Quantum Engineering Centre for Doctoral Training

Individual Project A list

Cohort 2017-2018

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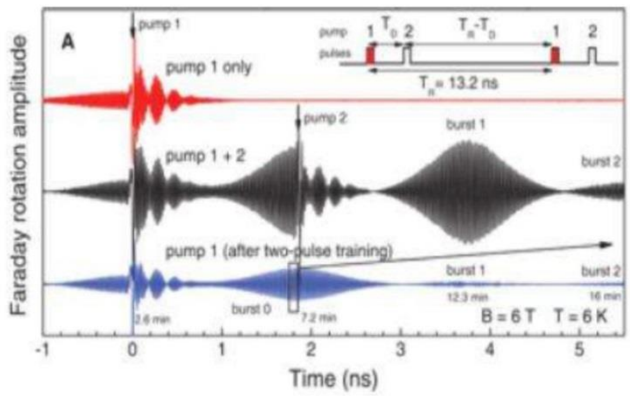
Experimental
Quantum dots, Electronics

1 Optimal spin quantum control using an electro-optical pulse sequence

Andrew Young, Ruth Oulton

Abstract:

Quantum dots will act as the next generation single photon sources, switches and quantum gates in scalable quantum integrated photonic circuits. However, challenges remain, including ultrafast optical control of the spin environment of the quantum dot. By generating arbitrary pulse sequences using an electro-optic modulator (EOM) one may implement optical domain NMR type sequences which will overcome nuclear spin environmental spin dephasing to allow the electron spin in the quantum dot to be used as a deterministic quantum switch. This project will focus on producing controlled pulses using the EOM by constructing a radio-frequency amplifier.



Project Description

The student will design and construct a high voltage, low power (variable gain) and broadband radio frequency (DC-100 MHz at least) amplifier for controlling a Newport 4002 broadband optical phase modulator (PM). This PM will modulate the phase of an input laser beam at a tunable frequency of 10-100MHz, which is then directed onto a quantum dot (QD). The modulation of the phase in turn modulates the precession of a single electron spin within the QD. This is predicted to act to preparing the QD's local environment to reduce noise.
The student will construct and test the amplifier based on circuit designs in ref [1], with the close aid of PhD student and postdocs. Basic testing will be done by using the amplifier to drive the PM, and the laser input monitored by passing the resultant phase modulated light through a Mach-Zehner.
The student will also construct a simple optical experiment to characterise the phase behaviour with the PM and confirm whether the amplifier behaves as intended for various input signals. This optical experiment can be worked on in parallel to the circuit design, using commercially available driving electronics to characterise the PM with slow modulations (< 1 MHz) until the custom amplifier is ready.
Extensions of the project could include the development of FPGA code to interface with the amplifier and provide input signals in the form of pulsed waveforms.

Expected outcomes

Technical outcomes

- Design and construction of a broadband radio frequency amplifier using designs available in the literature.
- Construction of an optical Mach-Zehnder interferometer to test modulation of laser using PM.
- Use of correlation measurements to verify MZ interference fringes at driving frequency

General learning outcomes

- experience in designing and developing bespoke instrumentation for lab work
- verifying and prototyping their design
- an understanding of the context of how instrumentation ties into experimental work
- Radio frequency electronics (used in many solid state emitter systems for quantum control)
- Ability to co-engineer multiple devices and instruments to function together across different engineering fields.

References

[1] Holder Muller arXiv:physics/0506050

Required Skills

Ideally the candidate will have some prior experience with electronics, however this is not a hard requirement, and the project would act as an ideal starter project for anyone who would like to learn some electronics skills. This project, while challenging, should be achievable and rewarding for the motivated student of any background.

Project Location

University of Bristol

Experimental
Quantum dots, Photonics Device Engineering

2 The Ultimate Quantum Dot Indistinguishable Single Photon Filter

Andrew Young, Ruth Oulton, Petros Androvitsaneas

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.

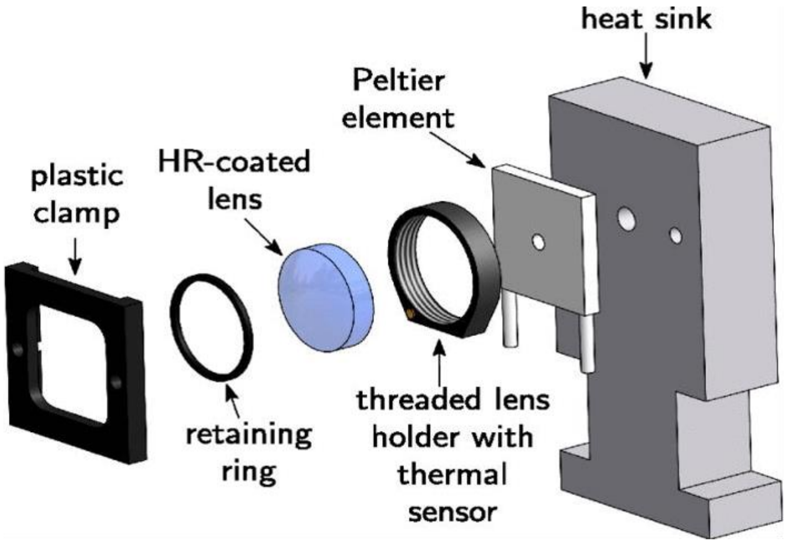


Figure 1. Schematic of a possible filter design taken from [1]

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], consisting of two thermally controlled monolithic Fabry-Perot filters. By combining two Fabry Perot filters one can ensure high transmission over a narrow bandwidth, whilst also extending the effective free spectral 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.

References

Andreas Ahlrichs, et al, Appl. Phys. Lett. 103, 241110 (2013)

Required Skills

None, expect a desire to learn about optics

Project Location

University of Bristol

Experimental
Photonics Device Engineering, Device Fabrication, SNSPD Characterisation

3 Fabrication and characterisation of Superconducting Nanowire Single Photon Detectors targeted for 2um wavelength light.

Ben Slater, Dondu Sahin, Mack Johnson

Abstract:

Quantum optics has been heavily researched using an integrated Si platform. This platform provides benefits through its optic properties such as its refractive index, established industry and non-linear optic properties, but the latter is a double-edged sword. 1550nm is the wavelength of light used in telecoms and vastly in Si photonics. An effect known as Two Photon Absorption (TPA) occurs where two photons are absorbed into the material increasing the refractive index. This effect increases with photon number, creating a hindering threshold for experiments. This holds back, Quantum computing, boson sampling and entanglement within photonics. 2um light does not have this effect due to the two photons’ low energy, not closing the band gap. Therefore, utilising this rarely used frequency range can be powerful.
Unfortunately, the most efficient detectors for Si photonics (Superconducting Nanowire Single Photons Detectors: SNSPDs) are not very efficient at this wavelength. The new fabrication capabilities recently achieved by the University of Bristol has allowed us to put the groups Quantum optics in Si expertise’s to be realised. The cleanroom has many processes such as Optical Lithography, Reactive Ion Etching, Sputtering and E-beaming that the student can use to make the designs. They will work closely with the supervisor in fabricating the first waveguide integrated 2um SNSPD. While under fabrication, tools to analyse the process such as AFM, SEM, profilometer and the probe station will need to be used and further understood to ensure the end component gives the highest efficiency. Lastly once the detector on chip is fabricated, characterisation of the chips components will be tested that can lead to publication of a novel and important area. Potentially in using the probe station, dip stick and the ICE Oxford to achieve this. The chance to earn a magnitude worth of skills while developing a field changing SNSPD.

Expected outcomes

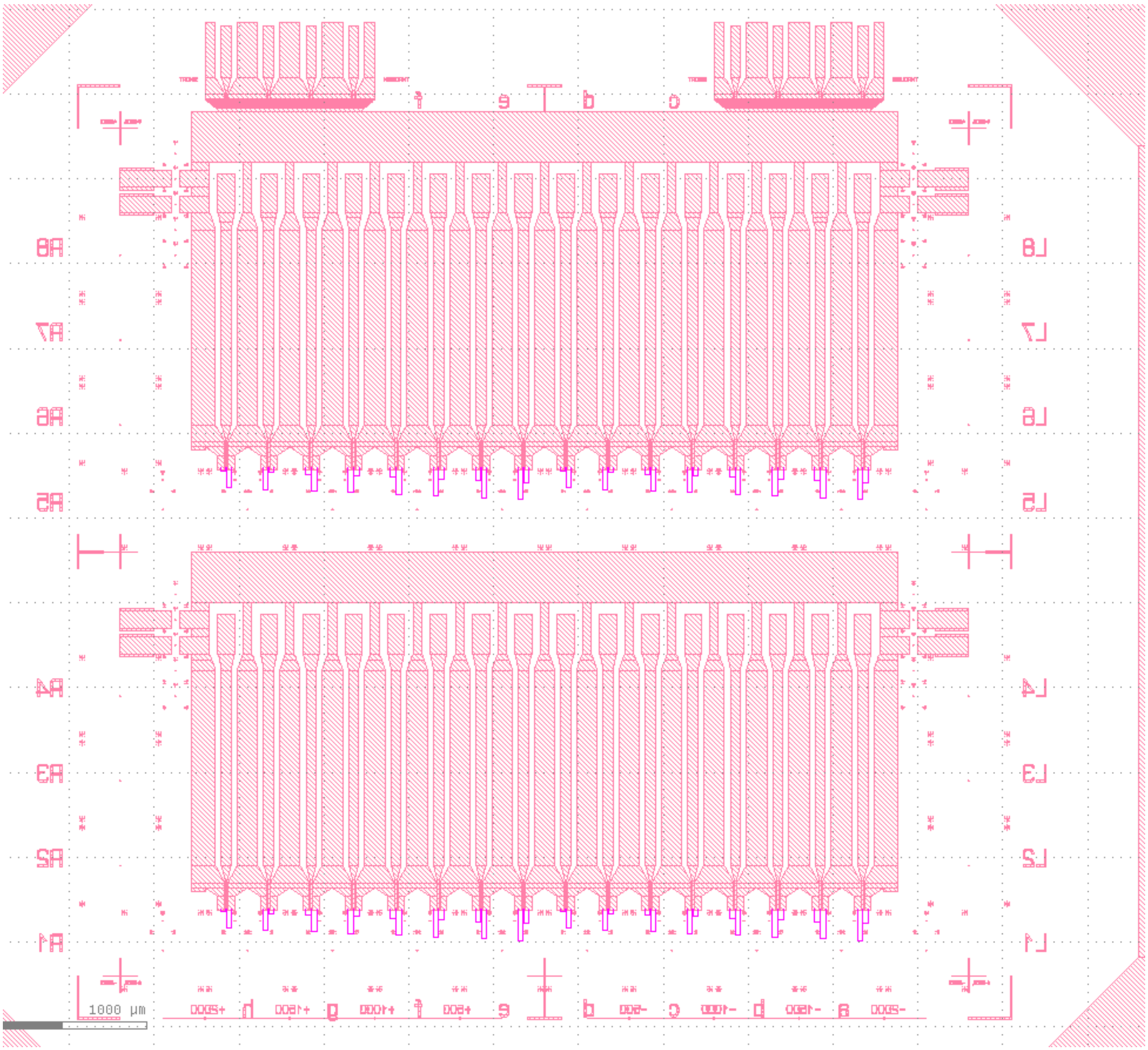
The student would be expected to have fabricated a SNSPD detector and proven that it can detect counts. The detector can be a photon spot detector, integrated waveguide detector, cavity enhanced detector. The fabrication process would be refined and go through a cycle of fabrication and testing to maximise the efficiency of the detectors. If a detector that is characterised that is designed for 2um efficiency would be part of a publication. If the detector itself was of novel design (which is available) and characterised this could find a publication in of itself. The student would have gained a huge amount of skills in SNSPD, cleanroom work, Cryogenics and quantum optics testing.

References

F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin, and S. W. Nam, "Detecting single infrared photons with 93% system efficiency," Nat. Photonics 7, 210– 214 (2013)

F. Marsili, F. Bellei, F. Najafi, A. E. Dane, E. A. Dauler, R. J. Molnar, and K. K. Berggren, "Efficient Single Photon Detection from 500 nm to 5 μm Wavelength," Nano Lett. 12, 4799–4804 (2012).

Chandra M Natarajan, Michael G Tanner and Robert H Hadfield, “Superconducting nanowire single-photon detectors: physics and applications”, SUPERCONDUCTOR SCIENCE AND TECHNOLOGY (2012)



Required Skills

Quantum optics, Condensed matter physics, SNSPD, Si chip characterisation, cleanroom work, microscopes.

SEM, AFM, Profilometer, Optical Lithography, evaporator, sputterer, RIE etcher, Fume hood and chemicals, HF training, probe station, automated testing bed, dip stick cryo stat and ICE Oxford. (have training in some of this methods/equipment. Not the E-beam as this requires extensive training)

Project Location

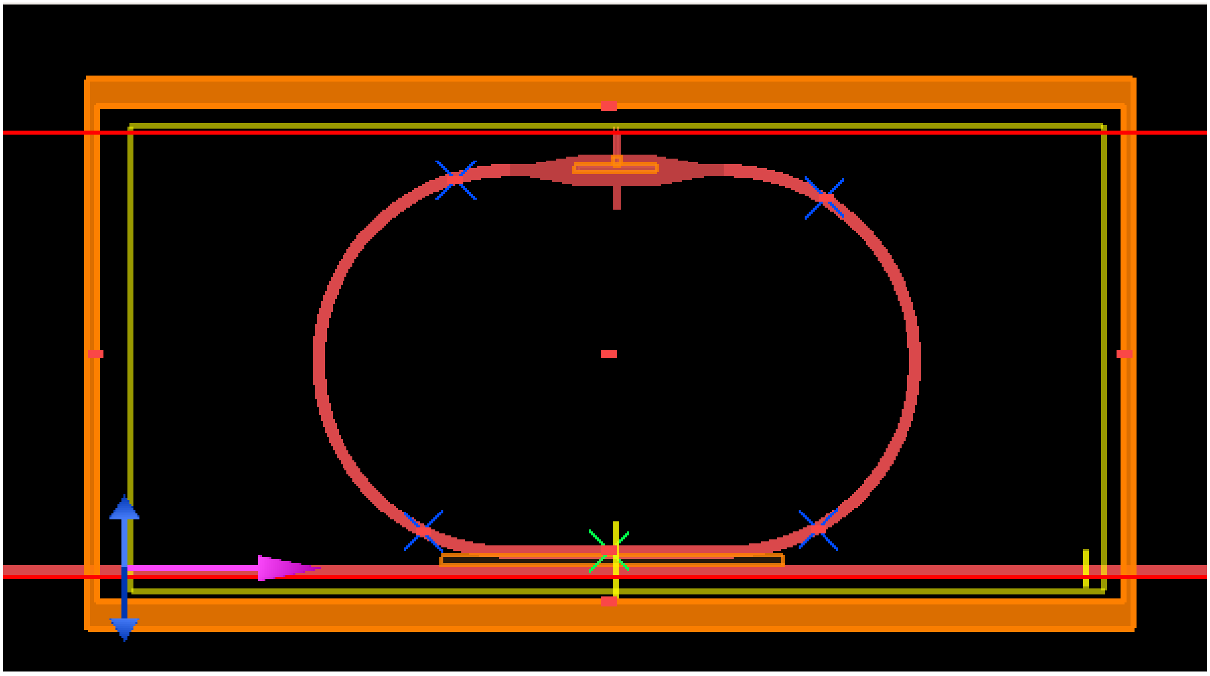
University of Bristol

4 Designs and Simulations of Superconducting Nanowire Single Photon Detectors targeted for 2um light, using a cavity.

Ben Slater, Dondu Sahin, Jorge Barreto

Abstract:

Quantum optics has been heavily researched using an integrated Si platform. This platform provides benefits through its optic properties such as its refractive index, established industry and non-linear optic properties, but the latter is a double-edged sword. 1550nm is the wavelength of light used in telecoms and vastly in Si photonics. An effect known as Two Photon Absorption (TPA) occurs where two photons are absorbed into the material increasing the refractive index. This effect increases with photon number, creating a hindering threshold for experiments. This holds back, Quantum computing, boson sampling and entanglement within photonics. 2um light does not have this effect due to the two photons' low energy, not closing the band gap. Therefore, utilising this rarely used frequency range can be powerful.
Unfortunately, the most efficient detectors for Si photonics (Superconducting Nanowire Single Photons Detectors: SNSPDs) are not very efficient at this wavelength. Many metrics that define the qualities of SNSPDs have yet to be explored. Using knowledge of existing detectors that are currently available and under research (especially SNSPDs), you will design new ideas of detectors. Cavities are a utilised idea to boost efficiency of detectors trapping unabsorbed light. You will be using programming in IPKISS (design software) to construct your ideas and then simulating their capabilities using Lumerical (Photonics Simulation software). These designs will be targeting above 90% detection efficiency and will be later fabricated in house Qupic facilities inside University of Bristol. These results would show how the designs of these new detectors can out-perform and overcome the current problems with SNSPDs at 2um wavelength.



Expected outcomes

The student would be expected to design a handful detector ideas that have a logical and estimated opportunity to be fabricated using our capabilities. Most of the designs are to be put through simulations and the parameters/ properties of these components are to be tweaked to find the highest efficiency possible. These designs will be then taken forward after in our fabrication facility and tested. Any designs that are successful and fabricated individually and work would be viable for publications. Also, the simulations and designs of all the detector ideas could be submitted as a potential publication.

References

N.tyler, J. Barreto, G. Villarreal-Garcia, et al, “Modelling superconducting nanowire single photon detectors in a waveguide cavity” Opt. Express 24, 87-97 (2016)

K. M. Rosfjord, J. K. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. M. Voronov, G. N. Gol’tsman, and K. K. Berggren, “Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating,” Opt. Express 14(2), 527–534 (2006)

A. Vetter, S. Ferrari, P. Rath, R. Alaee, O. Kahl, V. Kovalyuk, S. Diewald, G. N. Goltsman, A. Korneev, C. Rockstuhl, and W. H. P. Pernice, “Cavity-enhanced and ultrafast superconducting single-photon detectors,” Nano Lett. 16(11), 7085–7092 (2016)

J. P. Sprengers, , A. Gaggero, , D. Sahin, , S. Jahanmirinejad, G. Frucci, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Höfling, R. Sanjines, and A. Fiore “Waveguide superconducting single-photon detectors for integrated quantum photonic circuits” Appl. Phys. Lett. 99, 181110 (2011)

Required Skills

The skills that will be used during the project will be python to design new structures in integrated Si photonics. This is IPKISS where many people in the group use it day to day to design their chips. There is a huge database called SVN to get ideas from how to use the software and how to integrate the designs to test. After the design, simulations using the Lumerical softwares called MODE Solutions and FDTD will take place. The imported design can be manipulated to maximise transmission and absorption to give a detector that is a viable solution. There is also an IQT server to run the simulations on, giving faster results.

