High-efficiency quantum state engineering

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ABSTRACT

Efficiently creating optical quantum states, both simple (e.g., pure single-photon states) and complex (e.g., polarization-entangled but spectrally unentangled photon pairs), remains an experimental challenge. We report on a novel method that allows for efficiently preparing certain classes of states: by weakly driving repeated downconversion in a cavity, we can pseudo-deterministically add photons to a state, preparing Fock states of definite photon number. We discuss expected performance and experimental limitations, including the difficulty of creating pure photons at a high rate. Additionally, we report on our progress in engineering high-rate spatio-spectrally unentangled downconversion, a key technology for optical quantum information processing, and propose a novel 4-photon experimental scheme to test the intrinsic indistinguishability of the photons from this source.

Keywords: Quantum optics, quantum information, entanglement, downconversion, single photon, number state

1. INTRODUCTION

The eventual success of optical quantum information processing depends critically on the available technologies. Photons produced via the nonlinear process of parametric downconversion have now been used in a vast array of experiments, from fundamental tests of quantum mechanics, to quantum cryptography and teleportation, to implementing small quantum algorithms. However, many sources to date have still not been well optimized, e.g., for multi-photon experiments. For instance, there is yet no good source of single photons on demand, and creating states with multiple photons is typically very inefficient, e.g., in order to prepare a particular state with six photons, one must wait until three pairs are emitted simultaneously, a very low probability occurrence. Here we discuss several proposals – and our experimental work toward realizing them – aimed at vastly improving the production efficiency of high-fidelity quantum states of one and more photons. We believe that these schemes will greatly enhance the capability of optical quantum information processing, and enable the practical use of downconversion photons in many more applications.

2. SINGLE-PHOTON SOURCE

Despite its apparent simplicity, producing a single-photon state is experimentally quite challenging. Specifically, there is a need to create single photons, on demand, in a useful spatio-temporal mode. The nonlinear process of spontaneous parametric downconversion (SPDC)[1], in which one high-energy photon splits into two lower energy photons (called the signal and idler), has been used for many years to produce high-quality "heralded" single-photon states (conditional on detecting the signal photon, the idler is prepared in a well-defined single-photon state)[2]. One of the main drawbacks of this process is that it is nondeterministic, i.e., the number of pairs produced is governed by a random (thermal) distribution[3], so the probability of producing exactly one pair can never be more than 25%. This makes downconversion alone unsuitable for creating deterministic single-photon states. However, by monitoring the signal arm of several sources of downconversion (each with a low individual probability of producing a pair, but a high probability of producing at least one pair among them), the experimenter can select the source that produced a pair, and route the corresponding idler photon to the desired output. If the photons produced from the different sources are indistinguishable and not entangled to their corresponding signal photons (see Section 4), then the output, with high probability, is in a pure single-photon state.

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Creating a single-photon source in this way has been proposed using both spatial[4] and temporal[5,6] multiplexing. The former involves multiple physically separate sources and detectors, and the equipment necessary to select and direct the output from any of the sources. In contrast, temporal multiplexing involves a single source and detector, with several pump pulses passing through the downconversion crystal. By storing the single photon in a high-efficiency cavity when it is created, and releasing it at a predetermined time, a single photon can be produced with high probability. Below we describe our progress on this approach, which has the advantage over spatial multiplexing of involving fewer optical elements.

A diagram of the experimental setup is shown in Fig. 1. We start with an IR pulse (1064 nm) from a Q-switched YAG laser, with an average repetition rate of 44 kHz. This light is frequency doubled and tripled to a UV pulse (355 nm), which is delayed for approximately 100 ns in order to synchronize the electronics. The UV pulse then enters a switchable storage cavity through a Brewster-angle polarizing beamsplitter; it is kept in the cavity by rotating the polarization with a Pockels cell. In every subsequent pass through the cavity, the UV pulse passes through a BBO crystal phase-matched for type-I downconversion. If a pair is created, and the signal photon is detected, its conjugate idler photon is switched into a storage cavity similar to the one used for the UV pulse (again after undergoing a delay to synchronize the electronics). After the desired number of cycles in the storage cavity, the single photon is released. In this way, a completely random production process can nevertheless be used to create a pseudo-deterministic source.

