Review of Photon Counting Modules

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***Abstract*—Growing interest in the field of physics to obtain photon counts for various experiments in a faster way have led to the development of different photon counting modules. This paper gives a brief survey of various Time to Amplitude converters and Time to Digital converters. The Converters are compared based on time resolution, differential non-linearity, high counting rate, power dissipation and crosstalk.**

Keywords — Photon counts, Time to amplitude converters, Time to digital converters

I. INTRODUCTION

A number of branches in science require the detection of single photons and the determination of the statistics of their arrival times. These have applications in many fields, ranging from quantum communication and cryptography to photo-dynamics in biology. Photon counting is used to detect very low level light obtained from Raman spectroscopy, fluorescence analysis and chemical or biological analysis. There are several measurements that are required to be performed using single photons. The most common is Coincidence detection and Delayed Coincidence. Coincidence detection refers to the simultaneous detection of photons at two or more different detectors. Delayed coincidence refers to the occurrence of a count in one detector at a short but measurable time later than a count in another detector.

Photon counting is usually done using low power light. There are different methods of signal processing in photon counting like Gated photon counting; Multi channel Scalars and Time Correlated Single Photon Counting methods.

Gated photon counting uses a fast gate in front of a counter. The gate is used to count the photons only within short time intervals. Gating in conjunction with pulsed light sources can be used to reduce the count rate or to distinguish between different signal components.

Multichannel scalars are the photon counting equivalent of a digital oscilloscope. They record the input pulses directly into a large number of consecutive channels of fast memory. In this device they switch through subsequent memory locations of a high speed memory and drop the detected photons into a current memory location.

Time correlated single photon counting(TCSPC) method are used along with Time to Amplitude Converters(TAC) or Time to Digital Converters(TDC) currently as it has high levels of accuracy. In the previous methods of signal processing the time resolution was limited either due to gate width or by speed of memory. In TCSPC, the arrival times of photons are measured and histogram is constructed.

II. TIME TO DIGITAL CONVERTERS

Time to digital converters provide a digital output signal which is proportional to the measured time. These converters provide better power dissipation and dead time intervals compared to their TAC counterparts, but fail in the time resolution property. Below we discuss some recent papers on Time to Digital Converters:

The need of various research groups for different number of inputs to the existing TCSPC instrument led Michael Wahl and his colleagues [1] to design a multichannel time correlated single photon counting module. This module was used for fluorescence measurements to study single molecule emissions. The module consisted of multiple TDC based inputs which were scalable. These modules consist of 64 channels as inputs. Depending on the number of inputs required it could be scaled down to two or five as per necessity. Here the TDC had a resolution of 1 ps. Clocks were used to ensure that the timing units worked with a common time base. FIFO buffers were used for recording the events occurred but then they posed problems in time tagging of events. To overcome this sorters were used which helped in proper streaming of data to the outputs. There were three different data acquisition schemes used for this module namely Histogramming mode, T2 mode & T3 mode. In the Histogramming mode the histograms are plotted on the onboard memory and are not time critical. T2 and T3 modes were time tagged data acquisition systems. The difference between these two modes depends on the use of sync events. In T2 mode, sync event module is bypassed and it consists of 32 bits carrying channel number and a time tag. In T3 mode, the sync channel is not bypassed & it consists of 32 bits carrying channel number, start stop time & sync count.

Although the timing resolution was fixed to 1 ps by the TDC design (using HydraHarp 400 PicoQuant), there were always chances of a timing uncertainty due to jitter. From the experimental results it was seen that there was a timing jitter of 10 ps added to the time resolution. In the case of differential non-linearity as well as integral non-linearity it was seen that there were small errors. As the time span was increased, chances of error also increased.

To overcome the use of large electronic blocks, FPGA's came into picture. JianSong, Qi An and Shubin Liu in their paper [2] used general purpose FPGAs from Altera and Xilinx which had dedicated carry lines for the purpose of designing TDC's. These carry lines were used to form carry chains to implement arithmetic function like adders, counters & comparators. Using these modules a high resolution two channel TDC was built in the FPGA. Here the fine time was measured using a multibit adder. For this measurement input A had got all ones & the other input B had all ones with LSB set to zero. The LSB of B is a hit signal. This signal was responsible for the change in outputs. When there was a hit signal, the sum would change to zero step by step. This change is the fine time measurement. A synchronous counter is used to realize a coarser time measurement. Two gray counters are used to avoid ambiguous states when one counter is in phase & other is out of phase. Depending on the phase of the clock, at arrival of hit signal, one of the counters output is selected to be the coarse time. Hence the total time measured was the sum of coarse and fine time. The TDC developed was tested on 2 FPGA's. The delay of each carry line in the FPGA's are different. Hence when implemented on Altera FPGA[3] the resolution was 100ps and on Xilinx[4] it was 65ps which after calibration resulted in 65ps for the former and 46.2ps for the latter.

