Towards Linear Optical Quantum Computers

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(Dated: February 4, 2004)

Abstract

Scalable quantum computation with linear optics was considered to be impossible due to the lack of efficient two-qubit logic gates, despite its ease of implementation of one-qubit gates. Two-qubit gates necessarily need a nonlinear interaction between the two photons, and the efficiency of this nonlinear interaction is typically very tiny in bulk materials. However, we recently have shown that this barrier can be circumvented with effective nonlinearities produced by projective measurements, and with this work linear-optical quantum computing becomes a new possibility of scalable quantum computation. We review several issues concerning its principles and requirements.

PACS numbers: 03.67.Lx, 03.67.Pp, 42.50.Dv, 42.65.Lm
PRINCIPLES

There are three key principles in the Knill, Laflamme, and Milburn (KLM) proposal [1] for efficient and scaleable quantum information processing (QIP):

- conditional non linear gates for two photon states
- teleportation to achieve efficiency
- error correction to achieve scalability

Conditional non linear gates are based on the non-unitary state change due to measurement. The gate works with some probability, but correct functioning is heralded by the measurement result. We seek to implement a nonlinear transformation (NS gate) on an arbitrary two photon state of a single mode field:

\[ |\psi\rangle = \alpha_0|0\rangle_1 + \alpha_1|1\rangle_1 + \alpha_2|2\rangle_1 \rightarrow |\psi'\rangle = \alpha_0|0\rangle_1 + \alpha_1|1\rangle_1 - \alpha_2|2\rangle_1. \]  

(1)

This is done using the linear optical network shown in figure 1. The signal state is first combined with two ancilla modes, one in a single photon state and one in the vacuum. At the end of the optical processing, photon counting is done on the ancilla modes. If the number of photons is unchanged from the input, the desired transformed state exits the signal mode port. This will happen with probability 0.25.

In order to use this result to implement QIP we code the logical states as physical qubits using one photon in one of two modes: \[ |0\rangle_L = |1\rangle_1 \otimes |0\rangle_2, \quad |1\rangle_L = |0\rangle_1 \otimes |1\rangle_2. \] Single qubit gates are then implemented by a beam splitter. A two qubit gate, the conditional sign-flip gate, can then be implemented using the Hong-Ou-Mandel (HOM) interference effect to first

\[ r_1 = r_3 = \cos(22.5^\circ) \]
\[ r_2 = -\cos(66.53^\circ) \]

FIG. 1: The conditional Nonlinear Sign (NS) gate.
convert two single modes each with one photon into an appropriate entangled two-photon state, figure 2. Such a gate uses two NS gates and thus succeeds with probability 0.125. A general formalism for the effective photon nonlinearities generated by such conditional measurement schemes in linear optics can be found in Ref. [2].

We have also shown that probabilistic quantum logic operations can be performed using polarization-encoded qubits [3], as illustrated by the controlled-NOT gate shown in Fig. 3. This device consists of two polarizing beam splitters and two polarization-sensitive detectors, along with a pair of entangled ancilla photons.

The correct controlled-NOT logic operation will have been performed whenever one and only one photon is detected in each of the two detectors, which occurs with a probability of 0.25. Feed-forward control [4] must also be applied, depending on what polarization states were measured. From an experimental perspective, this approach has the advantage of being
relatively simple and insensitive to phase drifts.

A sequence of probabilistic gates is of course not scalable. However, the Gottesman and Chuang protocol for implementing gates via teleportation \[5\] can be used to fix this. Implementation of the gate then reduces to preparing the appropriate entangled state resource. That can be done off line using conditional gates and only when success is achieved is the teleportation gate completed. Using a resource with \(n\) photons in \(2^n\) modes this decreases the gate failure probability as \(n^{-1}\), or even as \(n^{-2}\) \[6\]. Gates can thus be implemented efficiently.

When a teleportation gate fails it does so by an making a measurement of an incoming qubit. This is always heralded and can be fixed using detected measurement codes. This enables the scheme to be scalable (i.e., fault tolerant) provided the error probability is less than 0.5, but at the expense of very complicated multi-mode entangled resource states for teleportation. The other major source of error is photon loss. In principle this can also be corrected using teleportation gates. Scalability requires that loss probability per gate be less than 0.01. Not detecting a photon is equivalent to loss.

Three experiments have implemented conditional two qubit gates: Pittman et al. \[7\], O’Brien et al. \[8\], Sanaka et al. \[9\]. The first experiment \[7\] is based on the Pittman and Franson’s polarization-encoded scheme. The second \[8\] is based on a simplification of the

![Theory vs. Experiment](image)

FIG. 4: Implementation of a probabilistic CNOT gate using polarization-encoded qubits \[7\].
KLM-NS gate that requires only two photons. The last is a full four photon version of KLM. However, all experiments only work in the coincidence basis. This means that successful implementations correspond to 2 or 4 fold coincidence counts. However, no light leaves the device as all photons are detected.