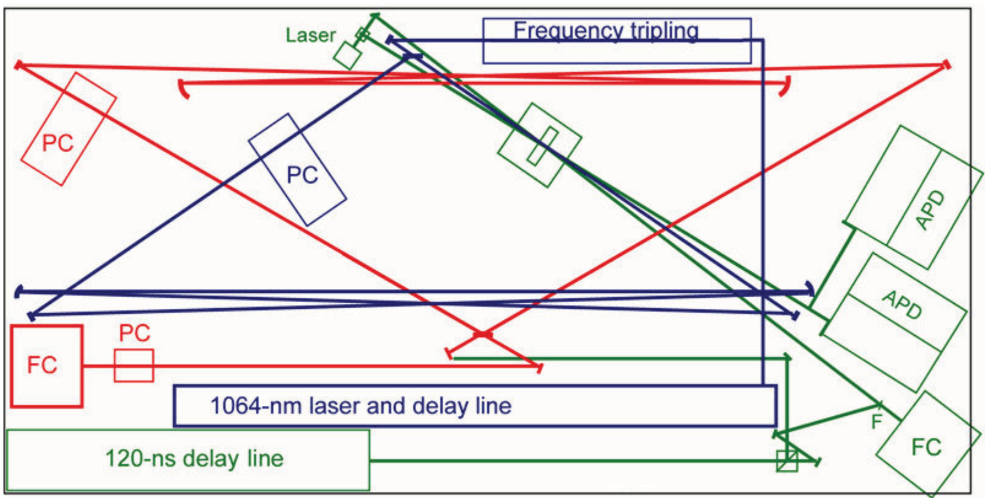

Fig. 1. Diagram of single-photon source. Blue: an IR (1064 nm) pulse is converted to a UV (355 nm) pulse, and switched into a storage cavity containing a nonlinear crystal. Green: an alignment laser indicates the paths of the signal and idler photons. When a pair is created, the signal photon is detected by an avalanche photodiode (APD), and the idler is delayed and then switched (via a Pockels cell (PC) that rotates the photon polarization from horizontal to vertical) into a cavity. The in-/out coupling fiber for the cavity is made with a Brewster-angle polarizing beam splitter. A flipper mirror (F) allows us to detect the idler photon immediately for alignment purposes. Red: the single photon is kept in the storage cavity until a predetermined time, and then released.

The predicted performance of this source depends on many factors, both theoretical and experimental. Assuming lossless optics, this source can achieve arbitrarily high probability of producing a single photon, by driving the downconversion crystal weakly, and allowing for a large number of passes through the system. In reality, the number of passes will be limited by losses in both the UV and single-photon storage cavities. The performance is also limited by the collection efficiency of the downconversion, i.e., the probability of collecting the idler photon if the signal photon is detected. This can be made near unity by adjusting the size of the collection irises on the two modes, but if the iris on the idler arm is too big, additional modes are collected that can lead to detecting extraneous and undesired photons. Finally, the performance is limited by the losses at the various optical elements, including mirrors, lenses, filters, beamsplitters, and Pockels cells. These losses are most significant inside the storage cavities, since the loss is encountered many times. Our UV cavity currently has a transmission of approximately 90% (limited mostly by the downconversion crystal and Pockels cell), while the single-photon cavity has a transmission of approximately 96% (see Fig. 2). Plots of predicted performance are shown in Fig. 3 using values reflecting performance of current components (left), as well as values for optimized—but realistic—components (right).

