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# Periodic Single-Photon Source and Quantum Memory

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## ABSTRACT

Although there has been tremendous progress in the development of true “on-demand” single-photon sources, periodic or “pseudodemand” single-photon sources can be a sufficient resource for many optical quantum information processing applications. Here we review a recent experimental demonstration of a periodic single-photon source based on parametric down-conversion photon pairs, optical storage loops, and high-speed switching. We also review an experiment in which high speed switching and storage loops were used to implement a periodic quantum memory device for polarization-encoded single-photon qubits. Finally, we describe a method in which two of these periodic quantum memory devices are used to facilitate the production of a periodic source of entangled photon pairs. These experiments and proposals are all motivated within the context of linear optics quantum computing.

**Keywords:** single photon, quantum memory, linear optics, parametric down-conversion

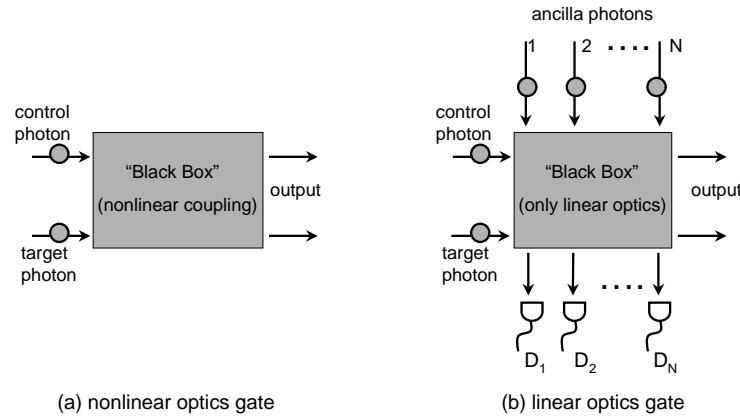
## 1. INTRODUCTION

The recent development of linear optics quantum computing (LOQC) by Knill, LaFlamme, and Milburn (KLM)<sup>1</sup> has led to a renewed interest in optical approaches to quantum information processing.<sup>2</sup> Although significant innovations will be required for a full scale linear optics quantum computer,<sup>1,3-5</sup> useful small-scale devices based on simple linear optics quantum gates<sup>6-9</sup> appear to be within the reach of near-term technology.<sup>10</sup> One of the primary resources required for quantum devices of this kind are large numbers of highly synchronized indistinguishable single-photon states. At the present time, it seems likely that this will involve the use of a master laser pulse train (such as that produced by a mode-locked laser) to provide a natural clock-cycle for the resource production and logic gate operations.

In such a periodic system, true “push-button” sources capable of emitting single photons at arbitrary times are not required; rather, it is sufficient to have periodic photon resources that are only capable of releasing single-photons at well-defined time intervals corresponding to the clock-cycle. This represents a significant relaxation on the requirements of the photon sources and, as will be shown below, even allows the use of photon sources that are inherently random. In addition to periodic single-photon sources,<sup>11</sup> periodic short-term quantum memories<sup>12</sup> and periodic sources of entangled photon pairs<sup>13</sup> can also be extremely valuable. In this paper we review several proof-of-principle experiments and proposals along these lines. The common theme is the use of high-speed switches and simple optical storage loops designed to match the clock-cycle of an envisioned circuit of linear optics quantum gates.

To understand the use of these periodic resources, we first provide an overview of a single linear optics quantum gate,<sup>1</sup> such as the controlled-NOT (CNOT) gate,<sup>2</sup> shown in Figure 1. In contrast to an optical CNOT gate based on direct nonlinear couplings between the control and target photons (Figure 1(a)), the required nonlinearity of the linear optics gate illustrated in Figure 1(b) is obtained by mixing the inputs with  $N$  ancilla photons in a “black box” containing only linear optical elements, and then measuring the state of the ancilla photons after the interaction. Because the state reduction and measurement process is inherently nonlinear, it can be used to project out the desired logical output state when certain measurement results are obtained. Linear optics gates of this kind are therefore probabilistic, in that the correct logical output is signalled by specific measurement results which only occur some fraction of the time. However, the success rate of these gates can approach unity with sufficient resources; it has been shown the failure rate can scale as  $\frac{1}{N}$  or  $\frac{1}{N^2}$  depending on the specific approach that is used.<sup>1,3</sup>

