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Photonic crystal fibres (PCFs) continue to yield unexpected optical properties and lead to possible novel applications. An example is twisted PCF, which creates optical vortices that carry orbital angular momentum, as well as providing an elegant means of providing circular birefringence and dichroism, most recently in hollow-core PCF. Intense interactions between light and sound in solid-core PCF enable stable all-optical mode-locking of fibre lasers at a high harmonic (a few GHz) of the round-trip frequency. Single-ring hollow-core PCF, comprising a ring of thin-walled capillaries surrounding a central hollow core, guides over an extremely wide frequency range and, through pressure-adjustable dispersion, provides a simple means of compressing pulses down to single-cycle durations, as well as underpinning a range of unique and extremely bright sources of tunable deep and vacuum ultraviolet light.

During the seminar, a selection of recent results from work carried out at MPL will be presented.
EFFICIENT AND TUNABLE SPECTRAL COMPRESSION USING FREQUENCY-DOMAIN NONLINEAR OPTICS

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Femtosecond lasers are powerful light sources for spectroscopy and imaging applications because of the high peak power to induce nonlinear effects and ultrashort laser pulse width to achieve high temporal resolutions. However, for the circumstances that also require high spectral resolution, for example, femtosecond stimulated Raman spectroscopy (FSRS) and microscope and time-resolved sum-frequency generation spectroscopy, a spectral compressor to convert the broadband pulses to narrow bandwidth is essential. In this study, we perform a new method to compress the spectral bandwidth of femtosecond pulses by sum frequency generation of two laser pulses with opposite spatial chirp at the Fourier plane. Compared with the conventional techniques, our approach features with simplicity, high conversion efficiency, and wavelength tunability. Finally, we demonstrate a home-built FSRS system based on the new spectral compressor.

References

Optical microresonators is currently a hot topic since they have the capability to efficiently generate nonlinear signals at very low driving powers [1]. To date, most studies have been focused on using microresonators for frequency comb generation [2]. However, recently a new approach of generating new frequencies has emerged [3-6], based on χ(3) parametric oscillation in microresonators with carefully tailored higher order dispersion.

In this paper, we used three magnesium fluoride microresonators of different diameters: 1.03, 0.80 and 0.53 mm to phasematch large frequency shift parametric oscillation between 1.08 and 2.7 μm. Sideband tunability is achieved through small changes in the pump wavelength between 1530 and 1570 nm. Fig. 1(a,b,c) show representative spectra observed in each resonator. Fig. 1(d) shows the combined phasematching curves of the three resonators and demonstrates the almost continuous wideband tunability possible in these systems. We note that the largest frequency shift we experimentally observe (≈ 81.1 THz), corresponds to signal and idler waves separated by more than an octave of optical frequency (λ_s = 1089 nm, λ_i = 2647 nm). As such these devices are promising candidates for low-cost, low-power, optical sources suitable for mid-infrared spectroscopy.

Figure 1: (a,b,c) Experimentally measured optical spectrum at three different resonator diameters (1.03, 0.8 and 0.53 mm) for a pump wavelength within C-band range. The output spectrum is measured using two optical spectrum analyzers (blue and orange) and a Fourier-transform infrared (FTIR) spectrometer (red). (d) Experimentally measured parametric sideband wavelengths as a function of pump wavelength for the three different diameter resonators (1.03 mm resonator, open circles; 0.8 mm resonator, solid circles and 0.530 mm resonator, solid stars). The solid lines show the theoretical phase-matching curves while the dotted lines indicate the positions of the three zero-dispersion wavelengths.

References


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Large ring lasers have improved significantly over the last year, so that we can now begin to separate and mitigate error sources that are not related to the rotation sensing process from the Sagnac interferogram. As a result of that we were able to reduce the measurement noise of the 16 m² G ring laser of the Geodetic Observatory Wettzell by more than a factor of two to about 8 μHz and 1 hour of averaging. At the same time the residual sensor drift reduced significantly. This was achieved by a much tighter control of the laser intensity. Fig. 1 shows the result. The raw measurements including a variety of geophysical signals are shown in the top panel, while the remaining residuals are shown at the bottom, after all known corrections for the sensor drift and the geophysics [1] are applied. Over a period of 30 days the currently remaining rotation rate residuals stay within ±25 μHz, which makes the G ring laser the most stable inertial gyroscope on Earth. Until

**Figure 1**: Time series of ring laser measurements. The top panel shows the raw readings of the Sagnac beat note, while the lower panel shows the remaining residuals after all known effects have been subtracted from the measurements.

now most of the investigations on large ring laser gyroscopes were dealing with a single component ring laser, orientated horizontally on the ground. Over the last two years we have constructed a four component ring laser structure ROMY¹, which is arranged in the form of an inverted tetrahedron with the tip in the ground. For the first time this arrangement can provide simultaneous three degrees of freedom rotation sensing with additional redundancy [2]. Although the system currently operates in the free running mode, it can determine the orientation of the instantaneous Earth rotation vector with high resolution.

With a Q factor exceeding $10^{12}$ the ring laser cavity exhibits a very narrow line width. Locking it to a H-maser via an optical frequency comb achieved a frequency stability of the optical resonator of less than 1 part in $10^{15}$. On this road of high resolution monitoring of a global measurement quantity (earth rotation) with a local sensor (ring laser), we have encountered a number of serious challenges. This talk illustrates the recent progress in high resolution Sagnac Interferometry and its application to the geosciences and beyond.

**References**


INITIAL GYROSCOPIC OPERATION OF A LARGE MULTI-OSCILLATOR RING LASER FOR EARTH ROTATION SENSING

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A frequency-upscaled large ring laser operating at shorter wavelength than the standard 632.8 nm has great potential in yielding higher resolution of Earth rotation sensing. We demonstrate a 2.56 $m^2$ He-Ne based multi-oscillator ring laser with the capability of simultaneously operating at three different wavelengths – 612 nm, 604 nm and 594 nm, which correspond to $3S_2 \rightarrow 2P_6$, $3S_2 \rightarrow 2P_7$ and $3S_2 \rightarrow 2P_8$ neon transitions respectively. Provided by Research Electro-Optics, cavity mirrors that sustain multiple resonant frequencies are IBS-coated supermirrors with fused silica substrate. The best cold cavity ring-down time of 612 nm, 604 nm and 594 nm laser obtained are 38 $\mu$s, 51 $\mu$s and 64 $\mu$s independently, yielding quality factor $Q$ of $1.2 \times 10^{11}$, $1.6 \times 10^{11}$ and $2.0 \times 10^{11}$ correspondingly. The Earth rotation rate is indicated by the Sagnac beat frequency generated from the recombination of two counter-propagating beams. For 612 nm, 604 nm and 594 nm operation, anticipated Sagnac frequencies are 117.4 Hz, 118.8 Hz and 120.9 Hz respectively. We have achieved Earth rotation sensing with operation of these three wavelengths individually. For a cavity filled with 0.3 mbar natural neon and total 4 mbar helium-neon gas, single-mode operation with 612 nm wavelength resulted in sagnac frequency in the vicinity of 117.4 Hz (0.5 Hz frequency excursions) and the minimum short-term Allan variance achieved is $1.5 \times 10^{-4}$ relative to $\Omega_E$ at $\tau = 10$ s. Due to the fact that 604 nm and 594 nm wavelengths operation can only run with unstable multimode, the operation with these two wavelengths yielded beat frequencies fluctuated around their expected value with much higher frequency excursions – 5 Hz and 7 Hz separately. Early results show that except for 612 nm operation, both 604 nm and 594 nm operation showed their impossibility in sensing earth rotation with single longitudinal mode or stable phase-lock regime. The objective is to operate ring laser at three wavelengths with single-mode or stable phase-lock regime for each wavelength to yield their best sensor resolution, therefore investigation into optimal helium and neon\textsuperscript{50:50} $^{20}$Ne:$^{22}$Ne gas mixture is still on-going.

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APPLICATIONS OF HIGH-PRESSURE LASER ULTRASOUND TO ROCK PHYSICS MEASUREMENTS

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Laser ultrasound is a powerful tool for investigating the physical properties of a variety of media, including ice, fruit, and even human tissue. The entirely non-contact method provides fast, high-resolution, and accurate measurements of elastic wavefields, from which the elastic properties or physical structure of the medium can be inferred. The elastic properties of rocks are of particular interest, important for geoscientists across a range of disciplines for calibrating field data and understanding the subsurface. However, lab measurements of rocks are only useful when they are performed under in situ pressure and temperature conditions, often achieved with transducers coupled to rock samples inside fluid-filled pressure vessels.

In the Physical Acoustics Laboratory, we have developed a new methodology which combines the precise high-resolution capability of the laser ultrasound technique with the in situ nature of the high-pressure transducer measurements for measuring the elastic properties of rocks. This is achieved by measuring the rock samples inside a gas-filled pressure vessel with two optical windows, allowing the source and receiver laser beams line-of-sight to the surface of the sample (Figure 1). The vessel is designed for pressures of up to 40 MPa (6000 psi) and temperatures of up to 200°C, equivalent to typical subsurface conditions at a few kilometres depth.

We present an overview of this methodology, and explore some of its unique applications and strengths. These include investigations into how the wavespeed and radiative transfer within rock samples depend on pressure, temperature, and direction of propagation.


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Ultrasound (US) is one of the most regularly used imaging techniques in clinics today. This is largely due to its portability, real-time imaging capabilities, and the use of non-ionizing (safe) radiation. US capabilities are continuing to advance in terms of frame-rate, imaging resolution, and functional imaging capabilities, however, limitations remain. For example, piezoelectric elements used in clinical probes have inherent resolution limitations, and require contact with the sample and an acoustic coupling medium, which limits reproducibility and increases inter-operator variability. US is also prone to speckle, which is considered either a diagnostic property or a troublesome artifact, depending on the application.

Photoacoustic imaging (PAI) is based on optical absorption, which is a high contrast property of biological tissues. In contrast to purely optical imaging techniques, PAI uses diffuse light to generate acoustic waves inside of the body. This allows optical properties to be imaged up to centimeters deep in tissue with PAI, whereas purely optical imaging techniques are limited to millimeter depths. The inherent optical absorption contrast of hemoglobin (a primary constituent of blood) is orders of magnitudes larger than surrounding soft tissues, making PAI an excellent candidate for imaging blood vessels. In contrast to US, PAI does not suffer from speckle artifacts.

In this talk, I will discuss my work in medical imaging. The field of PAI has made significant efforts to advance optical detection techniques, which overcome the resolution/sensitivity trade-offs of piezoelectric elements. I will discuss our all-optical approach, including a fully non-contact PA imaging system.

Translating the principles of PAI to US has opened up the field of medical laser-ultrasound (LUS) imaging [1, 2]. This hybrid technology can address several challenges for US, including enhanced repeatability, the generation of user-defined wavefields, improved axial/lateral resolution, and the potential for non-contact imaging. I will discuss the specific application of all-optical LUS imaging of a diseased carotid artery.

Finally, imaging beyond soft tissue is not possible with traditional PA and US systems, because the speed of sound in tissue is assumed to be isotropic and uniform. However, US imaging has recently been extended into bone by accounting for refraction and anisotropy [3, 4]. I will discuss real-time US imaging
of bone anatomy, and the development of Doppler imaging techniques for blood flow imaging in bone.

References


NEAR-INFRARED SPECTROSCOPY FOR KIWIFRUIT WATER-SOAKED TISSUE DETECTION

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For most fruits, cool-storage is the main means by which quality is maintained after harvest. However, prolonged low-temperature storage can cause the breakdown of tissues which is known, for kiwifruit, as low temperature breakdown (LTB) or chilling injury (CI). The resulting damage reduces the fruit quality and shelf-life, leading to economic losses [1, 2]. Symptoms of kiwifruit CI include grainy tissue in the outer pericarp and water-soaked areas in the outer and inner pericarp [1, 2]. The expression of CI is dependent on the storage duration and temperature of chilling as well as the fruit maturity stage [1-3].

Currently, the presence of CI in kiwifruit can only be detected when the fruit is cut open. A non-destructive means of detecting kiwifruit CI would be beneficial. Near-infrared spectroscopy (NIRS) is a popular and efficient non-destructive method for internal quality evaluation of fruits and vegetables, such as soluble solids content (SSC), dry matter, acidity and firmness [4, 5]. A typical NIRS set up employs a broadband light source to illuminate the sample, and the reflected or transmitted light is measured by a spectrometer.

This report focuses on the symptom of water-soaked tissue, the most prominent sign of CI in kiwifruit. Comparisons were made between water-soaked tissue induced by CI and by impact damage, another common cause of water-soaked tissue in kiwifruit. Impact damage was induced by dropping a mass against the fruit, using a pendulum system to control the impact energy. All fruit with water-soaked tissue showed higher detected NIRS light intensity, suggesting lower light scattering in the tissue. However, normalised spectra (standard normal variate transformation) revealed differences between water-soaked tissue caused by impact damage and CI, namely that differences from control fruit were absence for impact damage kiwifruit but prominent with the CI-affected kiwifruit. The NIRS method provides a new understanding of kiwifruit CI.

![Figure 1: Normalised spectra of fruit with impact injury (Red) and control set (Blue).](image1)

![Figure 2: Normalised spectra of fruit with chilling injury (Red) and control set (Blue).](image2)

References


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Rare Earth Doped Nanoparticles for Quantum Technologies

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Nanoscale systems offer new functionalities in quantum technologies, like single qubit control and detection, or extremely localized sensing. The ability to couple qubits with light is an attractive feature for these systems to enable interfacing with photonic qubits, creating light matter entanglement or fast processing of quantum information. Rare earth ions are promising candidates for this purpose\textsuperscript{1-3}, as they can show record long optical and spin coherence lifetimes in bulk crystals\textsuperscript{4}. However, maintaining these properties at the nanoscale can be challenging, as surface effects for example can cause strong dephasing.

In this talk, we will discuss recent results obtained in our group on europium doped nanoparticles. These materials show optical and spin coherence lifetimes of 7 µs\textsuperscript{5} and 1.3 ms at low temperature\textsuperscript{6}. Moreover, spin dephasing can be controlled by trains of optical pulses, resulting in coherence lifetimes up to 8 ms\textsuperscript{6}. This is the highest reported value for optically addressable spins in any nano-material. These particles could be placed in high-finesse fiber-based cavities to achieve efficient optical control and readout of nuclear spin qubits\textsuperscript{7}. Combined with rare earths unique coherent properties, this scheme opens the way to quantum memories with single ion processing capabilities, single photon sources or highly scalable quantum processors.
References:
TRANSFERABILITY OF CRYSTAL-FIELD PARAMETERS FOR RARE-EARTH IONS IN Y$_2$SiO$_5$ TESTED BY ZEEMAN AND LASER SPECTROSCOPY

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One of the challenges for practical quantum-information applications, such as encryption and computation, is the preservation of quantum coherence. Quantum coherence may be stored by making use of the nuclear spins of rare-earth (lanthanide) ions, which are coupled to the electronic states via the hyperfine interaction. Storage of quantum coherence for over six hours using magnetic-hyperfine levels of Eu$^{3+}$ ions in Y$_2$SiO$_5$ (YSO) has been achieved by using the ZEFOZ (ZEro First-Order Zeeman) approach, where the direction and magnitude of an applied magnetic field is adjusted to yield a radio-frequency transition that has no first-order dependence on magnetic field variations, and is thus insensitive to magnetic field inhomogeneity [1].

Applications development, such as the location of ZEFOZ points, requires accurate modelling of hyperfine and magnetic interactions, which is usually done using a spin Hamiltonian. Spin-Hamiltonian parameters are not transferable to other electronic states, or to other ions, so each electronic state requires a different spin Hamiltonian. Our aim is to model electronic and hyperfine energy levels consistently across the rare-earth series [2] using a crystal field model [3]. This will enable more efficient investigation of candidates for applications. The lack of symmetry in YSO makes a conventional crystal-field approach impossible. However, by adding magnetic and hyperfine data to remove ambiguities, we have recently shown that it is possible to perform accurate fits for Er$^{3+}$ [4].

In this paper we report Zeeman and laser spectroscopy measurements for two other ions: Nd$^{3+}$ and Sm$^{3+}$. We demonstrate that crystal-field parameters may be transferred from Er$^{3+}$ and that a combination of experimental measurements and theoretical calculations can identify the two different rare-earth substitutional sites [5]. Future work will use Zeeman, laser, and hyperfine spectroscopy to refine the crystal-field parameters across the rare-earth series. This will provide improved modelling relevant to the development of quantum-information applications.

References


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CONTROLLING COLD MOLECULAR COLLISIONS

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The ultimate goal of chemistry is the complete control of both reactants and products. In cold collisions molecular processes are simplified and thus more amenable to control. Thanks to recent experimental progress it is now increasingly possible to study molecular collisions at an energy as low as a couple of degrees Kelvin [1, 2]. I will explain how varying the relieve orientation of collision partners can be used to exert control over the outcome of molecular collisions, using the HD+H₂ system as a prototypical example [3].

References

Collective Rydberg excitations in an ultracold atomic ensemble can harbour giant optical nonlinearities at the single photon level. Strong photon-photon interactions in this system has enabled photonic transistors, phase modulators [2, 3, 4] and microwave-to-optical converters [5]. We are building a novel experimental platform for studying Rydberg quantum optics where a deeply degenerate gas of fermionic atoms will host Rydberg excitations. An optical pulse containing a single photon can be stopped and stored in an atomic ensemble as a collective atomic excitation - called a Rydberg spin-wave or polariton - by using electromagnetically-induced transparency. Contemporary experiments suffer from strong density-dependent dephasing of Rydberg polaritons, limiting their coherence times to a few microseconds even at moderate atomic densities. This is owing to the density fluctuations which cause several atoms inside the extended electronic orbital of the Rydberg atom resulting in strongly inelastic losses and dephasing [6]. This has so far imposed a significant obstacle for Rydberg quantum optics.

