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Peter Shadbolt

Complexity and Control in Quantum Photonics

Doctoral Thesis accepted by
the University of Bristol, UK

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To my parents

Supervisor's Foreword

Since 2001, it has been known that a universal quantum computer can be built using single photon sources, single photon detectors, and an adaptive interferometer. There has since been a great deal of interest in practical implementations of such a machine. Early experiments were performed using bulk-optical elements: macroscopic beamsplitters, lenses and filters bolted to an optical bench. However, a useful, universal device will require many thousands of components, and can only be realised in an integrated, lithographically fabricated platform. Over the past decade, the capability of integrated photonics has grown to meet the needs of the classical telecommunications and computing industries, to the extent that lasers, filters, switches, and optical interconnects can all now be implemented in planar waveguide chips using standard semiconductor fabrication techniques.

Proof-of principle experiments, performed over the last few years, have demonstrated that this hardware is suitable for applications in quantum photonics. Although the overarching goal is the development of practical quantum technologies, these experiments also provide tangential benefits, enabling tests of foundational quantum mechanics with a degree of complexity and control which would be extremely challenging—if not impossible—using bulk-optical apparatus.

Pete Shadbolt's thesis captures both sides of this coin. His work showcases the utility of integrated photonics for optical quantum computing, demonstrating novel on-chip implementations of quantum state preparation, logic gates, quantum algorithms, and state characterization methods. Meanwhile, he has used the same reconfigurable hardware to explore foundational quantum physics, including complementarity and nonlocal quantum correlations.

A large fraction of Pete's thesis makes use of a reconfigurable two-qubit silica-on-silicon chip. Pete has shown how this device can be used to generate and characterise Bell states, perform quantum process tomography, and violate Bell tests. While these experiments have previously been performed in bulk optics, these were the first on-chip demonstrations of these essential protocols. Pete went on to use this chip to test a new method which guarantees Bell violation in the absence of a shared reference frame, a situation which can occur due to polarization rotations in optical fiber, for instance. He describes an extension of this scheme which greatly facilitates the characterisation of entangled photon sources in the presence of realistic experimental noise.

The same device was used to implement a novel twist on Wheeler's classic delayed choice experiment, testing the counterintuitive wave-particle duality of the photon. In this new experiment, Wheeler's binary "choice" was replaced by a qubit, allowing wave and particle behaviours to be simultaneously observed in coherent superposition.

With respect to applications, Chap. 5 of Pete's thesis describes the experimental implementation of a new and unorthodox algorithm for quantum chemistry on a quantum computer. This algorithm has potential benefits in terms of the depth and complexity of the quantum circuit required to solve the electronic structure problem using a quantum computer.

In Chap. 6 of this thesis, the experimental complexity is significantly increased. Pete describes the development of a 16-channel multiphoton detection system, used in a series of experiments which examine quantum interference in waveguide arrays. These devices include continuously coupled quantum walks, and a Haar-random unitary circuit. Using up to 5 photons in 21 waveguides these experiments access a Hilbert space of around 50,000 dimensions, providing insight into the challenges associated with state characterization and algorithmic verification in large-scale quantum devices.

This thesis is characterised by the breadth of topics covered, from practical time-correlated single photon counting through to quantum algorithms and foundational quantum theory. It describes a large number of new results from an experimental standpoint, with extensive, practically relevant detail. As such, I believe that it will be an invaluable addition to the library of any student of experimental integrated quantum photonics.

Bristol, UK
September 2015

Prof. Mark Thompson

Abstract

Quantum mechanics predicts phenomena which have no classical analogue. This modifies our understanding of the capability of physical machines. Single photons, together with simple interferometers and single photon detection have been shown to be universal for the construction of many such machines. The nascent field of integrated quantum photonics addresses the scalability and practicality of such machines, and their integration in miniaturized monolithic chips.

In this work, we explore the scope and flexibility afforded by integrated quantum photonics, both in terms of practical problem-solving, and for the pursuit of fundamental science. We demonstrate and fully characterize a two-qubit quantum photonic chip, capable of arbitrary two-qubit state preparation. We make use of the unprecedented degree of reconfigurablility afforded by this device to implement a novel variation on Wheeler's delayed choice experiment, and test a new technique to obtain nonlocal statistics without a shared reference frame. We demonstrate a new algorithm for quantum chemistry, simulating the helium hydride ion. Finally, we demonstrate multiphoton quantum interference in a large Hilbert space, and discuss implications for computational complexity.

Acknowledgments

I have been enormously privileged to spend the past 4 years of my life studying physics in Bristol. I owe this privilege Jeremy O'Brien and Mark Thompson, who first gave me this opportunity, and who have given me supervision, advice, and freedom throughout.

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Acronyms

APD	Avalanche photodiode
API	Application protocol interface
BB84	Bennett & Brassard 1984
BBO	β-barium borate (β-BaB_2O_4)
BD	Beam dump
BiBO	Bismuth borate (BiB_3O_6)
BS	Beamsplitter
CHSH	Clauser-Horne-Shimony-Holt
CNOT	Controlled-not
CNOT-MZ	Reconfigurable two-qubit chip
CNOT-P	Postselected linear-optical CNOT
CPU	Central processing unit
CW	Continuous-wave
CZ	Controlled-Z
DAC	Digital-to-analog converter
DC	Directional coupler
DI-QKD	Device-independent quantum key distribution
DM	Dichroic mirror
ECC	Error-correcting code
ECT	Extended Church-Turing thesis
FCI	Full configuration interaction
FPGA	Field-progammable gate array
FWHM	Full-width half-maximum
GUI	Graphical user interface
HBT	Hanbury-Brown-Twiss
HOM	Hong-Ou-Mandel
HTTP	Hypertext transfer protocol
HWP	Half wave plate
IF	Interference filter
IQP	Integrated quantum photonics
KLM	Knill, Laflamme and Milburn

LOCC	Local operations and classical communication
LOQC	Linear optical quantum computing
MMI	Multimode interference
MZI	Mach-Zehnder interferometer
NV	Nitrogen vacancy
PBS	Polarising beamsplitter
PCB	Printed circuit board
PEA	Quantum phase-estimation algorithm
PMF	Polarization-maintaining fibre
QFT	Quantum Fourier transform
QKD	Quantum key distribution
QPT	Quantum process tomography
QST	Quantum state tomography
QW	Quantum walk
QWP	Quarter wave plate
RSA	Rivest-Shamir-Adleman
RTP	Room temperature and pressure
RU	Random unitary
SHG	Second-harmonic generation
SMF	Single-mode fibre
SPDC	Spontaneous parametric down conversion
SPS	Single-photon sources
TCSPC	Time-correlated single photon counting
VG	V-groove array
XOR	Exclusive-OR