Linear Optics Quantum Computation Program – Theory

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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 as was demonstrated by us in J.L. O'Brien, G.J. Pryde, A.G. White, T.C. Ralph and D. Branning, Nature **426**, 264 (2003). 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 Australian Research Council and United States Government (IARPA) funding. This year, 9 papers by group members were published including two papers in *Nature Physics*, one in *Nature Photonics* and one in *Physical Review Letters*. We also published a major review of Optical Quantum Computation in *Progress in Optics*. In the following we briefly discuss some of the highlights.

1. Spectral Structure of Quantum Gates and Sources

Typically, optical quantum computing 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 optical quantum gates. Previously we have studied this effect for linear optical quantum gates [P.P. Rohde and T.C. Ralph, Phys. Rev. A **71**, 032320 (2005)] and the chi-2 non-linearity [Patrick M. Leung, William J. Munro, Kae Nemoto, Timothy C. Ralph, Phys. Rev. A **79**, 042307 (2009)].

This year we have studied the effect of spectral structure on the operation of the Kerr non-linearity. The Kerr nonlinearity featured in the first suggestion for optical quantum gates [G.J. Milburn, Phys. Rev. Lett **62**, 2124 (1989)]. and has been explored extensively since. However most of this work has used the single mode approximation – ignoring the spectral structure of the interaction. It was pointed out recently by Shapiro, Phys. Rev. A, 73, 062305 (2006), that the Kerr effect cannot be used for quantum gates if these spectral degrees of freedom are included. Two problems must be overcome in order for successful gate operation to be recovered: (i) the appearance of spectrally induced entanglement must be prevented; and (ii) Raman induced phase noise must be quenched. We have studied this system and found conditions under which both these problems can be overcome, specifically by: (i) introducing dispersion into the crystal and (ii) introducing spectral filtering in the crystal. This work was performed in collaboration with the National Institute for Informatics, Japan and Hewlett Packard, UK and is available as "Spectral Effects of Fast Response Cross Kerr Non-Linearity on Quantum Gate", P.M. Leung, T.C. Ralph, William J. Munro, Kae Nemoto, arXiv:0810.2828.

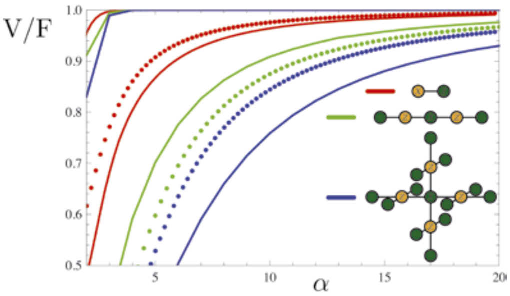
Another application in which spectral structure plays a key role is in the generation of single photon states suitable for use as quantum bits (qubits). For example, the generation of heralded pure Fock states via spontaneous parametric down conversion (PDC) relies on perfect photon-number correlations in the output modes. Correlations in any other degree of freedom, however, degrade the purity of the heralded state. This year we have investigated spectral entanglement between the two output modes of a periodically poled waveguide. With the intent of generating heralded 1- and 2-photon Fock states, we expand the output state of the PDC to second order in photon number. We explore the effects of spectral filtering and inefficient detection, of the heralding mode, on the count rate, g(2) and purity of the heralded state, as well as the fidelity between the resulting state and an ideal Fock state. We find that filtering can decrease spectral correlations, however, at the expense of the count rate and increased photon-number mixedness in the heralded output state. As a physical example, we model a type II PP-KTP waveguide pumped by lasers at wavelengths of 400 nm, 788 nm and 1930 nm. The latter two allow the fulfillment of extended phase matching conditions in an attempt to eliminate spectral correlations in the PDC output state without the use of filtering, however, we find that even in these cases, some filtering is needed to achieve states of very high purity suitable for quantum computation applications. This work was performed in collaboration with the Max Planck Institute for the Science of Light, Erlangen, Germany and is available as "Optimised generation of heralded Fock states using parametric down conversion", Agata M. Branczyk, T. C. Ralph, Wolfram Helwig, Christine Silberhorn, arXiv:0909.4147.

2. Quantum Computation with Cat States

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). Recently we have shown how to make this scheme fault tolerant [A.P. Lund, T. C. Ralph, and H. L. Haselgrove, Phys. Rev. Lett. **100**, 030503 (2008)] and have demonstrated production of the equal superpositions of coherent states, also known as cat states, that are required as resource states for this protocol [Alexei Ourjoumtsev, Hyunseok Jeong, Rosa Tualle-Brouri and Philippe Grangier, Nature 448, 784 (2007)].

FIGURE 1

We show the visibility of stabilizer measurements (solid lines) and fidelity against the optimal state (dashed lines) for the construction of various coherent state topological 3D cluster states (shown on the right hand side) using beam splitters with a reflectivity of $\pi/2\alpha^2$. As a reference, we include the visibility for the corresponding ideal coherent state cluster states in the top left hand corner.



