Quantum logic operations using linear optical elements

J. D. Franson, B. C. Jacobs, and T. B. Pittman
Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723

phone: 443-778-6226
FAX: 443-778-6904
e-mail: franson@jhuapl.edu

Knill, Laflamme, and Milburn [1] have shown that probabilistic quantum logic operations can be implemented using linear optical elements, such as beam splitters and phase shifters, additional photons (ancilla) and post-selection based on the results of measurements on the ancilla. This may seem somewhat surprising, since logic operations are inherently nonlinear. Here the nonlinearity is produced by the quantum measurement process used in the post-selection. Nonlinearities of this kind are inherently quantum-mechanical and have no classical analogy.

In an earlier paper [2], we showed that several quantum logic devices of this kind, including a controlled-NOT gate, could be implemented in a simple way using polarizing beam splitters. Our approach eliminates the need for interferometers, which makes the devices more stable as well as requiring fewer elements. Here we report the experimental demonstration of several devices of this kind, including a quantum parity check and a destructive controlled-NOT gate [3]. The destructive CNOT gate performs the logical operation of a conventional CNOT gate but destroys the control qubit in the process. Figure 1 illustrates the implementation of these devices using a polarizing beam splitter and a polarization-sensitive detector. The experimental results obtained from these two devices are shown in Figures 2 and 3, which clearly demonstrate that the intended quantum logic operations have been performed. The simplicity of logic devices of this kind should be a major advantage in practical applications.

We have also recently demonstrated the use of feed-forward quantum control to correct potential errors in the output of the logic devices. The output photons were stored in an optical fiber for approximately 100 ns while the results of the measurements were being processed, after which the necessary correction was applied using a Pockels cell. The throughput of the logic devices was increased by a factor of 2 using this technique.

Elementary devices of this kind can be combined to implement a standard controlled-NOT gate. We will describe experiments currently in progress to implement a conventional CNOT gate, a quantum encoder, and other logic devices with reduced error rates and increased probabilities of success.

We recently showed [4] that the probability of success of these devices can be made arbitrarily close to unity by using larger numbers of ancilla photons. In our new approach, the logic devices always produce an output with an intrinsic error rate that scales as $1/n^2$, where n is the number of ancilla photons. This corresponds to a post-correction process rather than post-selection. This new approach should have important implications in quantum computing applications, where the error rate must be relatively small in order to permit the use of fault-tolerant quantum error correction algorithms.

[1] E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).

[2] T.B. Pittman, B.C. Jacobs, and J.D. Franson, Phys. Rev. A 64, 062311 (2001).

[3] T.B. Pittman, B.C. Jacobs, and J.D. Franson, submitted to Phys. Rev. Lett. (quant-ph/0109128).

[4] J. D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, submitted to Phys. Rev. Lett. (Quant-ph/0202160).

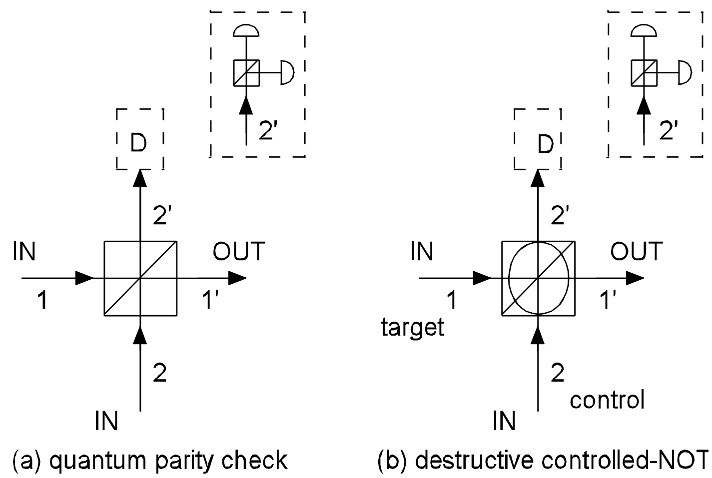

Figure 1: Implementations of two non-deterministic logic devices using polarizing beam splitters (PBS). A PBS inscribed with a circle denotes orientation in the 45° basis.

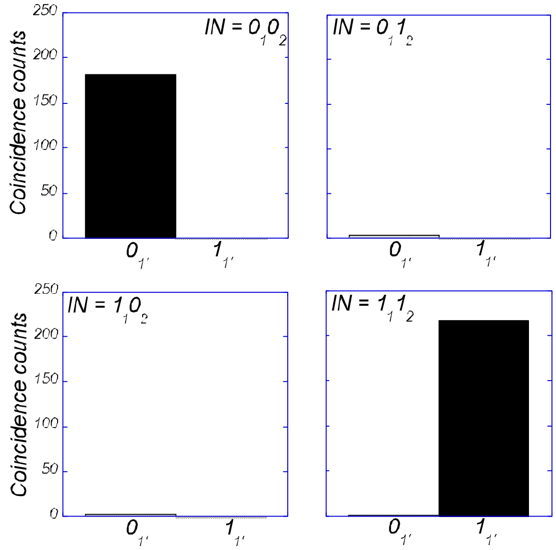

Fig. 2. Results from the quantum parity check experiment.

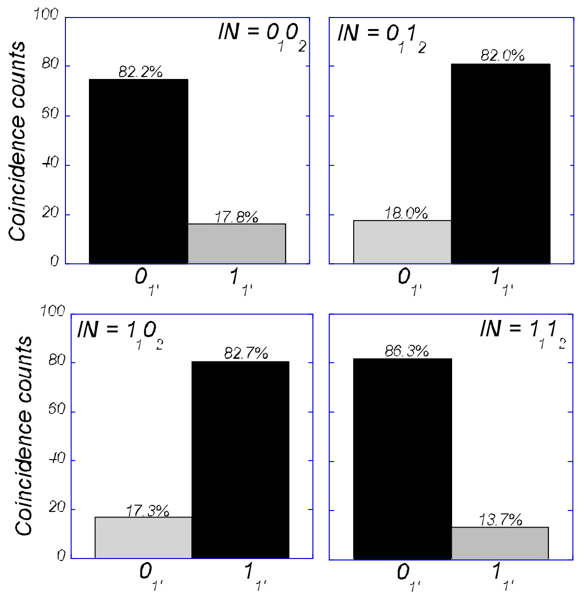

Fig. 3. Results from the destructive CNOT experiment.