EPJ Web of Conferences **287**, 06014 (2023) https://doi.org/10.1051/epjconf/202328706014
EOSAM 2023

Spatially entangled states of light in nonlinear waveguide arrays - INVITED

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Abstract. We demonstrate a nonlinear AlGaAs photonic chip generating biphotons with nonclassical spatial correlations. Photon pairs are generated by parametric down conversion in a waveguide array and simultaneously spread through quantum walks along the various waveguides. This concept implements a compact and versatile source of spatially entangled states, operating at room temperature and telecom wavelength, that could serve as a workbench for simulating condensed matter problems on-chip.

Introduction

High-dimensional degrees of photons – such as orbital angular momentum, spatial modes of frequency – provide a powerful mean to increase the density and security of quantum communication, and to enhance flexibility in quantum computing. In particular, the spatial degree of freedom is particularly suited to on-chip integration. Rapid progress has been made in recent years to develop integrated circuits achieving on-chip quantum interference, entanglement and gate operations on spatially encoded states, culminating in the demonstration of the Boson Sampling task on-chip [**?**]. While many of these demonstrations have relied on external sources to generate quantum states of light, which were then fed into a passive circuitry, a next step has been taken recently with the demonstration of active chips combining the generation and manipulation of spatially encoded states [2].

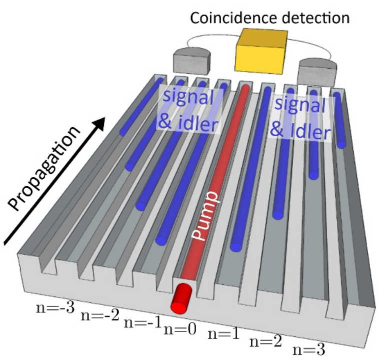

Figure 1: (a) Sketch of a nonlinear waveguide arrays for cascaded quantum walks.

Principle

Among these active photonic circuits, *arrays of nonlinear waveguides* appear as a promising candidate to investigate quantum simulation tasks. The working principle of the studied device is shown in Fig. 1a: pumping the central waveguide with a visible pump laser (775 nm, sketched in red) leads to the generation of photon pairs at telecom wavelength (sketched in blue) by spontaneous parametric down conversion (SPDC). Thanks to evanescent coupling these photons pairs then undergo quantum walks by tunnelling to the neighbouring waveguides. In contrast to previous experimental studies of quantum walks [1, 3], the walkers are here directly created within the device, and the generation can take place at any position along the propagation axis. Besides a gain of integration, such *cascaded quantum walks* allow for a significantly higher level of spatial entanglement, due to the interference between quantum walks initiated at all possible longitudinal positions [4].

The resulting spatial entanglement of the biphotons can be visualized on a map of the spatial correlations, as shown in our simulations in Fig. 2. When pumping only the central waveguide $n = 0$ (Fig. 2a), we observe that photons have an enhanced probability to exit the device either through the same waveguide (spatial bunching) or through opposite waveguides (spatial antibunching). When pumping guides $n = 0$ and $n = 1$ in phase (Fig. 2b), antibunching is selectively enhanced; when pumping those guides in phase opposition (Fig. 2c), bunching is favored.

Experiments

We have investigated nonlinear waveguide arrays based on AlGaAs Bragg reflection waveguides, realized by molecular beam epitaxy followed by ICP dry etching. Figure

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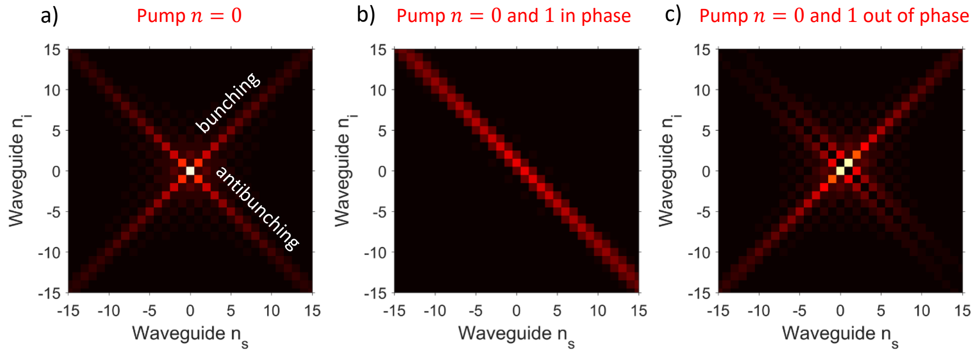

Figure 2: Calculated spatial correlations at the output of the lattice, when pumping (a) only the central waveguide $n = 0$, (b) guides $n = 0$ and $n = 1$ in phase and (c) guides $n = 0$ and $n = 1$ out of phase.

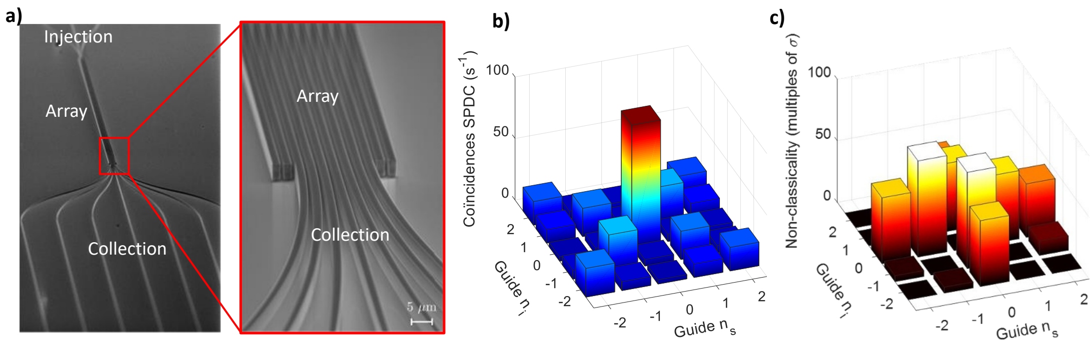

Figure 3: (a) SEM image of an AlGaAs waveguide array. (b) Measured spatial correlations and (c) non-classicality violation matrix.

3a reports SEM images of a fabricated sample, showing the evanescent coupling region (array, where the quantum walks take place), fan-in S-bent waveguides for the injection of the pump beam and fan-out waveguides for the collection of the SPDC photons out of the array.

The quantum state of the biphotons at the array output is characterized by measuring the coincidences within each waveguide, and between all possible couples of waveguides, using superconducting nanowire single-photon detectors connected to a time tagger. The result is shown in Fig. 3b for the Hilbert space spanned by the 5 waveguides around the pumped waveguide (labeled $n = 0$). We observe strong correlations along the diagonal, corresponding to a spatial bunching of the photons, and along the andidiagonal, corresponding to a spatial antibunching of the photons, in good agreement with our simulations (Fig. 2a). To establish the nonclassicality of the measured correlations, an entanglement witness can be used, leading to an average violation of the classical limit by up to 40 standard deviations for several points of the correlation matrix (Fig. 3c).

A wider zoology of quantum states can be produced by further tailoring the pump configuration, leading to a compact and versatile source of spatial entanglement operating at room temperature and telecom wavelength. In the future, other lattice geometries can be envisaged: e.g. alternating two coupling distances implements a nonlinear version of the SSH Hamiltonian, allowing to investigate

the topological protection of photon pairs. Alternatively, disorder can be introduced deterministically in the array to study e.g. the Anderson localization of multi-particle states, making this platform appealing to simulate physical problems otherwise difficult to access in condensed matter systems.

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