PUBLISHABLE SUMMARY

QUIPS was intended to make silicon the material of choice for integrated quantum photonics. We have gone about this by inventing and developing new methods and designs in order to produce single photon sources and ultrafast optical switches.

The first step was to develop the design for the ultrafast optical switch. To do this, we employed finite-difference time-domain electromagnetic simulations. We exploited the ability of Lumerical FDTD Solutions to write "plug-in" materials in order to model arbitrary time-dependent refractive indices. We investigated designs based on photonic crystal waveguides, Mach-Zehnder interferometers and photonic crystal cavities. Although we achieved encouraging results (e.g. the adiabatic frequency conversion of a pulse by 15nm for a refractive index change of 1%), the lasers available at the University of Bristol proved inadequate to provide the necessary optical power without also causing detrimental losses. We investigated ways around this – for example, using pump-pulse in the mid-IR would circumvent many of the nonlinear losses, or using materials other than silicon, where the nonlinear losses are smaller and/or the $\chi^{(2)}$ coefficient can be used to provide an electro-optic effect. We choose to pursue the last option, and developed a process for making barium titanate (BTO). BTO is a ceramic material with a high electro-optic coefficient, and we have developed a sol-gel method starting with simple chemical precursors. This method has the advantages of being cheap, scalable and the thin films can be deposited on silicon waveguides in a simple spin-coating procedure. We have determined that our films are polycrystalline BTO and measured an electro-optic coefficient of 7pm/V in the presence of a poling field to align the ferroelectric domains. We are now integrating this material with silicon waveguides, as well as working on ways to improve the electro-optic coefficient. This work has the potential to be transformative to the CQP, as it provides a fast and low-loss switching technique that works at cryogenic temperatures.

A second steps was to pursue a modified design based on the ultrafast adiabatic control of photons in a photonic crystal cavity. This work would combine aspects of both work parts in the original proposal (frequency conversion and optical switching). The device is developed in collaboration with Kyoto University, and it uses the adiabatic frequency conversion to transfer a photon between two distant photonic crystal cavities. We have developed the design, and Kyoto University have demonstrated its viability in the classical optics domain. Work is proceeding to demonstrate it also in the single photon regime. Because of the high-Q photonic crystal cavities that the design users, we needed single photons of similarly narrow bandwidth. We have modelled and fabricated a device that can provide such photons, based on spontaneous four-wave mixing in the supermodes of three coupled cavities. Heaters are present near each cavity in order to tune the resonance frequencies and ensure both energy and momentum conservation in the four-wave mixing process. We have measured the first single photons from these devices with a coincidental-to-accidental ratio (CAR) of over 2. The high-Q and small mode volume of the photonic crystal cavities allows us to operate in a low pump power regime, negating the problems found in the designs discussed above. The work on the single photon source is now being prepared for publication, after which the experimental work on the switch will go ahead.

In other work on single photon sources, we have developed a spin-photon interface that can entangle spin-encoded static qubits with path-encoded flying qubits. Although not originally envisaged in the proposal, this work will be important in many quantum information applications, and is in fact already having an impact in the community, with our paper having been cited 28 times in the first year of publication. We have worked out many of the details in a series of theoretical and computational

works, and are now working with collaborators at the University of Würzburg to make experimental demonstrations.

Encoding qubits in the spin-state of electrons is the canonical example of a solid state qubit, whereas path-encoding is the preferred method in integrated optics. Their entanglement relies on an optical phenomenon first studied here in Bristol over 40 years ago: polarisation singularities. A polarisation singularity is a position in a vector field where one of the parameters describing the local polarisation ellipse (ellipticity, orientation or handedness) is singular or undefined. At a C-point, the orientation is singular and such C-points allow the waveguide to display local chirality, despite no overall chiral symmetry existing. This chirality has particular consequences for quantum emitters placed at the position of the C-point. Such polarisation singularities are rare in waveguide optics, as they occur at positions where the longitudinal electric field is as large as the transverse one. However, the unique properties of photonic crystal waveguides promotes their existence, and we found designs where many C-points exist within the waveguide. Using finite-difference time-domain electromagnetic simulations, we confirmed that a dipole-like quantum emitter placed at a C-point has a spin-dependent emission direction, with >99% correlation between spin and direction. We found predicted efficiencies of over 90%, an emission rate of 1.7GHz and a Purcell factor of 1.8. Such properties make C-points in photonic crystal waveguide attractive for a range of quantum information applications, from a spin-photon interface to cluster-state generation.

Photonic crystals are, however, notorious for the optical losses due to the disorder that they contain as an inevitable consequence of the fabrication procedure. Therefore, we conducted a study to check on the robustness of the C-points existence to the introduction of this disorder, and we found that they are remarkably robust. Using simulations of a statistical ensemble of many disordered waveguides, we found that there is less than 3% chance of a C-point disappearing altogether after the introduction of disorder. Furthermore, we found that the positions of the C-points in the disordered waveguides are on average only 20nm from the expected positions in the ideal waveguides. From the statistics that we collected, we calculated an expected fabrication yield of 54% for a spin photon interface using current state-of-the-art fabrication and placement techniques for quantum emitters and photonic crystal waveguides.

We also studied the effect of slow-light on the emission from a C-point. Slow-light has successfully been used to enhance the light-matter interaction between solid state quantum emitters and optical waveguides, as the local density of optical states (LDOS) is high. We anticipated that similar techniques could be applied here at a C-point. However, we found that the time reversal symmetry that is found in a standing wave puts severe limits on using the slow-light regime. The unidirectional emission dependent on spin that is so attractive a property for quantum information applications relies on the propagation direction of a mode in order to break the symmetry between propagating and counterpropagating modes. This propagation direction is no longer present for standing waves with $v_g = 0$ (at the bandedge of the dispersion relation), and so no chirality nor C-points can exist in a standing wave. Therefore we have a situation where just away from the bandedge, as $v_g \to 0$, the chirality must also vanish. How this happens is actually quite remarkable: we found that C-points still exist for any arbitrary non-zero value of $v_g$, but pairs of left- and right-handed C-points approach each other and collide and annihilate at the bandegde. The point of annihilation is also necessarily a node of the field where $|\mathbf{E}|^2$ is equal to zero. Therefore, in the slow-light regime we have a region where as the C-points approach, the field strength and therefore local density of states drops. We found that $v_g = c/10$ is the group velocity that optimises the LDOS at the position of C-point in a W1 photonic crystal waveguide. We are currently investigating waveguide designs to further enhance the coupling.