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Scalable Quantum Networks for Distributed Computing and Sensing

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14. ABSTRACT
We identified two barriers to the implementation of large-scale photonic quantum networks. First, as scalability requires creation of reliable and efficient network components that can be operated in large numbers, we developed chip-integrated photon sources and circuits achieving low-loss transmission in a small footprint, including a guided-wave photon pair source in femtosecond-laser written waveguides and chip-integrated interferometers for complex preparation of entangled states. Second, scalability requires a method to synchronize protocols on inherently probabilistic measurement, so we developed quantum memories and guided-wave implementations of same, demonstrating controlled delay of a heralded single photon.

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In devising this project, we identified two major barriers to the implementation of large-scale photonic quantum networks for applications in computing and sensing. First, technical scalability requires creation of reliable and efficient network components that can be operated in large numbers. To this end, we developed novel chip-integrated photon sources and photonic circuits that achieve low-loss transmission in a small footprint. Second, fundamental scalability requires a method to synchronize protocols based on quantum measurements, which are inherently probabilistic. To meet this challenge, we developed a broadband quantum memory in an integrated package that enables repeat-until-success protocols. Detailed project outcomes are summarized below.

Work Package 1: Integrated structures and architectures for photonic quantum networks

Milestone 1.1: Guided-wave photon pair source using the 3rd-order response of silica in novel femtosecond-laser written waveguides.

We developed the first on-chip silica photon pair source in birefringent fs-laser written waveguides [1]. Construction of a matched array of waveguides was not achieved, due to limited control of the fs-laser writing process. Instead, we used UV-written silica-on-silicon guides fabricated through partnership with the group of Prof. Peter Smith at the University of Southampton. With this approach, we have demonstrated an array of over 20 identical heralded photon sources [2].

Milestone 1.2: Waveguide circuits that enable complex conditional preparation of entangled and discordant states.

Through our partnership with the University of Southampton, we also developed chip-integrated programmable multiport interferometers. We use thermo-optic controllers to adjust on-chip optical path lengths within fractions of an wavelength. These devices were used to generate three- and four-photon entangled states for computation and sensing [3-5]. We have further developed strain-optic control for silica photonic chips, which offers higher control bandwidths and compatibility with cryogenic operation [6].

Milestone 1.3: Develop theoretical tools that provide objective certificates of quantum enhancements.

We have developed and applied theoretical tests for non-classicality for on-chip multiphoton interference [3, 4] and quantum teleportation [5]. We have developed new theoretical approaches to characterising the quantum response of photon counting detectors [7] and tests of quantum correlations that combine photon counting detectors with a classical local phase reference [8]. We have developed approaches and criteria for quantum enhancement in multiparameter optical sensing, including the joint estimation of phase and phase diffusion [9] and the simultaneous estimation of multiple phases [10].

Work Package 2: Integrated quantum memories

Milestone 2.1: Optimize memory performance for quantum networks

The performance of an ensemble Raman memory in warm Cs vapour was characterised and optimised [11]. Through this work we have identified readout noise as the key obstacle to practical applications. To meet this challenge, we have developed a cavity-based approach which supresses this readout noise [12].

Milestone 2.2: Guided-wave implementation of the memory

We constructed an ensemble quantum memory using Cs vapour confined within a hollow-core photonic crystal fibre, in collaboration with Prof. Russell at the Max Planck Institute for the Science of Light. This work included demonstrating methods to load vapour and initialise the memory [13], to store and retrieve optical signals [14], and to enhance memory efficiency and operating time [15].

Milestone 2.3: Synchronization of probabilistic heralded single photon sources

We studied theoretically how the performance of a synchronized photon source depends on the performance of a broadband quantum memory [16]. We have demonstrated actively controlled delay of a heralded single photon, the essential element of a synchronized source [11]. A practical synchronized source, however, was not achieved due to the new readout noise discussed above in 2.1. Rather than proceed with synchronization, which would have produced synchronized signals that do not maintain the quantum character of single photons, we focused on design of the new noise-supressed memory discussed in 2.1 [12].

Publications

[1] 10.1364/OE.21.013522
[2] 10.1364/QIM.2014.QW1B.6
[3] 10.1038/ncomms2349
[4] 10.1126/science.1231692
[5] 10.1038/nphoton.2014.217
[6] 10.1364/OE.22.021719
[7] 10.1088/1367-2630/17/10/103044
[8] 10.1038/ncomms6584
[9] 10.1038/ncomms4532
[10] 10.1103/PhysRevLett.111.070403
[11] 10.1088/1367-2630/17/4/043006
[12] arXiv:1510.04625
[13] 10.1088/1367-2630/15/5/055013
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[15] arXiv:1509.04972
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