EPSRC Centre for Doctoral Training
Quantum Engineering

Individual Project B list

Cohort 2017-2018

Experimental;Theory;Simulation;
Location: University of Bristol

Device Development (Hardware);

1 Engineering photon pairs out of the fundamental mode and into the SWIR

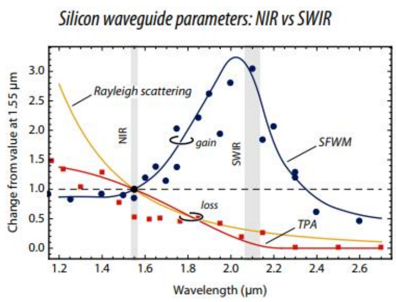
Dr. Joshua Silverstone
Lawrence Rosenfeld, Dr. Massimo Borghi, Dr. Pisu Jiang, Dr. Krishna Balhram

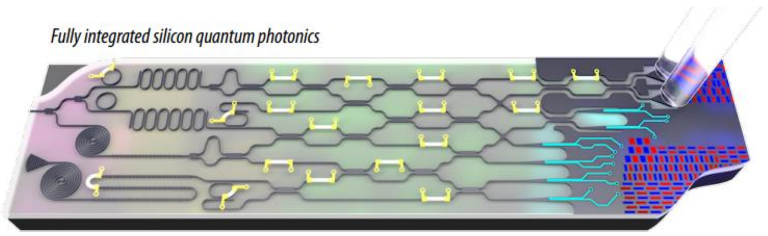
Abstract

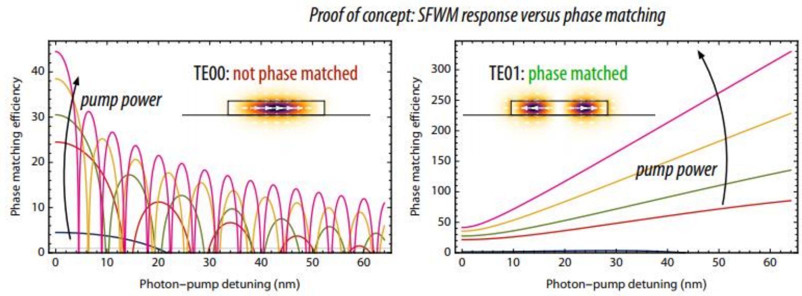
A good source of quantum light is essential for any quantum optical system. Parametric photon pairs can be exceptionally indistinguishable, and emerge in well-defined spacial, temporal, and spectral output modes. With spontaneous four-wave mixing (SFWM) in silicon, pair sources have become available at scale.

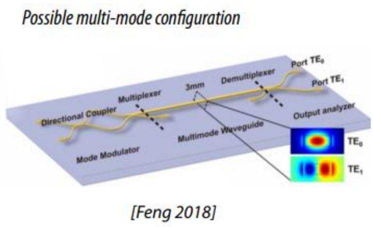
Telecom-band SFWM in silicon suffers from parasitic two-photon absorption, fundamentally limiting brightness and heralding efficiency. Extreme measures are needed. One exciting route involves translating our silicon quantum photonic technology to longer wavelengths. The short-wave infrared, where silicon's two-photon band edge lies, is the destination.

The SWIR presents challenges to photon-pair generation. Careful waveguide engineering is needed to achieve nonlinear phase matching. A phase-matched waveguide's group velocity, strangely, must decrease with optical frequency. High-order waveguide modes can achieve this. In this project, we will explore the design, manufacture, and test of sources based on these ideas, yielding the first correlated photons in the SWIR.









Project Description

This project operates in the exciting new space of mid-infrared quantum photonics, overcoming the optical limitations of silicon quantum photonics [Silverstone 2016], and allowing quantum optics to continue to flourish with the natural scale and manufacturability of silicon. The project will contribute to key infrastructure—the source of photons—which will be used well beyond the scope of this project. This project can offer the dedicated student perspective on the full lifecycle of a quantum photonic device, from design, through manufacture (in our cleanroom), to quantum optical test and analysis. Our apparatus and capability in this new SWIR band is continuously evolving, and the student can have as much or as little input in this evolution as he or she likes. We are setting up the SWIR from scratch, and this project is a key part.

Theory and design (3 weeks)

We will start with a careful study of spontaneous four-wave mixing in silicon waveguides. A focus on phase matching, and waveguide dispersion will develop, with emphasis on practical aspects, naturally feeding into waveguide design. Lumerical's MODE package will solve for waveguide eigenmodes, and existing Mathematica scripts will perform mode analysis and basic SFWM calculations.

Optionally, the effect of carrier and Kerr electro-optic modulation on waveguide SFWM can be investigated numerically.

With target waveguide geometries and modes in mind, methods for coupling into them from the fundamental mode will be investigated. Combinations of waveguide tapers, Mach-Zehnder interferometers [Feng 2018], directional couplers, ring resonators [Stern 2015], and mode converters [Lee 2003] will be evaluated. A total design will be developed, with predicted performance.

After iteration with cleanroom staff, a layout of the total design will be produced and submitted for manufacture in house.

Manufacturing (2 weeks, distributed)

In the Bristol cleanroom, lithography and etching will proceed on our new, state-of-the-art electron-beam lithography and etching tools. The student will have the option to contribute to this cleanroom processing, shadowing mainline personel. During the manufacturing process, SFWM theory and experiment can be carried out in parallel.

Experiment (7 weeks)

Familiarity with quantum optics experiments in general, and photon-pair measurements in particularly, will be acquired over the remainder of the project. Initially, other, non-purpose-designed silicon photon-pair sources will be tested, including single-mode waveguides and ring resonators. When manufacturing completes on the designed higher-order-mode devices, testing will switch over to these.

Our 10-kW picosecond-pulsed laser, oscillating at 2.07 microns, will provide the pump for the nonlinear pair-generation process. Pump cleaning and filtering will occur via our four grating monochromators (two of which are motorised). Possible experimental signatures of SFWM will be studied and sought: spectra, rates of singles, power dependence, coincidences, etc.

Finally, full coincidence measurements, using the full extent of our new SWIR single-photon detection capabilities will be attempted. If successful, this would represent the first corellated photons measured in the SWIR, and the first mid-infrared correllated photons generated on-chip.

In the course of this project, the student will naturally discover new techniques and innovations in photon-pair source design, which can lead to new devices and systems for processing optical quantum information on chip.

Experimental;Theory;Simulation;

Location: University of Bristol

Context

The student will interact with the ongoing activity in pioneering quantum optics in the mid-infrared. Data collected by a student working on my other project B (“Nonlinear silicon in quantum photonics”) could be fed into the pair source design, improving performance predictions. The optional investigation of phase matching in electro-optic structures will also interact with this other project.

Further Details

Ready to go: Yes

Skills:
Ambition to make quantum devices relevant to society, through clever design and engineering. Teamwork. Familiarity with integrated photonics and photonic design will accellerate the project. Necessary theory, modelling, and laboratory skills will be learned in the course of the research.

Alignment to PhD [0-5]: 5

References

[Silverstone 2016] Silverstone, J. W., Bonneau, D., Brien, J. O. & Thompson, M. G. Silicon Quantum Photonics. Selected Topics in Quantum Electronics, IEEE Journal of 23, 6700113 (2016).

[Feng 2018] Feng, L.-T. et al. On-chip transverse-mode entangled photon source. arXiv.org 1802.09847 (2018).

[Stern 2015] Stern, B. et al. On-chip mode-division multiplexing switch. Optica 2, 530–535 (2015).

[Lee 2003] Lee, B.-T. & Shin, S.-Y. Mode-order converter in a multimode waveguide. Opt. Lett. 28, 1660–1662 (2003).

Experimental;Simulation;
Location: University of Bristol

Device Development (Hardware);

2 Nonlinear silicon in quantum photonics

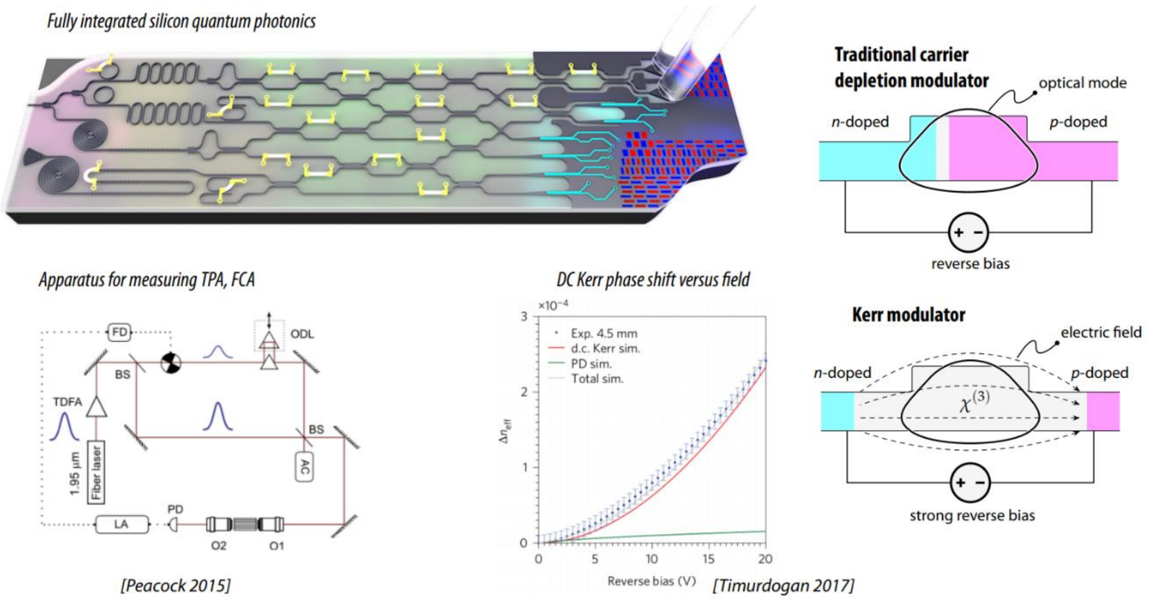
Dr. Joshua Silverstone
Lawrence Rosenfeld, Dr. Gary Sinclair, Dr. Krishna Balhram

Abstract

Nonlinearities drive quantum information forward. They provide interaction between particles, and produce highly unnatural initial states of light and matter. In linear optics, the source provides the nonlinear power, via highly squeezed (e.g. Fock) states and time-energy-entangled resources.

Silicon quantum photonics, pioneered in Bristol, has recently revolutionised large-scale quantum optics [Silverstone 2016]. Silicon is naturally blessed with a strong optical nonlinearity, which can be used to generate photon pairs [Silverstone 2014] and to achieve a variety of classical control tasks (e.g. [Timurdogan 2017]). This nonlinearity has a dark side, though—multi-photon absorption—which motivates a move to wavelengths beyond the comfortable telecommunications band.

This project will bootstrap photon-pair source engineering, by improving the underpinning nonlinearity data. Combining old and new techniques, we will estimate the nonlinear coefficients over a huge range of frequencies, from 0 Hz (DC) up to 150 THz, by using electro-optic and photo-optic devices in concert.



Project Description

This project will accellerate the photon-pair source and high-speed modulation efforts in silicon quantum photonic engineering by reinforcing the data upon which that engineering is based. The DC, RF, and optical frequency nonlinear parameters have never been compared in silicon, and this data is novel and of great interest to the community. With support, the student will become an expert in the physics and techniques of nonlinear-, integrated-, and electro-optics, which together form the basis of quantum optics technology.

Fundamentals (1 month)

Experimental;Simulation;

Location: University of Bristol

The project will start with a careful study of the bulk and waveguided silicon nonlinear optics literature, to understand what people have done before, and how this work fits in. The relationship between the various 'AC' and 'DC' Kerr parameters will be established. The effect of two-photon absorption (TPA), and its relationship to the nonlinearity will be studied qualitatively.

In the AC Kerr case, a method will be adapted for the prediction of self-phase modulation (SPM) spectra, based on an existing nonlinear Schroedinger equation solver, and for the experimental estimation from such spectra of the nonlinear parameters, based on . For the DC Kerr case, existing numerical techniques for predicting the phase modulation from Kerr electro-optic modulators will be learned and used to predict the phase shift resulting from a certain nonlinearity.

Optionally, the student may wish to gain a deeper understanding of the effect of the various nonlinear parameters on the pair generation process, spontaneous four-wave mixing (SFWM), making clear the motivation for moving to the 2-micron band.

Experiment (2 months)

Experiment forms the bulk of this project. Experiments will be carried out to measure nonlinear parameters at both optical frequencies and at DC, matching the resulting values with the models developed in the first stage.

To obtain the AC Kerr and TPA coefficients, we will use self-phase modulation, which spectrally broadens a bright pump, depending on (1) its peak power, and (2) the waveguide nonlinearity. Our 2.07-micron 10-kW-peak-power pulsed laser will be used to pump. An autocorrelator will be used to characterise the input pulses, and peak power. By varying the input power, we will get an accurate estimation of the waveguide nonlinearity and TPA coefficients. Optionally, the cross-TPA phenomenon, which fundamentally limits telecom-band heralding efficiency, can be investigated at this point.

To obtain the DC Kerr coefficient, we will measure the phase modulation due to the electro-optic Kerr (KEO) effect in purpose-designed devices from both IME (Singapore) and Cornerstone (Southampton) foundaries. Using our Keithley Source Meter, we will characterise the avalanche-limited break-down voltages of chip-scale KEO devices, applying up to 200 VDC, and measuring reverse leakage currents on the pA scale. The optical transmission in both phase modulators and Mach-Zehnder intensity modulators will be correllated with the model from the first stage to estimate the nonlinear susceptibility. Depending on progress, the response to RF (< 1 GHz) excitation may also be explored.

In the course of this project, the student will naturally discover new ways to improve our estimates, and to apply these powerful tools to new devices for optical quantum information processing.

Context

The student will interact with the ongoing activity in pioneering quantum optics in the mid-infrared, with these data directly informing the next generation of photon-pair source and electro-optic modulator designs.

Further Details

Ready to go: Yes

Skills:

Ambition to make quantum devices relevant to society, through clever design and engineering.

Teamwork. Necessary theory, modelling, and laboratory skills will be learned in the course of the research.

Alignment to PhD [0-5]: 4

References

[Timurdogan 2017] Timurdogan, E., Poulton, C. V., Byrd, M. J. & Watts, M. R. Electric field-induced second-order nonlinear optical effects in silicon waveguides. Nature Photonics 11, 200–206 (2017).

[Silverstone 2016] Silverstone, J. W., Bonneau, D., Brien, J. O. & Thompson, M. G. Silicon Quantum Photonics. Selected Topics in Quantum Electronics, IEEE Journal of 23, 6700113 (2016).

[Peacock 2015] Peacock, A. C. et al. Two-photon absorption and all-optical modulation in germanium-on-silicon waveguides for the mid-infrared. Opt. Lett. 40, 2213–2216 (2015).

[Wang 2013] Wang, T. et al. Multi-photon absorption and third-order nonlinearity in silicon at mid-infrared wavelengths. Op. Ex. 21, 32192 (2013).

Device Development (Hardware);

3 Superconducting nanowire detector development at 2.1 µm

Dondu, Sahin
Ben Slater, Mack Johnson, Archan Banerjee, Jorge Barreto

Abstract

Single photon detectors based on thin superconducting nanowires are promising for quantum technologies with their unprecedented performance in detection efficiencies, dark count rates, jitter and dead times. Superconducting nanowire single-photon detectors (SNSPDs) are promising for short-wave infrared on the cavity-integrated silicon-on-insulator platform. This architecture is promising to increase the speed and the yield for detectors. Furthermore, it allows us to tune the detection bandwidth. In order to implement these detectors on integrated silicon quantum photonics circuits beyond 1550 nm, we will fabricate these detectors in our cleanroom.

Project Description

Integrated silicon photonics has risen as a promising candidate for quantum information processing through various demonstrations. One exceptional aspect of the architecture is its ease of integrating superconducting nanowire single-photon detectors (SNSPDs) on-chip, which has been demonstrated for simple travelling-wave detectors [1-3]. In this project, the aim is to fabricate silicon-on-insulator photonic circuits in-house to characterise and optimise loss properties at 2 µm wavelength and optimise nanowires devices on top of them. This is designed to support the ongoing activity in QETLabs at 2.1 µm where two-photon absorption (TPA) in silicon is significantly reduced. Furthermore, non-linear response (spontaneous four wave mixing) increases which is responsible for generating the correlated bi-photons. We have studied some designs to optimise device efficiency at this wavelength of interest, including the straight waveguide where the evanescent field is coupled into the nanowires and upon absorption they generate a photon click.

The waveguide detectors are optimised to operate at 2.1 µm wavelength and the purpose of this project is to understand, and improve if necessary, and implement that design in our cleanroom. The fabrication process follows the steps of:

1- Generating patterns (electron beam [or e-beam] lithography mask) to be transferred to EBL (electron beam lithography) system
2- dicing the silicon chip
3- cleaning the chip
4- spinning an e-beam sensitive resist
5- exposing the chip to generated pattern at EBL
6- develop the resist using specific developer for the resist used
7- repeat 4-6 if multi-level exposure is required
8- testing*

*Testing of the devices will include room temperature testing (initially) as well as cryogenic testing for both electrical and optical properties of the devices.

Room temperature testing will initially be performed on the waveguides to measure the transmission and loss parameters. Furthermore, room temperature 4-point probe measurements will be performed on the nanowires when they are fabricated as it is a good indication for their performance quality. Cryogenics testing will be performed on the nanowires to measure their critical temperature as well as their critical current and current density.

Context

Superconducting nanowire detectors are essential for ever demanding quantum photonics applications from quantum computing and communication to quantum metrology, simulation and communication. There is an ongoing effort on 2um photonics within QETLabs to address two-photon absorption that happens at 1550 nm. Furthermore, IR detection >2 µm is challenging for classical detectors due to their low energy and we aim to increase the detection efficiency at this regime by using superconducting devices for sensing and metrology.

Further Details

Ready to go: Some setting up is required

Skills:
The student is expected to gain experience in nano- and micro-fabrication techniques tailored for photonics applications. This includes hands-on experience in spin coating, EBL, development and RIE. Skills learned will include surface analysis techniques such as profilometry, scanning electron microscopy (SEM), atomic force microscopy (AFM). There is chance to learn mask design on the VOYAGER NanoPECS suite. Furthermore, characterisation of integrated optics and cryogenics will be part of the skill sets to be learned.

Alignment to PhD [0-5]: 5

References

[1] J. P. Sprengers et al. Applied Physics Letters, 99, 181110 (2011)
[2] F. Marsili et al., NAture Photonics, 7, 210 (2013)
[3] W. H. Pernice et al, Nature Communications, 3, 1325 (2012)
[4] C. Schuck et al, Scientific Reports, 3, 1893 (2013)
[5] N. Tyler et al, Optics Express, 24, 8 , 8797-8808 (2016)

Theory;Simulation;
Location: University of Bristol

Integrated photonics;Quantum Metrology and Sensing;Trapped Ions / Cold Atoms
;

4 Integrated micro-resonators for the miniaturisation of optical atomic clocks

Dara McCutcheon
Graham Marshall, Matthew Day

Abstract
With each improvement in the precision of portable clocks has come increased technological capabilities. The best portable clocks today are based on atomic microwave transitions, and form the basis of our global navigation systems and precision timing distribution. Clocks based on atomic optical transitions now outperform microwave atomic clocks by several orders of magnitude in the laboratory. The miniaturisation of these laboratory systems would allow for portable atomic clocks with increased accuracy and stability, providing a technology to revolutionise areas of society such as navigation, gravitational mapping and secure communications.

Optical atomic clocks currently depend on ultra-narrow linewidth laser sources, and frequency combs. Both the cavity required to linewidth narrow the laser source and the femtosecond laser frequency comb are bulky and provide a major roadblock to developing a portable optical atomic clock. Recent advances in integrated micro-resonators provide a potential platform for the miniaturisation of both of these components such that a portable optical atomic clocks becomes feasible. This project aims to explore the frequency instability mechanisms in integrated microresonators, and therefore their applicability to ultra-precise timing.

Project Description
The current way to measure ultra-precise optical frequencies is using a femtosecond laser, whose spectrum resembles a comb of equally spaced frequencies. The frequency we wish to measure is beat against a comb tooth to obtain a microwave signal. Importantly, the accuracy of the THz frequency can be transferred onto the microwave signal. Recent advances in microresonators coupled to integrated waveguides have provided a platform for generating frequency combs on chip. These microcombs make use of high Q-factor microresonators such that continuous-wave laser radiation can have long interaction lengths with the waveguide material. The third-order (Kerr) nonlinearities of the waveguide material cause cascaded four-wave mixing, generating a symmetric frequency comb around the pump. The microresonator is designed such that its resonant modes are congruent with the frequency comb. Dispersion engineering of the waveguides allows the octave-spanning frequency comb to co-propagate in the waveguide. The dispersion engineering requirement currently restricts microcombs to wavelengths >700 nm, as material dispersion tends to increase at shorter wavelengths. The desire to use microcombs to reduce the footprint of an optical atomic clock requires a search for a trapped ion species with a clock transition at a wavelength >>700 nm. The only ion to fulfil this requirement is barium at 1.76 um, which also has a very competitive 1 mHz linewidth.

Recent work has demonstrated a microwave-to-optical frequency synthesiser on chip, based on Kerr microcombs, with fractional instabilities of 1E-15. There is an open question of using the scheme to convert from optical-to-microwave frequencies with the same stabilities. The project would explore all possible sources of frequency instabilities in Kerr microcombs and perform a comprehensive design of a microcomb suitable for referencing 1.76 um laser light that has been referenced to the clock transition in barium ions.

