The Conversion Revolution: Down, Up and Sideways

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INTRODUCTION

Continued progress in quantum communication and optical approaches to quantum computation, requires the development of enabling technologies for photonic quantum information processing [1]. Such resources include high efficiency single photon detectors, high-fidelity single-photon sources, high brightness sources of entanglement, and multiple microsecond optical quantum memories. Here we discuss our current efforts to improve this quantum information "toolbox". Section II describes the realization of an extremely bright, high-fidelity source of entangled photon pairs, created via the process of parametric downconversion, as well as one possible method for storing such quantum bits. Section III presents one application for entanglement: the realization of the quantum communication protocol of remote state preparation, a "sideways" conversion of the state of one photon contingent on particular measurements made on the other. Finally, Section IV describes an inverse nonlinear process which enables efficient and coherent detection of infrared photons by first *up*-converting them into visible frequencies.

ENTANGLEMENT FROM DOWNCONVERSION

A variety of approaches have been pursued to produce polarization-entangled photon pairs via the process of spontaneous parametric downconversion, including post-selected 2-photon interference [2, 3], single-crystal Type-II phase-matching [4], two-crystal Type-I phase-matching [5], and several interferometric schemes [6, 7, 8, 9]. These different approaches have met with varying degrees of success, quantified by the brightness of the source (the total number of useful entangled pairs emitted per second), and the quality of the source (indicated by the amount of entanglement, or the fidelity with one of the maximally entangled Bell states). The development of these sources has seen remarkable progress over the past decade. In fact, if one plots the reported rates of polarization-entangled photon pairs as a function of time, one notes a Moore's law-like exponential growth rate (see Fig. 1). One common limitation is that there is often a trade-off between the brightness and fidelity: one can achieve higher rates, but often only at the expense of reduced entanglement per pair, or conversely, one can achieve quite high quality of entanglement, but only for a rather small fraction of the downconversion pairs which are emitted [10]. For example, this trade-off exists for the two-crystal entanglement source [5], though to a substantially lesser degree than with some of the other approaches.

The essence of the two-crystal technique is that diagonally polarized pump photons are given an opportunity to down-convert in one of two adjacent perpendicularly oriented nonlinear crystals (see Fig. 2a). The downconversion process can therefore take place in either the first crystal, producing a pair of horizontally polarized photons, or in the second crystal, producing a pair of vertically polarized photons. As long as the two processes are indistinguishable, they will be coherent, resulting in a polarization-entangled state. One complication to the process, however, is that the photons which are born in the first crystal are extraordinarily polarized within the second crystal. The consequence of this is that the phase shift acquired by the joint horizontally polarized pair depends on the precise propagation direction of the photons in the second crystal. When one opens the collection irises to collect more of the downconverted pairs, one collects entangled states $|HH\rangle + e^{i\phi}|VV\rangle$ with a range of values for ϕ. Averaging over the relative phase ϕ leads to mixture in the final detected quantum mechanical state and is the source of the two-crystal trade off between brightness and fidelity. Once one is aware of this effect, it is possible to design a suitable birefringent phase compensation

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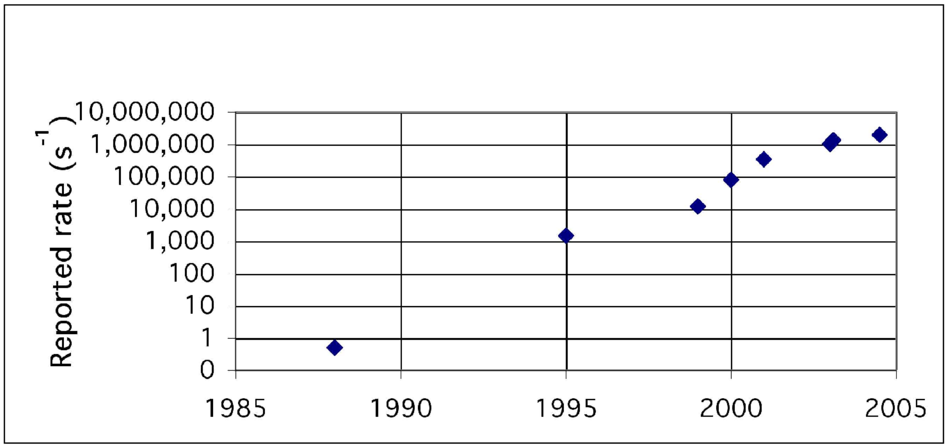


FIGURE 1. History of entangled photon pair production.

