A Coincidence Counting System for Twelve-photon Entanglement Experiment

Yi Hu[1,2], Wei Li[1,2], Yue-fei Wang[1,2], Ge Jin[1] and Xiao Jiang[1,2]
[1]*Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*
[2]*CAS Center for Excellence and Synergetic Innovation Center in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

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Abstract: Multi-photon entanglement is an important resource for photonic quantum information, and its scale has reached 6 photons with 18 qubits or 10 photons with 10 qubits. The upcoming challenge will be 12 photons with 12 qubits. In the entanglement experiments of such a plurality of photons, the coincidence counter has always been an important tool, and the experiment of 12 photons poses new requirements. Here we report the upgrading of a coincident counting system that worked well in 6-photon and 10-photon experiments to the coming 12-photon one. The scalability of the coincident counting system has been shown. By optimizing the logic in the Field Programmable Gate Array(FPGA) and the LabVIEW program, not only the number of input channels has been increased for 12 photons, but also the functions of signal alignment and status monitoring have been improved. The coincidence result can be analysed both in real-time and off-line. The system is capable to extend to 104 channels at most for channel consuming application.

1 INTRODUCTION

Quantum information science makes great progress in recent decades, where quantum entanglement(Einstein et al., 1935; Schrödinger, 1935) always lies at the heart. At the most fundamental level, quantum entanglement represents the intrinsic non-locality(Brunner et al., 2014) and thus serves to clarifying essential understandings of quantum physics. On the other hand, quantum entanglement is the resource of quantum computation(Knill et al., 2001; Kok et al., 2007). For these reasons, generating and testing the quantum entanglement of a large quantity of qubits in experiments becomes one of the main target of the quantum information science.

To study the quantum entanglement, the system of linear optics constitutes one nice platform due to the well-developed techniques to control photonic qubits. However, the non-deterministic generation of entangled photon pairs prevents the scaling-up of the system. In order to overcome this bottleneck, efforts are made to improve the entangled photon pair source, which is normally from an ultrafast pulsed laser pumped spontaneous parametric downconversion (SPDC)(Pan et al., 2012; Kwon et al., 2008; Kim, 2003). Recently, with the progresses of the SPDC, the entanglement of 10 qubits with 10 photons(Wang et al., 2016; Chen et al., 2017) and 18 qubits with 6 photons (Wang et al., 2018; Wang et al., 2015) are realized. What's more, as an optimal SPDC photon source of 97% heralding efficiency and 96% independent single photons' indistinguishability has been achieved(Zhong et al., 2018), it is hopeful to increase the number of entangled photons continuously. Now the next landmark is the 12-photon entangled state. In this context, for the detection of entanglement of more photons, the correlated measurement brings new challenges for the coincidence counting system.

The coincidence counting system usually corresponds to a type of instrument that records the time correlation between single-photon detectors(SPDs)(Hadfield, 2009; Farr, 2012) within a small time window. Historically, an general method of coincidence counting called time-to-amplitude(TAC)(Crotti et al., 2012; Simms, 1961) is proposed and implemented, in which the arrival times of different photons are converted to the pulse amplitudes. Though having a high time resolution on the order of picoseconds, this method consumes a large amount of resource. An alternative way is to initiate the pattern sampling(Gaertner et al., 2005) into a latch with trigger signals generated by a electronic

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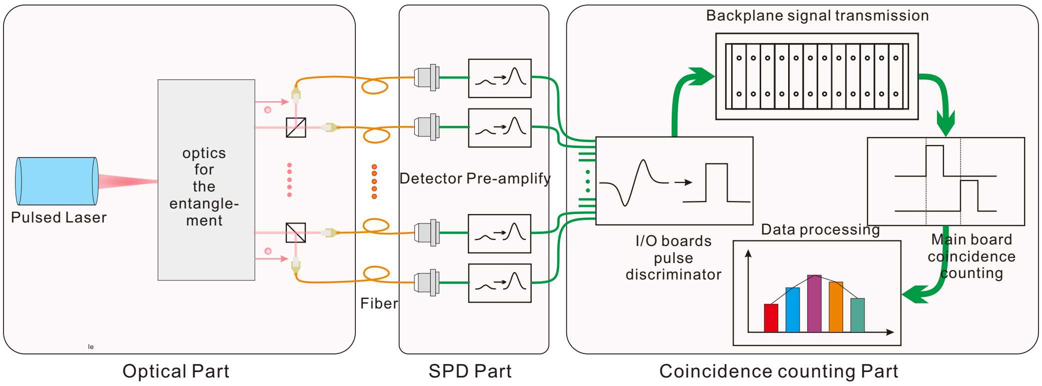


