

Linear Optics Quantum Computation Program – Theory

PROGRAM MANAGER

Prof Timothy Ralph – UQ

LOQC-THEORY RESEARCHERS

Students Ms Agatha Branczyk (PhD), Mr Alex Hayes (PhD), Mr Patrick Leung, Mr Austin Lund (PhD), Mr Peter Rohde (PhD)
Staff Dr Hyunseok Jeong, Dr Alexei Gilchrist

COLLABORATING CENTRE RESEARCHERS

University of Queensland, Australia

Mr Nathan Langford, Mr Till Weinhold, Mr Ben Lanyon, Prof Andrew White, Prof Gerard Milburn

Griffith University, Australia

Prof Howard Wiseman, Dr Geoff Pryde
UNSW@ADFA Dr Elanor Huntington, Dr Charles Harb

OTHER COLLABORATORS

University of Queensland, Australia

Prof Michael Nielson

Defence Science Technology

Organisation, Australia

Dr Henry Haselgrove

Institut d'Optique, France

Prof Philippe Grangier

Hewlett Packard, UK

Dr William Munro

University of Warsaw, Poland

Dr Magdalena Stobinska

Louisiana State University, USA

Prof Jon Dowling

Erlangen University, Germany

Dr Christine Silberhorn, Prof Gerd Leuchs

University of Waterloo, Canada

Dr Casey Myers, Dr Kevin Resch,

Prof Norbert Lutkenhaus

University of Oxford, UK

Prof Ian Walmsley, Dr Pieter Kok

National Institute of Informatics, Japan

A/Prof Kae Nemoto

Korean Institute for Advanced Study

Dr N.B.An

Imperial College, UK Dr Kenneth Pregnell

PROGRAM DESCRIPTION

Linear optics is an incredibly precise technology. As such it is a natural candidate for quantum information processing. However quantum computation gates require non-linearities. Non-linear optics is not so precise. The idea of linear optical quantum computing (LOQC) is to do all the qubit manipulations with linear optics and apply non-linearities via the introduction and measurement of special ancilla quantum states, as described by E.Knill, R.Laflamme and G.J.Milburn, *Nature* **409**, 46 (2001) (KLM). At the basic level KLM describes a tractable way to build non-deterministic, 2-qubit quantum gates in optics. By non-deterministic we mean the gates do not always work, but successful attempts can be unambiguously identified. At its highest level KLM delivers an in principle recipe for the construction of an optical quantum computer.

The LOQC theory program addresses a broad range of issues associated with optical quantum computation from close collaborations on experimental demonstrations to alternative architectures and fundamental issues of scaling. We are supported by ARC, US Government (IARPA) and Queensland State Government funding. This year 16 papers by group members were published including 1 *Nature*, 3 *Physical Review Letters*, 1 *Reviews of Modern Physics* and a commentary in *Science*. We have 4 more papers submitted, 2 of which are in press. In the following we briefly discuss some of the highlights.

1. Spectral Structure of Optical States

Typically linear optical quantum computing (LOQC) models assume that all input photons are completely indistinguishable. However photons have a spatio-temporal structure that can introduce a degree of distinguishability between them, and as a result can compromise LOQC algorithms. Previously we have studied this effect at the single photon level [P.P.Rohde and T.C.Ralph, *Phys. Rev. A* **71**, 032320 (2005)].

This year we have studied the spectral structure and decomposition of multi-photon states. Ordinarily 'multi-photon states' and 'Fock states' are regarded as synonymous. However, when the spectral degrees of freedom are included this is not the case, and the class of 'multi-photon' states is much broader than the class of 'Fock' states. We discuss the criteria for a state to be considered a Fock state. We then address the decomposition of general multi-photon states into bases of orthogonal eigenmodes, building on existing multi-mode theory, and introduce an occupation number representation that provides an elegant description of such states that in many situations simplifies calculations. Finally we apply this technique to several example situations, which are highly relevant for state of the art experiments in quantum computation. This work was performed in collaboration with the Max-Planck Forschungsgruppe at the University of Erlangen, Germany and has been published as "Spectral structure and decompositions of optical states, and their applications", Peter P Rohde, Wolfgang Mauere and Christine Silberhorn, *New J. Phys.* **9**, 91 (2007).

2. Creating Cat States for Coherent State LOQC

A quite different version of the LOQC paradigm involves encoding the quantum information in multi-photon coherent states, rather than single photon states [T.C. Ralph, A. Gilchrist, G.J. Milburn, W.J. Munro and S. Glancy, *Phys. Rev. A* **68**, 042319 (2003)].