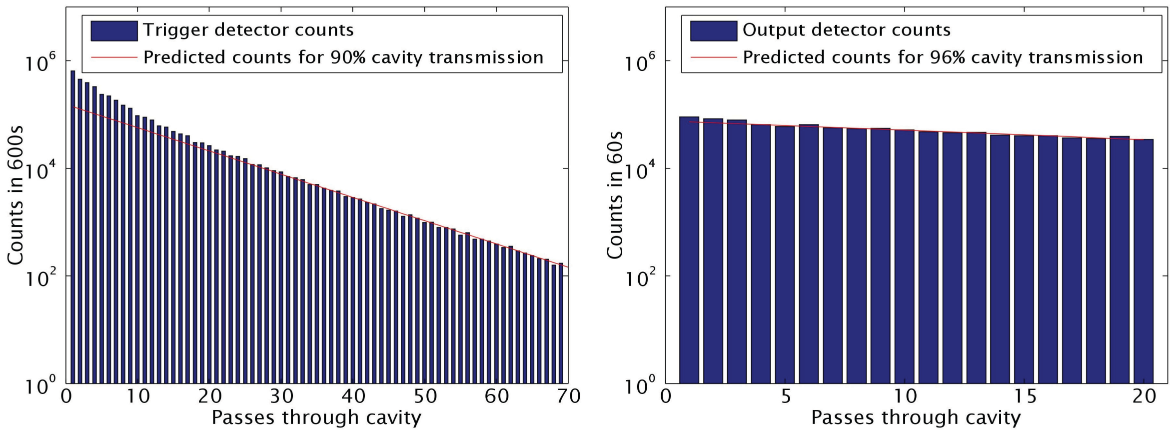

Fig. 2. Experimental performance of storage cavities. Counts as a function of number of passes through the cavity for both the pump cavity (left) and single-photon cavity (right). The apparent high loss in early passes through the pump cavity is due to a limitation in the counting electronics.

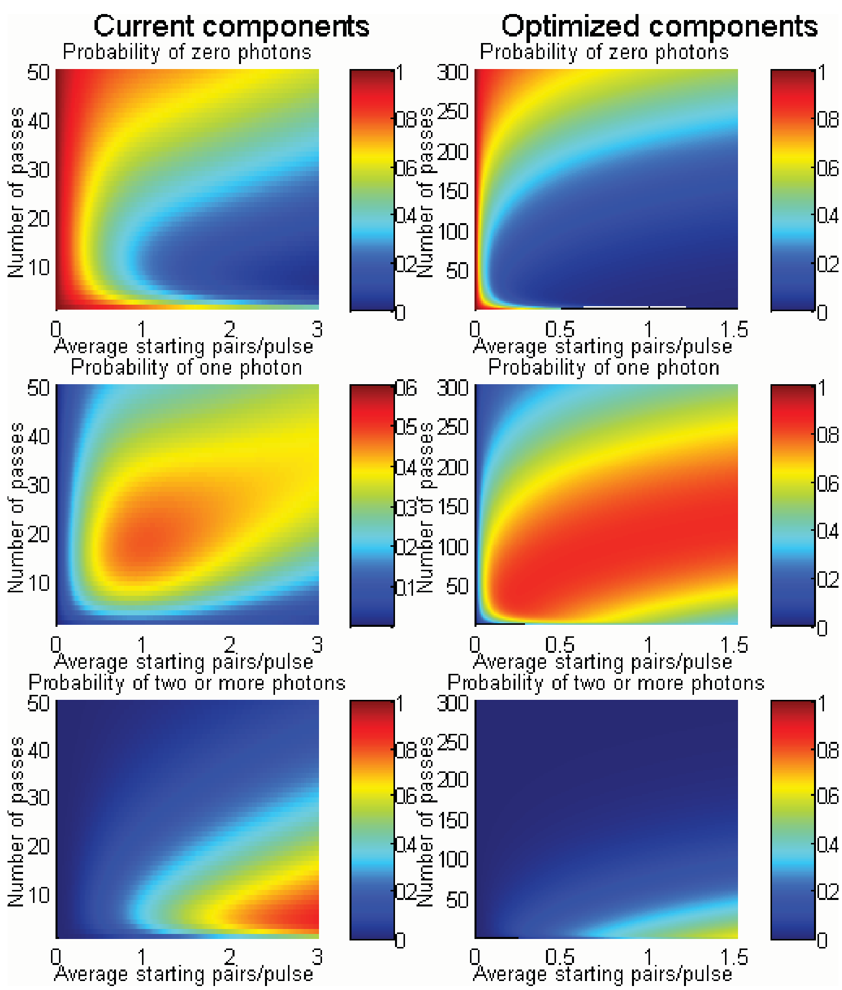

Fig. 3. Predicted performance of single-photon source. Probability of producing zero (top), one (middle), and two or more (bottom) photons, using specifications of components currently in place (left) and realistic optimized components (right).

