Multiplexed Photon-Counting Detectors

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ABSTRACT

We discuss a scheme for a photon-counting detection system that overcomes the difficulties of photon-counting at extremely high rates. Our 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. Detector deadtime is significantly reduced by an active routing of single photons to the detector that has had the most time to recover from its last firing. In addition to deadtime reduction, our scheme reduces afterpulsing and background counts (such as dark counts). We present experimental results showing the advantageous performance of our system as compared to passive multi-detector detection systems. We conclude that intelligent active management of a group of N photon-counting detectors yields the highest photon counting rates, an important technological challenge for fast developing quantum metrology and quantum key distribution applications. Also, we report our experimental progress in developing an integrated device based on this scheme.

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

1. INTRODUCTION

Single-photon technology is an emerging field that is growing as interest in quantum communication and computation intensifies [1,2]. In particular, a major limiting factor in developing Quantum Key Distribution is efficient and error-free single-photon detection [3,4]. Because of growing demands for higher-rate secret key distribution, the single-photon detector (SPD) developer community is focused on improving relevant properties of detectors. Among these are the detection efficiency (DE) [2, 5, 6], the detector timing jitter [7], and the detector deadtime [8]. Deadtime is the major factor impeding higher photon-counting rates. However, because SPD properties are related to one another, one cannot focus on optimizing one property alone. For example, it is often the case that reducing deadtime increases afterpulsing (the subsequent retriggering of a detector caused by the nonideal nature of the detector rather than by a new input photon). Therefore, our goal is to present a detector arrangement that reduces deadtime while other important characteristics are kept constant (or improved). The detector arrangement presented here relies on an active multiplexing of many imperfect components into one detection system with better characteristics. While in this study we use several stand-alone SPDs, the method discussed here is increasing in feasiblity as progress to integrate detectors in microchip arrays continues [9-11].

Deadtime, defined as the time a photon-counting detector and any necessary electronics needs to recover after it registers a photon, is present in most SPDs but has different physical origins for different detectors. For instance, in photomultiplier tubes (PMTs) the deadtime due to the detector itself is associated with the speed of electrons and is almost negligible, so it is the pulse processing electronics that ultimately sets the deadtime. On the other hand in single-photon avalanche photodiodes (SPADs), which are our main focus here, the detector deadtime due to carrier trapping in the detection region is dominant. For SPADs every avalanche must be quenched to allow the complete release of trapped carriers from the detection zone before the detector is ready for another photon, resulting in a deadtime range of few tens of nanoseconds to tens of microseconds. Afterpulsing in SPADs is highly process-dependent, with the trap decay rate dependent on the concentration of defects and impurities in the semiconductor lattice. Operational parameters like the detector bias level during the dead time, also influence the afterpulse probability. In this paper we deal with this problem by using standard processing electronics and optoelectronics to reduce the effect of detector nonidealities. This should be

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a much easier route to faster counting than pushing for significant improvements in individual detectors, such as by reducing trap concentrations. In addition, it should be possible to build our multidetector system with the associated electronics integrated together on the same chip, which is important for integrating multiple detectors into a practical scalable system. We review here our proof-of-principle experiment and discuss issues of how to improve the related electronic processing.

2. THEORY OF OPERATION

The actively multiplexed detector arrangement is based on an array of N photon-counting detectors connected via a 1-by-N optical switch (Fig. 1). 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 detector has fired most recently, and then routes subsequent incoming pulses to another detector that is armed and ready to detect the subsequent photons during the deadtime of the former detector. 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 overall deadtime fraction. To understand the process, consider a time independent Poisson continuous-wave (cw) input photon source. At first, all detectors are ready to detect a photon. The optical switch is set to direct the first incoming optical 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 optical 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 armed detector that fired the longest time ago. At high count rates, many of the detectors may fire in a short period of time, 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 rather than a detector that fired more recently is that in a typical SPAD, the afterpulsing probability is inversely related to the time the detector was inactive: hence the firing order will have a reduced afterpulsing rate. Thus we have an arrangement that not only allows higher photon-counting rates, but reduces unwanted background counts, such as dark counts and afterpulsing. (This assumes detectors with equal characteristics. It may be that for unequal efficiencies, dark rates, etc., other arrangements might be employed to advantage.)

