Towards a quasi-deterministic single-photon source

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ABSTRACT

A source of single photons allows secure quantum key distribution, in addition, to being a critical resource for linear optics quantum computing. We describe our progress on deterministically creating single photons from spontaneous parametric downconversion, an extension of the Pittman, Jacobs and Franson scheme [Phys. Rev A, v66, 042303 (2002)]. Their idea was to conditionally prepare single photons by measuring one member of a spontaneously emitted photon pair and storing the remaining conditionally prepared photon until a predetermined time, when it would be "deterministically" released from storage. Our approach attempts to improve upon this by recycling the pump pulse in order to decrease the possibility of multiple-pair generation, while maintaining a high probability of producing a single pair. Many of the challenges we discuss are central to other quantum information technologies, including the need for low-loss optical storage, switching and detection, and fast feed-forward control.

Keywords: downconversion, single-photon source

1. INTRODUCTION

Single-photon states are useful for a variety of quantum information tasks including quantum cryptography and quantum computation. When a message is encoded on one degree of freedom of a photon, it cannot be cloned by an eavesdropper without introducing errors that ultimately will prevent its use in a secret cryptographic key.[1] While not optimal, single photons may be useful for cryptography even if they are created at random times. However, some protocols require single photons that are produced at a particular time, i.e., "on-demand". A single photon source (SPS) that periodically outputs only *one* photon with a high probability seems to be essential for linear optics quantum computing (LOQC). While the Knill-Laflamme-Milburn (KLM) LOQC approach assumes the availability of SPSs,[2] another attractive approach, using cluster states, assumes the availability of, or the ability to create many-photon entangled states.[3] Currently it is difficult to make large entangled states suitable for LOQC, with the best five-photon entangled state produced at the rate of about one every minute.[4] However, the availability of single-photon sources should not only increase the efficiency of entangled-state creation, but also enable the creation of even larger entangled states.

In this proceeding we describe an approach to realizing single-photon sources, via the process of spontaneous parametric downconversion (SPDC). Single photons are conditionally prepared at random times by measuring one member of a spontaneously emitted photon pair.[5] To control the time when this randomly created photon is released from the SPS, one may store it until a predetermined time when it would be "deterministically" switched out of storage, as shown by Pittman, Jacobs and Franson[6]*.

Under typical experimental conditions, the output of SPDC is effectively in a Poisson number distribution. Thus, if there is a high probability to create one pair of photons, and ultimately one conditionally-prepared photon, there is also an appreciable probability to create two or more pairs. Such multiple photon-pair creation events would increase the likelihood of having more than one photon in the output of the SPS,

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*Other downconversion approaches gated downconversion[7] and spatial multiplexing.[8]
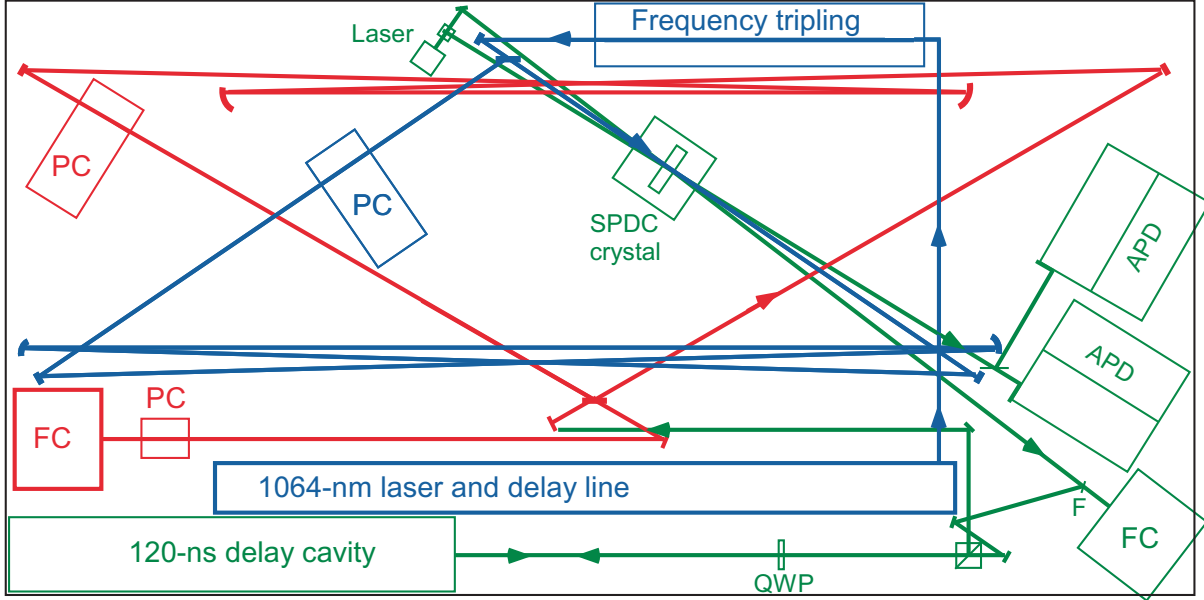
Figure 1. Scale drawing of single-photon source on a 8' x 4' optical table.