As the clock transition in trapped ions is inherently ultra-narrow (<1Hz), the clock laser must be of comparable linewidth. The current way of linewidth narrowing the clock laser it to use a large, thermally isolated etalon mounted on an optical bench. Very recent work on using nonlinear effects (stimulated Brillouin scattering) in microresonators has allowed for sub-Hz linewidth lasing on chip. The frequency instabilities of these lasers is unknown and so must be explored in a similar fashion to the Kerr microcombs. For example, to what extent does the instability in the pump laser have on the sub-Hz laser light? The project would aim to answer these open question and potentially design a microresonator for generation of ultra-stable, ultra-narrow and tuneable 1.76 um light.

The student would have a large amount of autonomy to explore the areas of most interest to them. Any advances on any of the posed open questions would be invaluable for the development of a portable optical atomic clock, that if realised would provide unrivalled timing capabilities in a commercialisable product. There is scope to extend the project onto a PhD for the full development of integrated optics for portable atomic clocks.

Work breakdown structure

- Frequency instability effects in integrated microresonators (1 month)
  - Effect of material
  - Effect of dispersion
  - Effect of temperature
  - Effect of pump laser stability
  - Effect of nonlinearities (e.g. Kerr effect)
  - Misc. effects
- Microresonator design (1 month)
  - Material choice
  - Analytical and numerical design of microresonators for frequency comb generation
  - Analytical and numerical design of microresonators for linewidth-narrowing
  - Waveguide and microresonator simulations in Lumerical

Context

A micro-optical assembly for ion microtrap arrays – Matthew Day, Mark Thompson. Ruth Oulton, Alastair Sinclair, Graham Marshall (PhD Project)

Further Details

Ready to go: Yes

Skills:
Materials physics
Integrated photonics
Nonlinear photonics
Integrated photonic design

Alignment to PhD [0-5]: 5

Theory;Simulation;

Location: University of Bristol

References

Sherman, Jeff A. "Single barium ion spectroscopy: light shifts, hyperfine structure, and progress on an optical frequency standard and atomic parity violation." arXiv preprint arXiv:0907.0459 (2009).

Gundavarapu, Sarat, et al. "Sub-Hz Linewidth Photonic-Integrated Brillouin Laser." arXiv preprint arXiv:1802.10020 (2018).

Pasquazi, Alessia, et al. "Micro-combs: A novel generation of optical sources." Physics Reports(2017).

Spencer, Daryl T., et al. "An integrated-photonics optical-frequency synthesizer." arXiv preprint arXiv:1708.05228 (2017).

Experimental;
Location: University of Bristol

Nonlinear optics;Quantum Metrology and Sensing;

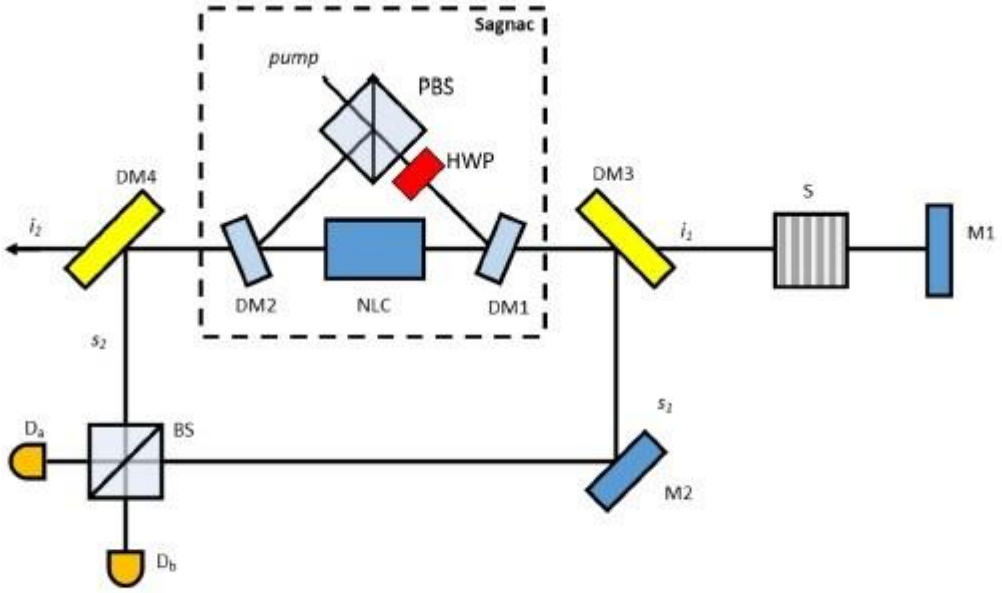
5 Sensing with undetected photons

A. McMillan
J. Rarity, S. Wollmann, J. Matthews

Abstract

Examples of measurements where light is used to probe the properties of samples are ubiquitous across a broad range of scientific disciplines. The wavelength of light required varies considerably depending on the specific application, from UV absorption measurements on single cells in biology, through to mid-IR remote gas and sensing, and beyond. However, existing light detectors that operate efficiently at the single photon level cover a relatively limited range from ~500nm – 1600nm.

This project will explore an alternative approach to performing measurements at unconventional wavelengths - measuring using undetected photons. In this approach, photons are generated in pairs using the process of parametric downconversion in a nonlinear crystal (at non-degenerate wavelengths), with one the photons probing a sample of interest. Subsequently, these photons pass again through the same nonlinear crystal, undergoing further nonlinear interaction. As the phases of the fields at both wavelengths contribute to the nonlinear process, properties of the sample can be determined by measurement at a wavelength which did not interact with the sample.



Project Description

Sources of photon pairs, developed at Bristol, are already being used to demonstrate sub-shot-noise absorption spectroscopy near 800nm [1]. Present work is targeting the demonstration of quantum advantage for measurement of delicate samples. More generally low power, high precision spectroscopy and imaging is of considerable interest for gas sensing at IR wavelengths and bio-sensing in the UV spectral range. However in some spectral ranges (deep UV and far IR) photon detectors are noisy and inefficient, and single photon sensitive imaging and sensing is impossible.

A recently published experiment [2] has demonstrated an approach which avoids the need for detection at problematic wavelengths, by taking advantage of the inherent correlation present between the signal and idler photons emitted in down-conversion. In this work, two separate down-conversion crystal sources were pumped coherently, and arranged such that idler photons from the first source pass through the second source to stimulate emission of further idler photons. Changing the idler path changes the intensity/phase between crystals and then leads to phase and amplitude differences in stimulated signal-idler pairs, which can be detected by interfering the signal photons. Hence, by measuring signal photons we can detect the effect of the sample on idler photons (even when we subsequently discard the idler photons). This experiment was technically demanding, as it involved careful alignment of multimode images between spatially separated crystals.

Here we propose an alternative scheme based on a double pass of the undetected idler photons through a single nonlinear crystal arranged in Sagnac loop configuration. The main goal of this project is to experimentally demonstrate the principle of measurement with undetected photons by making use of a pre-existing high efficiency pair photon sources operating near 800nm [4] . This source will be used to perform a measurement of a small phase-shift applied to the idler photon beam, directed out of the system, using an interferometric measurement applied only to the signal photons. The results from this demonstration of remote sensing with undetected photons across a short distance will be used to inform the design of future planned experiments at more exotic wavelengths

This experiment is another example of the strange consequences that arise from the non-local correlations that are possible in quantum mechanics, where measurement of photons that never interacted with a sample can nonetheless be used to obtain information about it. It is also of considerable practical interest for spectroscopy and imaging at the single photon level, removing the compromise required when selecting an operating wavelength - suitable as a probe and also efficiently detected. In the near future, we anticipate that this approach will enable quantum enhanced measurements of many interesting biological samples that would be impossible with current techniques.

Context

This experiment is strongly aligned to the research interests of the Bristol group of the UK quantum hub for imaging (QuantIC), due to its potential to expand the range of wavelengths over which low loss imaging and sensing are viable. Additionally, the currently active EPSRC grant held by John Rarity for Single Photon Range Imaging for Natural Gas Sensing (SPRINGS), is seeking to use this measurement approach for improved sensitivity detection of bright light at 3.3um for methane gas sensing applications. These are two possible routes by which this CDT Project could progress to a full PhD.

Further Details

Ready to go: Yes

Skills:
The project will have a strong experimental focus and the majority of the student's time will be spent designing, building and subsequently characterising the experimental setup.

The student will develop experience in various experimental areas including design and fabrication of highly efficient down-conversion pair photon sources, setting up and testing interferometer arrangements, and photon counting measurements and quantum state tomography.

Alignment to PhD [0-5]: 4

References

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[2] G. B. Lemos et al., "Quantum imaging with undetected photons," Nature 512, 409 (2014).
X. Y. Zou et al., "Induced Coherence and Indistinguishability in Optical Interference," PRL 67, 318 (1991).
[3] T. J. Herzog et al., "Frustrated Two-Photon Creation via Interference," PRL 72, 629 (1994).
[4] Ryan S. Bennink, "Optimal collinear Gaussian beams for spontaneous parametric down-conversion," PRA 81, 053805 (2010).

Experimental;Simulation;
Location: University of Bristol

Nonlinear quantum optics;

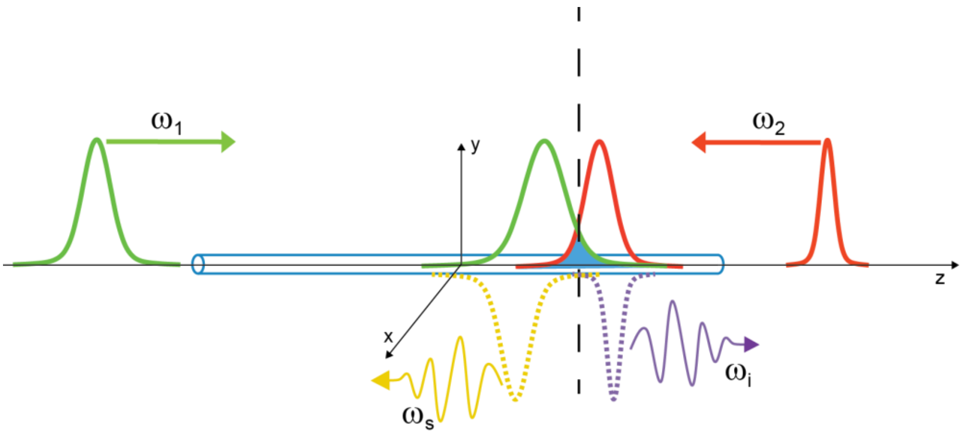
6 Narrowband pair photon generation by counter-propagating four-wave mixing

A. McMillan
J. Rarity, J. Monroy-Ruz, S. Wollmann, J. Matthews

Abstract

Photon pair sources are a key element in photonic implementations of quantum communication, computation, and metrology. Such sources can be realised using photon pairs generated by nonlinear parametric processes such as spontaneous parametric down conversion (SPDC) in chi(2) nonlinear crystals [1,2] and spontaneous four wave mixing (SFWM) in chi(3) materials, including optical fibres [3,4]. In the case of SFWM, through the design of fibre parameters, it is possible to engineer the two-photon state such that high spectral purity of the generated photons can be achieved.

This project will use computer simulation to investigate a recently identified novel arrangement for phase-matched SFWM, based on counter propagating lasers. Based on the results of these simulations, an experimental demonstration of this approach will be conducted, using either a highly nonlinear glass fibre, or gas filled hollow core fibre. Successful demonstration of this effect is anticipated to lead directly to next generation pair photon sources with ultra-narrow bandwidth and high purity, which cannot be matched by conventional approaches.



Project Description

In this project we aim to build the first photon pair source based on counter-propagating SFWM (CSFWM) in optical fibres [5]. This counter-propagating scheme allows for significant tuning of the pair photon wavelengths and improved stability against small fluctuations in waveguide parameters, due to minimal sensitivity to the waveguide dispersion. Other more significant advantages of this approach include the possibility to herald ultra-narrowband single photons emission without the use of optical cavities [6] and spectral factorability of the generated two photon states. The generated photons are expected to be well suited for quantum metrology applications, such as precision sub-shot noise spectroscopy at unusual wavelengths, due to the wavelength tunability of the process. Furthermore, the extremely narrow photon bandwidth allows for efficient interaction with atom-like systems, which can enable compatibility with demonstrated implementations of quantum memories, interactions with quantum dots for operations such as entanglement generation, and matching to important spectral lines of atoms such as Rubidium for use in deterministic qubit gates and photon generation.

CSFWM is expected to occur when coupling two pump lasers of different frequency into opposite ends of an optical fibre. In contrast to most existing parametric photon pair sources, where the pump, signal, and idler all propagate in the same direction, the use of counter-propagating fields leads to qualitatively different phase-matching behaviour of the CSFWM process. In this configuration, phase-matching is attained automatically across a broad range of pump wavelengths, allowing the generated wavelengths to be readily tailored to a specific application, and easily tuneable via control of the pump light properties. A particularly interesting special case of CSFWM occurs in the limit where one of the two pump sources is CW. In this case, the bandwidth of the generated photons is predicted to become extremely narrow, addressing the significant issue of bandwidth mismatch between the photon states generated by single emitter sources (and required for interaction with atomic systems), and the bandwidths which are typically attained in parametric nonlinear processes. Furthermore, the joint spectral intensity of the two photon state becomes factorable, allowing pure single photon states to be heralded without the need for lossy narrowband spectral filtering.

The initial phase of the project will involve computer simulation of the nonlinear process, to determine the optimal fibre structure to use for later experimental work. This study is anticipated to cover both high nonlinearity, glass-core fibre structures, and hollow-core photonic crystal fibres (PCF) filled with high pressure gas as a nonlinear medium.

By default, the phase-matching for CSFWM leads to degeneracy of the generated wavelengths with the incident pump wavelengths, making the generated photon pairs difficult to distinguish from back scattered pump light. Several mechanisms are known to break this degeneracy including waveguide birefringence, intermodal phase-matching and self-phase modulation of the pump beams. Simulations will also be used to identify the most promising of these mechanisms to employ, and incorporate this into the fibre design.

The final part of this project will be an experimental demonstration of photon pair generation by CSFWM for the first time (in gas filled or conventional PCF) using counter-propagating pulsed and CW light from free-space Ti:Sapphire lasers. The generated light will be characterised using tools such as a single photon spectrometer to determine the photon bandwidth, and APD detectors to look for the characteristic coincidences of correlated pair photon generation processes. If successful, this would represent a very significant result, with the potential to develop into a world-leading, unique, and highly flexible source of quantum light.

Context

The content of this CDT project represents a new research activity for the group which is not currently being pursued under any existing projects. However, the end goal of a high purity, narrowband pair photon source based on CSFWM will be of significant interest across a range of research activities within the group, as well externally.

Further Details

Ready to go: The project will start from zero

Skills:
This project is expected to have a strong emphasis on simulation. The student will learn about both linear guidance and relevant nonlinear effects occurring in optical fibres. This background theory will then be applied to modelling of pair photon generation in optical fibres. In particular, we will look to

determine the maximum offset between pump and generated photon wavelengths that can be expected for realistic fibre designs.

In addition to simulation, the student will conduct an experimental study on the feasibility of this technique as a photon pair source using a photonic crystal fibre. This will involve using coincident photon detection to look for the signature of correlated pair generation events.

As this project will have an emphasis on simulation, prior experience with scientific scripting software like Matlab or Mathematica would be useful. Prior experience working in experimental optics, particularly with high power lasers, optical fibres and/or single photon detection is also desirable.

Alignment to PhD [0-5]: 4

References

[1] M. M. Weston et al., "Efficient and pure femtosecond-pulse-length source of polarization-entangled photons," Opt. Express 24, 10869 (2016)
[2] C. Chen, et al., "Efficient generation and characterization of spectrally factorable biphotons," Opt. Express 25, 7300 (2017)
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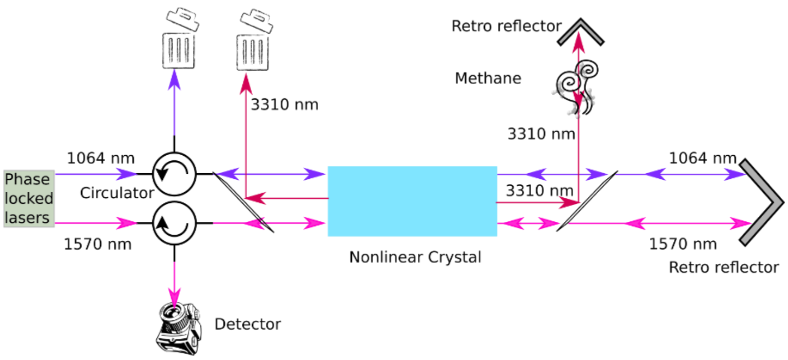
Photon sources and frequency conversion;Quantum Metrology and Sensing;

7 Nonlinear interferometry and sensing in mid-IR without detection

S K Joshi
J Rarity , Xiao Ai (QLM Ltd. – A spin off from Bristol made possible by QTEC)

Abstract

For most applications the choice of wavelength is crucial. So far, quantum tools and experiments have been created/performed at all wavelengths from visible to near infrared (IR). However, the longer wavelength region has been a challenge for most quantum experiments. Here we propose an experiment to create photon pairs in the approx. 3300 nm regime. This wavelength range is particularly interesting because of the vibrational absorption lines of many organic molecules including important gasses like methane. We propose a scheme to measure the absorption at 3310 nm without using the expensive and inaccurate detectors available at this wavelength.



Project Description

The phase matching conditions in Lithium Niobate (LN) allow the conversion of a single photon at 1064 nm into two photons at approx. 1570 nm and 3310 nm. Thus, we can easily access the desired wavelength region using Difference Frequency Generation (DFG) with a commonly available pump laser. However, the detection of single photons at mid IR (MIR) is exceedingly difficult. The energy of each MIR photon is much smaller than the thermal noise levels in all non-cryogenically cooled detectors. Such detectors are bulky and prohibitively expensive.

Classically, methane sensing is performed using the much weaker transitions at near IR wavelengths. Building a significantly better classical system, would force us to either use very expensive detectors or use enough power (at near IR or MIR) to risk an explosion. Fortunately, we can think of a way around this. What if we could make measurements of the absorption at 3300 nm without ever measuring light at this wavelength?

Consider a non-linear optical crystal, when pumped, it will downconvert a pump photon into a signal and an idler photon. This is a three wave mixing process. There ae several other three wave mixing processes that can also occur. For example, a signal and idler photon can combine to create a pump photon or a pump and idler photon can induce the creation of a signal photon

The figure shows a simplified scheme of the experiment. The pump (1064 nm) creates a signal (1570 nm) and an idler (3310 nm). All beams are retro reflected, but the idler first passes The Idler passes through a methane cloud. However, the retroreflected pump and idler, will induce the creation of signal photons in the reverse direction. By detecting the change in intensity of the reverse direction signal, we can infer the absorption at the idler wavelength.

The current project consists of creating the DFG setup and achieving generation of MIR photons. The phase locking of lasers, non-linear interferometry and production of bright modes are further steps that will most likely extend beyond the initial 3 months. It can continue into a PhD whose scope will be the creation and improvement of a methane sensing and ranging tool. The difficulty in this project stems from our inability to detect single photons in MIR. Instead, we must use coincidences between the two signal modes at 1570 nm to infer the presence of the idler. The first month will be spent learning the basics of creating a DFG source. The second month will consist of testing and characterizing the source, detectors, etc. During this time, we will also tackle, stability issues, synchronization, and software/hardware requirements. The last month will be used to make measurements. Further, to identify methane, we must ensure that the source produces a narrow bandwidth capable of addressing the molecular transition. The source should also be wavelength tunable.

Context

This project is closely related to the imaging and metrology quantum hub and thus other projects with similar physical concepts are ongoing. However, this project is unique in terms of the wavelengths used and the experimental techniques that will be used. Other projects will benefit greatly from the skills learnt here. Given the unique wavelengths used, resources used for this project are unlikely to be shared on a day to day basis. This project is supported the independently funded SPRINGS initiative.

Further Details

Ready to go: Some setting up is required

Skills:
Building downconversion and DFG sources.
Aligning and using optical setups with invisible lasers.
Measurement without detection and efficient wavelength conversion.
Hands on experience with lasers, electronics, optical modulators and QKD.

Alignment to PhD [0-5]: 5

References

1] Petrov, Valentin. "Parametric down-conversion devices: The coverage of the mid-infrared spectral range by solid-state laser sources." Optical Materials 34.3 (2012): 536-554.
[2] Matveev, Boris A., et al. "Backside illuminated In (Ga) As/InAsSbP DH photodiodes for methane sensing at 3.3 µm." Photodetector Materials and Devices VII. Vol. 4650. International Society for Optics and Photonics, 2002.
[3] Huang, Kun, et al. "Efficient generation of mid-infrared photons at 3.16 µm by coincidence frequency downconversion." Laser Physics 23.4 (2013): 045401..
[4] https://www.rp-photonics.com/sum_and_difference_frequency_generation.html
[5] Roussev, Rostislav V., et al. "Periodically poled lithium niobate waveguide sum-frequency generator for efficient single-photon detection at communication wavelengths." Optics letters 29.13 (2004): 1518-1520.

8 Analysis and comparison of quantum network topologies

S K Joshi

J Rarity, D Aktas

Abstract

Quantum communication, offers the highest known levels of security. Unfortunately, most protocols are intrinsically two party and point to point. However, almost all modern communication is network based. Creating quantum communication networks is of the utmost importance. Several network architectures have been implemented and many topologies have been proposed. For real world implementations of quantum communication networks, factors such as the cost, compatibility with a wide number of protocols, key rate, channel redundancy, upgradeability, maximum number of users and ease of inter network connections must be considered.

