Engineering exotic hybrid states

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Abstract

Entangled quantum states find themselves in many active fields, such as cryptography and information transfer. High dimensional states are desirable as they can carry large amounts of information. One method used to scale the amount of information carried by these states is to use higher dimensional degrees of freedom (DOFs). However, these states are fragile, easily disturbed by noise, and difficult to measure. Conveniently, one can create a hybrid entangled state, where we entangle higher dimensional DOFs with robust, 2D DOFs. This shifts us from one high dimensional fragile entangled state to multiple robust 2D entangled states, allowing us to leverage the advantages of both DOFs. Using a novel interferometric device, hybrid states were generated using a spin to orbit conversion technique implemented on photons produced from a spontaneous parametric down conversion process. This compactly designed interferometer was used to digitally generate arbitrary hybrid states entangled in orbital angular momentum and polarisation. Several hybrid states of high purity were generated using this interferometer and Bells inequalities were violated with high visibilities. Our approach allows for a wide variety of hybrid states packed with a large amount of easily measurable information. These hybrid states have great potential for use in real world information transfer.

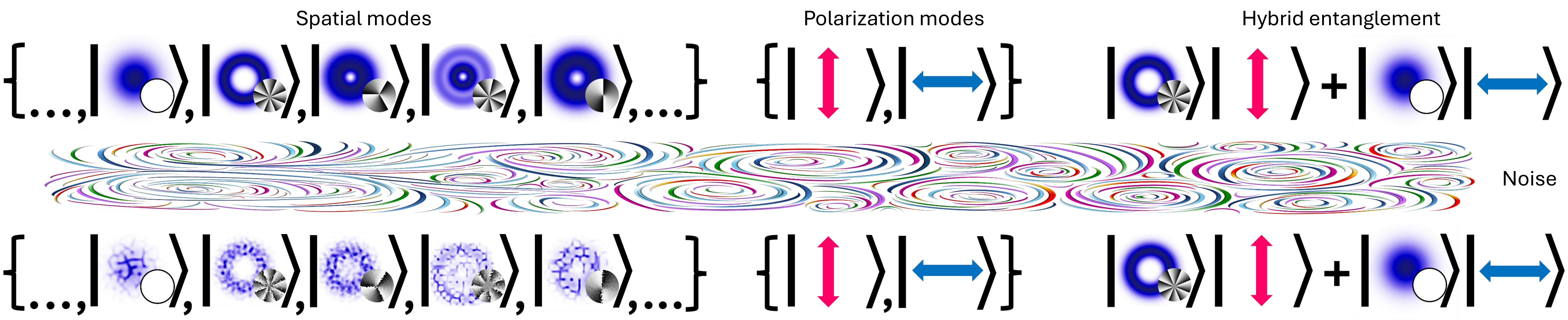


Fig. 1: Rich library of spatial modes and two dimensional set of polarization modes. Spatial modes get significantly distorted once subject to noise, whereas polarization modes remain intact. Hybrid states are created by coupling a spatial mode to a polarization mode and thus can link the numerous spatial modes and the information they carry to the robust polarization modes, allowing them to be sent through various different noisy channels.