decreasing performance as multiple-photon events would have to be discarded. Our approach attempts to increase the likelihood of single-photon outputs while decreasing multiple-photon outputs. By decreasing the pump power, we can decrease the likelihood of creating multiple pairs at the expense of decreasing the possibility of generating exactly one photon pair. To mitigate the latter effect, we use a cavity to *recycle* the pump pulse so that it has many chances to produce exactly one photon pair in the nonlinear crystal.[9]   Thus we can decrease the possibility of multiple-pair events while maintaining a high probability of producing a single pair. In addition, if one can efficiently detect multiple-pair creation in the "trigger" mode, one can discard the resulting conditionally prepared multiple photons. Finally, this approach can be extended so that a conditionally prepared photon created on an early pump cycle may be replaced by a photon prepared on a later pump cycle. This improvement will help to mitigate loss effects of the storage cavity as the later photon will not have to be stored for as many cycles.

2. EXPERIMENTAL DESIGN

Our single-photon source consists of three sections: the pulsed-laser pump and its recycling cavity, the creation and detection of downconversion, and the active storage and retrieval of the conditionally prepared photon. These three sections are shown in Fig. 1 in blue, green and red, respectively. Note that this and the variable delay cavity for the conditionally prepared photon have slightly different designs to more easily accommodate them on the table, they must have the same round trip time for synchronization purposes. The size of the cavities is set by the minimum time it takes to fire a Pockels cell twice (for switching in and out, as described below).

2.1. Pump laser and cavity

The UV pump laser is constructed using a 1064 nm Nd:YAG laser (JDS Uniphase) that is frequency tripled. As shown in Figure 2, the 1064-nm pulse passes through a Herriot cell optical delay line, giving a ~240-ns optical delay, necessary because the laser output is not completely periodic.

