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[Quantum Accelerator] Efficient Fast Photonic Integrated Circuits for Photonic Quantum Computing

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Final Technical Report

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14. ABSTRACT
The major activities in this project were modelling, fabrication, and testing of out-of-plane couplers and waveguide crossings, as well as ring resonators and beamsplitters we used to form test circuits for the first two components. The modelling and fabrication included waveguides in both Silicon-on-insulator (SOI), and Silicon Nitride on a Silicon Oxide substrate; preliminary tests were conducted on both the waveguide crossings and the out-of-plane couplers.

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BAA Name: FA9550-19-S-0003 - PKG00249980
Proposal Title: [Quantum Accelerator] Efficient Fast Photonic Integrated Circuits for Photonic Quantum Computing
Name and Title of Principle Investigator: Prof. Andrew White, andrew.white@uq.edu.au, +61 4 6625 6329
Submission Date: 30th August 2023
DUNS Number: 7528984030000
EIN Number: 98-0127096
Key Researcher(s) involved in the Project:

Dr Marcelo Almeida	The University of Queensland
Assoc.-Prof. Jacq Romero	The University of Queensland
Dr Till Weinhold	The University of Queensland
Mr Ming Su	The University of Queensland

Recipient Organization: The University of Queensland, Brisbane, QLD 4072 Australia
Recipient Identifying Number or Acct Number: 025865
Project/Grant Period: 12 months
Report Term: 1 January 2021–31 December 2021
Final Report? Yes
Signature of Submitting Official:

ACCOMPLISHMENTS

What were the major goals and objectives of this project?

The project objective was to develop efficient Photonic Integrated Circuit (PIC) components for quantum computing, particularly quantum neural nets (QNNs), which utilize quantum effects to model complex data sets.

The major goals were to realise by project end:

1. Efficient (>80%) out-of-plane couplers for coupling photons into and out of PICS at any point in the net;
2. Efficient (95–99%) waveguide crossings to allow large neural fanouts in small footprints; *and*
3. Combine these, along with interference beamsplitters, into test circuits which uses four independent photons to generate event-ready two-photon entanglement; we will quantify component performance through state and circuit tomography.

What was accomplished under these goals?

The major activities in this project were modelling, fabrication, and testing of out-of-plane couplers and waveguide crossings, as well as ring resonators and beamsplitters we used to form test circuits for the first two components. The modelling and fabrication included waveguides in both Silicon-on-insulator (SOI), and Silicon Nitride on a Silicon Oxide substrate; preliminary tests were conducted on both the waveguide crossings and the out-of-plane couplers.

The pandemic caused significant and unanticipated delays to our fabrication program. In February 2020 the Oxford Instrument Reactive Ion Etcher used to etch our PICs was under repair. The technician returned to the UK to obtain a part necessary to complete the repair and was subsequently unable to return to Australia to complete the repair until April 2023. In the interim we jury-rigged the device, spending much time to find a combination of operating parameters and chemistry that enabled us to obtain test devices and circuits. (These were of a lower quality than those subsequently obtained with the new Plasma-Therm Versaline Deep reactive ion etcher (DRIE) system—an inductively coupled plasma (ICP) etch system for deep silicon etching using the Bosch process—that became operational in 2023).

The significant results from this project were as follows.

Waveguide crossings. Using traditional design, the efficiency of a SiN waveguide crossing at 930 nm is 77.5%, i.e. each crossing experiences 1.1 dB loss. We found an inverse design that increases the crossing efficiency to 97%, reducing the crossing loss to 0.13 dB. We tested the fabricated crossings by sending light into one of two crossing waveguides, and then measuring the output intensities from each of the waveguides. Preliminary imaging and measurements show only the desired output being illuminated, and to date we have not been able to measure light from the non-desired waveguide. Experiments are ongoing to reduce the measurement noise floor so that we can measure light from the latter, and so obtain a value for the fabricated efficiency.

Out-of-plane couplers. Using traditional design, the efficiency of a SiN out-of-plane coupler at 930 nm is 11%, i.e. each coupler experiences 9.6 dB loss. We found an inverse design that increases the coupler efficiency to 68%, reducing the coupler loss to 1.7 dB. If the same design incorporates an Al backreflector, the coupler design efficiency becomes 83%, reducing the coupler loss to 0.81 dB. We explored both full and shallow etch designs, finding an parameter regime that is highly robust with respect to fabrication imperfections. However, the issues with the reactive ion etcher mean that to date our test devices have fallen well short of the design efficiencies. We expect this to improve when we refabricate the devices with the new plasma etcher installed this year.