Using degenerate fermions as the storage medium offers robust protection against the loss and dephasing mechanisms of Rydberg polaritons. In degenerate fermions that are spin-polarized, spatial anti-bunching of atoms occurs naturally due to Pauli blocking - the corresponding length scale is determined by density and the scaled temperature $T/T_F$, where $T_F = E_F/k_B$ is the Fermi temperature. As shown in the figure, the overlap between the Rydberg orbital and the ground state atom is significantly lowered at low temperatures, strongly inhibiting inelastic mechanisms. Pair correlations in this case also offer noise reduction resulting in strongly reduced density fluctuations [7]. We estimate an order of magnitude enhancement of the spin-wave coherence time in this system. We will discuss our current state of the experimental progress: the production of high atom numbers and the preparation of many Rydberg polaritons. In degenerate fermions, the interaction of Rydberg polaritons with the environment can be enhanced by using strong magnetic fields which pushes them away from inelastic mechanisms. In this way, we can achieve a coherence time of several microseconds even at moderate atomic densities.

Figure 1: a. Radial electronic probability distribution for 70S$_{1/2}$ Rydberg state of 40-K. b. Pair distribution function of a homogeneous fermionic system with a density $4 \times 10^{12}$ cm$^{-3}$ for various values of the reduced temperature. A significant spatial anti-bunching is evident on the scale of the size of the Rydberg electronic orbital. c. With no spatial antibunching (left), Rydberg excitation encounters electron-atom collision due to density fluctuations, which vanishes when perfect anti-bunching is present (right). d. Monte-Carlo simulation of spatially varying energy shifts in a Rydberg spin wave stored in a 1D box of size 30 μm and containing 100 atoms. Thick solid lines indicate the mean energy shift, thin lines illustrate a single Monte Carlo realization and the shaded region the standard deviation. Inhomogeneous energy shifts are strongly suppressed at low $T/T_F$.

References


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Towards Experimental Studies of Quantum Droplets and False Vacuum Decay

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We report on an experimental platform for producing ultra-cold gases in arbitrary potentials based on steerable optical tweezers [1]. The apparatus is capable of loading a 3D potential with low temperature bosons ($^{87}$Rb) or fermions ($^{40}$K) which can be degenerate, or cooled to degeneracy by modulating the potential [2].

We propose extensions to our setup allowing us to cool and manipulate $^{41}$K. This species shows potential for producing a metastable relative phase between two spin states. This is done with modulation similar to a Kapitza pendulum. The interactions in this system are equivalent to those allowing false vacuum decay. Here, a two spin component system with positive intra- and negligible inter-species scattering lengths give rise to a symmetric false vacuum [3]. $^{41}$K has a convenient Feshbach resonance with these properties near 675 G. The scattering lengths are shown in figure 1.

Bosonic potassium isotopes have also been proposed [4] and realised [5] as a medium for the formation of quantum droplets. The existence of rubidium in our setup puts us in a position to produce $^{41}$K-$^{87}$Rb dual-species droplets. We present preliminary results of cooling and trapping $^{41}$K in our apparatus.

![Scattering Length Diagram](image)

**Figure 1:** The computed scattering lengths for the $|1\rangle = |1, 1\rangle$ and $|2\rangle = |1, 0\rangle$ hyper-fine ($|F, m_F\rangle$) states of $^{41}$K beside a Feshbach resonance. The regimes for producing a false vacuum and for droplet production are marked. The parameter $\delta a = a_{12} + \sqrt{a_{11}a_{22}}$ expresses the mean-field stability of the mixture, and droplet formation is possible when this is negative.

References


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CONTROLLABLE VALLEY POLARIZED EXCITON-PLASMON POLARITONS IN 2-DIMENSIONAL SEMICONDUCTORS

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Monolayers of transition metal dicalcogenides are newly emerged two-dimensional semiconductors with direct bandgaps at degenerate but inequivalent electronic “valleys”, supporting distinct excitons that can be selectively excited by polarized light\textsuperscript{[1, 2]}. These valley-addressable excitons, when strongly coupled with optical resonances\textsuperscript{[3, 4, 5]}, lead to the formation of half-light half-matter quasiparticles, known as polaritons. Here we report self-assembled plasmonic crystals that support tungsten disulphide monolayers, in which the strong coupling of semiconductor excitons and plasmon lattice modes results in a spectral Rabi splitting of 160 meV as well as valley-polarized photoluminescence at room temperature. More importantly we find that one can flexibly tune the degree of valley-polarization by changing either the emission angle or the excitation angle of the pump beam. Our results provide an effective platform that allows the precise detection, control and processing of optical spin and valley information at the nanoscale under ambient conditions.

![Figure 1](image)

**Figure 1:** (a) schematic of plasmonic crystals (PC) coated with WS\textsubscript{2} monolayer; (b) schematic of angle-resolved photoluminescence (PL) measurement pumped by circularly polarized laser excitation. PL spectra at $\theta_{\text{exc}} = 0^\circ$ and $\theta_{\text{ex}} = 20^\circ$ with different helicity: $\sigma^+$ (red line) and $\sigma^-$ (black line) and polarization degree (blue circles) for the (c) PC-WS\textsubscript{2} and (d) bare WS\textsubscript{2}. Polarization degree for the (e) PC-WS\textsubscript{2} and (f) bare WS\textsubscript{2} samples under different $\theta_{\text{exc}}$.

**References**


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Optical frequency combs (OFCs) are light sources whose spectra consists of equally spaced frequency lines in the optical domain [1]. OFCs are being researched for a wide variety of applications such as high-capacity data transfer, all-optical atomic clocks, spectroscopy, astronomy, and high-precision measurements [2]. We present a novel method of generating OFCs by using second-order non-linear effects in a whispering gallery mode (WGM) resonator made of lithium niobate (LN) [3, 4]. In this scheme, two continuous waves, one in the optical domain ($\omega = 193$ THz) and another in the microwave region ($\Omega = 8.9$ GHz) are coupled to the WGM of a LN disk resonator [5]. The optical pump power is coupled by using a standard prism coupling method that is based on frustrated total internal reflection. The microwave power is coupled using a coaxial probe coupler attached to a 3-D copper cavity specifically designed to have the optical free spectral range (FSR) of the LN resonator equal to the microwave resonant tone frequency (FSR = $\Omega$). In addition, the cavity design also provides a very good spatial overlap between the microwave and optical modes by confining the microwave power to the rim of LN disk. The resonant hybrid structure allows for efficient nonlinear mixing which leads to frequency comb generation via cascaded symmetric sum frequency generation (SFG) and difference frequency generation (DFG) [6]. Our system can generate frequency comb spanning over 100 comblines with the combline separation of 8.9 GHz. Compared to previously reported OFCs generation scheme, this method has a two major advantages: inherent phase stability and better power efficiency.

![Figure 1](image-url)

**Figure 1:** (a) Simplified schematic of the setup for the creation of electro-optic comb generation using lithium niobate (LN) disk resonator clamped in the centre of a copper cavity. (b) Schematic of an optical frequency comb generation via cascaded sum frequency generation (SFG) and difference frequency generation (DFG) around the optical pump ($\omega$).

Quantum information science is one of the most dynamic fields in contemporary physics. It poses several fundamental questions which are at the core of quantum theory, e.g., what is entanglement and how one could detect, measure and characterise entanglement. Experimentally the drive is the prospect of harnessing entanglement for faster computation and developing novel types of algorithms, perhaps successfully attacking the P-NP question. However, entanglement is a fragile property and – as widely believed – any interaction with a thermal bath would severely suppress the likelihood of measurable entanglement. Here we explore the entanglement of multipartite and multidimensional system as mediated by the bath. We show that at low temperatures and intermediate coupling strengths multipartite entanglement may form between higher spins, i.e., qudits. Furthermore, we also demonstrate an approximate power law relation for multilevel and bipartite systems to show the entanglement peaks in both cases obey a unique relation.

We build a theoretical model to generate steady state multipartite and multilevel entanglement mediated solely by the environment. First we consider a general open quantum system coupled to a bath and then we explain the equilibrium reduced density matrix of non-interacting qudits through the analytical polaron treatment, complemented by numerically exact path-integral approach. Next, we demonstrate the use of the structure-factor-based and global entanglement witnesses to compute entanglement in bipartite and multilevel systems. We show that the entanglement peak drops drastically in qutrits system ($d = 3$) and the peaks occur at smaller system-bath coupling. Finally, we present an approximate power law scaling which shows optimum entanglement peaks obey of a power law relation in qudit systems.

Figure 1: (Colour online) The schematics of the physical system consisting of $N$ $d$-level systems (qudits) and a bath of harmonic oscillators. The qudits do not directly interact with each other, but they are all coupled to the bath.
ANDERSON LOCALIZATION IN ULTRACOLD GASES

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Just as the control of the flow of electrons lead to the field of electronics, it is hoped that control of the flow of superfluid cold-atoms will give rise to atomtronic technology. The emerging field of atomtronics is based on the investigation of atom circuits - i.e. systems of ultracold atoms constrained to flow around a closed channel. One of the major challenges in the field of atomtronics is to find equivalents of electronic components such as resistors, capacitors and inductors. Many landmarks experiments have been performed which were designed to use neutral atoms in optical lattices in order to explore atom circuits\(^1\).

We typically use the time-dependent Gross-Pitaevskii equation (GPE) to explore atomtronic systems. In this project we will numerically simulate an atomtronic system using the GPE to consider a Bose–Einstein condensate (BEC) confined in a 2D optical dipole potential, which we expect to behave as a neutral atom RLC circuit.

In previous investigations an atomtronic capacitor was created by connecting a full reservoir to an empty one by a channel of varying width and length\(^2\). We seek an atomtronic resistor by simulating this experiment with the addition of impurities in channel. The combination of the wave-like nature of BEC systems and disordered media naturally leads us to consider Anderson localization. The absence of waves diffusion in a disorder medium is actually defined as Anderson localization\(^3\).

This is a general wave phenomenon that applies to the transport of electromagnetic waves, acoustic waves, quantum waves, spin wave and etc. Anderson localization is the result of wavefunction localization in a disorder medium. The wave function lays off diffusion freezes out is known as the localization length and depends on the amount of noise in the system.

This phenomena can be investigated by manipulating of 2D optical potential which exists in the experiment that our simulation is based on. In order to understand the purpose of this project a summary of the experiment is essential to overview\(^2\),\(^4\),\(^5\). The experiment is comprised of a Bose–Einstein condensate of \(^{87}\)Rb of about \(10^4\) atoms confined in a quasi-2D potential consisting of two reservoirs which are connected by a channel. The atoms are initially confined in a harmonic trap in the right-hand reservoir and then released to flow down the channel into the left reservoir. We are interested in the differences between the number of atoms in the right reservoir, normalized by their sum. The reason is that imbalance number gives us an understanding of atom circuit in this experiment.

In addition, Anderson localization will be investigated by putting impurities through the channel and exploring the imbalance number to measure localization length and see how this model as a resistor behaves.

References


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RESONANTLY ENHANCED MICROWAVE UP-CONVERSION

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There are two typical energy scales for quantum technologies. Qubits based on superconducting circuits, spins hosted in semiconductors and optical lattices, and charge configurations in single electron devices, tend to be characterized by microwave frequency transitions. Optical frequency technologies include self-assembled quantum dots, defect centers in diamond, and efficient single photon detectors. To couple these two worlds, we need coherent conversion between microwave photons (~ 10 GHz), and optical photons (~ 200 THz).

To couple two electromagnetic frequencies, a non-linear medium is required. A variety of materials and effects have been suggested and exploited; the electro-optic Kerr effect in media with a \(\chi^{(3)}\) non-linearity\(^1\), the magneto-optic Kerr effect in YIG spheres\(^2\), lambda systems in rare earth ions\(^3\) and nanomechanical resonators\(^4\). Here, we use the Pockels effect, which relies on a \(\chi^{(2)}\) nonlinearity\(^5\). We enhance the coupling by confining microwave and optical photons to two overlapping modes: the microwave mode of a 3D copper cavity, and a whispering gallery mode (WGM) in a lithium niobate disc, which also provides the necessary non-linearity (Fig. 1).

**Figure 1:** WGM-based resonant-enhanced frequency up-conversion. a) Interacting fields are resonantly enhanced by a lithium niobate whispering gallery mode (WGM) optical resonator and a 3D metallic microwave cavity. The microwave field phase-modulates the light via the Pockels effect and a frequency comb is generated, which is measured with an optical spectrum analyser (OSA). b) The optical modes are separated by a free spectral range (FSR) which, due to dispersion, is not constant. The microwave pump frequency \(\Omega\) can be tuned to FSR\(_{\perp}\), thus preferentially selecting sum frequency generation.

For such a device to be a useful part of a quantum network, its quantum efficiency must approach unity. This requires a combination of strong non-linearity, high field strengths and a high overlap between the microwave and optical modes. To achieve this, we will design a stripline-coupled microwave ring resonator, with a geometry optimized for coupling to WGM. We will cool it to millikelvin temperatures using a dilution fridge, in order to reduce ohmic losses in the microwave resonator and suppress the thermal occupancy of the microwave modes. This will allow us to coherently couple a superconducting qubit to technologies outside of the cryogenic environment.

**References**


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Abstract:

Seafood farming yield is critically depending on the nutrients in the surrounding seawater. Today, marine farmers place farms based on experience. They infrequently measure the nutrients by taking water samples and wait for laboratory results. However, these nutrients vary with seasons and weather conditions as well as water depth. Hence, a spectroscopic sensing device, measuring the chemistry of water in-situ in real time at any given time and depth is highly attractive for marine farmers. We utilize ultrafast broadband coherent anti-Stokes Raman scattering (CARS) as spectroscopy tool to interrogate the seawater regarding nutrients. Our three-color femtosecond CARS research combines the use of broadband molecular excitation and non-resonant background suppression by temporal beam shaping for probing and Sapphire, femtosecond supercontinuum generation. We show our latest achievements and essential factors in such a setup such as the difference to a two-colour versus a three-color CARS system as well as the background free CARS spectrum of various chemical substances.
Polar core vortices are the topological defects of the easy-plane ferromagnetic phase of a spin-1 Bose–Einstein condensate, and play a fundamental role in the phase transition and rethermalization dynamics of this system [1, 2]. In this work we characterise the properties of a polar core vortex (PCV). We do this by examining the properties of the stationary state PCV solutions (see Fig. 1), obtained by solving the three-component $(\phi_{-1}, \phi_0, \phi_1)$ spin-1 Gross-Pitaevskii equations. We also examine the excitations of the PCV obtained by solving the associated Bogoliubov-de Gennes equations. This gives us a window into the nature of the excitations of this vortex, such as the Kelvin wave (helical) excitations and how these excitations couple to spin and density degrees of freedom.

![Figure 1](image-url)

**Figure 1:** PCV profiles. (a) The $\phi_{\pm 1}$ component wavefunctions for a PCV for $q/q_0 = 0.1$ (blue lines) and $q/q_0 = 0.8$ (red) for (from top to bottom) $g_s/g_n = -0.8, -0.5, -0.1$. (b) The $\phi_0$ component wavefunctions for the cases corresponding to (a), noting that the curves have opposite order as $g_s/g_n$ changes compared to the $\phi_{\pm 1}$ results. The asymptotic decay of the numerical solutions for the (c) $\phi_{\pm 1}$ and (d) $\phi_0$ component wavefunctions compared to our analytic result (dots). Here $q$ is the quadratic Zeeman energy, $g_s$ and $g_n$ are the density and spin-dependent interaction parameters and $q_0 \equiv 2|g_s|n$ is the characteristic spin energy, where $n$ is the condensate density. We have also introduced the density healing length $\xi = h/\sqrt{M g_n n}$, and the background (homogeneous) condensate amplitudes $\phi_n^0$.

**References**


EXCITATIONS OF A VORTEX LINE IN AN ELONGATED DIPOLAR CONDENSATE

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We characterise the properties of a vortex line in an elongated dipolar Bose-Einstein condensate. Increasing the strength of the dipole-dipole interactions (DDIs) relative to the short ranged contact interactions we find that the system crosses over to a self-bound vortex droplet stabilized from collapse by quantum fluctuations. We calculate the quasiparticle excitation spectrum of the vortex state, which is important in characterizing the vortex response, and assessing its stability. When the DDIs are sufficiently strong we find that the vortex is dynamically unstable to a quadrupolar mode.

Figure 1: Density isosurface of the $s = 1$ vortex state of a condensate for (a) purely contact interactions and (b) a dipole interaction strength close to instability. In subplot (a) a Kelvin-wave quasiparticle is superimposed on the condensate causing the vortex line to wiggle. In subplot (b) a quadrupolar quasiparticle is superimposed on the condensate causing the density around the vortex to split into two pieces. Isosurfaces indicate a density of $10^{20} \text{ m}^{-3}$. Here $a_{dd}$ is dipole length determined by the magnetic moment of the particles.

We benchmark our calculations against the results of Ref. [1] for the contact interacting condensate. Then we calculate the influence of DDIs and quantum fluctuations on the vortex properties including its excitation spectrum. This allows us to quantify the Kelvin wave excitations of the vortex line (cf. [2]) and to assess the modes that lead to the dynamic instability of the system.

References


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A cat state is a superposition of two quasi-classical states analogous to Schrödinger’s original Gedankenexperiment. Such states are interesting for the field of quantum metrology as they might allow for quantum-enhanced measurements. While cat states have been successfully experimentally implemented with a number of different systems, it still remains a great hurdle to produce spin cat states in large atomic ensembles, as the decoherence scales with the size of the system.

We examine trajectories of collective atomic spin states (with total spin $S$) of an effective Dicke model [1] for an integer-spin atom ensemble, described by the Hamiltonian and master equation

$$\hat{H} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{S}_z + \lambda (\hat{a} + \hat{a}^\dagger) \left( \hat{S}_+ + \hat{S}_- \right), \quad \dot{\rho} = -i \left[ \hat{H}, \rho \right] + \kappa \mathcal{D}[\hat{a}] \rho, \quad (1)$$

where $\Gamma = -\frac{\kappa}{\omega}$ and $\Lambda = -\frac{4\lambda^2 \omega}{(\omega^2 - \Lambda^2)^2}$. We can adiabatically eliminate the cavity mode in the limit $\omega \gg \omega_0, \lambda$. In that limit the system evolves effectively with a one axis-twisting Hamiltonian,

$$\hat{H}_{\text{eff}} = (\Lambda - i\Gamma) \hat{S}_z^2, \quad \dot{\rho} = -i \left[ \hat{H}_{\text{eff}}, \rho \right] + 2\Gamma \hat{S}_x \rho \hat{S}_x. \quad (2)$$

In the case of vanishing cavity decay ($\Gamma = 0$), and starting with a Dicke state of maximum polarisation in the $z$-direction, we obtain a spin cat state after a time $t = \frac{\pi}{2\Lambda}$ as given by

$$|\text{Cat}\rangle = \frac{1 - i}{2} |S, S\rangle_z + (-1)^{s} \frac{1 + i}{2} |S, -S\rangle_z. \quad (3)$$

We study the effect of decoherence on said cat state production. In the case of non-vanishing decay, but no jumps (photon emissions from the cavity), states close to the cat state can still be reached. While the fidelity drops quickly when the strength of the dissipative effects increase, the Quantum Fisher Information, which quantifies the usefulness of the state for quantum metrology, remains quite robust, as can be seen in Figure 1.