Specifically, the passively Q-switched Nd:YAG laser has a shot-to-shot pulse jitter of ~2 μs, requiring a synchronization of the entire SPS for each laser pulse. The optical delay provides time to switch the optical
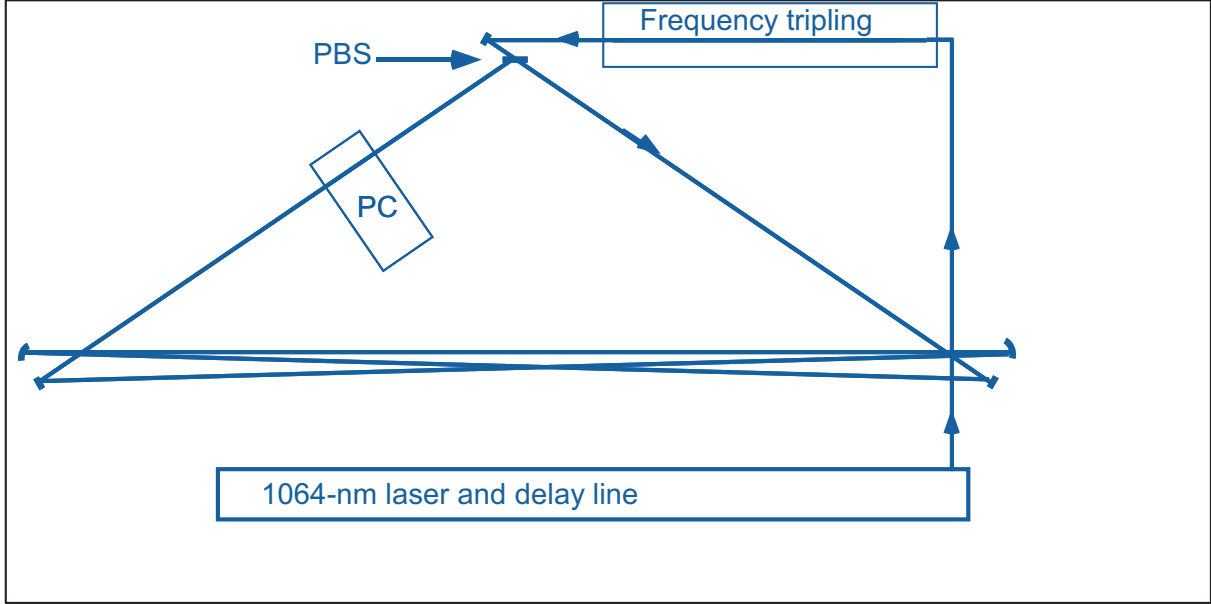
Figure 2. Pump laser and pump pulse recycling cavity.

pulse into the pump cavity. The minimum optical delay is set by the electrical pulse latency of the pump laser ($\sim$3 ns); the latency of the Pockels-cell driver control electronics (62 ns, for the BME Bergmann SG05p2 digital delay card); and the latency of the Pockels cell driver (34 ns for a BME Bergmann PCD_dpp). Thus, one needs $\sim$100 ns of delay plus time for electrical propagation through the cables. After a fixed delay line (see Fig. 3), the beam is frequency tripled from 1064 nm to 355 nm.

The resulting UV pump pulse is switched via a Pockels cell (PC) into the pump cavity (see Fig. 2), constructed with a Brewster-angle polarizing beam splitter (PBS) (CVI TFP-55-PW-2025-UV), two flat mirrors, and two 2-m radius of curvature concave mirrors (CVI Y3-0537-0-2.00CC). The cavity stores vertically polarized light. We selected a Brewster-angle UV PBS to reduce cavity loss, and maximize the benefits received from recycling. A BME Bergmann Pockels cell driver charges a Pockels cell (BBO, Cleveland Crystals Light Gate 5, chosen for its high transmission) to switch the pump pulse into the recycling cavity by rotating the pump's horizontal polarization to vertical. The driver provides variable pulse lengths, with rise and fall times less than 5 ns.

Once the pump pulse is switched into the cavity, we expect the cavity transmission to be $\sim$91% per round trip, due to losses in the Pockels cell ($\sim$2%), mirrors ($\sim$0.5% loss per mirror for four mirrors), downconversion crystal ($\sim$1%) and UV PBS ($\sim$4%). As this loss reduces the strength of the pump pulse, it decreases the likelihood that a successive pulse will generate a conditionally prepared photon; thus, it is an important consideration. Such loss can be compensated somewhat by using a stronger initial pump pulse if one can detect and veto multiple-pair events.