Recently it has been suggested that topological quantum computing using 3D cluster states might be efficiently and robustly implemented in an optical achitecture [S.J. Devitt, A.G. Fowler, A.M. Stephens, A.D. Greentree, L.C.L. Hollenberg, W.J. Munro, K.Nemoto, New. J. Phys. **11**, 083032 (2009)]. The suggested implementation employed nonlinear gates that, as discussed in the previous section, have several drawbacks. This year we have studied a linear version of this scheme based on CSQC. We find that for the simplest possible scheme fault tolerant operation is possible for cat states with an average photon number of about 40 when the bulk loss is below 1 in 100 thousand (see Figure 1). These are not nice numbers, but they show that the scheme is possible in principle. We are currently examining the improvement that can be obtained by implementing a slightly more complicated scheme using teleportation to enhance the gate operation. This work was presented as an invited talk at the International Conference on Quantum Information and Technology, Tokyo, Japan (2009) as “3D Cluster State Construction using Linear optics gates”, C.R. Myers and T.C. Ralph.

3. Circuits and Gates using Spatial Degrees of Freedom

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 sooner. In optics, particular types – or sequences – of gates can be difficult to implement, involving many applications of primary gates and ancilla photons. Recently we have developed techniques for utilizing the multilevel structure of quantum systems [T.C. Ralph, K. Resch and A. Gilchrist, Phys. Rev.A **75** 022313 (2007)], that enable the demonstration of otherwise intractable gates [B.P. Lanyon, M. Barbieri, M.P. Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. Pryde, J.L. O’Brien, A. Gilchrist and A.G. White, *Nature Physics* **5**, 134 (2009)].

This year we have extended these techniques by considering the use of entanglement between additional degrees of freedom – specifically spatial degrees of freedom – to further expand the horizons of experimentally accessible optical quantum gates. In collaboration with the University of Bristol, UK we have demonstrated a more general Controlled Unitary gate and a novel entanglement filter as well as designing more ambitious gates and circuits that should be experimentally tractable in the near future. This work was presented as a talk at the 9th Asian Conference on Quantum Information Science, Nanjing, China (2009) as “Photonic Quantum Logic in Waveguide Circuits” Xiao-Qi Zhou, Timothy Ralph, Mian Zhang, Pruet Kalasuwan, Anthony Laing, Alberto Politi, Jonathan Matthews, Andre Stefanov and Jeremy O’Brien.

4. Cluster State Quantum Computation

Another potentially promising method for implementing a linear optical quantum computer is continuous-variable cluster states [N.C. Menicucci, P. van Loock, M. Gu, C. Weedbrook, T.C. Ralph, M.A. Nielsen, Phys. Rev. Lett. 97, 110501 (2006)].

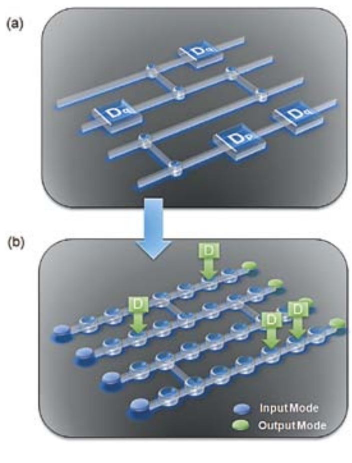


FIGURE 2

(a) Any unitary on multiple qumodes may be written as a quantum circuit consisting of quantum nondemolition interactions (CZ) and single-qumode unitaries diagonal in either the position or momentum basis. (b) Any such circuit may be directly translated into an appropriate graph state. Here the arrowed qumodes are measured in the appropriate basis that implements their corresponding single-qumode unitary. All other non output qumodes are measured in the p basis.

Cluster states are large entangled states of a special form. Measurements on the cluster can simulate the quantum evolution of a quantum circuit (see Figure 2). This year we have extended and further refined theoretical foundations and protocols for the experimental implementation of this technique. We give a cluster-state implementation of the cubic phase gate through photon detection, which, together with homodyne detection, facilitates universal quantum computation. In addition, we have characterized the offline squeezed resources required to generate an arbitrary graph state through passive linear optics. Most significantly, we have proven that there are universal states for which the offline squeezing per mode does not increase with the size of the cluster. Simple representations of continuous-variable graph states have been introduced to analyze graph state transformations under measurement and the existence of universal continuous-variable resource states. This work has appeared as “Quantum Computing with Continuous-Variable Clusters”, Mile Gu, Christian Weedbrook, Nicolas C. Menicucci, Timothy C. Ralph, Peter van Loock, Phys. Rev. A **79**, 062318 (2009).

5. Entanglement and Spacetime Curvature

An interesting issue surrounding entanglement is its behaviour in the presence of spacetime curvature. Understanding such behaviour could be important for large scale distributed quantum computation as well as nearer term quantum communications. Also, because a full theory of quantum gravity has yet to be formulated, an investigation of this problem could lead to fundamental advances. This year we investigated an alternative formulation of the problem of quantum optical fields in a curved space-time using localized operators. We contrast the new formulation with the standard approach and find observable differences for entangled states. We propose an experiment in which an entangled pair of optical pulses are propagated through non-uniform gravitational fields and find that the new formulation predicts de-correlation of the optical entanglement under experimentally realistic conditions. This work was also supported by the Defence Science and Technology Organization and has appeared as “Quantum Connectivity of Space-Time and Gravitationally Induced De-correlation of Entanglement”, T.C. Ralph, G.J. Milburn and T. Downes, Phys. Rev. A. **79**, 022121 (2009).