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Large-scale free-space photonic circuits in two dimensions

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Abstract: Here we demonstrate a compact photonic circuit in free space that implements all-optical mode-coupling operations in two spatial dimensions, operating in large-scale regimes on transverse modes of structured light.

Photonic circuits, engineered to couple optical modes according to a specific map, serve as processors for classical and quantum light. They can be employed for tasks like vector-matrix multiplications, unitary transformations, and nonlinear operations, forming the basis for applications in quantum computing, optical simulations, and AI systems [1–3]. Liquid-crystal metasurfaces (LCMSs) have recently been employed for optical simulations of quantum walks (QWs), by coupling transverse light modes with the polarization degree of freedom[4-5]. These can be modeled as patterned waveplates, whose optic-axis orientation angle $\theta(x, y)$ is non-uniform in space, as shown in (see Fig.1 (a)).

In general, the size and complexity of the setup (here, the number of LCMSs) increases with the complexity of the simulated evolution. A technique allowing the compression of an arbitrarily complex evolution into only three LCMSs has recently been demonstrated for 1D QWs, significantly reducing optical losses [6]. However, extending this method to 2D evolutions poses relevant challenges due to discontinuities in the LCMS patterns that naturally emerge from a direct application of the compression technique on 2D arrays. This work introduces a routine that addresses these issues by generating quasi-continuous patterns [7], only embedding isolated singularities in the form of vortices, enabling 2D QWs with up to 200 modes. This ultimately offers enhanced scalability and reduced diffraction compared to the previous 1D implementation [6].

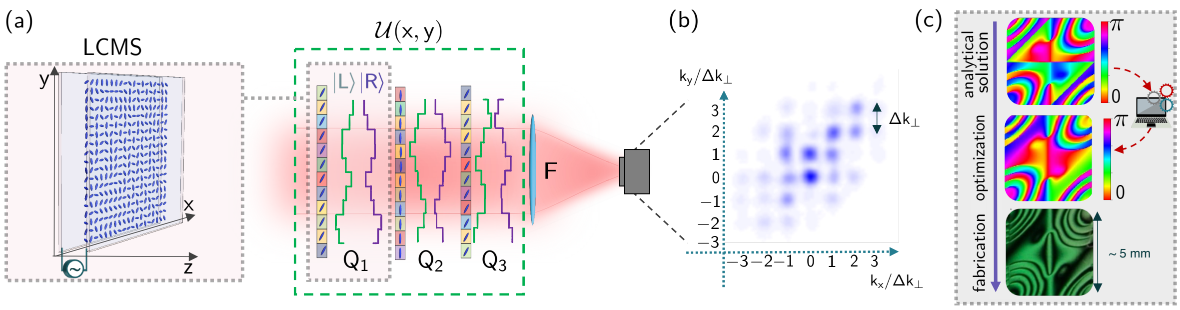

Fig. 1 (a) A liquid-crystal metasurface (LCMS) acts as a patterned waveplate which modifies the beam transverse polarization profile by adding conjugate phases to the two circular polarization components. Based on this mechanism, a minimal set of three LCMSs can be adopted to simulate arbitrary unitary operations in a discrete two-dimensional space. (b) This space is populated by circularly-polarized optical modes carrying a quantized amount of transverse momentum along two orthogonal directions, which can be resolved on a camera placed in the focal plane of a lens. (c) When computing the liquid-crystal patterns required for a specific simulation, the obtained solutions typically feature numerous discontinuous jumps. An automated routine is executed to remove all discontinuities except isolated vortices that can be tolerated in the fabricated devices.

Our photonic implementation of QWs employs optical modes having the following expression:

$$|m_x, m_y, j\rangle = A(x, y, z)\, e^{i\, k_z z} e^{i(m_x x + m_y y)\Delta k_\perp}\, |j\rangle,$$

where $A(x, y, z)$ is a Gaussian envelope with a beam waist ω_0, k_z is the wavevector z component, $\Delta k_\perp$ is a unit of transverse momentum, and $|j\rangle$ is a left/right circular polarization state $|L\rangle/|R\rangle$, respectively. To have negligible crosstalk between these modes, their waist radius must be greater than $2\pi/\Delta k_\perp$ [5] (see Fig.1 (b)).

By leveraging the possibility of patterning the optic axis of LCMSs, we realize arbitrary space-dependent transformations, modeled in terms of inhomogeneous Jones matrices. These implement the desired optical modes mixing corresponding to a 2D QW for the prepared input state.
The light intensity after the walk is collected in the focal plane of a lens, performing the mode sorting. The obtained image is processed and a normalized probability distribution is extracted.

