QUANTUM GATES FOR PROPAGATING MICROWAVE PHOTONS

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Quantum computing has been an active area of research ever since its initial considerations in the 1980s suggesting superior performance in certain computational tasks. Out of many different proposals for quantum computer platforms, photonic systems have attracted great attention. Their strengths are weak decoherence and directly implementable high-speed communication.

The minimal requirements for the realization of a path-encoded photonic quantum computer are the following: high-fidelity photon sources and single-photon detectors for the initialization and measurement of the quantum states, respectively. In addition, tunable single-qubit gates are required to program the desired unitary evolutions. A convenient way to realize arbitrary single-qubit gates is with static beam splitters and tunable phase shifters. Finally, nonlinear qubit-qubit interactions are necessary in order to create entangling two-qubit gates. In the microwave regime, reliable photon sources and single-photon detectors have been demonstrated. However, no scalable, high-fidelity phase shifter for propagating microwave photons has been proposed to date.

Here, we demonstrate that a transmission line interrupted by three superconducting quantum interference devices (SQUIDs) behaves as a compact linear phase shifter with full transmission. The amount of phase shift introduced by the SQUIDs depends on their flux bias, and hence, can be tuned in situ. We experimentally study the SQUID-based phase shifter and show that a wide rage of phase shifts can be achieved and that the results are in a good agreement with theoretical predictions. Furthermore, we theoretically show that a tunable phase shifter with full single-photon transmission can be also realized if the SQUIDs are replaced by superconducting qubits capacitively coupled to the transmission line. Strikingly, the qubit-based phase shifter exhibits a strongly nonlinear phase shift.

The nonlinear phase shifters, together with the linear ones and beam splitters, opens up the intriguing possibility of implementing a controlled-phase gates and any single-qubit gate for propagating microwave photons. This constitutes a universal set of quantum gates allowing the realization of arbitrary many-qubit gates. Hence, our work renders quantum computing with propagating microwave photons an attractive future goal.