This project aims to survey the various existing network topologies, distil criteria for an ideal quantum network in different usage scenarios and compare topologies to find the ideal type of network for mass scale deployment in various use cases. We shall also attempt to create a new network topology to address the identified drawbacks of existing networks.

Project Description

If quantum communication is to be taken seriously by the public and telecommunication companies, then it must, at the least, provide similar conveniences and services as classical networking. From the end user perspective, the driving factors are cost per bit of secure key, key rate and the total amount of secure key a user can obtain before the system needs to be serviced or upgraded. However, several other factors such as reliability, redundancy, traffic management, network maintenance, forward and backward compatibility of infrastructure, etc. play a key role when an industry decides to adopt a technology.

This project is entirely theoretical in its initial phase. The project can continue into a PhD which has the option of experimentally implementing novel network topologies. The first month of the project will be spent surveying existing quantum networks and identifying criteria on which to classify and rank these networks. Month 2 will be spent is calculations and simulations of selected topologies while the third month will be spent modifying and adapting existing schemes to create new topologies/architectures.

Scientifically, the main challenge will be the creation of a new topology that can out perform currently proposed networks. The most likely approaches to creating novel topologies are limited by practical device performance issues many of which have fundamental and unavoidable bounds. However, by combining network technologies, like different forms of multiplexing, or by creating new protocols, such as schemes to encode routing information, we could potentially create a new advanced quantum network.

A significant draw back of most networks today is their inability to perform “coherent internode operations”. For example, a network based on wavelength multiplexing will not have all nodes capable of receiving photons form two other nodes and performing an interference experiment between these two photons (because of the difference in wavelength). This severely limits the number of protocols the network is suitable for. In the above example, such a wavelength multiplexed network cannot implement teleportation, entanglement swapping, or several types of gates. A potential extension to the project is the study of which classes of protocols are suitable for each type of network.

Context

We have a massive in-house effort focusing on quantum networking. Ongoing projects involve creating Bristol's own citywide QKD network and interconnecting connecting several cities in the UK. This project will help guide the larger efforts and contribute the creation of ever better networks under the quantum communications hub. We are currently planning to implement the worlds largest quantum network within the year. A staggering 30 to 40 node network will be put together in collaboration with several international research groups. This project will form part the initial phase of this monumental experiment. Consequently, this project will rapidly develop into a much larger and much more complex effort that is the ideal start for a PhD.

Further Details

Ready to go: Yes

Skills:
Understanding of QKD networks.
Simulations of real world QKD performance, appreciation of practical difficulties.
Understanding of industrial concerns.

Alignment to PhD [0-5]: 5

References

[1] Wengerowsky, S., Joshi, S. K., Steinlechner, F., Hübel, H., & Ursin, R. (2018). Entanglement-based wavelength multiplexed quantum communication network. arXiv preprint arXiv:1801.06194.
[2] P. D. Townsend, Nature 385, 47 (1997).
[3] M. Pivoluska, M. Huber, and M. Malik, arXiv preprint arXiv:1709.00377 (2017).
[4] H. J. Kimble, Nature 453, 1023 (2008).
[5] X.-Y. Chang, D.-L. Deng, X.-X. Yuan, and et al., Nat. Publ. Gr. , 1 (2016).
[6] C. Elliott, A. Colvin, D. Pearson, and et al. (2005) pp. 138–149.

Experimental;
Location: An industrial/business partner

Quantum Communications;

9 Integration of QKD and KORUZA FSO system

Luka Mustafa
David Lowndes, John Rarity
Joe Smith

Abstract

Quantum communication, utilising free-space and atmospheric quantum channels, has in recent years become a feasible option for the future development of the quantum internet and current quantum applications, such as Quantum Key Distribution (QKD). For maximal flexibility in development of new applications and optimisation of the existing one, based on quantum communication, the development of the Free Space Optical (FSO) communication system, based on an existing open source FSO KORUZA system [1], is proposed.

KORUZA is an innovative open-source open-hardware wireless communication system, employing a low-cost approach to designing free-space optical network systems, enabling connectivity with a highly collimated infra-red light beam at a capacity of 1 Gbps or 10 Gbps at distances up to 150 meters. The completely open-source, open-hardware design allows for approachable modification to support quantum key distribution as well as general quantum communication.

In the proposed project the aim is to, in collaboration with the development team of KORUZA, adjust the existing system to support quantum communication, integrate it with latest sources and detectors at Bristol and then perform extensive testing of the suitability of free space channel and system performance.

Project Description

The main goal of the project is the modification of a FSO KORUZA system to support quantum data exchange. The student will closely collaborate with KORUZA in-house development in Slovenia and engineering team, to first determine the key areas of modification, design to produce a prototype system and then perform extensive testing to identify optimisation before evaluating the system performance for various quantum applications.

The work plan for the project:

1. Firstly, the student will be introduced to the general concept of FSO technology, key components and other technological aspects, with the emphasis on the KORUZA FSO system. This includes a hands-on approach to electrical, mechanical and optical engineering as well as designing, prototyping and manufacturing practices.
2. Existing system requirements for free-space QKD links will be evaluated from expertise in Bristol and the Quantum Communications hub.
3. Modification of the Koruza system will be developed in close collaboration with KORUZA development team, with the emphasis on constructing a robust, easy to manufacture system suitable for in-band optical data communication and quantum distribution.

4. Student will get familiar with useful prototyping and manufacturing techniques, utilising a CNC mill, CNC laser cutter, 3D printers and other available machinery, to quickly bring his design ideas to practice, test them out and make modifications if needed.
5. Once the functional prototype is made, extensive testing of the system needs to be performed with the emphasis on quantum key distribution as the go-to application.
6. Detailed documentation, including mechanical design, manufacturing parts plans, any developed software components and testing results should be produced during the project.

Further Details

Ready to go: Yes

Skills:
During this project student will develop strong understanding of FSO systems and their application for quantum communication. He will also get familiar with smart product design and advance prototyping and manufacturing techniques, as well as testing protocols, useful both with FSO and quantum communications technology.

Alignment to PhD [0-5]: 5

References

[1] www.koruza.net
[2] http://irnas.eu/

10 Integrated Photonic Devices for Quantum Key Distribution

P Sibson

Chris Erven, Mark Thompson

Abstract

Quantum Key Distribution (QKD) provides a provably secure approach to share keys used to encrypt secret information by transmitting single photons [1]. This is one of the first commercial quantum technologies available, and Bristol is heavily involved in UK Quantum Communications Hub [2].

Integrated Photonics provide a stable, compact, miniaturized and robust platform to implement complex photonic circuits amenable to manufacture and therefore provide a compelling technology to implement future QKD systems. Bristol has led the development of Quantum Communication devices in integrated photonics, with the world's first chip-to-chip quantum key distribution experiment [3,4,5,6].

We are currently developing integrated photonic devices for use in full QKD systems allowing for a scalable production approach for personal and commercial use. The miniaturised components allow for multiple photonic circuit per device for Wavelength Division Multiplexed (WDM) QKD link over a single channel increasing channel capacity dramatically. The increased functionality can also allow for Measurement-Device Independent (MDI) QKD, removing detector vulnerabilities, and "hacking" approaches.

Project Description

A number of activities and projects are available in the larger project of delivering a fully operable chip-based QKD system to be demonstrated on the Bristol is Open Network. This includes the robust electronic and optical packaging of integrated devices, electronic hardware development including bespoke time-to-digital conversion of detector events, classical communications, development of high-speed gated detectors, and software development for automated hardware control, calibration, initialisation and post-processing.

Further projects include exploration of WDM protocols using InP transmitters and SiON receiver. Assessing the increase in channel capacity and experimentally demonstrating increased data rates. The WDM of signals could be the combination of two or more quantum signals on the same optical fibre or even quantum and classical signals. The photonic devices are already fabricated and available immediately for demonstrations.

We are also exploring the suitability of InP QKD transmitters for MDI-QKD, where two transmitters (ALICE and BOB) interfere signals at a third party (CHARLIE) containing detectors. The focus on this experiment would be the use of homodyne detector technology to provide locking between independent laser sources required to perform the key exchange protocol. The photonics devices are already fabricated and available immediately for demonstrations, but future demonstrations could incorporate a fully integrated superconducting single photon detector technology currently been developed by QETLabs.

We further wish to explore the use of entangled photons, generated on silicon photonic chips, for time-bin entanglement and teleportation in quantum networks, integrated quantum random number generators, as well as the use of a multi-functional centralised node with shared detector resources.

Context

These activities form part of the overarching strategy of the Quantum Communications Hub and their contributions will lead to eventual publication.

Further Details

Ready to go: Yes

Skills:
It will allow students to become experienced in quantum and classical communications on the physical layer as well as integrated photonic devices used in both classical and quantum photonic experiments

Alignment to PhD [0-5]: 5

References

[1] M. C. &. K. T. Hoi-Kwong Lo, "Secure quantum key distribution," Nature Photonics 8, pp. 595-604, 2014.
[2] EPSRC, "Quantum Leap," 2014. [Online]. Available: http://www.epsrc.ac.uk/newsevents/news/quantumtechhubs/.
[3] P. Z. e. al., "Reference-Frame-Independent Quantum-Key-Distribution Server with a Telecom Tether for an On-Chip Client," Phys. Rev. Lett, 2014.
[4] P. Sibson et al. "Chip-Based Quantum Key Distribution", Nature Comms, 2017
[5] P. Sibson et al. "Integrated silicon photonics for high-speed quantum key distribution", Optica, 2017
[6] Raffaelli et al. "A SOI Integrated Quantum Random Number Generator Based on Phase fluctuations from a Laser Diode" Arxiv 2018

11 Networking Quantum Key Distribution

Chris Erven
Philip Sibson, Emilio Hugues Salas, Djeylan Aktas, Richard Collins

Abstract

Quantum Key Distribution (QKD) provides a provably secure approach to share keys used to encrypt secret information by transmitting single photons. This is one of the first commercial quantum technologies available, and Bristol is heavily involved in the UK Quantum Communications Hub.

The Bristol team aims to establish a quantum-secured metropolitan network across the city of Bristol and UK Quantum Backbone network between Bristol and London. It will use Bristol is Open (BiO) and will be a test-bed for chip based and hand held quantum technologies developed in Bristol, and the National Dark Fibre Infrastructure Services (NDFIS). Bristol will develop algorithms and tools to allow and demonstrate the composition and operation of multiple co-existing quantum logical networks between different client groups on the same physical infrastructure. It will integrate existing telecoms nodes with optical switching to bypass classical elements such as optical amplifiers.

Project Description

Our larger hub goals aim to demonstrate the interoperability of differing QKD systems on the same network; i.e. the ability to use technology developed in Bristol alongside commercially available QKD systems. Metropolitan networks have been successfully demonstrated with commercial systems and basic classical networking protocols. By collaborating with the High Performance Networking (HPN) group in Bristol, that specialise in the creation of dynamic software defined networks, a clear goal is to be able to add quantum-secure keys as a resource and a method to secure the BiO network and the process of functional network virtualisation.

The objective of the project is to perform quantum secure communications across the BiO network. This will initially involve performing quantum secure key exchange between the NSQI and the MVB lab using commercial IDQuantique systems. The second objective would be to perform encryption of data (on a separate fibre) using these keys.

A further aim of the project is to perform co-propagating quantum and classical signals on the same fibre core. This can be achieved by spectrally and temporally separating the signals. These systems will be further deployed in the BiO and the NDFIS for long-term field trials of quantum-secured technologies.

Students will be able to utilise the prior understandings and infrastructure developed to initially demonstrate this technology, and develop the systems and experiments to evaluate the suitability and implement the integration of commercial QKD systems into the BiO network.

Context

These activities form part of the overarching strategy of the Quantum Communications Hub and their contributions will lead to eventual publication.

Experimental;

Location: University of Bristol

Further Details

Ready to go: Yes

Skills:
The experiments will require use of commercial QKD systems, and the ability to route quantum signals through potentially uncontrolled infrastructure (ie fibre in the ground, server rooms, etc). Additionally the student will use the systems devised by HPN to integrate QKD into the metro network. Many resources and infrastructure is currently available, as well as increasing equipment from quantum technology hub procurement.

Alignment to PhD [0-5]: 5

Theory;Simulation;
Location: University of Bristol

Quantum Communications;Device Development (Hardware);Protocols and Algorithms (software);

12 Comparison of DV-QKD and CV-QKD for Long Range Free-Space-Optical Communications

D, Lowndes (UoB); Bowyer, M (Airbus DS Ltd.)

Abstract

Two major approaches to Quantum Key Distribution (QKD) are Discreet Variable (DV-QKD) and Continuous Variable (CV-QKD). DV-QKD is the older more established and proven approach. By comparison, CV-QKD is far less established and unproven over long distances. However, it is believed that CV-QKD may offer a superior path to lower cost more integrated solutions. The object of this research is to compare and contrast from scientific and engineering perspectives the two approaches, and establish which is really best for future long range free space optical QKD to satellites (LEO, MEO, GEO) and high altitude platforms (HAPS).

Project Description

Literature review and familiarisation with Free Space Optical (FSO) communications and QKD.
Detailed literature review of DV-QKD and CV-QKD techniques and systems (past, present and proposed)
Block diagrams and Bill of Materials (BoM) for reference DV-QKD and CV-QKD systems.
Establish assessment framework for DV-QKD vs. CV-QKD e.g. Maturity of Security Proofs;
Impacts of operating at different wavelengths (e.g. 850/1050/1550nm) - performance vs. dependencies;
Scientific issues for long distance daylight operation (e.g. ground to 1000km LEO satellite);
Engineering issues concerning QKD transmitter (high power optical modulators for CV-QKD) and QKD receiver (e.g. dependency on super-cooling 1550nm DV-QKD receiver);
Ease of consolidating communications, beacon and QKD functionality (e.g. by using WDM);
Software complexity; dependency on high performance DSP; Mass, Power & Volume; Estimated Cost;
Operation in space environment (vacuum, temperature variation, solar radiation)
Apply assessment framework to compare DV-QKD and CV-QKD.
To include analysis and simulations as needed.
Final Report and Presentation.

Further Details

Ready to go: The project will start from zero

Skills:
Deep understanding of QKD and FSO theory, techniques and systems
Modelling: analysis and simulation
System Engineering Trade-Offs (for various HAP, LEO, MEO, GEO platforms).

Alignment to PhD [0-5]: 4

Theory;Simulation;

Location: University of Bristol

References

2018 Feb, Kahn, Optical society of America. "Satellite-based QKD Overview". https://www.osa-opn.org/home/articles/volume_29/february_2018/features/satellite-based_qkd/

Quantum Communications;Quantum Metrology and Sensing;

13 Novel CV-QKD scheme and security proof

Siddarth K Joshi
Will McCutcheon, Jason Mueller (CDT cohort 2), Jonathan Matthews, John Rarity

Abstract

Quantum Key Distribution promises information theoretic security but at a very high cost because many implementations need sophisticated sources, modulators, or detectors. Continuous Variable (CV) QKD has shown that it is possible to use bright squeezed states to overcome the need for single photon detectors. However, CV-QKD still lacks the rigorous security proofs offered by the discrete variable case. On top of which, the implementations often need complex setups involving several modulators, squeezed states, and or homodyne/heterodyne detection.

In this project we aim to simultaneously address the theoretical security proofs and eventually implement a novel method for CV-QKD based on sub-Shot noise intensity measurements. Although the applicability of this scheme will be limited to low loss (< 3dB) scenarios, its simplified setup, high brightness and intuitive security could make it an ideal candidate for the future of short distance secure communication.

Project Description

This project is primarily theoretical during the three month period after which it will continue with a strong experimental component. The novel QKD scheme we propose is based on sub-Shot noise measurements using a bright intensity correlated source. The source that inspires this project was recently developed in Bristol. It consists of an optically pumped Photonic Crystal Fiber (PCF) which generates bright signal and idler modes through four wave mixing. The phase matching conditions imply that the number of photons in each output mode are exactly identical (assuming that there are no other competing processes like fluorescence, phosphorescence, etc.). By measuring the intensity fluctuations on the idler mode, we can perform sub-Shot noise measurements using the signal. It is important to note that the total loss should be < 50% and the detectors and their electronics should be Shot noise limited. Now assume that Alice creates these intensity correlated modes, measures the idler and sends the signal to Bob via a low loss channel. Bob performs an intensity modulation, to encode information, on the signal and sends the modulated mode back to Alice. Suppose that the intensity modulation of Bob is well below the Shot noise level of the signal mode, then the only way to extract the information is to perform a sub-Shot noise measurement. Intuitively, an eavesdropper –Eve cannot perform this measurement because she does not have access to the idler. Eve's next best strategy is to perform an intensity correlated measurement between the transmitted and received beams of Alice. However, to be able to perform a sub-Shot noise measurement, Eve must have < 50% loss. If Eve were to extract >50 % of the beam, Alice would no longer be able to perform a sub-Shot noise measurement and Eve's attack would be detected.

The project consists of theoretically proving the security of such a scheme. The initial approach would be to assume an infinite key length and perfect experimental realization. We would then attempt to show security against various possible classes of attacks. The first month will be spent in understanding the sub-Shot noise measurement scheme and the basics of QKD security. We then expect to obtain a basic outline for the proof within the next two months. The project could also involve experimentally implementing the scheme by modifying an existing setup (Subject to availability of the setup) or in further refining the theoretical security proof.

This project has a large scope for expansion both theoretically and experimentally and is thus ideal for a PhD. On the theoretical side, it may be possible to adapt the security proofs obtained here to other CV-QKD schemes. Currently, proving security beyond 50% loss is an open question for most CV-QKD schemes. In our scheme, we have a clear reason why it is impossible. It might be possible to extend this reasoning to other CV schemes. In either case, this scheme has the potential to be the first CV-QKD implementation with tight upper and lower bounds on security when considering losses, noise, etc.

The main challenges in this project will be theoretical. Theoretically, proving the security of a protocol can quickly get complex, especially when real world imperfections must be accounted for. The most challenging aspect will be the relative lack of similar security proofs due to the unusual nature of this protocol. Should you choose to continue this project as part of your PhD, the experiment challenges include the low loss intensity modulation scheme and the construction of Shot noise limited detection systems.

Context

In Bristol, we have worked extensively of sub-Shot noise measurements, using heralded single photons and recently with bright correlated beams. We also have extensive expertise and experience with QKD. This project will bridge these two fields and is closely related to ongoing experimental and theoretical work in both these areas. The initial experimental demonstration will borrow time on an existing setup and must be coordinated with other ongoing experiments.

While this project is theoretical, you will work closely with experimentalists. The project has a clear route into either theory based or experiment based QKD protocol research. It also lays the foundations for on-chip work.

Further Details

Ready to go: Yes

Skills:
Understanding of sub-Shot noise measurements and CV-QKD.
Ability to analyze and prove security of QKD schemes.

Alignment to PhD [0-5]: 5

References

[1] Hillery, Mark. "Quantum cryptography with squeezed states." Physical Review A 61.2 (2000): 022309.
[2] Laudenbach, Fabian, et al. "Continuous-Variable Quantum Key Distribution with Gaussian Modulation--The Theory of Practical Implementations." arXiv preprint arXiv:1703.09278(2017).
[3] Jouguet, Paul, et al. "Experimental demonstration of long-distance continuous-variable quantum key distribution." Nature photonics 7.5 (2013): 378-381.
[4] Grosshans, Frédéric, and Philippe Grangier. "Continuous variable quantum cryptography using coherent states." Physical review letters 88.5 (2002): 057902.

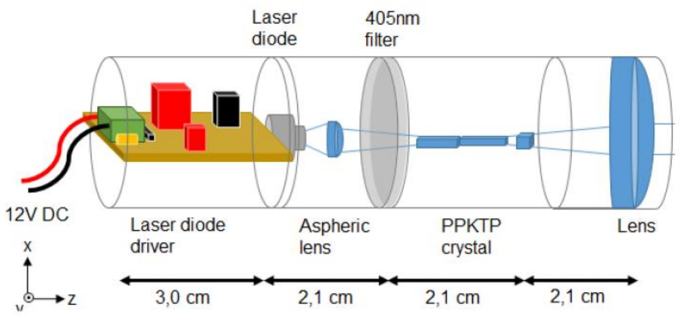
Quantum Communications;Quantum Metrology and Sensing;

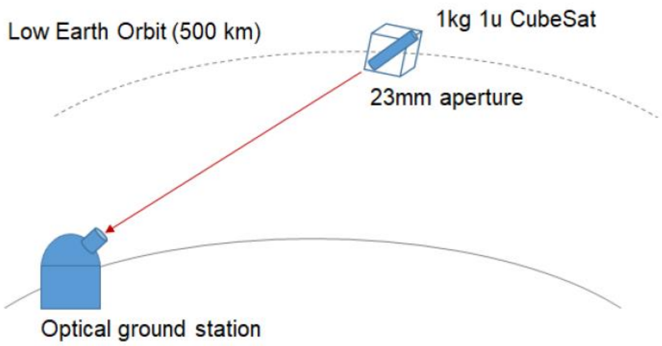
14 Laser pointer size polarization entangled photon pair source

Siddarth K Joshi
J Rarity, J Matthews

Abstract

Entangled photon pair sources are ubiquitous in most quantum optics experiments. Nevertheless, these sources are often large and bulky and thus unsuitable for a wide range of experiments that require a plug and play source of entanglement. In this project we attempt to create a polarization entangled collinear source of photon pairs in a small, compact and robust package. Such a source will find immediate applicability, in CubeSats, free space quantum communication links and teaching laboratories.





Project Description

The technology used to create entangled photon pairs is well known. However most projects start by creating their own laboratory-based photon pair source setups. A simple, versatile entanglement source should be a standard laboratory product much like a laser. The natural candidate for such a compact source is chip-based technologies. Unfortunately, these miniature quantum chips are a relatively new technology which are (currently) not rugged enough for CubeSats and hard to disassemble for teaching purposes.