Figure 1: Experimental setup. The pulsed laser generates at most 12 entangled photons. The two states of each photon could be distinguished with two SPDs. The I/O boards collect and discriminate the input signals. I/O boards are inserted in Backplane to transfer signals to the Main board. The Main board implement coincidence logic and complete statistic analysis on personal computer.

logic OR gate. This method suffers from an low event rate of 0.8MHz. Now there are also some commercial solutions for Time-Corrected Single Photon Counting (TCSPC)(Wahl et al., 2013) . Nevertheless, the measurement range is restricted in 5ns and can only be used with double channels. Therefore a home-made coincidence counting system should be designed for multi-photon entanglement experiments.

Previously, a coincidence counting system with 48-channel input signals(Zhang et al., 2016) is established for 6-photon entanglement experiment. The system utilizes the internal delay line of Field Programmable Gate Array (FPGA) to align the input signals and compress the pulses by logic constrains. After these pre-processing of input signals, the clock phase is shifted to sample signals and the results are stored in the external random access memory. The system following the same structure shows the fine scalability and reconfigurability, which supports 104 channels and 1 Gbit data size at most. While in the 12-photon entanglement experiment, the channel number and the data volume are both within the maximal range. So it is practical to upgrade and remodule the original system to service the new experiment and meet new requirements.

In this letter, we present a coincidence counting system with 24 input channels for 12-photon entanglement experiment on the basis of the coincidence counting scheme for 6 photons. This successful upgrading confirms the fine scalability of the 48-channel coincidence counting system in the 6-photon entanglement experiment.

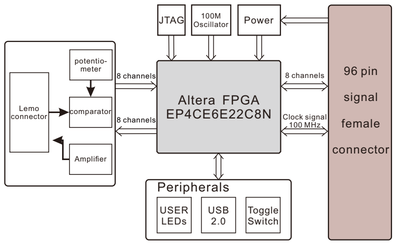
2 REALIZATION

The holistic structure of the 12-photon entanglement experiment is shown in Figure 1. The whole experiment can be divided into three parts: the optical Part, the single photon detector(SPD) part and the coincidence counting part. In the optical part, a 76MHz laser produces pulses of photons, which go through the system of linear optics for generating the 12-photon entanglement. Later for each photon its two states can be distinguished with two SPDs, thus 24 SPDs are needed to record those 16,777,216 (2^{24}) sorts of coincidence events. These detectors sample the optical pulses and pre-amplify input signals. Finally the coincidence counting part relies on a suit of hardware which consisted of six I/O boards, one Main board and one Backplane, shown in Figure 2.

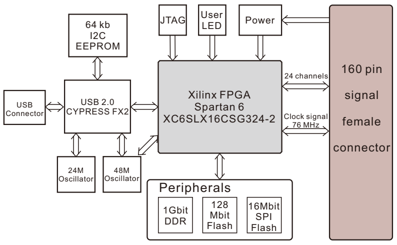
2.1 The Hardware Platform

The I/O board is used to capture and transfer the input signals from detectors. One I/O board has 8 identical channels composed of an I/O port, an amplitude, a comparator and a digital potentiometer. They work together as an flexibly adjustable threshold discriminator uniting the configurable FPGA(EP4CE6E22CSN) for adapting the amplitudes of input signals. To reduce crosstalk between channels, the input and output channels in I/O boards are arranged in a staggered configuration: the adjacent channels of the inputs are configured as output GNDs. So each I/O board supports 4 channels of input signals and 6 pieces of I/O board are required for the 24 channels of the 12-photon entanglement.

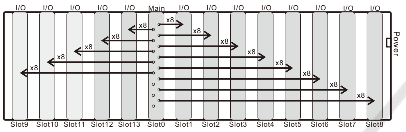
In the system, the Main board plays a central role of performing coincidence logical operations,



(a) I/O board



(b) Main board



(c) Backplane

Figure 2: (a) The framework of I/O board. (b) The framework of Main board. (c) The framework of Backplane.

system control and data processing. It contains a low-end spartan6 (XC6SLX16CSG324C) FPGA, a USB2.0 (CY7C68013A) and a 1 Gbit low-power DDR (MT46h64M16LFCK). The FPGA realizes the architecture of a WISHBONE bus. The DDR is put into use to store the excess data when the data size exceeds the volume of on-chip memories. And the reading and writing of the DDR by FPGA is completed by the MCB(Memory Control Block). The address space of the WISHBONE bus is divided into several blocks for DDR, Block RAM on-chip and Register groups. Accessing these different addresses leads to the operations for corresponding memory devices. Here all the devices communicate with the personal computer(PC) via the USB.

