Experimental demonstration of an all-optical CNOT gate

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Abstract. We report the first unambiguous experimental demonstration and comprehensive characterisation of quantum CNOT operation: producing all four entangled Bell states with high fidelity as a function of only the input qubits' logical values, for a single operating condition of the gate. The gate is non-deterministic and the qubits are lost upon failure, but with the addition of linear optical quantum non-demolition (QND) measurements it is equivalent to the CNOT gate in the scalable all-optical scheme of Knill, Laflamme and Milburn (KLM).

Keywords: Quantum computing, linear optics

Introduction: An extensive effort [1] to build a quantum computer has been fuelled by the promise of tremendous computational power, coupled with the development of robust error correcting schemes [2]. The requirements for realising such a device, however, are confounding: scalable physical qubits which can be well isolated from the environment, but also initialised, measured, and controllably interacted to implement a universal set of quantum logic gates [3]. The usual set consists of single qubit rotations and a controlled-NOT (CNOT) gate, which flips the state of a target qubit conditional on the control qubit being in the state 1.

Optical CNOT gates: A qubit can be encoded in any two level quantum system. The horizontal and vertical polarisation basis of a single photon is an attractive choice since single qubit rotations are straightforward, and decoherence is inherently very low. Such an encoding has been widely used in quantum cryptography and communication protocols, where only single qubit operations are required. Unfortunately, the non-linear interactions between such qubits, necessary for quantum computation, are difficult to realise. However, this problem can be overcome by using the non-linear nature of measurement [4]: efficient (i.e. scalable) quantum computation is possible using only single photon sources, passive linear optical elements and photo-detectors. In this scheme a non-deterministic CNOT gate can be made scalable by using a teleportation protocol. We describe an alternative CNOT gate requiring only a two-photon input and operating in the coincidence basis [5, 6]. A qubit is encoded in the polarisation state of each of the photons and transferred to a spatial encoding, as indicated in Fig. 1. This gate, combined with quantum non-demolition (QND) measurement of the output (possible with linear optics and ancilla photons [8]), is equivalent to that proposed by Knill, Laflamme and Milburne (KLM) [4], and can be made scalable using the same teleportation protocol [7].

Results: We use pairs of daughter photons at 702.2±2 nm produced through the process of spontaneous parametric down conversion in a non-linear beta-barium borate (BBO) crystal pumped with 500 mW at 351.1 nm operating in the beam-like phase matching condition [9] as shown in Fig. 2. We have conducted extensive studies to maximise the brightness and mode quality of this source and have optimised coupling of these photons into single mode fibres [10]. This has enabled us to optimise

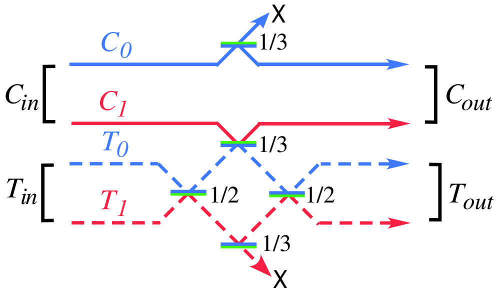

Figure 1: A schematic of the non-deterministic two-photon CNOT gate, where the beam splitter reflectivities and asymmetric phase shifts are indicated. A spatially encoded single photon qubit is prepared by separating the polarisation components of a polarisation qubit on a polarising beam splitter (not shown). In this dual rail logic notation C_0 and C_1 are the two bosonic mode operators for the control qubit, and T_0 and T_1 those for the target. Transformation between this dual rail logic and polarisation encoding is achieved with a half wave plate and a polarising beam splitter. One can understand the operation of this gate in the computational basis by considering the case where the C_0 mode is occupied: the target interferometer is balanced and the target qubit exits in the same mode as it enters (if it is not lost through a $\frac{1}{3}$ beam splitter). Conversely, if the C_1 mode is occupied, there is a non-classical interference of the two qubits at the central $\frac{1}{3}$ beam splitter and when a coincidence event is observed, the target mode is flipped. The operation extends straightforwardly to the case of arbitrary input states: with probably $\frac{1}{9}$ a photon is simultaneously measured in one of the control and target modes and the gate has performed the required CNOT logic operation.

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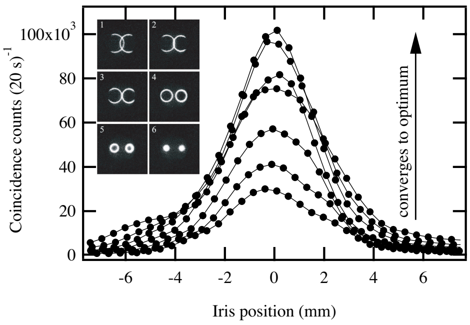

Figure 2: Characteristics of the beam like two-photon source used for the CNOT gate. The inset shows a sequence of images where the normal ring-like type-II emission is tuned to be beam-like by adjusting the angle between the pump beam and the optic axis of the BBO crystal.

the classical and non-classical interference effects, central to the successful operation of the two-photon CNOT gate.

The CNOT operation has been characterised in detail: We present a series of measures of increasing complexity. We demonstrate classical CNOT gate operation: a flipping of the target qubit conditional on the control qubit being in the logical state 1 with high probability. More importantly, we describe the quantum operation of this gate: the production of all four maximally entangled Bell states with high fidelity. Production of these Bell states was confirmed by quantum state tomography [11]: a series of sixteen two qubit measurements on an ensemble of identically prepared qubits is used to reconstruct the two qubit density matrix for the output state of the gate, providing all information that can be known about the two qubit state. In each cases, the degree of entanglement and mixture was measured to be in the range where a Bell inequality can be violated [12]. Finally complete characterisation of the gate has been realised via quantum process tomography [2]: Quantum state tomography is performed on the output state of the gate for a particular set of sixteen input states. This has enabled the construction of the super-operator for the quantum process implemented by the gate.

Conclusions: We have demonstrated a two photon CNOT gate operating via coincident photon detection. We demonstrate logical basis operation as well as production of entangled output states for separable input states — an important functional demonstration of quantum CNOT operation. Note that these results go beyond a recent report of an alternative optical CNOT gate architecture [13] which shows logical basis operation, but only a single coincidence fringe with a visibility of 61.5±7.4%. The CNOT gate presented here combined with QND is equivalent to the KLM CNOT gate, and could be made scalable with the same teleportation protocol. It therefore provides the first experimental indication that all-optical quantum computing is possible. The next step will be to incorporate the gate demonstrated here in simple optical circuits to demonstrate simple algorithms and error correcting schemes [14].

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