PHOTON14

## Monday 1 September

## Session 1: Quantum Optics – Entangled Photons (10:45 – 11:15, Huxley LT311)

**(invited) Interfacing single photons and semiconductor spins**

Y Delley

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The superior optical properties of optically active self-assembled quantum dots and the possibility of integrating them in photonic nanostructures can be used for realizing indistinguishable single-photon sources, all-optical spin manipulation and to demonstrate a quantum interface between flying photonic qubits and stationary spin qubits. In this talk, I will highlight a few experiments establishing the steps required to achieve this goal. I will then focus on the properties of quantum dot molecules and their prospects for combining all required properties in one system.

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## Session 1: Quantum Optics – Entangled Photons (11:15 – 11:30, Huxley LT311)

### Bright indistinguishable photons from a “noisy” quantum dot in a planar cavity antenna

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Quantum dots (QDs) are promising for applications as quantum light sources. Two demanding properties for exploitation of such quantum light sources in quantum technologies is (i) a high collection efficiency, $\eta$, and (ii) a high degree of indistinguishability among the photons emitted by the QD. Here we investigate the resonance fluorescence (RF) from a QD located inside a GaAs membrane cavity with Au back reflector and a top solid immersion lens. For QDs in our particular device geometry, highly directive far-field radiation patterns are predicted with $\eta$ ~ 22% into an NA = 0.68 lens [Y. Ma *et al,* J. Appl. Phys. 114, 023106 (2014)] - without challenging spatial or spectral matching of the QD and cavity mode.

We characterize single QDs using both non-resonant and resonant excitation. In RF, we observe ~ 3 MHz count rates at saturation on a single photon counter (SPAD), which corresponds to a time-averaged $\eta$ ~ 6% - much brighter than bulk samples but less efficient than predicted by simulation. We demonstrate the reduction in RF count rates is due to spectral flickering caused by the dot’s energy level moving out of resonance with the laser due to charge noise in the device. We find this sample has relatively high intrinsic charge noise, which we can characterize with unprecedented precision due to the brightness. We will discuss the direct time-resolved measurement of charge noise in our sample and its impact on the overall collection efficiency of the device. In spite of the large charge noise, high resolution spectroscopy reveals transform limited linewidths in RF and at small Rabi frequencies elastically scattered photons with the linewidth of the excitation laser are observed. Finally, we probe the indistinguishability of photons emitted or scattered from the QD in the presence of large charge noise using Hong-Ou-Mandel interference.

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## Session 1: Quantum Optics – Entangled Photons (11:30 – 11:45, Huxley LT311)

### Production and analysis of qubit entanglement on a silicon photonic chip

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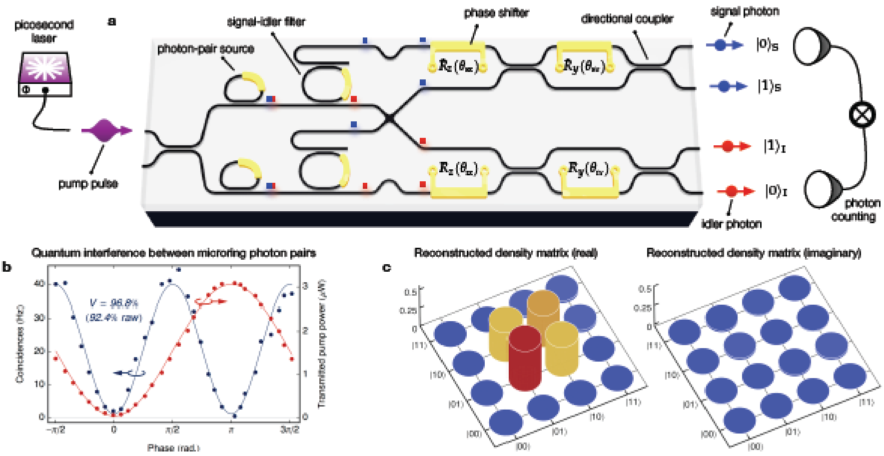
Silicon quantum photonics promises to take quantum optics to the large scale, where single photons carry the quantum information which can accelerate difficult computational problems, provide perfectly secure communication, or allow high-accuracy measurements. The silicon photonics platform offers miniature, high-yield, and high-performance photonics which are integrable with CMOS electronics and telecommunications-band optics.

To date, only non-scalable photon-pair sources, based on spontaneous four-wave mixing (SFWM) in straight silicon waveguides have been shown to interfere [1]. Until now, single-photon experiments in silicon [2] have exclusively used an off-chip apparatus, such as a silica arrayed waveguide grating, to control and manipulate photon frequency. We present a silicon-on-insulator quantum photonic device (Fig. 1a) able to generate and analyse two maximally entangled qubits. We use this device to demonstrate high-visibility quantum interferencebetween resonant SFWM sources (analogous to [1]), phase-stable frequency-selection, and quantum state tomography.

We varied the phase $\theta_{IZ}$ to obtain the fringes shown in Fig. 1b, with a visibility of 96.8%. This high visibility indicates that the two microring sources are substantially identical. We setup the entangled state via the on-chip 17-dB extinction filters, and used quantum state tomography to analyse it (Fig. 1c). We measured a fidelity of $F = \langle\Psi^+|\rho|\Psi^+\rangle$= 0.8.

