Photon-Pair Generation in Defect-Free Surface Modes

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Abstract: We experimentally demonstrate simultaneous generation and propagation of photon pairs in defect-free surface modes in an array of coupled sinusoidal waveguides. The measured biphoton correlations remain robust to tuning the curvature.

1. Introduction

The generation of photon pairs is of a paramount interest within the field of quantum information, computing, and communications. In quantum photonics systems, photon pairs can propagate macroscopic distances with minimal decoherence, but system disorder and fabrication imperfections can still disturb the quantum state. The use of topological lattices has been recently investigated for the robust generation and manipulation of various photon-pair states. [1-3]

Following the theory [4] and the experimental demonstration [5] of defect-free surface modes in waveguide arrays, we deploy an array of sinusoids in order to investigate the generation and propagation of correlated photon pairs. The array is implemented in a fully CMOS-compatible Silicon-on-Insulator (SOI) platform. There we leverage high nonlinearity available in silicon waveguides to generate correlated photon pairs through spontaneous four-wave mixing (SFWM), a χ^3 nonlinear process in which two photons at the pump frequency get annihilated and give rise to a signal and idler photon-pair satisfying energy and momentum conservation. [6] We show that the spatial evolution of the biphoton probability (a wavefunction spanning the real-space indexed by the waveguide numbers for the signal and idler photons) remains localized at the edge for certain amplitudes of the curvature, a fact which relies not on any defects within the lattice array, but on the periodic curvature itself. Specifically, the biphoton probability remains localized as long as the amplitude of curvature A within 10% of the critical bending amplitude $A_0 = \xi\lambda L/4\pi^2 n_0 d$, where ξ is the first root of the Bessel function of the first kind, λ is the wavelength, L is the period of curvature, n_0 is the refractive index, and d is the center-to-center spacing of the waveguides at the crest of curvature, as shown in Fig. 1(a). For our experiment, we use three different structures with amplitude ratios $A/A_0 = 1.0$, $A/A_0 = 1.1$, and $A/A_0 = 1.2$. Thus, we demonstrate that the propagation remains robust even when the geometric parameters are significantly detuned from their optimal values.

2. Results

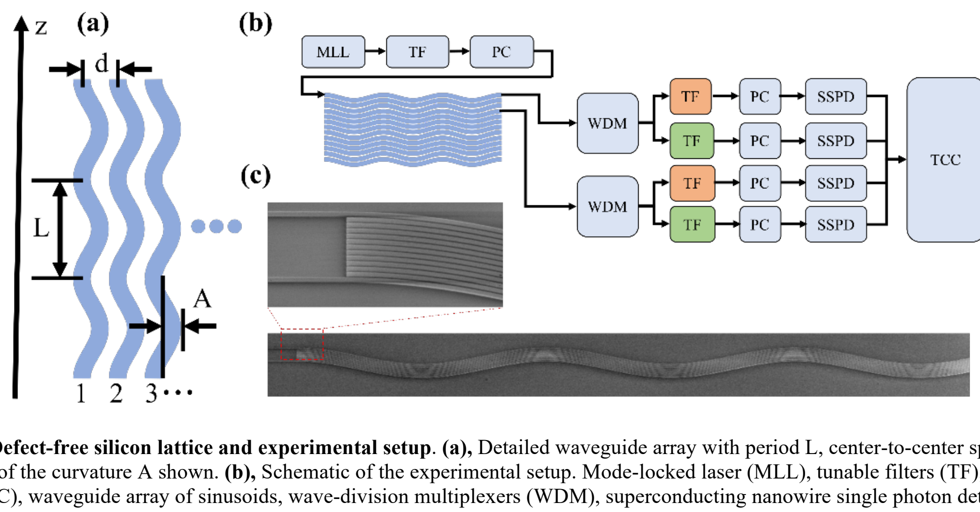

Figure 1 Defect-free silicon lattice and experimental setup. **(a),** Detailed waveguide array with period L, center-to-center spacing d, and amplitude of the curvature A shown. **(b),** Schematic of the experimental setup. Mode-locked laser (MLL), tunable filters (TF), polarization controllers (PC), waveguide array of sinusoids, wave-division multiplexers (WDM), superconducting nanowire single photon detector (SNSPD), and time-correlation circuit (TCC) labeled in the appropriate order of forward light propagation. **(c)**, SEM images of the sinusoidal waveguide array with inset showing more detail. Also shown in the inset are the two waveguide inputs at each edge.