The I/O and Main boards are all plugged into the Backplane and then integrated in 3U chassis. The Backplane has 14 slots in total: the slot0 is for the Main board and the other 13 slots are for the I/O boards. The slot1 to slot13 each has 8 data wires connecting with the slot0 individually. The output signals from I/O boards are collected at the Main board by the backplane data buses.

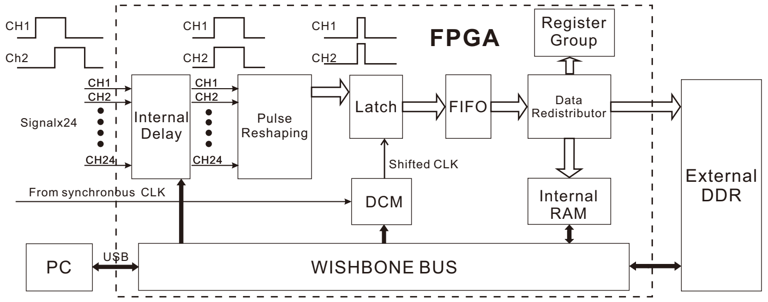
2.2 The New Challenges

In the coincidence counting system for the photon entanglement, there are 4 key elements: signal alignment, pulse width, signal sampling and data processing. In order to carry out these tasks, a logic architecture is designed in the FPGA of Main board and the corresponding software is programmed. In the 12-photon entanglement experiment, we face with similar difficulties in general. Besides, new challenges arise due to the increase of photon number and also new requirements from users. Firstly, the new system is expected to show more sorts of counting results in real-time and enable the control of the motion controller(ESP301) to scan the length of optical path of entangled photons. Furthermore, arbitrary type of coincidence events needs to be read out while previously only some specific coincidence events can be shown. Another tough task is to adopt the different address definition for different number of photons. In other words, the modules involving the access to the addresses of coincidence events all need to be redefined. Here we make partial adjustments to complete the new architecture depending on the existing one, which is Shown in Figure 3.

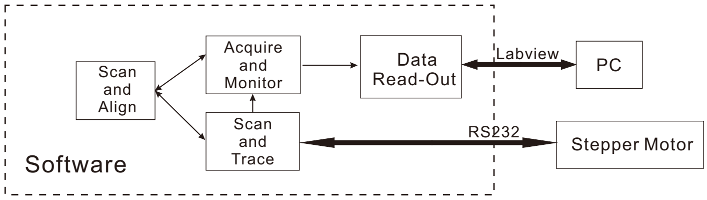
2.2.1 Techniques of Pulse Scan

Signals would have different time delays accumulated in different optical and electronic paths. In the past, after comparing these signals with a oscilloscope, the alignment of signals is performed by changing the lengths of cables manually, which is repetitive and onerous work. In the 6-photon entanglement experiment, techniques of pulse scan are adopted to align the input signals. Shifting the phase of clock step by step, the relation between the single photon count and the shifted clock phase is obtained, based on which the arrival time of signals can be determined. Then all the other signals would be aligned with the last arriving one by the internal delay block. Thus, the manual adjustment of the cables is no longer necessary.

In our new coincidence system, we modify and improve these pulse scan techniques. First of all, we scan the single-channel count instead of the single-photon count. The single channel count includes not only the single-photon count but also the multi-photon counts involving this channel together, which indicates the counting would get started as soon as the detector has response. The counting result in this way is more accurate than before since the multi-photon coincidence events are not missing in the statistics. This is also better cost-saving during the test because we can obtain the whole channel scan curves simultaneously in a clock period with a signal source. While



(a) Logic architecture of Main board



(b)Software architecture for Main board

Figure 3: (a)The logic architecture of the Main board. The internal delay block adjust the delay line of FPGA to align the input pulses. The pulse reshaping block narrow the pulsed width. The clock phase can be shifted by step and the sampled data is distributed to different memory. (b)The software architecture for Main board. The software access the address of the memories by WiSHBONE bus and the software are programmed by Labview.

in the past, to produce the single photon event of the all channels, we have to set up an additional test system to send signals in sequence every other cycle.