Experimental results obtained from a CNOT gate in Ref. are shown in Fig. Here a single ancilla photon was used, which restricts the operation of the device to the case in which a single photon is detected in each output port (the so-called coincidence basis). This was a three-photon experiment in which two of the single photons were obtained using parametric down-conversion while the third photon was obtained by attenuating the pump laser beam. Optical fibers were used instead of free-space components in order to reduce errors due to mode mismatch. The fidelity of the output qubits was limited in this case by the degree of indistinguishability of the three photons. Experimental demonstrations of several other simple quantum logic gates have also been performed, including a quantum parity check and a quantum encoder.

REQUIREMENTS

There are three major technical requirements that must be met:

- single photon sources
- discriminating single photon detection
- feed-forward control and quantum memory

The required ideal single photon sources are transform-limited pulses with one and only one photon per pulse. In practice this means that one must be able to exhibit HOM interference between photons from different pulses. The required single photon detectors must be able to detect a single photon with efficiency greater than 0.99 and discriminate between 0, 1, and 2 photon counts.

One approach to implementing such a single-photon source is illustrated in Fig. A pulsed laser beam generates pairs of photons in a parametric down-conversion crystal. Detection of one member of a pair signals the presence of the other member of the pair, which is then switched into an optical storage loop. The single photon can then be switched out of
FIG. 5: Single-photon source using parametric down-conversion and an optical storage loop. Similar storage techniques can also be used to implement a quantum memory device for single photons.

The ability to switch a single photon into an optical storage loop and then retrieve it when needed [13]. Although this kind of approach cannot produce photons at arbitrary times, it can produce them at periodic time intervals that could be synchronized with the cycle time of a quantum computer. A prototype experiment of this kind demonstrated the ability to store and retrieve single photons in this way, but its performance at the time was limited by losses in the optical switch.

The ability to switch a single photon into an optical storage loop and then retrieve it when needed can also be used to implement a quantum memory for single photons. This application is more demanding than the single-photon source described above, since the polarization state of the photons must be maintained in order to preserve the value of the qubits. A prototype experiment of this kind has also been performed, where the primary limitation was once again the losses in the optical switch [14].

Furthermore, the ability to perform quantum logic operations using linear elements raises the possibility of using quantum error correction techniques to extend the coherent storage time of the quantum memory described above, see Fig. 6. The primary source of error is expected to be photon loss, which can be corrected using a simple four-qubit encoding scheme [15] as illustrated in Fig. 7. Provided that the errors in the logic gates and storage loops are sufficiently small, techniques of this kind can be used to store photonic qubits for an indefinitely long period of time.
An essential component in this kind of quantum memory is the single-photon quantum nondemolition (QND) measurement device [16]. Again a simple way to perform a single-photon QND measurement can be provided by quantum teleportation technique. If the input state is in a arbitrary superposition of zero and one photon with a fixed polarization, the detector coincidence in Bell state measurement, signals the present of a single photon in the input and also the output states [17].

Similar techniques can also be used to compensate for the photon loss in optical fiber transmission lines, which would allow the development of a quantum repeater. A quantum repeater is a device for achieving remote, shared entanglement by using quantum purification and swapping protocols [18]. A simple protocol for optical quantum repeaters based on linear optical elements and an entangled-photon source has been developed [19]. On the other hand, utilizing quantum error correction, one can relay an unknown quantum state with high fidelity down a quantum channel. This device we call a quantum transponder, and it has direct applications to quantum repeater and memory applications.

Quantum mechanics enables exponentially more efficient algorithms than ones that can be implemented on a classical computer. This discovery has led to the explosive growth of the field of quantum computation [20]. Many physical systems have been suggested for building a quantum computer, but the final architecture is still to be determined. These systems include ion traps, cavity QED, optical systems, quantum dots, nuclear magnetic resonance, and superconducting circuits. In linear optical quantum computing, the desired nonlinearities come from projective measurements.

Projective measurements simply carry out measurements over some part of the quantum system, and project the rest of the system into a desired quantum state. Additional photons,
known as ancilla, are mixed with the inputs to the logic devices using beam splitters while single-photon detectors are used to make measurements on the ancilla photons after the interaction. The nonlinear nature of single-photon detection and the quantum measurement process then project out the desired logical output. Therefore, although logic operations are inherently nonlinear, our approach uses only simple linear optical elements, such as beam splitters and phase shifters. Building a quantum computer will be a major challenge for a future quantum technology; requiring the ability to manipulate quantum-entangled states of large numbers of sub-components. Systematic development of each component of preparation, control, and measurements will facilitate the task of building a quantum computer.

Acknowledgements

Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We wish to acknowledge support from the National Security Agency, the Advanced Research

FIG. 7: Quantum error-correction code that recovers photon loss using two ancilla photons. The QND box represents a single-photon quantum nondemolition measurement device. The inset shows the two-to-four qubit encoding.
and Development Activity, the Defense Advanced Research Projects Agency, the National Reconnaissance Office, the Office of Naval Research, the Army Research Office, the IR&D funding, and the NASA Intelligent Systems Program.

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