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Annular waveguide single photon tomography

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***Abstract*— Photonic chips are devices capable of integrating optomechanical components—such as waveguides, beamsplitters, single-photon sources, and detectors—into compact platforms. The waveguide used in this project enables the conversion of Gaussian modes to orbital angular momentum modes by tuning the input beam. The resulting state superposition is characterized using quantum state tomography (QST), allowing reconstruction of the state vector ρ.**

***Keywords*— Photonic chips, orbital angular momentum, quantum state tomography, single photon, annular waveguide.**

I. Introduction

Integrated photonics has emerged as a promising field, enabling the study of fundamental quantum mechanics and quantum information phenomena through compact and scalable devices. Photonic chips, are capable of providing scalable, realiable fast processing of data and can be used in quantum communication, including quantum key distribution protocols (QKD) and quantum teleportation [1]. These devices have also been integrated with interferometers for quantum cryptography as well as with quantum dots integrated into photonic nanostructures [2-3]. One of the most fundamental properties of photons is ther momentum. Allen et al. [4] introduced the concept of OAM in vortex beams, noting that optical vortices propagate within paraxial beams. These vortex beams are defined by an azimuthal phase term $e^{i\ell\phi}$, carrying OAM equivalent of $\ell\hbar$ per photon, where ℓ is known as the topological charge that defines the OAM of the light field [5-6]. A notable example is the Laguerre-Gaussian (LG) family of beams.

Conservation of OAM at the single-photon level in Spontaneous Paramentric Down Conversion (SPDC) sources have been reported in [5]. The OAM of light and the direct laser writing of annular waveguides on photonic chips are reported in [7-8]. The work presented in [7] opens the door to a new challenge: Is it possible to couple single photons and generate OAM using an annular waveguide? How can one discriminate between the types of mode superpositions that are produced? In this work, we present the quantum state tomography of single photons in annular waveguides fabricated via direct laser writing in the LG modes, analyzing the preservation of the correlations of heralded pairs during the process of coupling and propagation. The goal of this work is to measure the single photon density operator in the LG basis after transversing the annular waveguide.

A. Quantum tomography

Quantum systems often exhibit important features, such as quantum coherence and entanglement, which are of great interest in quantum information science. However, in most experimental settings, complete information about a quantum system is either unknown or inaccessible, rendering the state vector representation inadequate. The system of interest can be in a statistical mixture of pure states or be a part of a state of an composed system. When one aims to fully characterize an unknown quantum state, reconstruction quantum state methods must be employed.

Quantum State Tomography (QST) is a powerful technique for experimentally reconstructing an unknown quantum state by estimating the operator density ρ from measurements in a well-known basis of state [9].

We use a spatial light modulator (SLM) to generate phase masks/holograms that modify the OAM of the waveguide output beam. By projecting unknown superpositions of LG modes onto these holograms, we perform QST with respect to a known basis of OAM states to reconstruct the density operator after coupling of the gaussian beam with the waveguide.

For example, if the waveguide outputs a pure LG mode with $p = 0$, $l = 1$–known for its doughnut-shaped intensity profile–this beam can then be directed onto a SLM encoded with a hologram for a mode with $p = 0$, $l = -1$. The SLM produces a projection onto the Gaussian mode, $l = 0$, that is a flatten wavefront phase and can be transmitted to a single mode fiber. By comparing power measurements before and after projection, one can infer the modal purity of the waveguide output and quantify the generated OAM.

This projection process on pure LG modes and superposition of LG modes enables quantum state tomography of the guided light. Holograms on the SLM act as POVM (Positive Operator-Valued Measure) or projectors for quantum state tomography. This method allow us perform the desired reconstruction of the vetor state ρ.