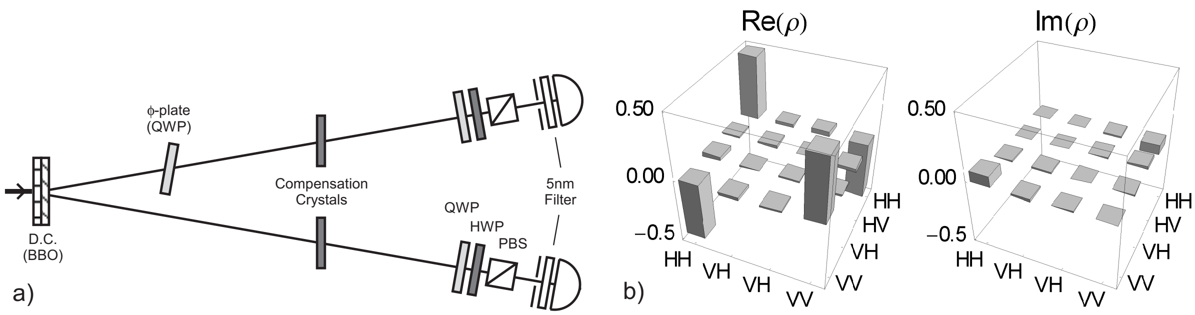


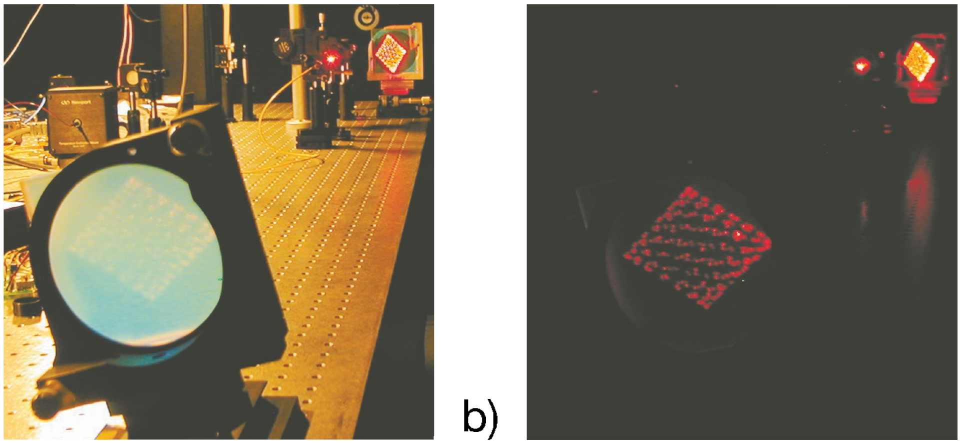
FIGURE 2. a) Compensated 2-crystal scheme. b) Density matrix for compensated entangled state.

element, in order to eliminate, or at least substantially mitigate, the effect [11]. We have done this – our compensation is performed by placing additional thin pieces of BBO in each of the downconversion arms. By appropriately orienting the compensators, one is able to greatly reduce the phase variation over the solid angles collected by the irises. This, in turn, has enabled us to employ much larger collection irises while still maintaining a very high quality output state. To date we have managed to detect up to two million polarization-entangled photon pairs per second, using a pump power of approximately 350 milliwatts. At that level, the detectors (Si avalanche photodiodes) begin to saturate; moreover, preliminary measurements indicate the onset of crystal damage (though we have some reason to believe that the damage is actually due to the crystals' protective coatings, and might be reduced by an improved coating process).

A typical density matrix of the quantum state produced using this improved compensated two-crystal source is shown in Fig. 2b. The essential difference between this and other previously reported similar tomographies of Bell states is that, whereas low counting rates previously necessitated total counting times on the order of one hour, the current results were taken with less than one second of total collection time. Such a bright, high quality source may find immediate application to further quantum information studies, as well as some quantum communication protocols, such as a source for entanglement-based free-space quantum cryptography [1].

It is interesting to note that this rate of production is, for the first time, sufficiently high that it overlaps with our ability to efficiently *store* photons. Specifically, using specially designed custom optical delay lines, we have been able to store light – though not yet photons from parametric downconversion – for durations greater than 1 μs (see Fig. 3) [12, 13]. This is significant because it represents an overlap of the quantum state generation and quantum

[1] Because the photons are emitted into a variety of spatial modes, there is less of an advantage to using this technique for a fiber-based quantum cryptography system.



a) b)

FIGURE 3. Photons enter the optical storage line through a small hole in one of the end mirrors. After bouncing back and forth a preset number of times (e.g., 100) determined by the curvature and relative orientation of the (cylindrical) mirrors, the photons exit via the same hole. For a 2-m mirror separation, times in excess of 1μs are readily achieved. Preliminary measurements indicate that the output state has a very high fidelity with the input state, i.e., the storage line is acting as a faithful quantum memory.

memory capabilities, though obviously significantly more development is needed in both of these areas.

