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Generation and Manipulation of Spatially Entangled Photon Pairs in Nonlinear Waveguides

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Spatial encoding of photonic quantum information offers the advantage of high dimensionality, which can increase the throughput and security of quantum communication protocols. Truly secure quantum communication protocols rely on entanglement. Here we show multimode nonlinear waveguides as a viable platform for integrated generation and manipulation of transverse-mode photonic entanglement. We describe a scheme for generation of spatial entanglement and an integrated electro-optic mode converter for manipulation and verification of spatial entanglement. We numerically show that the proposed devices can be realized in potassium titanyl phosphate (KTP) platform.

Let us consider the process of spontaneous parametric down-conversion in a few-mode $\chi^{(2)}$-nonlinear waveguide, pumped with a beam in single spatial mode. Photon pairs can be produced in different transverse mode pairs. Due to spatial-mode-dependent phase matching different spatial mode pairs are produced in different spectral regions [1]. We show by finite difference modelling that for appropriate choice of periodically poled KTP channel waveguide geometry SPDC processes leading to two spatial mode pairs can be made spectrally indistinguishable. This, combined with appropriate spectral filtering [2,3] leads to production of a transverse mode entangled two-photon state between modes 10 and 00 of the waveguide, exhibiting high fidelity to the maximally entangled state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|10\rangle_H \otimes |00\rangle_V + |00\rangle_H \otimes |10\rangle_V), \quad (1)$$

where H, V label orthogonal polarizations. More complex waveguide geometries could lead to generation of higher-dimensional transverse mode entangled states [4].

Applications of photonic entangled states in quantum-enhanced technologies require the ability to coherently manipulate and detect superpositions of basis states. We propose an integrated dynamic mode converter based on the electro-optic effect in nonlinear channel waveguides for deterministic transformations between mutually non-orthogonal bases of transverse spatial modes. Coupling between two waveguide modes is introduced by means of an appropriately positioned periodic electrode, as shown in Fig. 1(b). Maximum coupling is achieved for spatial frequencies of the electrode patterns equal to the difference in propagation constants of the two spatial modes. For a given electrode length the coupling constant between the spatial modes

can be fully controlled by the voltage applied to the electrodes. This enables converting a photon in one of the basis states $|00\rangle$ or $|10\rangle$ into a superposition of the form:

$$|\phi\rangle = \sin\theta|00\rangle + \cos\theta|10\rangle. \quad (2)$$

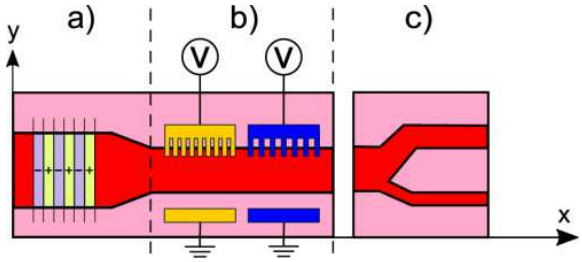

Fig. 65. Top view of the waveguide design for generating and testing of spatially mode entangled state. Region (a) is a multimode channel waveguide with a single QPM grating for generating spatially mode entangled states and region (b) is a two-moded channel waveguide with two asymmetric electrode patterns of different periods to independently control coupling among the H and V polarized spatial modes. Part (c) is an asymmetric Y-splitter separating modes 00 and 10 into distinct output ports. [5]

We theoretically show capability to demonstrate a close-to-maximal violation of a Bell-type Clauser-Horne-Shimony-Holt inequality [6] by measuring spatially mode-entangled photon pairs generated by an integrated photon pair source using the device. The proposed configuration, numerically studied for the potassium titanyl phosphate (KTP) material, can be easily implemented using standard integrated optical fabrication technology.

Summarizing, we demonstrate that nonlinear integrated structures can be efficiently used for generation, manipulation and detection of transverse mode entangled two-photon states of light. This can lead to improvements in spatially multiplexed quantum communication channels.

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