Modified single photon counting modules for optimal timing performance

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A modification of a standard Perkin Elmer SPCM-AQR photon detector module that remarkably improves the photon timing performance is presented here. The modification consists of an additional timing circuit board, which is inserted in the module without modifying the original circuit board. The essential feature is a pulse pickup linear network, connected to the high-voltage terminal of the photodetector, which extracts a short pulse signal with fast rise, coincident with the rise of the avalanche current. The information about the photon arrival time is obtained by sensing the onset of the rise. At low counting rates ($<10^5$ counts/s) time-correlated photon counting tests show that the instrumental resolution function (IRF) thus obtained has full width at half maximum (FWHM) narrower by about 40% with respect to the original module. At higher counting rate, up to few Mcounts/s, the advantage is even more remarkable: The timing circuit practically eliminates the drawbacks that plague the original module, namely, a progressive increase of the FWHM and a progressive shift of the peak position of the IRF with increasing counting rate. The modified SPCM-AQR module is therefore suitable also for applications requiring subnanosecond time resolution at high and/or variable counting rate, such as fluorescent decay measurements, fluorescent lifetime imaging, single molecule detection and spectroscopy, and optical radar techniques. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2183299]

I. INTRODUCTION

The time-correlated single photon counting (TCSPC) technique[1] is nowadays widely employed for time-resolved measurement of fast and/or weak fluorescent emission in a wide range of scientific applications in chemistry, biology, medicine, and material science. Typical examples are single molecule detection and spectroscopy,[2-4] DNA sequencing,[5-7] and fluorescent lifetime imaging.[8] Similar techniques based on the precision detection of time of arrival of photons are employed in other fields, such as fiber optic characterization with optical time domain reflectometry,[9-11] profiling of remote objects with optical radar techniques,[12,13] quantum cryptography,[14,15] and picosecond imaging circuit analysis.[16,17]

The time resolution obtained with the said techniques is characterized by the instrumental response function (IRF) of the TCSPC setup, which is determined by the precision with which the arrival instant of the incident photon on the photodetector is identified. The figure of merit usually quoted is the IRF full width at half maximum (FWHM). In the last four decades, photon timing systems have been developed relying on photomultiplier tubes (PMTs), that is, vacuum tube devices. Available PMT models can attain better than 100 ps FWHM, but because of the intrinsic limits of the photocathodes they have moderate or low photon detection efficiency, particularly in the red and near-infrared spectral range. In recent years, a solid state alternative to PMTs has been provided by the development of special avalanche photodiodes. These devices work in Geiger mode at voltage higher than the breakdown level and have the capability of detecting single optical photons. They are therefore called[18] single photon avalanche diodes (SPADs). Besides the well known advantages of solid state versus vacuum tube devices (small size, ruggedness, low power dissipation, low supply voltage, high reliability, etc.), they provide higher quantum efficiency, particularly in the red and near-infrared spectral regions.

Perkin Elmer Optoelectronics (formerly EG&G Optoelectronics) manufactures a popular single photon counting module (SPCM-AQR) based on a proprietary silicon avalanche photodiode called Slik™.[19,20] These modules have very good photon detection efficiency and low noise, but the time resolution is not equally satisfactory. FWHM values of less than 200 ps have been obtained with Slik™ detectors operating with dedicated circuits, specifically devised for timing,[2,21,22] but remarkably higher FWHM values have been reported from tests on SPCM-AQR modules.[23] In fact, the SPCM-AQR data sheet[20] quoted a typical time resolution of 350 ps FWHM and fairly wider FWHM is often measured for the SPCM-AQR samples. It can be concluded that the SPCM-AQR circuitry does not fully exploit the intrinsic time resolution of the Slik™ detectors. Furthermore, as the counting rate is increased, the FWHM increases and the peak position of the IRF shifts with increasingly steeper slope, causing a substantial progressive degradation of the SPCM timing performance at counting rates above 100 kcounts/s.[23] This represents a serious drawback for applications requiring subnanosecond time resolution along with capability of operating at high and/or varying counting rate.