Bulk optics, on the other hand, is already commercially used for very similar technologies. For example a typical green laser pointer uses Potassium titanyl phosphate (KTiOPO4) aka KTP crystals for the second harmonic generation of an infrared laser into a green beam. Second harmonic generation is the exact reverse process of downconversion – the process we use to create photon pairs. KTP is the same nonlinear crystal we commonly use for many entangled photon sources.

In order to create the source in the tiny form factor of approximately 10 cm long and 1-3 cm wide, we need to utilize a linear scheme that requires minimum alignment. The “cross-crystal” source of polarization entanglement is the ideal choice. In this type of source a laser pumps two PPKTP crystals which are rotated by 90° with respect to each other and about the axis defined by the pump beam. The pump is polarized at 45° with respect to the first crystal. In this scenario, downconversion occurs in both crystals. At the output of the source we should be unable to distinguish which crystal a given single photon was generated within. For type II downconversion, a given H polarized photon (say) could either be the signal produced by the first crystal or the idler produced by the second. This results in polarization entanglement. To improve the visibility of the entanglement, we must address the walk-off between the two PPKTP crystals. This can be easily achieved by a third YVO4 crystal.

The figure shows a schematic of the setup on the top, the bottom shows how we could potentially fit the source into a CubeSat or another portable and self-contained device.

This project is envisioned as a standalone experiment designed to create a tool that is useful for other experiments while teaching elements of optical design and entangled photon sources. Extensions to the project would include, improving the mode matching and thus the heralding efficiency, adapting the source for a CubeSat design and constructing separate pointing and tracking systems for each photon of the entangled pair. These extensions are in line with Bristol’s broader research goals and are good projects for a PhD. The challenges faced during this project primarily deal with optical design, aligning optics without alignment degrees of freedom, and compensation and characterization of the entangled state. The first two weeks will be spent in learning as well as performing calculations and simulations of the system. The next three weeks will be spent in building the setup in a standard optical setup as well as building the measurement and characterization setups needed. A further week will be needed to create a basic and miniature laser driver. The remaining time will be spent miniaturizing the entangled photon pair source. Given time, demonsrations of this source in long distance free space experiments can be implemented.

Context

In Bristol, efforts are underway to build CubeSats for quantum communication, hand held QKD and several metrology experiments that aim to be deployed outside of the quantum optics laboratory. All these experiments will benefit from a small portable entangled photon source. The project is primarily a technology demonstrator and as such will enable several future experiments and technology miniaturization. This project spans the communications and Imaging hubs and enjoys support from both.

Further Details

Ready to go: Yes

Skills:
Building of collinear photon pair sources.
Measuring and creating entanglement.

Alignment to PhD [0-5]: 3

References

[1] Juan Rafael Alvarez Velasquez, bachelors internship report. (Please ask S.K. Joshi for the full report)
[2] Fink, Matthias, et al. "Experimental test of photonic entanglement in accelerated reference frames." Nature Communications 8 (2017): 15304.
[3] Kuklewicz, Christopher E., et al. "High-flux source of polarization-entangled photons from a periodically poled KTiOPO 4 parametric down-converter." Physical Review A 69.1 (2004): 013807.
[4] Steinlechner, Fabian, et al. "A high-brightness source of polarization-entangled photons optimized for applications in free space." Optics express 20.9 (2012): 9640-9649.

15 Quantum computing by cooling

V. Kendon
P. Turner
N. Chancellor; A. Callison; two Summer UG project students (TBC)

Abstract

Instead of the standard gate model, quantum computing can use a continuous time evolution. We still encode the problem into qubits, but then, instead of applying quantum gates, we apply a Hamiltonian-based, continuous time evolution to produce the final state of the qubits, which contains the answer to the computation. The time evolution can include coupling to a thermal bath, or other non-unitary dynamics. This model of computation includes as special cases: adiabatic quantum computation (AQC), computation by (continuous-time) quantum walk (QW), quantum annealing (QA), and many types of special purpose quantum simulation. This project will explore what roles the cooling and environmental coupling play in computation. Simple models will be used to investigate, building on work done comparing AQC and QW [1], and on single qubit studies [2]. Some insights can be gained analytically, but simulation of these quantum systems will be needed to explore the relevant intermediate coupling regimes.

Project Description

Scope

Ref [1] describes a study of unordered search (Grover's) using QW and AQC, with interpolation between these two providing hybrid algorithms exploiting both mechanisms. Hybrid algorithms are shown to be especially useful in realistic situations with noise and imperfect hardware. Ref [2] describes simple one qubit models for AQC with environmental coupling. These relate well to the single avoided crossing model in Ref [1], which is the limit for large sizes of the search problem for both AQC and QW. However, in [2] they consider only weak and strong coupling limits, and do not explore the temperature dependence. Both intermediate coupling regimes and temperature dependence are relatively easy to do numerically, even if more challenging analytically, and this will form the starting point of the project. There are many details that need to be understood properly to use these models correctly, and the aim will be to complete these numerical studies by the mid-point of the project, having gained a thorough understanding of the context and details in the process, including solving the models analytically where possible.

Searching is in many ways a toy problem, with some quite extreme characteristics compared with more realistic optimisation problems. The next step will be to apply the insights and methods from the single qubit system to the smallest instances of the spin glasses that Imperial PhD student Adam Callison has been studying. This will definitely require numerical simulation, but it should still be reasonably fast on desktop/laptop computers. HPC access will be available if more computing power would be useful. There is an extra layer of complexity that arises when coupled qubits are in contact with the same heat bath, so the simplest two-qubit model will be studied first, to develop intuition for the quantum effects that might be observed in multi-qubit systems. A full treatment of multi-qubit systems would take longer than the time available, so specific simple models will be considered, chosen in the light of results from the one and two qubit studies.

Methodology
Analytical derivation of master equations and their solutions where tractable; exact numerical simulation of the models to produce graphs of the behaviour as the temperature and coupling strengths are varied, and to solve models that are analytically intractable (or tedious). Guidance will be provided for the most appropriate and accurate numerical methods.

Workplan
1. one qubit models following Refs [1] and [2] for first half of project; analytic and numerical.
    a) work through and reproduce the results in [2] for the weak and strong coupling limits. Plot the temperature dependent success probabilities (not in [2], but has been done by UG project student).
    b) adapt the model in [2] to match the single avoided crossing model in [1]. Produce a full range of results for the success probability and optimal hybrid algorithm against temperature for this model (numerical).
2. two qubits coupled to a single thermal bath model: analytic treatment in the weak coupling limit to fully appreciate the quantum effects. Numerical exploration of intermediate coupling regime.
3. several qubits (three to six) coupled by a frustrated spin glass Hamiltonian; numerical exploration guided by results from 1. and 2. for the most interesting regime to consider.

Other comments
- You can choose to work in Bristol or Durham for the project. It will be beneficial to visit Durham at some point during the six week undergraduate Summer projects being run on related topics; a small workshop will be organised to promote discussion and exchange between the different projects.
- This project can easily lead into a full PhD project, most likely by studying other Hamiltonians that could be used for continuous-time computation, e.g., Jaynes-Cummings and variants, but many other related directions are possible.

Context
- Quantum walks applied to finding frustrated spin glass ground states: PhD project of Adam Callison (Imperial CQD CDT, cohort 8). This project is exploring how well quantum walk computation can solve realistic problems that AQC is known to provide some advantage for.
- Ref [1] reports on an MRes project of James Morley (UCL CDT) - this project is essentially finished, and has established the value of this approach, considering continuous-time quantum computing as a family of related methods for quantum computing.
- various undergraduate projects have started to explore other topics, including temperature and open systems effects in continuous-time quantum computing, all results so far a preliminary steps.

Further Details
Ready to go: Yes

Skills:
Understanding of continuous-time methods for quantum computing.
Understanding of open quantum systems with time-varying Hamiltonians.
Application of effective computational methods for simulating quantum systems.
Effective presentation of analytical and numerical results in graphs or other formats.

Alignment to PhD [0-5]: 5

Theory;Simulation;
Location: University of Bristol

References

[1] Morley et al, arXiv:1709.00371
[2] Albash/Lidar PRA 91, 062320 2015

16 Variational quantum eigensolvers for the Hubbard model

Ashley Montanaro

Other members of the PhaseCraft team

Abstract

The (Fermi-)Hubbard model is of fundamental importance in the study of strongly interacting electronic systems. Developing our understanding of this model could lead to the design of revolutionary batteries, solar cells and high-temperature superconductors. Solving the Hubbard model appears to be hard for classical computers, yet has been predicted to be one of the earliest applications of near-term intermediate-scale quantum (NISQ) computers. One of the key quantum algorithms used to address this is the variational quantum eigensolver (VQE). This project will investigate the VQE algorithm, emulate it classically for small system sizes, develop optimisations for the algorithm, and determine its likely performance for larger-scale systems.

Project Description

This theory/algorithms project is about approximately producing an encoding of the ground state of the Hubbard model on a quantum computer, in order to understand its properties. Classical methods for this task are limited to approximately 20 sites, so might be outperformed by very near-term quantum computers with 50-100 qubits. One method to construct the required ground state is the variational quantum eigensolver (VQE) algorithm, which uses a classical optimisation routine to optimise over the space of quantum circuits for constructing the desired state. The algorithm uses a quantum computer to determine the quality of each trial state produced.

Obtaining good performance from the algorithm requires a number of important choices to be made, such as the initial state; the family of circuits to be optimised over; and the optimisation algorithm used. This project will characterise and optimise the performance of the VQE algorithm for small instance sizes that can be emulated classically, using a software framework such as ProjectQ. This will provide essential guidance for how to make the VQE algorithm truly useful for system sizes beyond the classical limit. This guidance will be crucial if we are to use the algorithm to obtain a quantum speedup: perhaps the first one ever for a practically-relevant problem.

The project is in partnership with PhaseCraft, a quantum software startup whose initial goal is to deliver the first post-classical simulation of a quantum-physical system, running on a near-term universal quantum computer. The founders of the company are Toby Cubitt (UCL), Ashley Montanaro (Bristol), John Morton (UCL), and Simone Severini (UCL). This is a unique opportunity to be part of the early development of a company in the field of quantum software. The project could naturally lead on to a PhD in the same area, sponsored by PhaseCraft.

This project would suit a student with an interest in the theory of quantum computing and quantum algorithms. Writing code and running numerical optimisations will be important parts of the project. Knowledge of condensed-matter physics would be helpful, but is not required.

* If you are potentially interested in the project, please contact Ashley directly (ashley.montanaro@bristol.ac.uk) to set up a meeting to discuss this, during the week of 30 April - 4 May. This is an essential prerequisite. *

Tentative workplan:

- first month: familiarisation with VQE and Hubbard model, and with software tools; initial computational experiments
- second month: optimisation over choice of initial state and families of circuits
- third month: develop different optimisation algorithms, write up results

Further Details

Ready to go: Yes

Skills:
An excellent understanding of the VQE algorithm and other quantum algorithmic tools, the Hubbard model, and classical numerical optimisation algorithms. Coding abilities. Understanding the relevant academic literature.

Alignment to PhD [0-5]: 5

References

- The theory of variational hybrid quantum-classical algorithms, J. McClean et al, NJP 18, 2016
- Hardware-efficient Variational Quantum Eigensolver for Small Molecules and Quantum Magnets. A. Kandala et al, Nature 549, 2017
- ProjectQ: An Open Source Software Framework for Quantum Computing, D. Steiger et al, Quantum 2, 2018

17 Exploring the activation of Einstein-Podolsky-Rosen Steering

Pete Turner
Paul Skrzypczyk

Abstract

This project will study the activation of EPR steering, where an entangled state that is unable to demonstrate this nonlocal effect at a single copy level, is able to demonstrate it when two or more copies are shared between the parties. The aim is to show that the states from the important class of Bell-diagonal states exhibit activation in the simplest setting, where only two copies are shared. This will shed light on the connection between entanglement and EPR steering, and is relevant for semi-device-independent quantum information protocols.

Project Description

1. Background

The way cause and effect functions in quantum theory is much more intricate and interesting than in classical physics. In particular, due to the fact that quantum systems can be entangled, it is possible to have non-local effects, such as violations of Bell inequalities and Einstein-Podolsky-Rosen (EPR) Steering.

One of the most basic questions about nonlocal phenomena are their relation to entanglement. As famously first shown by Werner, there exist entangled states that are incapable of demonstrating nonlocal effects if one has access to only a single copy of the state. However, if one considers pre-processing the state, or allows for multiple copies to be shared, then "activation" can occur - states which were previously unable to demonstrate nonlocality, now gain this ability.

Very little is known about activation of EPR steering (See, e.g. [1,2]). Since nonlocal phenomena form the basis for "semi-device-independent" and "device-independent" quantum information protocols, understanding activation is not only important from a fundamental perspective, but also from a quantum information theory perspective.

2. Main Research Challenge/Question

The main question to be studied in this theoretical project is to study the activation of EPR steering of Bell diagonal states. These states are a simple class of entangled states for which we have a good understanding of EPR steering at a single copy level [3,4]. This will facilitate the search for activation using small numbers of copies (starting with two copies).

3. Objectives

- Understand the formalism of EPR steering, including, detection, quantification, and activation [5] [2-3 weeks]
- Devise a method and computer codes (based upon seesaw type methods) that will heuristically search for activation [2-3 weeks]
- Determine whether Bell diagonal states display activation or steering or not and focus on analytical results (i.e. proofs of activation if found, or arguments against activation if evidence suggests this is the case) [5-6 weeks].

Theory;
Location: University of Bristol

Further Details

Ready to go: Yes

Skills:
Quantum nonlocality and the formalism for EPR steering.
Semidefinite programming and convex geometry
Quantum Information theory

Alignment to PhD [0-5]: 3

References

[1] M. T. Quintino, N. Brunner, M. Huber, Superactivation of quantum steering. Phys. Rev. A. 94, 062123 (2016).
[2] C.-Y. Hsieh, Y.-C. Liang, R.-K. Lee, Quantum steerability: Characterization, quantification, superactivation, and unbounded amplification. Phys. Rev. A. 94, 062120 (2016).
[3] S. Jevtic, M. J. W. Hall, M. R. Anderson, M. Zwierz, H. M. Wiseman, Einstein–Podolsky–Rosen steering and the steering ellipsoid. J. Opt. Soc. Am. B, JOSAB. 32, A40–A49 (2015).
[4] H. C. Nguyen, T. Vu, Nonseparability and steerability of two-qubit states from the geometry of steering outcomes. Phys. Rev. A. 94, 012114 (2016).
[5] D. Cavalcanti, P. Skrzypczyk, Quantum steering: a review with focus on semidefinite programming. Rep. Prog. Phys. 80, 024001 (2017).

Experimental;Simulation;
Location: University of Bristol

Quantum Information;Device Development (Hardware);Diamond;

18 Wiring up solid state emitters for quantum information processing

Krishna Balram

Joe Smith, Jorge Monroy Ruz, John Rarity

Abstract

Solid state emitters (like NV centres and Quantum dots) provide unique advantages for quantum information processing in terms of both their spin properties (which provide a natural platform for the development of quantum memories) and the potential for deterministic single photon generation (which solves many of the issues that plague photon sources based on nonlinear photon pair generation). The main problem preventing the scaling of solid state emitter-based platforms is the random location (and dipole orientation) which prevents one from adopting top down fabrication methods to build scalable platforms. In this work, we look to overcome these problems and build scalable quantum circuits using NV centres.

Project Description

Motivation:

Solid state emitters (like NV centres and Quantum dots) provide unique advantages for quantum information processing in terms of both their spin properties (which provide a natural platform for the development of quantum memories) and the potential for deterministic single photon generation (which solves many of the issues that plague photon sources based on nonlinear photon pair generation). The main problem preventing the scaling of solid state emitter-based platforms is the random location (and dipole orientation) which prevents one from adopting top down fabrication methods to build scalable platforms. In this work, we look to overcome these problems and build scalable quantum circuits using NV centres.

While there have been tremendous strides made in the scale and complexity of linear optical quantum computing, the probabilistic photon generation and interaction impose resource overheads that can be prohibitive if one needs to approach fault tolerance. Solid state emitters are naturally suited to address these issues. The big challenge, as described above, is figuring out how to connect and wire up a system made of emitters with random locations and dipole orientations.

Our (proposed) solution:

We plan to work with NV centers in high pressure high temperature (HPHT) nanodiamonds embedded in a silicon nitride platform. The main advantage of these NV centres is that the spin of a single NV can be optically addressed at room temperature. Silicon nitride is a CMOS-compatible material that is transparent at the NV emission wavelengths. Borrowing ideas from localisation microscopy, we identify the position (and dipole orientation) of optically active NV centres on a wafer with respect to alignment markers. Using the precision of our electron-beam lithography system (positioning accuracy < 10 nm), we then write waveguides and optical cavities at the determined locations. Finally, we can overlay DC and RF electrodes for Stark tuning and spin manipulation. In principle, this provides us all the tools for controlling and manipulating an NV centre on a photonic chip.

Experimental;Simulation;
Location: University of Bristol

What we plan to do in the next 3 months:

The first task is to couple the light efficiently from a single NV centre into an optical waveguide. This requires addressing two issues through numerical electromagnetic simulations (FDTD):

1) What is the optimal thickness of the silicon nitride (unlike SOI which comes in pre-determined thickness, we can tune the thickness of the nitride layer)?
2) Designing efficient waveguide to free space couplers. Exploring the trade-offs involved in bandwidth and coupling efficiency.

Once the designs have been optimized, we can fabricate the devices at the state-of-the art Bristol nanofabrication facility. The availability of an in-house fab means that one can go from design to testing in around 3 days (as opposed to 3 months at least for external foundries). This allows one to rapidly iterate on the design ideas, which is critical at this early phase.

Finally, we would like to test the performance of the passive devices (without the NV centers) in the lab. We would like to know the propagation loss for the waveguides, Q factor for the ring cavities and the light extraction efficiency from the waveguide (coupling efficiency from waveguide to free space). We will then fabricate the optimal design around the NV centres.

Why is this an exciting PhD project:

Integrating solid state emitters in nanophotonic platforms has been a long standing problem in the research community. We believe our approach is promising for solving a number of problems that have plagued past attempts. Progress in this problem is expected to have an enormous research impact.

Context

There has been a long standing research activity in John Rarity's group on NV centers for QIP. This work will build on all the knowledge the group has accumulated over the years and apply it towards the problem of wiring the NVs together on chip.

Further Details

Ready to go: Yes

Skills:

1. *Design of electromagnetic structures at visible wavelengths using numerical solvers*
2. *Fabrication of novel nanophotonic devices in the Bristol cleanroom using electron beam lithography*
3. *Characterisation of integrated nanophotonic devices at visible wavelengths.*

Alignment to PhD [0-5]: 5

References

A nice recent review article:
Sipahigil, Alp, and Mikhail D. Lukin. "Quantum optics with diamond color centers coupled to nanophotonic devices." arXiv preprint arXiv:1712.06693 (2017)..

Experimental;
Location: University of Bristol

Quantum Information;Quantum Communications;

19 Floodlight quantum key distribution & Stabilisation systems

D. Aktas

J. Kennard, C. Erven, J. Rarity

Abstract

Quantum information is evolving towards next generation quantum technologies, such as the realisation of completely secure quantum communications. But quantum information is more fragile than its classical counterpart, so that the ideal performances of quantum protocols may rapidly degrade in realistic practical implementations. State of the art of QKD realisations seems to have reached performances close to the theoretical bound known for users applying local operations assisted by unlimited two-way classical communication (LOCCs) over a lossy bosonic channel and it's not enough. Recently, a new kind of approach has emerged exploring the potential of exploiting many modes per channel use called Floodlight QKD. It is a new paradigm because all other existing protocols inherently cannot do the same unless they employ a massive amount of wavelength-division multiplexing rendering the solution highly complex and demanding in term of resources, which is unrealistic for large scale implementations.

FL-QKD is capable of gigabit-per-second SKRs over metropolitan-area distances and has been proven to be secure against collective attacks. Thus, it is worth investigating further and showing that it can be deployed in a real metropolitan network.

Project Description

QKD takes advantage of the ability of some quantum systems to privately share randomness. This feature enable two remote users to implement protocols for the exchange of secret keys with unconditional security, they can then communicate with information-theoric security using OTP encryption.

Quantum information is more fragile than its classical counterpart, so the ideal performances of quantum protocols may rapidly degrade in realistic practical implementations. In particular, this is a basic limitation that affects any point-to-point quantum communication protocol over a quantum channel, where remote parties transmit qubits, distribute entanglement or Secret Key. It has been shown that for a lossy channel and for quantum limited amplifier, the SK capacity is given by K=-log2(1-n) n being the transmissivity. At long distances, the optimal rate-loss scales of K=1.44n so 0.15 secret bits per channel use at 50 km. The implications of this are tremendous: CV-QKD operates at one optical mode per channel use to ensure maximum mixing efficiency of a shot-noise limited coherent detection, BB84 protocols (without demultiplexing) also takes no advantage of multiple modes per channels use.

It's true that lately the field has seen an emergence of several demonstrations using demultiplexing strategies and High-dimensional QKD but with secret key rates that don't exceed the ideal decoy-state BB84 bound and only reaching previous state of the art of 1 Mbit/s @50km (10^-3 bits per channel use).

In this context, Flood Light QKD is a brand new paradigm capable of gigabit-per-second SKRs over metropolitan-area distances. Transmitting many photons per bit duration without compromising security is possible because FL-QKD utilises an optical bandwidth that is much greater than its modulation rate; i.e., it employs many modes per channel use. Furthermore, using a unique broadband homodyne receiver allows to effectively leverage a huge optical bandwidth without having to resort to a cumbersome and costly demultiplexing strategy.