REMOTE STATE PREPARATION

One application of a source of tunable high-fidelity entanglement is Remote State Preparation (RSP). This quantum communication protocol, proposed several years ago [14, 15, 16], is related to, but somewhat simpler than, the task of quantum teleportation. In the latter, Alice tries to transport an *unknown* quantum state to Bob without sending it directly. She can accomplish this if she and Bob share an entangled pair of photons, and if she can perform a Bell-state analysis on the unknown photon and her half of the entangled pair. In the RSP protocol Alice tries to cause Bob to possess a photon in a particular quantum state, which Alice *knows*. Again, Alice and Bob require pairs of correlated particles, e.g., entangled photons, as a resource. However, because Alice knows the state she is trying to prepare on Bob's side, it is not necessary for her to perform the difficult Bell-state analysis. Instead, it is sufficient for her to perform a particular generalized measurement on her quantum system, and then to relay the outcome of that measurement (i.e., the photon was detected or not) to Bob. Contingent on this single classical bit of information, Bob either accepts the photon coming to him, which will then be in the desired quantum state, or he discards it. It is easy to see that if Alice wants to remotely prepare Bob's photon in the pure polarization state $|\chi\rangle$, and Alice and Bob start with a pair of photons in the maximally entangled state $|\psi^-\rangle = (|H_aV_b\rangle - |V_aH_b\rangle)/\sqrt{2} = |\chi_a\chi_b^\perp\rangle - |\chi_a^\perp\chi_b\rangle)/\sqrt{2}$, Alice simply needs to make a strong projection measurement with a polarizer to pass only polarization state $|\chi^\perp\rangle$. Whenever she detects a photon in this state, she has remotely prepared Bob's qubit into the state $|\chi\rangle$. The efficiency of this scheme is thus 50%. In addition, if Alice wishes to be able to control the mixedness, i.e., the entropy, of Bob's photon, she can achieve this in two ways. If Alice and Bob share a non-maximally entangled state $(\cos\theta|H_aH_b\rangle + \sin\theta|V_aV_b\rangle)$, then Alice may prepare Bob's photon into a mixed state simply by making a polarization-*insensitive* detection of her photon. From Bob's perspective, this is equivalent to tracing over the state of Alice's subsystem of the joint state, leaving his qubit in the partially mixed state $\cos^2\theta|H_b\rangle\langle H_b| + \sin^2\theta|V_b\rangle\langle V_b|$. As two extreme examples, if Alice and Bob start with the pure state $|H_aH_b\rangle$, then Bob's photon is obviously in the pure state $|H_b\rangle$; if instead Alice and Bob start with the maximally entangled state $(|H_aH_b\rangle + |V_aV_b\rangle)/\sqrt{2}$, the state of Bob's subsystem alone is completely mixed[2]. Obviously with this scheme Alice cannot control the direction of any pure component of Bob's qubit. In order to allow Alice to prepare Bob's photon into a completely arbitrary state of polarization, and without the need to adjust the entanglement

[2] Although the detection of the photon by Alice does not alter the polarization state of the photon on Bob's side, it does herald the existence of this photon, essentially preparing the state of light in Bob's arm into an excellent approximation of a single-photon Fock state [17].

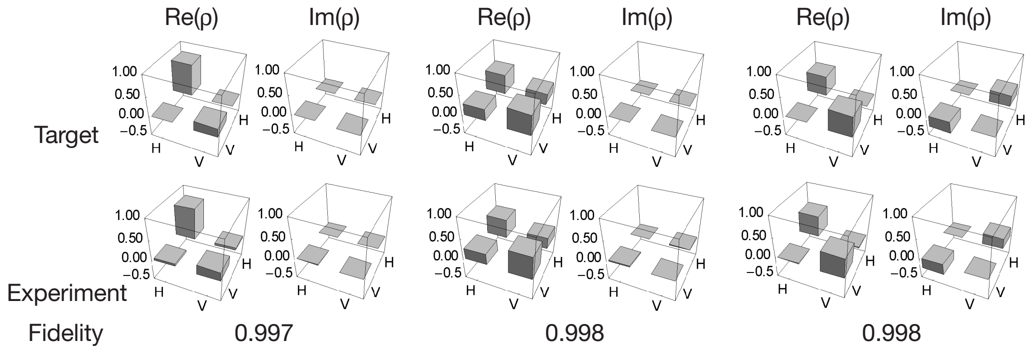


FIGURE 4. Tomographies of remotely prepared states. By making a generalized measurement on her half of a maximally entangled pair, Alice prepares Bob's photon in an arbitrary state. The accuracy of the process is very high, as indicated by the fidelities between the target and the experimentally produced state.