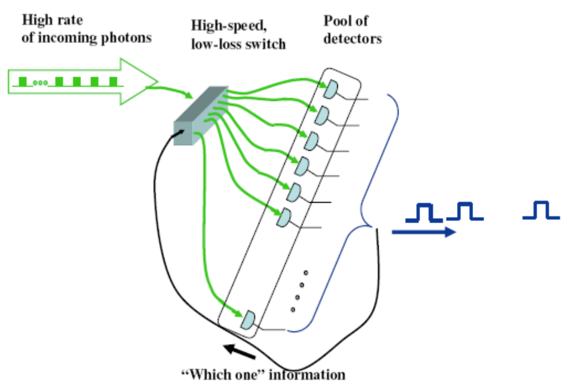

Fig. 1. Intelligent deadtime management scheme.

We test the performance of this arrangement by measuring it experimentally and comparing the results with two other arrangements: an 'improved detector' (hypothetical) that has a deadtime N times shorter than the SPADs in our system and a 'tree' of N detectors connected with a series of passive beam splitters. As stated before, deadtime improvement alone is often not sufficient, but has to be considered along with changes to other important characteristics such as afterpulsing probability and dark count rate.

To compare detector arrangements we introduce a device-independent quantity that is based on general properties of single-photon detection. We define deadtime fraction (DTF) as the ratio of missed detection events due to deadtime, to the total number of detection events that would occur with a detector of the same characteristics, but no deadtime. Alternately, in the case of a time-independent Poissonian (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. We can see that higher DTF increases the chance that an incoming photon will arrive during the deadtime, so the higher the DTF, the larger the nonlinearity of detection. While the acceptable DTF for a photon-counting system is application specific, for comparison purposes we chose a single DTF level for these different detector arrangements. For our analysis, we assume DTF = 10 % to be a reasonable limit for most detection applications. The DTF of a generic photon-counting detector can be written as:

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

where $\lambda_{\mathrm{registered}}$ is the count rate registered by the actual detector, λ is the count rate of a hypothetical detector with no deadtime (assuming Poissonian statistics), T_{d} is the deadtime of the detector. This definition can be generalized for 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 us to compare somewhat dissimilar device systems. Our analytical calculations have been previously presented, so here we only briefly describe key definitions and results [12, 13].

The theoretical treatment of the intelligent multiplexing arrangement is best understood when starting with the ideal case, when electronic switching delay is negligible as compared to the SPAD's deadtime. It can be shown, that in such an ideal case, the actively switched detector arrangement with only 3 detectors can match the performance of a hypothetical detector with 10 times shorter deadtime (at DTF = 10 %)! In practice however, this is not the case because switching time T_{s} can be a sizable fraction of deadtime (from a 1 % to 10 %). While this limits the performance improvement, the results seen for arrangements with a small number of detectors still offer a significant advantage over the passive arrangement. Importantly, switching time can be significantly improved by integrating switching electronics. We discuss our efforts in decreasing switching time by optimizing the switching electronics below.

Some SPADs require gated operation, especially those that operate at telecom wavelengths with their high dark count rates. They become active for a pre-set period of time only when triggered. Such detectors (with their associated electronics), after accepting one trigger pulse, cannot accept a subsequent trigger pulse for a period of time T_{t}. We call T_{t} the 'trigger system deadtime.' Indeed, because usually one triggers detectors only when a photon is expected at the input, this inability to accept a trigger is operationally similar to the usual 'dead' state of the detector. Further, even though trigger system deadtime is small compared to T_{d}, this trigger deadtime is not negligible, as there are usually many more trigger pulses than there are photon detections. This effect is more pronounced if the probability to detect a photon per trigger pulse, μ, is low. We model the effect of a nonzero trigger system deadtime for arrangements with one or two detectors and for the parameters close to our experiment. Namely, $T_{\mathrm{d}}=10\mu s$, $T_{\mathrm{t}}=0.02\,T_{\mathrm{d}}$, $T_{\mathrm{s}}=0.01\,T_{\mathrm{d}}$ and $\mu=2$ %. Fig. 2 shows that the incident photon rate for DTF= 10 % suffers significantly for all arrangements when $T_{\mathrm{t}}\neq 0$. Based on this result, it is best to minimize trigger system deadtime. It is evident from Fig. 2 that regardless of the presence of the trigger system deadtime, the actively multiplexed arrangement remains the preferred architecture.