There are two key aspects of this project that need a fair amount of investigation and ingenuity, one theoretical and the other experimental. As always, quantum communications is offering versatility as for which amount of either a student want to invest his skills and time in.

Since FL-QKD is fairly new, it is most likely for the protocol to evolve and change with the needs to coincide with the challenges of a real metropolitan implementation. This fact implies an obvious need for the new security proof to be found along the way, but already, the current security against frequency-domain collective attacks need to be extended to all coherent gaussian collective attacks. On the other side, the main challenge for deploying FL-QKD in urban condition is the necessity for stability. As such, the protocol need a very precise synchronisation between a local oscillator kept on Alice's station and the modulated signal generated at Bob's remote location. This huge interferometer needs also to be actively phase stabilised in order for the protocol to be operational.

A first task would be to build a demonstrator of the system. In the beginning, a comprehensive tutorial on how to realised a useful laser reference will be provided to design a Rubidium saturated absorption spectroscopy setup.

Then, the student will use this reference as a starting point to frequency lock other laser sources in a scheme where a cavity and a nonlinear crystal will serve as a transfer lock to obtain a stable telecom light.

After designing this laser source station with absolute frequency references, the next step will be to use them to actively stabilised a fibered interferometer. The system will be used along side entangled photon pairs travelling in the same interferometer, so one goal will be to obtain an error signal for the feedback loop in a regime that doesn't register on the APD dedicated to the FL-QKD protocol.

Further Details

Ready to go: The project will start from zero

Skills:
The student will earn multiple skills with this project:

- *A good understanding of QKD state of the art (protocols, security, limitations, implementations).*
- *How to deal with bulk/fibers optics to design a compact photonics setup (from design to alignment skills).*
- *(re-)Learn about some basic atomic physic.*
- *Spectroscopy (saturated absorption).*
- *Stabilisation systems with absolute laser frequency reference.*
- *Some basics about electronics to build the feedback loops needed for stable interferometry.*

Alignment to PhD [0-5]: 5

References

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https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-21-24550
https://arxiv.org/pdf/1611.01139.pdf

Experimental;Simulation;
Location: University of Bristol

Quantum Information;Quantum Communications;Device Development (Hardware);

20 An (actually) fully integrated quantum random number generator in SOI

Krishna Balram
Jake Kennard

Abstract

Random numbers are ubiquitous in areas ranging from Monte Carlo simulations to public key cryptography. While software-based pseudo-random number generators are widely used, there are certain applications, especially in cyber-security that require a true random number generator, one whose randomness is tied to physical laws. The randomness of photon statistics emitted by light emitting diodes (LEDs) is one such example. While LEDs are commonplace, they are hard to integrate in a silicon-based CMOS platform where the signal processing electronics, which converts the photon statistics to a binary random sequence is implemented. In this project, we hope to address this issue by implementing CMOS compatible light sources and detectors for a fully integrated on chip random number generator.

Project Description

Motivation:

Random numbers are ubiquitous in areas ranging from Monte Carlo simulations to public key cryptography. While software-based pseudo-random number generators are widely used, there are certain applications, especially in cyber-security that require a true random number generator, one whose randomness is tied to physical laws. The randomness of photon statistics emitted by light emitting diodes (LEDs) is one such example. While LEDs are commonplace, they are hard to integrate in a silicon-based CMOS platform where the signal processing electronics, which converts the photon statistics to a binary random sequence is implemented. In this project, we hope to address this issue by implementing CMOS compatible light sources and detectors for a fully integrated on chip random number generator.

Developing a monolithic fully integrated quantum random number generator becomes critical if we want to integrate these systems into mobile platform where power and space constraints are brutal. As more and more financial transactions are carried out using a mobile phone, the presence of a true RNG fully integrated as a smart phone module would be revolutionary from a security perspective.

Our (proposed) solution:

We would like to implement CMOS compatible light sources by running the germanium (Ge) photodetectors available on the platform in forward bias. Ge, while an indirect bandgap material, has a direct bandgap at 1.55 um. This has fuelled a great research effort in trying to implement lasers in Ge [MIT, Stanford, IME etc]. For our application, we can work with the standard Ge photodetectors available on the platform. While the emission efficiency of the sources is low (~ 1e-5), the brightness is sufficient for measuring photon statistics because the Ge photodiodes have very high detection efficiency (~ 90%) and the emitter and receiver are integrated on the same chip, which minimizes the photon loss incurred with off-chip coupling (~3 dB).

Experimental;Simulation;
Location: University of Bristol

The plan for the next 3 months:

We would like to implement the protocol developed in Prof. Gisin's group in an SOI platform with Ge photodiodes serving as both emitters and receivers. The experimental plan is as follows:

1) Using a fiber array, couple the light from the emitter diode to the receiver diode. Find the optimal operating conditions for emitter and receiver to maximize SNR. In particular, the key question we would like to address is whether the receiver photodiode needs to be run as an APD to enhance the gain?
2) Implement the Gisin protocol using off-the shelf electronics (amplifiers and A-D converters). The electronics was already implemented by Francesco et al. for their paper. In this project, we would like to implement the whole system and get an understanding of the key rates possible in this integrated platform and the various factors that affect system performance.
3) Building on the results in (1) and (2), we would like to design a Ge based light emitter that is optimized for QRNG. We plan to implement these designs in the next active run from IME.

Why is this an exciting PhD project:

Integrated QRNG are expected to be one of the first quantum inside products on the marketplace. Given the explosion of smart phones worldwide and the increasing trend towards mobile transactions, the need for these devices is expected to be enormous. The PhD project thus has a chance to have a huge research impact.

Context

This is a new research activity.

Further Details

Ready to go: Yes

Skills:

1. *Characterisation of integrated photonic components: light emitters and detectors. Making sensitive measurements with custom-built electronics.*
2. *Modelling light emission from indirect bandgap semiconductors and understanding system tradeoffs in engineering design.*

Alignment to PhD [0-5]: 5

References

The Gisin paper:
Sanguinetti, Bruno, et al. "Quantum random number generation on a mobile phone." Physical Review X 4.3 (2014): 031056

Quantum Information;Quantum Computation;

21 Topological codes with photons

Jiannis Pachos

Jorge Barreto

Abstract

Quantum error correcting codes allow for the realisation of quantum computation in the presence of errors. A particular subset of these codes, known as topological or surface codes, enjoys very high error thresholds and they have a simple geometrical configuration with local syndrome measurement. These characteristics make them the weapon of choice of current small scale realisations of quantum computation. The project will consider the Toric Code and its photonic implementation. It has been recently shown that the toric code can be full implemented with fermionic linear optical elements [Meichanetzidis et al. arXiv:1705.09983; Bravyi et al. arXiv:1710.02270]. The project aims to translate this formalism to the quantum states of photons and provide a full set of manipulations for its quantum optical realisation.

Project Description

It has been recently shown [Meichanetzidis et al. arXiv:1705.09983] that the toric quantum error correcting code can be expressed in terms of Gaussian fermionic states. This dramatically simplifies its description and makes it amenable to both theoretical analysis and experimental implementations. For example, it has been used by Bravyi et al. [arXiv:1710.02270] to identify the error thresholds of coherent errors. The project aims to employ this relation in order to simplify the experimental realisation of the toric code. In particular, it aims to map the fermionic Gaussian states into bosonic ones that can be realised with linear optical elements. Such a relation [Xu et al. Nature Commun. 7, 13194 (2016)] can facilitate the linear quantum optics implementation of the toric code, which is the goal of the project.

Further Details

Ready to go: Yes

Skills:
The project is theoretical. It requires knowledge of simple topological codes (provided by set of five lectures by Jiannis Pachos). Knowledge on quantum optics is needed for the second part of the project that proposes the photonic realisation of the code with linear quantum optics. Knowledge of numerical simulations with Matlab or Python could be useful for verifying the thresholds of the toric code quantum error correction.

Alignment to PhD [0-5]: 5

References

Konstantinos Meichanetzidis, Christopher J. Turner, Ashk Farjami, Zlatko Papić, Jiannis K. Pachos, Free-fermion descriptions of parafermion chains and string-net models, arXiv:1705.09983.

Sergey Bravyi, Matthias Englbrecht, Robert Konig, and Nolan Peard, Correcting coherent errors with surface codes, arXiv:1710.02270.

Jin-Shi Xu, Kai Sun, Yong-Jian Han, Chuan-Feng Li, Jiannis K. Pachos, Guang-Can Guo, Simulating the exchange of Majorana zero modes with a photonic system, Nature Communications 7, 13194 (2016).

22 Equivalence determination of qutrit unitary operations.

P S Turner
Prof M Murao, University of Tokyo

Abstract

This project aims to generalize recent results in higher order quantum operations -- namely unitary equivalence determination -- from qubits to qutrits.

Project Description

Unlike usual quantum operations which can take quantum states as input and output, higher order quantum operations can take quantum processes as input and output other quantum processes. Recent examples of higher order operations include indefinite causal order, and equivalence determination. This project deals with the latter.

Equivalence determination is an analogue of the well known problem of quantum state discrimination: given one of two candidate quantum processes (say, unitaries) determine which one it is. Unlike standard quantum state discrimination however, in this case we do not assume that classical descriptions of the candidates are known. Instead, we are only given samples of the quantum processes -- from these known samples, we must then decide what the unknown process is. Thus, we can imagine we are given a red box and a green box, both of which are promised to perform distinct unitary operations (say, in Hilbert space dimension d). Then we are given a black box which is promised to be equivalent to either the red or the green, and our task is to determine which one using the means at our disposal: arbitrary state preparation that can be fed into the boxes, and arbitrary measurement of the outputs.

Many variations of this kind of problem can be imagined. Following arXiv:1803.11414, the project will start by studying the case of qubits (d=2). The solution to the equivalence determination problem in this case relies heavily on the representation theory of the unitary group U(2). Once this is reviewed and understood, we will then investigate it's generalization to the unitary group U(3). A stretch goal will be understanding the problem for arbitrary dimensions, using known results from the representation theory of arbitrary unitary groups.

Context

This project could take our work in the representation theory to multi-photon, multi-mode linear optics in a very interesting new direction.

Further Details

Ready to go: Yes

Skills:
Quantum information theory in finite dimensions, including unitary operations, POVM measurements, and positive maps. The student will learn state discrimination and representation theory under the guidance of the supervisor, on the way to mastering the theory of equivalence determination.

Theory;

Location: University of Bristol

Alignment to PhD [0-5]: 4

References

arXiv:1803.11414

Experimental;Simulation;
Location: University of Bristol

Quantum Information;Quantum Computation;Device Development (Hardware);

23 Hybrid platforms for photonic quantum information processing

Krishna Balram

Laurent Kling, Pisu Jiang

Abstract

While the scale and complexity of the circuits fabricated in silicon has steadily increased in the past decade, the device performance has plateaued. Silicon as an optical material is fundamentally limited, primarily in terms of providing mechanisms to dynamically modulate its refractive index at high speeds with low insertion loss. The impact of photon loss on quantum photonic circuits is far greater than that in classical photonic circuits, primarily due to the low average brightness of the single photon sources. This problem needs to be addressed if quantum photonic circuits need to achieve the scale and complexity needed for implementing fault tolerant quantum information processing. In this work, we look towards developing hybrid platforms for addressing this problem.

Project Description

The problem:

While the scale and complexity of the circuits fabricated in silicon has steadily increased in the past decade, the device performance has plateaued. Silicon as an optical material is fundamentally limited, primarily in terms of providing mechanisms to dynamically modulate its refractive index at high speeds with low insertion loss. The impact of photon loss on quantum photonic circuits is far greater than that in classical photonic circuits, primarily due to the low average brightness of the single photon sources. This problem needs to be addressed if quantum photonic circuits need to achieve the scale and complexity needed for implementing fault tolerant quantum information processing. This problem becomes especially pertinent as quantum photonic circuits move towards low temperature operation, wherein these index modulation problems become greatly exacerbated.

Our (proposed) solution:

One possible solution to this problem is to combine what silicon does well (passive low loss waveguides and parametric down-conversion based photon sources) with a non-CMOS material like InP, GaAs or $LiNbO_3$ (LN) which implements the refractive index modulation. In this work, we will work with a silicon on LN platform. LN is the default material of choice for building high speed electro-optic modulators for telecom, mostly on account of its strong X(2) nonlinearity. By applying a voltage across the LN, the refractive index of the LN is changed due to the Pockel's effect. Since the evanescent field of the guided mode is primarily in the LN ($n = 2.2$), this allows us to modulate the refractive index of the guided mode and thus build phase shifters and modulators that do not depend on temperature or free carriers.

The main advantages of working with a Si on LN platform are the availability of a potentially strong, high speed modulation mechanism that operates with low loss down to 1K (the X(2) nonlinearity is weakly dependent on temperature). The low temperature operation is critical because thermal phase shifters are not really an option at low T. The main challenge (as with all hybrid platforms) is to engineer the designs to reduce the overall system loss.

Experimental;Simulation;
Location: University of Bristol

What do we plan to do in the next 3 months:

Simulation:

While there are a lot of standard reference designs and PDKs for SOI, for Si on LN, we are essentially in uncharted territory. In this project, we would like to develop a base set of designs for characterizing this platform:

1) Efficient grating couplers: the main challenge being the high index of the substrate (n = 2.2 for LN vs 1.5 for SiO2).
2) Low loss & ultra-low power phase shifters: explore the trade-off between insertion loss and modulation strength.
3) Design of resonant modulators: how do you design for ex: ring modulators taking into account the crystal (a)symmetry of LN.

Fabrication & Characterisation:

The UoB has a state of the art cleanroom for nanophotonic device fabrication. One of the main advantages of having an in-house foundry is the ability to rapidly iterate on designs. For example, for all the designs discussed above it takes ~ 3 days to go from having a finished design to a fabricated chip, in comparison with ~ 3 months for a regular foundry process. We hope that all the designs developed above will be fabricated and tested in the timeframe of this project.

Why is this an exciting PhD project?

I believe hybrid platforms will play a very important role in the development of quantum photonic information processing systems. Given that very little has been done in exploring both the materials (what are the best Si+X combinations & why?) and device aspects (do we design the modulators the same way as we do in SOI?) of engineering these platforms, this project has the potential for having an enormous foundational research impact.

Context

This is a new research activity.

Further Details

Ready to go: Yes

Skills:

Photonic device design and simulation using numerical tools like Lumerical .
Device characterisation: measuring integrated photonics devices and circuits
Nanoscale device fabrication: e-beam Lithography, dry etching and metallization
Alignment to PhD [0-5]: 5

References

On hybrid platforms in general:
Kurizki, Gershon, et al. "Quantum technologies with hybrid systems." Proceedings of the National Academy of Sciences 112.13 (2015): 3866-3873.
More directly relevant to this work:
Chiles, Jeff, and Sasan Fathpour. "Silicon photonics beyond silicon-on-insulator." Journal of Optics 19.5 (2017): 053001
Rao, Ashutosh, and Sasan Fathpour. "Compact lithium niobate electrooptic modulators." IEEE Journal of Selected Topics in Quantum Electronics 24.4 (2018): 1-14

Experimental;Simulation;
Location: University of Bristol

Quantum Information;Quantum Computation;Device Development (Hardware);Superconducting Qubits;Protocols and Algorithms (software);

24 Benchmarking quantum computers, from superconducting qubits to photonics, via quantum simulation and machine learning

Raffaele Santagati

Brian Flynn, Raphael Pooser, Antonio Andrea Gentile, Anthony Laing, Eugene Dumitrescu, Kathleen Hamilton

Abstract

Benchmarking quantum hardware is essential for the development and optimisation of next generation quantum technologies. This project will leverage quantum simulation and machine learning protocols developed in Bristol in recent years, with the aim of developing new benchmarking techniques. Proof-of-principle implementations were so far limited to photonic devices. In this activity, the student will program Python middleware provided by the project supervisors at Oak Ridge National Laboratory (ORNL) to test such protocols on alternative available quantum hardware (e.g. Rigetti and IBM). The final scope will thus be benchmarking the various approaches.

The student will first get familiarity with the protocols described in recent publications [1,2,5,6]. They will then learn how to program the interface provided by ORNL, and implement these protocols in a platform-independent program. This program will then be run on the available architectures. The student will then compare the performance and output of the various systems, with focus on accuracy of results and timing.

Project Description

In recent years Bristol QETLabs have demonstrated several quantum information and machine learning protocols amenable for application on non-error-corrected quantum hardware. The Witness Assisted Variational Eigenvalue Solver (WAVES) can be used to find with high fidelities ground and excited states of physical Hamiltonians, starting from limited aprioristic knowledge on the system under study. Also, the algorithm displayed a high resilience to experimental noise [1]. This approach can be combined with novel machine learning enhanced quantum algorithms, such as the Bayesian phase estimation [2], to further increase its tolerance to noise and decoherence. The student will program Rigetti and IBM superconducting quantum computers to test the performances of WAVES on these machines.

Oak Ridge National Labs (ORNL) have developed Python middleware, called eXtreme-scale Accelerator programming framework (XACC) [3], used to interface software with numerous quantum hardware systems. This allows a user to write a single program which is mapped to the hardware via drivers, where the user need not be aware of the specifications of the machine. Then the program can be quickly applied to numerous platforms, enabling fast comparisons [3]. In particular, ORNL have drivers for Rigetti, IBM machines, DWave, various quantum simulators, and plan to access more devices in future, including near-term access to ion trap machines.

The second step of the research program will focus on the study of the dynamics of quantum hardware using machine learning techniques. Quantum Hamiltonian learning [4] has been demonstrated as a new tool for the efficient characterisation of quantum systems. The approach combines quantum simulators and machine learning protocols, based on Bayesian inference, to estimate the parameters of the system Hamiltonian. An implementation of Hamiltonian learning on such devices can serve simultaneously as additional benchmark, when applied to train the device to "learn" a known system, but can also better understand the physics of untrusted devices, using a trusted simulator to verify their behaviour. In the first case, we will run the single parameter, 1 qubit case studied in [4]. If this works fully using ORNL's XACC framework, we will have produced a cross-platform untrusted device verification protocol, for small devices, among the firsts of its kind. We can then scale the algorithm to more parameters, and larger systems.

Context

This is strongly related to the existing quantum Hamiltonian learning and quantum simulation projects already existing in Bristol and to the quantum hardware benchmarking project at ORNL

This project will be part of a collaboration between different partners: UOB, ORNL, Microsoft, Rigetti, and others. It will be possible to integrate the student to in this collaboration and expand this research into a proper PhD program, where quantum simulation and quantum machine learning are used for benchmarking quantum computers for practical applications. While new quantum simulation protocols are already being developed in the Bristol research unit, we also hope to exploit neural networks and/or other likelihood free methods. The student might join such efforts as initial activities of their PhD. Furthermore, new drivers for interfacing to reconfigurable quantum photonic hardware will be developed in order to expand the capabilities of the XACC framework, adding new capabilities and enabling the development of a unique benchmarking system for different hardware.

Further Details

Ready to go: Yes

Skills:
The student will familiarise with different quantum hardware, mostly superconducting qubits, which will be remotely controlled. The student will learn the basics of state of the art quantum simulation techniques and how to implement them on available hardware. They will also familiarise with cutting edge machine learning techniques and how to apply them to quantum systems characterisation. The programming language used for the simulations and for the control of the experiments is Python. Familiarity with Mathematica to migrate portions of pre-existing code would be useful.

Alignment to PhD [0-5]: 5

References

[1] Santagati, Raffaele, et al. "Witnessing eigenstates for quantum simulation of Hamiltonian spectra." Science advances 4.1 (2018): eaap9646.

[2] Paesani, Stefano, et al. "Experimental Bayesian quantum phase estimation on a silicon photonic chip." Physical review letters 118.10 (2017): 100503.
[3] McCaskey, Alexander J., et al. "Extreme-Scale Programming Model for Quantum Acceleration within High Performance Computing" arXiv:1710.01794 (2017). https://github.com/ORNL-QCI/xacc
[4] Wang, Jianwei, et al. "Experimental quantum Hamiltonian learning." Nature Physics 13.6 (2017): 551.
[5] Carolan, Jacques, et al. "Universal linear optics." Science 349.6249 (2015): 711-716.
[6] Neville, Alex, et al. "Classical boson sampling algorithms with superior performance to near-term experiments." Nature Physics 13.12 (2017): 1153.

Experimental;Theory;Simulation;
Location: Another academic institution

Quantum Information;Quantum Computation;Device Development (Hardware);Trapped Ions / Cold Atoms ;

25 Designing ion trap arrays and shuttling protocols for a quantum computer prototype

Winfried Hensinger
John Rarity
Dr Seb Weidt, PDRAs and Phd students

Abstract

This projects contains practical steps towards engineering a practical trapped ion quantum computer focusing on ion transport and the design of ion trap arrays.

Project Description

Impressive progress has been made in the implementation of quantum information processing with trapped ions. This includes the realization of high-fidelity quantum gates, quantum error correction, teleportation and many quantum algorithms. At Sussex , we are in the process of constructing a microwave ion-trap quantum computer demonstrator device. This device is based on the use of microwave radiation. This technology is ground-breaking as it permits to replace thousands or even millions of laser beams that would be required in a large scale quantum computer with a few microwave emitters that are located outside the vacuum system hosting the quantum computing microchip architecture. Recently, we have been able to demonstrate a two-qubit microwave gate with fidelity close to the fault-tolerant threshold using this technology. We have invented a new approach to quantum computing with trapped ions where quantum gates are carried out by the application of voltages, similar in nature to the operation of transistors in a classical computer. The device only requires a single set of global radiation fields, with the number of fields independent of the number of qubits required. Constructing a quantum computer demonstrator device encompasses numerous challenges such as the design of the actual device, the development of microchips that form the core of the device, development of reliable ion transport within ion trap arrays, sympathetic cooling and the implementation of fault-tolerant single and two-qubit gates.

