

Optical Quantum Computation Program – Experimental

PROGRAM MANAGER

Prof Andrew White – UQ

OPTICAL QUANTUM COMPUTING RESEARCHERS

Students Mr Matthew Broome (PhD), Mr Rohan Dalton, Mr Benjamin Lanyon, Mr Till Weinhold, Mr Geoffrey Gillett
Staff Dr Marcelo Pereira de Almeida, Dr Marco Barbieri, Dr Alessandro Fedrizzi

COLLABORATING CENTRE RESEARCHERS

Griffith University, Australia
A/Prof Geoffrey Pryde
Macquarie University, Australia
A/Prof Alexei Gilchrist
University of Toronto, Canada
Prof Daniel James

OTHER COLLABORATORS

University of Bristol, UK
Prof Jeremy O'Brien
University of Illinois, USA
Prof Paul Kwiat
University of Vienna, Austria
Dr Thomas Jennewein
University of Toronto, Canada
Prof Aephraim Steinberg

PROGRAM DESCRIPTION

The aim of this program is to construct the basic building block of an optical quantum processor, focussing on the key 2-qubit entangling gate, and to develop the foundations for a scaleable architecture. Our strategy involves both experimental and theoretical research, including: developing measurement techniques for characterising the relevant quantum states and processes; improving photon source and optical circuitry performance; development and application of measures of gate performance; and the realisation of simple quantum circuits.

1. Background

Modern optical technology allows very precise manipulation and measurement of light; the basic particles of light, photons, experience very little intrinsic decoherence, as the electromagnetic environment at optical frequencies is a vacuum. These two features combine to make photonic qubits very appealing, as single qubits can be produced, manipulated and measured with low error rates. Quantum computation also requires that two photonic qubits be able to interact and influence one another, the typical example being via the entangling controlled-NOT, or CNOT, gate. This cannot be achieved via normal nonlinear optical methods, as available materials produce interactions that are 10 million times weaker than required. However, in 2001 Knill, Laflamme & Milburn (KLM) proposed a scheme for efficient quantum computation combining linear optics and measurement [1] – the gate is non-deterministic, but can be made deterministic by using teleportation.

In this scheme a single photon is used to encode each qubit. Attenuating a standard laser beam produces low average photon numbers, but this is not sufficient for quantum computation as we require exactly one photon in a given time period to avoid error. The current gold standard for photon sources is spontaneous parametric downconversion (SPDC), which produces photon pairs in well defined spatial and frequency modes, albeit non-deterministically. When used as a two-photon source, SPDC yields high rates, typically tens of thousands of photon pairs per second; when used as a four-photon source, the rates are much lower, typically a thousand counts per hour. High count rates are desirable both because they allow good statistical analysis in a reasonable time frame, and because they minimise the effect of long-term drift in the apparatus. The original KLM proposal required ancillary photon for each logical photonic qubit: a two-qubit gate required four photons. In 2001 both our and a Japanese group [2,3] published proposals to realise a CNOT gate with only two photons, suggesting that comprehensive optical quantum computing experimentation could be achieved using high count-rate (bright) two-photon sources. The final stage in any quantum computation scheme is measuring the logical state, 0 or 1, of the output qubits. However during development of a quantum computer it is necessary to be able to fully characterise output states – and even better gate processes – to determine gate behaviour in terms of noise and entangling capability. Methods for measuring qubit states are now well developed: qubit state tomography with photonic qubits was demonstrated in [4], and a comprehensive theoretical analysis that allows for the effects of measurement uncertainty was given in [5].