Figure 1(b) presents a schematic of the lattice of sinusoidal silicon-on-insulator waveguides (rectangular cross-section height h = 220 nm, width w = 450 nm, and center-to-center spacing d = 650 nm) comprising three periods and the experimental setup used to achieve generation and propagation of photon pairs on defect-free surface modes. We chose L = 100 µm, which leads to A_0= 4.14 µm at λ = 1550 nm. Picosecond pulses from a mode-locked laser (MLL) at 1550 nm are input into the edge waveguide of the array, giving rise to photon pairs through SFWM upon propagation in the waveguides. At the output of the array, signal and idler photons, at 1542.75 nm and 1552.78 nm wavelength, respectively, are spectrally separated and detected with superconducting nanowire single photon detectors (SNSPDs). Their correlations are identified using a time correlation circuit (TCC). Figure 1(c) depicts the SEM imaging of the structure with the input waveguides shown in the inset.

Figures 2(a-c) shows the characterization of the classical pump for the defect-free surface modes. Here, we compare the theoretical finite element method (FEM) first-principles modeling (left) to the measured pump power from the experimental setup (right). As expected, the pump mode localizes at the edge of the lattice for the $A/A_0 = 1.0, 1.1$ cases but begins to discretely diffract into the bulk for the $A/A_0 = 1.2$ case.

Figures 2(d), (f) and (h) show the measured correlated photon-pair counts between waveguides for the amplitude ratios $A/A_0 = 1.0, 1.1, 1.2$, respectively. The photon pair localizes to the edge for the appropriate amplitude ratios and begins to delocalize for the $A/A_0 = 1.2$ case. The measurements qualitatively match the theoretical predictions in Figs.(e-i). The Schmidt decomposition of the output states reveals a larger number of significant coefficients for the delocalized measurements in Fig. 2(h) than for the localized cases in Figs. 2(d) and (f).

In conclusion, we demonstrated the simultaneous generation and propagation of photon pairs in defect-free surface modes in curved silicon waveguide array. We have shown that the degree of biphoton localization can be tuned by changing the amplitude of the curvature, providing an additional mechanism to control biphoton correlations in waveguide arrays. This work also represents an analogy to dynamic localization of charged particles in AC fields.

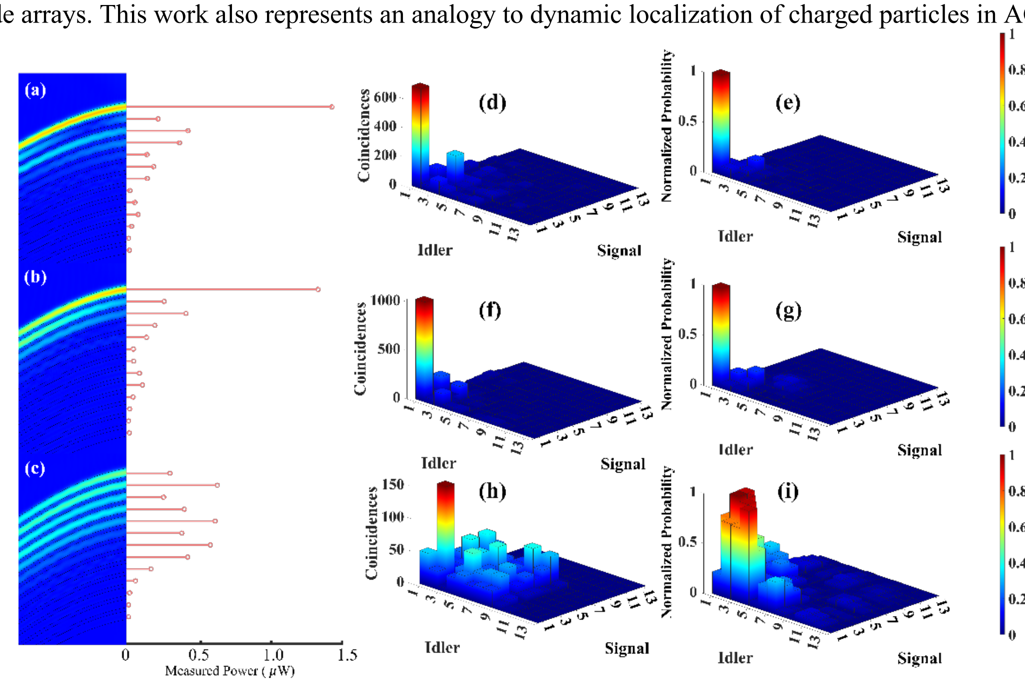

Figure 2 Photon-pair wavefunction. **(a), (b), (c),** Shown here from top to bottom are the first-principles FEM simulations for the pump after propagating through three periods of the sinusoidal curvature, the predicted electric field norm along the transverse direction of the waveguide array at the edge, and the measured power for each waveguide for the experimental setup. **(a), (b), (c)** represent the measured classical pump power for $A/A_0 = 1.0,1.1,1.2$ respectively. **(d), (f), (h)** represent the measured correlation counts for the experimental setup for $A/A_0 = 1.0, 1.1, 1.2$ respectively. **(e), (g), (i)** represent the theoretical photon-pair wavefunction for $A/A_0 = 1.0, 1.1, 1.2$ respectively.

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