We refer to this as Coherent State Quantum Computing (CSQC). It has been known for some time that it is theoretically possible to perform universal quantum computing in CSQC with the proviso that the two coherent states can be considered orthogonal. This requirement simplifies the analysis immensely as then the two coherent states can be treated much like standard qubits. However, this leads to a practical problem as the coherent state amplitude must be large for this orthogonality requirement to be met. The scheme requires superpositions of coherent states (also known as cat states) be generated and high efficiency photon number resolving measurements be performed. These requirements are far from trivial when the coherent amplitude is large.

Last year we observed that large coherent state amplitudes are not required if one is willing to encode the information in an error correcting code and perform fault-tolerant quantum computing in this way. The scheme is different from the standard fault tolerant paradigm in two ways. With the coherent amplitude small the qubit basis states on which the gates act become non-orthogonal: that is, the overlap of the basis states is non zero. Also, the gates which act on these states are necessarily non-unitary and so must be implemented by measurement (not state evolution) and have at least one failure mode in which the gate does not perform correctly. This year we completed our study of the threshold properties of such a scheme and showed that the overheads required were potentially many orders of magnitude lower than those required for standard LOQC. This work has now been published as "Fault-tolerant linear optical quantum computing with small-amplitude coherent states", A.P. Lund, T.C. Ralph, and H.L. Haselgrove, *Physical Review Letters* **100**, 030503 (2008).

A major issue for CSQC is how to produce the necessary resource cat states. This year we developed and implemented a scheme for the creation of cat states of the required size in collaboration with the Institut d'Optique, CNRS, France. The idea employs post-selection performed on photon number states using homodyne detection [A.M.Lance, H.Jeong, N.B.Grosse, T.Symul, T.C.Ralph, P.K.Lam, *Phys. Rev. A* **73**, 041801 (R) (2006)]. The resulting "squeezed" cat states had an effective coherent amplitude of 1.6, easily the largest yet produced. The protocol straightforwardly generalizes to cat states of higher amplitude. Figure 1 shows the quasi-probability distribution (Wigner function) of the experimental states. This work has been published as "Generation of optical 'Schroedinger cats' from photon number states", Alexei Ourjoumtsev, Hyunseok Jeong, Rosa Tualle-Broui & Philippe Grangier, *Nature* **448**, 784 (2007).

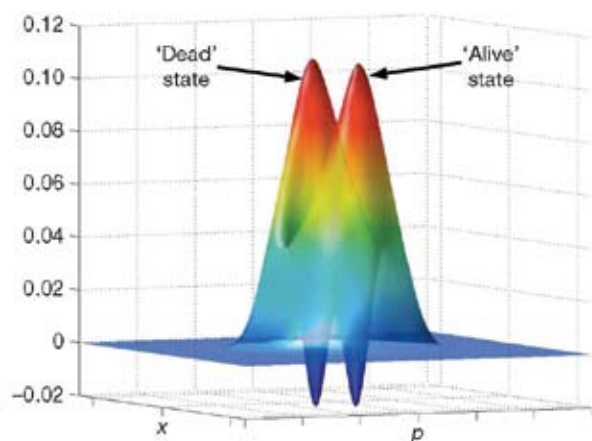


FIGURE 1

Quasi-probability distribution (Wigner Function) of the cat state produced in collaboration with Institut d'Optique. The negative regions of the distribution indicate the strong non-classical nature of the state [A.Ourjountsev, H.Jeong, R.Tualle-Broui & P.Grangier, *Nature* **448**, 784 (2007)].

3. Controlled Unitaries

A challenge facing quantum computing is that large circuit depth (number of gates) is often required to perform even simple tasks. Finding more efficient ways to implement quantum gates may allow small scale quantum computing tasks to be demonstrated on a shorter time-scale. In optics particular types, or sequences of gates can be difficult to implement. For example, using standard techniques, the controlled unitary (CU) gate, a two-qubit gate which can implement (or not) an arbitrary unitary operation on a target qubit based on the logical value of a control qubit, requires 6 photons to demonstrate. Given the difficulty in producing multi-photon number states, this would be a difficult experiment to perform.