By using the TDC module[2] of 100ps (Altera board before calibration), Quirong Yan and his colleagues [5] devised an FPGA module for measuring the arrival times of photons emitted from an x-ray source. Along with this TDC a preamplifier, CFD, a quartz crystal oscillator and Random Access Memory (RAMs) were used, which was built on an FPGA [6, 7]. Additionally to the circuit included x-ray tube, a Ti target, HV power supplier, choppers, attenuators and single photon detector based on micro channel plate. An oven controlled crystal oscillator was also used (instead of atomic clock to save cost) to give precise clock timing to FPGA. There was a start measuring signal given by a manual trigger circuit given to the FPGA to help in easy computation of photon time. The arrival time of x-ray photon sequence was recorded with a time resolution of 500 ps and the profile of x-ray pulse was constructed. The average count rates were 12.511counts/s. The data obtained was also used for determining time interval between two photon executions, fluorescence correlation spectroscopy, Light Detection and Ranging measurements & fast particle detection.

III. TIME TO AMPLITUDE CONVERTER

Time to Amplitude Converters are devices that outputs a signal having amplitudes generated proportional to the time interval between receipt of "start" and "stop" pulses. When a circuit is activated by the start pulse the capacitor is charged by a constant current source and continues to do so until the stop pulse arrives. Here, the constant current generates a linearly increasing voltage in the capacitor.

In [8], a four channel fully integrated TAC was designed and made on 0.35µm Si-Ge technology. The four channels were used to minimize crosstalk between adjacent channels. Here time was measured using time correlated single photon method in which the difference between the photon emitted from the sample and the reference pulse given by the laser is taken for computation of detection of several photons. The TAC consists of an input stage, conversion stage, output stage and control logic. There is a start signal given which charges the capacitor based on the conversion current to give an output voltage. When there is a stop signal given, the capacitor is discharged. In the output stage the single ended voltage generated by the conversion stage is converted to differential voltage for better resolution and to minimize crosstalk. Here the TAC is built using basic electronic components such as op-amps, resistors, capacitors, flip-flops and transistors which is then embedded onto a chip. The resolution on this chip was 40ps and the dissipated power was 50mw. The differential non-linearity is less than 0.02 LSB peak-to-peak with a converter dead time of 60 ns.

The TAC devised in [8] was modified to have 8 input channels as seen in reference [9]. In this an acquisition system[9] consisting of a TAC, D/A converter and a parallel adder stage is used. Here 8 independent TAC converters are used to obtain maximum conversion rate of 50 MSPS. The ADC and adder were used to reduce the dithering effect produced by the TAC converter. The ADC outputs are processed in an FPGA and then send to PC through USB interface. This acquisition system has a time resolution of 20 ps, differential non-linearity <0.04 peak-to-peak and very low crosstalk between channels.

MoezKanoun, Yves Berube-Lauziere and Rejean Fontaine in their paper [10] used a four input TAC in which the laser pulses obtained were partially deflected and detected using a detector to output a START pulse. When the photons were detected by a set of detectors, the STOP signals were generated. The Digitized time interval obtained was the time difference between the START and STOP events,which were then plotted onto a histogram. Using this histogram of various detectors the image was reconstructed to be used in diffuse optical Tomography. This TAC gave a resolution of 5 ps along with an ADC. A dead time of 150 ns along with a time window of 13 ns was used for getting the desired results. When the TAC was implemented in CMOS the power consumed was about 160mW.

[11] discusses about a circuit which can be used in two modes namely time correlated mode and time uncorrelated mode. In the time uncorrelated mode each detected photon activates the charge of capacitors for a fixed time slot while for the time correlated mode only the arrival time of the first detected photon within the observation window is measured. The circuits consist of the TAC(Time to Amplitude Converter) along with a AEC(Analog Event Counter). The time correlated mode uses a TAC while the time uncorrelated mode uses an AEC. When a pulse is generated by the Single Photon Avalanche Diode we see the TAC or AEC converter is used based on the requirement of the modes. The time resolution of the TAC is 160 ps with a DNL of 0.7 LSB and Power dissipation less than 0.3mW.

IV. SUMMARY

Papers	**TDC**				
	Time Resolution(ps)	***FSR(ns)***	***Peak–peak DNL (LSB)***	***Power Dissipation***	***Technology***
Wahl et Al.[1]	11	--	----	---	--
J. Song et Al.[2]	50	--	0.41	-----	0.12µm
Quirong Yan et Al [5]	500	--	-----	——	130nm
	TAC				
Crotti et Al.[8]	40	45ns	0.02	50 mW	0.35µm
Antonioli et Al.[9]	20	---	<0.04	6 W	---
Kanoun et Al.[10]	5	13ns	---	160 mW	0.18µm
Stoppa et Al.[11]	160	20 ns	0.7	<0.3 mW	130 nm

Table-1: Comparision of photon counting modules based on TAC and TDC.

The tabulated values of time resolution, differential non-linearity, high counting rate, power dissipation and crosstalk shown in Table-1 helps in understanding the drawbacks and benefits of each photon counting module discussed above.

V. CONCLUSION

This paper presents a review of various Time to Digital Converters as well as Time To Amplitude Converters. This review paper has focused mainly on the time resolution parameter. The analysis concludes that the best technique based on the said parameter is obtained as desired for the Time to Amplitude Converter.

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