Programming Single-Photon Wavefronts for Quantum Authentication

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35 word abstract: We demonstrate the ability to program the wavefront of single-photon states produced by spontaneous parametric down conversion into complex two-dimensional patterns with a spatial light modulator for application in quantum authentication and quantum communication.

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In quantum cryptography, the non-cloning property of quantum states is essential to achieve quantum security. For practical optical implementation, typically one optical mode is used, for instance that of a single-mode optical fiber, effectively limiting the spatial dimension of the system to one. Only recently researchers have begun to exploit higher dimensional Hilbert spaces for quantum communication [Por08, Sal02] by extending the spatial dimensionality of the system. This provides the unique opportunity to encode additional information in the wavefront of the light. Here we program the wavefront of single-photons with spatial light modulation. Single photons emitted by a bright single-photon source are shaped into a triangular test pattern. We discuss the possibility to use the inverse process: inverse projection, in which a complex spatial pattern is projected onto a single mode exploiting knowledge about the expected pattern. Inverse projection can be used to recognize quantum states of light with complicated spatial wavefronts containing much less photons than the dimensionality of the Hilbert space. Inverse projection is crucial for quantum authentication of physical unclonable functions and cryptography protocols [Sko13, Goo13].

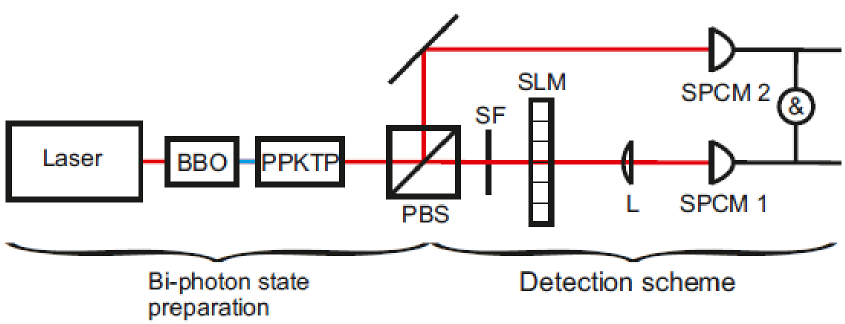

Fig. 1 Simplified setup for shaping the wavefront of single photons. A laser, BBO non-linear crystal (BBO) and a periodically poled KTP non-linear crystal (PPKTP) create entangled photon pairs. The photons of these pairs are separated with a polarizing beam splitter (PBS). The spatial mode of the transmitted photons of this polarizing beam splitter is spatially filtered (SF), expanded and incident on a spatial light modulator (SLM). The resulting wavefront is focused with a lens (L) and is monitored with a single-photon counting module (SPCM 1).

Figure 1 illustrates the setup used for the demonstration of programming the wavefront of single photons. The left part of the setup (up to the PBS) is used for the required heralded single-photon (also "bi-photon") preparation with type-II spontaneous parametric down-conversion, as discussed in Ref. [Hui13]. The spatial mode of the transmitted photons of the polarizing beam splitter (PBS) is spatially filtered with a single-mode fibre (SF) and projected on a spatial light modulator (SLM, Hamamatsu LCOS-SLM). The spatial light modulator projects the single incident mode into separate outgoing modes with different phases. The resulting wavefront is spatially Fourier transformed using a lens (L) and is monitored with a single-photon counting module (SPCM 1) that can be scanned in position for image reconstruction. The reflected photons from the PBS are monitored with a single-photon counting module after spatial filtering (SPCM 2), making it possible to measure coincidence counts with SPCM 1.

Before performing the experiment with single photons, we test the pattern-forming capacity of the SLM with more intense normal laser light. Figure 2a shows the programmed two-dimensional pattern obtained with a CCD camera using incident laser light on the SLM. The desired diffraction pattern is a triangle. In Fig. 2b the observed coincidence rate as function of position is depicted for this pattern with incident single photons (instead of laser light). This two-dimensional pattern clearly demonstrates that we can program single-photon patterns in two spatial dimensions. The resolution of the coincidence rate is limited by the step size to scan the diffraction pattern and the detection aperture of SPCM 1.

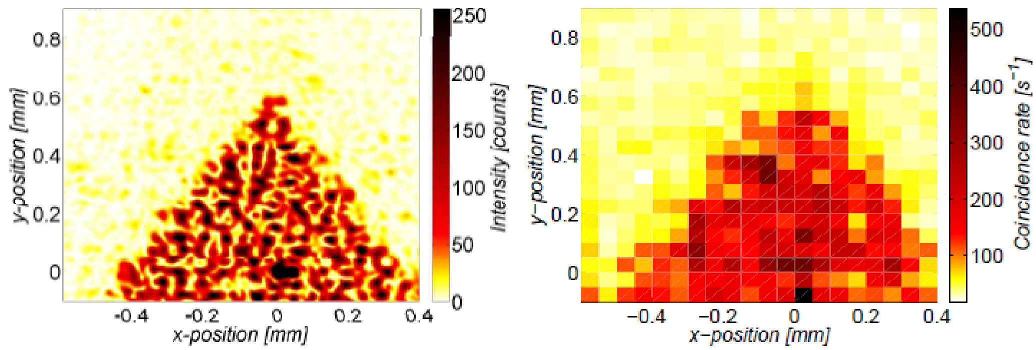

Fig. 2 Observing two-dimensional diffraction patterns. The origin (x = 0, y = 0) indicates the position where the focus of lens L in Fig. 1 would be for a constant phase on the spatial light modulator. (a) Observed diffraction pattern using a CCD camera and laser light. (b) Same diffraction pattern as (a) observed with single photons.

The same setup is able to perform wavefront shaping of single photons through a random scattering medium [Vel07], but it is challenging to take images in coincidence measurement with enough statistics. In Refs. [Hui13, Goo13] we demonstrate that this is possible.

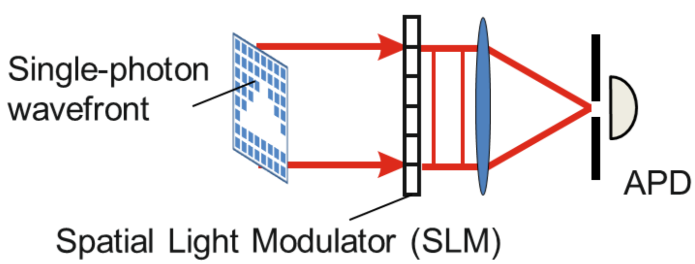

Fig. 3 Pattern recognition by “inverse projection”. If the test pattern (here illustrated by the triangle on the left) matches the expected pattern, most of the light is focused into a single focus. There it can efficiently be measured by a single-photon detector (such as an APD), even if the original pattern contained only a single photon.

An intriguing extension of this work is reversing the arrow of time by using a SLM to map a known complex pattern onto a single mode: inverse projection. The idea is illustrated in Fig. 3. It turns the setup in a pattern recognition system which can work with very few photons since they can be detected efficiently in a single mode. Theoretically it has already been proposed to use a quantum computer for pattern recognition with very few photons [Sch03, Sch06]. We propose a more practical approach by using spatial light modulation instead of a quantum computer. We use this principle to analyse if the light arrives in the expected shape. With spatial light modulation the complex-shaped wavefront is inversely projected onto a single mode. The signal in that mode can be analysed with the standard repertoire of quantum optical measurements, determining, *e.g.*, the field quadratures, the intensity or the number of photons.

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