A simple gate for linear optics quantum computing

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We describe a simple scheme for implementing the non-linear sign gate of Knill, Laflamme and Milburn (Nature, 409, 46-52, Jan. 4 (2001)) which forms the basis of an experiment underway at the University of Vienna.

It was recently shown [1] that efficient quantum computing is possible using only linear optics, single photon sources and single photon detectors. One of the fundamental gates of the proposed scheme is known as the non-linear sign (NLS) gate; it is a non-deterministic gate which implements the transformation (on states of photon occupation number) given by

\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle + \gamma |2\rangle \rightarrow \alpha |0\rangle + \beta |1\rangle - \gamma |2\rangle, \quad (1) \]

with probability of success 1/4.

The scheme suggested in [1] for implementing a NLS gate used a complicated interferometer requiring beamsplitters of variable reflectivity. We have found a scheme more amenable to an experimental demonstration of linear optics quantum computing, and it is depicted in Fig. 1. The input computational mode begins in a state of horizontal polarization, i.e. in general \[ |\psi_{in}\rangle = \alpha |0H\rangle + \beta |1H\rangle + \gamma |2H\rangle. \]

This mode passes through a polarizing rotator, of rotation angle \(\sigma\). As with the proposal of [1], our scheme makes use of a single ancilla photon, in this case prepared with vertical polarization. The ancilla photon and computational mode are mixed at a polarizing beam-splitter (PBS). One output of the PBS goes to a detector \(D_1\), and the gate’s success is conditioned on no photons being detected at \(D_1\). The other output mode of the PBS passes through a polarizing rotator set to an angle \(\theta\). This mode is subsequently subjected to a measurement, and the gate operation is successful if a single vertical photon is detected. This is indicated in the figure by the addition of a second PBS and detector \(D_2\). In general the detector \(D_2\) would need to be able to distinguish one from multiple photons, and such detectors are not readily available. However for the purposes of a 4 photon coincidence experiment such multiple photon events are excluded by the conditioning process, and so a simple demonstration of an NLS gate can be performed using commonly available single photon detectors.

If we take the transformation corresponding to a polarizing rotator of angle \(x\) to be \[ a'_{H} = \cos x a_{H}, \quad a'_{V} = -\sin x a_{V}, \]

then the (unnormalized) state of the output mode, given the correct conditioning at \(D_1, D_2\), is [2]

\[ |\psi_{out}\rangle = \alpha \cos \theta |0H\rangle + \beta \cos \sigma \cos 2\theta |1H\rangle + \gamma \cos^2 \sigma \cos \theta (1 - 3 \sin^2 \theta) |2H\rangle. \quad (2) \]

Note added. Recently a similar simplification of the NLS gate was presented [3] which shares the same probability of success as the one presented here. The scheme presented here enjoys the slight practical advantage of not requiring a beamsplitter with unequal reflectivity/transmittivity.

[1] E. Knill, R. Laflamme and G. Milburn, Nature, 409, 46-52, Jan 4 (2001).

[2] A Maple worksheet capable of calculating the state transformations associated with arbitrary linear optical interferometers (incorporating both spatial and polarization degrees of freedom) is available from T.R. on request.

[3] T. Ralph et. al., quant-ph/0108049.