In the 2D scenario, a direct application of the compression method typically yields discontinuities in the liquid-crystal patterns, manifesting as domain walls or extended lines of disclinations, which would be unstable due to the elasticity of liquid crystals. For this reason, an optimization algorithm was developed to enforce continuity in the optic-axis orientations, allowing for smooth patterns across the metasurface (see Fig.1 (c)). The optimization tolerates localized vortex singularities, ensuring smooth transitions and manufacturable patterns. These vortices represent the rotation of LC molecules around singular points and do not degrade optical performance.

This approach adapts to the increasing complexity of simulated processes, potentially enabling the implementation of several QW steps, while keeping the size of the setup the same. The resulting patterns feature spatial periodicity and allow for compact, low-loss photonic circuits. This development significantly enhances the scalability and stability of LCMS-based photonic platforms.
Experimental images for a localized $|R\rangle$ −polarized input after up to 20 steps reveal QW probability distributions where each light spot corresponds to a walker site with probabilities determined by normalized light intensities.

The agreement between the theoretical predictions and the experimental observations is quantified in terms of the similarity

$$S = \left(\sum_{m_x, m_y} \sqrt{P_{exp}(m_x, m_y) P_{th}(m_x, m_y)} \right)^2 ,$$

where P_{exp} and P_{th} are the normalized experimental and theoretical probability distributions, respectively.
Theoretical and experimental distributions show strong agreement, with similarity above 87%, as shown in Fig. 2.

We demonstrated a compact photonic platform capable of implementing 2D QWs with structured light, condensing multi-step dynamics into a minimal number of spin-orbit devices. This design ensures compactness while maintaining high-transmission efficiency.

Although the current system supports only translation invariant unitary transformations having the form of circulant matrices, breaking this symmetry — via diffraction or multi-plane light converters [8] —could enable universal transformations. The low-loss nature of the circuit will support the investigation of multi-photon evolutions, aided by advanced detection technologies like SPAD arrays, single-photon cameras [9,10], or superconducting nanowire-based ultra-sensitive cameras.

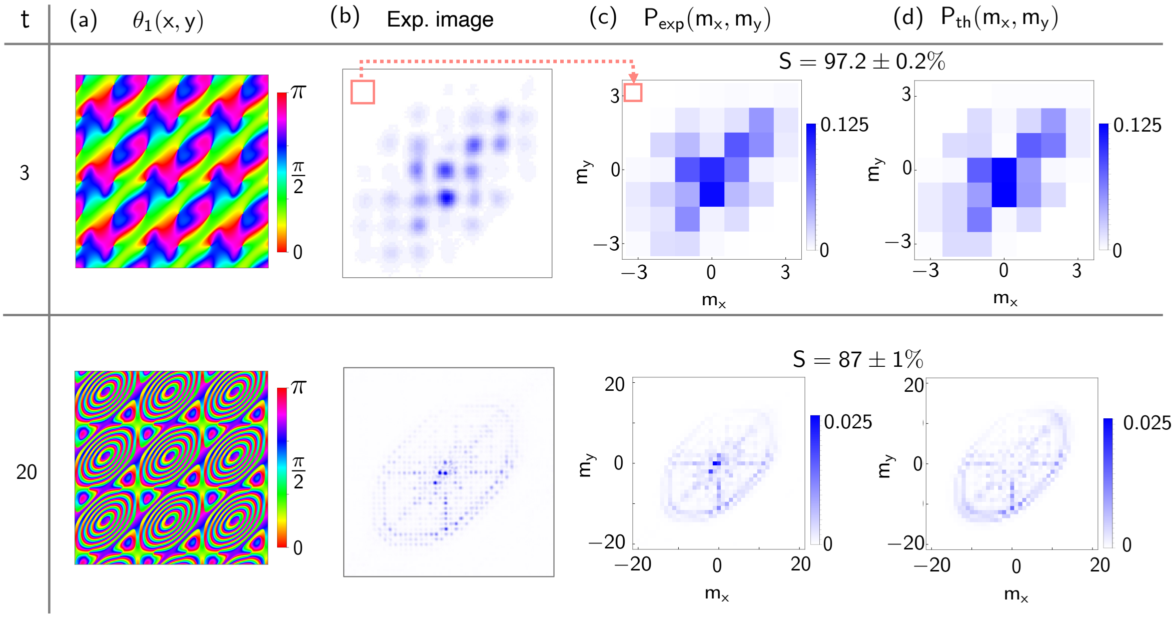

Fig. 2 (a) Optic-axis modulation $\theta(x,y)$ of the first metasurface employed for the simulation of the 2D QW. (b) Experimental image obtained for a $|R\rangle$ −-polarized input state, from which the walker probability distribution after 3 and 20 time steps (t) $P_{exp}(m_x, m_y)$ is extracted (c), and compared with the theoretical prediction $P_{th}(m_x, m_y)$ (d). We report the value of the similarity S, computed as the average of four independent measurements.

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