2.2. Conditional preparation of single photons from downconversion

Each time the 355-nm pulse cycles in the pump cavity it pumps the downconversion crystal to create a 718-nm trigger photon and a 702-nm conditionally-prepared photon (see Fig. 4). Each photon has a 5-nm bandwidth, determined by an interference filter in the trigger arm. We use a 6-mm thick piece of BBO with an optic axis cut at 33.6 degrees. After collection, the mode must be converted so that it is matched with the acceptance modes of each cavity. As yet, the best phase-matching choice for collecting the photon outputs
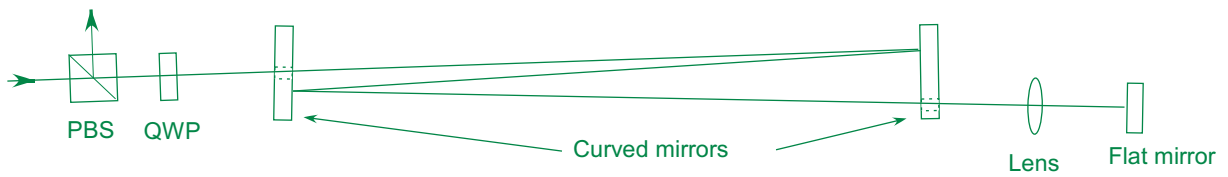
Figure 3. A more detailed view of the Herriot cells used to delay the pump and conditionally prepared photon. Light passes through a polarizing beam splitter at left and is rotated to a circular polarization by a quarter-wave plate. After passing through a hole in the leftmost curved mirror, the light bounces between the curved mirrors ~20 times before passing through a hole in the rightmost curved mirror. The light is then focused onto a flat mirror and is reflected back between the curved mirrors. Because the light travels the same path it did when it entered the curved mirror segment, but in the reverse direction, the spatial-mode aberations induced by the mirrors are canceled.
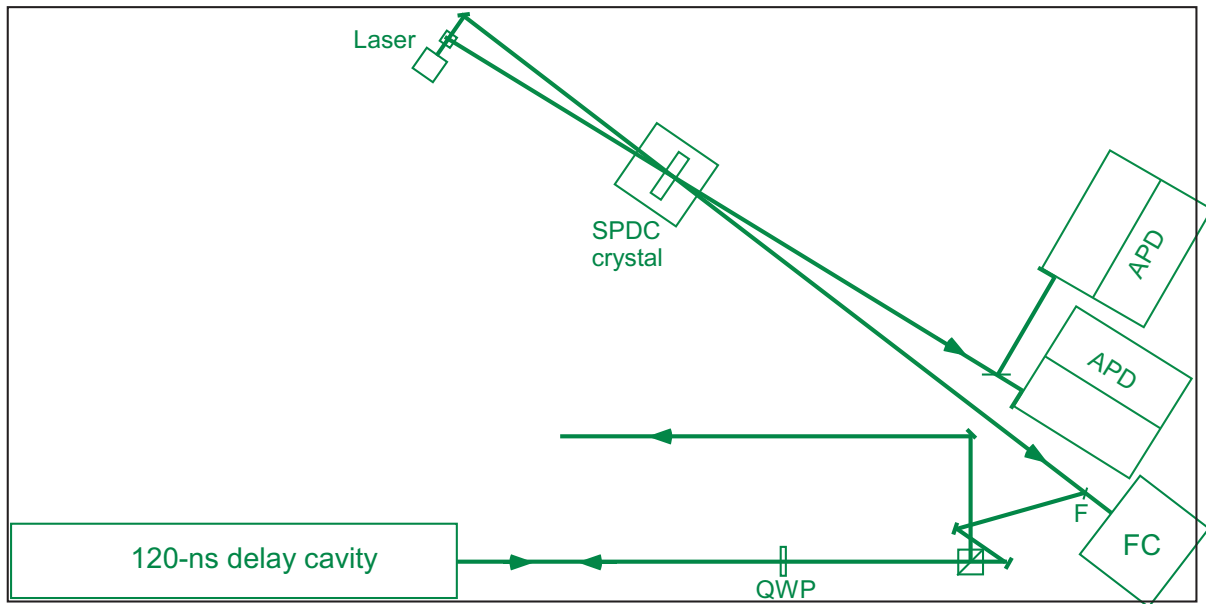

