APPARATUS AND DEMONSTRATION NOTES

Frank L. H. Wolfs, *Editor*

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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Low-cost coincidence-counting electronics for undergraduate quantum optics

D. Branning[1,a)] and S. Bhandari
[1]*Department of Physics, Trinity College, 300 Summit Street, Hartford, Connecticut 06106*

M. Beck[2,b)]
[2]*Department of Physics, Whitman College, Walla Walla, Washington 99362*

(Received 21 January 2008; accepted 19 March 2009)

Coincidence counting is a necessary ingredient for quantum optics experiments at the undergraduate level, but cost has created an entry barrier for many schools. We present a design of a coincidence-counting module that replaces the traditional method based on time-to-amplitude conversion and pulse-height analysis. Our module accepts inputs from up to four detectors, has a coincidence-time window of less than 10 ns, and has a throughput of more than triple that of the traditional method. The cost of our coincidence-counting module is less than 5% of the cost of the traditional method.
[DOI: 10.1119/1.3116803]

I. INTRODUCTION

Recently there has been a great deal of interest in using quantum optics experiments to enhance the teaching of quantum mechanics at the undergraduate level. Teaching laboratory experiments have been developed to explore nonclassical optical phenomena such as the indivisibility of single photons,[1] single-photon interference,[2] and the violation of local realism by tests of Bell's and other related inequalities.[3,4] These experiments provide an excellent platform to discuss quantization, entanglement, complementarity, and other concepts fundamental to quantum mechanics.

These quantum optics experiments have successfully migrated from research laboratories to teaching laboratories, predominately due to advances in technology. The new generation of high-power blue laser diodes, coupled with new techniques for the production of entangled photon pairs,[5] have significantly reduced the cost and the complexity of these experiments. However, one component of these experiments, the coincidence-counting electronics, has remained expensive and complex, involving nuclear-instrumentation modules (NIM) and a bin to house them. In this paper, we present a design of a coincidence-counting module (CCM) that is inexpensive (under $400), easy to build, and suitable for a wide range of quantum optics experiments.

II. COINCIDENCE-COUNTING MODULE

Coincidence counting is the simultaneous detection of two or more photons, or other particles, in different detectors. It is a central and widely used technique in quantum optics,[6] and is used in all of the aforementioned experiments. For example, the violation of Bell's inequality is performed by measuring the detection rates of pairs of polarization-entangled photons after each has passed through a polarization analyzer. When these coincidence detection rates are measured for various settings of the analyzers, they are in agreement with quantum theory, but contradict "local hidden-variable" alternatives to quantum mechanics.

The traditional method of coincidence counting is as follows: An electronic pulse from one detector is used to start a clock, and a pulse from a second detector is delayed and used to stop the clock. The elapsed time between the start and stop pulses is recorded, and events within a certain "coincidence time" of each other are considered to be simultaneous. For simultaneous measurements of four sets of coincidences, as is often used for tests of Bell's inequalities, this method requires about $10 000 worth of commercially available electronics: A NIM bin, four time-to-amplitude converters (TACs), and four single-channel analyzers (SCAs).

A more direct and compact method of coincidence counting is to use logical AND gates. The pulses from the two detectors to be compared are sent to the inputs of an AND

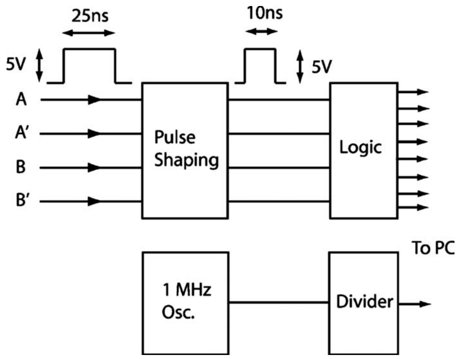

Fig. 1. A block diagram of the CCM circuit. The 1 MHz oscillator and divider are used to generate the clock signal required by the PCI-6602 counter/timer card.

gate, and the output of the gate is logically true (high) if and only if both inputs are simultaneously high—that is, if both detector pulses arrive at the gate at the same time. This is the technique used by our CCM.[7] Our design uses discrete F-series (fast bipolar) logic chips, which operate on 5 V logic with rise times of 2–5 ns.