The use of periodic resources in such a linear optics gate is illustrated in Figure 2. In this example, each of the  $N$  ancilla photons is supplied by a periodic source consisting of a storage loop and switch (labelled  $S$ ). The

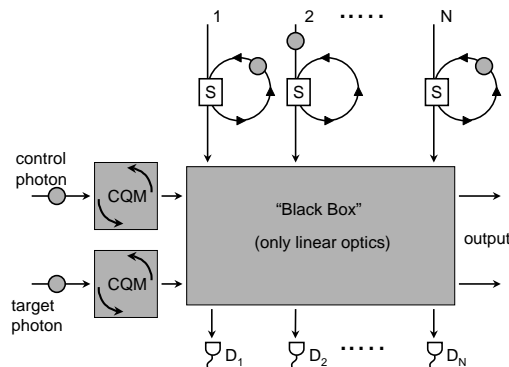


**Figure 1.** The basic idea of a two-qubit linear optics quantum gate. (a) illustrates a “traditional” controlled-NOT gate based on direct nonlinear couplings between the control and target photon qubits. (b) illustrates a probabilistic linear optics controlled-NOT gate,<sup>1</sup> in which the required nonlinearity is essentially obtained by mixing the control and target qubits with  $N$  ancilla qubits, and then making projective measurements with a series of  $N$  ideal single-photon detectors.

photons themselves are produced and heralded by low-efficiency random sources that are driven by the master laser pulse train, causing the various storage loops to become occupied with their single photons at potentially different intervals (for example, ancilla source 2 becomes occupied one period later than ancilla source 1 in the figure).

The basic idea is to start the entire ancilla generation process a sufficiently large number of cycles in advance of the pre-arranged gate operation time so that, with high probability, each of the  $N$  storage loops will be occupied with a single photon before the gate operation time. The  $N$  ancilla photons can then be simultaneously switched into the linear optics gate at the appropriate time. One subtlety of the particular gate illustrated in Figure 2 is that the  $N$  ancilla photons are not entangled. However, gates of this kind can be used to non-deterministically produce the specific entangled states required to implement high-fidelity linear optics logic gates.<sup>3,5</sup> This type of “bootstrapping” of single-photon resources is a basic feature of linear optics quantum computing.<sup>1</sup>

The other type of periodic device shown in Figure 2 is a periodic (or cyclical) quantum memory, which is placed in each of the control and target photon input modes. The cyclical quantum memories (CQM’s) are also based on storage loops and switches, and are capable of storing the qubits without measuring or altering their



**Figure 2.** A linear optics quantum gate using periodic resources. Each of the  $N$  ancilla photons is supplied by a periodic photon source consisting of storage loop and switch (labelled  $S$ ), while the input control and target photon qubits can be stored in cyclical quantum memory devices (CQM).

states. These CQM's would be particularly useful in a circuit where, for example, the input qubits are delivered to the logic gate a few cycles before the pre-arranged gate operation time.

We have recently performed proof-of-principle experimental demonstrations of periodic resources of the kind illustrated in Figure 2. In Section 2, we will review the demonstration of a periodic single-photon source where the single-photons were heralded from parametric down-conversion pairs and the real-time switching was accomplished with a high-speed Pockels cell.<sup>11</sup> In Section 3, we will review the results of a demonstration of a cyclical quantum memory (CQM) device using much of the same technology.<sup>12</sup> As will be seen, this CQM has a number of interesting features, including a natural resistance to a certain class of single-qubit errors. Finally, in Section 4 we highlight a recent proposal<sup>13</sup> to use two of these CQM's along with linear optics quantum logic gates to produce a periodic source of entangled photon pairs, which is another valuable resource in a number of optical quantum information applications.

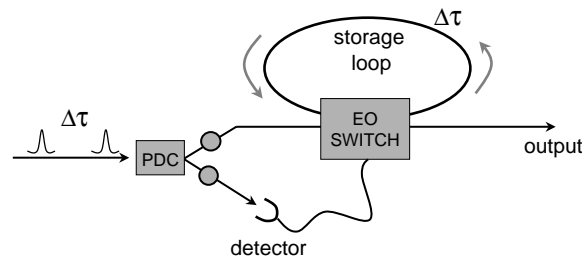
## 2. PERIODIC SINGLE-PHOTON SOURCE

A simplified schematic of our periodic photon source is shown in Figure 3. Here a parametric down-conversion crystal (PDC) is pumped by a train of ultra-short laser pulses with a repetition rate of  $\Delta\tau^{-1}$ . Within the context of the periodic linear optics quantum gate of Figure 2, this pulse train is derived from the master laser, and  $\Delta\tau$  is defined as the system's cycle-time.