Project Location

University of Bristol

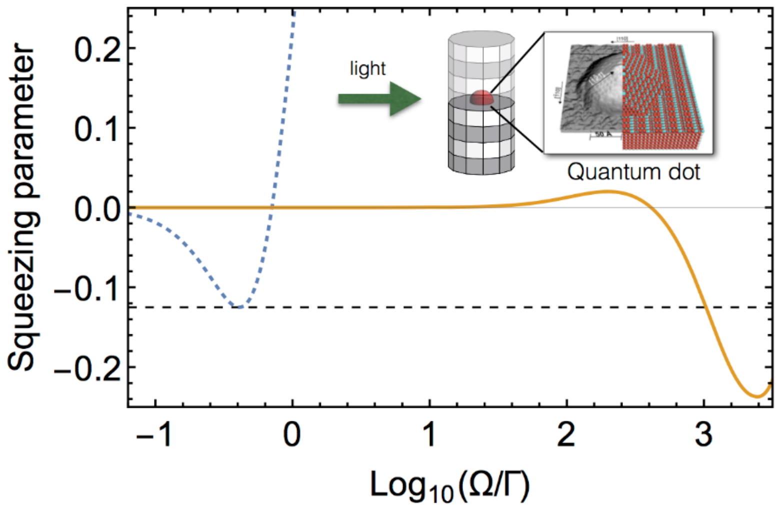
Theory
Quantum dots

5 Utilising phonon interactions in quantum dots for a source of squeezed photons

Dara McCutcheon, Ruth Oulton

Abstract:

Semiconductor quantum dots have recently emerged as an exciting and novel source of non-classical states of light. In particular, their discrete energy level structure has been shown to allow for the emission of single indistinguishable photons, as well as entangled photon pairs. This project will explore the possibility that interactions with lattice vibrations in quantum dots can also lead to the emission of quadrature squeezed photons, adding considerably to the utility of these solid-state systems. The research proposed will lead to strong and versatile expertise in applied theoretical quantum optics techniques, and also a good understanding of experimental considerations and concepts. Preliminary investigations have yielded positive results, and we expect a successful project to lead to a publication.



Project Description

This project aims to harness lattice vibrations in optically active semiconductor nanostructures to produce squeezed states light. The project will be largely theoretical in nature, though will feed into current experimental efforts taking place within the quantum dot group in Bristol. Quantum dots are semiconductor hetrostructures sharing many of the optical properties more commonly found in atoms, and this has led to great interest in using them to produce novel non-classical states of light. Being solid-state systems, however, quantum dots interact strongly with phonons in the host lattice, giving rise to optical properties which cannot be accurately described by a simple few-level-system. Although these interactions with phonons are usually considered to be detrimental to the optical characteristics [1], they can in fact give rise to interesting and useful photonic states which would otherwise not be possible, including squeezed light [2], and subnatural linewidth single photons [3]. This theoretical project will bring together techniques from solid-state physics and quantum optics to understand the influence of phonons on the optical properties of quantum dots, and investigate new regimes in which to produce squeezed states of light.

When a quantum dot is driven with a laser, the light that is scattered can contain information about the quantum dot, such as its energy level structure or temperature. Seen another way, the quantum dot can be used to impart useful properties onto the scattered photons, for example, polarisation rotations. How well these properties are transferred depends sensitively on the excitation conditions and the properties of the quantum dot itself. The main purpose of this research is to investigate how phonons in QDs can be utilised to generate squeezed states of light The main objectives of this project are to:

a) Understand how phonons influence the coherence of scattered light in the weak excitation power regime. In particular, do phonons reduce the level of quadrature squeezing imparted to the scattered light in this regime?

b) Investigate the extent to which phonons may actually increase the level of squeezing generated in the strong coupling regime.

c) Investigate how spectral filtering can be used to either suppress or enhance the influence of phonons on the detected light, and quantify how this affects efficiencies.

[In the attached figure is show]: Squeezing parameter (values <0 indicate squeezing) as a function of the optical driving strength with (orange) and without (dashed blue) including phonons. In the strong driving regime, phonons can lead to enhanced squeezing. The inset shows a schematic of a typical experimental setup, consisting of a semiconductor quantum dot in an optical micropillar cavity.

Expected outcomes

If successful this project will elucidate how coupling to phonons in quantum dots can lead to the emission of squeezed light. This would be a significant result for the community, significantly widening the utility of quantum dots, and an exciting example of how effects usually considered to be detrimental can actually add extra functionality. In this way it is expected that a successful project will lead to a publication. In terms of skills, the candidate will gain important and versatile experience in theoretical techniques in quantum optics, as well as an appreciation for experimental concepts.

References

[1] J. Iles-Smith, D. P. S. McCutcheon, A. Nazir and J. Mørk, Nature Photon. 9, 521 (2017)

[2] C. H. H. Schulte et al, Nature 525, 222 (2015)

[3] D. P. S. McCutcheon and A Nazir, Phys. Rev. Lett. 110, 217401 (2013)

Required Skills

Being theoretical in nature, a suitable candidate for this project will have strong analytical and numerical skills, with a particular interest in quantum optics and some solid-state physics. The project itself will involve a healthy mixture of pen and paper analytical work and numerical modelling. It is expected that computation skills will be obtained using e.g. Mathematica, Matlab or Python, although no large-scale simulations will be necessary. Although theoretical in nature, the project is very much related to ongoing experimental work, and a useful acquisition of the relevant concepts and language is expected.

Project Location

University of Bristol

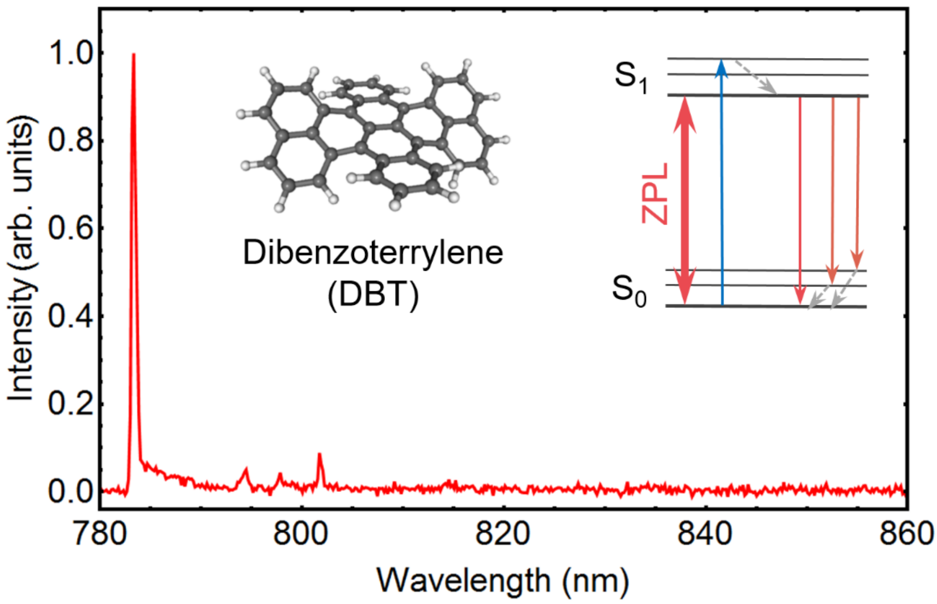
Theory
Quantum dots, Diamond, Single Molecules

6 Characterising phonon interactions in single molecules for non-classical light sources

Dara McCutcheon, Ruth Oulton; Alex Clark

Abstract:

Single organic molecules constitute a novel and exciting platform to explore the quantum optics of isolated few-level systems. Moreover, their properties offer an attractive degree of tunability, which leads to the possibility of tailored and highly desirable non-classical light sources. As with all solid-state emitters, it is essential that coupling to phonons and the behaviour with temperature is properly understood, as this then allows for the development of strategies to combat unwanted dephasing effects. In this project you will investigate the influence of phonon coupling on the optical properties of these single organic molecules. In collaboration with colleagues at Imperial College, we will analyse recent experimental data in order to understand the nature of vibronic modes within the molecule, and how these couple to the optical energy level structure, which in turn affects the emitted photon coherence. The project will be theoretical in nature, but will be strongly linked to ongoing experimental work at Imperial as well as here in Bristol. The research we propose will lead to strong and versatile expertise in applied theoretical quantum optics techniques, and also a good understanding of experimental considerations and concepts. With the experimental data at hand, we expect that a successful theoretical analysis will lead to a high-profile publication in the near future.



Project Description

Quantum optical experiments performed on single systems composed of only a few energy levels has led to the elucidation of a number of key concepts in quantum theory. These include photon bunching and anti-bunching, the dressed states picture, photon indistinguishability, and entanglement. In addition to providing these conceptual insights, these systems can also be viewed as sources of, for example, single photons or entangled photons for quantum information applications. Originally atoms were studied for these purposes, but more recently solid-state alternatives have gained considerable attention. These alternatives include semiconductor quantum dots, colour centres in diamond, and the subject of this project, single organic molecules

[1]. Unlike other solid-state platforms, well-established techniques mean that organic molecules can be tailored for specific optical characteristics such as emission wavelength. This is a significant advantage, as it allows these molecules to to be used in a far greater range of applications
Solid-state systems offer two primary advantages over atoms; they can be more easily spatially isolated, which more readily facilitates optical excitation, and they can be permanently placed inside optical structures such as cavities which allows for the nature of the light-matter coupling to be modified. The disadvantage, however, is that these solid-state systems typically suffer from various sources of decoherence, such as that caused by charge and spin noise, and the effects of phonons. Coupling to phonons in particular constitutes a problem rather inherent in any solid-state system, which cannot be overcome simply by improving fabrication techniques alone. In the case of a molecule, even at zero temperature and if it were isolated from all other interactions, an electronic excitation in the molecule can create a molecular vibration, which would affect the properties of any subsequently emitted photons, limiting its use as coherent source.
Semiconductor quantum dots couple to phonons in a similar way, and are perhaps the best understood of the solid-state platforms in this respect. Thanks to this deep understanding, we now know how best to combat phonon coupling in these systems, which is achieved by placing the dot inside an optical cavity [2]. We know that photons emitted after a lattice vibration has been created will have a different energy to those that are emitted directly. The cavity suppresses optical modes with this energy, which effectively prevents these processes from happening, meaning all photons are emitted directly into the zero-phonon-line (ZPL) and the dot can be used as a source of highly indistinguishable photons.
The purpose of this project is to deepen our understanding of phonon coupling in organic molecules so that we can develop similar strategies to combat decoherence, which will lead to new exciting designs for non-classical light sources. The challenge, however, lies in first gaining a sufficient knowledge of the phonon coupling in these systems. The fact that these are single molecules means we can expect both extra complexity and potential functionality. Compared to quantum dots, the phononic spectrum in a single molecule has considerable structure, which may be able to be exploited in ways that are currently unexplored.
The research undertaken in the project will be in close collaboration with experimental colleagues at Imperial College. By analysing recently measured data, including spectra such as those shown in the figure, the aim of this project will be to develop and test a theoretical model used to describe phonon coupling in single molecules, and how this manifests in the molecule's optical characteristics. Armed with this knowledge, we will explore ways in which the effects of phonon coupling can be suppressed or exploited in engineered photonic cavities, including nanophotonic devices and fibre microcavities.
[In the attached figure we show]: Emission spectrum of a single dibenzoterrylene (DBT) molecule taken at 4 K, showing the zero-phonon line (ZPL) and decays to vibrational levels of the ground state. Inset: the free space confirmation of DBT and an energy level diagram showing the ZPL (double ended arrow), pumping to a higher vibrational state (up arrow), non-radiative decays to purely electronic levels (grey dashed arrows), and decays back to the ground state which result in single photon emission.

Expected outcomes

The main outcome of this project will be a much sought-after characterisation of phonon coupling in single organic molecules. An accurate characterisation of phonon coupling in single molecules would constitute a significant contribution to the field, and as such we expect that work done as during this project may contribute towards a future publication. In terms of skills, the candidate will gain important and versatile experience in theoretical techniques in quantum optics, as well as an appreciation for experimental concepts.

References

[1] Grandi et al., Phys. Rev. A 94, 063839 (2016)

[2] J. Iles-Smith, D. P. S. McCutcheon, A. Nazir and J. Mørk, Nature Photon. 9, 521 (2017)

Required Skills

Being theoretical in nature, a suitable candidate for this project will have strong analytical and numerical skills, with a particular interest in quantum optics and some solid-state physics. The project itself will involve a healthy mixture of pen and paper analytical work, numerical modelling, and the analysis of experimental data. It is expected that computation skills will be obtained using e.g. Mathematica, Matlab or Python, although no large-scale simulations will be necessary. Although theoretical in nature, the project is very much related to ongoing experimental work, and a useful acquisition of the relevant concepts and language is expected.

Project Location

University of Bristol

Theory, Simulation
Quantum Information Science, Metrology, Computing, Quantum Optics

7 Quantum state engineering with an evolutionary algorithm

Dr Paul Knott, Dr Jonathan 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 which 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 parameters have not been considered. The goal of this project is to overcome this and develop the algorithm so that it can design practical schemes for building quantum states that can be realised in the laboratory.

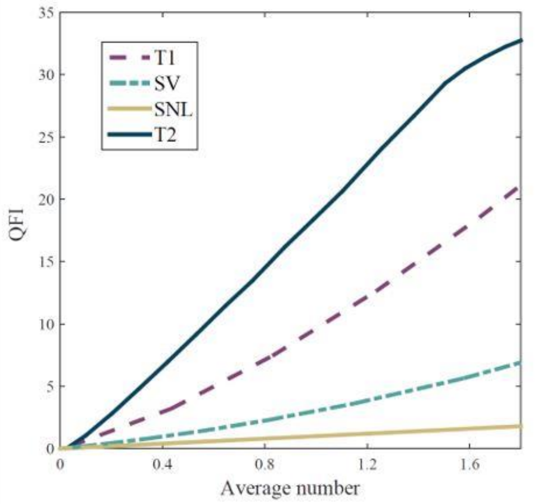


Fig 1: Comparing different quantum states using the quantum Fisher information (QFI). Here the QFI is plotted against the average photon number for two of the quantum states found by our evolutionary algorithm, labelled **T1** and **T2**. A state with a large QFI can make measurements to a high precision. We see that **T1** and **T2** give significant improvements over the squeezed vacuum (**SV**) and the classical shot noise limit (**SNL**), which are normally considered the state-of-the-art for quantum and classical systems, respectively. Therefore, the quantum states found by the algorithm significantly improve over the state-of-the-art.

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 develop the evolutionary algorithm so that it can find quantum states that can then be made in the laboratory, including in the labs in Bristol. 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. To find quantum states that can be made in the lab, realistic sources of

noise must be considered and incorporated into the algorithm – the two most dominant noise sources are photon loss and imperfect detectors.
Timeline:
Weeks 1-3: Learn about quantum state engineering and the evolutionary algorithm.
Week 4: Talk to experimentalists to learn about exactly what has been and what can be achieved in the lab, and what are realistic aspirations within the field.
Weeks 5-7: Incorporate photon loss into the algorithm.
Weeks 8, 9: Tailor the algorithm so that it can design experiments specifically using the equipment at Bristol.
Weeks 10-12: (If time, incorporate imperfect detectors into the algorithm.) The algorithm will be implemented to produce a range of quantum states. The student will input realistic parameters into the algorithm to provide examples and a clear method of how the states can be realised (a) immediately and (b) in the future.
The lead supervisor on this project, Dr Paul Knott, is based at the University of Nottingham. However, for the duration of this project both Dr Knott and a PhD student at Nottingham 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 there is funding available for the student to visit Nottingham.

Expected outcomes

- The dominant sources of noise in the experiments that we are considering are photon losses and imperfect photon detectors. A minimum outcome to this project will be incorporating photon loss into the algorithm (highly likely to succeed).
- A more challenging outcome is to incorporate imperfect photon detectors into the algorithm (less likely to succeed).
- Different laboratories have different equipment available to engineer quantum states. The second minimum outcome is to tailor the algorithm to incorporate most of the equipment available at Bristol (highly likely to succeed).
- The student will use the algorithm to design new quantum states – and realistic experimental procedures to produce the states – that can measure a phase shift in an interferometer to a high precision (likely to succeed).
- A more challenging outcome is to find quantum states and experiments for a wider range of applications, such as quantum computing and cryptography (less likely to succeed).

References

[1] Knott, Paul. "An evolutionary algorithm to engineer quantum states with an application in optical quantum metrology." arXiv preprint arXiv:1511.05327 (2015).

[2] E. Bimbard, N. Jain, A. MacRae, and A. Lvovsky, "Quantum-optical state engineering up to the two-photon level", Nature Photonics 4, 243 (2010)

[3] P. Kok and B. W. Lovett, Introduction to optical quantum information processing (Cambridge University Press, 2010)

[4] A. E. Eiben and J. E. Smith, Introduction to Evolutionary Computing (Springer Science & Business Media, 2003)

Required Skills

The project will largely involve coding, preferably 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 use of evolutionary algorithms, numerical approaches in physics, and the theory behind quantum state engineering with light. The student will also develop a detailed understanding of the state-of-the-art in experimental quantum photonics, for example typical and record single photon purities, optical losses that are typical in different materials, and measurement and tomography characteristics that determine detector performance. The main challenge in this project will be to translate theoretical quantum physics, and experimental procedures, into the language of computer coding.

Project Location

University of Bristol, Other academic partner

Theory, Experimental, Simulation
Photonics Device Engineering, Quantum nonlinear optics

8 Quantum light sources: flexibility by design

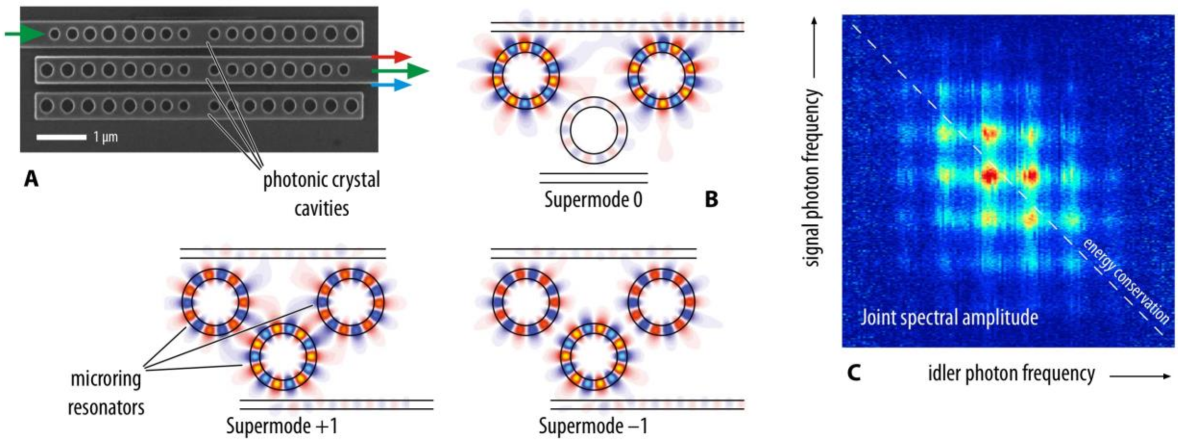
Dr. Joshua Silverstone, Dr. Jorge Barreto, Dr. Gary Sinclair, Dr. Will McCutcheon, Mr. Lawrence Rosenfeld

Abstract:

The only viable route to large-scale quantum systems is via integrated technology. Integration—by its nature—requires compromise. In optics, a sharp interaction exists between manufacturability, electro-optic functionality, nonlinear optics, spectral properties, propagation constants, loss, and footprint, depending on the material system and spectral band. The full power of integration is unlocked when individual components are flexible in their requirements, so can coexist with other components with disparate needs.

Sources of photons are fundamental to optical quantum systems, and, today, the best ones use quantum nonlinear optics. These sources, based on spontaneous four-wave mixing (SFWM) produce pairs of photons in well-defined spatial, frequency, and temporal modes. Dispersion in SFWM sources, however, must be delicately engineered to allow fields at different frequencies to mix. This requires a bespoke solution for every new integration platform. New material-spectral platforms are emerging all the time—low-temperature photonics, silicon photonics in the short-wave infrared (SWIR), silicon nitride and carbide photonics, and many more [Silverstone2016]—so a flexible solution is badly needed.

This project will develop structures which allow any nonlinear optical platform to efficiently produce photon pairs with arbitrary spectral detuning. Recent proposals for system-level separability engineering will also be investigated [Christensen2017, Vernon2017]. Concrete solutions will target the silicon quantum photonics platform, in the versatile near infrared (NIR) and new SWIR bands. Taking a flexible design-theory-experiment approach, we will explore the interaction between key source metrics—brightness, separability, and controllability—in novel SFWM structures. With high-performance, flexible components in hand, large-scale-integrated quantum systems will finally be within reach; humanity will finally harness the full quantum nature of light.



