New Linear-Optical Approach to Quantum Information Processing and Quantum Simulation

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Abstract

Linear-optical networks formed by beam-splitters and phase shifters are capable of carrying out many quantum information processing tasks, but at the cost of rapid growth in resources as the complexity of the task increases. The recently introduced directionally unbiased optical multiports ($N \geqslant 3$), where input ports can double as output ports, can be used as high-dimensional coins and lattice sites for quantum walks. This approach offers more compact setups with substantial savings in resources. We discuss major properties of these multiports and their potential use in executing quantum simulation tasks as well as in topological quantum information processing and neural networks.

The rapidly expanding research activity on quantum computing is ultimately an outgrowth of the profound Feynmanś observation that only quantum systems are capable to efficiently simulate other quantum systems. The approaches used up to now for quantum simulations of nontrivial physical systems have substantial limitations. For example, working with cold atoms or superconducting qubits requires extremely low temperatures in order to avoid decoherence. On the other hand, analogous simulations done with traditional optical quantum walks require a set of optical resources (beam splitters, mirrors, phase shifters etc.) that grows rapidly with the number of steps in the walk. These factors strongly limit the ability to use the current optical approaches for practical simulations of high-dimensional Hamiltonians on a large scale, and so it is of interest to investigate schemes that may be more easily scalable.

Recently, a novel linear optical multiport was proposed [1] which allows photons to reverse direction, thus transcending feed-forward linear optics by providing a linear-optical scattering vertex for quantum walks on arbitrary graph structures. The feasibility of a new design has been demonstrated using a table-top apparatus [2]. In the near future all required optical elements will be integrated onto optical chips that can be fabricated in large numbers and arranged into the desired configurations with high stability in order to implement reversible high-dimensional linear-optical quantum walks on much larger scales. A quantum walk using arrays of such multiports allows simulating a broad range of discrete-time dynamic Hamiltonian systems including cases where physical systems with both spatial and internal degrees of freedom [3] as well as SSH Hamiltonian with topological states are simulated [4].

We also discuss the use of linear-optical multiports for constructing systems in which a global topological variable such as winding number and a locally detected polarization variable are jointly entangled [5]. Topological numbers are highly stable against external perturbations to the system, making them attractive for processing qubits in a noise-resistant manner. At the same time, the linkage to polarization offers a practical mean to conduct a local measurement of topological variables.

Because input ports also double as output ports, there is substantial savings of resources compared to traditional feed-forward quantum walk networks carrying out similar functions. The $N \geqslant 3$ dimensionality of the coin helps to cover large parameter spaces faster. Furthermore, this scheme has the advantage that the parameters of the underlying system on which the walk occurs can be readily varied to produce a variety of simulated behaviors.

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