2.2.2 The Scheme of Data Storing

After the alignment of signals, the pulse reshaping block is then used to compress the pulse width and as a result the effects of inter-symbol interference and dark count are eliminated. This block is kept unchanged compared to the preceding coincidence system. The narrowed pulses will be registered into FIFO(First in, First out) at the rising edge of synchronous clock which shifts the phase to the center of the pulses. These data in the FIFO are then written into different memory locations according to their coincidence types. Thus, the scheme of address coding is determined by the number of entangled photons and the size of data in the experiment.

In the 12-photon experiment, only a single degree of freedom, ie. the polarization, of each photon is taken into account, so two detectors would respond to the state of one photon. For this reason, we can use 2 bits to describe completely the photon state. Totally, 24 bits are needed to record all sorts of 12-photon coincidence event, so each bit array can just take the place of the memory address to store the corresponding coincidence counting. Moreover, since the experiment of multi-photon entanglement normally lasts for several days and leads to a huge amount of data, a 64-bit counter is defined which ensures enough space for all counting results and any overflow can be avoided. The total storage space in need is 1 Gbits(2^{24}*64 = 2^{30} = 1 G) which exceeds the volume of the internal block RAMs, so the excess data should be distributed to the external DDR. In the experiment, the appearance of photons in pulses follows a Poisson distribution. The single photon and 2-fold events occupy the primary body, which respectively take 24 and 528 sorts of coincidence. Though the multi-fold (more than 2-fold) events is rare, their types of coincidence increase exponentially. So we put multi-fold events in DDR while single photon and 2-fold coincidence events are stored in the block RAMs with 10 bits of address.

In addition, register groups distinguished as the register-in group and the register-out group are added to the system. The register-in group collects read-out information from FPGA to PC like the status indicator and the single-channel coincidence counting results, while the register-out group carries the write-in messages from PC to FPGA including the control commands. The register groups can offer favourable communication medium for PC and the counting system.

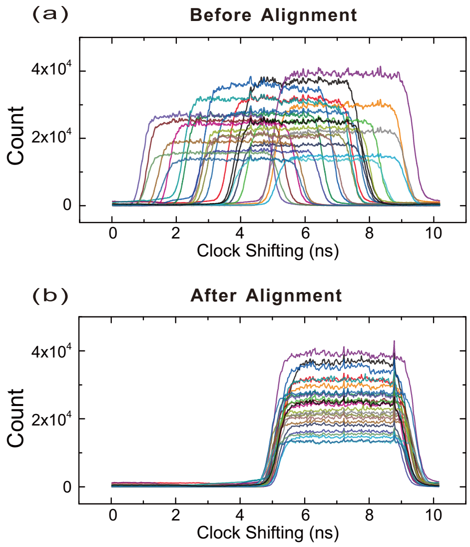


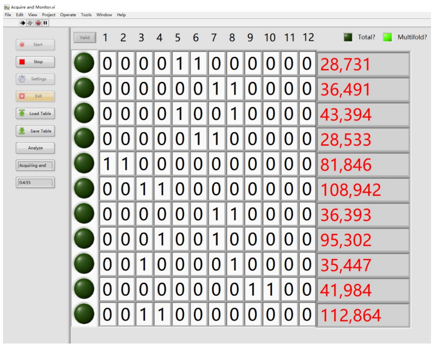
Figure 4: Pulse scan of 24 channels before and after alignment.(a)Before the delay adjusting, the arrival time of different channels differ greatly. (b)After the delay adjusting, the arrival time of different channels are almost uniform.

2.2.3 The Relative Software

All the programs controlling our coincidence counting are coded with Labview. One program named "Scan and Align" helps the users to set parameters concerning the alignment of the signals such as delay value and clock phase shifting. It can access the register groups and scan the single channel coincidence counting.

After the alignment, another program named "Acquire and Monitor" is used to configure the process to acquire and monitor the coincidence results. Particularly, with this program the measurement can be displayed in real-time, which makes it easier to take control over the experiment. To realize this function, we select the wanted type of coincidence events and read out the counting results from the memories. However, the exponential increase in the time cost to traverse all sorts of coincidence would retard the refreshing of the program. So in order to retain the refresh rate high than $1s^{-1}$, we calculate the approximate result for only including the appointed N-fold and the next (N+1)-fold coincidence counting and neglecting all the others.