3. FOCK-STATE SOURCE

The single-photon source is based on repeatedly attempting downconversion, and storing the idler mode of the downconversion in a cavity. As an extension of this, we propose to store the idler mode in a cavity that includes the crystal (see Fig. 4). As in the single-photon source, a pump pulse is repeatedly incident on a nonlinear crystal, with a chance to produce one or more pairs per pass. The signal photon is detected, and the idler is allowed to propagate through the cavity. The cavity length is such that when the pump pulse next passes through the crystal, the idler light does so as well, allowing for one (or more) photon(s) to be added to the state in the cavity. Repeating the process, we can "build up" a Fock (photon-number) state, which, apart from being of interest as arguably the most nonclassical state of light, is useful in several quantum information (QI) processes[7]. When the desired number of photons in the cavity is reached (as indicated by the total number of signal photons detected), the state in the cavity is switched out. If a photon-number-resolving detector is used[8,9], more than one photon can be added per pass, allowing a quicker and more efficient production of the desired state. As we discussed elsewhere[11], this method can be further extended to enable the efficient production of more complicated states e.g., number-path entangled states (commonly referred to as "N00N" states), by allowing the manipulation of the polarization of the photons in the idler storage cavity.

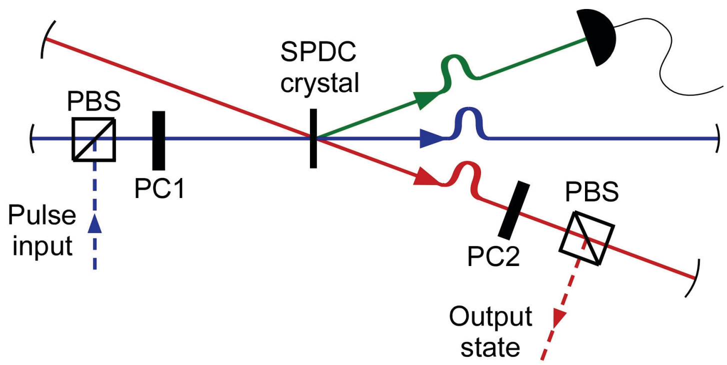

Fig. 4. Simplified diagram of proposed Fock-state experiment. A high-energy pulse is switched into a cavity using a polarizing beamsplitter (PBS) and Pockels cell (PC1), and passes through a downconversion crystal (SPDC crystal) several times. Each time it passes through, it has a chance to add one or more heralded photons to a storage cavity. Once the desired number of photons is in the cavity, the pulse is switched out, again using a PBS and Pockels cell (PC2).

The expected performance of this proposed method is shown in Fig. 5. A "success" is defined as having the desired number of photons exiting the cavity, which includes the possibility of a photon being lost from the cavity, but being replaced by a pair that is produced but not detected. This performance greatly exceeds current methods. For example, a single-pass downconversion approach cannot produce an N=4 Fock state with better than 19.6% probability, and the best

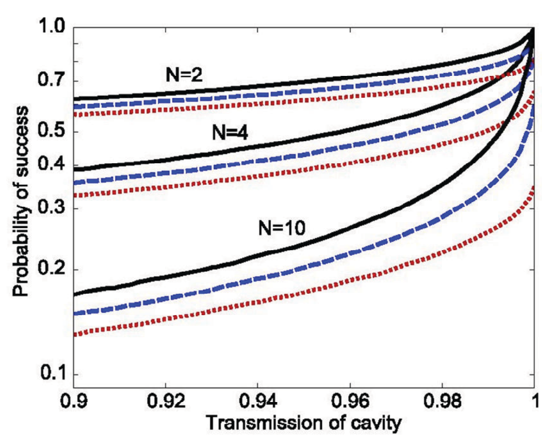

Fig. 5. Expected performance of proposed Fock state source, as a function of cavity transmission for different numbers of photons, and different detector efficiency (black solid, η=1; blue dashed, η=0.95; red dashed, η=0.9).