We did not meet our third stated goal of combining the elements into test circuits that can generate event-ready entanglement. This was due both to the fabrication issues described above, and also because our four-photon source was out of action for 12 months due to a laser malfunction that was not able to be repaired due to pandemic-induced supply chain issues.

What opportunities for training and professional development has the project provided?

The researchers—students (M. Su) and staff (T. Weinhold, M. P. Almeida, A. G. White)— involved with this project undertook the following training and professional development:

Scanning Electron Microscopy (SEM) for Biological and Physical Sciences. Operation of SEM up to an intermediate skills level. Topics include: sample loading, secondary and back scattered electron imaging, effect accelerating voltage has, depth of field, resolution, focusing, astigmatism and digital image acquisition. Sample preparation includes: sample mounting, sputter coating with metals, carbon coating, freeze drying, fixation, chemical dehydration, critical point drying.

Electron Beam Lithography. Researchers trained in operation of RAITH e-Line Plus and RAITH EBPG 5150.

Reactive ion etching is a type of dry etching which uses chemically reactive plasma to remove material from substrates. Researchers trained in operation of an Oxford Instrument PlasmaPro 80 Reactive Ion Etcher(RIE).

How were the results disseminated to communities of interest?
Results were disseminated to the quantum technology research community via the following meetings:

2021 12/07	Invited Speaker, *Australian Institute of Physics Summer Meeting*, Brisbane, Australia
2022 03/25	Invited Colloquium, *Centre for Nanosciences and Nanotechnology*, Université Paris-Saclay, France
2022 07/08	Invited Colloquium, *Institute of Science and Technology Austria*, Klosterneuburg, Austria
2022 07/11	Poster, *International Conference on Quantum Communication, Measurement and Computing*, Lisbon, Portugal
2022 08/23	Invited Speaker, The 15th Asia Pacific Physics Conference (APPC15), Gyeongju, South Korea (online)
2022 09/02	Invited Colloquium, *Institute for Quantum Optics and Quantum Information*, Innsbruck, Austria
2022 09/05	Invited Speaker, *25th Congress of the International Commission for Optics* (ICO-25), Dresden, Germany
2022 10/31	Invited Speaker, Single Photon Workshop, Seoul, South Korea
2022 12/05	EQUS Workshop

For the purpose of enhancing public understanding and increasing interest in learning and careers in science and technology, the work was also presented to the following student conferences:

2023 05/04	Invited Talk, *Optica Student Chapter*, Brisbane, Australia
2023 06/02	Invited Talk, ***S**ymposium on **Q**uantum **U**ndergraduate **I**nquiry & **D**iscovery* (S.Q.U.I.D.), quantumcoalition.io/squid2023 , United States of America

What do you plan to do during the next reporting period to accomplish the goals and objectives?
Nothing to Report.

Publications, conference papers, and presentations
Journal publications
Nothing to Report.

Books or other non-periodical, one-time publications
Nothing to Report.

Other publications, conference papers and presentations
E. Gaydon, M. Su, T. Weinhold, M. P. de Almeida, M. Rambach, and A. G. White
Fabrication sensitivity of inverse-designed grating coupler, in preparation (2023)
acknowledgement of federal support from this project: yes

Website(s) or other Internet site(s)
quantum.technology, the home page of the Quantum Technology Lab, is where all publications arising from this project will be reported.

Technologies or techniques

Identify technologies or techniques that resulted from the research activities. technologies or techniques that were shared.

USAF/USSF/DoD/Academia/Industry Relationship or Collaboration Highlights
Nothing to Report.

Follow-on awards or research milestones enabled by this grant

Type:	Australian Research Council Australian Laureate Fellowship
Title:	Energy-efficient artificial intelligence using quantum technologies
Duration:	2022–2027
Amount:	AUD 3,245,263 (~ USD 2,099,671)

Students involved at all levels (undergrad, MS, PhD, post-doc)

Mr Ming Su	PhD Student
Ms Emerald Gaydon	Honours Student (Year 4 undergraduate)

Expenditure
For project 025865, *[Quantum Accelerator] Efficient Fast Photonic Integrated Circuits for Photonic Quantum Computing* (FA9550-19-S-0003 - PKG00249980) was:

Salaries	T. Weinhold, July to December 2021	$62,971.86
Scholarship	M. Su, September to December 2021	$4,530.62
Project Overheads		$29,421.79