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Quantum-enhanced sensing and efficient quantum computation

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14. ABSTRACT

Project 13-3025 was a supplemental grant to 12-2076, focusing on near-term applications of single-photon detectors. The group installed high-efficiency Transition Edge Sensors from a collaboration with NIST, USA. The team created new methods to characterize and run TES detectors, and combined embedded photon-counting detectors with multiport inteferometers, and used many of the same techniques with nanowire (faster but less efficient) detectors. They demonstrated single-photon preparation efficieny of >60%, and measured the TES system detection efficiencies to be 92-100, with the ability to count photons with accuracy. The system was used to improve quantum boson sampling tests.

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Final report for “Quantum-Enhanced Sensing and Efficient Quantum Computation”, Project 13-3025

This document summarises project 13-3025 running from Feb 2013 through Jan 2015.

Our quantum photonics research programme aims to conceive and develop potential quantum–enabled information technologies based on single photons. To this end, we have identified four key technical components needed to realize wide-ranging applications: high-purity photon sources, low-loss optical circuits, broadband quantum memories, and high-efficiency single-photon detectors. We are actively developing each of these elements, in part through the complementary ongoing project, 12-2076. In project 13-3025, we aimed to bring together the state of the art in these components to investigate near-term applications with potential to demonstrate genuine enhanced performance.

The first application is quantum sensing. We build a low-power interferometer that uses few-photon quantum states to outperform classical methods using equivalent probe powers. The second application is quantum computation. Here we experimentally investigate the computational power inherent in multimode photonic interference. To pursue both applications, we identified the need to install high-efficiency superconducting detectors – technology we have previously developed through collaboration with the Single Photonics and Quantum Information team at NIST, USA – in Oxford for the first time.

Superconducting transition edge sensors

We commissioned the Oxford Cryogenic Detector Lab (CDL) to operate transition edge sensors (TESs) in Oxford, through collaboration with project partners at NIST. These detectors are an unmatched technology for photon counting. Demonstrated device efficiencies exceed 98% and a single detection element can maintain counting resolution for over 20 photons. Despite this potential, however, optimal signal processing in the multi-photon regime was poorly understood. To address this issue, we devised a novel quantum-tomographic approach to characterize and precisely run TES detectors. The methods were applied to our new detectors in Oxford, and these advances are reported in [1]. In parallel with this work, we have achieved increased optical complexity for photonic chips with integrated TESs [2]. Our latest work combines embeds photon-counting detectors with multi-port interferometers, which enables new capabilities for both state detection and in-situ quantum state engineering. Finally, we note that we have also adapted the CDL to simultaneously operate superconducting nanowire detectors along with TESs. While nanowire detectors have yet to match the efficiency or counting capabilities of TESs, detector response times shortened by a factor of nearly 100 enable to high-rate applications.

Application 1: Quantum enhanced sensing

The primary challenge to achieving enhanced measurement precision with quantum probes is that the potential enhancements rapidly degrade with dissipation of quantum coherences. Our approach to overcoming this challenge is twofold. First, we seek to design quantum probes that are robust to loss. To this end, we have expanded our initial theoretical proposal for loss-tolerant sensing [3] to cover imaging [4] and the joint estimation of phase and phase fluctuations [5].

Second, we have worked to improve the channel efficiency of quantum optical interferometers in the lab. The primary challenge in this regard is efficiently coupling a quantum light source to a single-mode circuit. We have now demonstrated a single-photon preparation efficiency of over 60% using heralded operation with spontaneous parametric down-conversion in a KTP waveguide. While KTP waveguides can potential provide exceptional squeezing, the asymmetric mode profile has limited its use. To achieve high efficiencies, we designed and implemented chip out-coupling optics to improve the mode quality. As an alternate light source, we have investigated spontaneous four-wave mixing in birefringent silica fibres. While the small nonlinearity of silica limits the achievable squeezing, our initial work suggests preparation efficiencies over 90% can be achieved. For interferometry with few-photon Holland-Burnett states (see [3]), we will thus pursue use of this source. We note that we have measured our absolute TES system detection efficiencies to be 92-100% [1]. This range, which indicates measurement uncertainty due to absolute power calibration, is sufficiently high for these protocols. We have built a new radiometer based on an erbium-doped-fibre-amplifier that is currently being used to improve the precision of this characterisation.

We have also investigated a novel quantum memory-based interferometer that enables efficient long distance measurements. In this scheme, half of the bipartite probe is transmitted to a remote object under test, while the other half is stored locally in an ensemble quantum memory. Direct interference of optical and matter excitations allows the memory to function as both a delay and processor. We have completed the first key step to realizing such an interferometer by demonstrating the interface of an ensemble memory with a quantum light source [6]. In this work, we identified an important source of noise in Raman-type memories that spoils processed light. We have now developed a novel memory design that suppresses this noise while preserving the memory interaction. A first prototype has demonstrated a three-fold suppression and further improvements are anticipated (report in preparation).

Application 2: efficient quantum computation

Initial tests of the quantum boson sampling (QBS) problem are reported in Ref. [7]. To substantially increase the scale of feasible tests, we developed a new variation of QBS based on probabilistic light sources, which makes the problem intrinsically scalable with available components. We are now devising an implementation of the new protocol by combining on-chip programmable multiport interferometers with silica-based source arrays (both components are developed in project 12-2076).

As the scale of feasible QBS tests increase, the role of sampling error due to experimental imperfections becomes a critical issue. We have investigated the consequences of photon distinguishability in multiphoton interference and identified several aspects of this type of error that have not yet been addressed. In particular, we have shown that errors can arise in the interference of three, and more, photons that cannot be understood from characterisation based on pair-wise interference – the standard methods used to date. Measurements of these phenomena in three-photon interference experiments are underway and a report on these finding is in preparation.

Publications

[1] arxiv:1502.07649
[2] 10.1364/OE.21.022657
[3] 10.1103/PhysRevA.83.063836
[4] 10.1103/PhysRevLett.111.070403
[5] 10.1038/ncomms4532
[6] 10.1088/1367-2630/17/4/043006
[7] 10.1126/science.1231692