experimentally has been 0.2%[10]. Our scheme could realistically produce this state with >50% probability. Here we have assumed the ability to tune the pump amplitude for each pass through the crystal, and the ability to add many pairs per pulse, although producing an average of more than one pair per pulse in the desired mode remains experimentally challenging (without this assumption, we would simply have to wait longer to produce the state). Because many passes through the cavity are necessary to build up the desired number of photons, the performance is highly dependent on the transmission of the cavity. Also, since each photon must be detected independently, the performance is very dependent on detector efficiency. Finally, in the single-photon source, for a pure Fock state (as opposed to a mixed state with a fixed number of photons), the idler photons need to be pure, i.e., not entangled in any way to the signal photons. Below we discuss our attempts to realize such a source.

4. UNENTANGLED PHOTON STATES

In addition to being crucial for single-photon and Fock-state generation, indistinguishable photon-pair sources, uncorrelated in spatial-mode and frequency, significantly improve several optical QI protocols. Interference, a required resource underlying the quantum advantage, manifests ubiquitously in linear optical quantum computing[13] and quantum communication[14,15], in the form of the Hong-Ou-Mandel (HOM) interferometer[12]. For most QI applications, including teleportation, a HOM measurement has to be performed between photons originating from *different* sources. Such an "event-ready" HOM consists of two independent sources, each of which generates two photons; one photon from each source is then combined at a beam splitter. Here, mere indistinguishability between the two interfering photons does not suffice; any "which-process" information carried by the non-interfering partner photons essentially makes the interfering processes distinguishable. Currently, nearly all experiments solve this problem by incorporating extremely narrow-band spatial and spectral filters to reduce any distinguishing information. However, filtering also drastically reduces the incident photon flux, thereby greatly lowering the overall efficiency. Figure 6 shows the tradeoff between interferometric visibility[†] (used to quantify the fringe contrast in any interferometer) and photon-count rates when employing filters in a typical HOM interferometer[16].

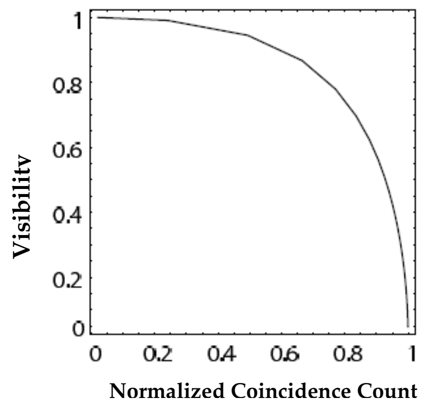

Fig. 6. Tradeoff between 2-photon interference visibility and count rates in a HOM interferometer (from Vincent et al.[13]) .

A better solution is to use unentangled photons[17-20], i.e., photons with no spatio-spectral correlations. Such truly indistinguishable photons (apart from the two interfering photons being indistinguishable in the HOM interferometer, the trigger photons do not carry any *which-source* information), provide high visibility interference without filtering. However, for QI we still need usable entanglement in at least one degree of freedom (DOF). Here, we describe our progress in engineering an ideal indistinguishable photon-pair source for optical QI — polarization-entangled photons with spatio-spectral *un*entanglement. We expect such a source to successfully enable many QI protocols with high fidelity and high efficiency, since there will be no need to filter the source.

