Experimental implementation of optimal linear-optical controlled-unitary gates

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quantum circuits implement desired multiqubit unitary transformation

any such transformation can be decomposed into a set of universal gates:

- single-qubit rotations
- controlled-phase gates

Barenco et al., PRA 52, 3457 (1995)
Probabilistic platforms (linear optics)

- on probabilistic platforms (linear optics) some gates can only be accomplished with limited success rate

- linear-optical c-phase gate: max. $P = \frac{1}{9}$ (without additional photon ancillae)

- goal: find optimal construction of unitary transformations that maximizes the success probability


Kiesel et al., PRL 95, 210505 (2005)
c-phase gate: introduces a phase shift if both the signal and target qubits are in logical state $|1\rangle$

traditional c-phase gate: $\varphi = \pi$

tunable c-phase gate: $\varphi \in [0, \pi]$

Can the tunable c-phase gate optimize unitary transformations?
Non-optimal schemes for tunable c-phase gate

- **theoretical proposal by J. Fiurášek (2006):**

  PHYSICAL REVIEW A 73, 062313 2006

  Linear-optics quantum Toffoli and Fredkin gates

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  Department of Optics, Palacký University, 17. listopadu 50, 77200 Olomouc, Czech Republic
  Received 2 March 2006; published 9 June 2006

- **proposal + experimental implementation by Lanyon et al. (2009):**

  ARTICLES
  PUBLISHED ONLINE: 7 DECEMBER 2008 DOI: 10.1038/NPHYS1350

  Simplifying quantum logic using higher-dimensional Hilbert spaces

  Benjamin P. Lanyon1, Marco Barbieri1, Marcelo P. Almeida1, Thomas Jennewein12, Timothy C. Ralph1, Kevin J. Resch13, Geoff J. Pryde14, Jeremy L. O’Brien15, Alexei Gilchrist16 and Andrew G. White1

  × non-optimal c-phase gate cannot lead to optimal circuit design
Optimal linear-optical tunable c-phase gate

- **proposed** in 2010 by K. Kieling *et al.*:
  
  **New Journal of Physics**

  On photonic controlled phase gates
  
  K. Kieling, J. L. O'Brien and J. Eisert
  

- **experimentally tested** in our laboratory in 2011:

  K. Lemr, A. Černoch, J. Soubusta, K. Kieling, J. Eisert, and M. Dušek,
  

✓ **maximizes success rate** for any given phase shift
Optimizing controlled-unitary gates

- **single-qubit controlled-unitary gate** (simple, yet prominent example):

\[
|0\psi\rangle \rightarrow |0\rangle|\psi\rangle \quad |1\psi\rangle \rightarrow |1\rangle \left[ U(\delta, \epsilon, \zeta)|\psi\rangle \right]
\]

If the control qubit is set to $|1\rangle$, signal qubit undergoes a unitary transformation $U$ (3 parameters)

❌ **Barenco**: In general 2 c-phase gates are needed:

✓ **our scheme**: one tunable c-phase gate suffices

![Diagram of controlled-unitary gates]
Experimental scheme

- Single-qubit rotations: HWPs and QWPs
- Tunable c-phase gate: complex interferometer
Measurements

- 6 different phase shifts + different settings of wave plates

- **signal mode process tomography** for both control qubit in $|0\rangle$ and $|1\rangle$

- process fidelities about 92%, success probability quite as predicted
Performance

**Resources:**
- 2 traditional c-phase gates

**Success rate:**
- $\frac{1}{81} = 1.2\%$

**Experimental considerations:**
- QND needed to join the gates

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**Barenco scheme:**
- 2 traditional c-phase gates
- $\frac{1}{81} = 1.2\%$
- QND needed to join the gates

**Our scheme:**
- 1 tunable c-phase gate
- 14% (in average)
- tunable c-phase gate

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Thank You for your attention.

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