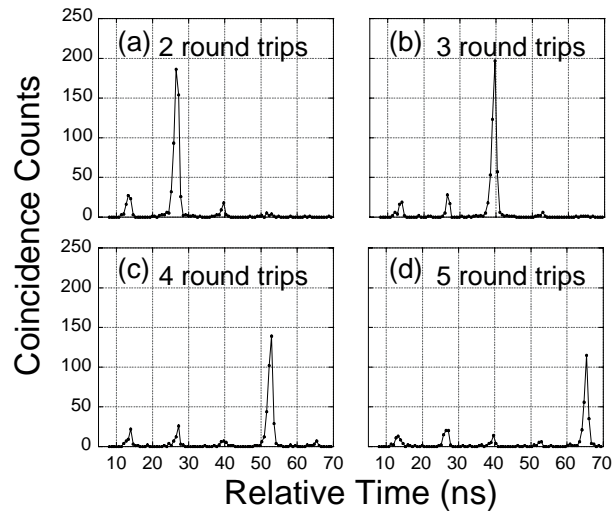
Although parametric down-conversion is an inherently random process, the use of a pulsed pumping train restricts the possible pair emission time to one of the short intervals separated by  $\Delta\tau$ . The pumping power is assumed to be sufficiently low that the probability of producing a pair during a given pump pulse is much less than one. However, when a pair is actually produced, the detection of one member of the pair is used to activate an electro-optic (EO) switch that re-routes the twin photon into the storage loop, and prevents any further photons from being stored. The stored single-photon is then known to be circulating in the loop, and can be switched out at a later cycle.

In this low-power pumping regime, the errant probability of producing more than one pair per pulse would be negligible and, in principle, could be definitively projected out by the use of an ideal photon-number resolving detector.<sup>14, 15</sup>

In our experiment,<sup>11</sup> the switch was constructed of a polarizing beam splitter, and a Pockels cell (EO device) that was used to rotate the polarization of the twin photon as needed to store or release it from the loop. The storage loop itself was a 4 meter free-space loop, providing a value of  $\Delta\tau = 13\text{ns}$ . Although the original experiments were actually completed with a cw pumping laser, this value of  $\Delta\tau$  was chosen to match the repetition rate of a master laser pulse train obtained from a standard 76MHz mode-locked Ti:Sapphire laser being used in our current experiments. The switching speed was dictated by the rise-time of the Pockels cell, which was roughly 10ns. Results from that experiment are summarized in Figure 4. The data shows the ability



**Figure 3.** A simplified schematic of our periodic “pseudodemand” source of single-photons.<sup>11</sup> A parametric down-conversion crystal (PDC) is pumped by a low-power laser pulse train providing a source cycle-time of  $\Delta\tau$ . When a photon pair is actually produced, the detection of one of the photons activates an electro-optic (EO) switch that is used to re-route the twin photon into a storage loop. The stored photon can then be switched out after some number of cycles.



**Figure 4.** Experimental demonstration of our periodic single-photon source.<sup>11</sup> The histograms show the number of coincident detections of the trigger photon and stored/released photon as a function relative time between the two detection events. The results indicate the ability to release the stored photon on command after 2, 3, 4, or 5 (13ns) round trips.

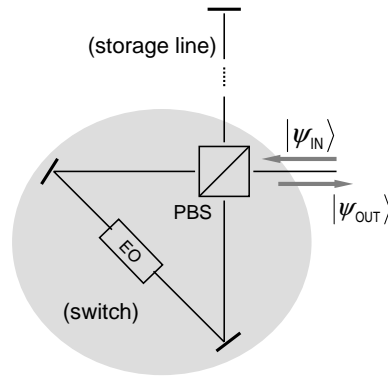
to store single-photons, and switch them out on command after a chosen number of 13ns round trips (cycles) through the loop.

