Experimental implementation of three- and four-qubit linear-optical quantum logic circuits

R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, P. Marek, M. Ježek, R. Filip, and J. Fiurášek

Department of Optics, Palacký University, 17. listopadu 1192/12, CZ-771 46 Olomouc, Czech Republic

Abstract

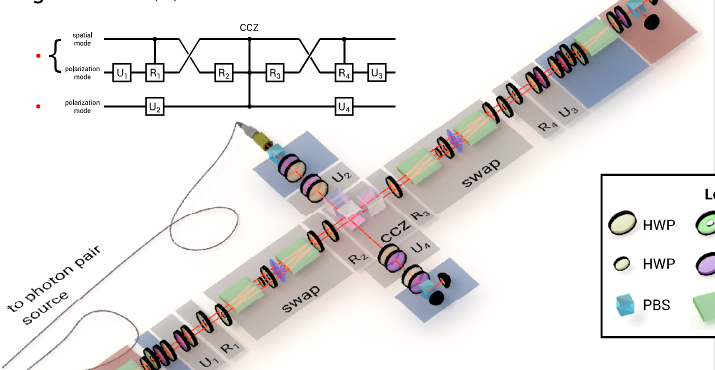
Proof of principle experiments realized with bulk linear optics are the testing ground for the design of integrated optical circuits. Our robust and versatile schemes exploit encoding two qubits into polarization and path degrees of freedom of a single photon, and involve several inherently stable interferometers. This approach allows us to design complex quantum logic circuits that combine several single- and multi-qubit gates and can realize genuine three-qubit quantum Fredkin gate and four-qubit Toffoli gate [1].

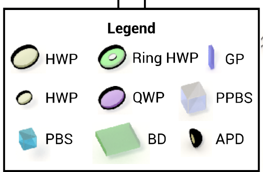
Gates implementation

Single-qubit unitary gates U_j are implemented by a rotated half-wave plate (HWP) followed by a quarter-wave plate (QWP), which address both paths in the Mach-Zehnder interferometer formed by two calcite beam displacers (BD). The two-qubit controlled-rotation gates (R_j) are realized by a rotated HWP inserted only in one arm of the interferometer. To compensate the path difference between the interferometer arms we inserted another HWP to the second one. Single-qubit phase gates V_j are achieved by tilting a glass plate GP inserted in one of the interferometer arms. The central three- and four-qubit controlled-Z (CZ) gate is implemented by two-photon interference on a partially polarizing beam splitter (PPBS) followed by two additional PPBSs which serve as partial polarization filters. Note that in four-qubit CZ gate only the left and the lower beams overlap and interfere on the first PPBS. The output states of photons are analyzed and detected using HWP, QWP, polarizing beam splitters (PBS), and avalanche photodiode detectors (APD).

Three-qubit logic circuit and Fredkin gate

The three-qubit Fredkin gate (known as controlled-SWAP) swaps two target qubits if and only if the control qubit is in the logical state $|1\rangle$.

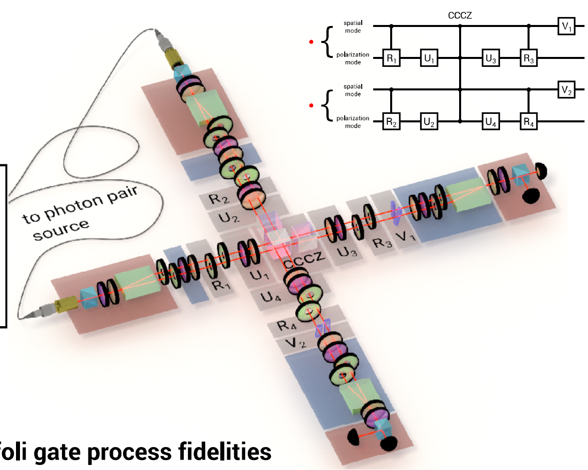




Fredkin gate process fidelity:
full process tomography $F_{ML} = 0.901$

Four-qubit logic circuit and Toffoli gate

The four-qubit Toffoli gate (known as controlled-controlled-controlled-NOT) flips the logical state of a target qubit if and only if all three control qubits are in state $|1\rangle$.



Toffoli gate process fidelities

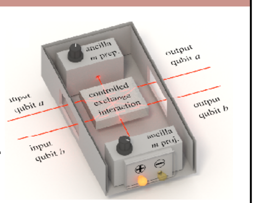
Hoffman fidelity bound [4]: $0.872(6) \leq F_H \leq 0.928(4)$
Monte Carlo sampling [5]: $F_{MC} = 0.91(4)$
Maximum likehood from incomplete data [6]: $F_{ML} = 0.914$

Four-qubit GHZ states preparation:

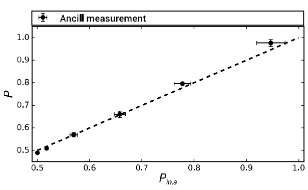
$|GHZ\rangle = (|0000\rangle - |1111\rangle)/\sqrt{2}$ $F_{GHZ} = 0.942(2)$
$|C4\rangle = (|0000\rangle + |0011\rangle + |1100\rangle + |1111\rangle)/2$ $F_{C4} = 0.915$

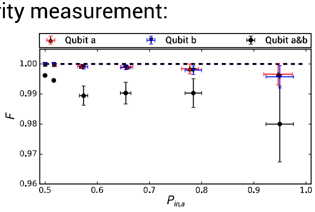
Circuit applications

We used this circuit as a non-destructive detector of exchange symmetry [2] to measure purity of an unknown quantum state and overlap of two quantum states without measuring them directly. Moreover we realized the quantum purification protocol [3].

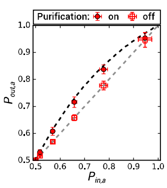


Non-demolition purity measurement:

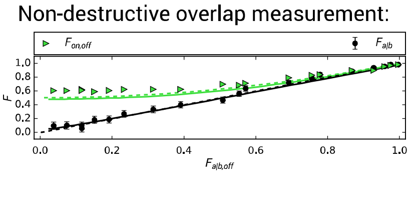




Purification:



Non-destructive overlap measurement:



References

[1] R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, M. Ježek, and J. Fiurášek, Sci. Rep. 6, 33475 (2016).
[2] R. Filip, Phys. Rev. A 65, 062320 (2002).
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Acknowledgments

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