![Figure 1: Fidelity and Quantum Fisher Information of the state at a time $t = \frac{\pi}{2\Lambda}$ as a function of the dissipative strength.](image)

If there is a jump, however, the system evolves probabilistically into one of $S$ entangled state cycles, where the system jumps indefinitely between two Dicke state superpositions in a rotated basis. The different cycles can be distinguished by the frequency at which jumps (photon emissions) occur.

Further investigations will also be aimed at the effects of decay and dephasing processes of individual atoms [2].

References


Developing Fluorescent Analogues of Vitamin B₁₂ for Imaging and Evaluation of Bacterial Uptake of Vitamin B₁₂ Therapeutics

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Vitamin B₁₂ is a cobalt-containing cofactor essential for the function of two B₁₂-dependent enzyme reactions in mammals and numerous B₁₂-dependent enzyme reactions in bacteria. In humans, early stages of B₁₂ deficiency are associated with pernicious anaemia and/or neurological deficits. Both mammalian and bacterial cells have specific B₁₂ uptake mechanisms for ensuring adequate intracellular concentrations of this essential enzyme cofactor. Since rapidly metabolizing cancer cells take up large amounts of B₁₂ for DNA synthesis, fluorescent B₁₂ analogues also show promise in imaging of cancers.

We are interested in developing fluorescent B₁₂ molecules (B₁₂ conjugates) with improved fluorescence properties for applications in cancer tissue imaging and to identify the most effective positions to tether antibiotics to B₁₂ and B₁₂ analogues to deliver antimicrobial drugs into resistant bacterial cells. However previous studies by others have shown that B₁₂ typically quenches the fluorescence of the fluorophore. The synthesis and characterization of our first B₁₂ conjugates will be presented. Preliminary studies have shown that adipic acid dihydrazide is an excellent linker between the B₁₂ molecule and the fluorophore, with essentially no fluorescence quenching of the fluorophore attached to B₁₂.

SELF-BOUND STATES OF A MIXTURE OF ATOMIC BOSE-EINSTEIN CONDENSATES

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Quantum droplets are localized 3D matterwaves that can be produced from ultra-dilute Bose-Einstein condensates. These droplets occur when attractive two-body interactions between particles, which lead to mechanical collapse, are balanced by beyond-meanfield quantum fluctuation effects. Previously our group has developed foundational theory for quantum droplets that arise in systems with magnetic dipole-dipole interactions \cite{1, 2} (e.g. see Fig. 1), which were the first type of quantum droplet realized in experiments \cite{3}.

Here we present initial results from our theoretical work in a new direction: quantum droplets in a (non-magnetic) mixture of atomic Bose-Einstein condensates. Here the attractive interactions arises between different components (atomic species or spin states) of the gas. This system has recently been realized in experiments in Spain \cite{4} and Italy \cite{5}, and these types of droplets are on the horizon as a potential future direction for the Kjærgaard lab at Otago.

Figure 1: Density isosurface of a dipolar droplet consisting of $80 \times 10^3^{^{164}}$Dy atoms with the dipole interactions 64\% stronger than the contact interaction (i.e. $\epsilon_{dd} = 1.64$). Here the droplet is in free space and is self-bound by its own attractive interaction.

References


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Titanium doped Sapphire (Ti:Sapphire) crystals have aided in the fabrication of continuous wave [1] and ultrashort pulsed lasers [2, 3]. Ti:Sapphire has also lead to the realization of amplified chirped optical pulses [4] and optical frequency combs [5]. In order to achieve lasing with gain materials, a feedback mechanism is required. Such a feedback can be provided by Whispering Gallery Mode (WGM) resonators [6]. WGM resonators demonstrate a high Quality factor (Q), which is mainly attributed to the continuous confinement of light due to total internal reflection [7]. WGM resonators come in various shapes, such as spheres [8], rings [9] and disks [10], being some of them. Ti:Sapphire has not been extensively studied as a possible material for WGM resonators. The existing studies on Ti:Sapphire WGM resonators mainly analyze the Q of the Ti:Sapphire resonators at various temperatures [11, 12, 13], i.e., frequency-temperature dependence of the Q. In this work, we have explored Ti:Sapphire as a material for fabricating a disk shaped optical WGM resonator. The fabricated disk resonator has a 4.35 mm diameter and a 0.78 mm thickness (see Fig. 1). By evanescently coupling to the Ti:Sapphire WGM resonator through a diamond prism, we have observed an intrinsic Q = \(8 \times 10^7\), at a wavelength of 1550 nm, and a similar Q at 795 nm. Furthermore, we report on a mechanism to enhance the Q of the resonator via stimulated fluorescence; which can be achieved by pumping the system with a green laser, tuned to the absorption of Ti:Sapphire.

Figure 1: (a) Top view of the Ti:Sapphire WGM resonator glued to the top of a brass rod, (b) side view of the resonator, where the polished sides can be observed.

References
Superconducting qubits are a particularly promising technology for practical quantum computing. However, the nature of these superconducting qubits means that they couple naturally to microwave photons. This is problematic for the long-distance transfer of the quantum information: at room temperature the signal is quickly swamped by the thermal noise. It is impractical to create superconducting transmission lines of any length, but we know that optical photons can travel well, either in free space or guided along optical fibre.

One method to coherently convert these microwave photons to optical photons is to use a three-level system in a sum-frequency-generation arrangement: to the microwave photon we add an optical pump photon which generates an output optical photon[2].

The rare-earth ions are particularly well suited to this method, having narrow optical transitions, and easily accessible microwave transitions. Erbium in particular is ideal for this, with optical transitions around the lowest-loss window in silica fibre, and having sufficient magnetic moment to allow microwave Zeeman splitting at reasonable fields. We have used erbium at natural isotopic abundance to obtain a conversion efficiency of $10^{-5}$ at 4 K[1]. Two of the limits on the efficiency are thermal population of the higher microwave state, and parasitic reabsorption by the $^{167}$Er isotope, which occurs at 24% abundance and has non-zero nuclear spin, giving hyperfine energy levels between those we use.

We have characterised the properties of an isotopically pure sample of $^{170}$Er:YSO, and have made measurements of it at temperatures well below 1 K in order to determine the extent to which temperature and parasitic reabsorption limit the conversion efficiency.

References


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A STABILISED CHEBYCHEV SOLVER FOR THE BOGOLIUBOV-DE GENNES MEAN-FIELD THEORY OF FERMIONIC SUPERFLUIDS

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The mean-field theory for fermionic superfluids requires solving the Bogoliubov-de Gennes (BdG) equations to self-consistency for the superfluid order parameter. For inhomogeneous superfluids in two or three dimensions this becomes a formidable computational task.

To solve the BdG equations one needs to find the order parameter, update the Hamiltonian accordingly and proceed with a new step until reaching convergence – i.e. finding a self-consistent solution. The most obvious method of finding the order parameter is diagonalization of the BdG Hamiltonian. However for large systems this can be very ineffective. Properties of the Chebyshev polynomials can be used to effectively find the Green function of given Hamiltonian [1]. Specifically, this method can be used as a fast and numerically stable method for determining the order parameter in BdG equations [2]. We discuss possible extensions of the method described in Ref. [2] with the aim of achieving additional speedup in calculations as well as obtaining insight into the analytical properties of the studied equations.

An additional complication is that on some physical problems the self-consistent solution becomes an unstable fixed point of the iteration procedure, e.g. for finite-velocity soliton solutions [3]. Here we are combining the Chebychev representation with a suitable stabilisation procedure in order to determine the physically relevant self-consistent solutions in a numerically efficient and scalable way. We present examples of numerical solutions for several inhomogeneous cases. In future work we intend to apply the numerical approach to the physics of topological superfluids [4].

References


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MICROWAVE TO OPTICAL PHOTON CONVERSION VIA FULLY CONCENTRATED RARE-EARTH ION CRYSTALS

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Most investigations of rare earth ions in solids for quantum information have used rare earth ion doped crystals \cite{1}. Here we analyse the conversion of quantum information from microwave photons to optical frequencies using crystals where the rare earth ions, rather than being dopants, are part of the host crystal. The potential of large ion densities and small linewidths makes such systems very attractive in this application. We show that, as well as high efficiency, large bandwidth conversion is possible. In fact, the collective coupling between the rare earth ions and the optical and microwave cavities is large enough that the limitation on the bandwidth of the devices will instead be the spacing between magnon mode modes in the crystal.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{device.png}
\caption{The device used to convert microwave photons into optical photons. A rare-earth crystal (doped rare earth crystal for previous device \cite{1}, fully concentrated for proposed device) is placed within a microwave resonator and an optical cavity. A static magnetic field is then applied in the $\hat{z}$ direction. This controls the frequency of the spin resonance (magnon resonance)}
\end{figure}

Magnon modes are theoretically well studied in materials with isotropic g-tensors, and experimentally well studied in YIG, however little research has been carried out in rare-earth crystals. It is therefore important to obtain a better understanding of the magnon modes within the rare-earth crystals that are suitable for our conversion device. We present preliminary results for investigations carried out in the crystals, Gadolinium Vanadate (GdV\textsubscript{0.4}) and Dysprosium Phosphate (DyPO\textsubscript{4}).

References

APPLICATION OF LOW FREQUENCY RAMAN SPECTROSCOPY ON ANALYSIS OF HUMAN TEETH

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Recently the use of Raman spectroscopy has significantly increased for biomedical applications due to the advances in instrumentation.[1] In particular, low frequency Raman (LFR) spectroscopy is emerging to be an attractive alternative to more traditional analytical techniques.[2] As it probes intermolecular vibrational modes, it is especially suitable for analysis of solid-state structural properties and has been successfully applied for large range of analytes. Nevertheless, to our knowledge, LFR spectroscopy has not yet been broadly used for analysis of human teeth.

As a proof of principle, it was important to investigate range of different specimens to evaluate the suitability of LFR approach. Our main focus was to analyze number of samples with interesting and unique features. Alongside healthy (control) specimens, teeth affected by molar incisor hypomineralization (MIH) and rare genetic disease (amelogenesis imperfecta) were comprehensively investigated. More specifically, 2D-spatial Raman maps of cross-sectioned samples were recorded. Our in-house experimental setup allowed for simultaneous data collection from broad spectral range. Accordingly, direct comparison between low and mid-frequency regions was carried out using principal component analysis (PCA). This chemometric technique was further used to relate spectral characteristics (i.e., structural and chemical information) to different features and sections (enamel, dentin and pulp) within samples.

Figure 1: Visual representation of the experimental design.

References


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Triplet down conversion is the non-linear optical process of splitting one photon into three. In order to obtain a strong interaction, experimental realisation of the process usually takes place within an optical cavity — such as a whispering gallery mode resonator — that contains a $\chi^{(3)}$ crystal as a non-linearity. High energy photons are supplied to the resonator, and the existence of the non-linearity allows them to be down converted to lower energy photons. Triplet down conversion was first observed experimentally as early as 2010 [1], and has interest due to its possible generation of squeezed light, and more recently for its applications to quantum information [2, 3]. To date there has been no experimentally measurable quantum entanglement as a result of triplet down conversion. Theoretical analyses typically implement optical phase space methods to describe the process, which unfortunately introduce approximations. Comparisons of various phase space techniques can be found in the literature [4], but no comparisons have been made to more exact approaches such as the Monte Carlo wavefunction approach.

In this work we carry out a systematic application of the positive-P phase space method to the quantum properties of degenerate intracavity triplet down-conversion. We find the steady states of the driven nonlinear optical cavity and find its regime of stable operation including the effects of quantum noise. We examine the fluctuation spectra of the steady state, focussing on the squeezing and entanglement of the output fields, finding regimes of usable entanglement. Considering the more general case of non-degenerate down conversion, we characterise the entanglement of the four distinct modes, finding regimes where steering is possible. Finally, we compare the positive-P phase space approach to the Monte Carlo wave function method, providing a test of our theoretical approach.

References

Towards the Extraction of Both the Optical and Mechanical Properties of Cartilage Using Polarisation-Sensitive Optical Coherence Tomography and Dynamic Compression

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Osteoarthritis (OA) is a debilitating disease that affects articulating joints, in which there is a gradual wearing away of the aneural cartilage covering the bone ends, resulting in pain. A standard clinical diagnosis of OA is made via weight bearing X-rays, in which joint space narrowing is seen as the hallmark sign of cartilage loss. There is no cure for OA, and prevention strategies are highly limited. Many believe one of the major obstacles in OA research is in determining the early or even pre-OA state of the joint [1]. Such a joint would appear to have normal full thickness cartilage, but with changes, at the micro-to-nano scales, and protein to molecular levels. With such changes, the challenge for most OA researchers, especially in the imaging domain, would be to develop ways in which this early and very mild cartilage degeneration is detected.

A recent study has shown that Polarisation-Sensitive Optical Coherence Tomography (PS-OCT) can differentiate a healthy cartilage sample from a degenerate one only if the sample is imaged in a compressed state [2]. By imaging during compression process we have found that the optical activity appears during loading and then disappears with relaxation (figure 1). This has opened up a detection window where further experiments need to be performed in order to identify and characterise key biomarkers related to osteoarthritis degeneration. A novel all-optical, semi-polarisation sensitive force probe is being developed in order to extract the mechanical and optical properties simultaneously. The probe uses a fabri-perot cavity to encode the force applied to the sample, while preserving one polarisation state allowing Young’s Modulus and birefringence to be quantified.

Figure 1: PS-OCT images of bovine articular cartilage taking at various times during loading. Top left: unloaded sample shows very little optical activity. Top right: sample after 150 minutes of compression shows strong birefringent banding. Bottom right: sample 20 minutes after the load was removed shows some optical activity. Bottom left: 16 hours after the load was removed the sample shows almost no optical activity. Black and white color corresponds to a phase retardation of 0 and 90 degrees respectively.

References


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Optical coherence tomography (OCT) is a real time, non-invasive, non-contact and three dimensional cross-sectional imaging technique with micrometric axial and lateral resolution. OCT is mainly used with samples and tissues that are semi transparent to light. OCT is based on white light interferometry and use the interferometric data to build a depthwise intensity profile, or A-scan, of the sample. OCT is widely used for in vivo imaging of the human eye. Over the last decades, rapid development in OCT has resulted in many functional extensions to the method enabling extraction of different optical and mechanical properties of the sample [1].

The most popular type of OCT is Fourier domain OCT (FD-OCT). In FD-OCT, the reference mirror position is fixed and an A-scan is obtained by Fourier transformation of the spectral interferences detected either by a spectrometer or by a photodiode while the sources spectrum is swept in time. The absence of moving parts allows the image to be acquired faster than in other types of OCT such as time domain OCT where A-scans are obtained using a moving reference arm.

The determination of Group Velocity Dispersion (GVD) could be considered as a method for material differentiation in OCT. A recent study have suggested to characterize ocular media using its GVD value [2]. Recently a novel purely software-based alternative has been developed, where the two OCT images are generated from a single broadband interference spectrum[3]. To add another layer of functional information, we plan to measure the refractive index - determination of which is still an issue in eye studies. We will measure it by using an optical coherence refractometry method at multiple angles of incidence [4]. Simultaneously, the refractive indexes we calculate will be used to infer the geometrical thicknesses from the optical thickness of sample layers information inherently provided by the OCT images. Having this parameter is crucial for the method for measuring GVD values, because its accuracy depends on how well the geometrical thickness of the investigated layer is determined.

Using the combination of GVD determination and refractive index measurements we aim to study different types of eye disorders. The very first targets of our studies are the leading causes of blindness in the western world - Age-Related Macular Degeneration and Diabetic Retinopathy. Previous studies have shown that such visual disorders are characterised by high levels of glucose which can cause an increase of salinity in body fluids [5]. These factors are believed to affect the optical properties of the ocular media and accordingly should affect GVD and refractive index. Taking into account this information, we will build a correlation-based purely post-processing predictive model for early stage of development of eye diseases.

References

Luminescent solar concentrators (LSCs) are devices that concentrate solar energy by absorption and wave-guided emission, with large potential for improving PV cost efficiency. A general LSC consists of a luminophore dispersed within a waveguide; direct and diffuse incident light is absorbed by the luminophore (Figure 1. (a)) and re-emitted, with a portion of the emitted light entering waveguide modes optically coupled to PV cells (Figure 1. (d)). Due to spectral overlap between the absorption and emission bands of luminescent species in LSCs, reabsorption (Figure 1. (c)) is one of the major loss mechanisms inhibiting commercialisation as it feed back into the other loss mechanism of non-radiative decay and non-waveguide emission (Figure 1. (b)).

Reabsorption can be decreased via transferring optical excitations to a redder-emitting species, via Frster resonance energy transfer (FRET), which has a greatly decreased optical density across the waveguide modes. In this way, the likelihood of reabsorption is decreased compared to the case where only one chromophore is employed. This presentation looks at three different methods of this:

1. Energy transfer within a molecule.
2. Energy transfer between monomers in a polymer chain.
3. Energy transfer between molecules in a polymer matrix.

Figure 1: Figure 1: LSC operation: (1) incident light, (2) escape cone loss, (3) reabsorption, (4) collection.

