Geometric-Phase Engineered Spin–Orbit Photonic Gates for High-Dimensional Quantum Information Processing

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Abstract: We introduce a geometric-phase photonic architecture enabling polarization-controlled spin–orbit transformations for hybrid SAM–OAM quantum gates. Gouy phase engineering enables deterministic qudit operations in a compact, non-interferometric platform for high-dimensional quantum information processing.

We introduce a geometric-phase-engineered photonic architecture enabling polarization-controlled spin–orbit transformations for hybrid quantum information processing. The platform exploits the Pancharatnam–Berry phase to induce polarization-dependent quadratic wavefront shaping, enabling deterministic and conditional manipulation of structured optical modes.

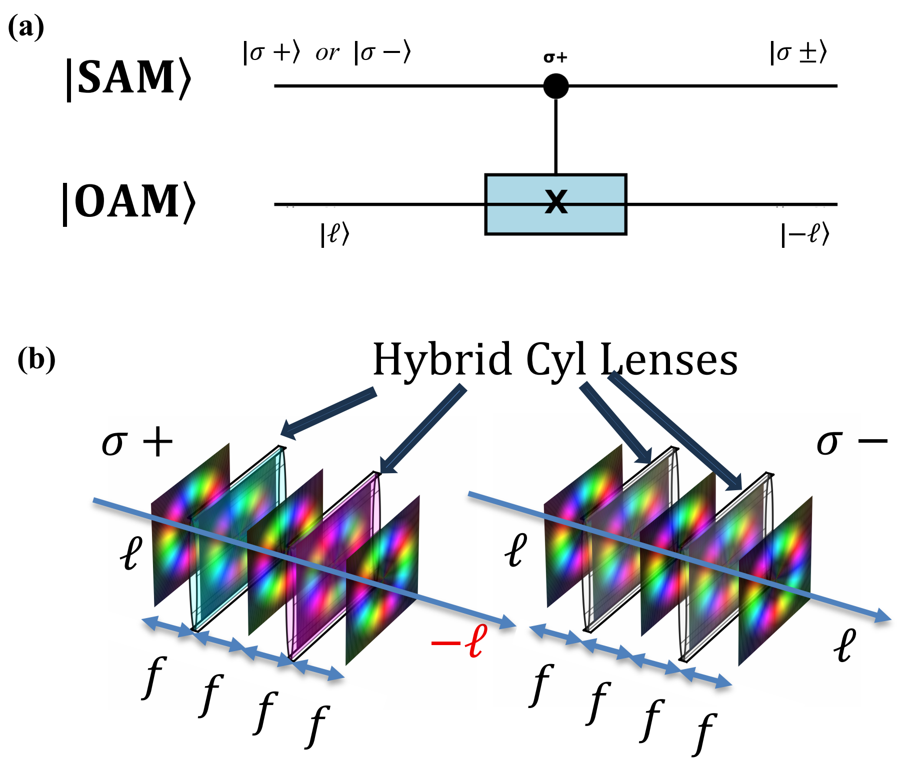

Fig. 1. Geometric-phase-controlled spin–orbit photonic gate for high-dimensional quantum processing.
(a) Polarization-dependent geometric-phase elements induce opposite wavefront curvatures, enabling conditional control of structured optical modes.
(b) Deterministic mode conversion enabled by π Gouy phase accumulation in a non-interferometric configuration.

In this scheme, polarization (spin angular momentum, SAM) acts as a control degree of freedom, while transverse spatial modes, including orbital angular momentum (OAM), define a high-dimensional target Hilbert space. Engineered geometric-phase elements produce opposite curvature transformations depending on the input polarization, enabling conditional evolution of structured beams without requiring interferometric stability. The underlying spin–orbit interaction framework of light is well established [1,2].

A key feature of the architecture is a π-phase propagation stage, where controlled Gouy phase accumulation is promoted from a propagation effect to a functional resource for deterministic mode conversion. This mechanism enables the implementation of CNOT-like operations between polarization and spatial degrees of freedom in a compact and intrinsically stable configuration. The relation between astigmatic mode conversion and Gouy phase accumulation is well established in cylindrical optical systems [3], and can be traced back to the fundamental phase anomaly originally identified by Gouy [4].

Previous CNOT proposals and implementations involving polarization and orbital angular momentum include the seminal theoretical work by Deng et al. [5] and the linear-optical implementation by Lopes et al. [6]; more recent high-dimensional extensions often employ polarization-controlled spatial/path targets rather than genuine OAM-encoded targets. In this context, the present approach provides a direct route toward polarization-controlled transformations in structured light modes within a unified wavefront-engineering framework.

Residual mode distortion arising from fabrication tolerances and finite propagation distances is analyzed within an effective wavefront description. Design conditions are identified to approach near-afocal behavior and suppress astigmatic aberrations through appropriate geometric-phase engineering.

The scheme naturally extends to high-dimensional quantum systems, enabling scalable qudit encoding in structured light. As a proof-of-principle application, we outline the implementation of the Deutsch algorithm in a qudit framework, highlighting the potential of geometric-phase spin–orbit coupling for compact and scalable quantum photonic processing.

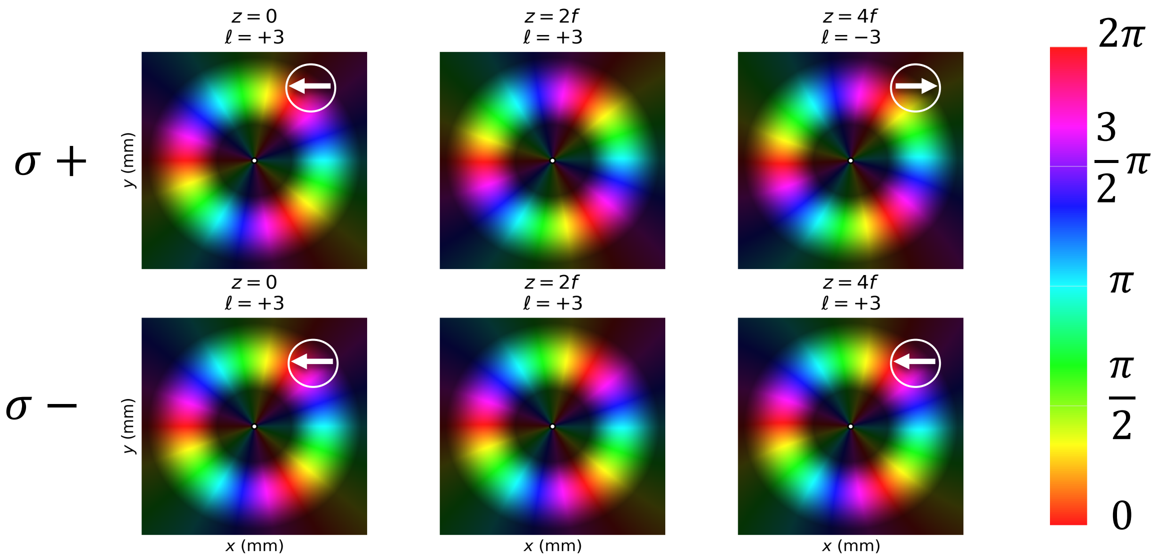

Fig. 2. Hybrid SAM–OAM CNOT gate: polarization controls the transformation of the spatial mode, realizing $\ell \to -\ell$ for σ^+ and identity for σ^- within a high-dimensional Hilbert space.

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