Using our recently developed techniques utilizing the multilevel structure of quantum systems [T.C.Ralph, K.Resch and A.Gilchrist, *Phys.Rev.A* **75** 022313 (2007)], we have now shown that a CU gate can be demonstrated using only 2 photons, see Figure 2. In collaboration with the experimental LOQC groups at University of Queensland and Griffith, we have demonstrated both the CU and 3 qubit Toffoli gate using these techniques and also shown that they generalize to higher order CU and Toffoli gates. This work has been submitted as "Quantum computing using shortcuts through higher dimensions", B. P Lanyon, M. Barbieri, M. P Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. Pryde, J. I. O'Brien, A. Gilchrist, A. G. White.

4. Fault Tolerance of Zeno Gates

Whilst considerable progress has been made on implementing two qubit gates in optics using the measurement induced

non-linearities proposed by KLM and theory has found significant ways to reduce the resource overheads, still the

number of photons and gate operations required to implement a near deterministic two qubit gate remains high. One possible solution to this problem is the optical quantum Zeno gate suggested by Franson et al (*PRA* **70**, 062302, 2004). This gate uses a passive two-photon absorber (i.e. a material that preferentially absorbs photons in pairs as opposed to individually) to suppress gate failure events associated with photon bunching at the linear optical elements. This is an example of the quantum Zeno effect. In principle a near deterministic, high fidelity control-sign (CS) gate can be implemented between a pair of photonic qubits in this way. Last year we showed how the resilience of this gate to single photon loss could be improved [Patrick M. Leung and Timothy C. Ralph, *Phys. Rev. A* **74**, 062325 (2006)].

This year we have investigated the fault tolerant threshold when using Zeno effect gates. We considered the use of measurement based quantum processing techniques to enhance the operation of the Zeno gate. With the help of quantum teleportation, we show that it is possible to achieve a Zeno CNOT gate that gives (near) unit fidelity and moderate probability of success of 0.8 with a two-photon to one-photon absorption ratio of $\kappa = 10^{-4}$. We include mode-mismatch effects and estimate the bounds on the mode overlap and κ for which fault tolerant operation would be possible. This work has been published as "Optical Zeno Gate: Bounds on Fault Tolerance", P.M.Leung and T.C.Ralph, *New J. Phys.* **9** 224 (2007).

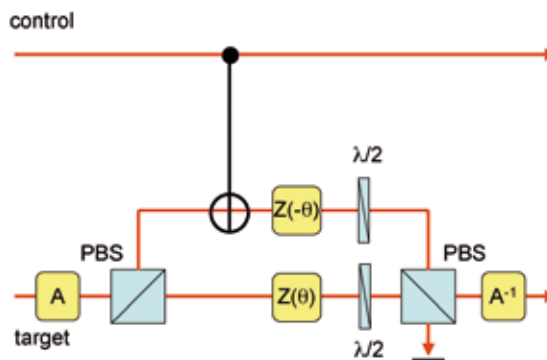


FIGURE 2

Schematic of the optical Controlled-Unitary gate. Up to a global phase factor the gate implements the identity when the control is in the "0" state and the unitary $AZ(\theta)A^{-1}$ when the control is in the "1" state. The gate operates with a probability of success of $1/12$. PBS stands for polarizing beamsplitter and $\lambda/2$ are half waveplates [T.C.Ralph, UQ internal report].

5. Cluster State Production using Weak Non-linearities

Strong nonlinear effects, if available, could be very useful for the generation of non-classical states and quantum information processing in optical systems. However, nonlinear effects in currently available nonlinear media are extremely weak compared with the required level for the non-classical state generation and quantum information processing. Recently, the idea of using weak nonlinearities combined with strong coherent fields was suggested by Nemoto and Munro (*Phys. Rev. Lett.* **93**, 250502 (2004)) for various applications including the generation of macroscopic quantum states and quantum computation. We have continued our investigation of the uses and practicalities of this scheme.

This year, in collaboration with the National Institute of Informatics, Japan and Hewlett Packard, UK, we examined the practicalities of using weak non-linearities to build multi-photon entangled states known as cluster states. Cluster states can be used to implement efficient LOQC schemes. In particular we discuss experimental effects in the implementation of a recent scheme for performing bus mediated entangling operations between qubits. This approach has the benefit that entangling gates are non-destructive, may be performed non-locally, and there is no need for efficient single photon detection. We analyze the effects of post-selection errors, qubit loss, bus loss, mismatched coupling rates and mode-mismatch. We derive error models for these effects and relate them to realistic fault-tolerant thresholds, providing insight into realistic experimental requirements. This work has been published as "Practical effects in the preparation of cluster states using weak non-linearities", P.P.Rohde, W.J. Munro, T.C. Ralph, P van Loock, and K Nemoto, *Quantum Information and Computing*, **8**, 53 (2008).