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DISTORTED Porphyrins: Ultrafast Excited State Dynamics of Boron Porphyrins and Porphyrinoids

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Ultrafast excited state processes of photoactive molecules are governed by the initial dynamics that occur on a femtosecond to nanosecond time scale. Those processes were probed for a library of boron porphyrin and boron porphyrinoid complexes with unique structural features using two pump/probe techniques: 1. transient absorption (TrA) spectroscopy and 2. time resolved fluorescence/phosphorescence spectroscopy. Further information was obtained using laser induced acoustic spectroscopy, quantum chemical calculations, resonance Raman spectroscopy and static spectroscopy methods. The structural features exhibited by the flexible boron porphyrins and boron porphyrinoids significantly affect the ultrafast excited state dynamics of the system and change the photophysical properties of those molecules in a very specific and potentially tunable way.\textsuperscript{[1]} Structural reorganisation through bond inversion is proposed to occur in the excited state of a boron porphyrin that shows the most significant change in the photophysical behaviour. (Fig.1)

\textbf{Figure 1:} Proposed bond inversion of the central boron moiety and a representation of a strongly enhanced vibrational mode in resonance Raman spectrum of a boron porphyrin (B_{2}OF_{2}(TTP)).

\textbf{References}


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The stochastic projected Gross-Pitaevskii equation (SPGPE) is a classical field theory for finite-temperature degenerate Bose gases where interaction with the thermal cloud is characterised by two processes, known as number-damping and energy-damping. While number-damping effects (also known as simple growth) have been extensively explored theoretically [1, 2, 3, 4], the energy-damping contribution has attracted less attention [5, 4]. We use Ito change of variables to obtain stochastic Ehrenfest relations for particle number, position, and momentum from the SPGPE. These relations include contributions from both the number-damping and energy-damping reservoir interactions, and in many cases transform multiplicative noise to additive noise, simplifying greatly the mathematical description of observables. The stochastic Ehrenfest relations show that the contribution from the energy-damping may be significant and even dominant, suggesting that the two dissipative process could be distinguished in particular experiments. We apply the stochastic Ehrenfest relations to a harmonically trapped degenerate finite-temperature Bose gas, finding analytic solutions for the position and momentum. These are compared to numerical results found by simulation of the SPGPE.

References


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STUDY ON PENETRATION OF CONSOLIDANT INTO NEW ZEALAND FLAX FIBRES USING RAMAN MICROSCOPY

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Previous studies have shown that important cultural Māori textiles produced from harakeke, New Zealand flax (*Phormium tenax*) fibres and dyed black iron-tannate dyes are liable to degradation via acid catalysed hydrolysis and iron catalysed oxidation [1]. For conserving these fibre textiles, conservators use various natural and synthetic consolidants to treat deteriorated fibres. However the effect of these consolidants on these fibres have not been previously studied using a non-destructive method, such as Raman spectroscopy. It is desirable to understand how each consolidant penetrates into the fibre and the outcome of concentration on this uptake into the fibre. To look at consolidant uptake, Raman microscopy coupled with chemometric methods was applied to analyse the distribution of consolidants within harakeke fibres.

Pre-aged harakeke fibre samples were treated with Sodium Alginate, Zinc Alginate, Paraloid B-72 (ethyl methacrylate), Funori (polysaccharide, seaweed extract), Klucel G (hydroxypropyl cellulose), and Methocel A4M 400 (methyl cellulose) with three different concentrations per consolidant (0.5, 1.0 and 2.0 % w/v). Treated fibres were sectioned, then analysed using Raman microscopy with line and mapping configurations under 785 nm and 582 nm wavelengths respectively. Relative levels of consolidant and fibre signals were used to give approximate distributions of consolidant within the fibres. Where distinct peaks were observed univariate methods were sufficient, however with some consolidants the spectral features overlapped with fibre signals therefore multivariate methods were investigated to distinguish between these signals. Principal component analysis and basis analysis methods were used in these samples. This study indicated the potential of using Raman microscopy as a non-destructive technique to guide conservators in choice of consolidant type and concentration for applying to valued Māori textiles.

Figure 1: Basis analysis of a cross sectioned, aged and consolidated harakeke fibre. (a) bright field image of the fibre cross section mounted in nylon, (b) selected reference spectra used for basis analysis (green = fibre, blue = consolidant and red = nylon), and (c) relative signal contribution of the three components measured with the analysis across the 2 % PB 72 consolidated harakeke fibre sample.

References


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The effect of vacuum conditions on feature quality and machining efficiency for ultrafast laser micromachining

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Ultrafast laser micromachining that utilises pulses on a femtosecond timescale is a rapidly growing area of research with applications in a wide variety of fields, from microelectronics to microsurgery. Femtosecond pulses are often praised for their ability to perform precise cutting of materials through a ‘cold-cutting’ mechanism which avoids mechanical and thermal collateral damage to the surrounding area. However, the high precision and clean ablation features associated with ultrafast laser micromachining can be counteracted through the intense plasma in air that is generated at high pulse energies. The highly reflective plasma generated above the sample surface can result in a distorted beam profile at the target machining plane, producing machined features with reduced edge quality and accuracy. In addition, the highly reflective plasma results in underutilised portions of the incident pulse energy, therefore decreasing machining efficiency.

We present the ablation threshold data and trends for a variety of materials including undoped silicon, stainless steel and sapphire laser machined under vacuum and other ambient conditions. Ablation thresholds were determined using the diameter regression technique with 130 fs, 800 nm laser pulses at a repetition rate of 500 Hz. Ablation features are analysed extensively to observe the impact of the ambient conditions on the resulting feature quality.
Superconducting microwave circuit build quantum computers are the most promising technology to achieve quantum supremacy, the state where quantum computers can solve some problems faster than classical computers. The underlying quantum bit (qubit) in these systems is encoded in a microwave photon with GHz frequencies. These photons in the gigahertz domain have too low energies to transmit them through the noisy room-temperature environment, where they would be dissipated due to thermal noises [1]. Optical photons however have the much higher photon energies and signals can be detected using highly efficient single-photon detectors. Here we present a device based on the electro-optic interaction that converts coherently photon from the microwave into the optical domain prior to detection as a promising alternative.

In this scheme, two continuous waves, one in the optical and one in the microwave range are to interact in a nonlinear crystalline whispering gallery mode (WGM) resonator. WGM resonators are particularly suited as they show extremely broadband confinement [2]. Nonlinear interaction requires high field amplitudes and we achieve these by confining the microwave fields and the optical fields simultaneously within the same resonator. The lithium niobate WGM resonator has an optical quality factor of $10^8$. In order to achieve a high efficient modulation, a strong confinement of the microwave mode is needed. Therefore, the high-quality optical WGM resonator was coupled with a 3D metal microwave cavity as shown in Fig.1. The conversion efficiency achieved is 0.2%.

In our future experiments, we are going to achieve a higher conversion efficiency. This can be done by designing a more efficient microwave system with a higher microwave Q factor and a stronger field confinement between the optical WGM resonators and microwave mode. We present new work on a new strip-line resonators design that is better phase matched and easier to fabricate [3].

![Figure 1](image.png)

**Figure 1:** The bottom part of the microwave cavity with the silicon coupling prism and the WGM resonator.

**References**

ON THE MODE EVOLUTION OF SEGREGATED CONDENSATE MIXTURES IN QUASI-2D CONFINEMENT

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We present new features of low energy Bogoliubov quasiparticle excitations of two component Bose-Einstein condensate (TBEC) in quasi-2D geometry at zero temperature. Starting from the generalized Gross-Pitaevskii equation, we obtain the Bogoliubov de-Gennes (BdG) equation for TBEC using the Hartree-Fock-Bogoliubov (HFB) theory with Popov approximation. In the immiscible domain of $^{85}\text{Rb} - ^{87}\text{Rb}$ TBEC, the position swapping of the constituent species is observed which is driven by tuning intraspecies scattering length of $^{85}\text{Rb}$. The appearance of a new zero energy mode is observed [1] in the elementary excitation spectrum which is an indication of the onset of dynamic instability within the mixture.

We also incorporate the effects of anisotropy in the confining potential and report the radial anisotropy induced structural transition [2] of the interface of $^{85}\text{Rb} - ^{87}\text{Rb}$ TBEC. The study of the dispersion relation shows two distinct branches, and anisotropy modifies the energy scale and structure of these two branches.

References


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Figure 1: Equilibrium condensate density profiles of $^{85}\text{Rb} - ^{87}\text{Rb}$ TBEC for three different strengths of anisotropy ($\alpha$). $s$-wave scattering length corresponding to the intraspecies interaction of $^{85}\text{Rb}$ is kept fixed at 10$a_0$ (Left) and 50$a_0$ (Right), $a_0$ being the Bohr radius
COMPACT LOCALISED STATES IN SPIN-ORBIT COUPLED BOSE-EINSTEIN CONDENSATES IN 2D LATTICES

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The creation of Bose-Einstein condensates (BECs) with ultracold atoms is now a routine procedure. We use an all-optical setup to create BECs of about 10,000 \(^{87}\text{Rb}\) atoms. After we create a BEC, we use a highly elliptical pancake trap to create strong confinement in the z-direction, which creates a 2D trap. Onto this trap we illuminate an arbitrary image with repulsive laser light [1]. The image is created by a spatial light modulator (SLM) (Figure 1).

![Figure 1: (a) The image projected by the SLM. (b) An average of 10 shots of the SLM image](image)

Spin-orbit coupling (SOC) is the linking of the spin of a particle with momentum. In an electron bound to a nucleus the intrinsic spin of the electron is linked to its angular momentum. In our experiments we link the spin of a BEC with linear momentum [2].

SOC is achieved by first breaking the degeneracy of magnetic-sublevels with a magnetic field. This induces a Zeeman shift in their energy levels. We eliminate one of the three sublevels with the quadratic Zeeman shift, which leaves two so-called pseudospin states. Raman laser beams, the required frequency of which depends on the strength of the magnetic field, are used to impart a momentum kick to the BEC depending upon its spin state.

Theoretical work has demonstrated that flat-band modes [3], in which the dispersion curve is flat, can be created with SOC on particular lattice arrangements [4]. Flat bands give rise to compact localised states (CLSs), in which the BEC is localised to particular lattice sites rather than being spread over the entire lattice. Our aim is to test this theoretical proposal. The creation of CLSs and their subsequent manipulation could provide tools for quantum emulation.

References


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MAGNETIC DARK SOLITONS IN TWO-DIMENSIONAL SPIN-1 SUPERFLUIDS

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A dark soliton is a nonlinear excitation that is known to exist in one-dimensional superfluids and in nonlinear optical fibres. Usually solitons are dynamically unstable in higher dimensions. In this work we report on a novel dynamically stable two-dimensional dark soliton—a soliton excitation of the magnetic moment that exists in a spin-1 Bose-Einstein condensate [1, 2]. It has two basic configurations: ring shape and string shape with endpoints on the boundary of the condensates. We have found an exact stationary solution for this soliton for a particular ratio of the density-dependent ($g_n$) and spin-dependent ($g_s$) interaction parameters. Away from this solvable point we propose ansatz, without any fitting parameters, that shows excellent agreement with the full numerical solution.

Figure 1: Numerical solutions (red dotted) against the approximate analytical solutions (blue solid) of the magnetic dark soliton at $g_s/g_n = -0.05$. The figure shows the component properties along an axis that crosses through the magnetic soliton: (left) the density of $m = \pm 1$ component, (middle) the phase difference between $m = +1$ and $m = 0$ components and (right) the magnetic moment density.

Figure 2: Real time evolution (oscillation) of a ring shaped magnetic dark soliton (blue line) in a circular spin-1 BEC.

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Additive manufacturing (AM), which is generally known as 3D printing, is the technology that transfers computer assisted design (CAD) into rapid prototyping, tooling and manufacturing. Within additive manufacturing, customized objects can be designed and produced from metals, ceramics, and polymers without the need for moulding or machining and can meet the demands of individual and specific applications. For polymer based 3D printing, besides the common fused deposition modelling (FDM) process, two other methods are stereolithography (SLA) and digital light processing (DLP) technologies. They cure the liquid photosensitive monomer to solid polymer by UV light. These technologies have outstanding advantages, such as high resolution and high build speed. [1]

Three types of polymerisation reactions have been used for SLA and DLP processes, including free radical polymerisation, free-radical addition reaction and cationic polymerisation. Compared with other two areas, free-radical addition reaction, which includes thiol-alkene and thiol-alkyne polymerisations, has not been developed extensively. Recently, it is reported that thiol-alkene polymerisation reactions have unique properties, including high reaction speed, good biocompatibility and high oxygen tolerance. Thiol-alkyne polymerisation reactions also have these advantages mentioned above. Moreover, according to the reaction mechanism, the reaction will be theoretically faster than thiol-alkene system. Additionally, polymers synthesized from this kind of reactions have high crosslink density that can bring better mechanical properties, such as toughness; and high refractive index. [2]

Based on the thiol-alkyne chemistry, current work is aimed to develop a faster photopolymerisation reaction for SLA or DLP 3D printing. To date, the ratio of reactants, optimizing the photoinitiators and the parameters of the additive manufacturing are underway. This study could have huge potential as the new photopolymer system for 3D printing.

References


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Quantum droplets occur in ultra-cold atomic gases when quantum fluctuations (QFs) stabilize the system against collapse due to attractive two-body interactions. Such droplets have now been studied using dipolar \cite{1, 2} and spinor \cite{3, 4} Bose-Einstein condensates. For the dipolar system the long ranged and anisotropic dipole-dipole interactions (DDIs) cause the droplets to elongate into filaments and neighbouring droplets to repel each other, potentially stabilizing multi-droplet configurations.

Our group has established the basic theory for describing dipolar quantum droplets \cite{5, 6} and is now pursuing the next generation of applications with this system. I will cover several of our current directions of investigation:

1. **Excitations of self-bound quantum droplet.** We have performed the first comprehensive theory for the excitations of a dipolar droplet with our results revealing the effects of QFs on the collective modes of an incompressible ultra-dilute quantum fluid \cite{7}.

2. **Droplet crystals.** An external confinement potential competes with the droplet self-binding mechanism, and can favour the system splitting into several droplets which interact via the long ranged DDI. This leads to a rich phase diagram consisting of various multi-droplet crystals as the system parameters are varied. We use analytic and numerical techniques to quantify the phase diagram. Additionally, the confining potential can be used to control inter-droplet tunneling and explore novel quantum phase transitions (see Fig. 1) \cite{8}.

3. **Quantum droplet vortices.** Vortices are often regarded as the smoking gun of superfluidity and so it is of fundamental interest as to whether quantum droplets can support vortices. We show that a vortex droplet can be produced by an adiabatic preparation scheme and predict that the dominant instabilities (limiting their lifetime) arise from quadrupolar collective modes \cite{9}.

![Figure 1](https://example.com/figure1.png)

**Figure 1:** Example of a low energy droplet crystal ground state and how trap compression can be used to engineer a quantum phase transition. (c) An insulating (no tunneling between droplets) crystal with a low density halo. (d) By compressing state shown in subplot (c) the system undergoes a phase transition to a conducting state where the atoms can tunnel between the droplets. System consists of $N = 97.7 \times 10^{16} \text{Dy}$ atoms.

**References**


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DYNAMIC COMPLEXITY IN TWO COUPLED PHOTONIC CRYSTAL NANOCAVITIES.

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Nonlinear optical resonators are the subject of much interest due to the plethora of effects that they may generate, including optical frequency combs and cavity solitons. In particular, introducing a small gap into a Photonic Crystal creates an optical resonator with a very large $Q$ and small mode volumes. Such nano-devices offer the possibility of doing nonlinear optics with small photon numbers, threshold-less lasing and many other intriguing experiments in both classical and quantum optics. Understanding and modelling the dynamics of such cavities is thus of vital importance since it provides guidance to experimentalists about what cavities are interesting and what the design tolerances are.

We consider an optical device consisting of two coupled nanocavities in a Photonic Crystal that are optically driven, which was designed and manufactured by Alejandro Giacomotti’s group in Paris [1, 2]. This experimental system is able to operate with only a few hundred photons and has been shown to exhibit spontaneous symmetry breaking and bistable behaviour [1, 2]. However, its more complex dynamics have not yet been characterised [1]. The overall behaviour of this type of device is captured by a four-dimensional vector field model. We conduct a bifurcation analysis to determine the dynamics that arises when the intensity and frequency of the optical input are varied. We find Shilnikov bifurcations and transitions to different chaotic attractors. Relevant behaviour arises from local and global bifurcations in parameter regions that are well within the range of future experiments.

Figure 1: Left column shows a MBE image of two cavities in the same Photonic crystal [1]. Right column shows two different types of chaotic behaviour for different parameter values of the cavities.

References

DYNAMICS OF AN ALL-FIBRE LASER WITH SATURABLE ABSORBER

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We present a detailed study, both experimental and numerical, describing the operation of a Q-switched all-fibre laser. The aim of this work is to understand the dynamics of the Q-switching behaviour especially how it relates to the length of the absorber section. Importantly we find that the simple Yamada model, typically used to describe Q-switching in single-mode semiconductor lasers, can be used with slight modifications be used to understand the behaviour of our multi-moded fibre laser. In particular, we find that the transition between dynamical regimes is well modeled by the Yamada equations and demonstrate this experimentally by varying the length of our saturable absorber.

Our laser is a simple Fabry-Perot cavity bounded by fibre Bragg gratings (FBGs) and pumped by a diode laser at 980 nm, with an erbium-doped gain section and a thulium-doped absorber section similar to that in Ref [1]. The HR-FBG has a high reflectivity of approximately 99% while the LR-FBG has a reflectivity close to 20% at 1550 nm. At these wavelengths, Thulium has a weak absorption that can be easily saturated. Thus it functions as a passively saturable absorber, leading to Q-switching behaviour for a range of pump powers and absorber lengths. We test for all observable dynamical behaviours for different absorber lengths ranging from 0.1m to 1.48m to characterize their behaviour.

Our numerical modeling extends the Yamada equations [2] to take into account unequal decay times of the gain and absorber sections, giving

\[ \dot{G} = \gamma_G (A - G - GI), \quad \dot{Q} = \frac{\gamma_G}{\sigma} (B - Q - \tilde{a}QI), \quad \dot{I} = (G - Q - 1)I, \]

(1)

where

\[ \sigma = \frac{\gamma_G}{\gamma_Q}, \quad \tilde{a} = \frac{a}{\sigma}, \]

(2)

for the gain G, the absorption Q, and the intensity I. The parameters are the pump(diode) current A, the coefficient of absorption B, the relative absorption vs gain \(\tilde{a}\), the decay time of the gain section \(\gamma_G\), and the ratio between the two decay times \(\sigma\). Using bifurcation theory along with associated continuations tools, we present two-dimensional bifurcations diagrams in the (A,B)-plane to elucidate and describe intriguing dynamics exhibited by this laser system. Good agreement is found between this simple model and our fibre laser [3]. Our demonstration that simple Q-switched fiber lasers can be modeled with the Yamada equations, leads to the possibility of simple experimental realizations of optical logic processing with networks of fibre lasers, which we hope to demonstrate in the near future.

