Remote shaping of photonic temporal modes via entanglement

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Photons are the prime candidate for deploying quantum communication protocols. They are excellent carriers of information over telecommunication networks and with diverse degrees of freedom for information encoding: polarisation, spatial, and time-frequency. Among these, the time-frequency degree of freedom stands out as it provides an unbounded space for high-dimensional information encodings compatible with the optical fibre infrastructure and integrated waveguide devices [1]. However, typical quantum protocols require rich entanglement resources which is a non-trivial experimental task, e.g. maximally entangled states. Here, we experimentally demonstrate a complete platform for controlled generation and manipulation of entanglement encoded in temporal modes of single photons. As a notable example, here we remotely prepare photons by projecting their entangled partner into a specific temporal mode.

The outline of our method is sketched in Fig. 1(top). To generate the entangled states, we drive an dispersion-engineered type-II paramteric downconversion (PDC) source by pulses in first-order Hermite-Gaussian temporal-modes. The emitted PDC state can be written as

$$|\psi\rangle_{\mathrm{PDC}} \approx \frac{1}{\sqrt{2}}\left(|\frown_{\mathrm{s}},\sim_{\mathrm{i}}\rangle + |\sim_{\mathrm{s}},\frown_{\mathrm{i}}\rangle\right), \tag{1}$$

which describes signal (s) and idler (i) photons in a coherent superposition of Gauss and first-order Hermite-Gauss modes. This resembles a temporal-mode $|\psi^+\rangle$ Bell state.

A challenging task in quantum communication protocols with temporal modes is the coherent manipulation of a state in this basis. This can be achieved by deploying a quantum pulse gate (QPG). A QPG is a dispersion-engineered sum-frequency generation in a nonlinear optical waveguide, where one photon from an ultrashort pump pulse and a quantum signal fuse into a *green* converted output photon (see Fig. 1(top)). If the QPG is mode-matched to the temporal-modes of the PDC source, it can perform a projective measurement on an arbitrary mode of the single-photon input state.

In Fig. 1(bottom), we show the measured spectrum of the idler photon conditioned upon measurement of the signal photon in different superpositions of Gauss and first-order Hermite-Gauss modes. As an example, when the signal photon is projected into the Gaussian mode, i.e. $\frown_{\mathrm{s}}$, from Eq. (1) is clear that the idler photon would be prepared in the first-order Hermite-Gauss mode, i.e. $\sim_{\mathrm{i}}$. Furthermore, we discuss scalability of the presented scheme for generating and manipulating high-dimensional entangled states.

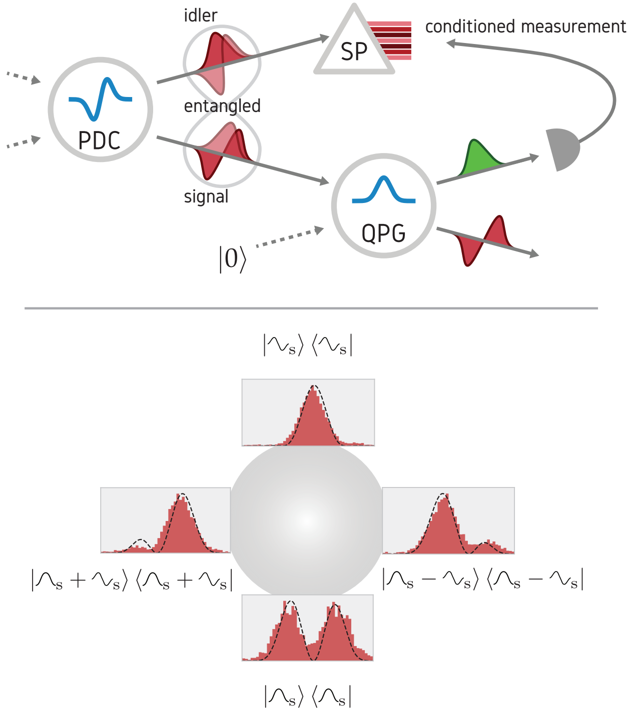

Figure 1: Top: The outline of experimental setup. To generate a Bell-like entangled state (see Eq. (1)), we pump a pp-KTP waveguide with pulses in the first-order Hermite-Gauss temporal mode, which crates signal (TM polarised) and idler (TE polarised) photons. The signal photon is then coupled to a QPG, a dispersion-engineered ppLN waveguide. When the QPG is pumped with a Gauss pulse, it coherently interact with the corresponding mode from the PDC beam and consequently up-converts this mode to a green colour. The idler photon is then characterised with a spectrometer (SP). Bottom: Conditioned spectral measurement of the idler photon upon different signal modes, selected by the QPG. The quantum operators in each case denotes the projective measurement of QPG on the signal photon.

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[1] B Brecht, et al. Photon Temporal Modes: A Complete Framework for Quantum Information Science. *Physical Review X*, 5(4):041017, October 2015.