Let us consider other important features of detector arrangements: dark counts and afterpulsing probability. For the purpose of quantitative analysis we will assume that all the SPADs have the same dark count rate, and we scale this count rate to a unitary value. Also, we assume that all detectors have the same relation between the afterpulsing probability and the deadtime. In reality, these values may vary significantly from detector to detector, and this can ultimately affect the design of multidetector arrangements, but here we ignore this for simplicity. More complex models may be considered in future work if required by particular implementations.

First, we consider dark counts. Because of the assumptions made, the scaling of dark count rates is simply proportional to the number of detectors, Fig. 3. It is clear that an active switching arrangement with its constant dark count rate, is superior to a tree configuration with its linearly growing dark count rate for every number of detectors *N*.

To estimate the afterpulsing probability, we use the fact that the afterpulsing probability in SPADs is related to the probability of trapping charge carriers in the active detection zone. If such a carrier 'survives' until the avalanche bias is activated again, it will start another avalanche and produce an afterpulse. It well known that the afterpulsing probability decreases exponentially with SPAD hold-off time as the trap sites have more time to depopulate. Thus, the afterpulse probability of the multidetector scheme will be reduced because each detector will have a longer rest time before it is reactivated. In 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 one live detector situation to happen assuming Poisson incoming photon statistics. For the specific case of a two-detector arrangement, the probability to receive one (or more) detectable photons during a deadtime of a single detector T_{d} is $P(n \geq 1) = 1 - \exp(-\lambda T_{\mathrm{d}})$. At this stage, the assembly will switch to the first detector immediately after its deadtime is over, thus it will produce an afterpulse with its unreduced (single detector system) probability. For more than two detectors, one writes: $P(n \geq N-1) = 1 - \exp(-\lambda T_{\mathrm{d}}) \sum_{i=0}^{N-2} (\lambda T)^i / i!$. 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. 4.

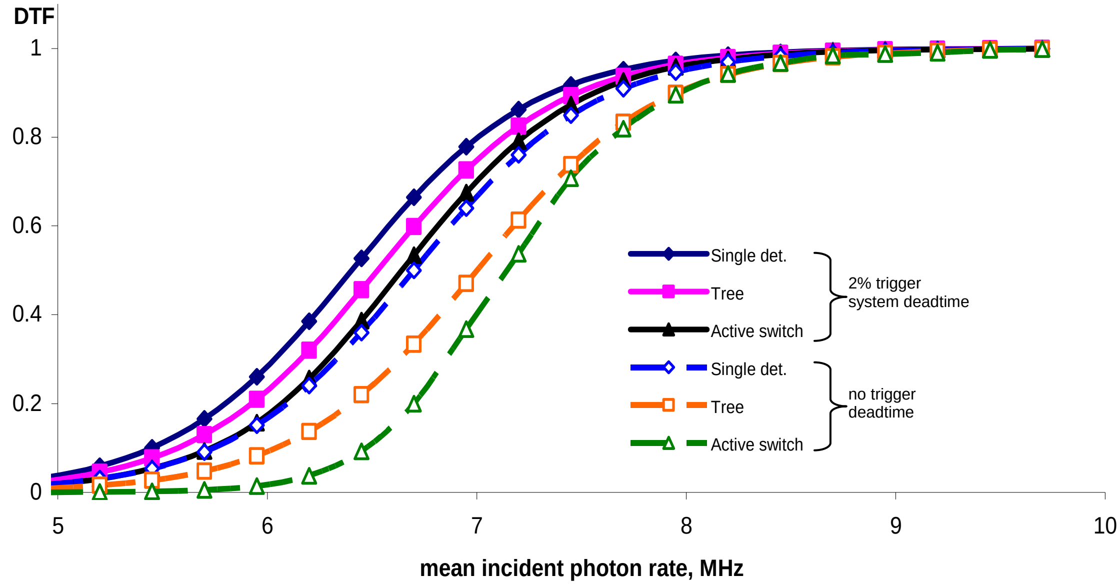

Fig. 2. Effect of nonzero trigger system deadtime on DTF for various detector arrangements of 1 and 2 detectors. Diamonds: single detector; squares: tree arrangement; triangles: actively switched arrangement; open markers: no trigger system deadtime; filled markers: trigger system deadtime $T_{\mathrm{t}} = 0.02\, T_{\mathrm{d}}$.

