Phase-Only Shaping of Single-Photon Pulses

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Spectral-temporal modes of quantum light have been recognized as a promising platform for quantum information processing (QIP) and metrology [1, 2]. However, a simple general tool for efficient conversion between spectral-temporal modes is still missing. A phase-only, i.e. in-principle lossless, approach is required for quantum light. The existing phase-only approaches for converting a given input spectral-temporal mode to a given target spectral-temporal mode rely on sequences of complex temporal phase modulations interleaved with propagation in second order dispersive medium, yielding complex setups with often formidable insertion losses. Here we show that such a transformation can be carried out by a single application of a complex temporal phase modulation, and a single application of complex spectral phase modulation.

We use the fact that application of a time-varying phase to an optical pulse results only in modification of its spectral intensity profile (spectrum), while leaving its temporal intensity profile unchanged. Similarly, an application of a spectral phase to a pulse results in modification of its temporal intensity profile leaving its optical spectrum unchanged (as in the case of, for example, chirped pulses). We employ these properties to show that the phases required to convert an arbitrary input single-photon pulse to an arbitrary output single-photon pulses can be found by solving the standard phase retrieval problem between the input spectrum and output temporal intensity profile.

We use the standard Gerchberg-Saxton phase retrieval approach, as well as machine-learning-based approaches to phase retrieval, to find transformations between Gaussian and exponential single-photon pulses and between Hermite-Gaussian spectral-temporal pulse profiles. We further analyse the feasibility of the approach in various regions of the optical spectrum, in particular in the mid-infrared.

We show the feasibility to experimentally implement the arbitrary temporal phase modulations required to realize the transformations. We apply a phase-wrapping approach, inspired by the Fresnel lens, to electro-optic phase modulation. By driving an electro-optic phase modulator with a voltage signal that is wrapped back to 0 upon the electro-optic phase reaching 2π we are able to realize complicated temporal phase variations while maintaining low values of driving voltages. We experimentally implement phase-wrapped parabolic temporal phase modulation of over 2 ns duration. We precede it by quadratic spectral phase modulation implemented using a chirped fibre Bragg grating dispersion compensating module introducing group delay dispersion of $1.2 \cdot 10^4$ ps^2. This allowed us to efficiently convert heralded telecom-wavelength single photons of 0.8 nm spectral bandwidth and 5 ps duration to below 4 pm (500 MHz) spectral bandwidth and above 1 ns duration [3].

The proposed techniques will allow spectral-temporal mode conversion for quantum networks, such as conversion of exponential pulses to Gaussians. The experimental results correspond to converting single-photon pulses compatible with standard optical telecommunication channels to pulses compatible with quantum memories or trapped ions. The techniques may also find applications in quantum metrology and multidimensional QIP.

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