectors, a (hypothetical) single detector with 1/10 of the deadtime of a conventional detector and a detector tree. a) DTF as a function of incident photon rate and b) incident photon rate that yields DTF=10% as a function of number of detectors.

Also notable is that a detector tree configuration is much less efficient and requires many more detectors to reach similar DTF levels. The second problem with tree arrangements is the fact that the darkcounts of a tree arrangement scale linearly with the number of detectors.

As already mentioned, in reality switching times can not be made arbitrarily small. State of the art electronics and optoelectronics allows the development of a switching module with switching times as low as ≈ 5ns, which is roughly 1/10 of the deadtime of a state of the art SPAD. It is clear that we need to include switching times in our consideration. Fig. 3, [14], shows that even for switching times as large as $T_s = 0.1\,T_d$, the active, multiplexed arrangement outperforms a detector tree, although this advantage decreases with the number of detectors used.

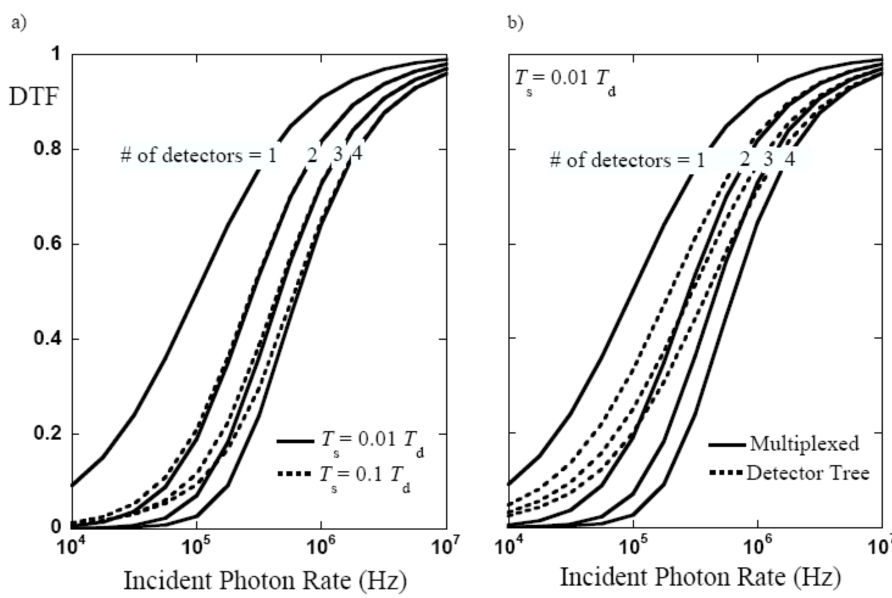

Fig. 3. Comparison of DTFs for multiplexed SPAD arrangements (a) DTF as a function of incident photon rate for actively switched systems with up to 4 detectors for $T_s = 0.1\,T_d$ and $T_s = 0.01\,T_d$ and (b) Comparing actively switched assemblies with $T_s = 0.01\,T_d$ to detector trees shows higher photon rates can be reached at a given DTF.

Finally, to match theory to the experiment, we note that in addition to the traditional deadtime described above, some detectors, especially at telecom wavelengths are not active all the time. They become active for a pre-set period of time only when triggered. Such detectors, after accepting one trigger pulse, cannot accept a subsequent trigger pulse for a period of time T_t that we will call 'trigger deadtime.' Indeed, because usually one triggers detectors only when a photon is expected at the input, this inability to accept a trigger is not operationally different from the usual 'dead' state of the detector. Further, even though trigger deadtime is small compared to T_d, this effect is not negligible, as usually there are many more trigger pulses than there are photon detections. Therefore this effect is more pronounced if the probability to detect a photon per trigger pulse μ is low. We model the effect of nonzero trigger deadtime for arrangements with one or two detectors and for the parameters close to our experiment. Namely, $T_d = 10\mu s$, $T_t = 0.02\,T_d$, $T_s = 0.01\,T_d$ and $\mu = 2\,\%$.