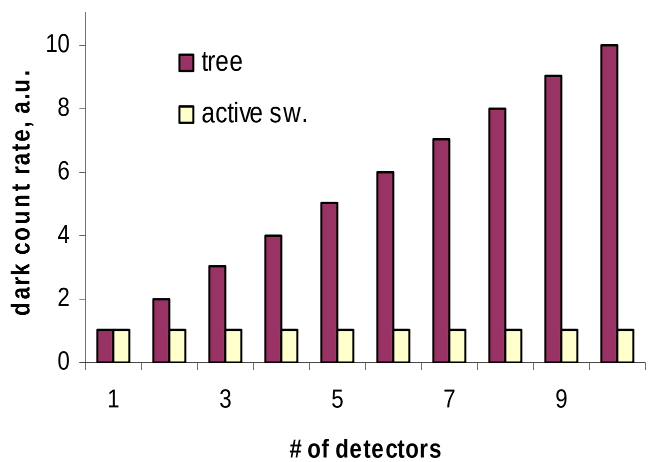

Fig. 3. Dark count rates for *N* detector arrangements in units of a single conventional detector.

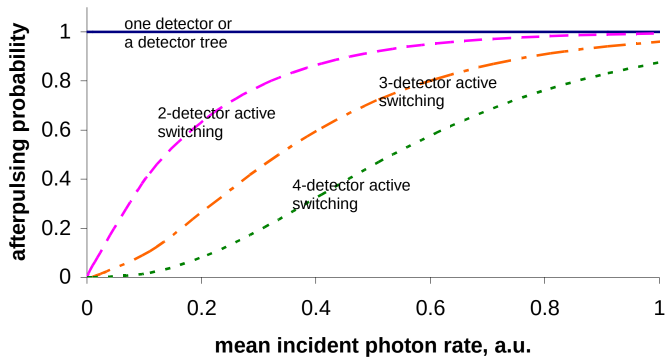

Fig. 4. Afterpulsing probability rate for an active switching multidetector arrangement with two (dashed line), three (dotted-dashed) and four detectors (dotted) and for a single detector or a tree arrangement (solid).

To summarize, the theoretical study shows that the active multiplexing arrangements scheme is superior to other, passive detector arrangements aimed at improving deadtimes. In particular, the direct comparison of detection rates seen with different arrangements at the same level of DTF, shows that the multiplexing arrangement compares favorably to a passive "detector tree," as well as to a (hypothetical) single detector with reduced deadtime. We show 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.

3. PROOF-OF-PRINCIPLE EXPERIMENT

The first proof-of-principle experiment is designed to evaluate the theoretical predictions described above. We are interested in showing experimentally that the active switching arrangement provides better (or at least equal) deadtime fractions, afterpulsing probabilities, and dark count rates at a given count rate. To compare deadtime effects, the most relevant test is a measurement of DTF as a function of a trigger detector rate for the various arrangements. To compare dark count rates in these systems, we estimate the signal-to-background ratio. Finally, to compare probabilities of afterpulsing, one directly compares the measured afterpulsing rates of the different arrangements. The experimental setup, presented in Fig. 5a, is based on 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 deadtime of 50 ns, that is negligible compared to the deadtime of the 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. We compared several detector configurations: (i) a single detector with improved deadtime, (ii) a detector tree, and (iii) two actively switched arrangements with different levels of optical loss (Fig. 5b). The switched arrangement 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 optical input to the detector that has had the longest recovery time. Two levels of optical loss were implemented to demonstrate that even with significant optical switch loss, the active switch scheme still has advantages for single photon detection over the nonswitched arrangements. To simulate a high loss optical switch and to match the optical losses of all the nonswitched arrangements, we simply inserted a 50-50 beam splitter in the optical path, effectively adding 3 dB loss. The logical circuit, presented in Fig. 5c, is implemented on a Field Programmable Gate Array (FPGA).

Fig. 6 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 a 10 µs deadtime is 4.2 kHz for a DTF of 0.1. A detector tree with two detectors yields a 6.7 kHz count rate at this DTF. Finally, with the controlled switch configuration the registered count rate increased to 9.9 kHz for the same DTF value. We measured the signal to background improvement relative to the detector tree for the cases of high- and low-loss active switching. The high-loss improvement was 1.83±0.05, while the low-loss active switching arrangement improvement was 2.0±0.1. We also gauged the improvement of our switching schemes relative to a single detector with its 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 afterpulsing is significantly reduced with the controlled switch system, because in most cases after registering a count, the detectors remain off for much longer than their individual deadtime. (We note that the high-loss switched result can not be compared directly to any other results shown in Fig. 6, because its DE is different from all the other InGaAs arrangements.)