A block diagram of the CCM is shown in Fig. 1. The input signals are voltage pulses from up to four single-photon counting modules (SPCMs).[8] The pulses enter a pulse-shaping circuit that either passes the pulses unchanged or reduces their width to 10, 14, or 18 ns. Reducing the pulse duration reduces the allowed time for two signals to overlap at the AND gates and reduces the number of accidental coincidences due to uncorrelated photons. The shortened pulses are passed to a logic section where AND gates and multiplexers are used to examine the various coincidence combinations selected by the user. The logic section has eight output channels, which can register the raw counts of the individual input channels and various two- or threefold coincidence counts between combinations of input signals. The output signals are sent over a cable to the eight input channels of a National Instruments PCI-6602 counter/timer board, installed in a personal computer. The counts are registered by the computer using LabVIEW software and may be displayed in real time and/or saved to disk.

A diagram of the pulse-shaping circuit is shown in Fig. 2. The pulse shaping is accomplished by using two copies of the same input signal. One copy is time-delayed and inverted with respect to the other copy. Both copies are used as inputs to an AND gate. The output of the AND gate will only be high for the duration of the time delay. The time delays are accomplished by sending the signal through additional gates, e.g., AND gates, that delay but do not alter the signal itself. These manipulations allow for various discrete shortened pulsewidths, to be selected by the user by adjusting the position of two switches (switches A and B in Fig. 2). The pulse shaping section can also be bypassed, so that the full width of each pulse is passed directly to the logic section.

The logic section in our CCM has two configurations of AND gates, corresponding to two different types of experiments. These two configurations are sufficient to perform all the experiments described above.[1–4] In "Bell" type experiments, one is interested in the singles rates from four different detectors (A, A′, B, and B′) and the twofold coincidence rates from four different pairings of these detectors (AB, AB′, A′B, and A′B′). In "$g(2)$" type experiments, one is interested in the singles rates from three different detectors (A, B, and B′), the twofold coincidence rates (AB, AB′, and BB′), and the threefold coincidence rate between all of them (ABB′). In this circuit, both sets of coincidences are computed, but only one set, Bell or $g(2)$, is actually passed to the output channels. The user makes the selection by adjusting the settings of a multiplexer.

The eight output channels are mapped to eight pins of a 68-pin connector, which allows a direct connection to the eight input channels of a National Instruments PCI-6602 counter/timer board, mounted in a peripheral component interface (PCI) slot of a personal computer. The CCM replaces the BNC-2121 Connector Accessory module that is normally used with the PCI-6602, with the benefit of coincidence counting included.[9] In addition, copies of the shortened input pulses are made available to the user at four BNC outputs. Our CCM also provides the clock signal required by the

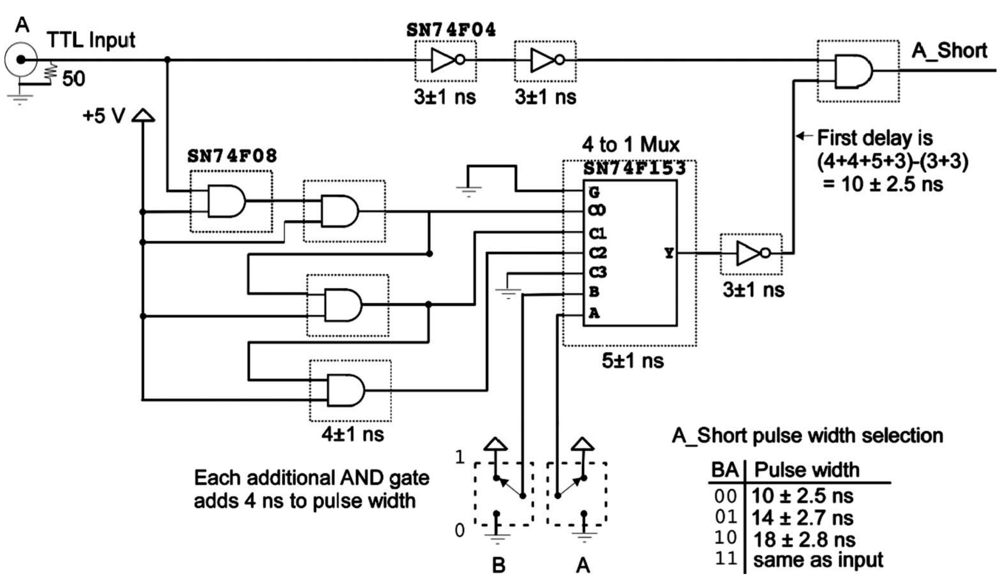

Fig. 2. Schematic diagram of the pulse-shaping circuit.