Figure 4. Downconversion crystal and fixed optical delay line. Also shown is an alignment laser, mirror on "flipper" mount (F), and detectors (FC for a fiber-coupled and APD for a free-space detector).
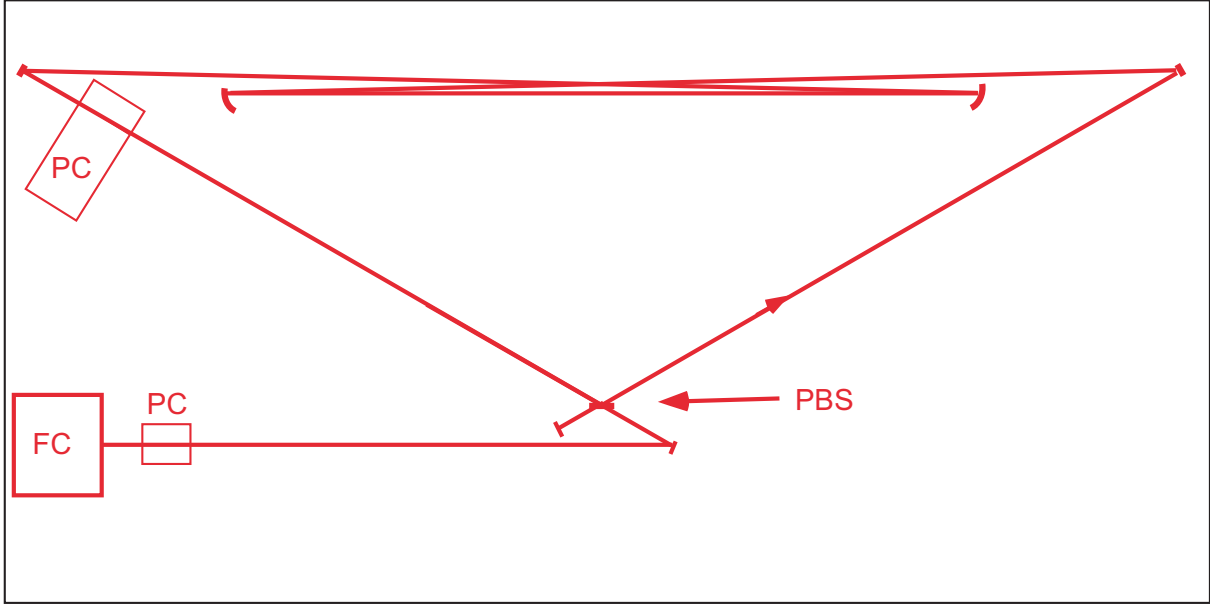
Figure 5. Switchable optical cavity.

is unclear (perhaps type-II "beamlike" downconversion[10, 11] will lend itself to better mode matching). This is a nontrivial issue that will have to be investigated theoretically and experimentally.

Following the downconversion crystal are several detectors. A beam splitter directs the trigger mode onto one of two APDs, giving partial multi-photon discrimination. Coincidence detection with the laser pulse is used, to only count trigger-detections associated with downconversion from the laser pulses. If both APDs fire within a narrow time window, we do not switch photons into the final cavity (described below) and therfore reduce the probability of multi-photon outputs[†]. On the conditionally prepared photon mode, a mirror on a flippable mount (labeled "F" on Fig. 4) may be folded down so that the conditionally prepared photons can be directly measured for alignment purposes.

When the mirror F is in place, the light is directed to a fixed optical delay that serves the same purpose for the conditionally prepared photon cavity as the delay does for the UV cavity. Again we employ a Herriot cell (see Fig. 3) using 2-inch diameter concave mirrors with a 1-m radius of curvature[‡]. Our 10-spot Herriot cell has a measured time delay of 121 ns, with a transmission of 78.4%, close to the expected transmission (79.5%), based on individual transmission measurements on the components.