Finally, the program named "Scan and Trace" serves to control the motion controller used for the optimization of the photon coherence. The controller moves step by step to obtain a curve of the count rate which helps to adjust the optical path to the best state. The last program named "Data Read-Out" can read out the data of arbitrary appointed coincidence events.



Valid	1	2	3	4	5	6	7	8	9	10	11	12	
●	0	0	0	0	1	1	0	0	0	0	0	0	28,731
●	0	0	0	0	0	0	1	1	0	0	0	0	36,491
●	0	0	0	0	1	0	0	1	0	0	0	0	43,394
●	0	0	0	0	0	1	1	0	0	0	0	0	28,533
●	1	1	0	0	0	0	0	0	0	0	0	0	81,846
●	0	0	1	1	0	0	0	0	0	0	0	0	108,942
●	0	0	0	0	0	0	1	1	0	0	0	0	36,393
●	0	0	0	1	0	0	1	0	0	0	0	0	95,302
●	0	0	1	0	0	0	0	1	0	0	0	0	35,447
●	0	0	0	0	0	0	0	0	1	1	0	0	41,984
●	0	0	1	1	0	0	0	0	0	0	0	0	112,864

Figure 5: The working interface of the Labview-based controlling program. The test results are displayed on the interface and agree with the estimate from the Possion equation, demonstrating the right working status of the system.

3 TEST AND RESULT

To test the alignment of output signals in the experiment, we send simulating signals to all the 24 SPDs and then compare waveforms of the output signals before and after alignment, as shown in Figure 4. It can be seen that the maximum time difference before the delay alignment is about 3ns, but after adjusting the delay line, the time difference is around 0.4ns. The alignment operation provides a narrow time coincidence window and a wide steady sampling window. What is more, the pulse width can be deduced from the test. When the count is stable, the width of the flat top can be considered as the signal pulse width. In the experiment, the pulse width is about 3ns.

One of the user interface about displaying in real time during experiment is shown in Figure 5. In the figure, each row represents a sort of coincidence event ("1","2" represent the detector response, "0" represent opposite.). We choose to display coincidence of photon pairs from either the same entanglement source or different source. The users first count the every pair source event and then estimate the coincidence count by the Possion equation. When the result of computation agrees with that displayed in real time, the counting system is demonstrated to work reliably.

With our coincidence counting system, we are able to optimize the photon coherence at the detectors on the basis of a Hong-Ou-Mandel(HOM)-type interference test. The coincidence counting rates of four photon detectors recording the four output channels of the HOM experiment are measured, as the length of one interfering path is scanned via a mirror tunable with a motion controller. The optimal position of the mirror is approached when the detectors the coincidence of two transmitting photons and two reflecting photons reach its maximal value and at the same time the coincidence of one transmitting photon and one reflecting photon is the minimal, as shown in Figure 6.

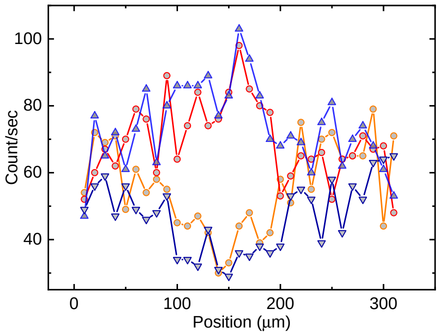


Figure 6: The coincidence counting rates of four photon detectors recording the four output channels of the HOM experiment.

4 CONCLUSIONS

Based on the original system applied in 6-photons 18-qubit experiment, we develop a reconfigurable coincidence counting system with 24 input channels for 12-photon entanglement experiment. Compared to the previous scheme, we apply the former architecture and perform a plenty of improvements. We adjust the delay to align the input pulses and after alignment, the maximum time deviations between output signals is no more than 0.4ns. We place pulse reshaping blocks to compress the input signals and achieve a average pulse width of 3ns. Furthermore, we adopt the different address coding method to count and distribute the data to different memories. The maximum bandwidth supports 90Mhz and the maximum data size supports over 1Gbit. Finally, this coincidence counting system is demonstrated to be feasible in the experiment of 12-photon entanglement.

In the future, some issues are still requires further optimization. With the quantity of channels increasing, the crosstalk between channels will get worse. Next we would take more attempts to improve signal integrity. Besides, since the backplane bandwidth is not high enough, the single-terminal routing can be changed to the differential routing to increase the bandwidth to GHz.

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