Experimentally, parametric downconversion can be used to generate polarization entangled photons. We use the two-crystal scheme (Fig. 7b)[21], where two adjacent thin $\chi^{(2)}$ crystals (e.g., BBO) are orthogonally oriented, such that a vertical (horizontal) polarized pump photon downconverts in the first (second) crystal into horizontal- (vertical-) photons. When pumped by photons polarized at an angle θ_p, the downconversion processes in each crystal are coherent with one another, thereby generating arbitrary superposition states of horizontally (H) and vertically (V) polarized photon pairs[22]:

$$\cos\theta_p \left| H_1 H_2 \right\rangle + e^{i\phi} \sin\theta_p \left| V_1 V_2 \right\rangle . \qquad (1)$$

The relative phase ϕ depends on the phase-matching conditions and crystal parameters. Typically, the downconverted signal and idler photons from a two-crystal source exhibit several different types of correlations. Mathematically, the two-photon downconverted state can be written in terms of creation operators acting on the vacuum state as

[†] Visibility $\equiv \frac{Max - Min}{Max + Min}$, where Max (Min) refers to the incident-photon count rate at the maximum (minimum) fringe intensity.

$$\left|\Psi\right\rangle = \int d\mathbf{k}_s \int d\mathbf{k}_i f(\mathbf{k}_s,\mathbf{k}_i)\hat{a}_s^+(\mathbf{k}_s)\hat{a}_i^+(\mathbf{k}_i)\left|vac\right\rangle \ , \tag{2}$$

where the subscripts s and i stand for signal and idler, respectively. f, the joint two-photon amplitude (JPA) that prescribes the signal-idler relationship, depends on the phase-matching conditions and SPDC parameters such as the crystal length L, pump beam waist w_0, position of beam waist x_0 and pump spectral bandwidth σ (see Fig. 7a). Figures 7b and 7c show the typical source geometry, which defines the polar (θ) and azimuthal (ϕ) downconversion emission angles. Correlations can exist in and between the spectral (ω) and angular orientation (both θ and ϕ) degrees of freedom of the downconversion beams. These correlations can be theoretically derived from the JPA, since f is a function of the wave vectors, which in turn depend on ω, θ and ϕ[23].

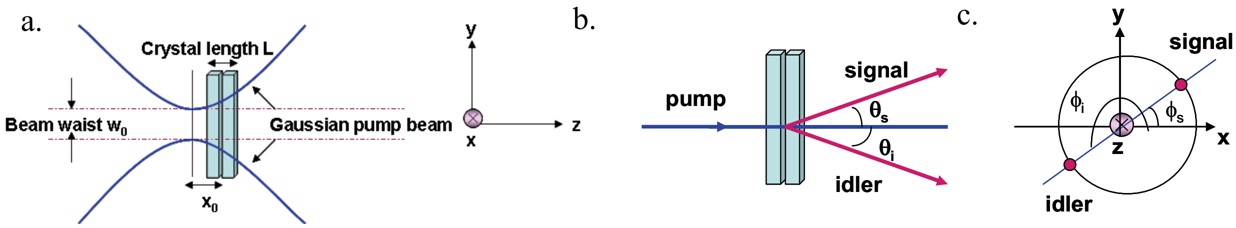

Fig. 7. **a**. Basic source geometry of the two-crystal scheme. **b.** Side view of the two crystals, showing the emission polar angles. c. Looking-into-the-pump view, showing the emission azimuthal angles.

Fig. 8 shows the different types of correlations that typically exist between the signal and the idler photons for a type-I downconversion source pumped with a pulsed laser. Internal or intraphoton correlations, denoted by the vertical dashed lines in Fig. 8, exist between the frequency and polar emission angle of the same photon; such correlations, e.g., lower frequency components of the downconverted photons emerging at wider angles, can be thought of as being similar to a chirp in a classical field. External or interphoton correlations also exist between the signal and the idler photons, and are denoted by solid lines in Fig. 8. These constitute azimuthal-azimuthal (e.g., photons are emitted on opposite sides of the pump beam as shown in Fig. 7c), spectral-spectral, polar-polar and hybrid spectral-polar entanglement between the photons in a downconversion pair[23].