In this article we present a technique for improving the photon timing performance of a standard Perkin Elmer SPCM-AQR photon detector module. To this purpose an additional timing board is inserted in the module without bringing any modification to the original circuit board, which still provides to quench the avalanche and to supply an output pulse suitable for pulse counting. The essential feature of this timing board is a patented pulse pickup linear network[24] connected to the SPAD terminal biased at high voltage (about 400 V). This network is specially designed for extracting a short pulse signal with fast rise, coincident with the rise of the avalanche current. A fast discriminator with very low sensing threshold is then employed for sensing the onset of this pulse. We demonstrate that by using the output of the additional board for timing tests, (i) the FWHM value at low counting rate ($<10^5$ counts/s) is reduced by more than 40% with respect to the performance of the original SPCM module and (ii) the dependence of the FWHM value and of the peak position on the counting rate is almost eliminated. The intrinsic time resolution of the Slik™ detector can thus be well exploited up to high counting rates of a few Mcounts/s. Section II gives a brief review of the main physical limits of the time resolution of SPAD devices having thick depletion layer ($>10\ \mu$m), as it is the case for the Slik™ detectors employed in the SPCM modules. The timing circuit board is described in Sec. III. The results of the experimental tests are reported and discussed in Sec. IV.

II. LIMITATIONS TO THE TIME RESOLUTION OF SPAD DEVICES WITH THICK DEPLETION LAYER

SPCM modules are based on the Slik™ devices, which are silicon avalanche diodes with fairly thick depletion layer ($\sim 20\ \mu$m). They were originally devised as analog amplifying avalanche photodiode with minimal multiplication noise. In fact, the field profile in the p-n junction was designed for minimizing the value of the effective k ratio (a weighted ratio of the ionization coefficients of holes to that of electrons) for a given thickness of the active volume of the device. The design approach adopted, however, also led to improve the operation in the Geiger mode employed for photon counting, making the Slik™ a high performance SPAD.[19]

It has been highlighted that in SPADs having a thick depletion layer the secondary photons emitted from the relaxation of hot carriers play a dominant role in the mechanism of avalanche spreading over all the active area.[25,26] In these devices, the avalanche current starts building up in a filament at the point where the photon is absorbed. Secondary photons emitted in the avalanching zone can be absorbed elsewhere in the active volume, where the impact ionization had not yet been triggered. Therefore, this mechanism randomly seeds the avalanche all over the active area. Since the current flowing through the device is proportional to the activated area, the statistical fluctuations in the number of emitted and reabsorbed photons cause a statistical fluctuation in the avalanche current leading edge. The threshold crossing time thus suffers a jitter, which adversely affects the detector timing performance. The time resolution can be substantially improved by focusing the incident light in the center of the active area.[2,23,27] This occurs because the secondary photons emitted in the center of the device have the maximum probability of being reabsorbed within the active volume, thus speeding up the rise and reducing the statistical fluctuations.

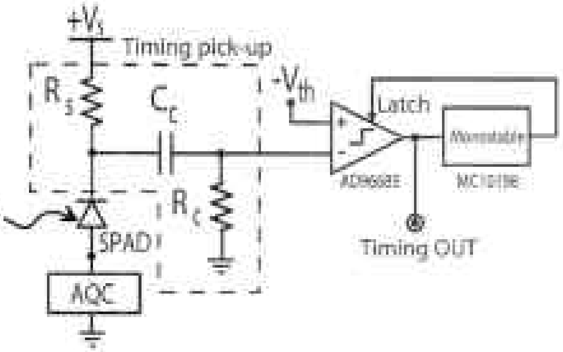

FIG. 1. Schematic diagram of the timing circuit board.

It has been suggested by Spinelli and Lacaita[26] that a further improvement in the timing performance may be achieved by sensing the avalanche current as soon as the first filament is generated and before the emission of the first secondary photon. Since the avalanche leading edge is usually sensed by using a fast discriminator, the above requirement can be fulfilled by bringing the sensing threshold down to sufficiently low level (typically a hundred microampere level), where the multiplication process is still confined within a small area around the point where the photon was absorbed. The time information thus obtained is not affected by the statistical fluctuations associated to the propagation of the current over the full area of the detector.

III. TIMING BOARD

In order to improve the photon timing performance, we devised and patented[22,24] a new technique for extracting the avalanche pulse produced by a SPAD device. The basic idea is to implement a suitable pickup of the fast avalanche current signal from the SPAD terminal biased at high voltage, leaving the SPAD terminal biased at ground potential connected to the active quenching circuit (AQC). As outlined in Fig. 1, the solution is a simple alternating current coupling (AC) network, consisting of a signal resistor R_s, a coupling capacitor C_c, and a coupling resistor R_c. The linear network makes it possible to extract the avalanche current from the detector without affecting the initial rise of the signal. This is mandatory for allowing a true low-level sensing of the avalanche current. The latter can be considered a square pulse, which is started by the incident photon and terminated by the active quenching circuit. The network exerts a differentiating action on this pulse; the usual art in ac coupling in amplifiers and other circuits employs a RC time constant much longer than the pulse, in order to transmit it faithfully. However, this inherently generates after the transmitted pulse a long tail with opposite polarity, equal area, and small amplitude that exponentially decays with the differentiating time constant. The random superposition of such tails due to the succession of pulses causes a shift of the base line affected by random fluctuations. This in turn causes a random walk of the point at which a pulse crosses the threshold of the fast comparator that senses its arrival, hence it produces a jitter in the crossing time. Therefore, in contrast with the usual art in ac cou-