Although the effects of storage loop loss and small switching errors due to experimental imperfections are obvious in Figure 4, a more significant type of error due to heralding-inefficiency is not seen in the figure. Heralding inefficiency errors occur when the triggering photon is detected, but the twin photon is not coupled into the storage loop for any one of a number of reasons. In our initial proof-of-principle experiments the heralding efficiency was very low (on the order of 1%), as most of the technical effort was spent on developing the real-time switching techniques needed to capture and release the photons.

However, it should be noted that the heralding efficiencies in parametric down-conversion can be quite high. Our current experimental efforts involve constructing two of these periodic sources, and demonstrating higher-order interference effects among the single-photons emitted from them. These higher-order interference effects are crucial to the performance of a linear optics quantum gate of the kind illustrated in Figure 2, as it can essentially be thought of as an  $(N + 2)$ -photon interferometer. The required mode-matching of these independent photon sources is being accomplished through the use of single-mode optical fibers for spatial mode-matching, as well as temporal mode-matching through the use of ultra-short pulsed-pump down-conversion and narrow-band spectral filtering as used, for example, in quantum teleportation experiments.<sup>16</sup> Even with the additional parametric down-conversion phase-matching complications arising from the use of femtosecond pumping pulses, and the restrictions of coupling light into single-mode fibers, we have recently achieved heralding efficiencies higher than 50% using variations on the coupling techniques described by Weinfurter's group.<sup>17</sup> In the near future, we hope for even further improvements through the use of custom optics and better source engineering.

### 3. CYCLICAL QUANTUM MEMORY DEVICE

An optical storage loop and high-speed switch can serve as a natural periodic quantum memory device for single-photon qubits. The primary complication is that such a quantum memory must be able to store arbitrary qubits (eg. superposition states) without altering or measuring them in any way. For the case of polarization-encoded single-photon qubits, this requires the device to operate in the same way for all states of the form  $|\psi_{in}\rangle = \alpha|H\rangle + \beta|V\rangle$ , where  $|H\rangle$  ( $|V\rangle$ ) denotes a single horizontally (vertically) polarized photon, and  $|\alpha|^2 + |\beta|^2 = 1$ . Although this can be easily accomplished in an (ideal) free-space storage loop, it prohibits the use of a simple polarization-based switch of the kind described in Section 2.



**Figure 5.** A schematic overview of the experimental apparatus used to demonstrate a cyclical quantum memory device for single-photon qubits.<sup>12</sup> The use of a polarizing-Sagnac interferometric switch allowed arbitrary qubit values to be coherently stored for a chosen number of cycles.

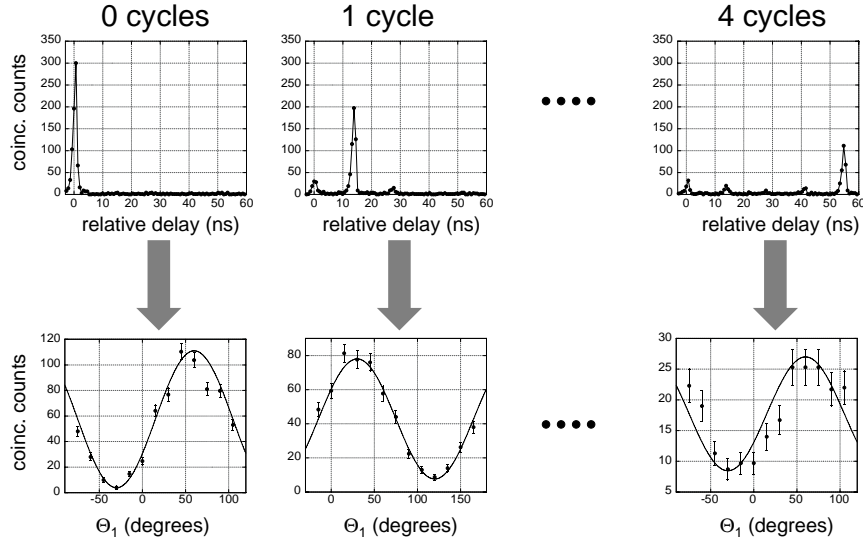
Our recent experimental demonstration<sup>12</sup> of a cyclical quantum memory (CQM) therefore involved the use of an interferometric switch, which is shown in Figure 5. The switch, which is highlighted in the gray circle, consisted of a polarizing Sagnac interferometer, and an electro-optic Pockels cell (EO) that was used to “bit-flip” the polarization basis states (eg.  $|H\rangle \leftrightarrow |V\rangle$ ) when it was turned on. In analogy to the periodic single-photon source, the round-trip time of the switch (and storage line) in our CQM experiment was designed to be  $\Delta\tau=13\text{ns}$ .