Project Description

The subject of this project is broad and far-reaching. The interested student will naturally chart a path through it, according to his or her own interests; we outline three potential routes, below.

A short literature review of resonant SFWM devices, and system-level photon-pair generating structures will be carried out. An understanding of the linear resonant behaviour of both standing- and travelling-wave optical cavities will be developed, sufficient to pursue one of the three pathways. An understanding of relevant photon-pair source metrics will be developed, with an emphasis on brightness/efficiency and resulting photon purity. A basic understanding of the structure and mechanisms behind the workhorse high-confinement silicon quantum photonic platform will be developed as needed.

Theory:

These devices present a rich physical system, combining quantum optics, linear and nonlinear optics, and solid state physics; a fundamental understanding of these physics is essential. Analytical methods based on previous work with resonant SFWM devices will be learned and applied. The transfer-matrix method (TMM) model of single-mode optics will be used to gain insight into the linear dynamics of the various single- and coupled-cavity systems, and qualitative consideration will be given to their nonlinear dynamics.

The output wavefunction of up to three candidate structures will be computed in the frequency domain, as a function of source internal parameters, and its properties will be explored. A model for continuous spectral entanglement [Law2000] in the output wavefunction will be developed, based on the joint-spectral amplitude (see Fig. C). Time-domain behaviour and/or internal quantum fields may also be explored, according to student interest.

Design:

To apply these devices to real integrated systems, a thorough design effort is required. We must focus the parameter space on a region of interest, and ultimately produce technical drawings which will allow us to manufacture and realise working devices.

A thorough understanding of microring, distributed feedback, and photonic crystal cavity structures, as well as frequency-selective asymmetric Mach-Zehnder interferometers will be developed. Device topologies will be explored, and the dependence of output parameters on the device structure will be established. A sensitivity analysis will be performed, addressing device yield and robustness. The student will learn to use industry standard optical solvers to translate geometric designs into optical performance. A previously developed genetic algorithm planar photonic design code will be applied to the problem, if time permits. There will be an opportunity in the last quarter of the project for the development of a design to be manufactured (expected manufactured device receipt in autumn 2018).

Experiment:

A small subset of possible devices is both in fabrication now, and already exists. The student may choose to apply his or her knowledge from the design and theory aspects of the project in the lab. Industry-standard techniques will be used to characterise device linear and nonlinear properties, using this real-world data to fine-tune our understanding of linear and nonlinear device physics. Training will be provided in a broad range of bulk and fibre test apparatus: pulsed and continuous-wave (CW) sources, spectral elements such as monochromators and dense wavelength demultiplexers, bright-light and single-photon detectors, fibre components, and nanopositioners. SWIR laser sources include a CW quantum cascade laser, a pulsed supercontinuum source used for ultra-broadband characterisation, and a picosecond-pulsed mode-locked laser, for pumping nonlinear processes such as SFWM. A wide variety of optics and sources are available in the NIR. Superconducting nanowire single photon detectors are used for detection in both the NIR and SWIR bands.

Figure caption:

Sample of previous system-level approaches to photon-pair generation. (A) Coupled PhC cavities [Azzini2013]. (B) The three supermodes of a triple-coupled-microring structure [Gentry2015]. (C) A separable joint-spectral amplitude originating from non-traditional phase-matching [Eckstein2014].

Expected outcomes

This project promises several concrete outcomes, if successful. This is a topic of active research, and is eminently publishable. The production of a manuscript is out of the scope of this two-month project, but we expect to publish the successful results of this work in due course. At least one of the novel structures in this project is patentable already, and other insights into the design and operation of this structure could form part of that patent. Other structures studied in this project may also be found to be sufficiently novel and useful to be similarly protected.
Much can be learned from this testbed microcosm of integrated quantum photonics, and integrated quantum systems as a whole. A motivated student will learn aspects of quantum optical theory, nonlinear optics, device simulation and design, and experimental techniques of integrated optics. A high-level view of integrated quantum optics, and the technology underpinning linear optical quantum computation (LOQC) will be acquired.
The student will be embedded in Bristol’s world-leading Centre for Quantum Photonics, and will start the construction of a valuable professional network, spanning theory, architectures, device design, optical engineering, test, and manufacturing.

References

Silverstone, J. W., et al. Silicon Quantum Photonics. JSTQE (2016) doi:10.1109/JSTQE.2016.2573218

Law, C. K., et al. Continuous Frequency Entanglement: Effective Finite Hilbert Space and Entropy Control. PRL 84, 5304–5307 (2000) doi:10.1103/PhysRevLett.84.5304

Gentry, C. M., et al. Four-wave mixing in silicon coupled-cavity resonators with port-selective, orthogonal supermode excitation. OL (2015) doi:10.1364/OL.40.002120

Azzini, S. et al. Stimulated and spontaneous four-wave mixing in silicon-on-insulator coupled photonic wire nano-cavities. APL (2013) doi:10.1063/1.4812640

Eckstein, A. et al. High-resolution spectral characterization of two photon states via classical measurements. LPR (2014) doi:10.1002/lpor.201400057

Christensen, J. B., et al. Engineering spectrally unentangled photon pairs from nonlinear microring resonators through pump manipulation. arxiv:1711.02401 (2017)

Vernon, Z. et al. Truly unentangled photon pairs without spectral filtering. arxiv:1703.10626 (2017)

Required Skills

All skills essential for this project will be learned on-the-fly. The ideal student will share our enthusiasm for engineering quantum devices to work in the real world. A basic understanding of optical physics is desirable, as is a proficiency with either Python or Mathematica.

Project Location

University of Bristol

Experimental, Simulation
Simulation, Quantum dots, Photonics Device Engineering, Device Fabrication

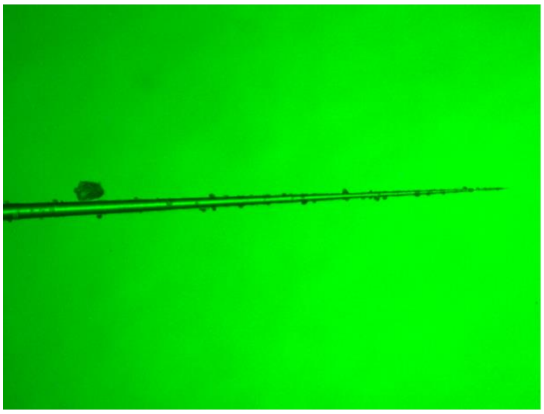
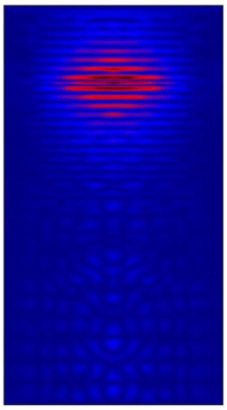
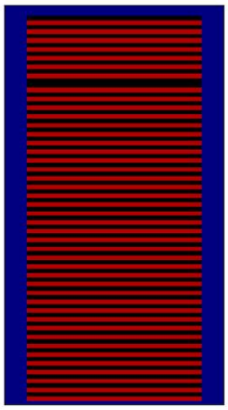
9 "Plug and play" source of single photons from quantum dots

Edmund Harbord, Edmund Harbord

Abstract:

Quantum dots (QDs) are potentially bright sources of single indistinguishable photons, an important resource for emerging quantum technologies from simulation to metrology. While the quantum dots offer a high internal quantum efficiency, the external quantum efficiency is limited by the photon escape from the semiconductor. Further, we would like the single photons in a single optical mode, ideally in an optical fibre. We design photonic structures that enhance the emission of the light from the semiconductor, and shape and direct it into a particular optical mode.

We are developing a matchbox sided source of single photons based of integrated fibre coupled QDs. We have designed an ideal pillar which emits with external quantum efficiency >90%. In the project, we are designing a fibre taper that matches the optical mode- the fibre is tapered adiabatically, to preserve all the photons, and at an angle that converts the mode from that of the pillar to that for the untapered fibre.

Expected outcomes

Student: will learn how to do photonic simulation and get to try out a range of cleanroom techniques.
Simulation: This project will deliver a design for an adiabatically tapered fibre that is mode matched to our ideal micropillar design, as well an estimate of the robustness of the coupling to misalignment for this design.
Experimental: the student will make fibre tapers in the cleanroom, using an etching process we have developed, and produce adiabatic tapers. Control of the angle will be achieved by the draw rate, and be characterised by optical microscopy and scanning electron microscopy.
Additional outcome: if time permits, the student will look at surface imperfections in the etching process, and model the effect of these on the optical mode.

References

Sonia Buckley et al 2012 Rep. Prog. Phys. 75 126503

Xilai Xu et al., Appl. Phys. Lett. 90, 061103 (2007)

Required Skills

All training will be provided for the cleanroom and the simulation software. This project would suit an enthusiastic, hands-on person keen to develop their skills in solid state quantum optics and who would like to try out device fabrication.

Project Location

University of Bristol

Theory, Simulation
Simulation, Quantum Machine Learning

10 Quantum neural networks: designing novel networks and architecture-learning schemes with quantum neurons

Jay Perrett, Anthony Laing, Raffaele Santagati, Will Dixon, Brian Flynn

Abstract:

Neural networks work by optimising weights between neurons. There has been a growing interest in the realisation of a new family of neural networks which take advantage of quantum hardware: quantum neural networks. This is a difficult task. Neural networks rely on nonlinear step-function calculations in order to be universal function approximators, whereas quantum computing is achieved by unitary operations which are inherently linear. Recently Cao et al. described a quantum neuron which uses ancilla qubits to achieve the nonlinear effect [1]. Neural networks are specified by their architecture, i.e. the number of hidden neurons employed (as well as some other key factors). Different architectures can achieve significantly better predictive power. Classically these architectures must be searched over and optimised individually. Da Silva et al. propose a Superposition-based Architecture Learning quantum algorithm, though do not account for the nonlinear step [2].
We will first construct a ‘toy model’ quantum neural network with the proposed quantum neuron as the building block. We may then investigate whether the enhanced quantum neuron of Cao can be used in a wider scheme where the neural network architecture is learned as well as the inter-neuron weights.

Project Description

Two CDT students worked on QNNs for project A in 2017, and found a limitation of the research to date, whereby classical neural networks rely on a nonlinear step calculation which did not seem straightforward to be realised on a quantum machine. A recent technical paper by Cao et al. suggests this limitation can be overcome using ancilla qubits. We aim to understand whether this approach satisfies the concerns raised last year. If so, we will use the quantum neuron as a building block for the real-world challenge in getting good predictive power using neural networks. It is relatively straightforward and well optimised to find the weights which best predict given outcomes from given inputs when you’ve chosen network parameters such as number of neurons and number of iterations. We are instead interested in the best network globally. E.g. a network with 10 neurons running for 1000 iterations gives 80% accuracy; a 20 nodes for 1100 iterations give 82% accuracy; but 30 nodes for 1500 iterations gives 75% accuracy. There is clearly a huge space of networks to study in order to get the truly strongest predictive power. Combining the novel quantum neuron with a superposition based architecture learning algorithm [2], or through a new approach composed by the student, we aim to consider whether quantum neural networks offer any advantage over classical neural networks.
An alternative route for this project is to consider tomography using neural-network quantum states, following Torlai et al. [3]. This would involve writing a neural network to represent a quantum state by learning from data obtained experimentally using a silicon quantum chip.
The project will be a collaboration with Aria Networks in Bath. They are a world-leading expert neural network solution provider. They work primarily with Telcom businesses to optimise routing of network data/traffic. The student will have the opportunity to visit and work from the Bath office, in order to first understand how neural networks achieve predictions (knowledge of neural networks is not needed initially, though the student will be encouraged to program one, so coding experience is preferred).

Expected outcomes

Depending on the student's preferences, we can work on:
1 Toy example using quantum neurons (e.g. XOR gate)
1.1 Write functional classical network
1.2 Then, recreate theoretically toy example using quantum neurons
1.3 Calculate resources to simulate to model with quantum neurons
1.4 Possibly simulate quantum neurons
2 Propose an architecture-learning scheme using quantum neurons.
3 Scalability of quantum neuron approach: can enough quantum neurons be tied together to reflect a useful neural network
4 How many qubits would be needed to build a useful neural network
4.1 Comparison with number of bits in classical networks
5 Computational complexity of quantum neural network
6 Energy/cost comparison between using a computer cluster versus hypothetical quantum machine
7 Calculate experimental requirements for single quantum neuron
7.1 Possibly propose experimental scheme
8 Which platform is best suited to achieving quantum neurons.

References

[1] Cao et al. Quantum Neuron: an elementary building block for machine learning on quantum computers.

https://arxiv.org/pdf/1711.11240.pdf

[2] Da Silva et al. Quantum perceptron over a field and neural network architecture selection in a quantum computer.

http://www.sciencedirect.com/science/article/pii/S0893608016000034

[3] Torlai et al. Neural-network quantum state tomography for many-body systems.

https://arxiv.org/pdf/1703.05334.pdf

Required Skills

Some programming experience required.

Project Location

University of Bristol, Industrial partner

Theory
Quantum Information Science, Computing

11 Topological Codes

Jiannis Pachos, Peter Turner

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 [Bravyi et al. arXiv:1710.02270; Meichanetzidis et al. arXiv:1705.09983]. 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.

Expected outcomes

The main outcome of the project is to propose a concrete scheme for the realisation of topic code error correction with linear optical elements.

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).

Required 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.

Project Location

University of Bristol, Other academic partner

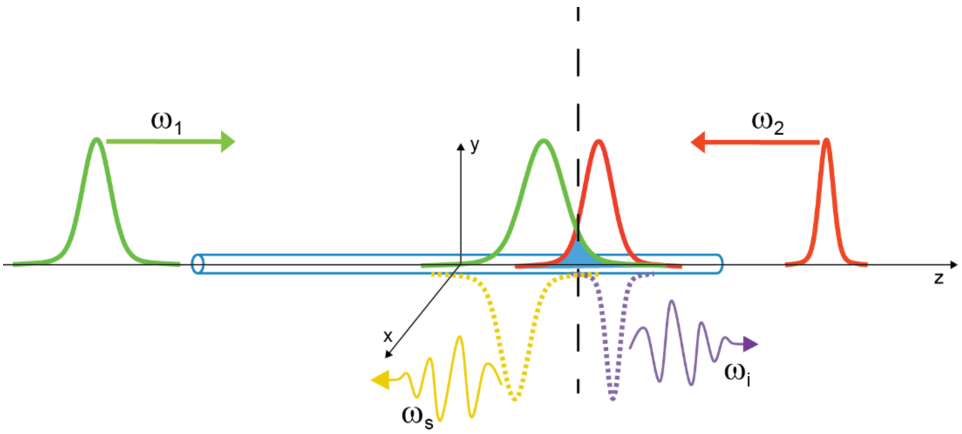
Experimental, Simulation
Photonics Device Engineering, Nonlinear optics

12 Narrowband pair photon generation in optical fibre with counter-propagating pumps

Alex McMillan, Sabine Wollmann, Jonathan Matthews, John Rarity

Abstract:

Single photon sources are a key element in photonic quantum information experiments, and optical implementations of quantum communication and computation. Such single photon sources can be realised using photon pairs generated by spontaneous nonlinear parametric processes like spontaneous parametric down conversion (SPDC) in chi(2) nonlinear crystals [1,2] and spontaneous four wave mixing (SFWM) in chi(3) materials such as optical fibres [3,4]. In the case of SFWM, through careful design of fibre guidance properties like dispersion and birefringence, the pair photon wavelengths can be chosen across a wide spectral range. Furthermore, it is possible to engineer the two-photon state such that spectral purity of the generated photons can be achieved.
In this project we aim to build the first photon pair source based on counter-propagating SFWM (CSFWM) on optical fibres [5]. In contrast to previously demonstrated schemes where the pump beams and generated photons propagate in the same direction, 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 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. Photons generated from this process are expected to be well suited for quantum metrology or interaction with atom-like systems, which is essential for compatibility with currently demonstrated implementations of quantum memories.



Project Description

CSFWM is expected to occur when coupling two pump lasers of different frequency into opposite ends of an optical fibre. At the point in the fibre where the counter-propagating laser beams overlap, counter-propagating signal and idler photon pairs can be generated by phase-matched CSFWM, with an interaction probability which depends on the brightness of the pump lasers and strength of the waveguide nonlinearity (see figure 1).
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 SFWM 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. Unusually, the process is also not strongly dependent on the fibre dispersion, relaxing the requirement for tight control of the fabricated fibre parameters. By default, the phase-matching for CSFWM leads to degeneracy of the generated wavelengths, in the sense that the signal and idler frequencies match those of the two pump beams, which makes the generated photon pairs difficult to distinguish from back scattered pump light. However, several mechanisms have been identified which can break this degeneracy including waveguide birefringence, intermodal phase-matching and other nonlinear effects which occur in fibre, such as self-phase modulation or cross-phase modulation of the pump beams. When these effects are strong enough, significant wavelength offset of the signal and idler photons from the pumps can be realised, allowing the pump light and other noise sources to be removed by spectral filtering.
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, in this limit, the interaction length where the laser pulses overlap is significantly increased. Provided that the interaction length exceeds a certain threshold, the generated two-photon state becomes spectrally factorable. When the joint spectral intensity of the two photon state becomes factorable, detection of one photon of the pair allows pure single states to be heralded without the need for lossy narrowband spectral filtering.

Expected outcomes

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 highly birefringent photonic crystal fibre. This will involve using coincident photon detection to look for the signature of correlated pair generation events.

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)

[3] M. Halder et al., "Nonclassical 2-photon interference with separate intrinsically narrowband fibre sources," Opt. Express 17, 4670 (2009)

[4] B J. Smith et al., "Photon pair generation in birefringent optical fibers," Opt. Express 17, 23589 (2009)

[5] J. Monroy-Ruz, et al., "Counter-propagating spontaneous four wave mixing: photon-pair factorability and ultranarrowband single photons," New J. Phys. 18 103026 (2016)

[6] M. Rambach et al., "Sub-megahertz linewidth single photon source," APL Photonics 1, 096101 (2016)

[7] F. Graffitti et al., "Independent high-purity photons created in domain-engineered crystals," arXiv:1712.07140v1 [quant-ph] (2017)

Required Skills

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.

Project Location

University of Bristol

Experimental
Metrology

13 Sensing using undetected photons

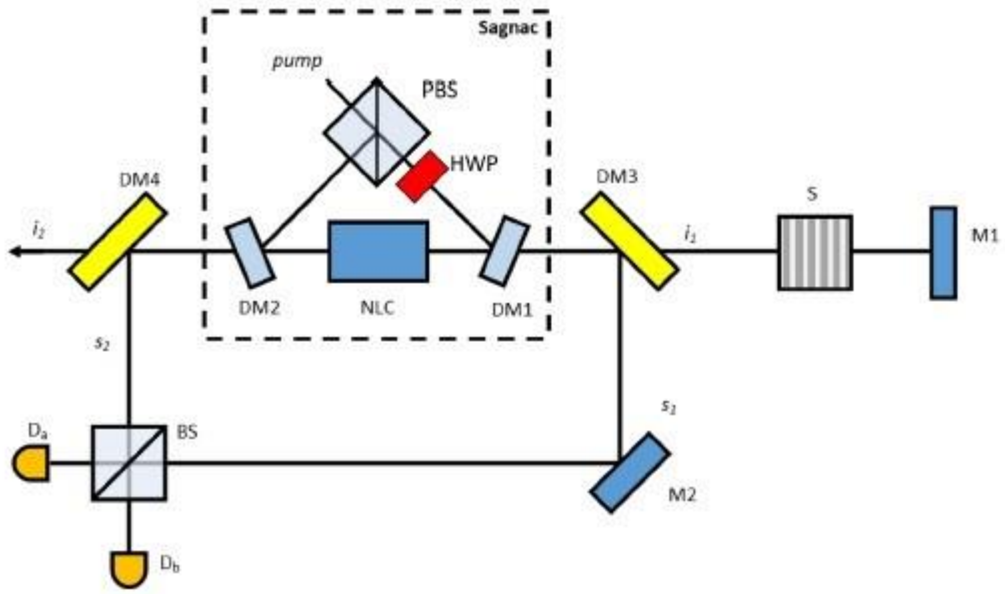
Alex McMillan, Xiao (Ross) Ai, Sabine Wollmann, Jonathan Matthews, John Rarity

Abstract:

Examples of measurements where light is used to probe the properties of samples are ubiquitous across a broad range of scientific disciplines. The suitable 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 sensing, and beyond. Unfortunately, currently available light detectors that operate efficiently at the single photon level only cover a relatively limited range from ~500nm – 1600nm.