Ion transport within ion trap arrays is a critical ingredient for an ion trap quantum computer. As part of this project, you will simulate electric fields for ion transport within X-junction ion trap arrays as well as developing relevant shuttling protocols. Outcomes from the project will include diabatic and adiabatic shuttling protocols. We will focus on separation and recombination of ion chains and transport through junctions. We will also develop shuttling protocols for mixed species transport.

The Ion Quantum Technology Group at the University of Sussex, Brighton is one of the world’s leading centres for the implementation of trapped ion quantum computing and simulation using microwave radiation. Microchips developed by the group provide state-of-the-art architectures for a large scale quantum computers, quantum simulators and quantum sensors. The group is part of the UK Quantum Technology Hub on Networked Quantum Technologies and the UK Quantum Technology Hub for Sensors and Metrology. The group currently spans 4 Postdoctoral Fellows, 15 PhD students, 6 undergraduate students, one senior scientist and the head of group. The group has numerous national and international collaborations. You will be part of a team working together to develop a large scale quantum computer. Some of the skills you will acquire include lasers and optics, ultra-high vacuum techniques, quantum information science, electronics, microfabrication and many other skills. The city of Brighton & Hove has everything - sun, sea, brilliant clubs, great places to eat, fabulous shops, a truly cosmopolitan vibe and is located only 50min from central London. Located on the beach, Brighton boasts beautiful seaside views and beaches, boating, sports and beach activities.

Further Details

Ready to go: Yes

Skills:
Competence in ion trapping experiments, competence in simulating complex electric fields and shuttling protocols

Alignment to PhD [0-5]: 5

References

S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)
B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S. J. Devitt, Ch. Wunderlich, and W. K. Hensinger, Science Advances 3, e1601540 (2017)
You can find more information including a virtual lab tour at:
http://www.sussex.ac.uk/physics/iqt

Experimental;Theory;Simulation;
Location: Another academic institution

Quantum Information;Quantum Computation;Device Development (Hardware);Trapped Ions / Cold Atoms ;

26 Quantum computing with trapped ions with global radiation fields

Winfried Hensinger
John Rarity
Dr Seb Weidt, PDRAs and Phd students

Abstract

This projects contains practical steps towards engineering a practical trapped ion quantum computer focusing on ion transport and the design of ion trap arrays.

Project Description

Impressive progress has been made in the implementation of quantum technologies with trapped ions. This includes the realisation of high-fidelity quantum gates, quantum error correction and many quantum algorithms. Large-scale quantum computers may require in excess of millions of individual quantum bits. Every single previously proposed method to implement quantum gates requires the application of radiation fields (either laser or microwave) where the number of radiation fields scales with the number of ions used in the quantum computer. This is why many people felt it to be tremendously challenging to build a large-scale trapped-ion quantum computer, imagining millions of laser beams that would need to be aligned to realize a large scale quantum computer. We invented a method where this scaling vanishes, significantly reducing the difficulty to construct a practical quantum computer. Here, quantum gates with trapped ions are executed by application of voltages in the presence a few global rf radiation fields analogous to the operation of transistors in a classical computer. We have already implemented two-ion quantum gates using this method close to the fault-tolerant threshold. We also developed a blueprint on how to construct a trapped-ion quantum computer. At Sussex , we are developing both a new generation of ion chips and coherent manipulation methods to develop fault-tolerant quantum gates with microwave radiation. This will allow for realization of quantum algorithms as well as the realization of quantum simulations of other physical systems eventually beyond what is tractable on a classical computer. Your primary location of work will be Sussex as part of the UK Quantum Technology Hub on Networked Quantum Technologies.

The project is meant as a key preparation step to implement and verify quantum gates with microwave radiation well beyond the fault-tolerant threshold, which you may wish to undertake as your PhD project. Specifically, you will devise a versatile toolset to characterize high-fidelity single and two-qubit gates as well as to accurately verify achieved fidelities. To more accurately verify the achieved gate fidelity, you will develop sophisticated statistical models to analyze the large amount of data generated by the experiment. You will also develop and implement experiments to perform tomography and randomized benchmarking which will allow us to better characterise single and two-qubit gates. In addition, you will investigate the possibility of applying the newly developed toolsets to gate operations implemented using NV centres in diamond.

The Ion Quantum Technology Group at the University of Sussex, Brighton is one of the world's leading centres for the implementation of trapped ion quantum computing and simulation using microwave radiation. Microchips developed by the group provide state-of-the-art architectures for a large scale quantum computers, quantum simulators and quantum sensors. The group is part of the UK Quantum Technology Hub on Networked Quantum Technologies and the UK Quantum Technology Hub for Sensors and Metrology. The group currently spans 4 Postdoctoral Fellows, 2 electronics engineers, 15 PhD students, 6 undergraduate students, one senior scientist and the head of group. The group has numerous national and international collaborations. You will be part of a team working together to develop a large scale quantum computer. Some of the skills you will acquire include lasers and optics, ultra-high vacuum techniques, quantum information science, electronics, microfabrication and many other skills. The city of Brighton & Hove has everything - sun, sea, brilliant clubs, great places to eat, fabulous shops, a truly cosmopolitan vibe and is located only 50min from central London. Located on the beach, Brighton boasts beautiful seaside views and beaches, boating, sports and beach activities.

Further Details

Ready to go: Yes

Skills:
Competence in ion trapping experiments, deep understanding of entanglement validation and verification

Alignment to PhD [0-5]: 5

References

S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)
B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S. J. Devitt, Ch. Wunderlich, and W. K. Hensinger, Science Advances 3, e1601540 (2017)
You can find more information including a virtual lab tour at: http://www.sussex.ac.uk/physics/iqt

Experimental;Simulation;
Location: Another academic institution

Quantum Information;Quantum Computation;Device Development (Hardware);Trapped Ions / Cold Atoms ;

27 Microwave delivery for a trapped-ion quantum computer prototype

Winfried Hensinger
John Rarity
Dr Seb Weidt, PDRAs and Phd students

Abstract

This projects contains practical steps towards engineering a practical trapped ion quantum computer focusing on relevant rf and microwave delivery.

Project Description

Impressive progress has been made in the implementation of quantum information processing with trapped ions. This includes the realization of high-fidelity quantum gates, quantum error correction, teleportation and many quantum algorithms. At Sussex , we are in the process of constructing a microwave ion-trap quantum computer demonstrator device. This device is based on the use of microwave radiation. This technology is ground-breaking as it permits to replace thousands or even millions of laser beams that would be required in a large scale quantum computer with a few microwave emitters that are located outside the vacuum system hosting the quantum computing microchip architecture. Recently, we have been able to demonstrate a two-qubit microwave gate with fidelity close to the fault-tolerant threshold using this technology. We have invented a new approach to quantum computing with trapped ions where quantum gates are carried out by the application of voltages, similar in nature to the operation of transistors in a classical computer. The device only requires a single set of global radiation fields, with the number of fields independent of the number of qubits required. Constructing a quantum computer demonstrator device encompasses numerous challenges such as the design of the actual device, the development of microchips that form the core of the device, development of reliable ion transport within ion trap arrays, sympathetic cooling and the implementation of fault-tolerant single and two-qubit gates.

This project is meant as the key preparation step for the construction of the demonstrator device which you may wish to work on as part of your PhD project. Specifically, you will design a scalable solution for the delivery of microwave and rf fields to the ion array. The microwave and rf field emitters should be in-vacuum, while allowing full control of the field polarization. Furthermore, the total power delivered to the ions should be maximized while maintaining a uniform power over the array. The design should be compatible with the modular approach of the demonstrator device, and thereby scalable to an arbitrarily large number of ions. You will also investigate microwave delivery schemes in NV centers and learn what aspects can be applied to the field of trapped ions and where there may be common challenges.

The Ion Quantum Technology Group at the University of Sussex, Brighton is one of the world's leading centres for the implementation of trapped ion quantum computing and simulation using microwave radiation. Microchips developed by the group provide state-of-the-art architectures for a large scale quantum computers, quantum simulators and quantum sensors. The group is part of the UK Quantum Technology Hub on Networked Quantum Technologies and the UK Quantum Technology Hub for Sensors and Metrology. The group currently spans 4 Postdoctoral Fellows, 2 electronics engineers, 15 PhD students, 6 undergraduate students, one senior scientist and the head of group. The group has numerous national and international collaborations. You will be part of a team working together to develop a large scale quantum computer. Some of the skills you will acquire include lasers and optics, ultra-high vacuum techniques, quantum information science, electronics, microfabrication and many other skills. The city of Brighton & Hove has everything - sun, sea, brilliant clubs, great places to eat, fabulous shops, a truly cosmopolitan vibe and is located only 50min from central London. Located on the beach, Brighton boasts beautiful seaside views and beaches, boating, sports and beach activities.

Further Details

Ready to go: Yes

Skills:
Competence in ion trapping experiments, electronics expertise, simulation of electric fields

Alignment to PhD [0-5]: 5

References

B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S. J. Devitt, Ch. Wunderlich, and W. K. Hensinger, Science Advances 3, e1601540 (2017)
You can find more information including a virtual lab tour at: http://www.sussex.ac.uk/physics/iqt

Theory;
Location: University of Bristol

Quantum Information;Quantum Computation;Quantum Metrology and Sensing;

28 Gaussian Quantum Information Techniques for Modelling the Generation of Large Entangled Photonic States in Realistic Settings

Dr Will McCutcheon
Dr Dara McCutcheon, John Rarity

Abstract
This project will address the generation of large entangled states of photons through the language of Gaussian quantum information allowing for complete consideration of the compound effects of realistic spectral imperfections in sources and fusion gates. The mapping between the Gaussian Hilbert spaces (with direct sum modal structure) and the non-Gaussian photonic Hilbert space with tensor product structure will be closely considered and implemented. Particular attention will be paid to photonic fusion gates with imperfect sources, shedding light on generalised HOM effects, and facilitating the design and characterisation of future large-scale photonic devices.

Project Description
Nonlinear quantum optical processes provide the key resources for quantum metrology, photonic quantum computing, and quantum communications. As such they have been the focus of intense theoretical and experimental investigation for many years, and the resulting models have been successful in understanding and predicting the behaviour of nonlinear optical systems and processes including parametric down conversion and four wave mixing in crystals, fibres, waveguides, and photonic crystals. In particular, nonlinear process at most quadratic/bilinear in the field operators admit a particularly concise representation since the dynamics can be fully represented by symplectic operations, allowing these Gaussian operations to be modelled in a remarkably straightforward formalism. The theory describing the evolution of Gaussian states under Gaussian operations is well developed and the field of Gaussian quantum information has been successful in determining the potential for states and channels to be used for discrimination and parameter estimation tasks and a great deal about quantum correlations in these states and processes.

A necessary ingredient for using the tools of Gaussian quantum information to model nonlinear quantum optical processes is to choose, from the infinite-dimension spectral-temporal modes of an optical field undergoing a nonlinear process, an appropriate finite-dimensional discrete basis upon which to use the finite-dimensional tools of Gaussian quantum information. Luckily, the question of the existence of such a modal basis has been answered in the affirmative, with Bloch-Messiah reduction (also known as Euler decomposition), providing a natural canonical form whilst establishing the irreducibility of single-mode squeezing operators, and providing insights into how two mode squeezers can be understood through their Schmidt decomposition. In this setting the book is widely believed to be closed, however a fairly strong assumption has been made regarding the degrees of freedom in the optical modes, i.e. each degree of freedom is treated equally. This assumption is suitable on a single spatial mode, where only the spectral-temporal degrees of freedom are at play, or for a single spectral-temporal mode distributed over many spatial modes. However, where spatial and spectral degrees of freedom are both present, such as in the increasingly complex devices being developed experimentally, all degrees of freedom are not equal. By introducing additional constraints into the Euler decomposition, this project will explore a new family of canonical forms available for modelling nonlinear processes.

Using this natural minimal modal basis to apply Gaussian quantum information techniques has demonstrated a number of results already, from maximal squeezing modes in lossy systems; irreducibility of multi-mode squeezing; and multimode correlations for post-selecting states for photonic quantum information.

The latter, concerning how multimode correlations can be used to post-select entangled photonic states is the subject of this project. The unitary bases from these decompositions define sets of orthogonal spectral and spatial modes upon which single photons will be postselected. However, contributions from outside of the ideal spectral / spatial mode reduce the fidelity of the postselected state. Choosing the appropriate n-photon representation of the unitary transformation between the conventional Euler decomposition (single-mode squeezing picture) and the generalised Euler (multimode squeezing picture), and projecting into a postselected subspace, we can transparently identify the structure of the state produced. In this setting we will address how spectral postselection could be used to improve schemes to postselect entangled photonic states; and how to use parameter estimation techniques to better characterise the full spectral behaviour of principle photonic elements, 'fusion' gates.

Context

Could choose to apply this to fit experimental data ongoing in 4photon GHZ state lab. It has application for CHIMERA, a cascaded nonlinearities chip. Wide applicability of techniques across nonlinear optics and quantum computing in the group.

Further Details

Ready to go: Yes

Skills:
Gaussian Quantum Information Formalisms, Nonlinear optics, LOQC primitives

Alignment to PhD [0-5]: 4

References

G. Adesso, S. Ragy, and A. R. Lee, Continuous variable quantum information: Gaussian states and beyond, Arxiv: 1401.4679 (2014)
S. L. Braunstein and P. van Loock, Quantum Information with Continuous Variables, Rev. Mod. Phys. 77, 513 (2005)
D. E. Browne, T. Rudolph, Resource Efficient Linear Optical Quantum Information, Phys. Rev. Lett. 95, 010501 (2005)

Experimental;
Location: University of Bristol

Quantum Information;Quantum Metrology and Sensing;

29 Quantum secured imaging

Sabine Wollmann
Jonathan Matthews

Abstract

This project combines two disparate fields -quantum nonlocality and quantum imaging - for the first time.

Project Description

The study of quantum mechanics and quantum information has given rise to several branches of quantum technology. Quantum enhanced measurement and sensing is closely linked to new approaches to increased precision in imaging and secure communications. In this project, we will apply quantum steering (an aspect of entanglement used in secure quantum communications) to quantum sensing and quantum imaging scenarios. The goal is to simultaneously enhance the quality of measurement and imaging, and use quantum steering communication protocols to securely transmit that information to a second party. This explores foundational aspects of the physics of measurement, whilst having longer term applications to scenarios where sensitive information is gathered from the environment and safely transmitted for use, such as in medical scenarios.

The project will be bringing together secure quantum communications and quantum sensing together for the first time and so opens up a fertile research area. Two tangible near term experiments are further possible. The first is to setup a steering experiment that performs measurement of a single parameter (an optical phase), and perform associated characterisation and benchmarking. The second experiment will be to convert this to a raster-scanned microscopy experiment.

Further Details

Ready to go: Yes

Skills:
experimentall skills such as setting up bulk optics; numerical simulations of the experimental parameters; programming of data aquisition

Alignment to PhD [0-5]: 5

References

Mehul Malika, Omar S. Magaña-Loaiza, and Robert W. Boyd, Appl. Phys. Lett. 101, 241103 (2012)

30 Adaptive tomography of time-varying quantum states

P S Turner

Abstract

This project will look at adaptive estimation in quantum state tomography problems with a (slowly) varying input. It will begin with a survey of recent advances in the field such as adaptive estimation of a varying quantum phase, in order to decide how the multi-parameter version of the problem might be formulated. If possible we will look at practical implementations in quantum photonics.

Project Description

Signal processing and control theory have been well developed in the engineering community in the context of analog and digital computing, data processing and communications. Classical signal processing is used to remove noise from data, compress information, adaptively cancel interference in communications channels, identify linear systems, and identify and model trends in time series such as stock markets. Control theory finds applications from thermostats to missile guidance systems. Given its wide scope, it is reasonable to suppose that there may be extensions of these subjects to quantum information theory. Well developed tools such as Kalman filtering are already finding applications in the field, and quantum equivalents of various digital signal processing techniques have been developed in the context of quantum information.

The object of this project is to review the area which might be called `quantum signal processing', with particular emphasis on design tools for quantum filters and potential applications. It will focus particularly on adaptive estimation of inputs that are slowly varying in time. It will begin with a review of recent work in the area, in particular reference 3 on estimation of a time-varying quantum phase in a continuous variable system. Once the background has been reviewed, we will look at generalizations of these results to multi parameter estimation, in particular quantum state tomography. Our goal will be the smallest non-trivial example of a discrete variable version of the problem -- qubit state tomography. If time permits we will consider larger dimensions.

For reasons both practical and in the interest of application, where possible we will study how such time-varying states might occur in integrated quantum photonics. This would include discussions with various experimental groups in QETLabs.

Context

Quantum metrology/estimation efforts in Bristol and the wider community could benefit greatly.

Further Details

Ready to go: Yes

Skills:

Estimation theory, both single and multi parameter. Advanced classical techniques such as Kalman *filtering. Quantum measurement theory as applied to tomography (informational completeness, etc.).*

Alignment to PhD [0-5]: 5

References

Audenaert, Koenraad MR, and Stefan Scheel. "Quantum tomographic reconstruction with error bars: a Kalman filter approach." New Journal of Physics 11.2 (2009): 023028.
Dong, Daoyi, and Ian R. Petersen. "Quantum control theory and applications: a survey." IET Control Theory & Applications 4.12 (2010): 2651-2671.
Kiarn T. Laverick, Howard M. Wiseman, Hossein T. Dinani and Dominic W. Berry. "Adaptive estimation of a time-varying phase with coherent states: smoothing can give an unbounded improvement over filtering." arXiv:1710.08548

Theory;Simulation;
Location: University of Bristol

Quantum machine learning;Quantum Information;Quantum Metrology and Sensing;

31 Designing quantum experiments using an evolutionary algorithm

P Knott
J Matthews

Abstract

For technologies to benefit from the inherent power of quantum mechanics, quantum states must be engineered with specific properties, for particular applications and operational parameters. This project explores the use of an evolutionary algorithm – a subset of artificial intelligence that mimics natural selection – that has been previously developed to design quantum states that can be used for applications such as quantum computing and quantum metrology. The algorithm has already found quantum states that can be used to make high-precision measurements of a relative phase in an interferometer. The algorithm also designs experiments to produce these quantum states, but up to now realistic experimental conditions and parameters have not been considered. The goal of this project is to overcome this and develop and run the algorithm to design practical schemes for building quantum states that can be realised in the laboratory.

Project Description

A typical method to engineer optical quantum states is the following: firstly, take two input states (in two separate modes), such as Fock states, coherent states, or squeeze states. Then mix the two modes in a beam-splitter, which can entangle them, and perform further operations, such as squeezing or displacements. Finally, a measurement on one of the modes heralds the final state in the remaining mode. As described in [1], this procedure can engineer a wide range of quantum states. However, it remains challenging to know which input states, operators, and measurements to combine in order to produce a desired output state, and we are far from knowing which procedures are optimal. The work in [1] provides a solution for this: an evolutionary algorithm is used to find experimental combinations that will produce a given output. However, while previous iterations of the algorithm were able to design quantum experiments that improve over the state-of-the-art, this was only in the ideal noise-free case.

The main challenge of this research is to use the evolutionary algorithm to find quantum states that can then be made in the laboratory, factoring in experimental imperfections and parameters. In this theory/computational project, the student will bridge the gap between theory and experiment to design novel quantum states that respond to both hypothetical and experimentally measured operational parameters.

Timeline:

Weeks 1-2: Learn about quantum state engineering and the evolutionary algorithm.

Weeks 3-4: design and program an addition to the evolutionary algorithm that measures the performance of different quantum states when used in realistic optical quantum metrology experiments.

Weeks 5-8: run the evolutionary algorithm on a desktop computer/laptop. Test the algorithm to see whether it is working correctly; evaluate the speed of the algorithm and perform simple improvements to boost the speed; and design and program a code that takes output from the algorithm (in terms of strings of numbers) and turns this into simple but clear blueprints for experiment designs.

Weeks 8-11:

Option 1 – modify the algorithm to run on a high-performance computing (HPC) platform, exploiting available enhancements, such as parallel programming, when possible. Run the algorithm on the HPC. Study the experiment designs that have been found by the algorithm, and simulate these to compare them with one another and to the state-of-the-art in the literature.

Option 2 – explore alternatives to an evolutionary algorithm, such as reinforcement learning [5], swarm optimisation, and convex optimisation. Compare these methods with the evolutionary algorithm, and evaluate how each method searches through the fitness landscape to produce desirable experimental designs.

Weeks 12: finalise the project and produce final report/presentation.

The lead supervisor on this project, Dr Paul Knott, is based at the University of Nottingham. However, for the duration of this project Dr Knott will be working full-time developing the algorithm. Therefore, ample support and supervision will be available for this project. Dr Knott will visit Bristol multiple times, and the student should visit Nottingham at least once (it is preferred that the student has their own funding for this, but if this is not possible alternative sources of funding can be arranged).

Context

This project directly follows the project A completed by Lana Mineh on "Quantum state engineering with an evolutionary algorithm". Lana designed and coded a number of modules for the evolutionary algorithm that simulate experimental imperfections, such as photon loss and inefficient detectors. This project B will run the evolutionary algorithm that Lana helped to develop to find optimal experiment designs that can be implemented in the lab.

This project forms an integral part of Dr Knott's fellowship project entitled "Employing computer algorithms to automate the engineering of quantum states", which itself is based on reference [1].