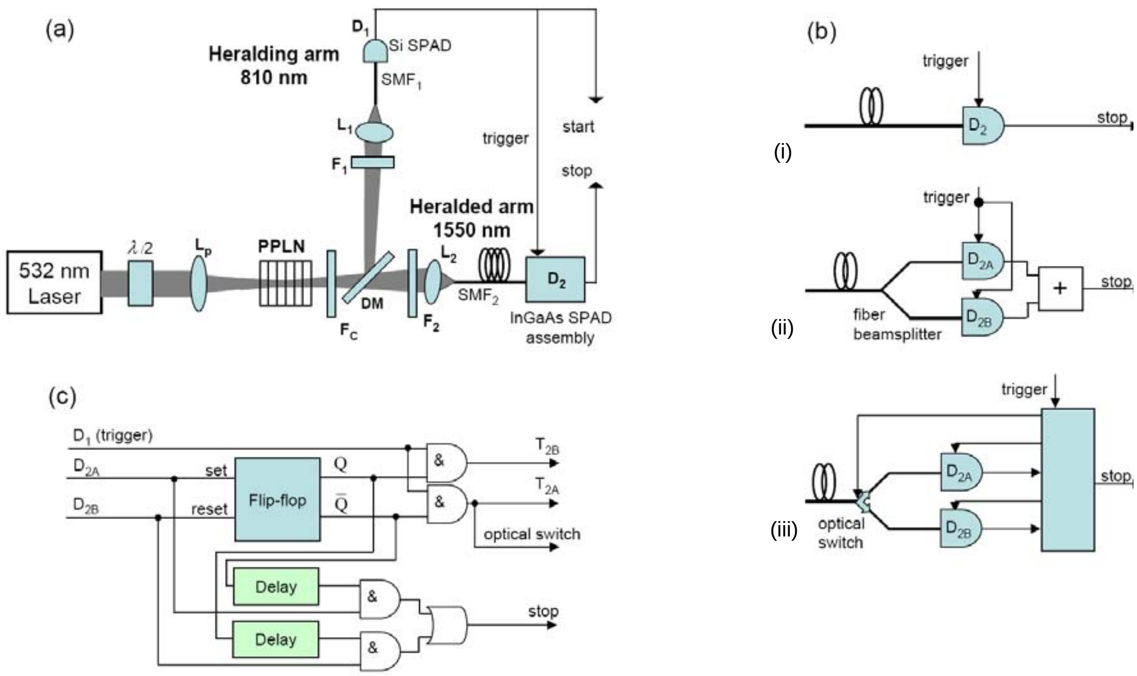

Fig. 5. Experimental setup and detector arrangements.

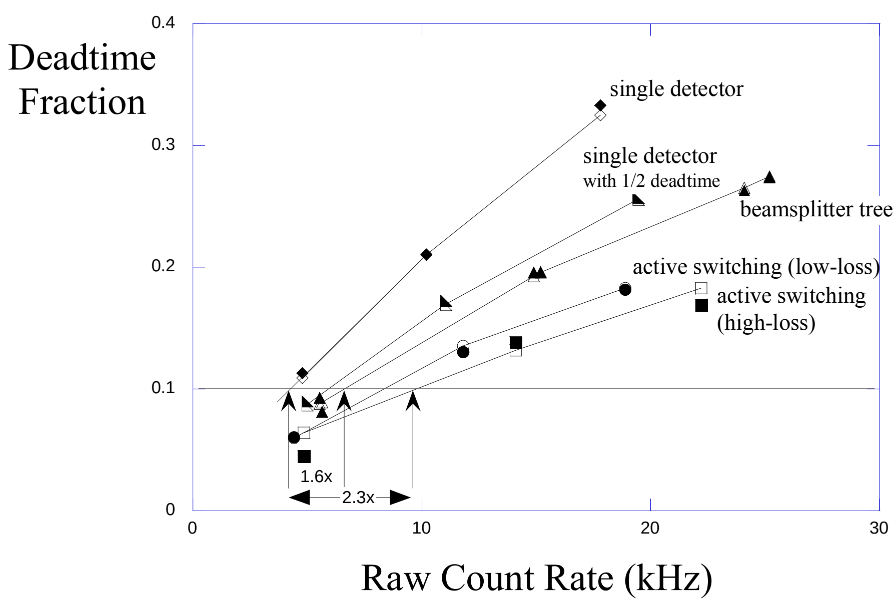

Fig. 6. Measured (solid points) and calculated (open points connected by lines to guide the eye) DTF versus the overall count rate on InGaAs for different detection arrangements.