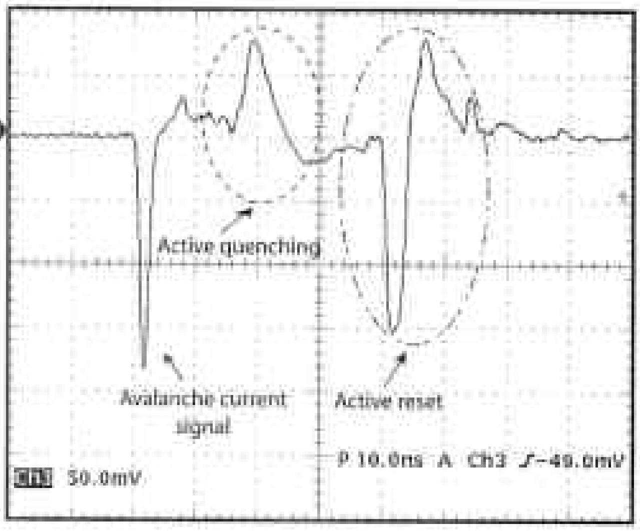

FIG. 2. (Color online) Voltage signal waveform at the input of the timing discriminator.

pling, an essential distinctive feature of the proposed technique is a short differentiating time constant. The time-walk effect described above is effectively avoided by employing a differentiation time constant much shorter than the average interval between pulses (i.e., than the reciprocal of the repetition rate) but keeping it anyway longer than the rise-time of the avalanche pulse. Details about the design of the timing pickup can be found in Ref. 24.

The voltage signal developed on R_t is fed to the inverting input of a fast comparator (Analog Devices, AD 96685) which senses the arrival of the pulse. Figure 2 shows the typical voltage wave form at the comparator input. The second negative pulse occurring about 40 ns after the avalanche current pulse is due to the fast reset transition of the SPAD voltage forced by the active quenching circuit. During the reset phase, the voltage at the SPAD anode is brought back to the ground level in less than 10 ns; due to the coupling through the photodiode capacitance, a spurious pulse is generated at the output of the coupling network. This pulse is potentially dangerous, since it may retrigger the comparator and result in a self-sustaining oscillation of the circuit. In order to avoid this drawback, the monostable MS (Motorola MC10198) is employed for generating a latch pulse, which disables the comparator during the reset phase.

It is worth noting that the coupling of the active quenching and active reset transitions inherently generates tails with opposite polarity (see Fig. 2). This reinforces the requirement of a short differentiating time constant for avoiding base line shifts.

Particular care has been devoted to the layout of the pulse pickup network for reducing the disturbances at the comparator input. Reliable operation free from false triggering of the comparator was thus achieved with a minimum threshold voltage of 8 mV. It is worth stressing that the timing board developed can be added to any of the quenching circuit configurations so far described in the technical and scientific literature. The only requirement is that the high-voltage terminal of the SPAD device be accessible for establishing the connection.

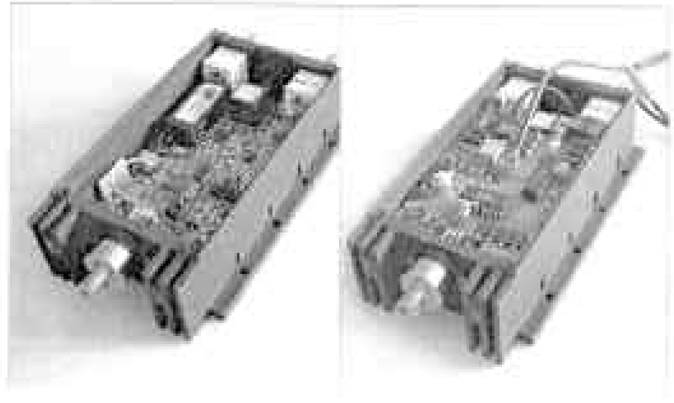

FIG. 3. (Color online) SPCM module with the top cover removed (left). The timing board was design to fill the empty room available in the package (right).