The operation of the polarizing Sagnac-interferometric switch can be understood by considering the storage of an arbitrary superposition-state qubit state  $|\psi_{in}\rangle$  for a single cycle, which corresponds to leaving the Pockels cell turned off. Note that the vertical component of the input state,  $\beta|V\rangle$ , which is reflected by the polarizing beam splitter (PBS), travels clockwise through the device and is reflected up into the storage line. At the same time, the horizontal component of the input state,  $\alpha|H\rangle$ , travels counter-clockwise through the device and is transmitted up into the storage line. Both components are then reflected by the termination mirror of the storage line, and the process essentially runs in reverse, providing an output state  $|\psi\rangle_{out} = |\psi\rangle_{in}$  after 13ns.

In order to store the qubit for more than one cycle, the Pockels cell must be quickly turned on while the photon is propagating in the storage line for the first time. Upon subsequent passes through the Sagnac interferometer, the counter-propagating horizontal and vertical components of the qubit are therefore repeatedly flipped ( $|H\rangle \leftrightarrow |V\rangle$ ), and the photon remains trapped in the device as long as the Pockels cell is left on. When the Pockels cell is finally turned off, it can be seen that the final values of the counter-propagating components are those required to release the qubit photon from the device. Consequently, qubits stored for an even number of cycles have bit-flipped values of the input qubit,  $|\psi\rangle_{even} = \hat{\sigma}_x|\psi\rangle_{in} = \alpha|V\rangle + \beta|H\rangle$ , while qubits stored an odd number of cycles are not bit-flipped,  $|\psi\rangle_{odd} = |\psi\rangle_{in}$ . The bit-flipped qubits can be easily re-flipped using single-qubit feed-forward control techniques.<sup>18</sup>

Clearly the effects of loss will have a detrimental effect on the fidelity of the stored qubit. However, one practical benefit of the polarizing-Sagnac switch is that phase-shift errors can, in principle, be totally avoided. First, because the counter-propagating components travel the same physical path, and the speed of light is much faster than typical thermally or vibrationally-induced path length changes, phase-shifts of this kind are minimized. Second, polarization-dependent phase shifts (ie. birefringence) are eliminated for qubits stored an even-number of cycles due to the repeated bit-flipping of the qubit values. In other words, the accumulated phase-shift is the same for both components, and simply factors out of the final state. In the same way, the net relative-phase shift, which is an error, for qubits stored an odd number of cycles is only due to the final cycle.

Results of our initial demonstration of the CQM<sup>12</sup> are shown in Figure 6. In principle, many of the features of our CQM could have been demonstrated using classical light pulses. However, in our experiment we chose to use single-photon qubits that were, once again, provided by parametric down-conversion: the detection of one member of a pair signalled the presence of the twin “qubit” photon and provided a relative start-time for the



**Figure 6.** Experimental results from our initial demonstration of a cyclical quantum memory (CQM) for single-photon qubits.<sup>12</sup> The data plots in the upper row demonstrate the ability to store and release photons after a chosen number of cycles. For each of these peaks, the qubit-value (eg. polarization state) was measured with a polarization analyzer  $\theta_1$  as shown in the lower row of plots. These results demonstrate the ability of the CQM to maintain the coherence of the single-photon qubit.

cyclical device. For the data shown in Figure 6, the input qubits were prepared in the state  $|\psi\rangle_{in} = \frac{\sqrt{3}}{2}|H\rangle + \frac{1}{2}|V\rangle$ , which corresponds to a linear polarization state of  $30^\circ$ .

In analogy with the periodic single-photon source results of Figure 4, the upper row of Figure 6 demonstrates the ability to store and switch out the photons after some chosen number of cycles. For each of the plots in the upper row, the corresponding plot in the lower row shows the results of measuring the polarization state (eg. qubit value) with a polarization analyzer. The results clearly showed the expected Cosine-squared signature of the  $30^\circ$  linear polarization state for photons stored an odd number of cycles, and the expected  $60^\circ$  linear polarization state (eg. bit-flipped value) for photons stored an even number of cycles.