Finally, to demonstrate the advantage and the feasibility of active routing of photons, we made a series of 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 modest DE increase is due to the relatively high insertion loss of our switch (2 dB) rather than any other switch or control circuit nonidealities.

4. OPTIMIZATION OF SWITCHING TIME

For the purposes of a proof of principle experiment, we used commercial equipment to build our optical switch control circuit. We observed switching times of ≈ 75 ns, which is sufficiently fast, given the deadtime of detectors under test. However, as discussed above, the multiplexed detector system's performance would benefit from shorter switching times. In particular, it is also beneficial for the switch time to be shorter than the heralding detector deadtime and associated processing time, which for our experimental setup (Fig. 5a) is 50 ns. Lower switching times allow for higher count rates at the same DTF level. To deal with this situation where the switching time exceeds the herald deadtime, all the delays in electronic processing were matched by extra fiber length in the heralded arm (i.e. before an optical switch). Ultimately, by reducing electronic processing times one could use shorter optical fiber delay lines, and thus increase the overall detection efficiency.

The analysis of our setup shows that the longest delay (50 ns) is due to a commercial triggered pulse generator that operates the switch. To address this delay, we implemented a fast switch driver capable of producing variable pulse heights. The simplified schematic of the circuit is shown in Fig. 7a. This driver used 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 low to 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 [15, 16[2]]. In a first prototype (Fig. 7b) the amplitude of the output voltage can be adjusted from 4 V up to 6 V with a total propagation delay (including rise-time and settling), of ≈15 ns. This circuit therefore allows for testing in the regime when all trigger pulses can be processed.

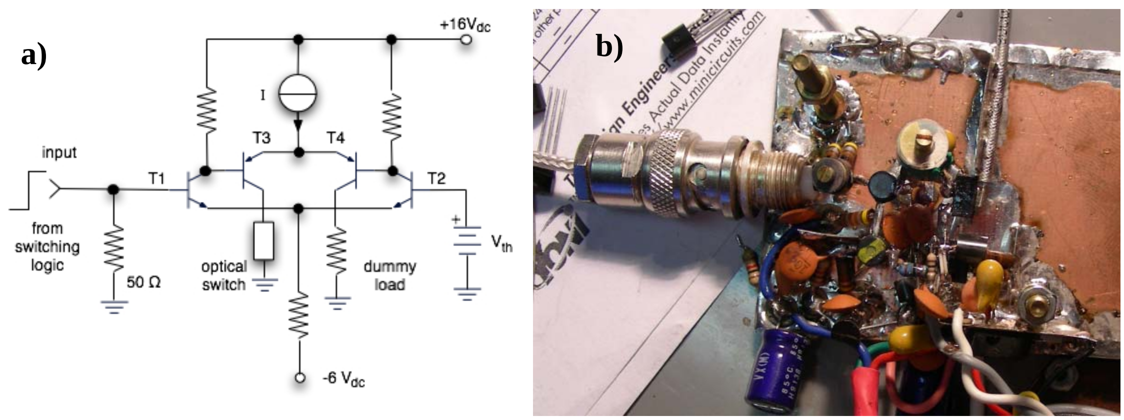

Fig. 7. Optical switch electrical driver a) schematic and b) prototype.

To further improve the performance of the control electronics we plan to integrate a FPGA and a driver on a single board. Having the board integrated 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 TTL signal, optimizing the rise-time of the driver. The development of this integrated board is underway.

5. CONCLUSIONS

We have presented a review of our theoretical and experimental efforts to support an actively switched arrangement of multiplexed detectors. We confirmed, both theoretically and experimentally, the superiority of the scheme not only in

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[2] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or by the Istituto Nazionale di Ricerca Metrologica, nor does it imply that the products are necessarily the best available for the purpose.

reducing the DTF which is the main goal of this study, but also in reducing afterpulse rates and keeping dark count rates independent of the number of detectors used. We reviewed our current efforts in optimizing control electronics, switching time, and developing an integrated optical switch driver.

6. ACKNOWLEDGMENTS

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