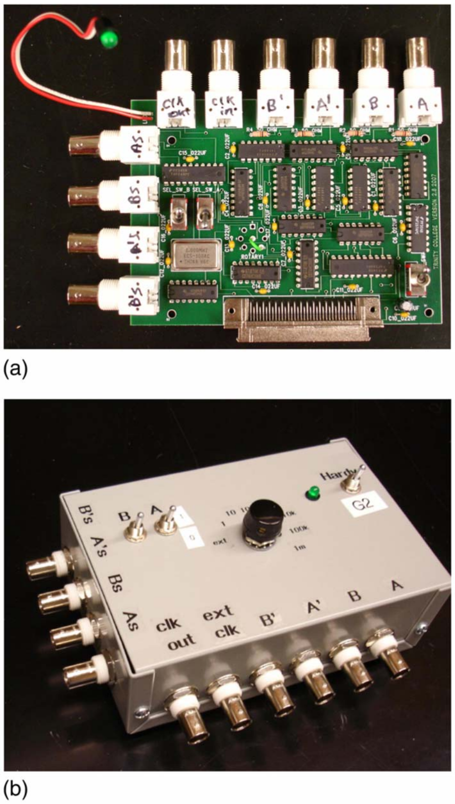

Fig. 3. (Color online) (a) A fully assembled CCM circuit board and (b) the CCM installed in its housing module.

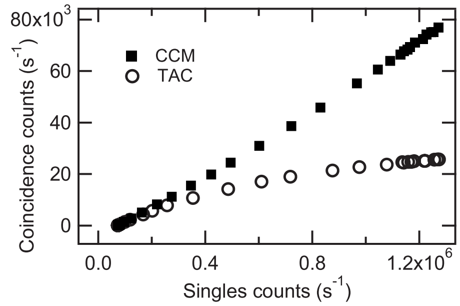

Fig. 4. Measured coincidence rate between detectors A and B versus the measured singles rate in detector A obtained with photon pairs from a parametric downconversion source. The measurements were performed with both a TAC-based system and our CCM. Accidental coincidences were not subtracted from the plotted coincidence rates and are responsible for the small nonlinear increase in the CCM coincidence rate at large singles rates.

PCI-6602, using a TTL oscillator and a series of decade-counter dividers. The clock frequency can be selected by the user in powers of ten, from 1 Hz to 1 MHz. However, the PCI-6602 and its LabVIEW drivers do not work well above clock rates of 10 kHz.

We created the four-layer printed circuit-board design using computer aided design (CAD) software. The CAD design files were sent electronically to one of several circuit-board fabrication corporations that manufactured boards for us. The design files, as well as a complete parts list and further information on the CCM, can be obtained by accessing our web site.[10] A full schematic of the entire circuit is also available online.[11] The cost of two circuit boards is approximately \$250; the cost per board decreases rapidly if more boards are ordered. The total cost of the rest of the parts of our CCM is less than \$100 per board. The PCI-6602 counter costs about \$650. An assembled board and a fully assembled CCM are shown in Fig. 3.

III. PERFORMANCE

Testing our CCM under real two-photon counting conditions alongside a traditional TAC-based system revealed that the CCM has a higher throughput. To demonstrate this, we used a parametric downconversion source to generate signal and idler photon pairs, with the signal photons impinging on detector A and the idler photons impinging on detector B.[1] Figure 4 shows the measured coincidence rate between detectors A and B as a function of the measured singles rate in detector A. The coincidence rate of the TAC-based system saturates at about 25 000 coincidences per second, while the CCM shows no signs of saturation, even at triple that rate. The saturation is due to the 1 μs dead time between events in the TAC-based system; our CCM has essentially no dead time. Count rates for experiments using our CCM are thus limited only by the dead time of the SPCMs, which is on the order of 50 ns.