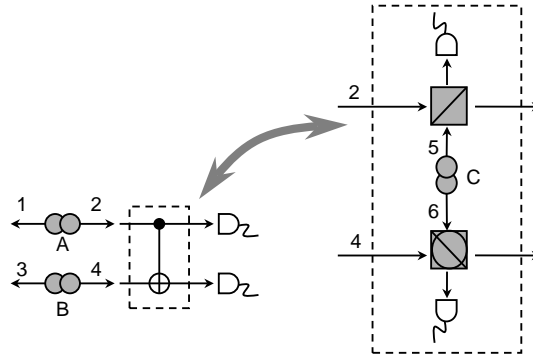
#### 4. PERIODIC ENTANGLED PHOTON-PAIR SOURCE

Many laboratory demonstrations of photon-based quantum information processing have been performed in the so-called “coincidence basis”. In other words, the effects of interest are post-selected and observed only when the relevant photons are simultaneously detected, and thus destroyed. From an experimental point of view, one of the primary advantages of the coincidence basis is an immunity to photon loss and detector inefficiency. This has allowed demonstrations ranging from quantum teleportation<sup>16</sup> and violations of Bell’s inequalities,<sup>13</sup> to our recent implementation of a probabilistic linear optics CNOT gate.<sup>20</sup> Indeed, all observations of entangled photon pairs produced from parametric down-conversion have been in the coincidence basis<sup>21</sup>; the presence of the pairs is only verified by detection.

Nonetheless, a source of *heralded* entangled photon pairs would be an extremely valuable resource for optical quantum information processing.<sup>13, 22</sup> In analogy with a heralded single-photon state produced by the detection of one member of a random down-conversion pair, the presence of a two-photon entangled state would be heralded by some kind of detection event, so that the pair could then be subsequently used as a resource.

This analogy can be taken one step further to provide a periodic source of entangled pairs. In Section 2 we saw how an essentially random, but heralded, single-photon source was converted into a useful periodic single-photon source through the use of a storage loop and switch. In this section we show how a random, but heralded,





**Figure 7.** Production of a heralded entangled photon pair by performing a CNOT operation on entangled pairs emitted by parametric down-conversion sources *A* and *B*.<sup>13</sup> Ideal detectors following the CNOT gate are used to post-select (and herald) those cases in which the remaining two photons are in a specific entangled state. In this scenario the CNOT gate can be probabilistic, and the expanded view of the dashed box shows the use of our proposed linear optics CNOT gate based on polarizing beam splitters.<sup>7</sup> The required values of the detected qubits are described in the text.

entangled-pair source can be converted into a periodic entangled pair source through the use of cyclical quantum memory devices of the kind presented in Section 3.

A random, but heralded, entangled photon pair could in principle be obtained from entanglement swapping<sup>23</sup> between two totally random entangled pair sources, provided that each of these sources was only capable of emitting a single pair at the relevant time. For example, such sources may be available through double photon emission from an isolated quantum dot with limited efficiency.<sup>24</sup> In contrast, conventional parametric-down conversion pair sources are capable of emitting two pairs at the same time, which prevents their use in this type of simple entanglement swapping scheme.<sup>25</sup>

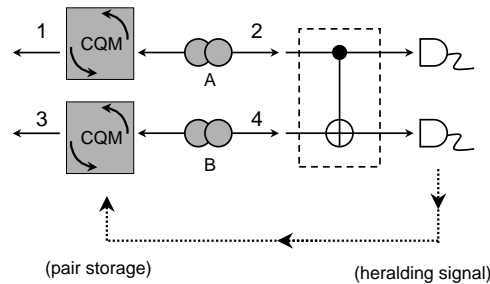
However, a heralded entangled pair may be obtained from two conventional down-conversion pair sources by performing a CNOT operation on one member of each pair, as illustrated in Figure 7.<sup>13</sup> Furthermore, the CNOT gate itself can be probabilistic. For example, the enlarged view of the CNOT gate within the dashed box of Figure 7 shows the use of our previously proposed probabilistic CNOT gate which uses two polarizing beam splitters and an ancillary pair of entangled photons.<sup>7</sup> The use of a probabilistic linear optics CNOT gate (as opposed to a deterministic one) in this protocol will reduce the rate at which entangled pairs are heralded but, at least in principle, will not affect their quality.