This project will explore a new 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 down conversion in a nonlinear crystal (at non-degenerate wavelengths), and subsequently one of the photons is sent through a sample of interest. After this, the generated photons pass again through the same nonlinear crystal, undergoing further nonlinear interaction. As the phase of the fields at both wavelengths contribute to the nonlinear process, properties of the sample can be determined by measurement at the wavelength which did not interact with the sample. This allows the wavelength of one photon of the pair to be tuned to interact with the sample, and its partner photon to lie in a wavelength range that can be efficiently detected.

The initial stage of this project will involve demonstration of this technique by modifying a pre-existing photon pair source to operating in a Sagnac configuration and measuring an optical phase applied to undetected photons. Following on from this, there are several further directions that the remainder of the project, and a potential PhD project, could take, including optimization of the detection scheme, design of photon pair sources with wide wavelength separation, and application of this technique to real world problems, such as long wavelength sensing and imaging.



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 a hero experiment involving careful alignment of multimode images.

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, as shown in figure 1. The main goal of this project is to experimentally demonstrate the principle of measurement with undetected photons by making use of pre-existing high efficiency pair photon sources operating near 800nm [4] . 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.

- Within the timeframe of the project, the student will investigate alternative experimental arrangements that improve upon the approach taken in [2], such as using two passes of the light through a single down-conversion crystal [3]. This will involve optimization of the collection modes and components in order to minimize losses and achieve indistinguishability of the two pathways to pair generation. We anticipate this will lead to improvements in the optical path length stability, and ultimately lead to a more compact, robust and practical setup.
- This source will be used to perform a measurement of a small phase-shift applied to the idler photon beam 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
- If this work extends beyond the initial CDT project into a full PhD project, one potential direction would be the design and fabrication of a 3.3 um sensor for gas sensing, based on this approach. This could also focus on two dimensional imaging schemes with multimode sources.

Expected outcomes

Although initial experimental demonstrations of imaging without detection have already been published, there has so far been very limited exploration of this approach in a practical measurement setting, or at novel wavelength ranges. There is considerable scope for future publication in this area and a great deal of flexibility in the focus of a potential future PhD project. In particular, some funding has already been secured for a future project to explore the application of this technique to long range sensing of gases near 3.3um for methane monitoring.

References

[1] R. Whittaker et al., “Quantum-enhanced absorption spectroscopy,” arXiv:1508.00849 (2015).

[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).

Required Skills

The project will have a strong experimental focus and the majority of the student’s time will be spent designing, building and subsequently characterizing 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.

Prior experience in these areas is desirable, but not required.

Project Location

University of Bristol

Theory, Experimental, Simulation
Fundamentals of Quantum Mechanics, Quantum Information Science

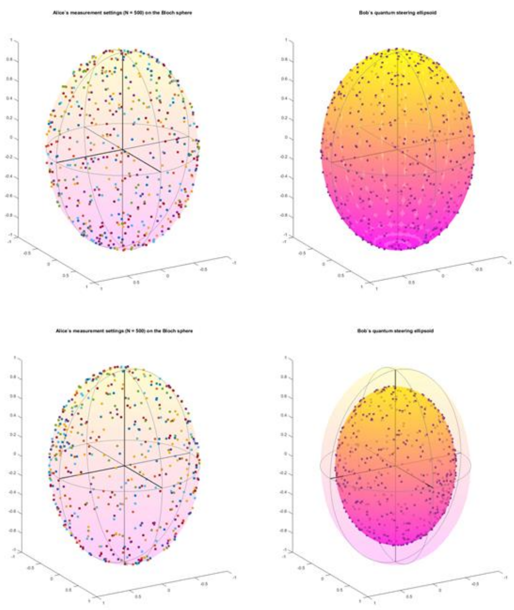
14 Quantum steering ellipsoids

Jonathan Matthews, Sabine Wollmann, Jianwei Wang

Abstract:

The Bloch sphere provides a simple geometrical representation for qubits which allows for an easy manipulation and visualization of quantum states in quantum information experiments. Similarly, a two-qubit system is the primitive unit for bipartite quantum correlations. For a faithful description of the two-qubit state space, all 15 real parameters have to be defined. This level of complexity makes it challenging to determine them all and gain an intuitive understanding for their properties.

Therefore, it is of interest to explore quantum steering ellipsoids as they are a natural extension of the Bloch sphere representation. Besides a faithful representation of arbitrary two-qubit states in three dimensions, fundamental properties of the state and its correlations are inherent in the geometric properties of the ellipsoid.



Quantum steering ellipsoid for a Bell state

Quantum steering ellipsoid for a Werner parameter with μ=0.8

Project Description

Einstein-Podolsky-Rosen steering (or quantum steering) is of foundational significance in quantum mechanics and is a nonlocal effect that is distinct from other nonclassical correlations such as Bell nonlocality [1] and quantum nonseparability. This distinction manifests as a hierarchy, with each effect witnessed by violation of a corresponding inequality that bounds measurement correlations [2]. In this hierarchy, moving from Bell nonlocality to quantum steering to nonseparability requires increasing the number of parties and apparatuses that must be trusted, but the corresponding protocols have been demonstrated to be progressively more robust to noise [3,4] for projective measurements.

EPR-steerable states are determined for classes of highly symmetric states [5,6]. However, the question what types of states are steerable is still ongoing research and has been studied using the so-called steering ellipsoid formalism [7-9].

Steering as quantum information task can be understood as Alice and Bob sharing a joint state and one may ask whether Alice can steer Bob, i.e., whether or not she can use her measurements to steer his measurement outcomes enough to violate a steering inequality. This requires correlations between Alice and Bob's qubit.
A general, arbitrary, description of a shared two-qubit state can be written as,
$\rho=1/4(I\otimes I+ a\cdot\sigma\otimes I+I\otimes\sigma\cdot b+\sum T_{(j,k)} \sigma_j\otimes\sigma_k)$,
where $\sigma\equiv(\sigma_1,\sigma_2,\sigma_3)$ are the Pauli spin operators and $a_j=tr[\rho\ \sigma_j\otimes I]$, $b_j=tr[\rho\ I\otimes\sigma_j]$, $T_{jk}=tr[\rho\ \sigma_j\otimes\sigma_k]$. a and b are Bloch vectors for Alice and Bob's qubit's and T is the spin correlation matrix.
Alice's measurement with projector E on her qubit then reduces Bob's state to
$\rho_B^E=1/2(I+b(e)\cdot\sigma)$,
with Bloch vector $b(e)=1/(2p_e)(b+T^\top e)$. p_e is the probability of the result `E=1' and is given by $p_e:= tr[\rho(E\otimes I)]=1/2\ (1+a\cdot e)$.
The quantum steering ellipsoid allows for a geometrical representation of Bob's steered states as the surface of the ellipsoid is defined to be the set of the Bloch vectors $\{b(e):|e|=1\}$ [10] while the interior points can be obtained by using POVMs for the measurement [9]. The center of this ellipsoid is given by $c=(b-T^\top a)/(1-a^2)$, while the orientation and semiaxes lengths $s_i=\sqrt{q_i}$ \cite{Jevtic2014} are given by the eigenvectors and eigenvalues q_i of the following ellipsoid matrix
$Q=1/(1-a^2)(T^\top-ba^\top)(I+(aa^\top)/(1-a^2))(T-ab^\top)$
Using symmetric, highly correlated states, such as Bell states and Werner states (attached figure) leads to steering ellipsoids that have the shape of a sphere with their center being at the origin of the Bloch sphere. However, there exist states that have highly asymmetric steering ellipsoids and are not centered in the origin of the Bloch sphere. This project is concerned in theoretically defining these states and implementing the first experimental observation using integrated photonics. Further, there is a relation between the dimensions of steering ellipsoids and one-way EPR-steering which could extend into further foundational investigations.

Expected outcomes

This project will be the first experimental demonstration of theoretically predicted quantum steering ellipsoids. The student will theoretically determine suitable states which allow for observation of an asymmetric quantum steering ellipsoids that are not centered at the origin of the Bloch sphere. This is followed by a realization of the states and the appropriate measurements on an integrated photonic platform. The student will analyse the data and reconstruct the quantum steering ellipsoid for comparison with the theoretical model.

References

1. J. Bell, Physics 1, 195 (1964).

2. H. M. Wiseman, S. J. Jones, and A. C. Doherty, Phys. Rev. Lett. 98, 140402 (2007).

3. D. Saunders, S. Jones, H. Wiseman, and G. Pryde, Nat. Phys. 6, 845 (2010).

4. A. J. Bennet, D. A. Evans, D. J. Saunders, C. Branciard, E. G. Cavalcanti, H. M. Wiseman, and G. J. Pryde, Phys. Rev. X 2, 031003 (2012).

5. H. M. Wiseman, S. J. Jones, and A. C. Doherty, Phys. Rev. Lett. 98, 140402 (2007).

6. S. J. Jones, H. M. Wiseman, and A. C. Doherty, Phys. Rev. A 76, 052116 (2007).

7. F. Verstraete, Ph.D. thesis (Katholieke Universiteit Leuven, 2002).

8. M. Shi, F. Jiang, C. Sun, and J. Du, New. J. Phys. 13, 073016 (2011).

9. S. Jevtic, M. Pusey, D. Jennings, and T. Rudolph, Phys. Rev. Lett. 113, 020402 (2014).

Required Skills

As this project will have an emphasis on simulation, prior experience with scientific scripting software like Matlab or Mathematica would be useful. Basic knowledge of quantum information science is required.

Project Location

University of Bristol

Experimental
Photonics Device Engineering

15 Cold non-linearities in next-gen photonic materials

Jorge Barreto, Dr. Gary Sinclair, Dr. Dondu Sahin

Abstract:

Integrated quantum photonics promises a route towards scalability backed by industrial fabrication standards. Despite the initial promising results, photon sources based on second-order non-linearities are limited by those very same non-linearities and the need for outstanding spectral filters. Driven by the need for full integration, it is essential to understand how these non-linear properties behave at low temperatures. This will allow us to design better single photon sources and fight the material limitations. Although silicon is often the material for choice for integrated quantum photonics, other well-performing platforms, such as silicon nitride, are gaining acceptance due to their fabrication tolerance, wide band-gap and compatibility with the existing SOI platform. This project aims to characterise the non-linear parametres of silicon nitride waveguide structures at temperatures below 4K. The results will enable an optimal design of photon-pair source structures and a better understanding of the material behaviour.

Project Description

Non-linearities are fundamental for the development of some essential building blocks for a quantum photonic computer such as single photon sources and switches. They also can affect the performance by introducing loss in the propagation path limiting the implementation of delay-lines. Different materials have different non-linear coefficients and hence are employed in different applications. Examples are Lithium Niobate optical switches and Barium Borate crystals are used for single-photon pair sources based on parametric-down conversion.

Silicon is the material of choice for most integrated quantum optics applications. It has a reasonably high non-linear coefficient that allows for four-wave mixing (SFWM) and potentially for switches based on the optical Kerr effect (3rd order nonlinearity coefficient). Two-photon absorption (TPA) is a non-linear phenomenon where light at frequencies below the bandgap is still absorbed if the field intensity is high enough. This happens in SFWM photon sources - where either of the photons generated is re-absorbed by the material in the presence of the pump used initially to stimulate the pair production.

Silicon nitride has similar properties to silicon, however, due to the low refractive index, the mode field density is lower, leading to lower pair production rates. Yet, the extremely wide band-gap of silicon nitride allows for visible light to be used and the TPA in the infra-red to be practically nonexistent.

How does the decrease in temperature – and therefore in available free energy in the semiconductor –affect the non-linear optical properties? How does the light-matter interaction balance in these extreme conditions? We have observed a small decrease in TPA, and we are currently analysing the mechanisms that have caused it. However, we are not sure how this is going to affect the photon pair

generation rate and/or even induce a shift in the resonance frequencies. Therefore, a comprehensive study by using building blocks is required for the understanding of performance of key optical circuit elements.

Previous experiments in silicon, as well as existing reports in literature on similar devices will provide an easier start towards the understanding of the optical non-linear properties of silicon nitride devices.

This project aligns with an existing collaboration with Dr. Alberto Politi at the University of Southampton as part of the QuCHIP european project. It also aligns with existing work by Dr. G. Sinclair in the framework of the QETLabs Programme Grant. It essentially aligns with the grand-strategic vision of a fully integrated re-programmable photonic quantum processor -where the need to operate at cryogenic temperatures leads into an unexplored area of optical properties of photonic materials at low temperatures.

Expected outcomes

Results can be potentially included in a paper being written on non-linearities of silicon waveguides at low temperatures. Alternatively, if the results are far from what is expected, they can be presented independently.
In addition, by the end of the project, the student will be able to:
a) understand the basic concepts of integrated photonics
b) perform measurements on a photonic chip
c) work with wet cryogenic systems
d) work with pulsed laser systems, OSAs and other optical test and measurement systems
e) understand how the non-linear processes can affect (positively and negatively) quantum photonic circuits
f) understand the limitations of photon sources based on centrosymmetric materials (second order non-linearity).

References

R. Soref – The past, present and future of silicon photonics, IEEE J.Sel.Top.Quant.Elect. 12(6), 1678 (2006)

T. Baehr-Jones et al. – Myths and rumours of silicon photonics, Nature Photonics 6, 206 (2012)

J. Leuthold, C. Koos & W. Freude - Nonlinear silicon photonics, Nature Photonics 4, 535 (2010)

W.H.P. Pernice et al. – Carrier and thermal dynamics of silicon photonic resonators at cryogenic temperatures, Opt. Express 19(4) 3290 (2011)

X.K. Sun et al. – Nonlinear optical effects of ultrahigh-Q silicon photonic nanocavities immersed in superfluid helium, Scientific Reports 3, 1436 (2013)

Required Skills

The project requires does not have any pre-requisites for QE-CDT students.

Project Location

University of Bristol

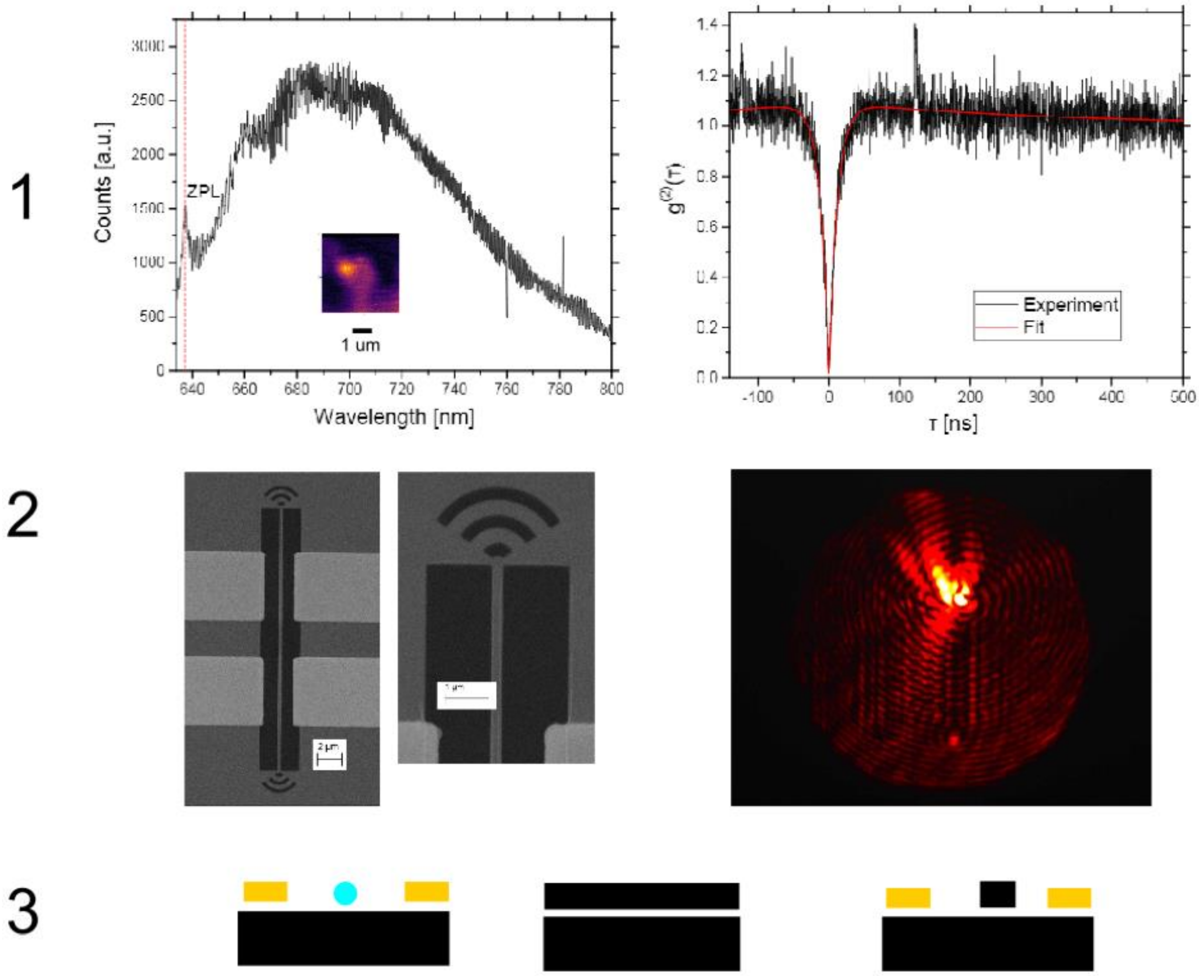
Experimental, Simulation
Computing, Diamond, Photonics Device Engineering, Device Fabrication

16 Towards telecoms-band cavity QED integrated in a silicon-on-insulator platform

Krishna Balram, Joe Smith, Jorge Monroy Ruz, John Rarity

Abstract:

One key component missing from linear optic quantum computing is entangling operations between photons. At Bristol we have looked at the 1D photonic cavity with an atom-like defect to fill this void, be it with the NV-centre in diamond or the quantum dot. However, both these systems are in non-CMOS materials and emit in the visible wavelength band, so are incompatible with scalable silicon-on-insulator photonics. In this project, we hope to push Bristol’s new state-of-the-art fabrication resources (electron beam lithography, photolithography, plasma etching and PECVD deposition) to couple NV-centres contained in nanodiamond to silicon in the dispersive regime, where the dynamics of the cavity are far off-resonance from the cavity wavelength. If this project is successful and repeatable, an atom-like cavity resource would be a leap forward for silicon quantum photonics.