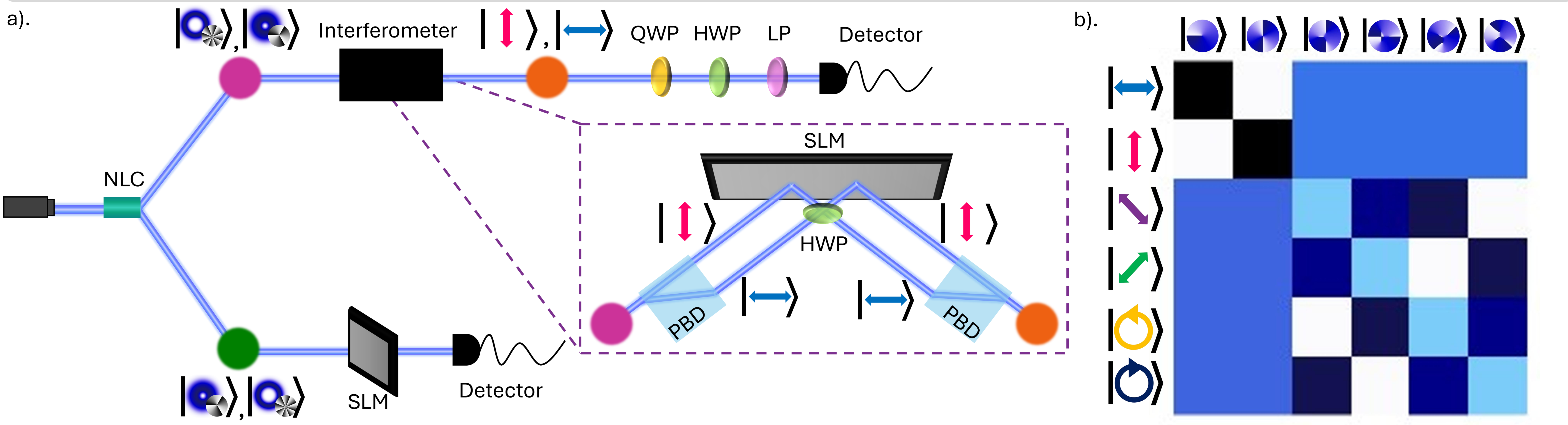
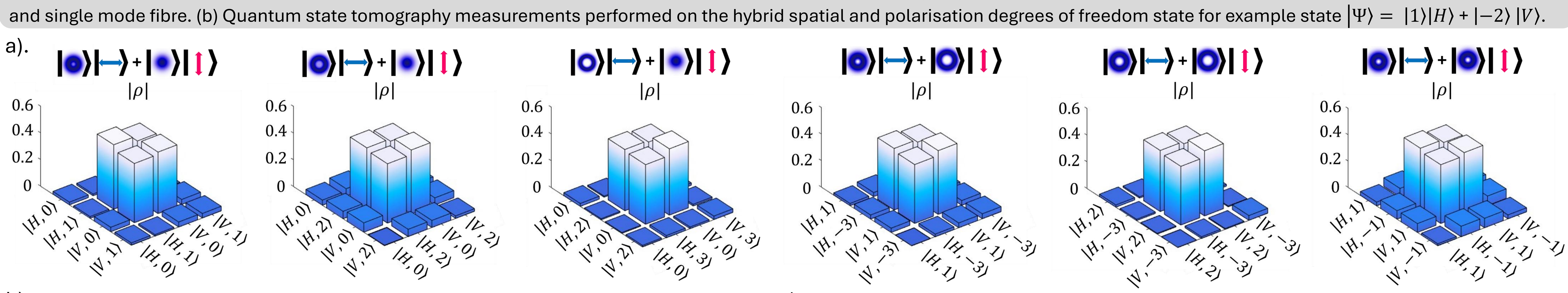
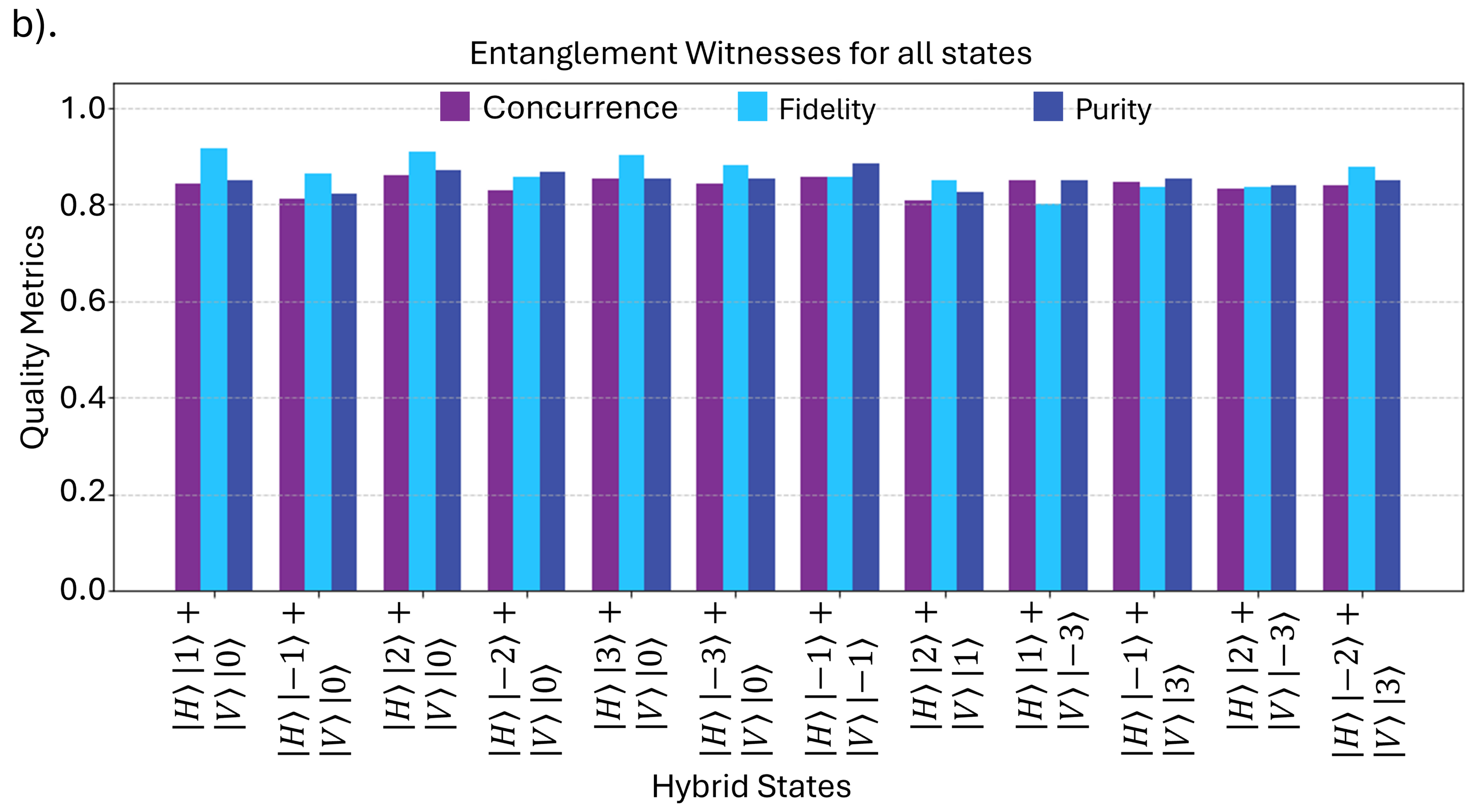
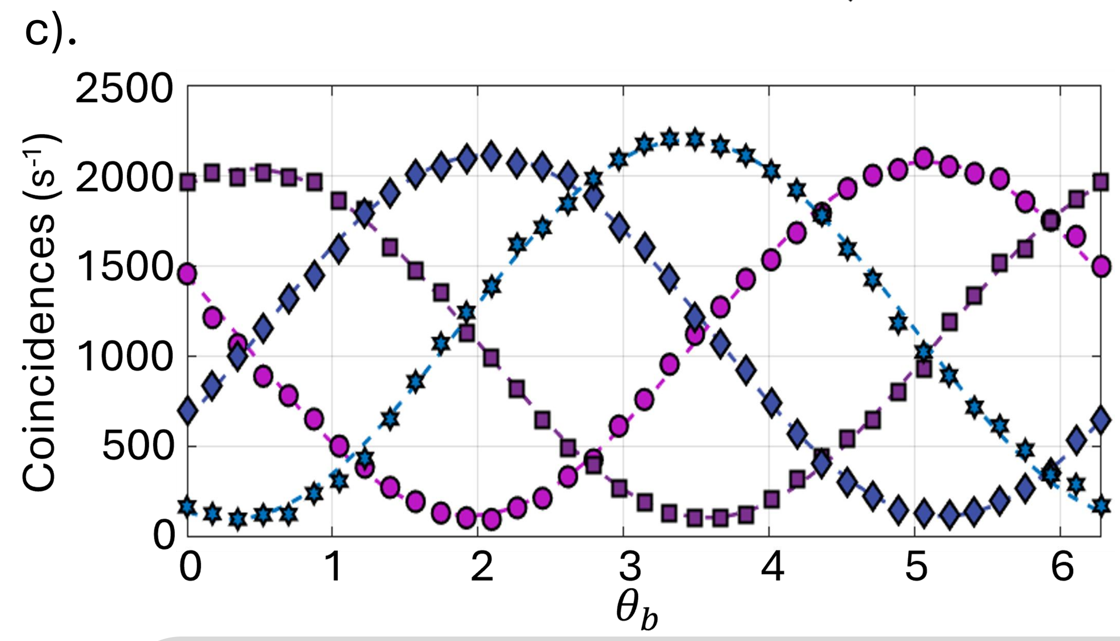


Fig. 2 (a): Experimental set up used to generate hybrid states showing the photons leaving the crystal entangled in orbital angular momentum. The signal photon is sent through the interferometer, which couples the internal spatial and polarisation DOFs as shown in the inset to create the hybrid states. Spatial measurements are made on the idler photon using a SLM and single mode fibre. (b) Quantum state tomography measurements performed on the hybrid spatial and polarisation degrees of freedom state for example state $|\Psi\rangle = |1\rangle|H\rangle + |-2\rangle|V\rangle$.







Subspace	Visibility	S_{bell}
{−1,1}	0.903	2.486
{−2,2}	0.900	2.539
{−3,3}	0.868	2.451
{−4,4}	0.797	2.250

Fig. 3 (a): Absolute density matrices of a small portion of all the states generated using the interferometer. (b) A summary of all the entanglement witnesses used to characterise the quality of the states produced. The entanglement witnesses consisted of concurrence, fidelity and purity. (c) A Bell curve for the subspace {-2,2}, Bell measurements were taken for the four subspaces shown in the table on the left. All visibilities were found to exceed 79% and Bells parameter was violated such that $S_{bell} > 2.2$.

[1] Isaac Nape *et al* 2022 *J. Opt.* **24** 054003