The Herriot cell's delay is chosen to allow enough time to measure the presence of a trigger photon and feed that information forward to fire the Pockels cell in the switchable cavity. The latency of our APDs (Perkin Elmer SPCM-AQR-14) is typically ∼13 ns. Combined with a digital delay card (BME Bergmann SG04p4, possessing a 47-ns latency) and a Pockels cell driver, we need an optical delay of ∼95 ns. Therefore, our measured optical delay of 121 ns leaves adequate time for the extra delay from connecting cables.

2.3. Switchable optical cavity

The conditionally prepared photon is then switched into an optical storage cavity, which for synchronization purposes is the same length as the UV cavity. A low loss per cycle in the optical storage is critical for

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[†]An advanced implementation could incorporate detectors with photon-number resolving capabilities[12, 13]

[‡]These mirrors are custom optics from CVI with the standard 'R1' coating. Each mirror has a ∼5-mm hole centered ∼7 mm from the edge of the mirror. The holes are used for coupling light into and out of the cavity.
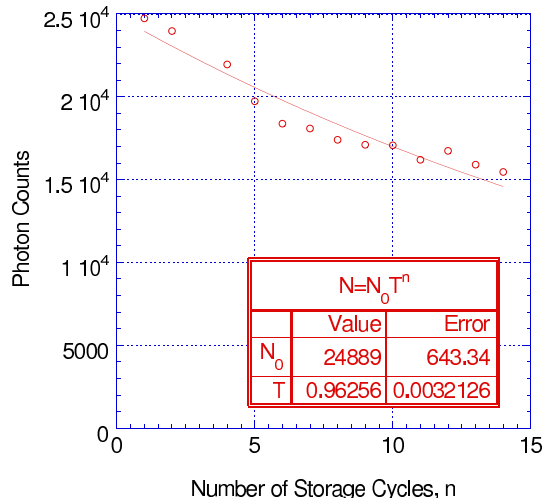
Figure 6. Switchable data.

overall high SPS efficiency. We utilize a custom low-loss Brewster-angle PBS (MLD Technologies) due to the critical nature of this cavity component. The PBS has a reflectivity for vertical polarization of 99.9% and a transmission for horizontal polarization of 99.3% at 702-nm wavelength. Because of the higher reflectivity, we designed the cavity to store vertically polarized light. Experimentally, we found that having the light reflect off the spherical mirrors at a non-normal angle of incidence introduced astigmatism in the spatial mode, which we confirmed theoretically using ray-tracing software in a model of our cavity. To get a stable, non-astigmatic cavity mode, the spherical mirrors are configured for $\sim 1°$ angle of incidence, as seen in Figure 5. Taking into account the measured transmissions of the Pockels cell (98.8%), the two CVI 'R1' coated spherical mirrors (99.7% each), and the two broadband-coated flat mirrors (99.9% each), we expect the overall transmission per cycle of the storage cavity to be $\sim 97\%$. The switching efficiency was tested experimentally at the single-photon level using a laser diode to generate 8-ns long pulses which were then attenuated to an average of less than one photon per pulse. Figure 7 shows a plot of the single-photon counts versus the number of cycles stored in the cavity. The 'n' parameter of the fit in Figure 7 represents the per-cycle transmission. We attribute the slightly-lower-than-expected transmission of 96.3% to imperfect mode matching.

There is a 50-ns minimum delay time between switch-in and switch-out with our Pockels cell driver (BME Bergmann PCD_dpp). As the construction of a 50-ns cavity on our table is difficult, we instead construct the cavity to have a one-cycle storage time slightly longer than 27.5 ns, so a pulse could be switched out after two cycles. The extra 2.5 ns per round trip allows for the rise time of the Pockels cell driver pulse.