Project Description

At Bristol, we have established an effort to locate nitrogen vacancy (NV) centres in 20 nm nanodiamond hosts on waveguide circuits. The NV-centre is an atom-like defect that emits into 637 nm and has been shown to teleport quantum states over 3 km [1]. Owing to phonon dephasing, the spectrum of an isolated defect is broad without the introduction of a cavity (Fig 1). We have produced a fabrication process where metal electrodes can be simultaneously used as alignment markers and to tune the properties of NV centres and have recently shown waveguide in a suspended silicon nitride (n = 2.0) device fabricated in-house (see Fig 2).
In this project, we would hope to start a new direction: coupling the NV-centre to a silicon (n = 3.5) resonator in the telecoms band (1550 nm). This area of research would provide an important resource for the generation of cluster states in silicon linear optics. In the dispersive regime, the cavity is far off-resonance from the NV centre dynamics at 637 nm. Cycling of the NV centre transition can be read-out as a perturbation in the resonance of the telecoms wavelength cavity [2]. The design of a cavity must be relatively high-Q to resolve this perturbation on the base resonance (~ 1e5 Q) [3]. In addition, the cavity defect should be designed to minimise the density of states (DOS) at the natural emission of the NV centre to limit cavity losses [4]. Foell et al. showed a photonic crystal (PhC) defect with a sub-vacuum DOS at 637 nm for a relatively low Q design (~ 1e3) with the specification that the nanodiamond could be placed in the low-index air hole of the cavity [4]. In this protocol, first the device is designed, then the defect parameters are modified, tuning the local DOS, before the bulk cavity properties are shifted to compensate back to the desired resonant frequency.

Using our new PECVD tool at Bristol we can encapsulate nanodiamonds in silicon through the deposition of silane. This gives access to a host of high-Q PhC cavities where the centre of the field intensity is in the higher-index material. The first step of this project will be to use the techniques of Foell et al. to model a high-Q resonator with a low DOS at the NV-centre emission, using a genetic algorithm from our in-house FDTD photonic component optimiser.
We have gained access to nanodiamond hosts that been grown in ultrapure high-pressure high-temperature conditions to show promising NV-centre spin dynamics [5]. In parallel, the student will learn how to identify an NV centre on a substrate rapidly using confocal microscopy. The student will be introduced to the python library under development to locate NV centres with respect to alignment markers.
In the last few years, PhC in silicon-on-insulator has matured to a level in which resonators with upwards of 1e6 Q can be produced repeatedly in a CMOS compatible (photolithography) process, a necessary condition for commercial use [6]. Using our new e-beam lithography, we can rapidly test high-Q designs that could be replicated in a future foundry run. The third part of the project will be to route the structures from the optimiser into a mask that can be patterned on the new e-beam using IPKISS and CQP's design libraries, around SOI wafers with the pre-located NV centres. If time permits, a motivated student will then partake in the e-beam patterning and preliminary testing of their devices.
This project will be hands-on and engineering-heavy in order to give the student an overview in modern micro fabrication techniques, applicable to quantum devices.
Figure caption:
1) Left: the NV centre spectrum showing emission at 637 nm. Inset: confocal image of an NV centre in a nanodiamond on a DBR substrate. Right: The g(2) function used to measure if emission is from a single quantum emitter.
2) Left: Current in-house device fabricated in silicon nitride showing grating couplers, 200 nm waveguide, and metal electrodes used for alignment and tuning the NV centre emission. Right: waveguiding through the device at the desired emission.

3) Device fabrication procedure. Left: NV centres optically located with respect to alignment markers. Centre: silicon overgrown. Right: electron beam patterns cavity with respect to markers and silicon etched away to form device.

Expected outcomes

Design of a high-Q telecoms band resonator in silicon
Working knowledge of CQP integrated photonic design tools
Appreciation of NV centre dynamics
Understanding of confocal microscopy and techniques used to find NV centres
Fabrication of designed devices (depends on progress of project, motivation of student, other time commitments)

References

[1] Pfaff, Wolfgang, et al. "Unconditional quantum teleportation between distant solid-state quantum bits." Science 345.6196 (2014): 532-535.

[2] Gywat, Oliver, et al. "Dynamics of coupled qubits interacting with an off-resonant cavity." Physical Review B 73.12 (2006): 125336.

[3] Zagoskin, A. M., et al. "Quantum information processing using frequency control of impurity spins in diamond." Physical Review B 76.1 (2007): 014122.

[4] Foell, C. A., A. M. Zagoskin, and J. F. Young. "Engineering silicon-based photonic crystal cavities for NV-center quantum information processing." Optics and Spectroscopy 108.2 (2010): 225-229.

[5] Knowles, Helena S., Dhiren M. Kara, and Mete Atatüre. "Demonstration of a Coherent Electronic Spin Cluster in Diamond." Physical review letters 117.10 (2016): 100802.

[6] Ashida, Kohei, et al. "Ultrahigh-Q photonic crystal nanocavities fabricated by CMOS process technologies." Optics Express 25.15 (2017): 18165-18174.

Required Skills

An interest in photonic devices

Some knowledge of programming, python preferred

Some understanding of atom-photon interactions

An interest in novel device fabrication

Some knowledge of bulk optics for using confocal microscope

Project Location

University of Bristol

Experimental
Photonics Device Engineering, Device Fabrication

17 Device Fabrication: Optimisation of in-house integrated silicon photonics for superconducting nanowire single-photon detectors

Mack Johnson, Döndü Sahin

Abstract:

Integrated silicon photonics has risen as a promising candidate for quantum information processing through various demonstrations [1,2]. One exceptional aspect of the architecture is its ease of integrating superconducting nanowire single-photon detectors (SNSPDs) on chip, which has been demonstrated with a travelling-wave detector based geometry [3,4]. In this project, the aim is to fabricate silicon-on-insulator photonic circuits in-house to characterise and optimise loss properties. This is motivated as a stepping stone towards realising the ring resonator cavity-enhanced SNSPD, where analytics of the concept were published by QETLabs in 2016 [5].
An exciting part of this project is the ability to use the newly obtained Raith VOYAGER electron beam lithography (EBL) system to pattern waveguides into resist that will be etched in the university clean room. You will also take part in optical measurements of these waveguides for characterisation. The major goal in this project is to improve the coupling and propagation losses in our circuits. If this is achieved before the project is due to finish, there is scope to move on to ring resonator based filtering or superconducting nanowire single-photon detectors which involve more advanced processing techniques.

Expected outcomes

The student will understand the process flow for simple single-etch processes from spinning on resist followed by baking and then onto electron beam lithography. From here, the student will learn about the fundamentals of electron beam lithography and get hands-on experience. Since using the VOYAGER generally requires months to learn, it is certain that they would be using it accompanied. Nonetheless, there is opportunity to learn mask design within the VOYAGER software and to learn many functions of the VOYAGER system. The student will also learn how to etch waveguides with a fluorine based reactive ion etching system. If necessary, there will be opportunities to learn surface based characterisation techniques and methods of determining etch rates for Si. The student will also learn the basics of measuring integrated photonic circuits.

References

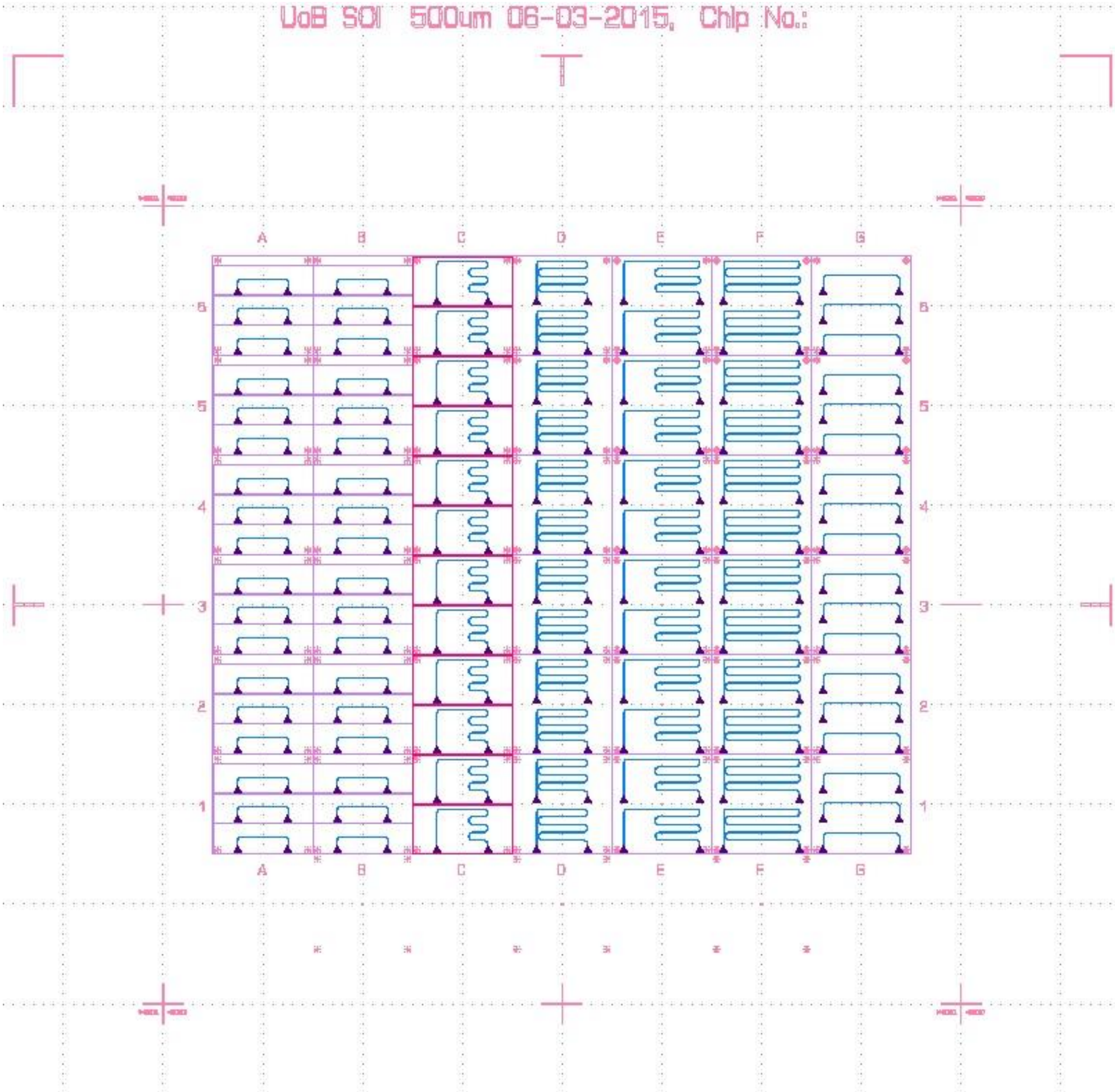
[1] C. M. Wilkes et al, Optics Letters, 41, 22, 5318-5321 (2016)

[2] J. B. Spring et al, Science, 339, 6121, 798-801 (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)



Required Skills

This project can be taken with minimal prior experience - since this is an opportunity to get into a clean room and use systems that most likely a student would not have used before during their undergraduate studies. However, any knowledge of fabrication and/or integrated photonic circuit characterisation would be very beneficial.

Project Location

University of Bristol

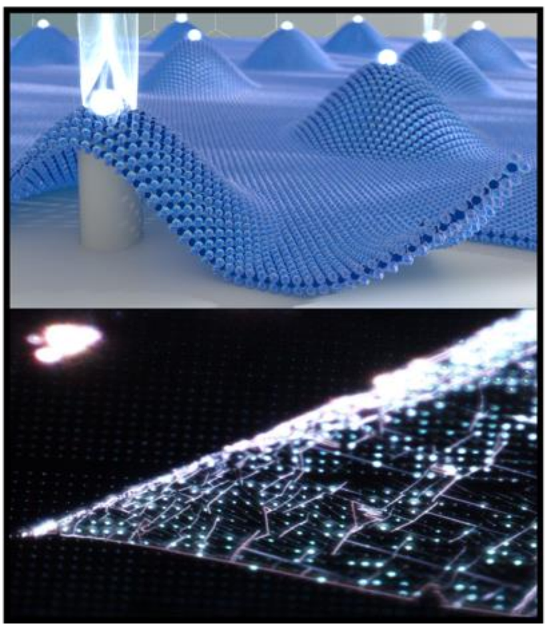
Experimental
Quantum Information Science, Communications, Quantum dots, Device Fabrication

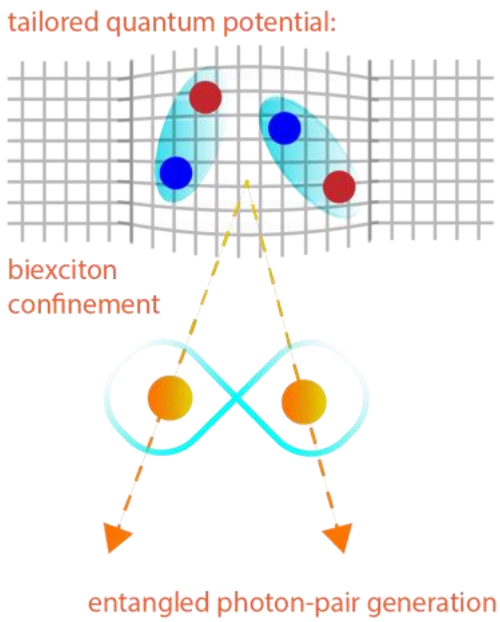
18 Quantum photonics with atomically thin layered materials

Mete Atature, John Rarity

Abstract:

Quantum dots (QDs) are 0-dimensional structures in a semiconductor with many properties resembling those of the atoms. For example, single excitons trapped in a QD can recombine emitting single photons. This provides a robust quantum interface between excitonic spin and photons. Such a light-matter interface lies at the heart of developing quantum networks and solid-state systems offer the great promise of efficiency. QDs in 2d-Transition Metal Dichalcogenides (2d-TMDs) such as WSe2 and WS2 have been observed only very recently: these atomically thin materials combine the advantages of light-matter quantum interfaces with the technological relevance and ease of photonic integration on chip. In Cambridge we have developed a technique to deterministically create large arrays of QDs in 2d-TMDs using nanopatterned substrates for strain engineering at the nanoscale[1]. This allows for conducting robust studies into the fundamental nature of these quantum confined excitons, as well as their promise for quantum photonics and information processing. Exploring the role of the deformation may allow direct tailoring of the quantum states hosted in the QDs: with the aim of fabricating QDs hosting biexcitons, which can recombine to emit entangled photons[2]. This level of control, and the ease of on-chip integration, offer exciting avenues in contemporary quantum optics research.
The main aim of this project is to demonstrate quantum entanglement in photons generated via a biexciton/exciton cascade photon pair emission. Photon correlations, quantum interference and Bell’s inequality measurements will be the standard tools. To investigate the control we can exert over the photonic properties such as wavelength and bandwidth, we will investigate various designs of pillar height, apex shape and material. The student will learn both quantum optics concepts and cleanroom fabrication techniques and handling of 2d materials (exfoliation and transfer).





Project Description

There are multiple research directions in this particular field including the creation of spin-photon interfaces as well as room temperature operational devices. While the project here is focused on photonic entanglement, the student will be encouraged to participate in other topics as well. If the student is interested, a placement may take place at BT research facilities to learn about the communications infrastructure for testing and implementing single-photon quantum communication protocols.
For more information about the project or about the research team and environment, please email Mete Atature (ma424@cam.ac.uk).

Expected outcomes

The student will work with a small team to achieve the following steps in the course of the PhD:
- demonstration of exciton/biexciton cascade emission
- demonstration of quantum entanglement in cascade photon pair emission
- integration of entangled photons into photonic wavequide circuits
- demonstration of electrically generated entangled photon pairs on chip

References

1. Palacios-Berraquero, C. et al. Large-scale quantum-emitter arrays in atomically thin semiconductors. Nat. Commun. 8, (2017).

2. He, Y.-M. et al. Cascaded emission of single photons from the biexciton in monolayered WSe2. Nat. Commun. 7, 13409 (2016).

Required Skills

The student must have a deep understanding of quantum optics and a strong interest in the topic. Skills in optical measurement techniques, as well as prior experience is highly desirable. A good understanding of solid-state physics is desirable, but secondary. Device fabrication will be done by multiple members of the research team, thus it is not a key requirement.

Project Location

University of Bristol, Other academic partner

Experimental
Quantum Information Science, Communications, Computing, Quantum dots, Photonics Device Engineering

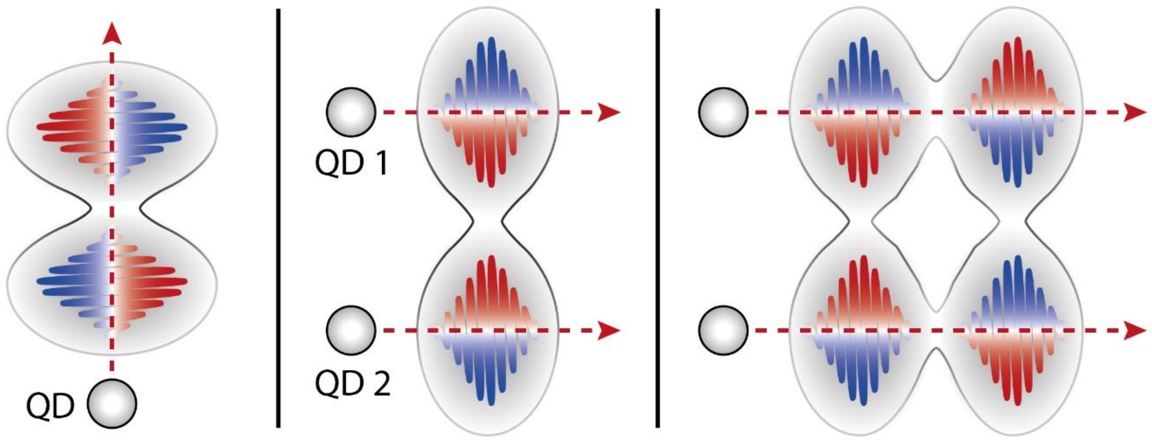
19 Photonic Cluster State Generation using Quantum-Dot Spins

Mete Atature, Ruth Oulton

Abstract:

Quantum dots are semiconductor structures that confine electron and hole motion in all three dimensions. Consequently, they provide very stable and optically accessible traps for individual spins. Significant progress has been achieved so far on developing both an understanding of the underlying physics of quantum dots and opportunities in using quantum dots for a number of quantum information processing concepts, including quantum networks. A very recent addition to the current state-of-the-art in this field is the achievement of a distant qubit-qubit entanglement via a common photonic channel with world-record operational bandwidth over all tested physical systems to-date. Such high bandwidth is also desirable for generating an entangled N-photon stream for quantum computing relevant applications such as boson sampling. Such photon streams, known as cluster states, can be generated using a single optically active quantum dot spin. The limit to the number of quantum-correlated photons in a stream is determined predominantly by the coherence time of the spin. In self-assembled quantum dots, this is typically a few microseconds, while the single photon generation time is sub nanosecond. Therefore, the potential to generate a very long stream is very high, and the challenge lies in the efficiency of detection.

This project aims to analyse and construct the system that will generate a photonic cluster state comprising more than four photons generated via optically accessed quantum dot spin. By accessing the quantum dot transitions selectively using resonance fluorescence single photon generation, and using all-optical coherent control of spins and high-bandwidth electronics, arbitrary number of entangled photon states can be generated in this system operating as a spin turnstile. The final goal will be to generate deterministically a two-dimensional photonic cluster state by incorporating a spin-spin entangling gate between two independent quantum dot systems.



Project Description

This is a high-risk high-reward project and there are multiple research directions in this particular field. While the project here is focused on photonic cluster state generation, the student will be encouraged to participate in other related topics as well.
For more information about the project or about the research team and environment, please email Mete Atature (ma424@cam.ac.uk).

