Quantum State Tomography and Channel Engineering with Liquid-Crystal Metasurfaces

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Liquid-crystal metasurfaces offer a versatile platform for engineering spin–orbit interactions of light. Although they lack the characteristic subwavelength patterning of conventional nanostructures, these devices achieve complex optical functionalities by exploiting gradients of the Pancharatnam–Berry phase. In this setting, the functional subunits are not discrete meta-atoms but local domains within the continuous liquid-crystal substrate, defined by the orientation of the molecular director. The latter can be patterned to realize space-dependent polarization transformations implementing target quantum information processing tasks. Here, we exploit this capability in two complementary directions: quantum state tomography and quantum channel engineering.

First, we introduce an optimal three-metasurface scheme for quantum state tomography of polarization qubits, in which projections of the input state onto a set of target bases are mapped onto a discrete set of transverse momentum modes. After an optical Fourier transform, the intensities of selected diffraction orders provide parallel access to the corresponding tomographic probabilities. Remarkably, this scheme naturally produces multiple replicas of the diffraction pattern, enabling experimental averaging and error estimation without physically repeating the measurement. Unlike previous implementations based on a similar spatial-multiplexing concept, our three-metasurface gadget supports an arbitrary number of input photons and can therefore be used to characterize high photon-number polarization states. By inverse-designing the liquid-crystal patterns, we experimentally demonstrate reconstructions of single- and two-photon polarization states in different measurement bases.

Second, the same platform can be designed to simulate open-system dynamics of polarization qubits. In this approach, photon polarization plays the role of a two-level system interacting with a high-dimensional environment, encoded into spatial modes of light. The interaction occurs in the form of a space-dependent polarization transformation implemented by liquid-crystal metasurfaces. By inverse-designing their patterns, we realize a global unitary evolution whose reduced action on the polarization qubit simulates a desired quantum channel for arbitrary input states. We experimentally validate this method by simulating common quantum noises, such as phase errors and depolarization. This work demonstrates a versatile approach for the simulation of open qubit dynamics, with implications for quantum error correction and environment-induced quantum phase transitions.

Together, these results establish liquid-crystal metasurfaces as compact and programmable spin–orbit devices for quantum-state characterization and quantum-channel engineering.