Further Details

Ready to go: Yes

Skills:
The project will largely involve coding on Matlab. To succeed in this project the student should have at least a basic familiarity with computer coding, and should be enthusiastic to develop a high level of competence by the end of the project. A range of skills will be learned, including:

- *the theory behind quantum state engineering with light,*
- *how to translate theory into computer code/simulation,*
- *optimisation methods such as evolutionary algorithms,*
- *high performance computing,*
- *the general method of using artificial intelligence to enhance quantum physics research (as part of the wider sub-field of quantum machine learning).*

Alignment to PhD [0-5]: 2

References

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Experimental;
Location: University of Bristol

Quantum Metrology and Sensing;

32 Sub-Shot noise measurements limited by sample damage threshold using a rugged platform

S K Joshi

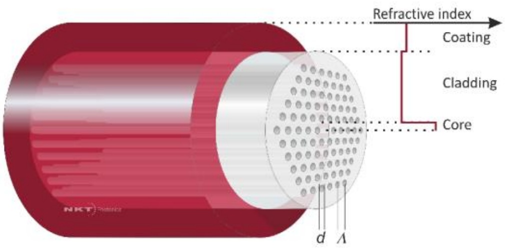
J Matthews, J Mueller (CDT cohort 2), J Rarity, A McMillian, P Mosely (Bath)

Abstract

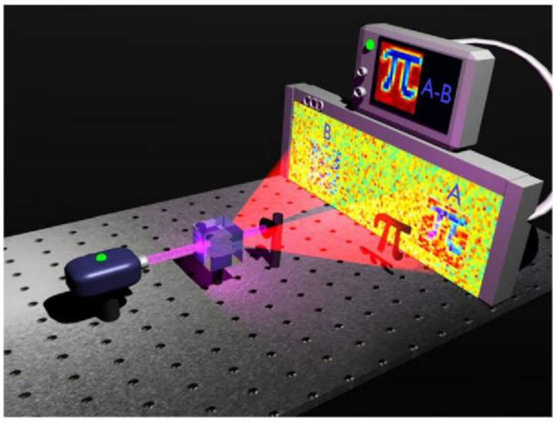
Quantum metrology -- the science of improving measurement precision by exploiting quantum properties – has distinct advantages over classical measurements. However, for optical systems, an advantage is usually gained in the “per photon” regime. Thus, optical quantum metrology is the preferred technique only for niche applications where the sample can be damaged by extremely small optical intensities. This is because a typical classical measurement can utilize milliwatts of power compared to the single photon signals typically used in quantum metrology.

Recent advances, in Bristol, have shown that we can obtain sub-Shot noise precision using microwatts of optical power. We achieve this by producing bright signal and idler modes with correlated intensities via stimulated four wave mixing in photonic crystal fiber. This project aims to increase the output power of such correlated intensity beams and to ruggedize the setup for in field use. Thus, creating a metrology tool that can out perform any classical measurement for a wide variety of samples.

Rugged Quantum Experiment in a drop tower



Photonic Crystal Fibre



Quantum Imaging

Experimental;
Location: University of Bristol

Project Description

The setup consists of an optically pumped Photonic Crystal Fiber (PCF). A four wave mixing process in the PCF produces two output modes – the signal in blue and the idler in red. Energy and momentum conservation implies that the number of photons in each output mode are exactly equal (assuming that there are no other competing processes like fluorescence, phosphorescence, etc.). By measuring the power in the idler with a high efficiency detector, we can use the correlated beam intensities to perform a sub-Shot noise measurement of the signal intensity. Currently, we pump the PCF close to its damage threshold to obtain <100μW of quantum correlated output power. A novel feature is our ability to generate one of these intensity correlated beams in blue – a very unusual wavelength for three or four wave mixing systems that is exceptionally useful in imaging because of its small diffraction limited spot size.

The first stage of the project will consist of investigating the damage mechanisms in the PCF fiber and testing strategies to increase the damage threshold. These will include: sealing the ends of the PCF, placing the fiber in an inert atmosphere, etc. To further increase the output power, we will use several strands of PCF in a self-built fiber bundle. We will couple the pump mode to the fiber using a custom designed micro lens array. The project will involve the design and construction/ordering of the fiber bundle and the micro lens array.

The second stage of the project is to build a rugged version of this optical setup. The final objective is to create a versatile and portable tool for sub-Shot noise absorption measurements that is useful for other disciplines such as biology, medicine, archaeology, etc. To achieve this, one must identify and use only the minimum necessary set of motional degrees of freedom needed for alignment. Each remaining alignment mechanism should then have a guiding and a locking mechanism. Such techniques have been used before in quantum optics drop tower and centrifuge experiments.

This project represents one of the leading attempts to create an optical quantum metrology tool that can beat any classical counterpart and is not limited to a small number of niche applications with highly photosensitive samples. Further, demonstrating the scalability and robustness of the system could result in a new standard industry tool for absorption measurements. We can use similar techniques to improve the resolution of interferometers, precision of range finders, sensitivity of gyroscopes, calibration of detectors, and many more. These experiments represent a radical improvement in measurement techniques and can form the basis of a PhD. Furthermore, improving and measuring the squeezing parameter of such a setup would also form a significant research project. Success of the project will result in incorporation of the setup as a demonstrator in the November National Quantum Technology program's "Quantum Showcase" in London.

The first month will be spent understanding the basics of four wave mixing and sub-Shot noise intensity measurements. During this time we will build the optical setup and detectors based on existing designs. We will also design the fiber bundle and micro lens arrays such that they can be fabricated and be available for use in month 3. The second month will be spent in improving the damage threshold.. We will also redesign the system to be rugged. The third month will consist of modifying the setup to incorporate the micro lens array and performing the final measurement. A few of the salient challenges faced during this project will be the Shot noise limited design of the detectors and electronics and the micro alignment of the fiber bundle and lens array in a repeatable but rugged manner. An ultimate test will include demonstration of the system outside of the laboratory.

Experimental;
Location: University of Bristol

Context

In Bristol, we have worked extensively of sub-Shot noise measurements, using heralded single photons and recently with bright correlated beams. This project will continue the current line of work and build upon the research experience of the last several years. This project follows the core theme of the Matthews group of combining quantum enhancement with application specific resource counting and photonics engineering. This project will adapt the setup and alignment strategies of existing experiments and create a commercially viable tool for intensity measurements. The project involves working with experienced researchers and earlier cohort CDT students who have built similar experiments, and improving upon them. In parallel to this project, we will continue work on our existing bright intensity correlated sub-Shot noise measurements and potentially two other closely related projects proposed as part of the CDT project B.

Further Details

Ready to go: Yes

Skills:
Understanding of spontaneous four wave mixing, sub-Shot noise measurements and PCF fibers.
Design and engineering experience of robust optical setups.
Hands on experience with lasers, electronics, sample preparation, etc.
Quantum sensing and resource accounting.

Alignment to PhD [0-5]: 5

References

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Experimental;Simulation;
Location: University of Bristol

Quantum Metrology and Sensing;Device Development (Hardware);

33 Ultra-low noise, broadband balanced detection for telecom band squeezing.

J. Matthews

J. Tasker – Lead Student, G. Ferranti, E. Allen, G. Atkinson, A. McMillan, S. Wollmann

Abstract

To measure quantum states, we require very low noise measurement apparatus. To measure squeezed states of light, whose key signature is noise in one optical variable below the classical shot noise limit, we require ultra-low noise detection electronics that have shot noise clearance well beyond the levels of squeezing expected. Similarly, to measure high frequency signals, we require detector bandwidths that reach typically 100s of MHz and beyond. This project aims to develop state of the art telecom band detection capability for on-chip squeezing quantum technology.

Project Description

Scope:

The measurement of optical shot noise is key to many continuous-variable quantum technologies including the detection of squeezing and state tomography. This is commonly achieved through balanced detection [3] and requires extremely precise instrumentation (shot noise photocurrents can have signal powers as low as picowatts!). In the detection of squeezing, for example, it is imperative to maximise the ratio of the optical shot noise to the electronic noise (shot noise clearance). Whilst our existing on-chip sensor has achieved a shot noise clearance of 11dB [4] in homodyne tomography experiments, our current free space detectors in the telecom band have a shot noise clearance of ~1dB. The lower optical power requirements for on-chip Kerr squeezing require a more sensitive detector. This requirement for ultra-sensitive, high-gain transimpedance amplification explores the limit of what is possible in low-noise electronics. Fortunately, novel JFET-buffer architectures have been developed which are able to significantly improve performance [1,2].

This project aims to explore these techniques in order to produce improved telecom squeezing detectors. Since these JFET-buffered approaches are also key in ultra-high bandwidth homodyne detectors [5], the project has scope to push the bandwidth limit of currently published homodyne detectors using the inherent speed advantage of integrated photodiodes.

A useful reference encompassing most aspects of detector design is [6].

METHODOLOGY:

The student will design and simulate a circuit of the proposed architecture, fitting the requirements (e.g. gain, bandwidth) for bulk optical telecom squeezing detection. This schematic will then be used to produce a PCB design which will be sent off for fabrication. The student will assemble the pcb and characterise the circuit using classical light, revising the design if necessary. Subject to the success of a fibre squeezing project conducted in parallel, the circuit will then be tested in a squeezing experiment which will involve collaboration with another student. Extension work—which may be conducted in parallel—will involve fabricating higher speed detectors for integrated photonic chips.

WORKPLAN TIMELINE:

Weeks 1-2 Some literature review reading. In parallel, practical electronics simulation iterated with reading to strengthen understanding and expand simulations. Small component PCB soldering training.

Weeks 3-7 PCB design. PCB design sent off for outsourced fabrication (e.g. to 'PCBtrain') --- expected lead time is less than one week. Assembling PCB.

Weeks 7-9 Characterisation and refinement of design. Iterating revised assembly.

Weeks 10-11 If design works, test with squeezing experiment in another project B (student succeeding in that project dependent). If squeezing not possible, the student will benchmark against other detectors in the group, using existing lasers.

Weeks 11-12 Finalising final report/presentation

Biggest risk identified to this project is difficulties associated with working with bulk photodiodes (e.g. detectors might break). Mitigation is to test design with a function generator. Colleagues involved in this project are sufficiently experienced that component lead time is a minimal risk.

If the candidate exceeds expectations with regards to the above plan, extensions include improving detector designs for on-chip balanced detection, prioritising high speed over low noise in extra designs.

Context

High quality balanced detection is needed for quantum sensing and continuous variables experiments that rely on squeezing. There are a number of experiments in the group now that work with similar detectors, many for efforts in developing fibre and photonic chip based squeezing experiments. E.g. F. Raffielli et al have been working with on-chip homodyne detector first proof of principles used for quantum random number generation --- extensions of this design will be incorporated into multi-detector experiments on chip in the near and long term. Higher performance will be pursued. While J. Meuller is using three photodiodes in a low noise detection system to observe two-mode squeezed states at different wavelengths (normalised to classical pump laser fluctuations). So there is a supportive community that exists and continues to grow in Bristol that needs low noise detectors for observing quantum states of light in the continuous variables regime.

Further Details

Ready to go: Yes

Skills:

The student will develop skills in: PCB design, electronics simulation (LT spice, MATLAB), some electronics assembly (soldering), noise analysis (e.g. spectrum analyser), complementary knowledge around squeezed light quantum optics is highly encouraged to be developed. There may also be scope for the student to learn wire-bonding for electrical control of photonic chips.

Alignment to PhD [0-5]: 5

References

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Experimental;Simulation;
Location: University of Bristol

Quantum Metrology and Sensing;Device Development (Hardware);

34 Demonstrating telecommunication squeezing in single mode optical fibre

J. Matthews

Euan Allen, George Atkinson, Alex McMillan, Alberto Politi (Southampton)

Abstract

Squeezed states are a broad family of non-classical states that have history of finding use in quantum technology. They get their name for suppressing uncertainty in measuring a variable, at the expense of increasing noise in the complimentary variable. For example suppressing noise in amplitude at the expense of increasing noise in phase due to Heisenberg's uncertainty relation. This has use in optical quantum metrology where suppressing noise in measuring one variable of light maps onto increased precision in measuring a physical parameter — for example, squeezed amplitude light offers enhanced precision in measuring the transmission of an optical channel or sample. This project seeks to implement squeezing at telecommunications using standard optical fibre as the nonlinear medium. This is achieved by interfering states that have been skewed in phase space by self phase modulation.

Project Description

A very nice overview of the squeezing community is presented in [Anderson16] and is recommended when considering this project. We will be looking at one favoured approach to implementing squeezing, that uses third order nonlinearity, instead of second order nonlinearity. Unlike the parametric downconversion approach, a cavity is not needed to achieve 5dB of squeezing and above — instead optical fibres can be used as the nonlinear material that are placed in inherently stable sagnac loop interferometers (e.g. see [Dong08] for 6.8dB measured squeezing). This strips infrastructure needed to generate squeezing and therefore greatly opens the way for practical demonstrations outside the quantum optics laboratory with low cost components (i.e. optical fibre vs bulk nonlinear chi-2 crystals that are AR-coated and placed inside locked optical cavities). In turn, such considerations enable more trials and applications outside of the vibrational stable optics labs, which is particularly pertinent for measurent and sensing scenarios. A second key consideration is that third order nonlinearity is prevalent in CMOS compatible photonic chip arcitectures, such as Silicon and Silicon Nitride. Together with results in on-SOI-chip homodyne detection (from the Bristol group!) [Raffielli18], developing this capability for realising, characterising and testing kerr-squeezing enables development of an all-on-chip continuous variables capability, with scale-up, electrical control and reduced demonstrator unit cost in the future offered by CMOS compatibility. Other subtle advantages are encouraged to be explored in this project.

I had drafted a nice description of the physics, but had to delete it to fit into the web submission form. More rigorous details can be found in the (non-exhaustive) references below on kerr-squeezing experiments. THIS PROJECT'S SPECIFIC GOALS are to implement amplitude squeezing at telecommunications using single mode fibre and soliton pulses.

METHODS to realise this will be to build on demonstrated experiments in the literature [Anderson16, Schmitt98] to provide squeezing capability at 1550nm in Bristol.

Experimental;Simulation;
Location: University of Bristol

MOTIVATION for this project it so use it as a benchmarking setup to ensure all components (laser, detectors, optics) are all performing correctly, when comparing to future attempts at squeezing on chip at the same wavelength and with the same components.

MAIN RISK TO PROJECT OUTCOMES is for the second stage of the project tied to the delivery of a shot noise limited fibre laser (due for delivery June 6). To mitigate this, we provide an alternative timeline of work in the same field to avoid experimental downtime.

TIMESCALES:

Weeks 1-2 — learn new material by combining literature review with computer simulation of the nonlinear process. Also get in the lab and try out your intuition as you learn. Safety briefing and operational briefing of the setup are supplied. Resources including detectors, Toptica fibre laser and balanced detectors are available.

Weeks 4-6 — Student will want to have seen soliton generation in the fibre and “Steps” in the nonlinear response (power in vs power out, see figure 2 a, b of [Schmitt98]). This is a necessary but not sufficient condition for kerr squeezing

Weeks 7-8 —New shot noise limited laser arrives and is confirmed ready for use. The student will be involved in fibre coupling this laser

Weeks 8-10 — Refinement of experimental measurements, iterating data analysis and de-bugging setup. This refinement may incorporate improved detectors developed elsewhere (another project B, if taken up).

Weeks 10-12 — Complete data analysis. More experiment if neneeded. But most of this time should be used to complete project B write-up/final presentation.

RISK MITIGATION:

Weeks 7-10 — if shot noise limited laser delayed, then perform a simulation analysis on squeezing with existing Silicon Nitride straight waveguides for 800nm. Experimental facilities for this are available.

Context

This project lays the foundation for exploring squeezing in straight waveguides on chip at 1550nm (led by Euan Allen) as well as more complex CV photonic circuits planned for the near and long term in the Matthews group. Importantly, this project aims to provide a test-bed system to confirm if all other components — i.e. laser source and detectors — allow or prohibit observation of squeezing. Successful outcomes from this project will be used for all future on-chip squeezing attempts at 1550nm attempted in Bristol. This project also aligns to a complimentary PhD sub-project (George Atkinson) that is at a different wavelength (800nm), to explore effects of dispersion on squeezing in PCF fibre. There is opportunity to collaborate with a second project B that is proposed for improving 1550nm detector electronics. Note there is a supportive community of researchers in Bristol that are working techniques similar to those that will be used in this project (e.g. optical noise analysis, resource counting in sensing, nonlinear optics used in pulsed kerr-squeezing) — these researchers will both support and challenge you in your learning and exploitation of the concepts and techniques explored.

Further Details

Ready to go: Yes

Experimental;Simulation;

Location: University of Bristol

Skills:

Key skills developed include: Nonlinear optics simulation, nonlinear optics characterisation, optical noise analysis (e.g. use of spectrum analyser, balanced detectors), practical experience with pulsed fibre lasers and fibre optics, optical alignment skills. Developing intuition over quantum sensing-relevant resource counting. Developing familiarity with practical parameters that impact on squeezing performance. The skills developed here are transferrable to attempting more general kerr-squeezing experiments in other platforms, including in waveguide.

Alignment to PhD [0-5]: 5

References

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Experimental;
Location: University of Bristol

Quantum Optics, photonic-crystal-fibre spontaneous four-wave-mixing sources;Quantum Information;Quantum Dots;

35 Tailoring four-wave-mixing correlated photons for high-fidelity interfacing with solid-state spins

A. Dada

Academic supervisors: R. Oulton , J. Rarity; Postdocs: A. McMillan, W. McCutcheon; MSc Project Student: Hongdi Zhao

Abstract

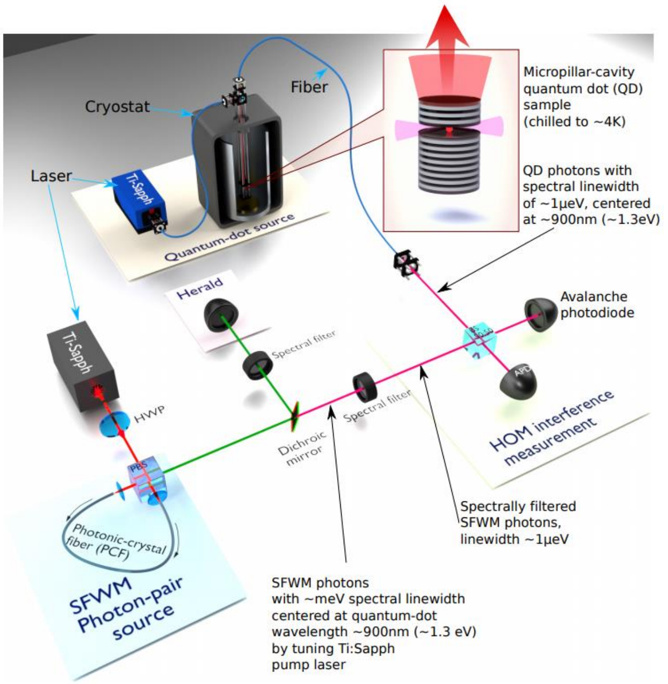
In the basic notion of a quantum network, quantum information is generated and processed locally in nodes, which are in turn linked by channels transporting quantum states from site to site. This invariably requires interfacing stationary and flying (photonic) qubits. Consider two of the leading source technologies for nonclassical light which play a pivotal role for the generation of such photonic qubits: semiconductor quantum dots (QD), and sources based on spontaneous nonlinear parametric processes, e.g., spontaneous four-wave mixing (SFWM). SFWM sources produce high-fidelity entangled photon pairs, while QDs excel at producing single photons with unprecedented brightness and near-ideal single-photon purity and indistinguishability. In addition, QD electron spins are promising stationary qubits for storing and processing quantum states due to their long coherence time (~µs) and relaxation time (~ms). In this project you will be building a key component in the experimental effort to combine the strengths of these two technologies by experimentally investigating and engineering conditions for optimal interference between these disparate light sources to lay the groundwork for scalable and robust hybrid quantum networks.

Project Description

A real-world quantum network would most likely be made up of nodes having different optical and electronic properties. To realize such a hybrid network that could utilize the best features of each system, a robust system of flying qubits that can form links between two disparate systems is needed. One way to achieve this is via interference of two photons from separate nodes. Alternatively, quantum information could be transferred from one node (source) to another via a flying photon qubit.

With an appropriate photonic-crystal fibre (PCF) design, a fibre-based spontaneous four-wave-mixing (SFWM) system can be used as a bright source of spectrally pure, heralded single photons, and entangled photon pairs [1-6] that are highly non-degenerate in wavelength, and tuneable by several hundred nanometres to create a quantum link between two systems operating at very different wavelengths. In addition, the spectral properties of the emitted photons can be tailored as required to realise an optimal quantum interface with solid-state qubits such as QD spins. This requires not only tuning the two systems into resonance with each other, but also matching of their spectral linewidths and shapes.

Semiconductor quantum dots (QDs) exhibit atom-like behaviour and have many advantageous properties, which include their well-characterized, optically and electrically accessible energy levels, low decoherence at moderately low temperatures, short radiative lifetimes, and high quantum efficiency. In addition, negatively charged excitons (trions) in an InAs QD have been shown to provide a key ingredient for deterministic spin-photon entangling interactions [7,8] and to generate spin-photon entangled states [9-11]. Also, teleportation and remote entanglement between two QDs have been demonstrated recently [12,13], making QDs particularly promising as a basis for a quantum spin network.



Visualization of a Hong-Ou-Mandel (HOM) interference experiment between single photons from a micropillar-cavity quantum dot and heralded single photons generated in a photonic crystal fiber via spontaneous four-wave mixing (SFWM). Your project will lead to achieving indistinguishability between single photons from these disparate sources, and this experiment could be one of its possible extensions.