II. Results

A. Heralded Single photons

We sucessfuly coupled single photons in the OAM conversor waveguide photonic chip. The annular waveguide converts gaussian modes in OAM modes. We employed the following method: a) We implemented a coupling system to the waveguide by using a multimode fiber and an objective lens to direct a photon from the pair generated by SPDC to it. The unused photon from the pair was directed through a similar coupling system for the heralding process. b) After one photon being transmitted through the waveguide, just before the detector coupling system photon, a $200\mu m$ pinhole was installed. Its

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purpose was to select the propagation direction and ensure only the guided SPDC photon from the pair was allowed through. c) By shifting transversely the pinhole in increments of 200μm and recording coincidence data between the guided photon and the other photon of the pair, we plotted the results using a software, to reconstruct the profile of the single photon spatial distribution. The results are shown in Figure 1:

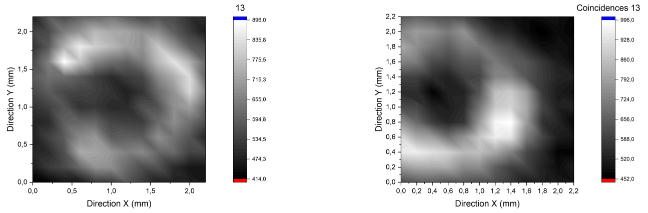

Fig. 1: Reconstructed images of heralded SPDC single photons that transversed through the annular waveguide, indicating the conversion of a Gaussian to an OAM mode.

B. QST of OAM modes

The projection process described in I-A, enables quantum state tomography of the guided light. Specific LG mode superpositions using holograms on the SLM are realized. These holograms act as POVM or projectors for quantum tomography. This method allow us perform the desired reconstruction of the vector state ρ in the LG basis [10-11]. The reconstruction is based on Born's rule, applied to the projector operators and using a Python script, the measured intensities are converted into the matrix elements of ρ, plotted, which were then visualized as bar plots. Figure 2 displays a state reconstruction performed over a determined superposition of OAM modes. Figure 3 displays the real and imaginary parts of the reconstructed density matrix for the Hilbert space $l = -2, l = -1, l = 1, l = 2$ (d=4).

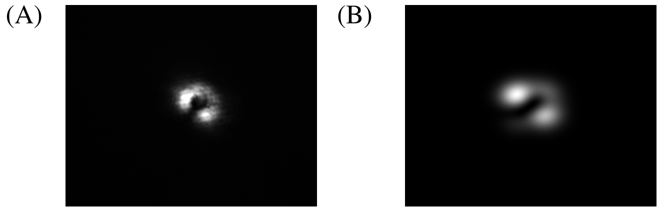

Fig. 2: Tomographic reconstruction of the guided single-photon OAM transverse profile. a)Profile measured with a laser beam. b) Single photon profile obtained from the measured ρ.

- Figure 3-a illustrates the real components of ρ, highlighting both positive (turquoise) and negative (violet) entries.
- Panel 3-b presents the imaginary components of the density matrix.

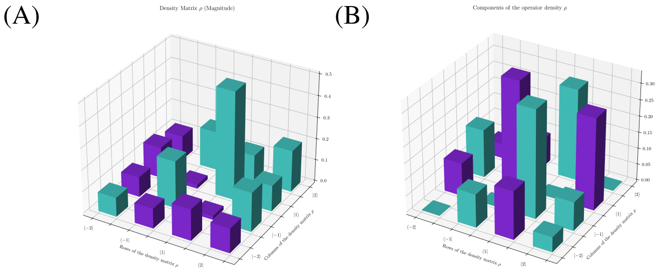

Fig. 3: Real (a) and imaginary. (b) components of the reconstruced matrix ρ in subspace d = 4 in the LG basis.

III. CONCLUSIONS

We successfully coupled heralded single photons into the OAM-converting annular waveguide chip. During the coupling process, the beam's wavefront that reaches the waveguide facet experiences a transversal displacement y, x, relative to the coupling reference axis $x = y = 0$, which corresponds to an optical path difference Δ between these points. Using carefully designed projection methods for QST we were able to discriminated and determine the superpositions of OAM modes created by the OAM waveguide and measure the density operator of the converted beam in the LG basis.

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