Saturation of the coincidence rates due to the dead time in the TACs can lead to systematic errors in measurements of $g^{(2)}(0)$.[12] It was found in Ref. 12 that our CCM yields accurate measurements of $g^{(2)}(0)$ at singles rates above 10^6 s^{-1}, without the need to renormalize the data to account for systematic dead time errors. Since measurements of $g^{(2)}(0)$ are at the heart of the experiment that demonstrates the quantum nature of light, described in Ref. 1, those wishing to duplicate that experiment in their undergraduate laboratories are encouraged to use our CCM, or a similar system based on logic, rather than a TAC-based system.

We determined the coincidence resolving time, or "coincidence time window," of our CCM using an incoherent source of uncorrelated photons. For such a source it is possible to determine this time interval by measuring the rate of accidental coincidences between two detector outputs and the singles rates of these two detectors.[6,12] Because of chip-to-chip variations in the CCM components, the coincidence time window varies for coincidences between different pairs of detectors, but does not vary over time for a fixed pair of detectors. With our pulse shortening circuit set to produce the shortest pulses, and hence the shortest resolving time, we measured coincidence time windows of 7–10 ns. This is only a factor of 2 to 3 longer than the coincidence time windows obtained in measurements with a TAC-based system, and is sufficiently short to provide very low backgrounds for the experiments described above. For comparison, the circuit described in Ref. 3 has a coincidence time window of approximately 25 ns, determined by the width of the pulses entering the circuit.

We have tested the CCM in an undergraduate teaching laboratory at Whitman College in the fall of 2007. As part of an upper-level quantum mechanics course, students performed four laboratory experiments: Measuring coincidences between photons from a parametric downconversion source, "proving" light is made of photons,[1] single photon interference,[2] and Bell's and Hardy's tests of local realism.[3,4] There were two experimental stations, each using a CCM, and both CCMs performed extremely well for all experiments. For more details on this course and laboratory sequence, please see our website.[10]

IV. CONCLUSIONS

We have designed a CCM suitable for the undergraduate teaching laboratory. The CCM has the functionality necessary to perform all the experiments described in Refs. 1–4. We have tested our unit by successfully performing these experiments in a teaching lab. Compared to a TAC-based coincidence system, our CCM has a higher throughput at a cost of only 5% of the cost of a TAC-based system. The CCM is also much easier to use than a TAC-based system. Because of these advantages, we suggest that anyone wishing to perform undergraduate laboratory experiments that require coincidence photon counting seriously consider using our CCM. All the information required to build a copy of our CCM is available by accessing our website.[10]

We are working on further improvements to the design of our CCM. In particular, we are following the lead of research groups at the University of Toronto and elsewhere to use a field programmable gate array (FPGA) to perform the logic operations of our CCM. With an FPGA we can incorporate the counting function into our CCM, obviating the need for the PCI-6602. The count data would then be transferred from the CCM to the personal computer via a serial connection or possibly a USB interface. Any future design improvements will also be available on our website.[10]

Note added in proof. We have recently implemented an FPGA version of our module which maintains all of the functionality and performance described above, while also incorporating counting. Please see our website for details.[10]

ACKNOWLEDGMENTS

The authors wish to acknowledge Larry North, Jesse Lord, David Ahlgren, Eli Roxby, Will Raymund, David Bowers, and Nabil Imam for their assistance in the design and construction of our CCMs. The authors also acknowledge financial support from the National Science Foundation, the Connecticut Space Grant College Consortium, Trinity College, and Whitman College.

[a]Electronic mail: david.branning@trincoll.edu
[b]Electronic mail: beckmk@whitman.edu

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[8] The detectors most widely in use in the photon-counting community are SPCMs based on avalanche photodiodes, which produce output pulses of the type described here.

[9] Although it is designed for use with the PCI-6602 card, our CCM could be used without the computer or card, by monitoring the TTL outputs on the appropriate 68-pin connector pins with pulse counters, and providing +5 V DC power on pin 1.

[10] http://www.whitman.edu/~beckmk/QM/

[11] See EPAPS Document No. E-AJPIAS-77-006906 for the complete circuit diagram. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.

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