Expected outcomes

The student will work with a small team to achieve the following steps in the course of the PhD:
- demonstration of quantum correlations in a one-dimensional photonic stream
- demonstration of spin qubit protection for enhanced entanglement fidelity
- multi-photon generation from distant entangled-spin systems
- demonstration of two-dimensional entanglement in a photonic cluster

References

1) N. H. Lindner and T. Rudolph"Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings" Phys. Rev. Lett. 103, 113602 (2009)

2) I. Schwartz et al., "Deterministic generation of a cluster state of entangled photons" Science 354, 434 (2016)

3) R. Stockill et al., "Phase-Tuned Entangled State Generation between Distant Spin Qubits" Phys. Rev. Lett. 119, 010503 (2017)

Required Skills

The student must have a deep understanding of quantum optics and a strong interest in the topic. Skills in optical measurement techniques, as well as prior experience is highly desirable. A good understanding of solid-state physics is desirable, but secondary. Device fabrication will be done by multiple members of the research team, thus it is not a key requirement.

Project Location

University of Bristol, Other academic partner

Experimental
Quantum Information Science, Communications, Diamond, Quantum Optics, Optomechanics, Coherent Spin-Photon-Phonon Interactions

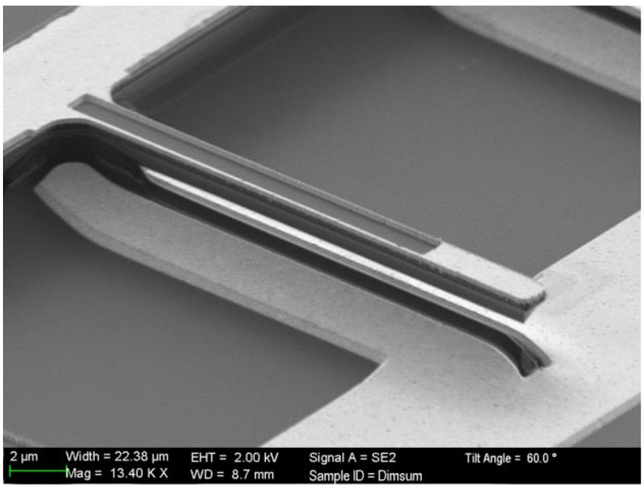
20 Quantum Control of Silicon-Vacancy Centres in Diamond via Optomechanics

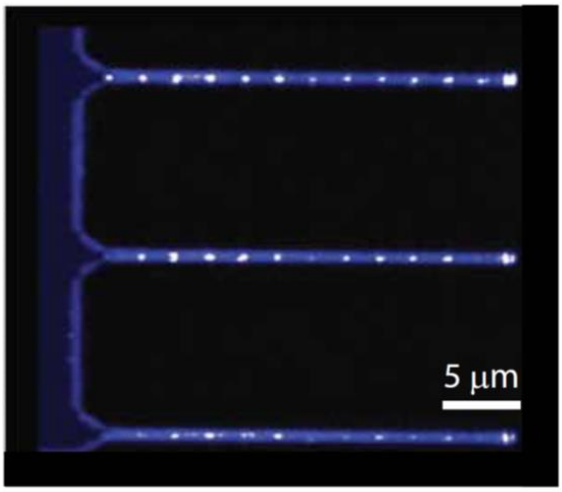
Mete Atature, John Rarity

Abstract:

The optical transparency of ultrapure diamond extends from the infrared into the ultraviolet. Single atomic impurities in the lattice can absorb and emit light in the near infrared region of the spectrum with no disturbance from diamond fluorescence. The most actively studied colour centre is the nitrogen-vacancy (NV) centre, which acts like an isolated single atom or a single trapped ion due to limited coupling to the diamond lattice. The NV centre enabled numerous milestone demonstrations in the field of quantum information science, perhaps the most noteworthy of them all being the distant qubit-qubit entanglement and the loophole-free violation of Bell's inequality. However, the NV's superb spin coherence is not well matched by its optical properties resulting in punishingly small fraction of photons to be useful for quantum network type applications. In contrast, there is a plethora of other optically active impurities including silicon vacancy (SiV) centres that offer promise for promising spin and photonic properties simultaneously, which would be relevant to quantum information processing other quantum-reliant technologies. The SiV centre offers a single electron spin as a stationary qubit and optical transitions as a spin-photon interface. The orbital states are split by 50 GHz in the ground state and can be tuned statically or dynamically by strain. Spin-orbit coupling in the electronic ground state opens the route to controlling the spin state via an applied strain. A diamond-based cantilever/waveguide structure with tailored mechanical resonance can therefore be used to manipulate the quantum state of the spin mechanically without microwave or optical pulses.

The main goal of the project is to achieve coherent control of single SiV spins through the mechanical motion of a diamond-based photonic waveguide. Once achieved, the project can then be extended to couple two SiV spins via a shared vibronic mode allowing phononic mediation of entanglement.





Project Description

There are multiple research directions in this particular field including the creation of spin-photon and spin-spin interfaces for quantum networks. In parallel, the group is investigating other colour centres in diamond which could operate at room temperature potentially. While the project here is focused on realising a spin-photon-phonon hybrid quantum systems, the student will be encouraged to participate in other topics as well.
For more information about the project details and methodology, or about the research team and environment, please email Mete Atature (ma424@cam.ac.uk).

Expected outcomes

The student will work with a small team to achieve the following steps in the course of the PhD:
- demonstration of spin state tuning by voltage-controlled waveguide cantilevers
- demonstration of coupling of SiV states to the motion of a driven waveguide
- demonstration of coherent spin rotation induced by mechanical motion
- demonstration of entanglement generation via the hybrid spin-photon-phonon interface

References

1) Y.-I. Sohn et al., "Engineering a diamond spin-qubit with a nano-electro-mechanical system" arXiv:1706.03881 (2017)

2) D. D. Sukachev et al., "Silicon-Vacancy Spin Qubit in Diamond: A Quantum Memory Exceeding 10 ms with Single-Shot State Readout" Phys. Rev. Lett. 119, 223602 (2017)

3) B. Pingault et al., "Coherent control of the silicon-vacancy spin in diamond" Nature Comms 8, 15579 (2017)

Required Skills

The student must have a deep understanding of quantum optics and a strong interest in the topic. Skills in optical measurement techniques, as well as prior experience is highly desirable. A good understanding of solid-state physics is desirable, but secondary. Device fabrication will be done by multiple members of the research team, thus it is not a key requirement.

Project Location

University of Bristol, Other academic partner

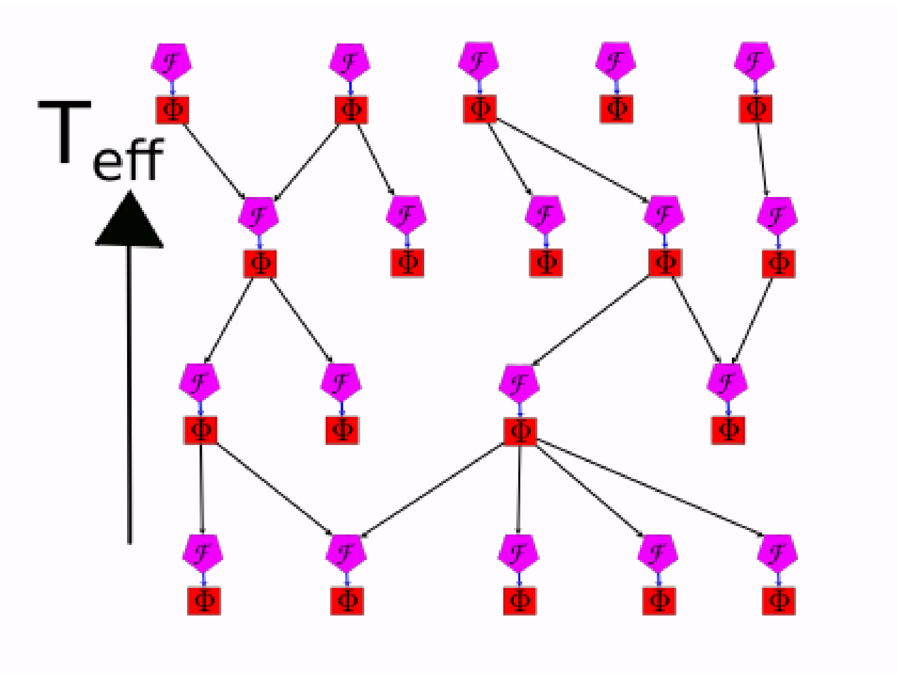
Simulation
Computing, optimisation

21 Multi-mechanism hybrid quantum optimization

Nicholas Chancellor, Viv Kendon; Peter Turner

Abstract:

Quantum computing devices, in particular quantum simulators, such as the devices manufactured by D-Wave systems Inc. promise to deliver powerful new computational tools, based on the fundamental laws of the world we live in. These devices are particularly appealing because they can be brought to bear on a wide variety of important real world problems. However, the early generations of these devices are going to be severely limited in both size and performance. For this reason it is necessary to consider how to employ these tools in the most effective way, which means using them as subroutines along with the very powerful classical algorithms we already know about. Moreover, to make these subroutines as robust and flexible as possible, we therefore construct protocols where multiple mechanisms can act cooperatively to help solve problems. We have designed such protocols, however they are untested, this project is to numerically test them.



Project Description

There are generally two approaches to quantum computing, gate based quantum computing, where the processing of information is performed by sets of discrete gates, and continuous time quantum computing, where the problem is mapped to an energy landscape and quantum fluctuations are used to search for optimal solutions, corresponding to low energy states, or to sample. This project will be based on the second approach, where the problem is mapped to an energy landscape and continuous time dynamics solve the problem. There are three established protocols for performing continuous time quantum computing. One is adiabatic quantum computing, in which the adiabatic theorem of quantum mechanics guarantees that a slowly changing system initialized in its ground state will remain in the lowest energy state even as this state changes between something easy to initialize to the solution of a difficult problem. Another approach is quantum annealing, where interactions with a low temperature bath drive a quantum system toward a low energy state, this is the dominant mechanism in the devices manufactured by D-Wave Systems Inc. Finally there is quantum walk, where hopping between potential solutions is driven at a fixed rate.

As they are traditionally formulated, continuous time quantum computing protocols (quantum walk, adiabatic quantum computation, and quantum annealing) start from an unbiased superposition of all possible solutions. While this is the simplest choice from a theoretical point of view, it is rather wasteful of information, in most real situation, something will be known about what the problem solution is expected to look like, either from using classical algorithms on the problem, or at the very least from previous calls to the quantum hardware. Some work has been done already to look into how to incorporate this information into open system protocols [1,2], closed system adiabatic protocols [3], and quantum walk like protocols [4]. In particular, protocols very similar to those proposed in [1] are actually going to be implemented on the quantum annealing technology produced by D-Wave Systems Inc. soon.

This project will consist of numerical examination of how protocols can be designed which on one hand are able to use biased starting conditions, while on the other hand are able to simultaneously take advantage of the underlying mechanisms of quantum walk, adiabatic quantum computation, and quantum annealing. We have already developed tools to simultaneously take advantage of the mechanism behind adiabatic quantum computing and quantum walk by interpolating between the two protocols [5], and have shown that these interpolated protocols can still retain a quantum advantage and improve performance on realistic systems. Furthermore, since the mechanism behind quantum annealing is dissipation which always drives the system toward low energy states, this mechanism will be compatible with any adiabatic protocol which keeps the system in its ground state.

Since open quantum systems are more difficult to simulate, this project will focus on proof-of-principle studies based on biased starting conditions for hybrid quantum walk and adiabatic quantum computing protocols. We have designed a mathematical construction to do this. We will first numerically demonstrate that our biased protocol construction does indeed preferentially find states which are on one hand near the state we bias the system toward, and on the other hand at a low energy. We will then start to examine simple algorithms which use these biased searches, and compare their performance with more traditionally formulated (i.e. unbiased) algorithms, as well as previously designed protocols in the adiabatic [3] and quantum walk [4] limit.

If time permits, we will also examine some other novel features of these protocols, such as the fact that they can encode not only information about a solution candidate, but also the bitwise certainty of these candidates. The protocols we will examine are a multi-mechanism generalization of the `inference primitive' concept proposed in [2], these computational primitives are versatile computational tools, and can be used to construct a wide variety of algorithms, the figure depicts a representation of an inference primitive based evolutionary algorithm, with the squares representing calls to a quantum device, and pentagons representing classical information processing.

Expected outcomes

i.e. What will the student be able to do by the end of the project? Please try and be as specific as you can, indicating how likely these outcomes might be.

This project will allow the student to have a lot of practice at programming and scientific computing. They will learn how to simulate quantum systems with time dependent Hamiltonians, a useful skill for a wide variety of applications. The core of this project will be based on numerical matrix diagonalization, a set of methods which have a wide applicability, not only within quantum simulations, but also very generally, most notably, the original Google search algorithm was based on numerical diagonalization of matrices. Since much of the project will essentially be performing numerical experiments, the student will also gain substantial experience in data analysis. Given the nature of the project, we will also teach the student about quantum algorithms, in particular about quantum optimization algorithms.

References

[1] Nicholas Chancellor, Modernizing Quantum Annealing using Local Searches New Journal of Physics 19, 2, 023024 (2017).

[2] Nicholas Chancellor, Modernizing Quantum Annealing II: Genetic algorithms with the Inference Primitive Formalism arXiv:1609.05875 (2016).

[3] A. Perdomo-Ortiz, S. E. Venegas-Andraca, and A. Aspuru-Guzik, A study of heuristic guesses for adiabatic quantum computation Quantum Inf. Process 10: 33. doi:10.1007/s11128-010-0168-z (2011).

[4] Tobias Grass and Maciej Lewenstein, Hybrid annealing: Coupling a quantum simulator to a classical computer Physical Review A 95, 052309 (2017).

[5] James G. Morley, Nicholas Chancellor, Sougato Bose, Viv Kendon Quantum search with hybrid adiabatic-quantum walk algorithms and realistic noise arXiv:1709.00371 (2017)

Required Skills

This project will require at least some previous experience programming and scientific computing. Basic knowledge of quantum mechanics is also expected. We usually work in python, but the project could be done in a different language depending on student experience and preference. Experience in data analysis is also a plus, but not required.

Project Location

University of Bristol, Other academic partner

Theory
Quantum Information Science, Metrology

22 Quantum optical designs.

Peter Turner, Stephen Bartlett

Abstract:

The jury is still out on which 'platform' will dominate the future of quantum information processing. One subfield is known as continuous variables, where quantum information is encoded into physical systems with infinite dimensional rather than discrete Hilbert spaces. In practice these are most often realized as optical modes.
For the multitude of quantum information concepts in discrete variables (DV), there is usually a continuous variable (CV) analogue. One example of this is state tomography, (or more generally quantum estimation), where in fact the CV approach preceded the DV approach, and continues to be very well studied. It is known in DV that mathematical concepts such as mutually unbiased bases (MUBs) and symmetric informationally complete POVMs (SICPOVMs) are useful for estimating various quantities, and so it stands to reason that these concepts (which are examples of a more general concept called a "t-design") should have CV analogues. However, previous work has shown that the analogy in this case is fraught -- if it exists at all, it will require some new lines of thinking.
This project is one attempt at a new line of thinking in this area. Rather than considering the entire infinite dimensional Hilbert space of a single mode, we will introduce subsets of states that are (hopefully) well behaved, e.g. expected number bounded states, or so-called "z-regular" states. We will then look at how one might realize the t-design conditions on these sets. We expect that the analogy between DV and CV should hold somehow -- there should be some set of measurements of a single mode, physically motivated, that reproduce at least some of the desired DV properties. We will use these properties as guidelines in our search, but will need to be creative in doing so. In particular, we will try to use quantum information concepts like entanglement fidelity to motivate new ways of looking at the problem.

Project Description

Please come speak to me if you have questions. This is joint work with Prof. Bartlett at the University of Sydney and could involve Skype meetings at weird hours of the day.

Expected outcomes

The ultimate goal would be a well defined, physically motivated set of states which have the desired t-design properties that make them useful for state estimation, (as well as other applications). This would find use in major CV quantum computation efforts such as those in Tokyo and Toronto. The student will come out with a thorough appreciation for the difference between DV and CV quantum mechanics and information, as well as hands on knowledge of quantum estimation.

References

R. Blume-Kohout and P. S. Turner, CMP 326, 755 (2014).

T. Tyc and B. C. Sanders, J. Phys. A 37, 7341 (2004).

Required Skills

Familiarity with the concepts and tools of CV will be required, most of which were covered in the quantum optics course. Quantum information concepts such as fidelity and entanglement measures will be useful.

This is an exploratory project so creativity will be required -- we'll need to think about the problem and bring both physical and mathematical intuition to bear. Therefore the student will need to be motivated to think about the various background concepts and try to apply them in new ways, as opposed to "turning the crank" as it were.

Project Location

University of Bristol

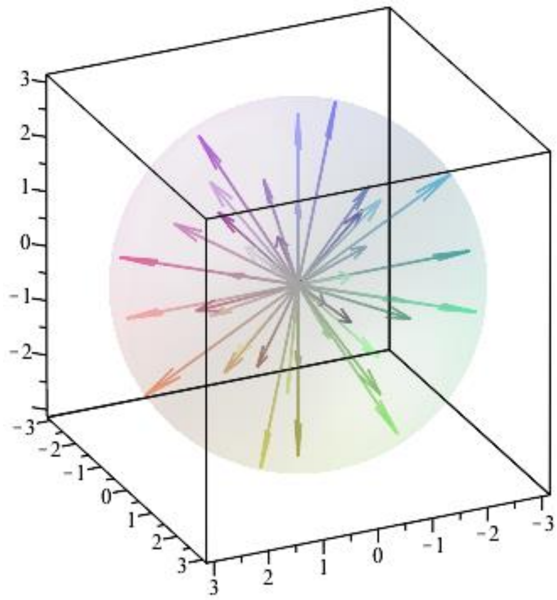
Theory
Quantum Information Science

23 Randomness resources for quantum technologies

Peter Turner, Damian Markham

Abstract:

Randomness is an important resource in both classical and quantum information theory, as well as in many other areas of physical science. However, true randomness can be a costly resource, and we often make do with pseudorandomness. In the context of quantum information theory, a useful pseudorandom resource is what's know as a "t-design" -- an ensemble of quantum operators that 'mimic' the ideal truly random ensemble. These find use in various areas of theory and also in practice, the best known of which is probably randomized benchmarking protocols that are now an 'industry standard' for characterizing real quantum hardware.
The search for t-designs takes many forms and touches on many areas of physics and pure mathematics. Motivated by linear optical quantum computing efforts, the concept of measurement based unitary t-designs were recently invented. These ensembles have a different structure than the 'usual' circuit based ones used most frequently, in particular the Clifford ensemble. Study of this structure has led to the discovery of a systematic construction of an infinite family of single qubit 2- and 3-designs, which could be useful in randomized benchmarking of qubit systems with particular noise models.
This project will look into the prospect of generalizing this construction to multiple qubits. This will involve reviewing the known results and tools used in the field. We will then attack the problem using these tools. The project is obviously amenable to a numerical approach, and so familiarity with software like MatLab would be useful. There are also analytical approaches we could take, including using group representation theory and/or entanglement theory -- this will depend on the student. There are many milestones along the way, including a 2 qubit construction, a single qudit construction, and restrictions to t=2 and/or t=3, which are already of practical interest.



Project Description

Please come speak to me if you have questions and I can try to do a better job of explaining!

Expected outcomes

The stretch goal of this project is to find a systematic construction of multipartite t-designs, which would be publishable -- however, we need to manage expectations. Along the way the student will learn about: formal approaches to randomness and pseudorandomness, the Haar measure on groups, unitary bases, t-designs and tools like the frame potential, as well as analytic and/or numerical techniques for implementing these tools. Understanding the role that entanglement plays in such a construction is another aspect of the problem.

References

P. Turner and D. Markham, PRL 116, 200501 (2016).

R. N. Alexander, P. S. Turner and S. D. Bartlett, PRA 94, 032303 (2016).

D. Gross, K. Audenaert and J. Eisert, JMP 48, 052104 (2007).

Required Skills

Computer algebra and/or numerical programming skills will be required. With enough computing power the problem can be brute forced if necessary, but some mathematical sophistication should go a long way.