of the source, if Alice and Bob have maximally entangled pairs of photons as a resource, Alice can make a generalized measurement, i.e., using an adjustable partial polarizer. When Alice detects her photons, she has remotely prepared Bob's qubit into an arbitrary quantum state. Figure 4 shows the tomographically reconstructed density matrices of several representative qubit states remotely prepared using this technique. The high fidelity of experimental states with target states indicate good agreement with theory[3]. Further details can be found in reference [19].

COHERENT UP-CONVERSION OF INFRARED PHOTONS

For many quantum communication protocols it is desirable to use photons at telecommunication wavelengths – 1300 nm or 1550 nm – as these wavelengths correspond to low-loss regions in standard optical fiber. One difficulty, however, is that these wavelengths are typically not optimal for detection or coupling to other stationary qubits. For the former, appropriate single-photon detectors are not readily available (typically used are cryogenically cooled InGaAs avalanche photo diodes, which have relatively low efficiencies and high dark counts) [20, 21]. For coupling to stationary qubits, one is constrained by the precise energy scales of the particular qubit system, e.g., the optical transition frequencies in a particular atomic species [22, 23]. Both of these issues can be addressed by using a nonlinear effect to perform a frequency conversion of the telecommunication-wavelength photon to a more optimal wavelength. We have previously demonstrated greater than 80% conversion efficiency of single photons at 1550 nm to 631 nm by combining them in a periodically poled lithium niobate (PPLN) crystal with a bright "escort" beam at 1064 nm (derived from a pulsed Nd:YAG laser) [24]. Detailed theoretical modeling suggests that conversion efficiencies in excess of 95% should be achievable [25]. To be optimally useful for quantum information processing, one must additionally be able to convert arbitrary quantum states, i.e., to demonstrate the coherent up-conversion of a general qubit. Although in this article we have thus far been focusing on polarization qubits, the time-bin qubit [26] has particular advantages for fiber-optic based systems (because, unlike polarization, it is generally unaffected by propagation through optical fiber). In order to demonstrate that our up-conversion process coherently preserves the phase in time-bin qubits, we prepared a coherent superposition of two temporal wave packets at 1500 nm, up-converted them to 631 nm, and demonstrated that they were still coherent. The experimental setup is shown in Fig. 5a, and the observed 90%-visibility interference fringes are plotted in Fig. 5b [27]. As we and others have previously shown that the up-conversion process is linear in the input intensity down to the single-photon level, we believe this is a demonstration of the capability of our up-conversion scheme to perform coherent conversion of arbitrary single qubit states, though experiments are underway to demonstrate this explicitly.

[3] The fidelity is a measure of state overlap [18]. For two general density matrices, ρ_1 and ρ_2, the fidelity is $F(\rho_1,\rho_2) \equiv |Trace(\sqrt{\sqrt{\rho_1}\rho_2\sqrt{\rho_1}})|^2$.

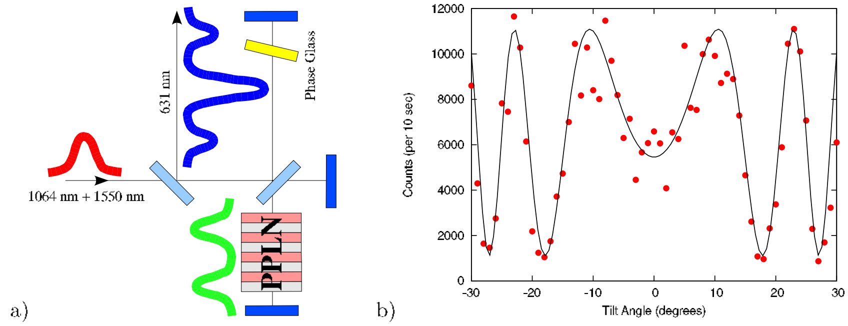


FIGURE 5. a) Schematic of an experiment to demonstrate temporal coherence of the up-conversion process. The escort and input beams travel through long and short arms before being up-converted. Then the output light also travels through long and short arms while the long arm picks up an additional phase based on the tilt angle of the glass. The output light is then detected and time-resolved to collect only photons produced via processes where the short path and long path are each traversed only once. b) The resulting interference fringes (with a visibility of 90%) are shown as a function of the tilt angle of the phase glass, along with a theoretical plot of the fringe pattern.

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