![Figure 1](image.png)

Figure 1: Experimental (a) and numerical (b) bifurcation diagrams showing regions 1 (off), 2 (stable Q-switching) 3 (irregular pulsing), pulsing thresholds (red and blue dots) and bifurcations of which details are described in [3].

References


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We study a model of the collective behaviour of $N$ two-level atoms interacting coherently with a single mode of the radiation field - the Dicke model. In this work we study a generalised form of the model which features unbalanced coupling, $\lambda_- \neq \lambda_+$, between the rotating and counter-rotating terms of the Hamiltonian. The model takes the form of an open quantum system with cavity decay rate $\kappa$, modelled by a master equation in Lindblad form. The Hamiltonian is (with $\hbar = 1$)

$$H = \omega a^\dagger a + \omega_0 J_z + \frac{\lambda_-}{\sqrt{N}} (a J_+ + a^\dagger J_-) + \frac{\lambda_+}{\sqrt{N}} (a J_- + a^\dagger J_+),$$  \hspace{1cm} (1)

where $a$ is the annihilation operator of the radiation field mode, $J_\pm$, $J_z$ are collective angular momentum operators for the atomic states, $\omega$ is the frequency of the radiation field mode, and $\omega_0$ is the frequency splitting of the atomic levels. In the thermodynamic limit $N \to \infty$, the model is described by a set of nonlinear ordinary differential equations,

$$\dot{\alpha} = -\kappa \alpha - i\omega \alpha - i\lambda_- \beta - i\lambda_+ \beta^*$$  \hspace{1cm} (2)

$$\dot{\beta} = -i\omega_0 \beta + 2i\lambda_- \alpha \gamma + 2i\lambda_+ \alpha^* \gamma$$  \hspace{1cm} (3)

$$\dot{\gamma} = i\lambda_- (\alpha^* \beta - \alpha \beta^*) + i\lambda_+ (\alpha \beta - \alpha^* \beta^*),$$  \hspace{1cm} (4)

where $\alpha = \langle a \rangle / \sqrt{N}, \beta = \langle J_- \rangle / N$, and $\gamma = \langle J_+ \rangle / N$.

Our work focusses on the dynamics of these equations under changes in the coupling strengths $\lambda_-$ and $\lambda_+$. In particular we study phase transitions between normal phases that feature zero photon number, $\alpha = 0$, at equilibrium to superradiant phases ($\alpha \neq 0$), and transitions to oscillatory phases. These phase transitions have been experimentally realised in [1]. In the theoretical model we find superradiant phase transitions manifest themselves as pitchfork and saddle-node bifurcations, with multistability and hysteresis possible. We find the oscillatory phase transition arises from Hopf bifurcations, where superradiant phases transition to oscillatory phases with a stable limit cycle. After the Hopf bifurcation, oscillations are initially simple, nearly sinusoidal oscillations. We find these oscillations can become much more complicated under a period-doubling bifurcation, where the limit cycle splits. The system can then undergo a period-doubling cascade, with an infinite number of period-doubling bifurcations signifying the system’s descent into chaos, illustrated in Fig. 1 below. We also find another chaotic attractor emerge from a Shil’nikov type homoclinic bifurcation, and then the death of oscillatory phases in other homoclinic bifurcations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{A period-doubling cascade on the Bloch Sphere. Here $\kappa = \omega = \omega_0 = \lambda_- = 1$, the initial condition is perturbed from the South Pole of the Bloch Sphere, $(\alpha, \beta, \gamma) = (0.001, 0.001, -0.5 + 0.001)$.}
\end{figure}

**References**


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Extreme events in optics have been recently attracting a great attention [1, 2] due to the well-known analogy between optics and hydrodynamics, where rogue waves formation and prediction is a priority field of investigations. In this contribution, we show numerical results about extreme events occurring in the field emitted by a monolithic broad-area semiconductor laser (VCSEL) with saturable absorber [3], as the one used in experiments [4].

For appropriate choice of parameters, the intensity profile of the field emitted by the laser may display spatiotemporal chaos [4], where extreme events are possible. At difference from previous literature about optical rogue waves in transverse spatial systems, we developed a numerical method for the individuation of the (2D+1) spatiotemporal maxima of the transverse field intensity [3]. Each maximum appearing in the space profile is followed during its time evolution, and an “event” is counted only when its peak intensity reaches the maximum value also in time (see Fig. 1(a)). This method allows a comparison, for example, with the hydrodynamical definition of “significant wave height”, corresponding to the mean value of the wave height (from trough to crest) of the highest third of the waves.

Figure 1: (a). Transverse intensity distribution showing an extreme event. (b). Density plot of the fraction of extreme events as a function of the pump $\mu$ and $r$ parameter (ratio of the carrier lifetimes in the amplifier and in the absorber). The experimental observation of extreme events should be more probable for low values of pump and high values of $r$ parameter (fast saturable absorber). [3].

We identify regions in the parameter space where extreme events are more likely to occur (see Fig. 1(b)) and we study the connection of those extreme events with the cavity soliton solutions that are known to exist in the same system, both stationary and self-pulsing [5, 6].

A similar system, also hosting cavity solitons, consisting in a broad-area VCSEL with coherent injection, has been also investigated and preliminary results about spatiotemporal extreme events are very promising. The role of the phase in extreme events formation has been investigated, showing a rich and complex scenario [7].

References


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Artificial structures with narrow resonance features are of tremendous importance to fully exploit the unique terahertz (THz) frequency range [1]. Despite an on-going effort, quality factors (Q-factors) higher than 1000 are hardly achieved in resonant THz structures. Here, we demonstrate a THz whispering-gallery mode resonator (WGMR) with unprecedented Q-factors of up to 22,000 operating over more than two octaves from 0.2 THz to 1.1 THz. The extremely broadband operation is achieved by implementing a prism coupling scheme which provides a much larger bandwidth compared to previously implemented coupling scheme using a single-mode waveguide [2]. We expect our results to pave the way for high-Q THz devices, operating over an extremely broad frequency range, like highly sensitive sensors and filters.

The WGMs are observed in an 8 mm diameter sphere made of high resistivity float zone grown silicon (HRFZ-Si) with a very low material absorption, which is essential to achieve high Q-factors. Prism coupling is implemented with a specifically designed HRFZ-Si prism, so that the evanescent field of the beam that experiences total internal reflection at the base of the prism is phase-matched to the fundamental mode of the WGMR at 0.25 THz [3]. The WGMs are experimentally characterized with continuous wave (CW) THz spectroscopy using Hilbert transformation [4].

The measured intensity profiles of the THz WGMR coupled to the prism in three representative scans covering more than two full octaves of the spectrum are shown in Fig. 1. Particularly the frequency regions from 250 GHz to 260 GHz, 500 GHz to 510 GHz, and 1050 GHz to 1060 GHz have been chosen [see Figs. 1(a)–1(c), respectively]. The measurements impressively reveal the excitation of high-Q THz WGMs over more than two octaves. For example, the WGM at 1054.43 GHz has a Q-factor at critical coupling of $2 \times 10^4$.

In conclusion, we have demonstrated the excitation of high-Q THz WGMs over more than two octaves from 0.2 THz to 1.1 THz using prism coupling of THz WGMs for the first time. The results provide manifold opportunities for future developments and applications like ultra-broadband highly-sensitive sensors.

References


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Experimental Observation of Differently Polarized Coexisting Cavity Solitons

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Temporal cavity solitons (CSs) are pulses of light that can recirculate in coherently-driven, dispersive, Kerr nonlinear resonators without changes in their shape or energy [1]. Under typical operating conditions, CSs are unique attractors. This means that the pump-resonator parameters completely set the soliton characteristics (peak power, duration), and that all simultaneously coexisting solitons are identical. However, recent studies have shown [2, 3], that if two different cavity modes are simultaneously driven, non-identical CSs can coexist. In [4] it is proposed, that non-identical vectorial CSs can coexist when two orthogonally polarized cavity modes are driven. This prospect has not yet been experimentally confirmed.

In this contribution, we report on the experimental observation of the coexistence between two non-identical, vectorial CSs with different polarizations. Our experiment is based on an 85-m-long fiber-ring resonator made out of standard single-mode fiber closed on itself with a 95/5 coupler. The resonator is driven with synchronized quasi-cw pulses. By changing the birefringence of our resonator with an intra-resonator polarization controller, the nonlinear resonances corresponding to the two orthogonal polarization modes supported by our resonator can be made to overlap, allowing for the coexistence of nonidentical CSs in our resonator. We monitor the intra-cavity intensity using a real-time oscilloscope and an optical spectrum analyzer. Polarization controllers and polarizing beam-splitters are used to separately monitor the two orthogonal polarization modes of the cavity.

Our experimental findings are summarized in Fig. 1. Here we show the roundtrip-by-roundtrip evolution of the intracavity intensity in the orthogonal polarization modes 1 and 2 [Figs. 1(a) and (b)], as well the the evolution of the total intracavity intensity [Fig. 1(c)]. Moreover, Figs. 1(d) and (e) show spectra measured for the two polarization modes (red curves) and corresponding results from numerical simulations (blue curves). Figure 1(c) clearly shows two CSs coexisting in our resonators, both trapped to opposite edges of our 4.5 ns driving pulses [5]. Evidently, the CSs are non-identical, exhibiting different polarization and spectral width i.e. temporal duration.

References


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Figure 1: (a, b) Roundtrip-by-roundtrip evolution of the intracavity intensity in the orthogonal polarization modes 1 and 2. (c) Evolution of total intracavity intensity. (d, e) Optical spectra measured for the two polarization modes (red curves) and corresponding numerical simulation results (blue curves).

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TUNABLE VISIBLE LIGHT SOURCES USING MAGNESIUM FLUORIDE MICRORESONATORS

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Through their small modal volumes and ultra-high finesse, optical microresonators are capable of exhibiting rich nonlinear behaviour, requiring only milliwatt power levels [1]. Microresonators with Kerr type nonlinearities have been the focus of much research, resulting in the demonstration of chip-scale coherent optical frequency combs, underpinned by four-wave-mixing.

Recently, four-wave-mixing in microresonators has been used to generate widely spaced sidebands, symmetrically spaced around the pump [2]. This has resulted in frequency generation well into the mid-IR. Furthermore, small changes in the pump wavelength lead to large shifts in the generated sidebands, providing quasi-continuous tunability over hundreds of nanometers. This makes microresonators an extremely versatile light source. These widely spaced sidebands are made possible by a combination of a normal (positive) second-order dispersion $\beta_2$ coefficient and an anomalous (negative) fourth-order dispersion $\beta_4$ coefficient. These dispersion coefficients can be modified by controlling the geometry of the microresonators. It has been shown that, for resonators with a major radius $R < 500 \, \mu m$, the geometric dispersion shifts the zero-dispersion wavelength to longer wavelengths. Such resonators can readily be fabricated using single diamond-point turning techniques.

Figure 1: (Left) Second-order dispersion $\beta_2$ of a magnesium fluoride microresonator, with a major radius $R = 165 \, \mu m$, tapering angle $\theta = 18^\circ$ and minor radii $r = 90 \, \mu m$ (orange) and $r = 2 \, \mu m$ (blue), with the zero-dispersion wavelength marked (dotted). Inset shows the field distribution of the corresponding mode on a logarithmic scale. (Right) The phase-matching curve of the $r = 2 \, \mu m$ microresonator. Inset shows a zoom of the lower branch of the phase-matching curve, between pump wavelengths of 1 $\mu m$ and 1.75 $\mu m$, showing sideband tunability into the visible.

Here, we consider the converse problem: by controlling the geometric dispersion, the zero-dispersion-wavelength can be shifted towards shorter wavelengths. By using full-wave simulations (COMSOL), we simulate magnesium fluoride microresonators, characterised by a major radius $R$, a minor radius $r$ and a tapering angle $\theta$. We find that the zero-dispersion wavelength can be dramatically shifted by reducing the minor radius of the resonator. In Fig. 1 (left), we show a shift of the zero-dispersion wavelength of $\approx 500 \, nm$ when the minor radius is reduced to 2 $\mu m$. The curvature of the second-order dispersion, corresponding to the fourth-order dispersion $\beta_4$ is also reduced. This shift in dispersion parameters can be explained by the redistribution of the mode into the surrounding environment, as $r \sim \lambda$. The tapering angle is also critical: for a large tapering angle, the mode shifts further into the magnesium fluoride bulk, and the effect of the minor radius $r$ becomes negligible (not shown). The corresponding phase-matching curve is shown in (Fig. 1 (right)). By choosing a pump wavelength $\lambda \approx 1 \, \mu m$, we can see that sidebands in the visible can be generated. Furthermore, tuning the pump over a $\approx 150 \, nm$ range tunes the generated sideband by $\approx 200 \, nm$, leading to quasi-continuous tunability in a significant portion of the visible spectrum. We anticipate that this tunability can be further improved by optimisation of the microresonator geometry.

References


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Experimental Observation of Internally-Pumped Parametric Oscillation in a Lithium Niobate Microresonator

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Microresonator-based frequency combs (MFCs) have shown great promise in all areas where precise frequencies of electromagnetic waves need to be created or measured. With a small footprint and high power efficiency, as well as high power modes that are widely spaced, MFCs are ideal candidates for a myriad of applications from spectroscopy to telecommunications [1, 2]. The vast majority of MFCs realised so far have been generated through Kerr nonlinear optical effects and form around the frequency of the pump laser. Recently, comb generation has also been demonstrated in $\chi^{(2)}$ nonlinear resonators with the promise of achieving combs in spectral regions where realising Kerr combs is difficult. The first demonstrations were reported in a bulky, macroscopic free-space cavity-enhanced second harmonic generation (SHG) system, where comb formation is said to occur via so-called internally-pumped optical parametric oscillations (OPO) [3]. More recently, preliminary results have also demonstrated the feasibility of comb formation in millimeter-sized periodically poled $\chi^{(2)}$ Fabry-Perot microresonators [4, 5], but demonstrations in homogeneous whispering-gallery-mode (WGM) microresonators, capable of achieving greater finesse and therefore increased nonlinear interactions, have yet to be achieved.

Here, we report on the first experimental observation of internally-pumped OPO in a naturally phase-matched $\chi^{(2)}$ WGM microresonator. Through a process of diamond turning and polishing, we shape a z-cut lithium niobate (LN) crystal into a disk with a major (minor) radius of 1.9 mm (0.25 mm) and a finesse of 10,000. In order to realise internally-pumped OPO (and subsequent comb formation), we need to achieve efficient and strong SHG. To this end, we must ensure phase matching conditions are met between the pump and its second harmonic. Leveraging the birefringence and temperature dependence of the refractive index of lithium niobate, we are able to use thermal tuning to meet the necessary phase matching conditions by heating the resonator. Implementing prism coupling allows us to couple our 1064 nm pump to the resonator with great control via frustrated total internal reflection at the back face of the prism. With optimised coupling and phase matching conditions satisfied, we are able to tune our laser frequency into a cavity resonance and generate a strong second harmonic at 532 nm (visible green), as shown in Fig. 1(a). The SHG component then undergoes spontaneous parametric down conversion (PDC) to form side-bands around the 1064 nm pump, as shown in Fig. 1(b). This result continues an experimental observation of internally-pumped OPO, and is the first step in subsequent frequency comb formation in a naturally phase-matched quadratic nonlinear microresonator. Our results represent crucial steps in verifying the theoretical work that has been done in this area [6].

Figure 1: (a) Green light scattered inside microresonator shows strong second harmonic generation. (b) Experimentally obtained spectrum showing the internally pumped side-bands around the pump wavelength.

References

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GIANT VORTEX CLUSTERS IN A QUANTUM FLUID

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In 1949 Lars Onsager published a ground-breaking theory predicting the existence of a negative-temperature regime for an idealized two-dimensional system of point-vortices [1]. Negative temperature is associated with seemingly ordered giant vortex clusters, a consequence of the bounded phase space of planar vortices confined to a finite domain. The physics of giant clusters has fundamental implications for our understanding of classical fluid turbulence in systems such as soap films and Jupiter’s Great Red Spot [2]. I will present our theoretical [3, 4] and experimental work [5] on realizing giant vortex clusters in a planar superfluid. Despite their high energy, we demonstrate that such clusters can be created and persist for long times, maintaining the superfluid system far from global equilibrium. These states are possible due to isolation of the vortex degrees of freedom from the superfluid phonons and thermal dissipation. Our experiments explore a regime of vortex matter at negative absolute temperature, opening new directions for research in two-dimensional turbulence, systems with long-range interactions, and the dynamics of topological defects. Our results have relevance to systems such as helium films, nonlinear optical materials, and fermion superfluids.

Figure 1: Left: Giant clusters of same-sign vortices form as the end states of decaying two-dimensional quantum turbulence [3]. Right: High-energy vortex clusters are created close to equilibrium in a hard-wall optical container, by forcing of the superfluid through an aperture [5].

References


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COUPLED NANOFIBRE FABRY-PEROT CAVITY-QED

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Recently, experiments in the group of Takao Aoki at Waseda University in Japan have demonstrated coherent coupling of two nanofibre cavity-quantum electrodynamic (QED) systems (Figure 1) separated by a distance of more than a meter [1]. Transmission spectra show dressed states of the atoms in the two cavities with a normal mode of the cavity/coupling fibre/cavity system that is in fact dark in the coupling fibre, hence offering a robust, coherent channel between the two distant atom-cavity systems. Complementary to this, another experiment [2] has demonstrated the existence of a dressed state of the distant atoms with only the coupling fibre, i.e., a dressed state that is dark in the two cavity modes.