Project Location

University of Bristol

Experimental
Metrology, Computing, Simulation, Diamond, Photonics Device Engineering, Machine learning

24 Towards a solid-state qubit photonic interface for electromagnetic field sensing and modular quantum computation

Raffaele Santagati, John Rarity, Graham Marshall, Anthony Laing, Matt Day

Abstract:

Converting the internal qubit state of a solid-state system to a photonic qubit can been used as a useful resource. An example use of the photonic quantum state is to learn about the spin systems’ properties with exponential speedup in the rate of learning over classical measurements of the system. Spin systems can be used as electromagnetic field sensors due to the sensitivity of their dipole orientation to external electromagnetic fields. The sensitivity of the dipole moments allows for sensing of single atoms, molecules or cells placed near the spin system. Monitoring the internal quantum state of a spin system using emitted photons as a coherent channel could be used to improve our knowledge of the dynamics of the physical system and improve the performances of the spin system as a sensor. Other applications of a solid-state qubit photonic interface include quantum information processing, where multiple spins could be entangled by interfering their emitted photons.

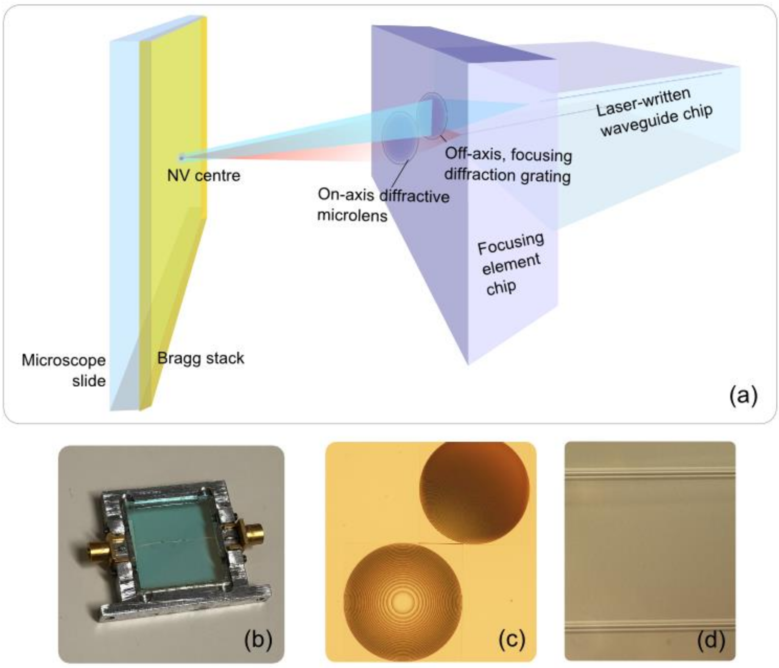
A previous attempt at transferring a spin qubit to photons have used laser written waveguides in diamond, however the result was lossy and had low yield due to diamond not being the ideal host for such waveguides. Therefore robust and coherent transfer of solid state quantum states into photonic qubit states still remains an open challenge.

We have developed a miniature confocal system based on diffractive lenses and laser written waveguides in glass as a photonic interface for NV centres located in nanodiamonds on a Bragg stack (see attached figure). The excitation and collection waveguide exist in the same substrate and are directly coupled into fibre. Diffractive lenses both direct the excitation light onto the NV centre and collect the resulting fluorescence into the waveguide. Once aligned, the full system will act as a fibrised source of coherent photons.

Project Description

The project will concentrate on using the fabricated micro-optical assembly for NV centre control and readout. First, a suitable NV centre will be found by using the lens and waveguide as a confocal microscope, using photoluminescence (PL). The spectrum of the NV centre will be confirmed and a g(2) correlation measurement will be performed to confirm that quantum states of light are being collected. Once an NV centre has been successfully coupled, a whole host of measurements can be performed including optically detected magnetic resonance (ODMR) and coherent Rabi oscillations.

Beyond the scope of the project, the collected photons can be used to learn the internal state of the NV centre and its Hamiltonian, applying it to magnetic field sensing. Advanced photonic interfaces can be designed and fabricated to increase the functionality and performance of the device, towards the realisation of the coherent transfer of the spin quantum state. There is significant scope for a full-fledged PhD project for developing integrated, compact and robust quantum sensors, as well as realising a modular NV centre quantum computing architecture.



(a) A schematic of the compact, micro-optical confocal microscope for photonically coupling to an NV centre
(b) The mounted NV centre sample with gold wire for microwave control.
(c) Diffractive optics fabricated using electron beam lithography, designed to couple waveguides to the NV centres
(d) A phase-contrast image of laser-written waveguides in the chip to be used for NV centre control

Expected outcomes

The student will learn the basic of quantum optics behind the physics of NV centres in diamond, the standard driving techniques (ODMR, Rabi, etc.) and the operating principles of the coupling scheme proposed here. The student will also learn the fundamentals of integrated quantum photonics and waveguide devices. Further they will operate a state of the art hybrid quantum system experimental set-up while designing the next generation of devices and systems towards a mature quantum technology.

References

Dolde, Florian, et al. "Electric-field sensing using single diamond spins." Nature Physics 7.6 (2011): 459-463.

Hong, Sungkun, et al. "Nanoscale magnetometry with NV centers in diamond." MRS bulletin 38.2 (2013): 155-161.

Paesani, Stefano, et al. "Experimental Bayesian Quantum Phase Estimation on a Silicon Photonic Chip." Physical Review Letters 118.10 (2017): 100503.

Nickerson, Naomi H., Joseph F. Fitzsimons, and Simon C. Benjamin. "Freely scalable quantum technologies using cells of 5-to-50 qubits with very lossy and noisy photonic links." Physical Review X4.4 (2014): 041041.

Hadden, J. P., et al. "Waveguide-coupled single NV in diamond enabled by femtosecond laser writing." arXiv preprint arXiv:1701.05885 (2017).

Required Skills

No specific skills are required, however the following skills will aid project progress:

- Alignment of optical devices
- Labview experience
- Passion for physics

Project Location

University of Bristol

Theory
Fundamentals of Quantum Mechanics, Quantum Information Science, Communications, Computing

25 Towards practical circuits for compression of quantum information

Sarah Croke, Peter Turner

Abstract:

Shannon's seminal work allowed information to be rigorously quantified – what is the minimum number of uses of a (in general imperfect) communication channel needed to reliably transmit a message? It proved so influential in launching the information revolution of the mid 20th century in part because good codes reaching or coming close to Shannon's bounds were quickly discovered, making this work not just of theoretical but of considerable practical interest. Shannon's bounds quantify fundamental limits on data compression and transmission, which further are realisable using coding techniques now in everyday use in every laptop computer, tablet and mobile phone. As we sit at the brink of a new quantum information revolution, good techniques for compression, storage and transmission of quantum information will be just as crucial in developing nascent quantum communication technologies and quantum memories. Although a complete understanding of the quantum analogue of Shannon theory remains an active area of research, quantum compression, quantum source coding, and entanglement concentration are three protocols which are rather well understood theoretically, and which provide an analogue to Shannon's noiseless and noisy coding theorems (although only for restricted kinds of noise). As quantum communications technologies continue to develop, we can expect these rather fundamental protocols to play an important role in the storage and transmission of quantum information. All three of these have at their heart the quantum Schur transform, and exploit permutation invariance to represent information efficiently.

This project will explore the resources needed to implement the Schur transform. In particular, it will investigate to what extent the required operations can be performed in parallel, in order to reduce the overall running time. It is a theoretical project, but aims to understand the experimental requirements for physical implementation of these protocols.

Project Description

Background and motivation:

There are three closely related tasks relevant to the storage and transmission of quantum information: quantum compression [1], entanglement concentration [2], and quantum source coding [3]. All of these take as a basic element the quantum Schur transform [1,4,5], a quantum algorithm which physically is equivalent to angular momentum addition.

Angular momentum is a fundamental conserved physical quantity, and addition rules for angular momenta – angular momentum coupling – in quantum mechanics are an important theoretical tool in understanding the behaviour of composite quantum systems. Angular momentum coupling arises, for example, in spin-orbit coupling in atomic physics, and in understanding the allowed spin states of a pair (or a larger number) of spin-1/2 particles. In quantum information processing angular momentum coupling, through the Schur transform, turns out to be an important primitive, and is likely to be a key component in developing secure quantum communication over long distances.

In essence, the Schur transform separates information about the total spin angular momentum (magnitude and direction) of a set of N spins from the information about whether each individual spin is aligned or anti-aligned with the total spin. An explicit high-level algorithm is known, which has running time polynomial in the number of systems processed, N [3-6]. This project will investigate alternative ways of performing the Schur transform, with the aim of understanding the ultimate experimental requirements.

There are examples in the literature of experimental implementations of compression of a quantum ensemble [7] and quantum source coding [8], in each case transforming the information represented by three qubits into just two. There are also quantum repeater schemes in the literature that are based on entanglement purification (of which entanglement concentration is a special case) [9]. What has not yet been achieved in any of these cases is an implementation that is i) universal – i.e. doesn’t rely on any prior knowledge, ii) optimal – achieves known theoretical bounds, and iii) scalable – not restricted to small numbers of input systems. This will soon be technologically feasible, and presents a challenge for early quantum information processors, currently under development.

The project:

The project will begin with a review of angular momentum addition (e.g. [10]), and of existing algorithms for performing the Schur transform [1,4-6]. These have in common that they read through a register of spins one at a time, performing angular momentum addition between each new spin and the total read so far. This has certain advantages: notably this may be performed in a streaming way, that is reading in and processing systems one at a time rather than all at once, which allows for a space efficient algorithm – a quantum processor of size O(log N) is enough to process N systems [6]. Further, only the Clebsch-Gordon coefficients (the matrix elements describing the angular momentum coupling) for adding a single spin-1/2 system to an existing spin d system are needed, and not more general angular momentum transformations. Nevertheless, there may be advantages to different couplings – for example performing existing protocols in parallel on two blocks of N/2 spins, and then combining the results has, at a naïve estimate, a running time that is polynomial in N/2 (rather than N), and could prove a more time efficient option. However, this requires consideration of more general angular momentum couplings, and the complexity of these transformations must also be carefully considered.

This project will consider different methods of processing a register of N qubits, all with the ultimate aim of achieving the Schur transform. We will focus in particular on the extent to which parts of the algorithm may be performed in parallel, by judicious choice of how to perform the angular momentum coupling. For small numbers of qubits this can be done analytically, to understand the general features of the scheme. Investigation of larger N may require numerical simulations.

The project will be co-supervised by Dr Sarah Croke, at the University of Glasgow, and Dr Peter Turner in Bristol. The project will take place in Bristol: we will hold regular weekly Skype meetings to get the project started, and Dr Croke will visit Bristol in the first few weeks of the project. Additional support between meetings as necessary will be available in person from Dr Turner, or by email or Skype from either supervisor.

Students with any questions about what the project entails are welcome to email me at sarah.croke@glasgow.ac.uk.

Expected outcomes

By the end of this project the student will:

- Understand the basics of information theory, in particular compression and entanglement concentration,
- Be able to calculate rules for angular momentum addition, as well as understand the relationship between the physics of angular momentum addition and theoretical aspects of quantum information,

- Be comfortable with the circuit model of quantum computation, and be able to make estimates of computational complexity,
- Understand how symmetries can be used to simplify the representation of data,
- Have gained some familiarity with group representation theory.

References

[1] M. Plesch and V. Buzek, Physical Review A 81, 032317 (2010).

[2] C.H. Bennett, H.J. Bernstein, S. Popescu, and B. Schumacher, Physical Review A 53, 2046 (1996).

[3] B. Schumacher, Physical Review A 51, 2738 (1995).

[4] D. Bacon, I.L Chuang, and A.W. Harrow, Physical Review Letters 97, 170502 (2006).

[5] W.M. Kirby and F.W. Strauch, arXiv:1709.07119

[6] R. Blume-Kohout, S. Croke, and Daniel Gottesman, IEEE Transactions on Information Theory 60, 334 (2014).

[7] L.A. Rozema, D.H. Mahler, A. Hayat, P.S. Turner, and A.M. Steinberg, Physical Review Letters 113, 160504 (2014).

[8] Y. Mitsumori, J.A. Vaccaro, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, Physical Review Letters 91, 217902 (2003).

[9] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, Reviews of Modern Physics 83, 33 (2011).

[10] J.J.Sakurai, Modern quantum mechanics (Addison-Wesley, 1994).

Required Skills

This is a theoretical project, suitable for a mathematically strong student. It will entail angular momentum algebra, some group representation theory, and the circuit model of quantum computation. Familiarity with these is not a pre-requisite, but an interest in and aptitude for the theoretical aspects of quantum information science would be advantageous.

Project Location

University of Bristol

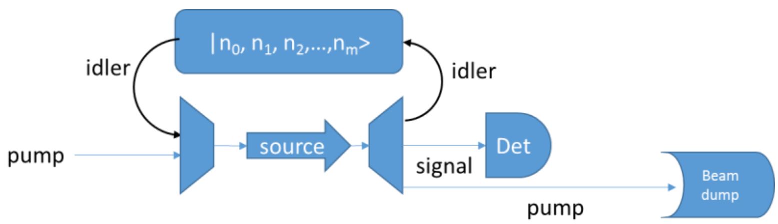
Theory, Simulation
Fundamentals of Quantum Mechanics, Quantum Information Science, Metrology, Simulation, Photonics Device Engineering

26 CHIMERA - Designing Nonlinear Photonic Feedback Devices

Will McCutcheon, Jorge Barreto

Abstract:

Nonlinear processes are the necessary ingredient for generating quantum states from classical resources. Particularly, the pursuit of pure single photons for computation, ultra-phase-sensitive states for quantum metrology, and squeezed states for communication and long range entanglement generation, all require control of nonlinear interactions engineered to the task. Whilst single photon generation in isolated nonlinear regions is becoming well understood, modelling coupled or cascaded nonlinear processes requires further advancement. Developing tools suitable to understand cascaded nonlinear processes is the aim of this project, with sights to apply these results to understand the states produced and their potential applications in fock state generation, and parameter estimation. We will develop a recently derived model for such systems, and explore how tuning the system affects relevant figures of merit for these purposes. Whilst the focus of this project is to develop an understanding of nonlinear processes to model and design a number of devices, in the longer term this will be leading to full mask design via QETLabs integrated photonics processes, and subsequent experimental characterisation. Ultimately, attaining a strong grasp of nonlinear quantum optics in the Heisenberg picture by reviewing and developing current state of the art models of such systems, will set the stage to further apply these techniques, ubiquitous to quantum optics.



Project Description

Control of non-linear optical processes provides the key tools to develop pure single photon sources, perform optical frequency conversion, generate Fock states, and mediate single photon interactions. Integrated optical circuits provide a testbed to develop models appropriate for these tasks and verify them experimentally. Whilst the majority of implementation focusses on the use of isolated nonlinear processes for photon generation, followed by linear optical manipulation, coupling multiple nonlinear interactions provides significantly broader scope for applications. To model these coupled nonlinear systems requires careful application of quantum optical principle, and expansion of theory in this direction, to new regimes of interest is a rapidly expanding area of photonics.

The traditional setting of Spontaneous four-wave mixing, involves two bright pump fields coupling to signal and idler fields, initially in the vacuum state, to generate photon pairs. In the presence of an optical cavity, such as a microring resonator the spectral properties of this process is dominated by the behaviour of the cavity modes. When considering just the single pair production a great deal is known about the process. When dealing with higher order terms, such as multiple pairs, or when considering signal or idler fields initially in a populated state, then more care must be taken to evaluate the result of this nonlinear process. In particular, CHIMERA, a device designed to feedback the exiting idler mode from a microring resonator source into its incoming idler mode, offers the opportunity to explore the properties of these nonlinear microrings with single photon inputs, to investigate and demonstrate four-wave mixing in the single photon stimulated regime. Previous theoretical work has derived expressions for the expected output states of this source, and the possibility for observing single photon stimulated emission in the system has been confirmed. Theoretically exploring generation in the system in the continuous-wave (CW) regime, and with an electro-optically modulated pump, will inform future experimental investigation, as well as future mask design. Evaluation of multi-photon events will highlight the propensity for generating Fock states using nonlinear processes in these systems.

We will plan to spend the first few weeks understanding models of classical cavities, reviewing Heisenberg picture QM with nonlinear Hamiltonians, observing Bogoliubov transformations that result, and beginning to familiarise with both the continuous variable nature of squeezed states and the photon-pair nature of their first-order expansion. We will then be in a good position to follow two existing models of nonlinear processes in cavities [1,5] and begin developing a toolkit necessary to fully understand and simulate them. We will assess these systems for the spectral properties of states produced, and evaluate the properties of squeezed states and heralded single photons generated by such systems.

Next, we will see how recent work developed here can expand these models to systems with cascaded non-linearities, and go on to evaluate and simulate properties of the Fock states produced. We will assess figures of merit for 'good' states, pursue criteria for systems to generate desirable states and model them both analytically and numerically.

This will open up the field for exploring the use of such states for metrology and more general parameter estimation.

Expected outcomes

We will understand the key methods used to model integral quantum systems, including Heisenberg picture quantum mechanics, quantum and classical models of cavities/resonators, Bogoliobov transformations for nonlinear processes, squeezing, and the nature of single photons and fock states. We will review and acquire a broad understanding of the mathematical techniques and figures of merit necessary to classify and characterise 'good' states for single photon generation, fock state generation, and parameter estimation. All these hinge upon the building of an understanding of the spectral properties and statistical properties of optical quantum fields, which underpin almost all applications in quantum engineering and can be readily transferred to systems beyond optics. Consideration of these high-dimensional systems also requires and develops a general understanding quantum information systems, their Hilbert space, the channels which act upon them, and means of modelling them, which describe more high level applications such as computing, communication protocols and the theory of entanglement and quantum correlations.

References

•[1]Spontaneous four-wave mixing in lossy microring resonators, PRA 91, 053802 (2015)

•[2]Strongly driven nonlinear quantum optics in microring resonators PRA 92 033840 (2015)

•[3]Single-photon stimulated four wave mixing at telecom band, arXiv:1607.04380v1 (2016)

•[4]Real-Time Quadrature Measurement of a Single-Photon Wave Packet with Continuous Temporal-Mode Matching, PRL 116, 233602 (2016)

•[5]Photon-pair generation in a lossy microring resonator. I. Theory ,PRA 96 033847 (2017)

•[6]Efficient recycling strategies for preparing large Fock states from single-photon sources — Applications to quantum metrology, PRA 94, 012344 (2016)

Required Skills

Being a theoretically inclined project, the project will involve developing skills learnt in theoretical quantum optics modules already covered, learning and understanding how these techniques are developed into more complete models of nonlinear processes[1,2,5], and applying these skills to expand these models analytically and explore them via simulation. Previous experience with Mathematica not necessary, but encouraged, as simulating and exploring results will likely take this route. Willingness to review mathematical and statistical techniques with regard parameter estimation encouraged. If desired, familiarity with python (and QETLabs' IPCIS packages) would be useful for mask design, though can be acquired.