IV. EXPERIMENTAL RESULTS

The timing board described in Sec. III was inserted in a standard Perkin Elmer SPCM-AQR photon detector module. To this purpose the connection to the high-voltage terminal of the SPAD was cut and a series resistor R_s was inserted. The pickup network parameters are R_s=470 Ω, R_t=100 Ω, and C_c=4.7 pF. As shown in Fig. 3, the whole timing board is easily accommodated in the free space available in the SPCM package above the original circuit board. Note that the modification brought to the SPCM module is reversible: The original configuration can be very simply restored, just by removing the additional board.

Time resolution measurements were performed in a standard TCSPC setup,[1] by using an ultrafast laser diode (Antel MPL-820 laser module) that emitted optical pulses at 820 nm wavelength with about 10 ps FWHM duration at 10 kHz repetition rate. The optical pulses were suitably attenuated, in order to limit to less than 1% the probability of detecting a photon in correspondence to a laser pulse.

The time resolution was first tested at low counting rate (1 kcounts/s). Figure 4 shows the IRF measured with broad illumination over all the active area in the two cases, namely, by employing either the original output pulse of the SPCM module or the pulse from the new timing circuit.

The original module has a FWHM time resolution of

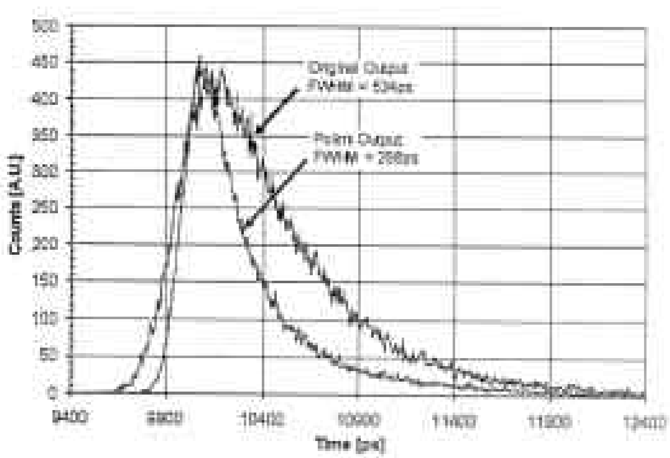

FIG. 4. Instrumental response function of a standard and modified SPCM at low counting rate (<1 kcount/s).

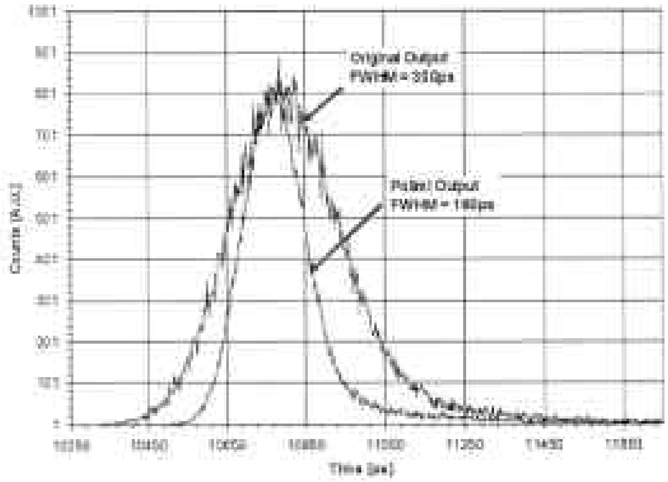

FIG. 5. Instrumental response function of a standard and modified SPCM at low counting rate (<1 kcount/s) measured by focusing the laser beam onto a 30 μm spot at the center of the active area.

$\sim$520 ps; a FWHM of $\sim$300 ps is obtained with the modification, that is, an IRF narrower by about 40%. As already pointed out in Sec. II and highlighted in Refs. 2, 23, and 27 by focusing the light at the center of the active area of the SPAD a remarkably better timing performance is obtained. Figure 5 shows the IRF of both the standard and the modified SPCMs measured with laser beam focused onto a 30 μm spot at the center of the active area. The FWHM is reduced from 300 to 180 ps in the modified module, i.e., the IRF is narrower again by about 40%.

Tests carried out on about 20 samples of SPCM-AQR modules showed a remarkable dispersion of the FWHM measured with the original pulse output, with values ranging from about 300 to more than 650 ps. Significant variations from sample to sample were also observed for other features of the devices, such as the breakdown voltage. The tests carried out on the same modules modified with the additional timing card confirmed that the intrinsic timing resolution of the detector device has significant variations from sample to sample. The FWHM of each module was improved by about 40% (even better in some cases) and the measured values ranged from less than 200 to more than 400 ps.