These phenomena are qualitatively well described by a relatively simple quantum optical model based upon treating the cavity and coupling fibre fields as single modes, with losses accounted for in a master equation approach. However, the long lengths of the cavities and the relatively low reflectivities of the (fibre Bragg grating (FBG)) mirrors mean that the single-mode picture can be limited in its applicability to this system.

As an alternative, one can develop a travelling wave picture and transfer (or scattering) matrix approach that incorporates all modes of the fibre system, giving an improved model of the transmission properties [3]. However, a drawback of this approach is that it is linear and only appropriate for weak excitations. Hence, strong excitation of the atoms and uniquely quantum effects cannot be considered.

In order to have a fully quantum description, we have implemented a numerical method based on tensor-networks, which handles the two-way cascade represented by the connecting fibre in a similar fashion to a coherent time-delayed feedback system [4]. Considering a finite variable length of fibre enables us to study the intermediate regime between the short-fibre-length limit of coherent coupling and the long-fibre-length limit of a Markovian reservoir. This will enable us to, for example, examine super- or subradiant emission phenomena with atoms separated by distances such that retardation effects start to play a significant role.

In this presentation I will sum up the experimental results and theoretical methods described above.

Figure 1: Schematic setup. Atoms are trapped in the evanescent field of the tapered nanofibre region. Longitudinal confinement of the resonant optical modes is enhanced around the nanofibre region by Fibre Bragg Grating (FBG) mirrors. Driving of the setup was investigated from the left-hand side as well as through the fibre beam splitter implemented in the connecting fibre.

References


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SENSING TEMPERATURE WITH LANTHANIDE BASED LUMINESCENT NANOPARTICLES

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Temperature is a variable that affects most of the natural and engineered systems. The measurement of temperature is a virtually ubiquitous requirement, as it governs the kinetics and reactivity of these systems from their atomic to macroscopic level. Conventional temperature sensors are ineffective for remote temperature measurement at the micro and nanoscale[1]. This has stimulated the development of non-invasive, non-contact and self-referencing nanothermometers exhibiting high thermal sensitivity. In this context, one of the most promising approaches proposes the use of trivalent lanthanide ions (Ln3+) that present temperature dependent photoluminescent properties[2]. Present work reports Ln3+-doped visible emitting upconverting (SrF2:Yb3+/Er3+) and near-infrared emitting downshifting (Gd2O3:Nd3+) nanoparticles as molecular temperature sensors [3].

References


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Solution-processed metal halide perovskites have attracted enormous interest due to their favourable semiconductor properties for light emitting and light absorbing devices. Layered Ruddlesden-Popper-type (2D) metal-halide perovskites exhibit markedly increased exciton binding energies, exceeding 150 meV, compared to their 3D counterparts. Many-body physics, enabled by Coulomb interactions, plays a strong role and raises the biexciton binding energy to 50 meV. Here, photoluminescence at a range of temperatures and carrier concentrations in thin films of the layered perovskite material (C$_{12}$H$_{25}$NH$_3$)$_2$PbI$_4$ is reported. Biexcitons are directly observed up to a sample temperature of 225 K. An optical microcavity (comprising a distributed Bragg reflector and a metal mirror), with photonic resonances tuned near to the biexciton energy, is constructed. Optically-pumped biexciton lasing up to 125 K, with a threshold peak excitation density of 5.6×10$^{18}$ cm$^{-3}$, is observed. The demonstration of biexciton lasing above liquid nitrogen temperatures is a crucial step for the application of layered perovskites in photonic applications[1].

References

PAPER 4A

THE USE OF OPTICS TO MONITOR VIABILITY OF Staphylococcus aureus IN NEAR REAL-TIME

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To aid diagnosis and advance treatment of infections, antimicrobial susceptibility tests (ASTs) determine the sensitivity of microbes to antibiotics, allowing targeted therapy. An alternative solution to slow, culture-based ASTs is fluorescence dyes that report on cellular viability and can be detected using optical techniques such as microscopy, spectroscopy or flow cytometry (FCM).

Spectroscopy and FCM meet criteria of being rapid and accurate. We have developed a fibre-based spectroscopic system called the optrode that excites and accurately detects fluorescence in bacteria. FCM allows single-cell measurements, indicating heterogeneity of the individuals in a population. Compared to FCM, the optrode has benefits of portability, affordability, and ease-of-use, although provides bulk measurements of a cell population.

In this study, fluorescent dyes SYTO9 and propidium iodide (PI) were used to differentially stain live and dead bacteria, respectively. The optrode and FCM methods were applied to the Gram-positive coccus Staphylococcus aureus ATCC 6538 to measure antibiotic kill kinetics after treatment with kanamycin and ampicillin. FCM data was compared with fluorescence microscopy, plate counts and spectra obtained from the optrode. The limits of detection of FCM and the optrode were explored using different live:dead ratios following treatment with 70 percent isopropanol. The findings of this study suggest that the optrode could be applied to quantify the effectiveness of processes that are designed to kill bacteria, including antibiotic treatment and food processing methods.

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POTENTIAL OF RAMAN SPECTROSCOPY FOR DISCRIMINATION OF DIFFERENT RED MEAT TYPES

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With increasing demand for quick, easy to use and reliable techniques for the identification of meat types, we further explored the potential of Raman spectroscopy for the discrimination of red meat samples. 31 Beef, lamb and venison meat samples were measured using Raman spectroscopy, with 1064 nm excitation. The spectra data were classified using support vector machine classification. Results show that all meat samples were correctly classified, highlighting the potential of Raman spectroscopy in combination with chemometrics as an effective technique in discrimination of different red meat types.

Figure 1: PCA of the three meat types highlighting groupings based on the spectroscopic signatures.

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NEAR-REAL TIME MONITORING OF LIVE TO DEAD BACTERIAL CELL RATIOS

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A rapid and easy method to determine the ratio of live to dead bacteria in a sample is important in pharmacodynamic studies and the monitoring of food safety and public health. Traditionally, bacterial viability is determined by the number of colonies grown on solid growth medium after multiple days of incubation. However, not all target organisms can be cultured \([1, 2]\) and this method does not quantify the number of dead bacteria present in the sample.

Live to dead bacterial ratios are commonly determined by fluorescence measurements of samples stained with dyes that have different cell permeability, e.g. SYTO 9 and propidium iodide (PI). The sample is then analysed using fluorescence microscopy or flow cytometry, however, these techniques require expensive and bulky equipment. We have developed the optrode, a fibre-based portable fluorometer for the measurement of SYTO 9 and PI fluorescence within bacterial solutions. The optrode consists of a single fibre dip probe, two stable solid state lasers, a photodiode for continuous measurement of incident laser intensity and a sensitive CCD spectrometer \([3]\).

*Escherichia coli* in the exponential growth phase at a concentration of approximately \(10^8\) bacteria/mL were used in the viability measurements. Dead *E. coli* cells were prepared by one hour incubation in 70% isopropanol followed by harvesting via centrifugation and resuspension in 0.85% saline. Dead cells were mixed with live bacteria to produce samples with live to dead cell ratios ranging from 0 to 100% live bacteria. These mixtures were stained with SYTO 9 and PI, and an excitation wavelength of 473 nm was used. Live to dead cell ratios were also determined using flow cytometry \([4]\). The fluorescence spectra recorded from the bacterial samples were processed using support vector regression (SVR), a multivariate analysis method, to predict the percentage of live bacteria present. SVR prediction models were built using \(N=56\) standard bacterial training samples (\(n=159\) spectra) and compared to the measurements obtained using flow cytometry. Predictive models relating the measured fluorescence intensity to the percentage of live bacteria in the solution have been generated for mixtures with total concentration of \(10^8\) and \(10^7\) bacteria/mL.

For both \(10^8\) and \(10^7\) bacteria/mL samples, the calibration models have obtained a linear relationship with \((R^2 > 0.9)\). This method is potentially applicable to the determination of live to dead cell ratios in a wide range of environments, and the next step is to apply this technique to antibiotic susceptibility tests.

References


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HOW CAN QUANTUM OPTICS BE USED TO CONTROL CHEMICAL REACTIONS?

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The science of catalysis traditionally falls into two domains: homogeneous or heterogeneous. We propose a third class of catalysts, using the strong coupling of light with chemical bonds inside optical cavities. A cavity is, at its simplest, two mirrors that can trap photons within, and by tuning the separation between these mirrors, constructive interference can occur at specific energies. These photon resonances, if appropriately tuned to a molecular resonance (electronic vibrational bands), can hybridize with them to produce new light-matter states known as polaritons. Ebbesen et. al. [1] recently discovered that polariton formation can slow down the rate of a chemical reaction. In our studies we have investigated whether using strong light-matter coupling and polariton formation can instead speed up certain types of reactions involving transition metal complexes. We will present the results of these studies. We will also discuss fundamental questions about the nature of the chemical bond within these polaritonic states, and what effect does strong light-matter coupling have on the strength of chemical bonds. Finally, we will briefly survey the different kinds of optical cavities that can be constructed (Fabry-Perot cavities, plasmonic nanocavities, and whispering gallery mode cavities), and assess the viability of using these in a chemical synthesis lab. In principle, this approach has the potential to be used as an unconventional tool to control the selectivity and speed of reactions, and broaden the traditional definition of catalysis.

![Figure 1: Hybridization of C=O vibration of a prototypical carbonyl complex with cavity, observed via Rabi splitting](image)

References

We propose optical coherence tomography (OCT) as the new fast, non-contact and non-destructive technique to check the meat quality in real time and it is an optical as well as non-invasive technique with a few microns resolution up to a few millimeters deep in tissues as opaque as meat [3, 1]. This could displace the existing chemical and mechanical methods used to determine the intramuscular fat (IMF), the tenderness and the pH of meat, which are often slow and destructive.

Meat mainly comprises of muscle fibres bounded together by the connective tissue, IMF, moisture and protein. Due to their structure, muscle fibers are highly birefringent compared to intramuscular fat. Therefore these tissues can be differentiated using polarisation sensitive OCT (PS-OCT) by studying the polarisation of the back-scattered light as the light passes through the sample [4, 2, 5].

PS-OCT is used to measure the attenuation and birefringence of meat samples to determine their IMF content and tenderness. The attenuation of light in fat and muscle was studied to find that the attenuation coefficient of fat is ≈ 9 times greater than muscle, which helps us to study the IMF content in the sample. Also the phase image tells about the changes in the polarisation of light due to the birefringence of muscle, which differ with tenderness and is being analysed to predict the tenderness of meat. The principal component analysis (PCA) on the attenuation and birefringence studies of meat samples could help us to group them according to their fat content and tenderness. The OCT results are compared to gas chromatography-flame ionization detection (GC-FID) fat estimate and Warner-Bratzler tenderness estimate results.

References


Recent advances and future directions of 3D printing using photopolymerization

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The field of 3D printing is developing rapidly in both academic and industrial research environments since the first commercial instruments were introduced.1 The development of 3D architectures with high resolution has opened new implementations in microfluidic, biomedical devices, soft robotics, surgery, tissue engineering, dentistry and drug delivery. Among different 3D printing techniques, photopolymerization-based process (such as stereolithography and digital light processing) has generated intensive interest which enables high resolution 3D fabrication of complex multifunctional material systems with controllable optical, chemical and mechanical properties.

In early 3D photopolymerization systems, photoinitiators with high molar extinction coefficients at short wavelength (UV < 400 nm) were commonly used to initiate the photochemical pathway.2 Although these photoinitiators offered good control over the photopolymerization systems, prolonged exposure to high energy wavelengths might result in side reactions with degradation of reactant and product. UV photons also present low penetration and therefore, in the field of 3D printing, the accessible layer thicknesses are usually remain low (below ~ 100 μm), resulting in slow 3D printing rate (specifically for large objects).3 Moreover, in the field of 3D bioprinting, the use of UV light also presents risk of cellular photodamage resulting in chromosomal and genetic instability in cells.

One possible solution to overcome these issues is the use of photoinitiator systems with enhanced absorption in the longer irradiation wavelengths to initiate the photopolymerization with the aim of: (i) obtaining mild and safe condition of 3D photopolymerization, (ii) reaching higher penetration depth (layer thickness) resulting in enhancement in the photopolymerization rate, and (iii) providing system that are benign to living cells for tissue engineering applications.4–7 This will pave the way to further extend and expand the scope of 3D printing applications.
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Microresonators enable generation of nonlinear optical effects with a low power, continuous wave source. Using an external cavity laser, the wideband tunability of optical parametric oscillation in a Kerr microresonator was recently demonstrated with shifts of up to 720nm[1]. However, pumping schemes utilising an external cavity laser require tuning the laser into resonance, and this can be a time consuming, laborious process.

We report on a microresonator pumping scheme that automatically operates on resonance and does not require an external cavity laser to run. We then explore the viability of our system in generating $\chi^{(3)}$ nonlinear effects. To this end, we employ two different Kerr microresonators to demonstrate a variety of $\chi^{(3)}$ nonlinear effects, and in particular we evaluate the feasibility of our pumping scheme in generating parametric sidebands, as well as their wideband tunability.

![Microresonator and fibre taper](image)

**Figure 1:** Microresonator and fibre taper.

**References**


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The surprising observation of several long-lived localized droplets arising from a trapped dipolar condensate [1], led to further experiments demonstrating macro-droplets [2] and the realisation of a self-bound dipolar droplet [3], i.e. a gas of atoms cohering without any external confinement.

Rapid rotation of the magnetic field was predicted to tune the magnetic dipolar interaction [4], including to negative values. Such tuned dipolar interactions have been recently observed [5].

![Phase diagram for self-bound droplets as a function of the number of atoms $N$ and $\epsilon_{dd} = a_{dd}/a_s$, where $a_{dd}$ is the dipole length and $a_s$ is the $s$-wave scattering length. The colored area is where a variational self-bound solution exists, with the colors representing the energy, $E$ in units of $\hbar^2/Ma_{dd}^2$ and in white region a trap is needed to contain the droplet. $E = 0$ is shown for the variational solution (thick black curve) and for the GPE solution (black circles). The insets are isosurfaces for the GPE solution with the indicated parameters.]

Here we develop a general theory for self-bound droplets of dipolar atoms based on the non-local generalized Gross-Pitaevskii equation (GPE) allowing for tuned dipolar interactions. In doing so, we open an entirely new region of the phase diagram for dipolar droplets, see Fig. 1. We show that negative dipolar interactions lead to oblate self-bound droplets: a radically different shape from those seen previously.

References

FILTERED PHOTON CORRELATIONS OF FLUORESCENCE FROM A Driven Three Level Atom

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In this work we develop a theoretical approach to investigate the nature of the fluorescence emitted by a driven three level atom as studied by Gasparinetti et. al [1, 2]. Using trajectory theory to model a photon counting experiment, we employ frequency filtering techniques to isolate different peaks of the fluorescence spectrum [Fig. 1 (Left)] and explore the second order photon correlations.

The fluorescence is split and directed into two separate scanning interferometers (cavities) modelled as a cascaded system [3] with the Hamiltonian (\(\hbar = 1\))

\[
\hat{H} = \hat{H}_A + \Delta_a \hat{a}^\dagger \hat{a} + \Delta_b \hat{b}^\dagger \hat{b} + \frac{i}{2} \sqrt{\frac{\gamma}{\kappa_a}} \left( \hat{\Sigma}^\dagger \hat{a} - \hat{\Sigma} \hat{a}^\dagger \right) + \frac{i}{2} \sqrt{\frac{\gamma}{\kappa_b}} \left( \hat{\Sigma}^\dagger \hat{b} - \hat{\Sigma} \hat{b}^\dagger \right),
\]

where \(\Delta_a(\Delta_b)\) is the cavity resonance frequency detuning from the drive frequency, \(\kappa_a(\kappa_b)\) is the full linewidth of cavity \(a(b)\), \(\hat{a}(\hat{a}^\dagger)\) and \(\hat{b}(\hat{b}^\dagger)\) are the photon annihilation and creation operators for cavity \(a(b)\), \(\gamma\) is the atom decay rate and \(\hat{\Sigma} = |g\rangle \langle e| + \xi |e\rangle \langle f|\) is the atom lowering operator with \(\xi\) the ratio of dipole moments for the two dipole transitions, \(|g\rangle \leftrightarrow |e\rangle\) and \(|e\rangle \leftrightarrow |f\rangle\); the atom has a ground state \(|g\rangle\), an excited state \(|f\rangle\) and an intermediate state \(|e\rangle\) with respective eigen-frequencies, \(\omega_g\), \(\omega_f\) and \(\omega_e\). The Hamiltonian for the driven atom is

\[
\hat{H}_A = -\left(\frac{\alpha}{2} + \delta\right) |e\rangle\langle e| - 2\delta |f\rangle\langle f| + \frac{\Omega}{2} \left( \hat{\Sigma} + \hat{\Sigma}^\dagger \right),
\]

where \(\Omega\) is the driving field strength (Rabi frequency), \(\delta = \omega_d - \omega_{fa}/2\) the detuning of the drive frequency from the two-photon transition and \(\alpha = \omega_{fe} - \omega_{ef}\), where \(\hbar\omega_{ij} = E_i - E_j\).

For a low driving strength \(\Omega\) tuned to the two-photon resonance frequency \(\omega_{fa}/2\), two single-photon peaks appear in the fluorescence spectrum corresponding to the cascaded decay of the atom [Fig. 1 (Left)]. The unfiltered photon correlation exhibits behaviour similar to that of a two-photon source [Fig. 1 (Right, black)]. By centering cavity \(a\) on the \(|f\rangle \rightarrow |e\rangle\) transition (\(\Delta_a = -|\alpha|/2\)) and cavity \(b\) on the \(|e\rangle \rightarrow |g\rangle\) transition (\(\Delta_b = |\alpha|/2\)), we find the auto-correlation of photons emitted by cavity \(a\) and the cross-correlation of photons emitted first by cavity \(a\) and after a delay \(\tau\) by cavity \(b\). We see anti-bunching for the \(|f\rangle \rightarrow |e\rangle\) autocorrelation [Fig. 1 (Right, red)] and bunching for the \(|e\rangle \rightarrow |g\rangle\) cross-correlation [Fig. 1 (Right, blue)]. As we increase the bandwidth for cavity \(b\) we find that the initial peak in the cross-correlation increases and becomes sharper as the response time of the cavity decreases.