In the basic protocol of Figure 7 we envision *A* and *B* as independent down-conversion sources designed to produce two-photon Bell states<sup>21</sup> of the form  $\phi_A^+ = \frac{1}{\sqrt{2}}[0_1 0_2 + 1_1 1_2]$  and  $\phi_B^+ = \frac{1}{\sqrt{2}}[0_3 0_4 + 1_3 1_4]$ , where the logical values 0 and 1 correspond to  $|H\rangle$  and  $|V\rangle$ . We assume that the detectors after the CNOT gate are ideal, and thus consider only those cases in which each source has emitted one pair. In this case, the state after the CNOT operation can be expressed as:

$$\psi = \frac{1}{2}[0_1 0_2 0_3 0_4 + 0_1 0_2 1_3 1_4 + 1_1 1_2 0_3 1_4 + 1_1 1_2 1_3 0_4] \quad (1)$$

We now consider the heralding signal to be the joint detection of a single photon with logical value 0 in mode 4, and a single photon with logical value  $\frac{1}{\sqrt{2}}[0 + 1]$  (or, say, a Hadamard followed by detection of value 0) in mode 2, in which case it can be seen from equation (1) that the heralded output in modes 1 and 3 is the Bell state  $\phi_{out}^+ = \frac{1}{\sqrt{2}}[0_1 0_3 + 1_1 1_3]$ . Additional complications arising from the use of the probabilistic CNOT gate shown in the inset of Figure 7 are described in reference,<sup>13</sup> but the basic idea of the protocol remains unchanged.

The conversion of this source of heralded entangled pairs into a periodic source of entangled pairs using two CQM's is shown in Figure 8. Once again the down-converters are assumed to be pumped by pulses derived from the master pulsed laser train, and the CQM storage time is designed to be  $\Delta\tau$ . In analogy with the periodic



**Figure 8.** The use of two cyclical quantum memory devices (CQM's)<sup>12</sup> to convert a source of heralded entangled photon pairs into a periodic source of entangled pairs.<sup>13</sup> The heralding signal is used to activate the CQM's, which stores the entangled pairs. The entangled pairs can then be switched out of the CQM's when needed.

single-photon source of Figure 3, the joint detection of two photons (with the specific values described above) is used to activate the EO Pockels cell in the polarizing Sagnac switch of each CQM, thereby storing the photons in their respective devices. The entangled pair is then known to be stored, and can be released as needed after some number of cycles.

Whereas loss in either of the CQM's will cause an obvious reduction in the quality of the stored and released entangled state, the effects of phase shifts between the two devices are not as detrimental. Overall phase shifts between the two devices essentially factor out of the two-photon state in such a way that phase-locking of the two memory loops is not required to maintain the coherence of the stored Bell state.

However, any relative phase shifts between qubit values 0 and 1 (ie. birefringence) in the individual memory devices will result in a final state of the form  $\frac{1}{\sqrt{2}}[0_1 0_3 + e^{i\phi} 1_1 1_3]$ , where  $\phi$  represents the total of these phase shifts. Fortunately, as described in Section 3, the CQM's are (in principle) immune to these phase shifts for pairs stored an even number of cycles.

## 5. SUMMARY

In this paper we have emphasized the use of periodic resources for optical realizations of quantum information processing tasks. It seems likely that near term implementations of small scale, but useful, optical quantum information devices will involve the use of a master laser pulse train to provide a natural clock cycle for logic gate operations and synchronization. In such a periodic system, the required resources of single-photon states and entangled photon pairs do not need to be supplied by true on-demand “push-button” sources. Rather, periodic sources based on optical storage loops can be sufficient. Although the discussions were based within the context of linear optics quantum computing,<sup>1</sup> we expect periodic resources will be useful in other areas such as quantum cryptography, for example.

Our recent demonstrations of a periodic single-photon source<sup>11</sup> and cyclical quantum memory for single-photon qubits<sup>12</sup> were of a proof-of-principle nature, and suffered from relatively large sources of errors. For example, both of these periodic devices suffered from losses on the order of 20% per round trip, which is clearly insufficient for a practical realization of applications such as the proposed method of producing a periodic source of entangled photon pairs.<sup>13</sup> Nonetheless, we are currently investigating the technologies required to reduce these errors, and hope these devices may be more practical in near future.

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