Four-Photon Polarization-Entangled States with Minimal Spectral and Spatial Entanglement

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Abstract: We present two schemes for generating four-photon states: one for direct GHZ state generation and another yielding an entire class of polarization-entangled states. Both begin with photon pairs having minimal spectral and spatial entanglement.

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Spontaneous parametric down-conversion (SPDC) is a reliable source of entangled photon pairs for fundamental studies of quantum mechanics, as well as for specific quantum information applications. Often, attention is restricted to entanglement in a single degree of freedom, such as polarization. In many cases, however, entanglement in auxiliary degrees of freedom must be managed so as to optimize the experimental effects of interest. This is the case, for example, in polarization entanglement swapping and quantum teleportation, where the best results are obtained when spectral and spatial entanglement are minimized [1]. The same can be said for schemes in which multi-photon states are formed from multiple SPDC pairs. That is, unwanted spectral and spatial entanglement in the constituent pairs can adversely affect the fidelity of the resultant multi-photon state. Recently, two-photon polarization entanglement was demonstrated using an SPDC source emitting photon pairs having minimal spectral and spatial entanglement [2]. We extend that work here with two schemes to generate four-photon polarization-entangled states.

Both schemes make use of an SPDC source designed specifically to achieve minimal spectral and spatial entanglement. Spectral purity is achieved through the choices of the pump properties and phase-matching characteristics [3], while spatial entanglement is minimized via a collinear configuration in periodically-poled potassium titanyl phosphate (PPKTP) that is non-critically phase-matched for type-II SPDC. This geometry eliminates walk-off effects and maximizes the overlap of the pump, signal, and idler fields. With a properly focused pump, nearly all of the photons are emitted into a single spatial mode, thus yielding a very bright source of orthogonally polarized photon pairs [4].

The set-up used for the generation of an entire class of four-photon entangled states is an extension of a scheme demonstrated previously [5]. In that work, the SPDC source was oriented for direct generation of a two-photon Bell state and the two outputs were combined on a polarization beamsplitter. For the source described here, the photons are emitted collinearly. Hence, the source configuration does not lend itself to direct Bell-state generation. However, by pumping two parallel regions in the same PPKTP crystal, it is possible to generate a Bell state using only a couple of waveplates and calcite beam displacers. Four-photon entanglement is achieved with a second set of beam displacers and waveplates. The set-up is shown in Fig. 1. A birefringent calcite beam displacer (not shown) divides the pump (776 nm, 1.3 ps) into two beams with orthogonal polarizations. A half wave plate rotates the pump polarization for Type II SPDC and the beams are subsequently incident on the PPKTP crystal. A lens preceding the beam displacer is aligned so that the pump waists are longitudinally centered in the the crystal and the divergence of the pump beam is chosen so as to minimize the spatial entanglement. The result is two independent sources of collinear signal/idler pairs with orthogonal polarizations and minimal spectral and spatial entanglement.

Upon exiting the PPKTP crystal, the signal/idler pairs are incident on beam displacer BD1, which splits them into four paths (two H and two V). A $\lambda/2$ waveplate rotates the polarization of the two center beams–one from H to V, and the other from V to H. The next beam displacer (BD2) then combines beams from different pump paths giving outputs a and b. At this point, the configuration is equivalent to the previously demonstrated two-photon source [2], with the result that a single down-conversion event yields the Bell state $|\phi_{ab}^{(+)}\rangle = [|H_aH_b\rangle + |V_aV_b\rangle]/\sqrt{2}$. When two down-conversion events occur simultaneously, the result is the state $|\phi_{ab}^{(+)}\rangle \times |\phi_{ab}^{(+)}\rangle$, which is further manipulated by another set of beam displacers and waveplates configured in a manner identical to the first set. Upon exiting BD4, the

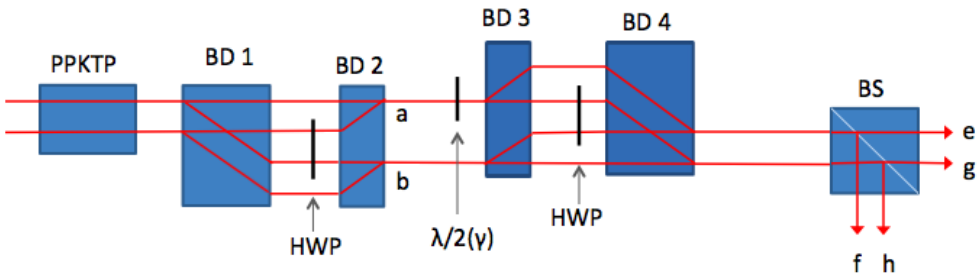

Fig. 1. Generation of a tunable class of four-photon polarization-entangled states.

photons are incident on a 50/50 beamsplitter. When one photon is present in each of the four output paths, the state can be written as $|\psi_4\rangle = \alpha(\gamma)|\psi_{ef}^{(+)}\rangle \times |\psi_{gh}^{(+)}\rangle + \sqrt{1-\alpha^2(\gamma)}|GHZ\rangle$, where $|\psi_{ef}^{(+)}\rangle$ ($|\psi_{gh}^{(+)}\rangle$) is a two-photon Bell state in paths e and f (g and h), and where $|GHZ\rangle = [|H_eH_fV_gV_h\rangle + |V_eV_fH_gH_h\rangle]/\sqrt{2}$ is the four-photon GHZ state. The coefficient $\alpha(\gamma)$ is a tunable parameter that is set by the $\lambda/2$ waveplate between BD2 and BD3. Rotating this waveplate allows one to shift continuously among an entire family of polarization-entangled states, as described in [5].

It is interesting to note that the scheme described above requires two sets of elements: one to transform the collinear photon pairs into Bell states; and a second to transform pairs of Bell states into the four-photon polarization-entangled states. Figure 2 shows a simpler scheme that transforms the collinear output directly into a four-photon GHZ state with no intermediate two-photon entanglement. Two beam displacers (not shown) are used to prepare four parallel pump beams, rather than two. Upon exiting the PPKTP crystal, the photons are split at a polarization beamsplitter, yielding four beams at each output face. These beams are recombined using beam displacers BD5 and BD6, which are of different lengths. The length of BD5 is such that adjacent beams are combined, while BD6 combines alternate paths. The GHZ state results whenever two pairs are created and one photon is detected in each output.

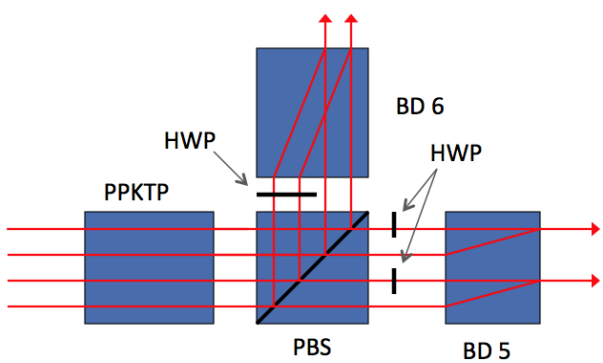

Fig. 2. Direct generation of the four-photon GHZ state.

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