\textbf{Figure 1: (Left)} Fluorescence spectrum at two-photon resonance for a low drive strength (black). The filter profile for cavity \(a(b)\) is shown in red (blue) over the peak it is resonant with. \textbf{(Right)} Correlation of the unfiltered fluorescence (black), filtered fluorescence (red), and the cross-correlated filtered fluorescence (blue). The parameters for these plots are, in units of \(\gamma\), \((\Omega, \delta, \xi, \alpha, \Delta_1, \kappa_1, \Delta_2, \kappa_2) = (5.0, 0.0, 1.0, -120.0, -60.0, 5.0, 60.0, 5.0)\).

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Distributed fibre optic sensors (DFOS) provide the ability to transform a fibre optic cable into a vast array of sensors, which are able to provide insight into temperature and strain variations with high spatial resolution and a high degree of accuracy. While there has been many advances in DFOS technology in the past decade[1], these efforts have been concentrated around short term monitoring as opposed to long term monitoring in a geophysical setting. In this research, we propose to investigate broadband DFOS for continuous passive monitoring of strain and temperature profiles in the geophysical setting of the DFDP-2B scientific borehole located in the South Island.

References

The concept of traceability is important because it makes it possible to compare the accuracy of measurements worldwide according to a standardized procedure for estimating measurement uncertainty. Development of standards for photon metrology from the signal level of existing radiometric standards \((10^{14} \text{ photons per second, } 100 \mu\text{W})\) [1] down to the single- and few-photon regime are critical in order to achieve traceability for areas moving into this regime such as medical imaging [2], remote sensing [3] and astronomy [4], and, for the rapidly evolving field of quantum information processing [5].

The development of single-photon sources and detectors, and the growth of associated technologies, such as quantum key distribution and quantum computing, require measurements at the single- and few-photon levels. The international acceptance of these new quantum-based technologies requires improved traceability and reliability of measurements at the photon-counting level. This has led to a proposal to expand the realization of the candela, the SI unit for optical power, to include one based on photon number [6].

The Measurement Standards Laboratory of New Zealand is investing in a few-photon facility which will be able to calibrate and characterise single-photon sources and detectors with traceability to international standards. At present, a setup is being built which will be capable of characterising single-photon detectors; namely, the detection efficiency, jitter, linearity, recovery and dead time, dark-count and after-pulsing probability, and, photon-number resolution. Broadband light sources covering a continuous range from 170 nm to 2400 nm will be capable of calibrating the spectral responsivity of a detector.

References

Ultrashort optical pulses of durations less than a picosecond have attracted deserved attention for their uses in non-linear optics, micro machining, and femtochemistry. To optimize the advantages of ultrashort optical pulses, near arbitrary control of pulse properties such as the temporal amplitude and phase is required. Femtosecond pulse shaping enables users to alter the amplitude and phase of an optical pulse through the method of Fourier transform pulse shaping [1]. An input pulse is Fourier transformed and a frequency dependent filter is applied. The filtered pulse is inverse Fourier transformed into temporal space.

\[ E_{\text{shaped}}(t) = F^{-1}[F[E_{\text{input}}(t)] f(\omega)] \]

Experimentally transitioning a femtosecond pulse from temporal space to Fourier space is typically realized with free-space gratings to spatially diffract frequencies. Unfortunately, this method involves the combination of fibre and free-space optics which introduces inherent losses and bulky components. In this research, we present an all fibre pulse shaper, using a highly dispersive element to apply temporal dispersion rather than spatial diffraction.

A linearly chirped fibre Bragg grating is used to apply the equivalent dispersion of 120km of single mode fibre to a 500fs optical pulse. The pulse undergoes a dispersive Fourier transform, mapping frequencies to time [2]. An electro-optic IQ modulator is used as the filter, modulating the amplitude and phase of the frequencies in time. The modulated pulse is then passed through the Bragg grating in the opposite direction which applies an equal but negative amount of dispersion, performing an inverse Fourier transform.

**Figure 1:** Schematic of our temporal pulse shaping system. CIR - Circulator, LC-FBG - Linearly Chirped Fibre Bragg Grating, MOD - IQ Modulator, AWG - Arbitrary Waveform Generator

Typically, \( f(\omega) \) should be complex valued which requires precisely synchronized concatenated amplitude and phase modulators[3]. However, with the use of an IQ modulator we can define two unique waveforms such that the transfer function of the modulator is complex. The shaped output pulse is a scaled Fourier transform of the transfer function and by varying the driving waveforms which are generated with an electrical arbitrary waveform generator, different output pulses can be produced. I present design specifications of our system, along with pulse shaping results.

**References**

PHOTOASSOCIATION OF TWO $^{85}$Rb ATOMS PREPARED IN OPTICAL DIPOLE TRAPS

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The formation of molecules is an important process in physics and chemistry. One way to initiate molecule formation is photoassociation of two atoms, where a laser pulse is used to transition from atomic states to the molecular state. This has been observed in many-body ensembles for several decades, but new techniques enable the investigation of photoassociation using exactly two atoms, thereby allowing a much higher degree of control over the process. Our current goal is to determine how fast this process is and what limits it.

Using light assisted collisions in Far Off Resonance Traps we are able to prepare a single $^{85}$Rb atom with high efficiency [1] and cool it to 40 $\mu$K. The atom is subsequently optically pumped into the $F = 2$, $m = -2$ ground state. Creating two such traps with one atom each and merging them adiabatically allows the preparation of a trap with exactly two atoms in known states which we can photoassociate to Rb$_2$ using light at a frequency below the 5S + 5P$_{1/2}$ dissociation limit of the molecule. By locking the photoassociation laser to an optical cavity together with a second laser which is itself locked to an atomic transition, we are able to measure the photoassociation frequency with an accuracy of 1 MHz.

For our investigations we chose a photoassociation peak in the $0^+_1$ band around 377.0006 THz identified previously [2]. By alternatingly modulating the trap light and the photoassociation light at a rate of 670 kHz, we can investigate the photoassociation in free space - thereby removing any light shifts caused by the trap - without loosing the atoms in the process. Successfull photoassociation is detected as loss of the atoms since the produced molecule spontaneously decays, allowing the atoms to escape the trap.

Using the described method allows us to measure the natural photoassociation resonance position as well as resonance width and frequency shift as a function of photoassociation power. Additionally, we measure the photoassociation rate coefficients in the intensity range of 0.24 - 480 W/cm$^2$ and we are able to observe saturation of the rate coefficient at high intensities.

![Figure 1](image1.png)  
**Figure 1:** Shift of photoassociation resonance and broadening at different intensities.

![Figure 2](image2.png)  
**Figure 2:** On-resonant photoassociation as a function of photoassociation time.

References


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One of the defining characteristics of superfluids is their ability to support quantized vortices that carry angular momentum. A singly quantized vortex is a topological defect in the macroscopic wavefunction of the superfluid in which the phase of the wavefunction winds around a core of zero density. In a Bose-Einstein condensate (BEC) under planar confinement, vortex bending is suppressed and vortex motion can become effectively two dimensional (2D) [1]. A quantum vortex dipole, comprised of a closely bound pair of vortices of equal but opposite circulation, is a localized excitation of a planar superfluid that carries linear momentum [2, 3], suggesting a possible analogy with ray optics. We investigate numerically and analytically the motion of a quantum vortex dipole incident upon a step-change in the background superfluid density of an otherwise uniform two-dimensional Bose-Einstein condensate. Conservation of fluid momentum and energy during the motion across the interface between regions of different particle density leads to a relation analogous to Snell’s law between the incident and refracted angles of the dipole. The predictions of the analogue Snell’s law relation are confirmed for a wide range of incident angles by systematic numerical simulations of the Gross-Pitaevskii equation. We find that the Snell’s law analogue governs the dipole motion even when temporary capture by the interface causes the strict analogy with ray optics to break down near the critical angle for total internal reflection.

Figure 1: Range of trajectories for a vortex dipole incident upon an abrupt step potential in the confining potential for the Bose-Einstein condensate.

References

SCALING BEHAVIOUR IN SIGN PROBLEM-FREE FULL CONFIGURATION Interaction Quantum Monte Carlo Simulations

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Accuracy and Efficiency are two of the most important characteristics of a computational method for solving quantum many-body problems. A highly accurate solution usually involves a huge computational effort that grows rapidly as the size of the system increases, such as with the Exact Diagonalisation approach. In contrast, The Full Configuration Interaction Quantum Monte Carlo (FCIQMC) method offers a more affordable way to obtain exact ground state properties by using a stochastic approach [1]. The method involves studying the population dynamics of a set of random walkers, where walkers evolve according to rules of spawning, death and annihilation. In a regular (fermionic) FCIQMC simulation, the annihilation step, where the pairs of walker with opposite signs cancel each other, is usually the bottleneck that limits the efficiency and controls the scaling behaviour [2]. However, in bosonic FCIQMC some problems are sign-problem free, as all walkers are spawned with the same sign, and the annihilation step is not triggered. Thus a new measurement of efficiency must be defined for sign-problem free cases. Here we are using the example of the one-dimensional Bose-Hubbard model to investigate the parameters that control the efficiency and to examine the scaling behaviour in bosonic FCIQMC within different physical regimes. The aim of this study is to gain a better understanding of the algorithm and potentially to further improve it.

Figure 1: (a) The population dynamics of walkers and (b) the corresponding energy estimators in a bosonic FCIQMC simulation of a 6-boson-in-6-site system within the strongly interacting regime (U/J=12). The population of walkers reaches equilibrium after a rapid growth, and the energy estimators are fluctuating around the exact energy.

References


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SPECTROSCOPY AND ELECTRONIC STRUCTURE OF RARE-EARTH DOPED CRYSTALS FOR QUANTUM INFORMATION STUDIES

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Currently there is a global interest in the development of quantum computers and long distance quantum communications. Both require the development of long-term storage of quantum information in solids. Lanthanide doped crystals such as yttrium orthosilicate (YSO) serve as exceptional candidates in use of such devices. This is due to such materials exhibiting long coherence times which can be used to preserve the quantum information encoded into a qubit. Recently, work has been performed in this field with multiple lanthanide elements already showing promising results for use in quantum storage. These works has shown that Pr3+:Y2SiO5 has a coherence time of over a minute; while Eu3+:Y2SiO5 has exhibited a coherence time of over 6 hours [1][2].

The key technique that has allowed for such long storage times is the use of the ZEro First Order-Zeeman (ZEFOZ) technique [3]. This technique uses an external magnetic field in order to eliminate the first order dephasing induced by spin flips in the host lattice. Analytically, this technique requires use of the spin Hamiltonian, which explains how the energy levels of the valence electron spins change with magnetic field [4][5]. However spin Hamiltonian parameters are only valid for a single energy level while crystal-field parameters (inferred from an effective Hamiltonian) are valid for an entire configuration. Crystal-field analyses for low symmetry systems (such as YSO) are challenging, requiring a global fit to 27 crystal-field parameters. Recently it has been shown that fitting to electronic, Zeeman, and hyperfine data can give a solution to the crystal-field problem using Er3+·Y2SiO5 [6].

In this paper we report progress on extending the crystal-field model to Sm3+:Y2SiO5. We have used FTIR spectroscopy with magnetic fields of up to 4T to obtain magnetic splitting data, and site selective laser excitation to distinguish between the two crystallographic sites that is present in YSO [7]. The crystal-field parameters for Er3+·Y2SiO5 were used as a starting point for crystal-field fits, and the theoretical calculations obtained from this gives a good account of the energy levels and magnetic splittings experimentally observed in Sm3+:Y2SiO5 [6].

References


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INVESTIGATING THE FEYNMAN CONJECTURE FOR 2D QUANTUM TURBULENCE

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Richard Feynman conjectured that a superfluid flowing at sufficient speed through a channel of sufficient diameter into an open reservoir would produce a street of vortex-antivortex pairs with uniform spacing \cite{feynman1955}. We use the 2D Gross-Pitaevskii equation to investigate this problem with numerical simulations of a Bose-Einstein Condensate confined within various optical potentials with differing channel width and velocity. We seek to first simulate scenarios that closely mirror the one in which the conjecture was made and determine how well Feynman’s proposed relation between the channel width and the critical velocity describes what we see. We then apply this relation to the more experimentally realisable scenario of effectively two-dimensional dumbell-shaped potentials, which may have interesting implications in the emerging field of atomtronics. Our investigation is inspired in part by recent work showing that a dumbell potential can be used to produce an atomtronic circuit which is similar to a variable-resistance RLC circuit \cite{li2017}.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Colourmap of numerical simulation data showing vortex formation as BEC flows through channel into reservoir.}
\end{figure}

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MODELLING AND ANALYSIS OF A RARE-EARTH ION MICROWAVE TO OPTICAL CONVERSION DEVICE

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Quantum computing and information is a quickly developing field, offering the promise of revolutions in encryption and algorithms faster than is possible with classical computers. One of the main candidates for quantum information processing are superconducting qubits, which operate at microwave frequencies. However, it would be convenient to be able to transfer this quantum information via optical fibers, which would require frequencies in the optical domain. Therefore the ability to convert between microwave and optical photons will be helpful in the development of practical quantum computers.

Conversion devices based on rare-earth ion doped crystals are a promising system to coherently convert from microwave photons to optical photons [1]. In a three level system, the input microwave photon is combined with an optical pump photon, to output an optical photon of the desired frequency. Experimentally this can be challenging due to real world effects such as temperature, impurities, and unwanted mixing of the fields.

Figure 1: The three-level atom conversion process, combining the input microwave photon and optical pump photon to generate the optical output photon, and the coherence $\sigma_{1,3}$ as a function of the detunings, compared with the dressed states of the Hamiltonian (orange).

References

Ultrafast and Stoichiometric HNO Release from a Photocaged (6-Hydroxy-2-Naphthalenyl)methyl Analogue of Pilotys Acid

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Nitroxyl hydride (HNO) is a biologically relevant, highly reactive molecule that requires precursors to be generated in situ\cite{1}. Our research group is interested in understanding the mechanisms of the reactions of HNO with biologically important molecules, including metalloproteins and transition metal cofactors\cite{2, 3}. Molecules that rapidly decompose on sub-second timescales to release HNO are required for mechanistic studies on the reactivity of this emerging biological signaling molecule. To meet this need, we developed a photocleavable HNO donor incorporating the (6-hydroxy-2-naphthalenyl)methyl (6,2-HNM) photocage coupled to the trifluoromethanesulfonamidoxy analogue of the well-established HNO generator Pilotys acid. HNO trapping and photoproduct characterization studies show that irradiation of this molecule selectively releases HNO at neutral pH conditions (approx. 98 %), as opposed an undesired N-O bond cleavage pathway. Additionally, ultrafast time resolved transient absorption studies indicate that release of HNO occurs within 1 microsecond upon excitation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Photorelease of HNO}
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References

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UNRAVELLING THE PECULIARITIES OF NEW ZEALAND LAKE SNOT THROUGH VIBRATIONAL SPECTROSCOPY AND CHEMOMETRICS

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Lake snot, a brown polysaccharide mucilage excreted by a microscopic algae called Lindavia intermedia has been found in at least a dozen lakes in New Zealand. It is causing significant problems by clogging public filtration systems, fouling boat motors, sticking to skin of swimmers and clinging to fishing lines. Monitoring programs are required to better understand the presence of lake snot within a lake to help more accurately determine linkages with environmental drivers [1]. Spectroscopy is suitable for providing real-time feedback for lake snot analysis as it is a fast, non-destructive technique with little or no sample pre-treatment, and has multivariate output. Various spectroscopic techniques were combined with multivariate analysis methods to identify lake snot from other common NZ lake algae and detect natural variance between and within lakes and depths of sample collected. Preliminary analysis of New Zealand lake snot samples were done using multiple complementary spectroscopic techniques: Fourier transform Raman (FT-Raman), FT-infrared (FT-IR), low-frequency Raman and Raman microscopy. These techniques coupled with principal component analysis (PCA) highlighted spectral and hence chemical differences between different algae samples, Figure 1, and lake snot samples from different lakes and across varying depths within one lake. These differences were from spectral characteristics which are caused predominantly by vibrations of polysaccharides, photosynthetic pigments and lipids [2, 3]. The different methods were able to distinguish and separate samples from different lakes, depths and concentration based on their bio-chemical components and spectroscopic selectivity. The classification and prediction studies were performed using the following methods: support vector machine (SVM), soft independent modelling of class analogy (SIMCA) and linear discriminant analysis (LDA), Figure 2. SVM gave the best model from view points of the classification and prediction.

Figure 1: PCA scores plot of different algae commonly found in NZ lakes.

<table>
<thead>
<tr>
<th></th>
<th>Lake Snot</th>
<th>Didymo</th>
<th>Nostoc</th>
<th>Spirogyra</th>
<th>Zygnema</th>
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Figure 2: Prediction results for each classification method.

References


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Magnetic Feshbach resonances are a key tool for atomic physicists interested in probing and controlling samples of ultracold atoms and molecules, as these resonances allow the experimenter to change the strength and type (attractive or repulsive) of interactions[1]. The level of control that one can attain with these resonances is then directly related to how well the magnetic field can be regulated relative to the width of the resonance. While Feshbach resonances with widths of tens to hundreds of Gauss can be found for many atom pairs, most resonances have widths of < 1 G and are located at relatively large magnetic fields of 100–1000 G. Controlling the interaction strength to the level of 1% thus requires that the magnetic field be stabilised to the level of < 0.01% of the resonance width, or < 100 ppm. Furthermore, constraints on the dynamic behaviour of the magnetic field, such as fast switching time, means that low-inductance electromagnets must be used with commensurately large electrical currents. The major challenge of stabilising these large magnetic fields, then, becomes that of stabilising large electrical currents to precisions of better than 100 ppm. While commercial solutions exist, these are typically expensive systems (∼ $50k NZD) with either limited power or dynamic range.

We present an inexpensive method for stabilising large electrical currents using a digital proportional-integral-derivative (PID) feedback loop and off-the-shelf components. A high-precision fluxgate current transducer senses the electrical current in the electromagnet, and this current is in turn converted into a voltage and digitised by a fully differential, low-noise 24 bit analog-to-digital converter. A field-programmable gate-array (FPGA) calculates transistor gate voltages used for regulating the current based on the PID parameters, the measurement, and an arbitrary and fully digital control signal. We demonstrate that electrical currents on the order of 200 A can be stabilised to the level of 1.3 mA (7 ppm), which is an order of magnitude better than the passive stability of the power supply. The total cost for our control system is less than $1500 NZD, making it an ideal method for upgrading relatively low-cost (< $15k NZD) power supplies.