Project Location

University of Bristol

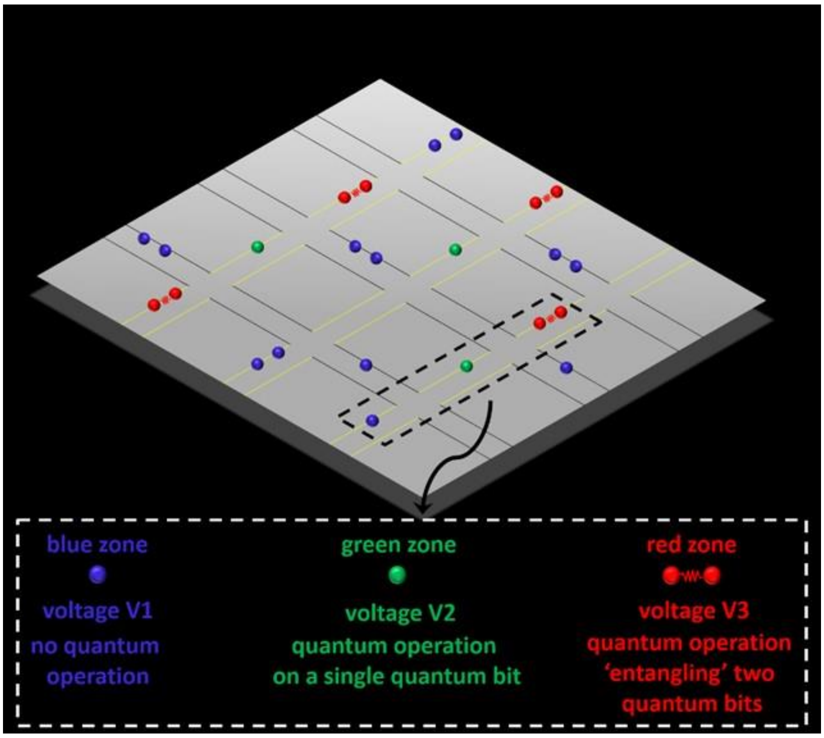
Theory, Experimental, Simulation
Quantum Information Science, Computing, Simulation, Device Fabrication

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

Winfried Hensinger, John Rarity

Abstract:

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.



Project Description

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.

Expected outcomes

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

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

Required Skills

Enjoy experimental physics, enjoy computer simulations

Project Location

Other academic partner

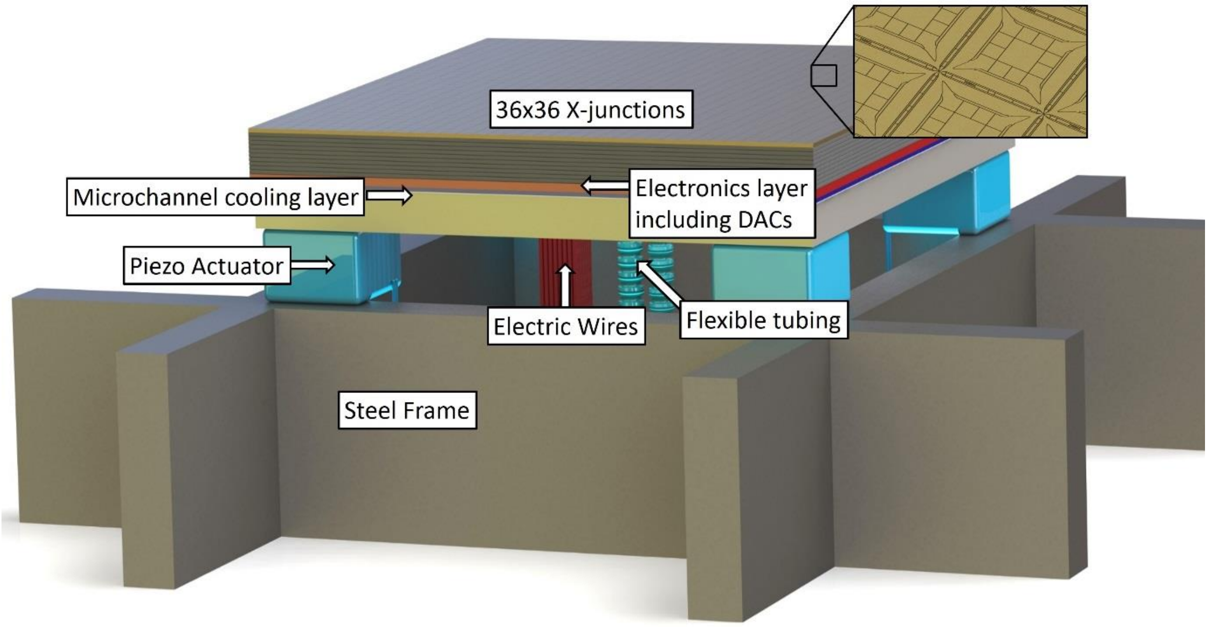
Theory, Experimental, Simulation
Computing, Simulation

28 Quantum computing with trapped ions with global radiation fields

Winfried Hensinger, John Rarity

Abstract:

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 c



omputer. 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.

Project Description

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.

Expected outcomes

Competence in ion trapping experiments, deep understanding of entanglement validiation and verification

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)

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Required Skills

Enjoy theory work, enjoy working in close collaboration with experimental physicists

Project Location

Other academic partner

Experimental
Cryogenics, Detectors

30 Make cryo-temperature photonic experiments viable again

A. Andreas Gentile, J. Barreto, B. Slater, D. Sahin

Abstract:

If moving to cryogenic temperatures is currently essential for the availability of performing single-photon detectors, a reliable protocol for coupling light into the chip's waveguides and keep the coupling along the many hours an experiment requires is a mandatory step. The student will work with a state-of-art closed loop cryostat, that will be adopted in experiments working towards progressively higher integration of quantum photonic experiments.
He will thus have the opportunity to contribute both to the final optimisation of the cryogenic setup, as well as the initial design and characterisation of protocols and tools for automated measurements. These will be required to test the thousands of components expected in photonic chips featuring large scale integration.

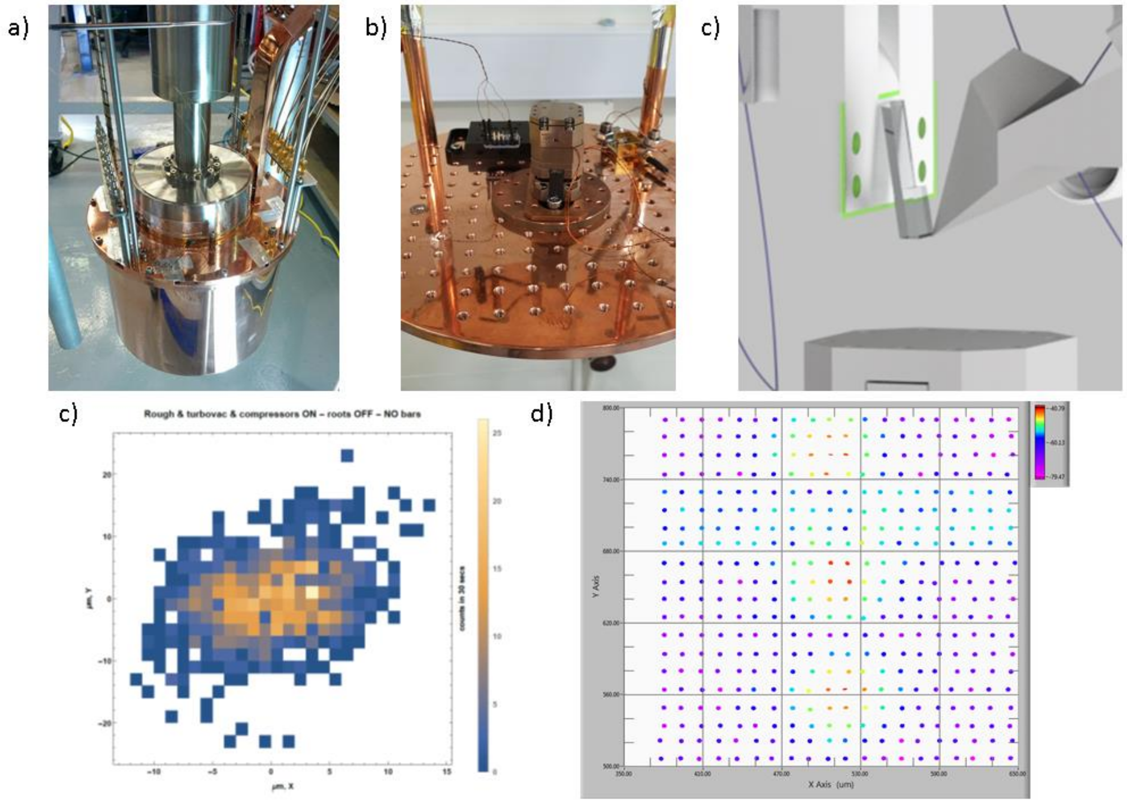


Figure 1: from left to right A) View of the (closed) 1K stage of the ICE-Oxford cryostat, with the closed loop He pumping line (the “piston-shaped” pipe descending from the top). B) Same stage open, hosting the stacked attocubes and the MEMS accelerometer. C) rendered view of the combined glass fibre array and RF probe tip to be installed in the cryostat. D) Histogram plot of in-plane vibrations at the sample stage in the best configuration found so far for the cryostat. It can be seen that if most absolute displacement events lay in the [- 5, +5] um interval, seldom events also occur at displacements as high as 20 um along the direction that is affected the most. E) Heat map obtained inside the old cryostat with the legacy LabView code, for the coupling of light into a chip. Notice the red pattern where the grating couplers are located.

Project Description

1. Background

The route towards highly integrated quantum photonic chips is currently focusing to challenges related to at least three crucial components. i) Sources, already successfully implemented in SOI chips, even if alternative materials and structures are actively investigated. ii) Filters, to attenuate the pump light: high extinction ratios are easy to obtain for non-integrated components, whereas

integrated equivalents are an active research field. iii) Switches, offering both high-speed and high extinction ratios, iv) Detectors, whose embedding in the photonic chip may grant a significant reduction in the coupling losses out-of-chip. Larger scale experiments will also require some degree of automatized manipulation , in order to perform systematic tests on hundreds of integrated structures.
A certain number of different technologies have been proposed along the years to detect single photons, exhibiting the key properties required for quantum photonic technologies [Hadfield09]. However Superconducting Nanowire Single Photon Detectors (SNSPD) have proven by far the most promising technology to detect photons in the mid-infrared spectral range [Natarajan12]. This is a limitation, though, in the range of operating temperatures for the envisaged integrated chip: for the current state-of-art, the circuit shall be hosted in (some different stages) of a cryostat. Nevertheless, the approach has provided promising results in proof of principle experiments [Schuck16].
If moving to cryogenic temperatures is currently essential for the availability of performing detectors, a reliable protocol for coupling light into the chip's waveguides and keep the coupling along the many hours an experiment requires is a mandatory step, as it lies at the heart of every integrated photonic technology. In room temperature experiments, the adoption of optical tables with appropriate dumping mechanisms offers plenty of solutions for interfacing the photonic circuits and to isolate the system from the environment. In a cryogenic environment, such as the required for the operation of integrated SNSPDs, this very same process becomes increasingly complicated with limitations arising from: a) low temperature, b) low pressure, c) no light/visibility and d) system vibrations.

2. Main Research Challenge/Question

The Detectors&Cryo group in Bristol recently acquired from ICE-Oxford a cryostat for performing experiments with potentially tens of active components at cryogenic temperatures (Fig 1A&B). In order to provide the cooling power without any external supply of cryogens (i.e. a closed loop cooling), the system hosts two He compressors, and two vacuum pumps that generate a fair amount of vibrations.
Chips currently adopted by the CQP research group embed grating couplers that allow vertical coupling of light into the chip. These grating couplers can achieve optical losses as low as 1.5 dB per facet, but at the same time they require a high degree of alignment (< 5 μm) between the grating coupler itself and the corresponding fibre, usually hosted in a fibre array (Fig 1C).
In order not to affect the sample stage with vibrations due to the setup (Fig 1D), to an extent that might prevent an effective coupling to the chip, an optimisation and testing of the system is currently underway. The final challenge is to demonstrate a stable coupling to standard grating coupler structures, that would allow sensible experiments to be performed. In order to do so, both optimisation on the current setup, as well as the design of new components specifically targeting this issue will be required.
The system is designed for hosting multiple chips (or large ones), and we plan to build on the long run an automatized characterisation system similar to those already available at room temperature [1].

Expected outcomes

a) implement a re-alignment algorithm for the optical coupling stages (using existing software)
b) test the best coupling that can be achieved at room temperature using standard photonic test structures
c) correlate the (de)coupling in the photonic chip with the vibrations of the experimental system (using existing software)

d) improve the long-term optical coupling stability in the system (suggest, implement and test)
e) (if there is time) evaluate the effect of mechanical vibrations on the electrical coupling of the system

References

[1] https://youtu.be/1TOyMUGIRAY "

- [Hadfield09] Hadfield, Robert H. "Single-photon detectors for optical quantum information applications." Nature photonics 3.12 (2009): 696-705.

- [Natrajan12] Natarajan, Chandra M., Michael G. Tanner, and Robert H. Hadfield. "Superconducting nanowire single-photon detectors: physics and applications." Superconductor science and technology 25.6 (2012): 063001.
- [Schuck16] Schuck, Carsten, et al. "Quantum interference in heterogeneous superconducting-photonic circuits on a silicon chip." Nature communications 7 (2016).

Required Skills

"None is specifically required to start the project.

However, it would be ideal if the student had previous knowledge/experience about:

- coding in Python / C /C++

- hardware interfaces

- working with cryogenic setups"

Project Location

University of Bristol

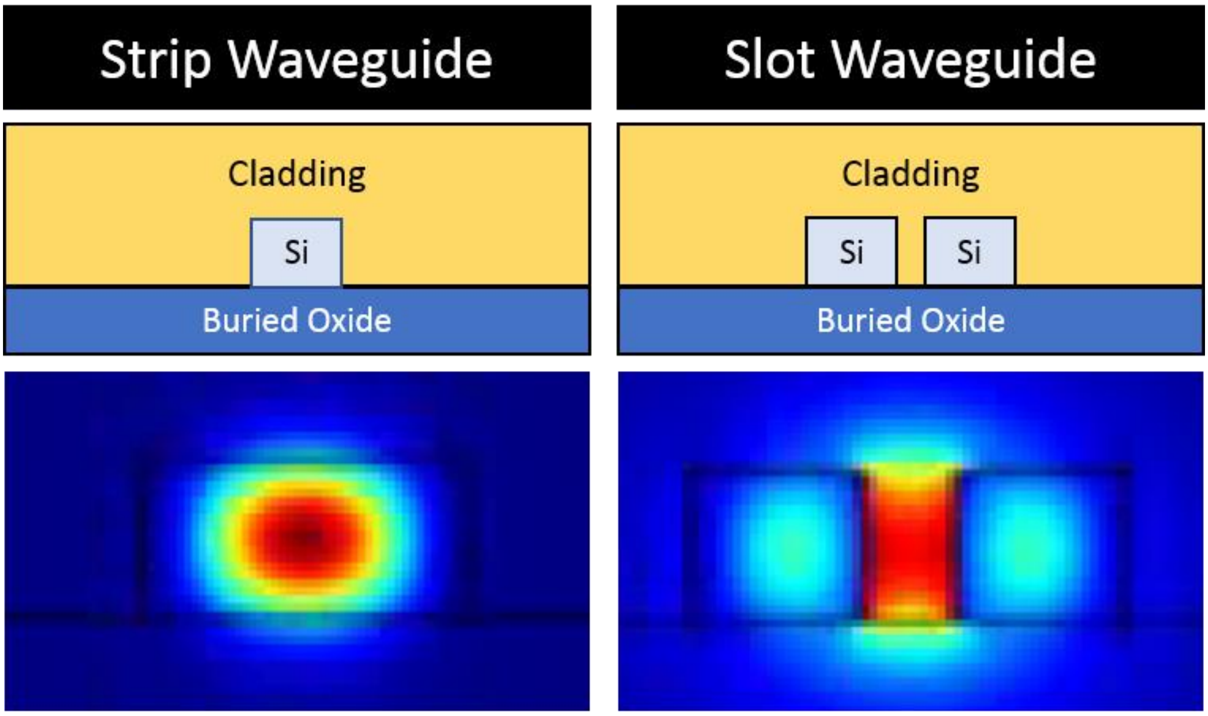
Experimental, Simulation
Metrology, Simulation, Photonics Device Engineering, Device Fabrication

31 Numerical study for optimising slot waveguides for quantum-enhanced on-chip gas sensing.

Euan Allen, Jonathan Matthews, Sabine Wollmann

Abstract:

Sensing and parameter estimation is of foundational and practical interest in the Quantum optics community. The advantage that quantum systems offer has been widely investigated [1,2,3] and enables improved sensing in terms of resource utilisation and precision.
Recently, gas sensing on integrated silicon photonic devices has been demonstrated [4] using gas-clad waveguides and measuring the absorption of the waveguide evanescent field. realising the technology's potential for highly efficient and compact sensing. Employing so-called slot waveguides (strip waveguides with a longitudinal etched channel, see Figure 1.) can significantly improve a sensor's performance compared to those using evanescent coupling [5]. Optimisation of the geometrical parameters of the slot waveguide and the strip-to-slot mode conversion is crucial for engineering a high-performance sensor and in obtaining a quantum advantage.



Adapted from [5]

Project Description

Several designs for integrated photonic sensors have been demonstrated [6,7], employing various techniques for measuring the absorption of a gaseous cladding medium. The most promising approach are slot waveguides [5]. These are strip waveguides with a longitudinal etched free space area inside the structure (Fig. 1). The optimal design maximises the electric field inside the free space region where it can interact with the gaseous cladding medium. The absorption or resultant phase shift allows us to gain information about the test sample.

Optimising the ratio of field-gas interaction to the waveguide loss is critical to maximise the resource (photon) efficiency. This is important for maximising the information per photon in both the classical and quantum regime. The coupling efficiency from strip waveguide to slot waveguide is, however, a crucial parameter to optimise for obtaining a quantum advantage in absorption measurements

Therefore, this project will involve the simulation and design of novel integrated photonic slot waveguides. Further, the designs will be investigated for demonstrating a quantum advantage in phase/absorption measurements that allow for highly sensitive and ultra-precise gas sensors.

Expected outcomes

The student will perform a literature review to get acquainted with the relevant concepts and existing designs for quantum enhanced sensors and integrated photonic devices. This will be followed by investigation of the optimal design for strip-to-slot coupling and slot waveguide geometry. The results of these numerical simulations will be used to design devices which will be fabricated by Applied Nanotools and measured by the University of British Colombia. This project will conclude with analysis of measurements of these devices and a re-evaluation of the designed geometries.

References

"[1] Slussarenko, S., Weston, M.M., Chrzanowski, H.M., Shalm, L.K., Verma, V.B., Nam, S.W. and Pryde, G.J., 2017. Nature Photonics, 11(11), p.700.

[2] Sabines-Chesterking, J., Whittaker, R., Joshi, S.K., Birchall, P.M., Moreau, P.A., McMillan, A., Cable, H.V., O'Brien, J.L., Rarity, J.G. and Matthews, J.C.F., 2017. Physical Review Applied, 8(1), p.014016.

[3] Moreau, P.A., Sabines-Chesterking, J., Whittaker, R., Joshi, S.K., Birchall, P.M., McMillan, A., Rarity, J.G. and Matthews, J.C., 2017. Scientific Reports, 7(1), p.6256.

[4] L. Tombez, E. Zhang, J. Orcutt, S. Kamlapurkar and W. Green, Optica, vol. 4, no. 11, p. 1322, 2017.

[5] Passaro, V. and La Notte, M. (2012). Sensors, 12(12), pp.2436-2455.

[6] Claes, T.; Girones, J.; de Vos, K.; Bienstman, P.; Baets, R. IEEE Photonics J. 2009, 1, 197–204.

[7] Passaro, V.M.N.; Dell'Olio, F.; Ciminelli, C.; Armenise, M.N. Sensors 2009, 9, 1012–1032."

Required Skills

Basic programming skills for (scripted) simulation of photonic devices using Lumerical. Prior experience with Lumerical not required as the student will have access to edX learning materials. Data analysis skills in MATLAB or similar programs are preferred, however, some learning materials will also be provided through edX.

Project Location

Other academic partner