Finally, at the output of the single-photon source, we have one last Pockels cell (Lasermetrics 1147-6, Rubidium Titanyl Phosphate [RTP]) and polarizer to ensure no photons leave the source except when that cell is energized. We estimate that the last cell and polarizer will have 97% transmission. After the polarizer is a fiber coupler to analyze the output using a fiber beam splitter connected to two APDs.

3. PERFORMANCE

The performance of a single-photon source can be characterized using the probability of success, i.e., the probability of obtaining exactly one photon, and the probability of failure, i.e., generation of no or multiple photons. Here we utilize a slight extension of the analysis in reference [9], which considers detection efficiency, cavity storage efficiency, and pump strength; we now also consider loss in the pump cavity and losses that the conditionally prepared photons encounter in addition to the per-cycle loss in the switchable cavity (we label
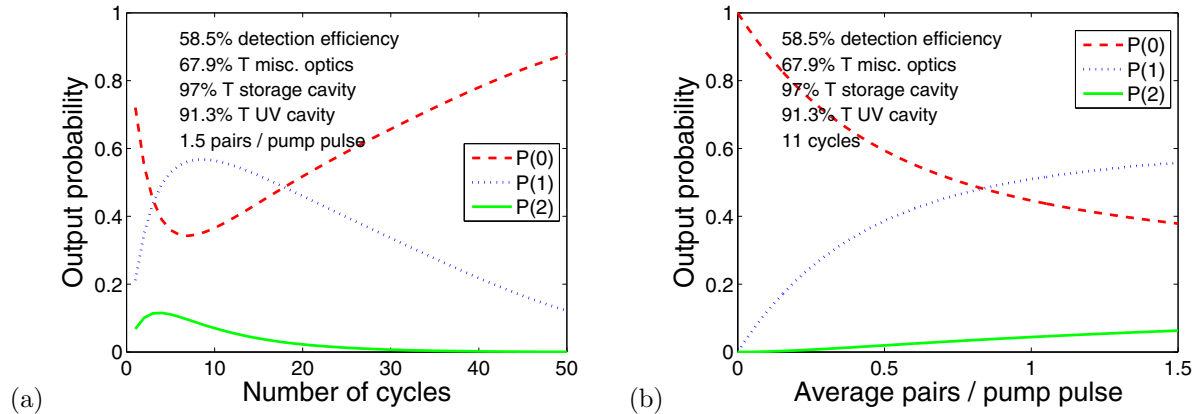
Figure 7. Expected single-photon performance based on measured experimental components. P(1) is the probability of emitting a true single-photon state at the output. P(0) and P(2) are failure probabilities, with 0 or ≥ 2 photons (exactly two photons accounts for most of this), respectively. (a) shows how the probabilities change as a function of the number of pump cycles for a fixed downconversion pair creation-probability of 1.5 pairs/pulse. (b) fixes the number of pump cycles at 11 and varies the pump pulse strength.

the associated transmission 'T misc. optics,' to be distinguished from the switchable cavity transmission, 'T storage cavity').

There are many aspects that contribute to the performance of the source, including the detection efficiency, the number of pump cycles, and the transmission (including mode matching) of cavities and optics used to hold and steer the photons. Some common reasons for failure to produce a true single photon are: no photon pair was produced, a photon pair was produced but the trigger photon was not detected (so the conditionally prepared photon was not switched into the holding cavity), the conditionally prepared photon is absorbed or scattered, or multiple photon pairs are created but not discarded.

Consider the detection of the trigger photon. We can construct a detector tree by sending the downconversion mode into a beam splitter that will create two more modes, each terminated by a detector allowing one to partially discriminate multi-photon events, thereby reducing the probability of a multiple-photon output. We assume these detectors have identical efficiency—where this detection efficiency is a combination of the collection efficiency of spatial and spectral filters and APD quantum efficiency. We represent all detection losses as a single lossy element followed by perfectly efficient detectors.