This is the first time an entangled state of photonic qubits has been both generated and analysed on-chip, and this generation has been done in a way which is scalable to larger photon number. These results represent a new step towards fully silicon-integrated quantum photonics.




[1] J. W. Silverstone et al., \On-chip quantum interference between silicon photon-pair sources,"Nature Photon. 8, 104{108 (2013).

[2] D. Bonneau et al. \Quantum interference and manipulation of entanglement in silicon wire waveguide quantum circuits," New J. Phys. 14, 045003 (2012).

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## Monday 1 September

## Session 1: Quantum Optics – Entangled Photons (11:45 – 12:00, Huxley LT311)

### Compressive coincidence imaging

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How many photons does it take to form an image? Although single photons can be spatially encoded to carry large amounts of information, real images are rarely orthogonal to each other and hence, realistically, require many detected photons to distinguish between them. Even if one has access to a pixelated, imaging detector with high quantum-efficiency the fidelity of a recorded or inferred, image critically depends upon the dark counts from the detector(s). Here we present our latest approach using heralded single-photons from a spontaneous parametric down conversion (SPDC) source and a time-gated intensified camera to virtually eliminate eliminate noise-events [1]. We show the possibility of recording images of biological specimens from a low number of photons, a considerable benefit when one considers the possible detrimental effects of a higher photon ux on such samples. However, images obtained in this way are subject to a noise inherent within the Poisson distribution of single-photon events. To improve the subjective quality of our images we employ techniques of compressive sensing [2, 3] whilst operating within the constraints of Poissonian statistics of single-events to obtain images of our samples at ultra-low optical exposures.

Adopting standard compressive techniques, we maximise the sparsity of the contributing spatial frequencies within the image whilst applying a likelihood constraint to the reconstructed images set by the Poissonian statistics of our original low-photon signal. Figure 1 shows an image of a y wing obtained from _10,000 photo-events on the camera and its corresponding sparsity promoted enhancement.

This approach can be useful when imaging weakly absorbing, fragile objects such as certain biological specimens.

Compressive coincidence imaging

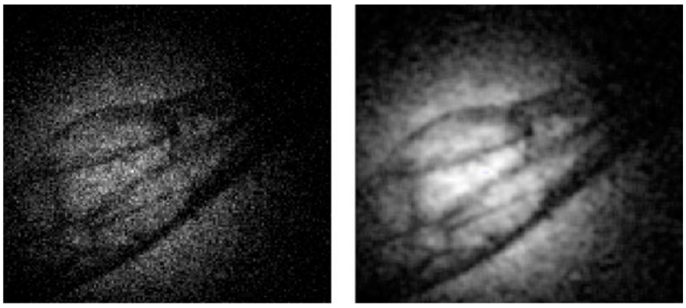

Figure 1. Raw image acquired by summing ≈10,000 single photon events and processed image following the maximisation of sparsity of its spatial frequencies within likelihood bounds.

We acknowledge the financial support from the UK EPSRC

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[2] E. J. Cand_es and M. B. Wakin. An introduction to compressive sampling. Signal Processing Magazine, IEEE, 25(2):21{30, 2008.

[3] J. Romberg. Imaging via compressive sampling [introduction to compressive sampling and recovery via convex programming]. IEEE Signal Processing Magazine, 25(2):14{20, 2008.

## Monday 1 September

## Session 1: Quantum Optics – Entangled Photons (12:00 – 12:15, Huxley LT311)

### Joint spectral characterisation of photons from spontaneous four-wave mixing: classical versus quantum

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The development of reliable photon sources is essential for the development of quantum photonic technologies. It is important to be able to characterise and engineer the entanglement between photons, whether this arises directly from the generation process [1] or it is introduced through manipulation of the photon pairs [2]. Spectral photon correlation measurements are often used to quantify the degree of entanglement present; however this typically requires long acquisition times and leads to limited and often low resolution. Recently, a method of characterising some types of entanglement, referred to as stimulated emission tomography (SET), was proposed [3] and subsequently implemented for measuring the joint spectral characteristics of photon-pairs from spontaneous parametric down-conversion [4]. In this paper I will discuss methods of characterising the joint spectral intensity of third-order nonlinear photon-pair sources. The first is a high-resolution quantum characterisation of photons generated via spontaneous four-wave mixing using a liquidcrystal-on-silicon automated filter [5]. The second is a purely classical method of an SET measurement using stimulated four-wave mixing. Both methods will focus on the use of integrated silicon photon-pair sources. The integration time, resolution and degree of spectral correlation from the two methods will be compared. Finally, future prospects for characterising other sources and different types of entanglement will be discussed.

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[2] A. S. Clark, B. Bell, J. Fulconis, M. M. Halder, B. Cemlyn, O. Alibart, C. Xiong, W. J. Wadsworth, and J. G. Rarity, *New J. Phys.* **13**, 065009 (2011).

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[5] I. Jizan, A. S. Clark, L. G. Helt, M. J. Collins, E. Mägi, C. Xiong, M. J. Steel, and B. J. Eggleton, E. Mägi, C. Xiong, M. J. Steel, and B. J. Eggleton, *Optics Communications*, accepted 13th March (2014).