Tests were then carried out also at high counting rate, that is, above 0.5 Mcounts/s. By letting stray light fall on the detector with progressively increasing intensity, the total counting rate due to dark counts plus stray light plus laser pulses was increased up to more than 2 Mcounts/s. For obtaining correct timing information also at such high repetition rates, a fast and accurate recovery to quiescent conditions in the pulse-processing circuit after each triggering is necessary. In particular, it is essential to have a quick and accurate recovery to the quiescent level of the pulse base line and of the threshold level in the stage where the pulse is sensed by means of the threshold triggering. Small deviations with long recovery may be caused by ac coupling with long time constants (see Sec. III) and by disturbances and imperfect reset in trigger circuits. Because of the superposition of small deviations generated by previous pulses, a pulse may be superimposed on a perturbed base line, shifted from its regular value, and/or meet a perturbed triggering threshold level. Due to the finite rise time of the pulse, this is translated in a shift of the actual triggering level on the pulse leading edge and in a corresponding shift of the triggering time. Since the previous pulses are randomly distributed in time, the shift of the triggering level will have both random fluctuations and a systematic mean value. The corresponding effects on the distribution of measured photon arrival time are a further contribution to the FWHM value and a systematic shift of the peak (and of the centroid) of the distribution, both of them increasing with the counting rate. Figures 6 and 7 illustrate that these effects are indeed remarkably intense in the original SPCM-AQR circuit and are strongly reduced by the modification. For the SPCM-AQR sample considered, at an incident count rate of 2 Mcounts/s the modified module gives FWHM $\sim$200 ps, to be compared with FWHM $\sim$430 ps of the original module at the same counting rate. At 3 Mcounts/s, the shift of the peak for the modified module is less than 40 ps, to be compared with a shift of more than 700 ps observed for the original module.

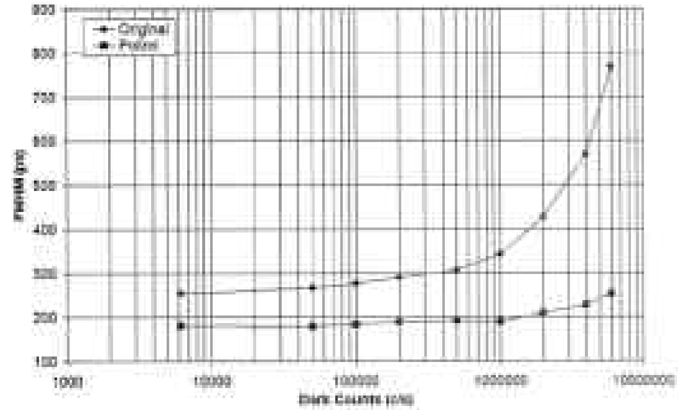

FIG. 6. FWHM of the IRF measured for the standard SPCM-AQR tested and for the same module with the additional timing circuit.

In conclusion, we have demonstrated that a fairly simple and economic timing board can be added to the Perkin Elmer SPCM-AQR modules for improving the photon timing performance both at low and at high counting rates. The timing board is inserted within the module without bringing modifications to the original circuit board and it is fully enclosed in the SPCM-AQR box. The modification is reversible; the

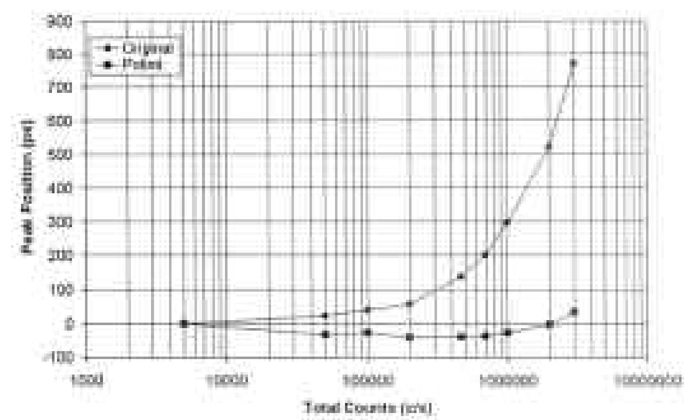

FIG. 7. Shift of the peak position of the IRF for the standard SPCM-AQR tested and for the same module with the additional timing circuit.

original configuration can be restored just by removing the additional board. Though the timing performance of the original SPCM-AQR modules has wide dispersion from sample to sample, due to the intrinsic dispersion of the Slik™ device features, a remarkable improvement of the IRF is obtained in all cases, with a reduction of the FWHM value by 40% or better and an almost complete suppression of the degradation of the FWHM and of the peak shift at high counting rate.

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