Quantum Integrated Photonics

Science Leader:
Michael Steel, +61 2 9850 8916,
michael.steel@mq.edu.au

Project Leader:
Chunle Xiong, +61 2 9036 9430,
chunle@physics.usyd.edu.au

Researchers:
Duk-Yong Choi, ANU
Alex Clark, USyd
Benjamin Eggleton, USyd
Christian Grillet, USyd
Yuri Kivshar, ANU
Barry Luther-Davies, ANU
Steve Madden, ANU
Graham Marshall, MQ
Arnan Mitchell, RMIT
David Moss, USyd
Dragomir Neshev, ANU
Michael Steel, MQ
Andrey Sukhorukov, ANU
Mick Withford, MQ
Chunle Xiong, USyd

Partner Investigators:
Thomas Krauss, University of St. Andrews
Christelle Monat, Ecole Centrale de Lyon
Jeremy O'Brien, University of Bristol
John Sipe, University of Toronto

PhD Students:
Matt Collins, USyd
Xin Gai, ANU
Thomas Meany, MQ
Alexander Solntsev, ANU

The vision of this project is to develop a flexible integrated platform for the generation and processing of non-classical light states – photonic quantum states - through nonlinear and tunable devices. In particular we aim to

- Generate photons with measurable quantum properties using highly nonlinear waveguides,
- Prepare and analyse these photonic quantum states in integrated waveguides.

This program in quantum science and quantum photonics brings together three CUDOS nodes, ANU, MQ and Sydney in collaboration with academics at the University of Bristol, University of St. Andrews and University of Toronto.

CUDOS has a wealth of expertise for this project. The group in ANU Laser Physics Centre has extensive experience in fabricating, characterizing and dispersion-engineering highly nonlinear glass waveguides. The Nonlinear Physics Centre at ANU is a world leader in the field of nonlinear dynamics in waveguide arrays. The group at MQ has world-class femtosecond laser direct writing capabilities to create complex waveguide circuits suitable for quantum logic, while the group at Sydney is at the forefront of manipulation of nonlinear processes in integrated circuits, the fundamental building block for generation of correlated photon states.

By combining sources and waveguide structures, we aim to ultimately produce fully integrated hybrid monolithic circuits that generate single photons and process their quantum states. Our work will have applications in communication security, quantum-limited measurement and the boundaries of fundamental quantum science.

Progress

In our first year, the team has achieved great progress towards our long-term goals. We recruited a new team of students and postdoctoral researchers for this new area of research, and established new capabilities for photonic quantum experiments including single-photon detection systems, quantum device fabrication systems, and single-photon generation.

Integrated quantum sources

An integrated single-photon source is one of the fundamental building blocks of integrated photonic quantum technology. There has been significant recent progress towards reliable high rate single-photon generation from compact nonlinear photonic devices, but there remain significant challenges in terms of increasing brightness, reducing size and controlling noise generated by sources including spontaneous Raman generation. This motivates the study of new materials and structures to improve performance and the degree of integration.

We made substantial advances in 2011 towards the development of quantum light sources suitable for photonic integration. In experiments using highly nonlinear planar chalcogenide circuits and silicon photonic crystals we were successful in demonstrating quantum-correlated photon-pair generation through spontaneous four-wave mixing. The use of one photon to 'herald' the other creates a pseudo-deterministic single-photon source.

In chalcogenide, we improved the quantum signal to noise ratio of As_2S_3-based correlated photon-pair sources by two orders of magnitude by using a pulsed pump and cooling the sample [1]. We proposed a new chalcogenide platform based on Ge_{11} nanowires for high-quality photon-pair generation in the large detuning regime with low Raman noise [2].

We generated pairs of correlated photons for the first time in dispersion-engineered silicon slow-light photonic crystal waveguides [3], creating a super-compact source of correlated photon pairs. The speed of light in these structures is slowed down by a factor of 10, which enhances the nonlinearity by 100 times and the efficiency of pair generation by two orders of magnitude per unit pump power and unit device length. We generated correlated photon pairs in a device of about 100 µm long, 100 times shorter than any nonlinear photon-pair emitter previously developed (Fig. 1). The compactness of this photon generator lends itself to the fabrication of many such generators on one chip, with the consequent production of large numbers of single photons. A compact and integrated single-photon source based on replication of this super-compact source offers a scalable approach to quantum information processing on a chip.

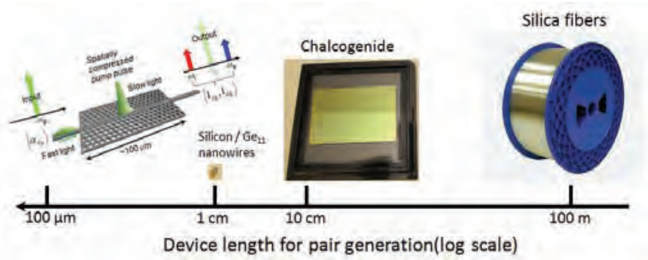

Fig. 1. Development of miniaturisation of photonic devices for photon-pair generation.