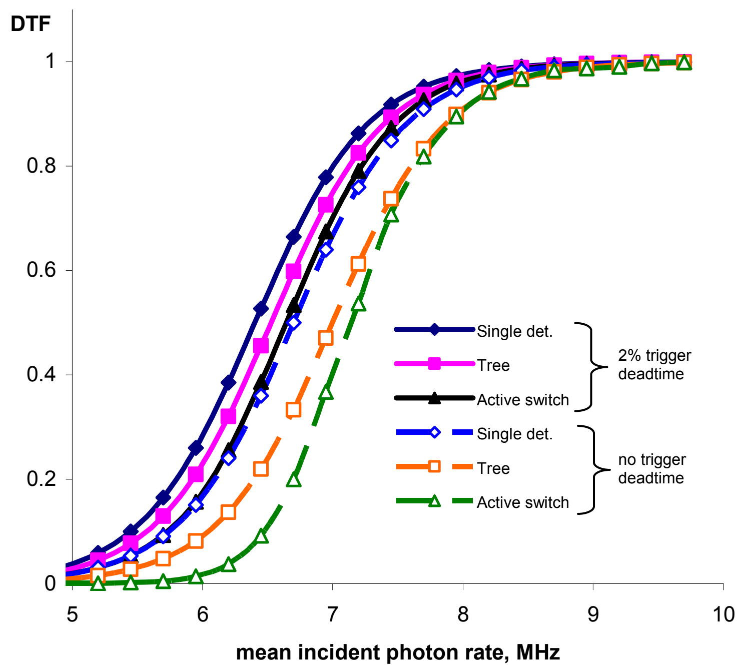

Fig. 4. Effect of nonzero trigger deadtime on DTF for various detector arrangements of 1 and 2 detectors. Diamonds: single detectors; squares: tree arrangements; triangles: actively switched arrangements; open markers: no trigger deadtime; filled markers: trigger deadtime $T_t = 0.02\,T_d$.

Fig. 4 shows that the incident photon rate for DTF= 10 % suffers significantly for all arrangements when $T_t \neq 0$. Based on this result, it is best to minimize trigger deadtime.

While we have so far limited our discussion to improving DTF, there are, however, other important features of 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. Obviously, in reality dark count rates may vary significantly from detector to detector, and this can ultimately affect the design of multidetector arrangements, but here we ignore this for simplicity. The scaling of dark count rates with a number of detectors is presented in Fig. 5. It is clear that an active switching arrangement bests a tree configuration for every number of detectors *N*.

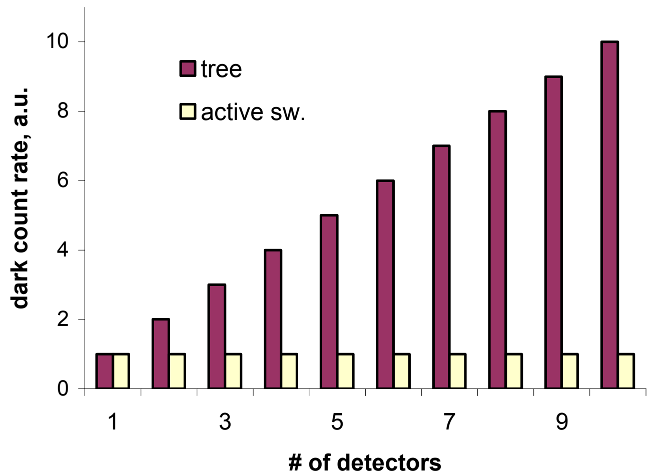

Fig. 5. Dark count rate for various multidetector arrangements in units of a single conventional detector.

Now we estimate the afterpulsing probability. To do so, notice 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 reverse bias is turned up to an avalanche level 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. 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 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 $P(n \geq 1) = 1 - \exp(-\lambda T_d)$. 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: $P(n \geq N-1) = 1 - \exp(-\lambda T_d) \sum_{i=0}^{N-2} (\lambda T)^i / i!$. Hence, the afterpulse probability in will be always lower than that of a single detector or a detector tree and will depend on a count rate. This dependence (in units of afterpulse probability of a single SPAD) is presented in Fig. 6. Thus, the presented treatment supports the conclusion that active switching arrangements are superior to all other detection arrangements studied and provide better (or equal) deadtime fractions, afterpulsing probabilities and dark count rates than a single SPAD.

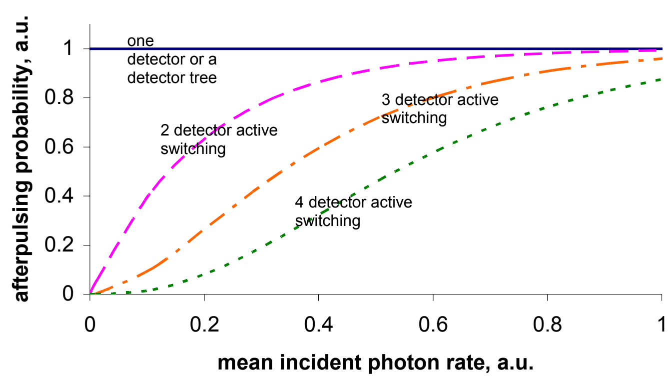

Fig. 6. Afterpulsing probability rate for an active switching multidetector arrangement with two (dashed line), three (dotted-dashed) and four detectors (dotted) and for a single detector or a tree arrangement (solid).

4. EXPERIMENTAL RESULTS

Our experiment compares the DTF as a function of the trigger detector rate (proportional to the incident photon rate) for three detector configurations: a single detector with improved dead time, a detector tree, and an actively switched arrangement (Fig. 7). The latter consists of an optical switch and a logic circuit, 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.