Much of this advancement is in InAs QDs emitting at ~900-950 nm which is not a suitable wavelength for long distance transmission in fibre-optical networks. SFWM generated photon pairs offers a yet-to-be-exploited route to converting flying photonic qubits at ~900nm to telecom wavelengths (1300nm or 1550nm) for long distance transmission, or otherwise creating quantum links between the two wavelength regimes. However, there is generally a large mismatch between the linewidths of photons emitted by InAs QDs (~few ueV) and SFWM (up to ~meV), which necessitates tailoring the spectral properties to match each other for optimal interference.

In this three-month CDT project, you will focus on a bite-sized and relatively self-contained body of work on tailoring the SFWM emission wavelength and bandwidth based on pump engineering and post-selective-filtering of very bright SFWM sources, to match typical QD emission spectra, and you will have the opportunity to implement and evaluate the performance of the scheme. Building on this, you will potentially perform two-photon interference between QD photons and heralded FWM photons. This will then lay the basis for quantum information and networking demonstrations ranging from entanglement swapping and quantum teleportation, to hybrid light-matter multipartite entanglement of photons of different wavelengths with a solid-state spin.

Workplan

- Characterization of >5 PCF samples (from the same batch as those used in Ref. [5])
- Free-space optical alignment and coupling into PCF with 2µm core.

- Determination and brightness and bandwidth of the sources at quantum-dot wavelengths (>900nm), involves operation and tuning of a Specra-Physics Tsunami® Ti:Sapph laser, and spectroscopy with LN2 cooled spectrometer CCD.
- HOM interference of successive FWM-generated heralded single photons
- Filtering of the FWM photons to match QD spectral properties (linewidth and shape), and HOM interference measurement of successive FWM photons after filtering

Context

This project is related to

"Project 1D QED" EP/N003381/1: a 5 year fellowship to create useable single photon sources and quantum photonic switching technology. Principal Investigator: R. Oulton

Further Details

Ready to go: Yes

Skills:
General learning outcomes

You will acquire skills that will prove valuable and highly transferrable to various aspects of experimental quantum optics and quantum information, quantum engineering and quantum photonics.

This project is expected to have a strong emphasis on experiment design and implementation with some scope for simulation of the experimental results. You will learn about both linear guidance and relevant nonlinear effects occurring in optical fibres, as well as about photon-pair generation in photonic-crystal fibres. You will also learn about both four-wave-mixing and quantum-dot spectroscopy.

You will learn how to operate a Ti:Sapph laser for generation of ultrashort pump pulses for SFWM in the PCFs, and how to use coincidence photon detection to look for the signature of correlated pair generation events.

Technical learning outcomes

- *You will gain experience in techniques for building state-of-the art experimental setups*
- *Optical alignment in free space and fibre optic coupling*
- *Spectroscopy and related experimental techniques*
- *Sample characterisation and spectral data analysis*
- *Time-correlated single photon counting (TSCPC) techniques*
- *Coincidence photon detection*
- *Experiment control software*

Alignment to PhD [0-5]: 4

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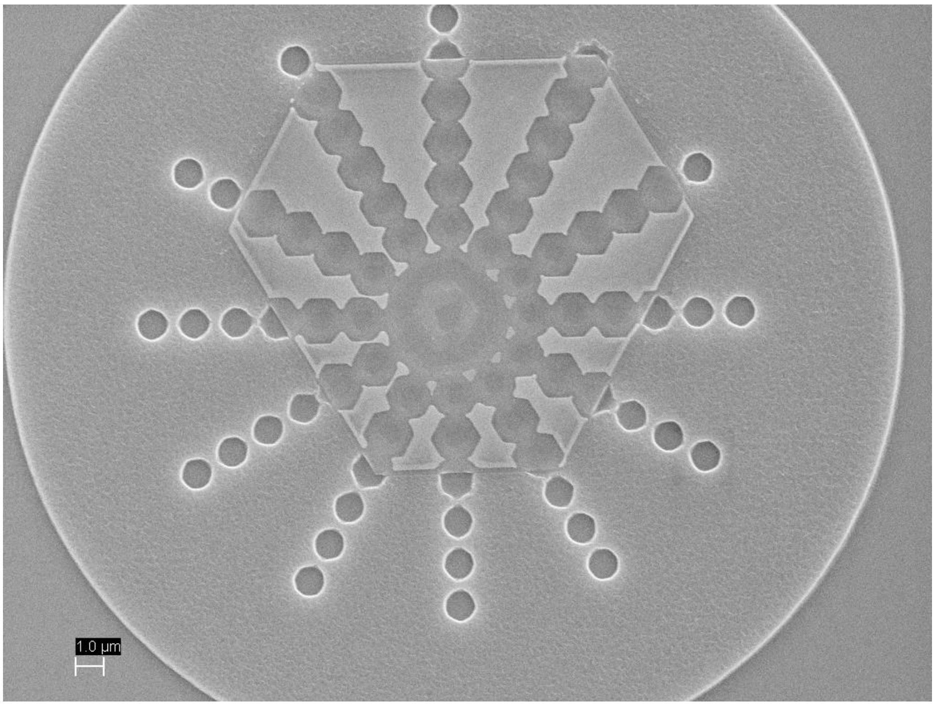
$\boxed{36}$ Demonstrating fluorescence lifetime narrowing of NV centres in nanodiamond deposited on two dimensional single crystalline gold nanostructures.

Dr Henkjan Gersen
Krishna Coimbatore Balram; Alex Greenwood (PhD student)

Abstract

Nitrogen vacancies (NV) defects in nanodiamond form an extremely stable photoemission center that acts as a single-photon emitter displaying quantum behaviour up to room temperature. To achieve strong coupling these emitters are often placed inside plasmonic cavities, using the high reflectivity and mode confinement offered by plasmonics. However as surface plasmon waves exist very close to the metal surface it is expected that their fluorescence lifetime will be influenced by surface roughness as well as the crystallinity of the metal films. In this short experimental project we aim to gain a deeper understanding of this dependence by performing a direct comparison of fluorescence lifetime of NV emitters deposited on two dimensional single crystal gold flakes versus emitters deposited on thermally evaporated gold films. This would establish whether lifetimes show a similar narrowing and shortening of lifetimes as observed for atomically smooth silver films as an important step towards obtaining a more deterministic coupling between emitter and plasmonic modes.



Example demonstrating anisotropic etching in single crystal gold flakes starting from circles as visible in the surrounding silicon.

Project Description

Motivation

Quantum plasmonics is an area of intense research at the intersection of the fields of plasmonics and quantum photonics, that uses the confinement of electrical fields to nanoscale dimensions intrinsic to surface plasmons to greatly enhance light-matter interactions. This exceptionally strong confinement would enable a quantum emitter to direct its emitted photons into a plasmonic mode with near unit probability. As a result hybrid systems consisting of quantum emitters coupled to plasmonic waveguides have received considerable attention as building blocks for future quantum plasmonic circuits. In particular as compared to structures fabricated in dielectrics the electrical field strengths in plasmonic structures can be several orders larger making it easier to induce non-linear behaviour. These non-linearities can not only shift the phase of propagating plasmons needed in interferometers, but also can induce plasmon-plasmon interactions, which takes place on picosecond timescales enabling new applications.

The ultimate vision in the field of quantum plasmonics is to build arbitrary complex plasmonic circuits in which the plasmons can strongly interact with emitters and thereby enable classical and quantum information processing with a very small footprint. To achieve this the development of advanced techniques for fabricating 2 dimensional metallic nanostructures with high quality and well-defined geometries is key. Unfortunately achieving this in practice is challenging as plasmonic structures fabricated with electron-beam lithography and thermal evaporated metals show strong plasmon propagation losses due to scattering induced by the polycrystalline nature of metals deposited in this manner. Surface plasmon waves are particularly sensitive to such surface inhomogeneities as they exist very close to the interface.

Solution: using crystalline structures

Although strong mode confinement and large propagation lengths have been achieved with chemically synthesized metallic nanowires that do not suffer from these drawbacks these structures are hardly suitable for a controlled circuit design. However two dimensional colloidal gold crystalline flakes can also be grown using chemical synthesis methods that are typically up to tens of micrometers in lateral dimensions, although examples of millimeter sized crystals have been reported. Top-down lithography on such colloidal gold crystals would combine the best of both worlds, i.e. well defined single crystal two-dimensional gold flakes as substrate in which a controlled geometry can be fabricated using simple and widespread electron-beam lithography and dry etching instrumentation.

We have very recently been able to demonstrate that it is possible to use the crystalline nature of these colloidal crystals to perform anisotropic etching as shown in Figure 1 that has the potential to fabricate atomically smooth plasmonic waveguide structures from in a single crystalline film, which is difficult to achieve in polycrystalline films. This observation can be exploited to fabricate more complex structures such as nanoplasmonic interferometer structures through a combination of e-beam writing and reactive ion etching, which is something that you would be directly involved in as part of this project.

Goal: demonstrating the influence of crystallinity on single emitters

As a first step towards performing a quantum entanglement experiment using with plasmonic waveguide structures fabricated in crystalline gold using this approach our aim here is to measure and compare the lifefime of individual quantum emitters in nanodiamond on these crystalline gold substrates. This would enable us to confirm whether the lifetime indeed exhibits a narrower distribution as observed in the case of atomically smooth silver substrates, which although atomically smooth were still polycrystalline.

Outlook towards PhD
This project is currently in a very exciting stage in which we are close to writin

Context
This is part of an ongoing PhD project that is working towards fabricating plasmonic waveguides in single crystals.

Further Details
Ready to go: Some setting up is required

Skills:
Single molecule spectroscopy, confocal imaging, lifetime measurements, exposure to clean-room fabrication, AFM imaging.

Alignment to PhD [0-5]: 5

References
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Theory;Simulation;
Location: University of Bristol

Trapped Ions / Cold Atoms ;

37 Design of a miniature trapped ion package for a portable barium ion atomic clock

Ruth Oulton

Graham Marshall, Matthew Day, Dara McCutcheon

Abstract

With each improvement in the precision of portable clocks, has come increased technological capabilities. The best portable clocks today are based on atomic microwave transitions, and form the basis of our global navigation systems and precision timing distribution. Clocks based on atomic optical transitions now outperform microwave atomic clocks by several orders of magnitude in the laboratory. The miniaturisation of these laboratory systems would allow for portable atomic clocks with increased accuracy and long-term stability, providing a technology to revolutionise areas of society such as navigation, gravitational mapping and secure communications.

Barium ions have one of the highest known Q-factor optical transitions of any alkali ions. The wavelength of the transition is also near the telecommunications band, allowing for leverage of existing laser and integrated optics technologies. Recent advances in portable frequency combs span this wavelength band, which is unique to barium. The proposed project will fully explore the feasibility of using barium ions as an optical frequency standard, identifying any potential drawbacks over other more widely used ion species. If it is found that barium is a suitable candidate, initial design will be performed of a manafacturable ion trap with low heating rates and frequency shifts on the ion. The project forms a small part of a wider endeavour to develop a portable optical atomic clock and could be extended into a full blown PhD project with aim at eventual commercialisation.

Project Description

The development of the first atomic clock, based on a microwave transition in caesium, helped to redefine the second. The development of microwave clocks into portable form factors has revolutionised broad areas of society, allowing global navigation systems and distributed precise timing from orbit. Atomic clocks based on optical atomic transitions are now outperforming microwave atomic clocks in labs by several orders of magnitude. A portable optical atomic clock has yet to be realised due to the added complexity of higher sensitivity of the optical transitions to environmental noise, as well as the added bulk of apparatus used to measure THz frequencies.

Barium ions have one of the highest known Q-factor electronic transitions of any alkali ions. The wavelength of the transition is also near the telecommunications band, allowing for leverage of existing laser and integrated optics technologies. Recent advances in portable frequency combs span this wavelength band, which is unique to barium.

Having selected barium as a candidate ion, a detailed study on its comparison to other elements and barium isotopes needs to be performed. It may be that there are unforeseen frequency shifts unique to barium that rules it out as a good frequency standard candidate. The goal would be to find a relatively insensitive transition between two hyperfine states in a barium isotope with non-zero nuclear spin.

Once an ion species and isotope has been selected, the goal would be to move onto ion trap design. Miniature ion trap packages have been demonstrated for microwave atomic clocks, and the project would translate this to the chosen trapped ion species. The design process would involve choosing the trap fabrication technology, miniature atom ovens and the vacuum cell. Micro-optical design would also have to be considered during this design phase.

It is not expected that the project finalise on the design of the trapped ion package, but serve as a feasibility study for a larger project which could then be taken on to PhD level and beyond. The development of a portable optical atomic clock is of great commercial interest and importance, with the ultimate goal to develop a robust product offering 2 orders of magnitude improvement in timing accuracy and stability over existing products.

Work breakdown structure

- Ion species and isotope selection (1 month)
- Famialirisation/refresh on atomic energy structures (1 week)
- Study of systematic frequency shifts of optical atomic transitions in ions (2 weeks)
- Literature review and calculation of frequency shifts in barium ion isotopes on the electric quadrapole transition. (.5 week)
- Comparison of frequency shifts to other measured and well-known ion species from literature. (.5 week)
- Ion trap design (1 month)
- Comparison of different ion trap architectures and dimensions, optimising for minimisation of frequency shifts on the ion, keeping manufacturability in mind. (1 week)
- Trap design for selected ion. (1 week)
- Simulation of designed trap, calculating motional frequencies, trap efficiencies and trap depth of the ion trap. (2 weeks)
- Schematic for the vacuum package, with outlines for how the optics for ion addressing and detection could be miniaturised and stabilised. (Stretch goal)

Context

A micro-optical assembly for ion microtrap arrays – Matthew Day, Mark Thompson. Ruth Oulton, Alastair Sinclair, Graham Marshall (PhD Project)

Further Details

Ready to go: Yes

Skills:

- *Atomic physics*
- *Ion trap design*
- *System engineering*

Alignment to PhD [0-5]: 5

Theory;Simulation;

Location: University of Bristol

References

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A The Ultimate Quantum Dot Indistinguishable Single Photon filter

Andrew Young
Ruth Oulton

Abstract
Indistinguishable photons are a key resource for quantum photonic technologies. Most practical sources require some form of spectral filtering to assure the single photon output is indistinguishable. In this project the aim is to build a highly efficient tuneable narrow band spectral filter using Fabry-Perot cavities. This can then be paired with a highly efficient quantum dot based single photon source, with the target of beating current records for brightness, and indistinguishability.

Project Description
Most single photon sources based on two level systems produce photons over a very narrow spectral bandwidth (<1GHz). There is no off the shelf filter that can cope with such narrow linewidths. The only solutions are either lossy, or expensive, or a combination of both. The idea in this project is to produce a reconfigurable narrow band, low loss spectral filter that can be used for a range of applications. The design is based on one from Ahlrichs, et al [1], consiting of two thermally controlled monolithic Fabry-Perot filters. By combining two fabry perot filters one can ensure high transmission over a narrow bandwith, whilst also extending the effective free spectal range of the system. The end result is a well isolated narrow spectral region of transmission. The project will involve the design, and building of the system, through to deployment in ongoing experiments.

Expected outcomes.
Technical outcome: construction of an optical Fabry-Perot filter with a bandwidth of <1GHz and transmission of >90%.

Learning outcome: By the end of the project the Student will have gained knowledge about optical cavities, interference, and general (optics) lab skills. Also the student will have designed and built their own bit of laboratory equipment (expected outcome), and be in the position to deploy this in more sophisticated quantum optics experiments (stretch goal).

A working filter will certainly be used in future experiments and so the likelihood is that you will be able to contribute to journal publications.

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B Single nuclear spin memories in Quantum Dot

Edmund Hardbord
Ruth Oulton

Abstract

Semiconductor Quantum Dots (QDs) are one of the proposed platforms for the next generation of Quantum Technologies. The field of semiconductor QDs the past few years has seen a remarkable progress achieving record indistinguishability and efficiency from the photons created in these systems embedded in photonic structures. In these systems single electrons may be trapped in the QDs and act as a quantum memory. The behaviour of the spin memory in these systems has not seen a similar progress. The presence of a quantum memory is a necessary condition for the use of these systems for quantum repeaters or general long-range quantum communication. The decoherence time (T2) for storing information in a single electron spin has remained of the order of a few μs. A remedy for this could be the use of one of the thousands long-lived "memories" making up the QD, where extremely long correlation times have been observed (100s of ms to seconds). For this the detection and manipulation of single isolated nuclear spins in the QD has to be achieved. Here, we have conceived a novel technique in order to attempt addressing single nuclear spins at extremely fast timescales via the use of nuclear magnetic resonance (NMR) techniques in conjunction with superconducting coils.

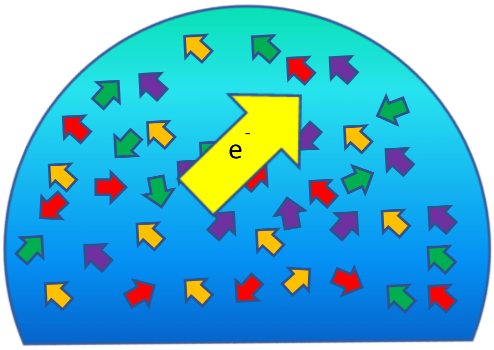

Fig.1 A cartoon of a QD, with the electron spin and nuclear spins depicted

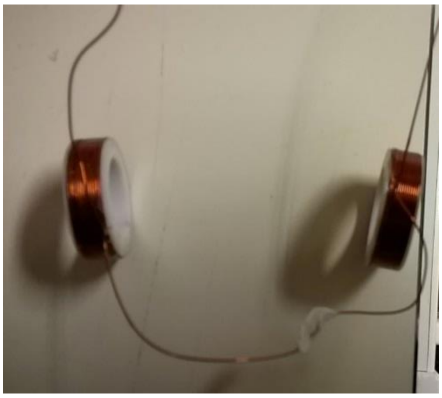

Fig.2 The supeconducting coils.

Project Description

The main aim of the project is the detection of single/few nuclear spins using interferometric and spectroscopic techniques. The manipulation of nuclear spins leaves a unique signature at the wavelength of the optical active transition this may be measured with the use of resonant spectroscopic techniques or interferometric analysis. These are well-developed and readily available techniques in the QD lab.

The use of homebuilt superconducting coils available in order to manipulate a single nuclear spin will be developed further. The coils have been tested in RF frequencies, but not in combination with optical detection. The combination of optical and NMR techniques is known as optically detected NMR (OD-NMR) and that would be the end goal of the project.

This will create a solid basis for exploring nuclear spins as a quantum memory and would be a unique and significant advancement.

Expected outcomes:

- The development of a full OD-NMR setup.
- The student will be familiarised with a variety of spectroscopic, interferometric and NMR techniques.
- The student will gain a deep understanding of the underlying solid state physics and the complex interplay of the different physics present from single nuclear spin (microscopic level) to the whole QD (mesoscopic level).

Further Details

Skills:
Knowledge of spectroscopic and NMR techniques, along with the use of RF electronics and lab interfacing software (e.g. LabView) would be an advantage. However, these are not hard requirements and there is an experienced team of postdocs and PhD students on these subjects, who will be present to help with the project.

References

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c Alternative Platforms for Quantum Photonics

Jorge Barreto
A.A. Gentile, G.E. Villarreal, D. Sahin

Abstract

Integrated photonics offer a promising approach towards quantum information processing using photons. Silicon photonics offers industrial-grade performance on wafer-scale devices but suffers from the lack of efficient active components and relatively high non-linear losses. Furthermore, the need for efficient single-photon detectors imposes the need for compatibility with cryogenic temperatures. This project aims at the characterisation of integrated photonic devices in non-silicon platforms for quantum information applications at low temperatures.

Project Description

Background

Silicon is a material with excellent properties for integrated photonics in the telecommunications bands. Most of the best quantum photonics experiments have been demonstrated using the silicon platform. Nevertheless it presents several scalability concerns, mainly: two-photon absorption, limiting the single-photon sources based on spontaneous four wave mixing and the lack of high-speed switches, with low loss and high extinction ratios. Other materials are compatible with silicon-fabrication standards offering the possiblity for hybrid integration and even stand-alone fully oeprational photonic platforms. Amongst the different possibilities silicon nitride appears to have an advantage due to the larger band-gap, making the material transparent for shorter wavelengths and dramatically reducing the two photon absorption while still presenting competitive (with respect to silicon) parametres.

Plan

For this project, the student will use the low-temp characterisation facilities in the group to test pre-existing silicon nitride photonic circuits. Once the classical characterisation is over, the cavities in the devices will be used as SFWM photon pair sources and their performance will be evaluated (g2 measurements).
Using a similar procedure, the performance of silicon photonic chips will be characterised before the devices are used in the SNOW project to test novel zero-power zero-loss swicthing mechanisms.

Expected outcomes.

The work on silicon nitride on itself will be used as a starting point for a future project on nitride-based quantum photonics and to support existing device development at Bristol. The work on the SNOW devices is expected lead to a publication and patent once the first demonstration is achieved.

Context

The project is a follow-up on a previous PhD project on low-temperature characterisation of photonic devices. It aligns with the core requirements for the development of scalable quantum information processors. The work in silicon nitride is in collaboration with Alberto Politi from the University of Southampton as a result of the european project QUCHIP. The low temperature work is part of the existing Programme Grant in Quantum Photonics and Psi Quantum Corp’s vision (a new collaboration project just started). The SNOW project is a stand-alone proposal (to be funded).

Further Details

Ready to go: Some setting up is required (software)

Skills:
Integrated photonics (fundamentals, design, characterisation), cryogenics, non-linear optics, single photon sources (fundamentals, design)

Alignment to PhD [0-5]: 3

References

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