In 2003 we constructed and observed quantum operation of a non-deterministic CNOT gate. Key design features were the use of polarisation displacers to produce a stable interferometric arrangement [6] and the use of wave-plates to produce beam mixing in a precise ratio. The operation of the gate was unambiguously quantum. This was determined by measuring the output density matrices for the logical-input data (i.e. the $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$ inputs), and, more significantly, for superposition inputs – in the latter case the outputs are entangled [7]. In 2004 we investigated important principles of characterising real-world quantum circuits, fully characterised our two-photon CNOT gate using quantum process tomography [8,9]. The CNOT gate, as well as being a key processing device in quantum computation, is also a key measurement device. At the simplest level it allows an ideal projective or quantum non-demolition (QND) measurement to be made on a single qubit. We simply modified our gate so that the strength of the measurement was

smoothly varied from weak to strong [10,11]. This generalised measurement demonstrated that the QND measurement is coherent – a key requirement for quantum computation applications. In 2005, simultaneously with groups in Germany and Japan, we proposed and demonstrated a new architecture for entangling optical gates [12-14]. The key advantage being its simplicity and suitability for scaling – it requires only one nonclassical mode matching condition, and no classical interferometers. In 2007, we used this architecture to implement a compiled version of Shor's algorithm in a photonic system, demonstrating for the first time – in any architecture – the core processes, coherent control, and resultant entangled states required in a full-scale implementation [15]. We presented two different implementations of the order-finding routine at the heart of Shor's algorithm, characterising the algorithmic and circuit performances. Order-finding routines are a specific case of phase-estimation routines, which in turn underpin a wide variety of quantum algorithms, such as those in quantum chemistry [16].

2. Quantum computing with zero entanglement

Quantum computing promises an exponential speed-up compared to classical computation for a range of problems. For schemes using only pure states, entanglement is a key ingredient in this speed-up [17,18], leading to a widespread perception that entanglement is what makes quantum computing powerful. A decade ago Knill and Laflamme proposed an alternative model, where a single pure qubit interacts with a register of completely mixed qubits: *deterministic quantum computation* (DQC1) [19]. Although this model does not allow universal quantum computation, it nevertheless can potentially efficiently perform important computational tasks thought to be classically intractable. DQC1 is attractive both experimentally, since it *dramatically* reduces coherence requirements, and conceptually, since intriguingly entanglement is, at most, marginally present [20].

We implemented the DQC1 algorithm for estimating the normalised trace of a unitary matrix [21]. Using linear optic circuitry, we compiled our circuits with a technique that takes shortcuts through higher dimensions [22]. Our implementation is the first in an in-principle scalable architecture. Despite *zero* measured entanglement, Figure 1 demonstrates that a speed-up is still present. The nonclassicality of the outputs is captured by the quantum *discord*, which vanishes only when a classical efficient simulation of our circuit is possible. It seems that discord, which for mixed states does not coincide with Schrödinger's definition of entanglement, may play an important role in understanding the power of quantum computing.

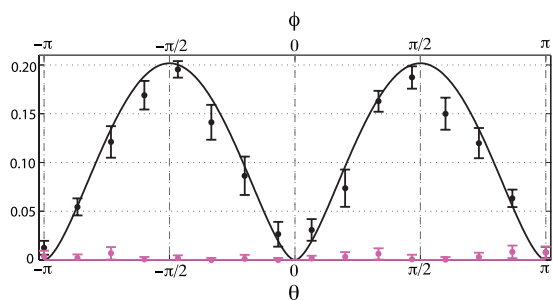


FIGURE 1

Discord (black) and Tangle (purple) measured at the output of our normalised trace estimation algorithm, over a range of θ . Discord quantifies the disturbance introduced on a system x , given a measurement on a correlated system y : no disturbance implies that x and y are purely classically correlated [20].