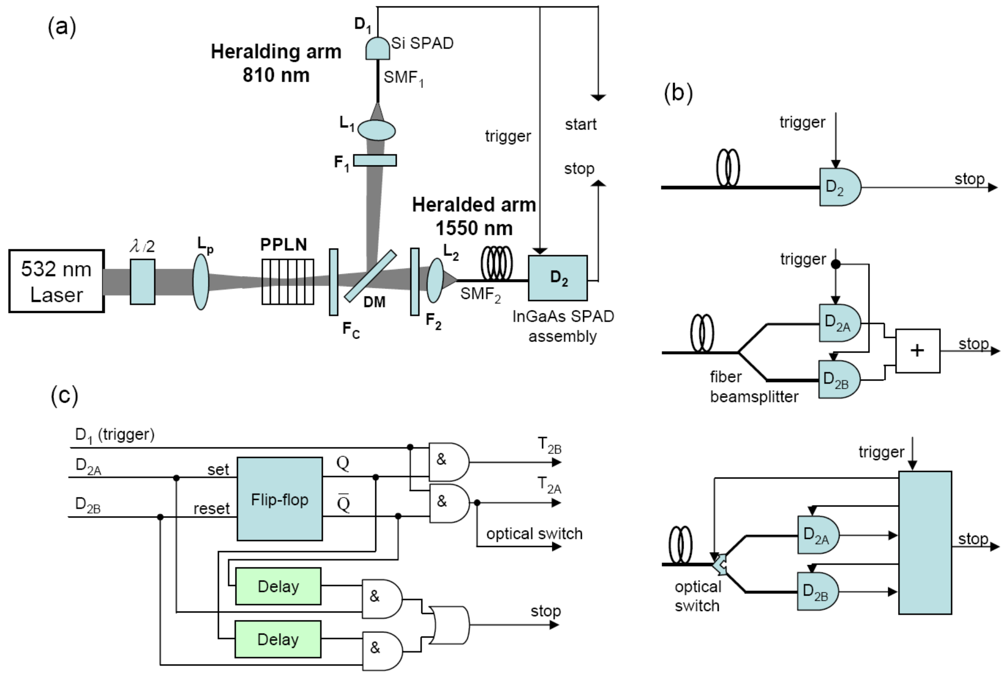

Fig. 7. Experimental setup and detector arrangements

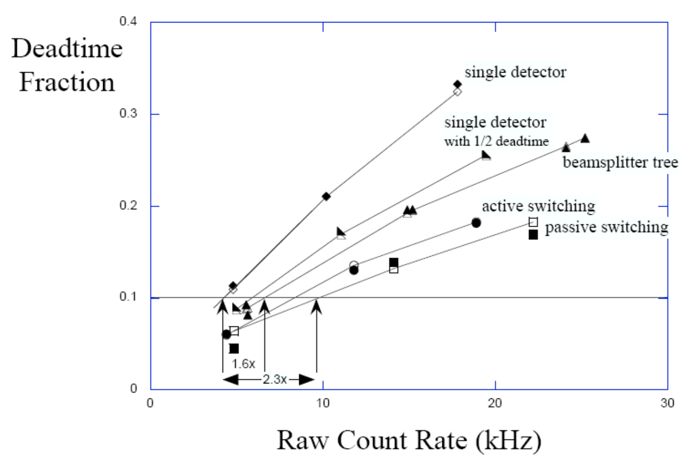

Fig. 8. DTF versus the overall count rate on InGaAs for different detection arrangements

To demonstrate the advantage and the feasibility of active routing of photons, we made a series of detection efficiency (DE) measurements at different trigger detector rates using a logic module with a beam splitter versus an active optical switch [14] and observed a 28 % increase in DE, while ideal lossless active photon routing would have resulted in a 100% increase. This rather moderate DE increase is due to the relatively high insertion loss of our switch (2 dB), rather than any other switch or control circuit nonidealities. We note that using the logic circuit to activate only one detector improves the signal to background ratio as compared to the detector tree arrangement or even compared to a single detector with half the deadtime. We gauged the signal to background improvement relative to the detector tree for the cases of passive and active switching. The passive scheme improvement was 1.83±0.05, while the active scheme improvement was 2.0±0.1. We also gauged the improvement of our switching schemes relative to a single detector with a deadtime reduced by half and found improvement factors of 1.3±0.1 and 1.4±0.2, for the two cases respectively. It is also evident from our experiments that the afterpulsing peak is significantly reduced with the controlled switch system, because in most cases after registering a count the detectors remain off for much longer times than their individual deadtime.

Fig. 8 shows that the observed decrease in DTF at a fixed trigger count rate allows operation at higher registered count rates, while maintaining the same value of DTF. Indeed, we see that the registered count rate of the single detector with 10 μs deadtime is 4.2 kHz for a DTF of 0.1. A detector tree yields a 6.7 kHz count rate at this DTF. Finally, with the controlled switch configuration, the registered count rate can be increased to 9.9 kHz for the same DTF value

5. CONCLUSIONS

We have presented a review of our theoretical and experimental efforts in support of a proposed intelligent management scheme of multiplexed detectors. We expanded our theoretical treatment of detector arrangements to include nonzero switching and electronic trigger deadtimes as well as the usual detector deadtimes to properly account for physical properties of multiplexed detectors. We showed the superiority of the intelligent management 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 a number of detectors used. We reviewed our proof of principle experimental efforts that support the theoretical findings.

6. ACKNOWLEDGMENTS

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