Other developments on integrated single-photon sources include demonstration of correlated photon-pair generation in a periodically poled MgO doped stoichiometric lithium tantalate reverse proton exchanged waveguide, which can operate at room temperature [4], and on-demand, high repetition rate sources of indistinguishable, polarized single-photons based on diamond NV centre [5].

Integrated quantum circuits

We are not only interested in quantum sources, but also their applications to quantum information processing including quantum simulation, quantum emulation, and quantum logic gate operation, particularly in 3D integrated quantum circuits [6]. Such circuits will allow us to explore quantum dynamics in systems not easily realised in 2-D planar structures. As a first demonstration, we fabricated an elliptic array of waveguides using a femtosecond laser direct-writing technique (Fig. 2a). We characterized the photonic chip with coherent light tomography and used the results to predict distinct differences between temporally indistinguishable and distinguishable two-photon inputs (Fig. 2b).

In collaboration with the University of Queensland, we performed the first quantum walk in a 3D waveguide structure with genuine non-classical inputs (Fig. 2c). By comparing the experimental observations (Fig. 2d) and theoretical predictions (Fig. 2e), we gained insight into the effect on quantum walks of waveguide imperfections such as polarization-dependent coupling and loss induced by the waveguide birefringence during fabrication. This work represents a significant step towards quantum emulation of a class of Hamiltonians from condensed matter and biological systems that can be approximated by evanescently coupled waveguides. This work revealed the need for a post-tuning capability for integrated quantum circuits, a task we will pursue in 2012.

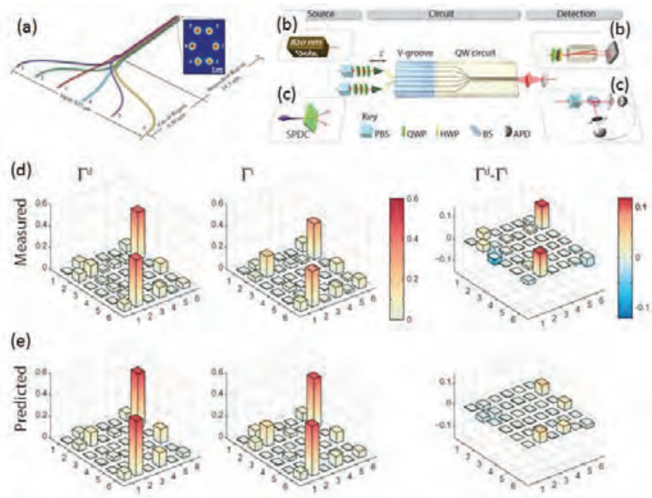

Fig. 2. (a) Schematic representation of the integrated waveguide circuit (drawing not-to-scale) and associated output. (b) The chip was characterized with an 820 nm laser diode, imaged onto a CCD camera via a polarizing prism. (c) Quantum walks were performed with two-photon inputs created via spontaneous parametric down conversion (SPDC). (d) The measured and (e) predicted correlation matrices for (left) temporally distinguishable photon pairs Γ^d, (center) temporally indistinguishable simultaneous walkers Γ^i and (right) the difference $\Gamma^d - \Gamma^i$.

Quantum Integrated Photonics Continued

Hybrid integration of quantum sources and circuits

The ultimate goal of this project is to integrate single-photon sources and quantum circuits on a photonic chip to form a monolithic quantum photonic processor. The most obvious way to achieve this goal is by the integration of nonlinear devices in which the single photons are generated with linear optical components from which the quantum circuits are fabricated.

A more sophisticated approach is to construct the quantum circuits using nonlinear materials so that the generation and processing of single photons take place simultaneously. We proposed and simulated a framework of such simultaneous photon-pair generation and quantum walks in quadratic nonlinear waveguide arrays [7]. We showed that the output quantum state can be controlled (Fig. 3) including dynamic switching from anti-bunching to bunching regimes. We fabricated waveguide arrays from lithium niobate and characterized them in preparation for full quantum experiments in 2012.

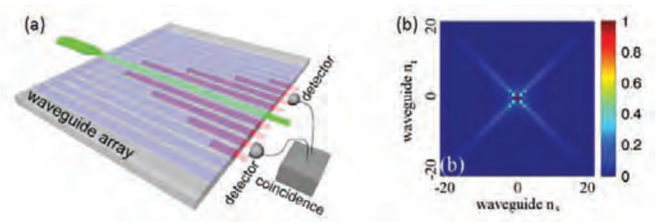

Fig. 3. (a) Schematic of a quadratic waveguide array: The pump beam generates photon pairs that couple to the neighbouring waveguides where quantum walks take place. (b) An example of photon-pair correlations (bunching) in real space (waveguide numbers) for a pump coupled only to the central waveguide n=0 with zero single-waveguide degenerate phase mismatch.