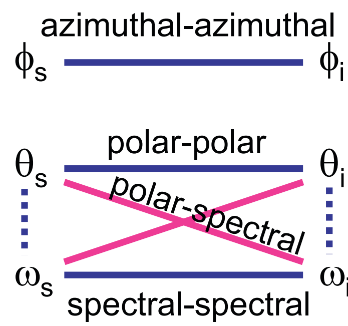

Fig. 8. Internal and external correlations in the JSA between frequency ω, polar θ and azimuthal angles ϕ. The subscripts, s and i, stand for signal and idler, respectively.

We engineer the two-crystal source to generate polarization-entangled, but spectrally and spatially unentangled photons, based on theory developed by U'ren[23]. Mathematically, for true indistinguishability the JPA has to be factorable in the different DOFs. The mechanism for selective entanglement relies on optimizing the phase-matching parameters, such as σ (by choosing a spectrally broad pump source), w_0 (by adjusting the pump beam focus), and L (by specifying the crystal length). However, it is primarily simultaneous group velocity matching (along with the required phase matching) that leads to negligible intraphoton and interphoton correlations[24]. From these conditions, it can be shown that type-I degenerate SPDC in BBO at 810 nm requires a pulsed pump centered at 405 nm with a ~7-nm bandwidth; such a pump can be obtained by frequency-doubling a femtosecond Ti-Saph laser at 810 nm. The BBO crystal's optic axis should be at ~41.3° for phase matching such that both the downconverted photons are emitted at θ =16°. Such an optimization predicts greater than 90% interference visibilities and a 230-fold improvement in the coupled brightness (compared to typical filtered geometries)[25]. While the required optimal parameters are feasible with current technology, note that a type-I source pumped with a pulsed laser (as opposed to conventional cw pumps) is a key requirement.

The integration of the spatio-spectral unentanglement methods with the two-crystal scheme for producing polarization entanglement leads to at least several challenges, including birefringent decoherence (significant for pulsed pumps), and considerable dependence of the downconversion polarization on emission-angle, due to the uncharacteristically large 16° cone (as predicted by Migdall[26], due to transversality conditions, the polarization state of the ordinary-polarized photons emitted in down conversion depends on the azimuthal angle around the downconversion cone into which the photons are emitted). Pulsed two-crystal type-I sources, unlike cw-sources, require temporal precompensation[27]: due to birefringence each frequency component of the broadband pump pulse sees a different effective length of the crystal, leading to a different relative phase φ in the generated entangled state $\left(|HH\rangle + e^{i\varphi}|VV\rangle\right)/\sqrt{2}$. On averaging over these phases, the state is effectively decohered. To (pre-)compensate for the different delays acquired by these components, and thereby increase the state fidelity, we can use an additional birefringent crystal that has a spectral-phase opposite to that of the downconversion. We have demonstrated such a source (Figure 9) using a frequency-doubled (to 410 nm with 3-nm bandwidth) ultra-fast (~90 fs) Ti-Saph laser. By incorporating optimized temporal and spatial compensation, we have achieved the highest reported visibility (98%) for downconversion at a typical emission angle of 3°.[28]