With a 98% lens transmission (typical for a generic broadband anti-reflection-coated lenses), $\sim$65% APD detection efficiency and $\sim$75% transmission of the interference filter, we expect a $\sim$48% detection efficiency, which may be further reduced by imperfect mode matching. Notice that one of the largest losses arises from reflection from the interference filter. We anticipate that a recycling technique (suggested by Andrew White) should increase the net transmission probability through the interference filter, increasing the net detection efficiency to 58.5%.

For 'T misc. optics', the loss from imperfect optics other than those suffered cycling in the switchable storage cavity, we expect each of two stock-coated mode-matching lenses (before the Herriot cell optical delay and the switchable cavity) to transmit 98%. Additionally, we assume 5 steering mirrors have reflectivities of 0.996, based on measurements of several similarly coated mirrors (CVI coating R1). Finally, we must account for the non-cycling loss of the switchable storage cavity: the 99.3% transmission through the custom Brewster-angle PBS on switch-in and switch-out. When the PBS, steering mirrors and mode-matching lenses are combined with the Herriot cell and the last Pockels cell/polarizer switch, we estimate that 'T misc. optics' is 67.9%.

Using the experimental parameters we have discussed and the results of reference [9], we can plot the expected performance of our single-photon source versus the strength of the pump pulse (λ, the average

number of photon pairs created each time the pump passes through the downconversion crystal) and the number of pump cycles before we attempt to switch out the conditionally prepared photon. For our experimental parameters, using λ=1.2 with 11 pump cycles seems close to optimal[§] giving P(0)=0.38, P(1)=0.56 and P(2)=0.06. See Fig. 7 for performance plots using different pump strengths and number of pump cycles.

In the preceeding analysis, it is assumed that the *first* conditionally prepared photon is switched into the variable storage cavity. If a photon is created on a later pump cycle, it is wasted. Provided that the variable storage cavity has negligible losses, this is of no consequence. However, as there is appreciable loss in the cavity, the probability of losing the conditionally prepared photon is greater with each cycle. To partially mitigate this loss, one can simultaneously switch out the "attenuated" photon and switch in the 'new' photon that was prepared on a later pump pulse[¶]. In this approach, we calculate that for λ=1.5 and 16 pump cycles the performance improves to P(0)=0.38, P(1)=0.57 and P(2)=0.05.

If one improves the performance of several components, one can increase the performance to an even greater level. These improvements include custom-coated low-loss mirrors (99.9% reflectivity, increasing the switchable cavity per-cycle transmission to 98.5% and the conditionally prepared photons' fixed delay line to 90%), UV PBS (increasing the UV cavity transmission to 96% per cycle), and lenses (with 99% tranmission). Additionally, if one utilizes high detection efficiency (90%) photon-number resolving detectors,[12, 13] we calculate the following performance using a pump that generates 1.5 pairs per pulse and 44 pump cycles: P(0)=0.23, P(1)=0.75 and P(2)=0.02.

4. CONCLUSIONS

We have discussed the design, performance and progress towards a periodic single-photon source from spontaneous downconversion. In particular, we discuss component selection considering the effects of loss and on switching times. We anticipate that in its current iteration, our single-photon source will create single photons with probability of greater than 50%, and multiple-photon probabilities of 5%. By making several realistic component upgrades, we further envision the single-photon output probability of our source to increase to 75% while the multiple-photon probability will decrease to 2%. Such a source of single photons should enable further exploration of LOQC protocols, including eventual on-demand sources of entanglement.

ACKNOWLEDGMENTS

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[§]Determined using a search over reasonable experimental parameters: from 1 to 50 pump cycles and from 0.1 to 1.5 average pairs per pump pulse (in steps of 0.1). This search maximized the difference P(2) - P(1).

[¶]A Pockels cell driver that fires three times in rapid succession with fast rise times is a challenge to find. However, BME Bergmann can provide a driver that will fire a third pulse 100 ns after the second pulse. This means that a 'fresh' photon would have to spend at least three cycles in our cavity. This minimum storage time is not accounted for in our analysis, nor is the two cycle minimum storage time after the first pulse.

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