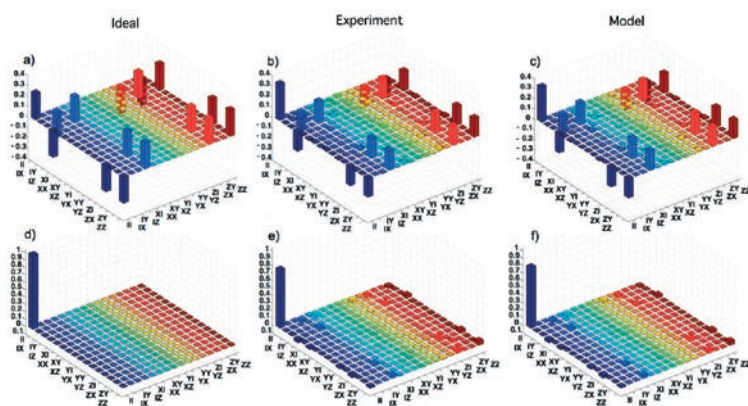


FIGURE 2

χ -matrices for a bit-flipped controlled-z gate, $(-I_1 I_2 + I_1 Z_2 + Z_1 I_2 + Z_1 Z_2)$, where the subscript indicates which qubit the operator acts on. (a), (d) are matrices for the ideal case; (b), (e) from the experiment; and (c), (f) from the model. Matrices (a)–(c) are in the traditional Pauli-basis, (d)–(f) are in the gate-basis, where the first element represents ideal gate operation and all other elements indicate errors [31]. In (d)–(f), the population of the first diagonal element is the process fidelity F_p ; the gate error is at least as large as the combined population of the remaining diagonal elements, $1 - F_p$. In the experiment, (b), (e), the process and average-gate fidelities with the ideal, F_p, F_{av} , are respectively $\{78.2, 82.5\} \pm 1.5\%$. In the model, (c), (f), the fidelities with the ideal are $\{81.4, 85.1\}\%$; with experiment $\{96.7, 97.4\} \pm 1.5\%$. *n.b.* only real parts shown; imaginary parts are ideally zero, for both for the experiment and model they are $<4\%$, with an average value of $<0.3\%$.

3. The road to fault-tolerance

Realising the full potential of quantum computers requires gates that are fault-tolerant: able to function correctly despite the presence of intrinsic errors. Gates are said to be scalable if the error probability per entangling quantum-logic gate is under a certain threshold value [23,24]. We introduce a general technique for comparing measured gate performance in quantum-logic gates to predicted fault-tolerance thresholds [25], enabling quantitative benchmarking quantum-logic gates, regardless of architecture. All demonstrated entangling gates suffer a variety of errors: architecture-specific error budgets identify sources of errors and suggest necessary technological improvements. They do not identify the action of the errors, or allow comparison with fault-tolerance thresholds: overcoming this requires a comprehensive theoretical model of the gate and its errors. We showed the first such comprehensive quantum-logic gate model for *any* physical architecture, using a photonic entangling gate based on measurement-induced nonlinearity. Our model identified small

amounts of multi-photon emission as the dominant, yet previously unrecognised, source of error. We concluded that removing multi-photon emission puts photonic quantum computing within striking distance of a recently predicted fault-tolerance threshold. We also followed up with a comprehensive analysis that examined how the various errors scale with source brightness [26].

In photonic quantum computing the major source of noise has previously been identified as mode mismatch [7,8,11], albeit with dependent photons. Here instead we use *independent* photons as these can be scaled to large numbers, unlike dependent photons. Our experiment is a photonic controlled-z gate which when used with dependent photons gives process fidelities of 90–95% – here, with independent photons, the process fidelity drops to 78%, Figure 2(b,e). To cleanly test the difference due to using independent photons, we constructed a model that accounts for all known error sources *except* mode mismatch: photon source characteristics, including higher-order photon terms; imperfections in the optical architecture; and photon loss. Figure 2(c,f) show the modelled results,

which have high fidelity with the measured gate, $F_p = 96.7 \pm 1.5\%$. The small difference in fidelities with the ideal between the full model and experiment, $\Delta F_p = 3.2 \pm 1.5\%$, we attribute to mode mismatch. The striking advantage of architectural models is that by varying the parameters between ideal and measured values we can explore the contributions of each error source. Our model finds that higher-order photon terms are the major source of noise in photonic entangling gates: the largest degradation from the ideal occurs when adding in the higher-order photon terms, $\Delta F_p = 15.8\%$. From our measurements and model, we estimate that if true single photon sources and efficient detectors were used, the gate error would be $p = 3.2 \pm 1.5\%$ – squarely within the range of fault-tolerant error thresholds predicted by Knill of 3 to 6%! This highlights that improved single photon sources and detectors will have an immediate and significant impact in photonic quantum computing.

References

- [**Bold**] indicates a paper by Centre Personnel.
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