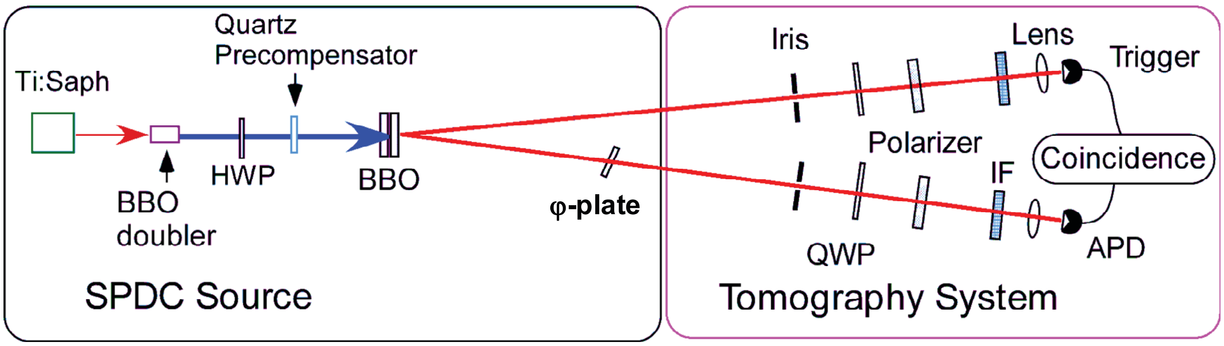

Fig. 9. Experimental setup for a pulsed two-crystal Type-I phase-matched polarization-entangled source. 810-nm light from a Ti-Saph laser is frequency-doubled by a BBO crystal. A half-wave plate (HWP) sets the pump polarization, while a quartz crystal is used for temporal precompensation. A φ-plate is used to adjust the relative phase. The tomography system is used to reconstruct the density matrix of the produced state[22] , using quarter-wave plates (QWP), polarizers (P) and interference filters (IF) centered at 810 nm.

To optimally check the factorizability of an engineered single crystal, one would need to perform an 'event-ready' two-crystal HOM, as discussed above. Here we propose an experimentally easier approach, essentially an extension of the two-crystal scheme typically used to generate polarization entanglement. The setup uses two of the engineered crystals, each pumped with a different polarization to emit HH and VV pairs (see Figure 10). On the signal side, a polarizing beam splitter (PBS) directs the H and V photons to detectors 1 and 2, respectively, used as the trigger detectors. When these detectors fire in coincidence, we have prepared the state HV in the idler mode. We then perform a polarization-based HOM experiment on these two idler photons — after passing through a non-polarizing beam splitter, the H- and V-polarized idler photons are analyzed using 45° polarizers. Birefringent elements (quartz plates) are used to vary the delay

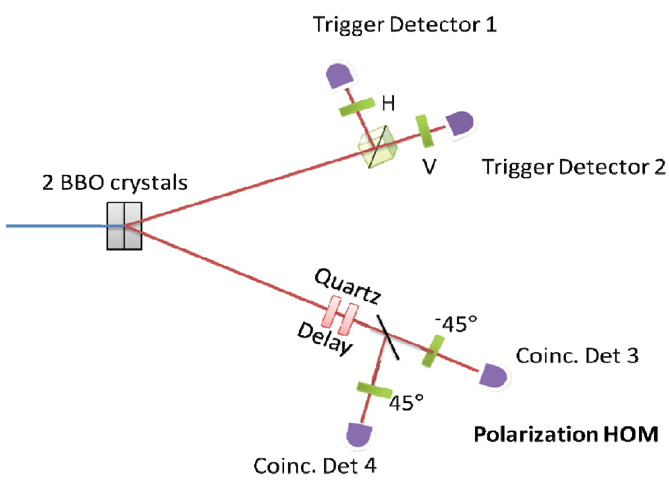

Fig.10. Experimental setup for an event-ready Hong-Ou-Mandel interferometer, by extending the two-crystal geometry.

between the interfering photons. When the arrival times of the two photons at the beam splitter are the same and if the photons are truly indistinguishable, without any innate which-source information, a dip in the coincidence rate should occur. On the other hand, any unwanted entanglement between the idler photons and trigger photons will reduce the destructive interference leading to the dip. There are several advantages to this scheme. Most significantly, because the interfering photons are all collinear with one another, the HOM interferometer is inherently very stable and easy to align. Also, note that polarization entanglement is *not* a prerequisite between the two pairs.

5. CONCLUSION

In summary, in this paper we have discussed several proposals and experiments in progress for engineering efficient sources of single- and multi-photon quantum states. In the former case, these would enable various quantum information protocols to at last leave the realm of post-selected experiments, moving toward much more scalable architectures. In the latter case, the pseudo-deterministic addition of photons one-by-one into a storage system allows for near-exponential gains in production efficiency. In order to realize either of these systems, it is required to have photons which are not only indistinguishable from each other, but also not entangled in unwanted degrees of freedom with their partner photons. We are presently working toward such a source, which would lead to great enhancements in the efficiency of many multi-photon quantum information experiments.

6. ACKNOWLEDGEMENTS

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