Highlights

- We have published 7 papers in prestigious journals such as Physical Review Letters, Applied Physics Letters, New Journal of Physics, Optics Letters and Optics Express. These represent extensive collaboration, both across nodes in CUDOS and with our partner investigators.
- Because of his work on photon-pair generation in chalcogenide As_2S_3 waveguides, Dr Chunle Xiong was awarded a travel grant in April 2011 by the Australian Academy of Science under the program of 2010-2011 Scientific Visits to Japan to carry out an entanglement generation experiment.
- Our PhD student Matt Collins gave an invited talk on behalf of Dr Chunle Xiong about our ultra-compact source of correlated photons at the International Conference on Photonics (ICP2011) held in Malaysia in October 2011.
- Professor Mark Dignam from Queen's University, Canada visited MQ to study the dynamics of correlated pair generation in structured materials.
- MQ planned a student exchange program with PI Sipe at the University of Toronto to commence in 2012. The first PhD student Luke Helt from Toronto has recently commenced his visit.
- The Sydney team was awarded a University of Sydney Major Equipment Grant for advanced superconducting single-photon detectors in November 2011, which will provide us with detector technology at the forefront in Australia and worldwide.
- Dr Chunle Xiong was awarded a fellowship by the Australian Research Council under the Discovery Early Career Researcher Award scheme. He will work on quantum entanglement on integrated photonic chips, which is complementary to the CUDOS quantum program.
- One of the most exciting achievements in 2011 was the demonstration of slow-light enhanced correlated photon-pair generation in an ultra-compact silicon photonic crystal waveguide. The first results were presented at a prestigious international conference CLEO in Baltimore, USA as a postdeadline paper in May, 2011. The news was reported by many online media such as Electronics News, Science Alert and i2p (Fig. 4).

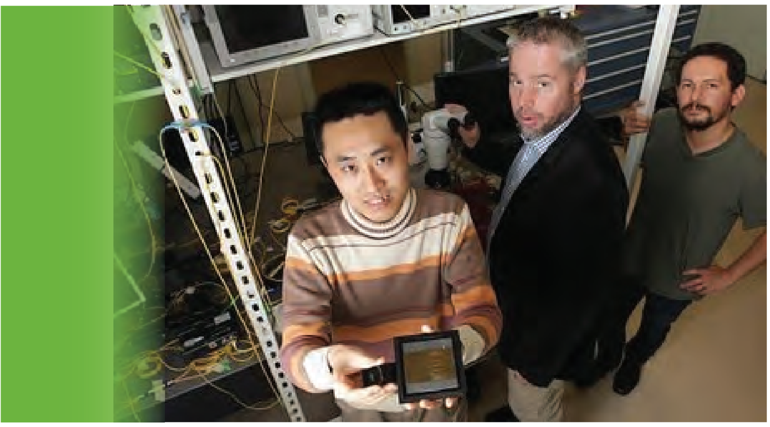

Fig. 4. Image from the Electronics News press release. Dr. Chunle Xiong holding the new (small) and old chip (big), Professor Ben Eggleton, CUDOS Director and Dr Christian Grillet.

Future Directions

2011 was an exciting year as CUDOS made its first contributions to quantum science. In 2012 we will build momentum towards the long-term vision: increasing the efficiency and density of our components and the scale of our characterisation systems. We will have a focus on the hybrid integration of different systems including an expansion of activity in quadratically nonlinear materials.

Publications and References

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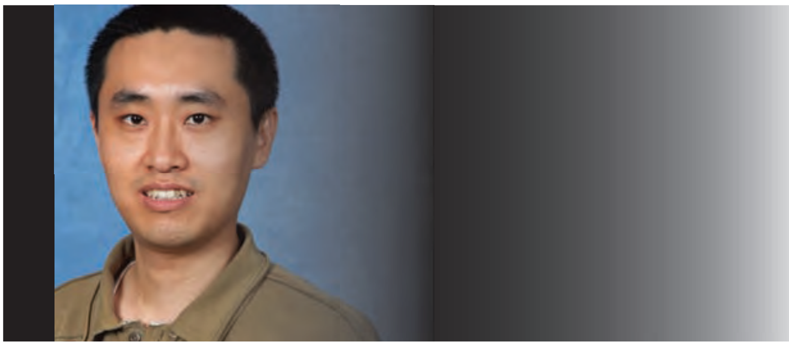
Project Leader



Chunle Xiong received the PhD degree in Physics from the University of Bath, UK, in 2008, for his work on nonlinear optics in photonic crystal fibres. He then joined CUDOS at The University of Sydney as a Postdoctoral Fellow. In 2011, Chunle was promoted to Research Fellow and appointed as the project leader of the CUDOS flagship project in Quantum Integrated Photonics. In 2011, Chunle was awarded a fellowship by the Australian Research Council under the Discovery Early Career Researcher Award scheme. He is now working on the generation and manipulation of quantum states of light in integrated waveguide systems.

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