Poincaré Electo-Optic Transporter for Quantum Logic Applications

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Abstract: We present an experimental scheme for realizing a connection on the Poincaré sphere enabling us to implement, with a single electro-optic device, dubbed Poincaré Electro-Optic Transporter (PEOT), any unitary transformation of a polarization-encoded single photon qubit.

Quantum computers leverage superposition, entanglement, and interference to solve problems beyond the reach of classical computation. Among various hardware platforms, **photonic systems offer distinct advantages**, including room-temperature operation, robustness against decoherence, and access to multiple degrees of freedom for **high-dimensional quantum encoding**. Despite the probabilistic nature of photon–photon interactions that limits deterministic gate implementation, these same properties have enabled complex tasks such as **boson sampling and multi-qubit entanglement generation**. This work presents an experimental scheme to realize a **connection on the Poincaré sphere** enabling us to implement, with a single electro-optic device, dubbed **Poincaré Electro-Optic Transporter (PEOT)**, any unitary transformation of a polarization-encoded single photon qubit. To realize a geometric connection on the Poincaré sphere, the device utilizes a sequence of **electro-optically driven retardation waveplates**[1] with differently oriented optic axes that can be selectively switched on and off with controllable phase retardations. This connection enables a **controlled transport** of the polarization state of single photons along an **arbitrary path on the Poincaré sphere**. Therefore, a single photonic device can be exploited to **implement any single qubit logic gate**.

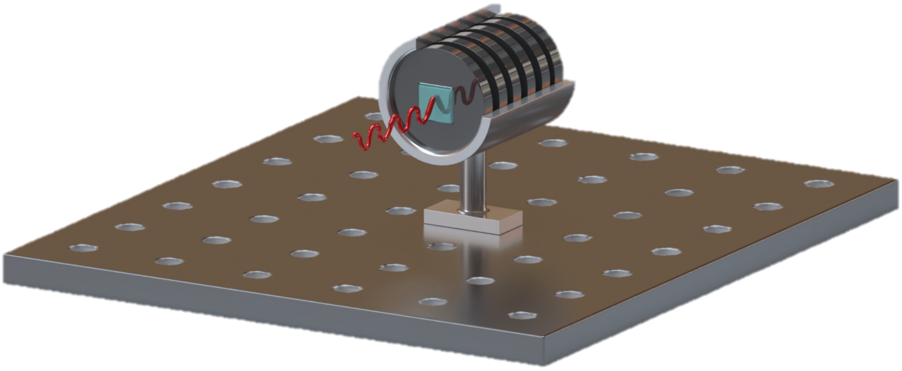

Fig. 1 3D Render of the PEOT. The image shows the physical realization of the PEOT, the series of electro-optically driven retardation plates is positioned in a way that allows the photons to go through without ever having to move the apparatus to switch on or off the plates.

The same device can be alternatively utilised to perform a spatially resolved **polarization map** of photon wavefronts turning into a **Polarization State Analyzer (PSA).**

It’s possible to obtain any given trajectory on a Poincaré sphere using electro-optically driven plates exploiting a configuration featuring a sequance of two retardation waveplates, By modifing the optical axis of the first electro-optically driven waveplate and the retardation of the second one, it’s possible to achieve any configuration, thus tracing every possible path on the Poincaré sphere. After a sequence of trasformations, in order to represent the trajectory on the sphere, we must use the Müller matrix representation, the overall transformation is described as follows:

$$S'_{out} = M_{retarder}(\delta, \theta) S'_{in} \qquad S' = (S_1, S_2, S_3)^T$$

in which matrix $M_{retarder}$ is a *3x3* submatrix of the full Müller matrix that effects the rotation, the overall trajectory is given by the cumulative effects of subsequent rotations.

Here we are able to give a demonstration of how using **Spatially Varying Retardation Waveplates (SVAPs)**, can be a powerful technique for **mapping the complete phase profile** of photons[2]. The key to this method is the ability to precisely determine the local optic axis pattern (Figure 1.a), which is mathematically complex (e.g., *q=1* starfish mode).

This pattern directly dictates the phase profile (Figure 1.b) imparted to the light. Crucially, standard observation methods using only crossed polarizers (Figure 1.c) are insufficient as they fail to distinguish between orthogonal axis orientations. The solution is the introduction of a second, known retarder - a birefringent λ-compensator - placed at *45º* (Figure 1.d). The resulting change in optical interference colour fully unveils the underlying optic axis pattern, which is the foundational map for generating complex polarization structures like starfish modes.

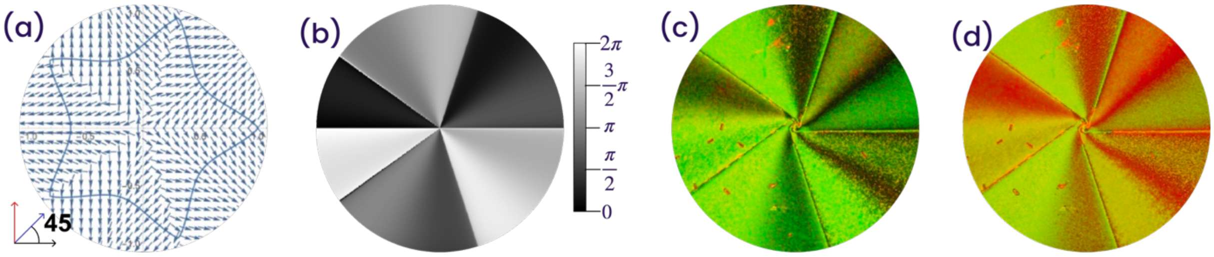

Fig. 2 Experimental observation of the optic axis distribution of the starfish SVAP ($q = 1, a = b, m = 5, n_1 = 1/2, n_2 = n_3 = 4/3$): (a) Optic axis pattern; (b) the phase profile imparted by the SVAP to an input beam; (c) a microscope image of the SVAP between crossed polarizers; (d) a microscope image of the SVAP between crossed polarizers and a birefringent compensator plate at 45°.

References

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[2] P. Darvehi, V. Vicuña-Hernández, L. Marrucci, E. Piedipalumbo, E. Santamato, and B. Piccirillo, "Increasing the topological diversity of light with modulated Poincaré beams," J. Opt. **23**, 054007 (2021).