Figure 1: Current servo performance at 180 A. a Fractional stability as a function of time. b Calculated distribution of current values for the power supply in current-controlled mode (red) and with stabilisation (blue).

References

A MULTI-SPECTROSCOPIC APPROACH TO DISEASE DIAGNOSIS - A PROOF OF PRINCIPLE STUDY FOR EX VIVO DETECTION OF COELIAC DISEASE


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Raman spectroscopy has been demonstrated in the literature for its potential to detect cancerous tissue[1, 2, 3]. The potential for this in non-cancerous illnesses is less explored. Five spectroscopic methods were tested in various combinations for their ability to detect and classify severity of coeliac disease. This study aims to identify the most promising combination of techniques for future development of fibre optic based probes for in vivo point-of-care diagnosis of gastrointestinal diseases.

Two to four additional biopsies of the duodenum were collected from participants undergoing gastroscopies at Dunedin and Mercy Hospitals. These biopsies were measured with FT-Raman (FTR), 532 nm Raman (Raman (532R) + fluorescence (532B) signal), low-frequency Raman (LFR) and near infrared (NIR) spectroscopic instruments. Participants histology results were used as the reference diagnosis. Spectra were analysed using support vector machine (SVM) classification based on the reference histology with 2/3rds of biopsies used for model creation and 1/3rd used as independent test set validation. Ethical approval was obtained from the central HDEC, reference 16/CEN/113.

Multi level classification (four levels: Normal, increased IELs, partial villous atrophy and complete villous atrophy) was carried out on all spectral combinations (Figure 1). In these instances the datasets were combined at the data level (low level fusion). The combinations LFR-FTR-NIR and LFR-FTR-532R-532B-NIR showed the most promise with respect to maximising all parameters (accuracy, sensitivity and specificity).

The combination LFR-FTR-NIR gave increased performance for detecting coeliac disease over each individual technique when combining at the data level. This will guide future development of a point-of-care diagnostic tool.

Figure 1: Accuracy, sensitivity and specificity for test set predictions from all spectroscopic combinations studied combined at the data level.

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References


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YTERBIUM-DOPED MODE-LOCKED FIBRE LASER WITH THREE GAIN MEDIA FOR MICRO-MACHINING

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Mode-locked fibre lasers are stable, compact, and are capable of producing ultra-short pulses. Because of these desirable salient characteristics, the range of fibre laser applications are on the rise, and so too is the need for improved performance [1]. We present here a new design for mode-locked fibre laser operating in the all-normal dispersion regime. Previously we have presented a mode-locked fibre laser design that contains two segments; the main loop cavity that is uni-directional and a bi-directional nonlinear amplifying loop mirror (NALM) that acts as the mode-locking mechanism of the laser[2]. Here we demonstrate that incorporating a third Yb-doped fibre third gain medium inside the main cavity significantly improved both the output power and the ease of mode-locking. Remarkable both the additional gain segment and the NALM can be pumped by the same laser diode making this design more efficient than the previous one.

Previous endeavours have shown that with the two gain media architecture, the laser successfully mode-locks at repetition rates between 500 KHz and 10MHz, however, this architecture suffered from lack of pulse energy, hence requiring additional amplifiers before they could be used in practical applications. The incorporation of a third gain medium has proved useful in improving the output power and bandwidth, and because the new design utilises the same number of components (which are all polarizing-maintaining), we also preserve costs.

Operating at 1030nm and with a repetition rate of 5.6MHz, we characterised and compared the laser before and after the insertion of the third gain media. We saw an improvement of average output power from 4mW to 9mW of power corresponding to 1.6 nJ of pulse energy. The spectral bandwidth is about 17 nm and upon taking a FROG trace, we find a pulse width of 16ps with a linear chirp. The linear chirp of the pulse allows us to compress the pulse using a single transmission grating (1600 lines/mm). The prism-grating compressor has an efficiency of 70%, and produced a compressed pulse duration of 291fs with an output pulse energy of 1.1nJ. The autocorrelation shows that the bulk of the energy is contained in the centre of the peak and that the side-lobes, although noticeable, hold little energy.

It has been observed that the laser mode-locks and single pulses more easily with a third gain medium. We attribute this to the bi-directional pumping of the gain medium in the NALM which produces a more uniform inversion profile. In conclusion the incorporation of a third gain medium has shown favourable results; increased output pulse energy, reliability in self-starting, ease of mode-locking and output pulses exhibiting linear chirp which allows for compression. Said features are largely attributed to the interactions of the third gain medium with the NALM to create uniform gain. All the while, utilising the same number of components and preserving costs. Further work will be done to test and optimise the laser architecture which will be tailored towards the purposes of micro-machining.

References


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Optical microresonators are simple dielectric cavities that confine light through continuous total internal reflection at the surface boundary. These ultra-high finesse cavities allow for the generation of new optical frequencies at low pump powers. They can therefore act as a potential source in the mid-infrared region functioning as an optical parametric oscillator [1]. The devices exploit the four-wave mixing process to produce symmetrically detuned Stokes and anti-Stokes sidebands through efficient parametric phasematching between the waves. With an appropriate setup, it is possible to engineer discrete and continuous wavelength tunability of the coherent sidebands at a resonable pump power. We employ a crystalline magnesium fluoride (MgF$_2$) microresonator with an axisymmetric spheroidal disk geometry and major radii $R$ ranging from 150 to 500 $\mu$m.

Tunability can be achieved through two approaches. Firstly, different spatial modes; $m$, $p$, and $q$ mode numbers, have different wavenumbers and corresponding resonant angular frequencies $\omega$. To model the spatial modes we incorporate material and geometric dispersion using the Sellmeier equation in conjunction with the refractive index for a spheroid given in [2]. The initial guess is implemented in the COMSOL Multiphysics finite-element solver to find the resonant frequencies of the spatial modes, permitting the phasematching equation

$$[2\beta (\omega_p) - \beta (\omega_p + \Omega_{PM}) - \beta (\omega_p - \Omega_{PM})] L - 2\gamma P L + \delta_0 = 0,$$

(1)

to be satisfied, where $\Omega_{PM}$ describes the sideband frequency shift from the pump $\omega_p$, where $L = 2\pi R$ is the length of the cavity, $\gamma$ is the nonlinearity ($\sim 1 W^{-1} km^{-1}$), $P$ is the intracavity power, and $\delta_0$ is the detuning of the pump from the closest resonance. The result of this is that at a 1550 nm pump we have discrete tunability as shown in Fig. 1 (Left) from 3649 to 3411 nm and 984 to 1003 nm for the Stokes and anti-Stokes sidebands respectively.

The second method relies on the temperature dependence of the free spectral range (FSR) of a microresonator given by $\text{FSR} = c/[n(T)L(T)]$. When tuning the pump closer to a resonance more light is coupled into the microresonator thereby increasing the temperature and shifting both the Stokes and anti-Stokes sideband equally to longer wavelengths. We experimentally show that with this method allows 10 GHz of continuous tunability in both sidebands.

![Figure 1:](image-url) (Left) Phase matching curves for different spatial TE modes ($q = 1, p = 0, 1, 2, 3$) in a $R = 150 \mu$m microresonator where the dashed lines indicate the zero-dispersion wavelength. (Middle and Right) 10 GHz continuous tunability for the anti-Stokes and Stokes sideband.

**References**


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YRAST STATES IN THE ATTRACTIVE FERMI HUBBARD MODEL

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In this work, we use the “Full Configuration Interaction Quantum Monte-Carlo”-method (FCIQMC) \cite{G. H. Booth, A. J. W. Thom, and A. Alavi, “Fermion Monte Carlo without fixed nodes: A game of life, death and annihilation in Slater determinant space,” Journal of Chemical Physics 131, 054106 (2009).} to study strongly correlated Fermi gases. In this method, the many-body wave function is expanded in terms of Slater determinants and the expansion coefficients are sampled by random walkers of two different signs. These walkers can spawn onto other determinants and annihilate each other, a process which addresses the so-called “sign problem”, which makes QMC studies of strongly correlated Fermi systems very challenging. Among the advantages of FCIQMC compared to other QMC methods is that it conserves total center-of-mass momentum. We therefore can access not just the ground state with zero total momentum, but the lowest-lying excitations with non-zero momentum, called \textit{yrast} states. It has been shown that in a homogenous 1D superfluid, dark solitons, localized non-linear wave phenomena characterized by a density depletion and a step in the phase of the order parameter, appear as linear combinations of yrast states \cite{S. S. Shamailov and J. Brand, “Dark-soliton-like excitations in the Yang-Gaudin gas of attractively interacting fermions,” New Journal of Physics 18, 075004 (2016)., S. S. Shamailov and J. Brand, “Quantum dark solitons in the one-dimensional Bose gas,” ArXiv:1805.07856 (2018).}

In our work, we study yrast excitations in the Hubbard model, starting from the 1D case, where we can compare quantum-Monte Carlo results with exact solutions from the Bethe-ansatz. We then examine the crossover to the 2D system, by adding more and more “rows” in a second dimension, a regime where analytic solutions are not known and FCIQMC can give us the exact wave function of yrast states. In this regime we also investigate the case of an imbalanced Fermi gas, where the number of fermions in one spin state is larger. Mean-field theory predicts that surplus atoms of the majority spin component will localize at the phase step of the soliton and we study the effect of correlation in a strongly attractive regime where mean-field theory is not valid anymore.

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References

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CHIRAL $p$-WAVE SUPERFLUID FROM $s$-WAVE PAIRING IN THE BEC LIMIT

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Two-dimensional (2D) spin-orbit-coupled Fermi gases subject to $s$-wave pairing can be driven into a topological phase by increasing the Zeeman spin splitting beyond a critical value $h_c$ [1–3]. In the topological regime, the system then exhibits the hallmarks of chiral $p$-wave superfluidity [4], including exotic Majorana excitations [5, 6] that are currently attracting great interest [7].

Previous theoretical studies [8–11] of this realization of the 2D topological Fermi superfluid have focused on the BCS limit where the $s$-wave Cooper pairs are only weakly bound. Utilizing approximate expressions for the self-consistent $s$-wave pair potential and the fermionic chemical potential in terms of the two-fermion binding energy $E_b$, spin-orbit-coupling strength $\lambda$, and Zeeman splitting $h$, we explore the BCS-to-BEC crossover for this system. Surprisingly, the topological (chiral $p$-wave) superfluid phase is found to persist even in the extreme BEC limit where $s$-wave Cooper pairs have morphed into tightly bound fermion dimers. This is illustrated in Figs. 1(a) and 1(b) via the low-energy Bogoliubov-quasiparticle dispersion and associated Nambu-spinor amplitudes. The presence of BCS-like $s$-wave and $p$-wave pairing in the limit of small $E_b$ is most clearly signified in Fig. 1(a) via the existence of points where $|\psi_L|^2 = |\psi_R|^2 \equiv 1/2$ and $|\psi_L|^2 = |\psi_R|^2 \equiv 1/2$, respectively. Intriguingly, BCS-like $p$-wave pairing emerges in the topological phase even in the situation for which the underlying $s$-wave pairing is in the BEC limit, i.e., for large $E_b$ [Fig. 1(b)]. The momentum-space distribution function found in the BEC limit [see Fig. 1(c)] shows a Fermi-surface-like structure on top of a uniform background. We associate the former (latter) with fermions forming the chiral-$p$ wave superfluid (fermions localized in tightly bound $s$-wave dimers). These results illustrate an interesting aspect of topological superfluidity and point towards a new method for its realization in ultra-cold atom gases.

Figure 1: The 2D topological Fermi superfluid in the BCS and BEC regimes. Panels (a) and (b) show the dispersion $E_k$ for the lowest-energy Bogoliubov quasiparticle excitation, together with the associated Nambu-eigenspinor amplitudes $\psi_L, \psi_R$ for spin-$\sigma$ particle (hole) degrees of freedom, for indicated values of the magnitude of two-particle binding energy $E_b$, spin-orbit-coupling strength $\lambda$, and difference $\delta h \equiv h - h_c$ of the Zeeman spin splitting from the critical value. The BCS limit is illustrated in panel (a), exhibiting signatures of both $s$-wave and $p$-wave pairing. In contrast, for the BEC limit shown in panel (b), only $p$-wave pairing remains in the topological regime. Panel (c) shows the momentum-space distribution function $n_{\mathbf{k}}$ for the system in the BEC regime, which indicates the coexistence of a Fermi surface underlying $p$-wave pairing on top of a background of fermions localized in tightly bound $s$-wave dimers. The red star indicates the analytical prediction for the location of a $p$-wave-pairing-related Fermi surface based on our approximate low-energy theory [12].

Here $E_F \equiv h^2 k_F^2/(2m)$ and $k_F \equiv \sqrt{2\pi n}$, where $m$ and $n$ are the fermions’ mass and 2D sheet density, respectively.

References


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Studies on the Mechanism of O-N Photocleavage for O-(2-Nitrobenzyl)-protected Analogues of Piloty’s Acid

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It has recently emerged that like NO, nitrosyl hydride (HNO, 1HNO, nitroxyl, azanone) may also be a signalling molecule in biological systems.1 HNO prodrugs are also interest of treating congestive heart failure.2 Several classes of HNO donors have been developed, including Angeli’s salt, Piloty’s acid and related derivatives.3 The main drawback of these HNO donors is slow release of HNO (HNO generation is typically minutes to hours), making them unsuitable for kinetic and mechanistic studies of the reactions of HNO with biomolecules.

Photolysis is widely used to rapidly generate molecules in situ for chemical and biological studies. A well-established photoprotecting group is the σ-nitrobenzyl moiety.4 Molecules which incorporate this group of the type NO2Bz-O-X (X = a leaving group) typically decompose via C-O bond cleavage.5 We present mechanistic studies on the photolysis of a series of σ-nitrobenzyl-protected Piloty’s acid derivatives. The photoproducts of steady state photodecomposition of (1) and (3) show formation of small amounts of CH3SO2- consistent with C-O bond cleavage and release of HNO. Interestingly, much larger amounts of CH3SO2NH2 were instead observed, suggesting that O-N photocleavage is the major mechanism for photodecomposition. For (2) and (4) only O-N bond cleavage occurs. Given the novelty of O-N bond cleavage, studies have been undertaken to probe factors which determine whether C-O or O-N bond cleavage occurs for these molecules.

References
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In this talk I give an overview of the progress made during the first four years of my group’s involvement with the Dodd-Walls Centre. Perhaps most prominently, we have consolidated the Marsden funded project “lHC – the littlest Hadron Collider” [1] in a series of experiments [2; 3; 4] investigating cold collisions of ultracold atoms using steerable optical tweezers. Figure 1 highlights a pinnacle in these efforts: The observation of the quintessential Fano profile in the heteronuclear scattering between K and Rb atoms at a magnetic Feshbach resonance [4]. More recently, we upgraded our optical tweezers system to manipulate multiple atomic clouds in three dimensions [5] and I will discuss possible future applications of this versatile experimental platform. Along a different strand of research, we have explored the interplay between off-resonant light and atomic ensembles. This has both offered practical solutions for monitoring atomic dynamics in real time [6; 7], but also revealed intriguing effects arising from quantum degeneracy and atomic lensing.

Fig. 1: Optical collider procedure. a $^{87}\text{Rb}$ (red, left) and $^{40}\text{K}$ (blue, right) atoms are held in two crossed optical dipole traps separated by $\sim 3 \text{ mm}$; COM indicates the center-of-mass for pairs of K and Rb atoms. b The two traps are accelerated towards each other, keeping $m_{\text{Rb}}v_{\text{Rb}} = -m_{\text{K}}v_{\text{K}}$, so that the COM of K and Rb pairs remain at rest in the lab frame. c When the wells are separated by $= 60 \mu \text{m}$, the trapping laser beams are switched off. d The atomic clouds collide in free space. e, f The K and Rb collision halos expand at different rates. We image the K halo at the time represented in (e), and then wait to image Rb until its halo has expanded to the equivalent size (f). g Measured scattered fraction (circles) as a function of magnetic field for a collision energy $E/\hbar = 52(1) \mu \text{K}$. h, i Absorption images and density profiles of K (h) and Rb (i) acquired at the magnetic fields indicated by the arrows.

References


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Figure 1: (Left) Momentum distribution of a Spin-Orbit coupled BEC after abruptly switching of laser coupling. (b) Truncated Wigner simulation showing qualitative agreement with the experiment.

Illuminating a Bose-Einstein condensate (BEC) with a pair of carefully chosen laser beams can couple the internal states together resulting in a collection of dressed states, superpositions of the bare uncoupled states. For small coupling strengths, $\Omega R < 4E_r$, the familiar parabolic dispersion of the particles becomes a double well in quasimomentum space, where the group velocity near the minima is zero. The dressed states near the two minima labeled $| \uparrow \rangle$ and $| \downarrow \rangle$ are pseudospin states that have a direct relationship between the particles spin and momentum known as spin-orbit coupling. The spin-momentum locking exhibited by the spin-orbit coupled states leads to an enormous array of exotic dynamics and phases.

We present our recent work on the experimental investigation of the dynamics of a spin-orbit coupled BEC (SOBEC) in two and three-dimensions. Abruptly changing the spin-orbit coupling strength results in an applied spin-dependent synthetic electric force. Following the same analysis performed in [1] we obtain measurements of the rate of thermalization and the temperature of the system as a function of the spin-orbit coupling.

References

TRANSMISSIVE ANDERSON LOCALISATION EXPERIMENTS WITH COLD ATOMS IN 2D: INSIGHT FROM LOCALISATION LANDSCAPE THEORY

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In early 2018, the Quantum Information laboratory has conducted a series of experiments designed to observe the effects of Anderson localisation with ultra-cold atoms confined to two dimensions (2D). A Bose-Einstein condensate (BEC) of Rb-87 was loaded into a 2D trap, and a repulsive dumbbell-shaped potential, created by a spatial-light modulator (SLM), was projected onto the atomic plane such that the BEC was initially located in one of the reservoirs. Point-like potential scatterers were created in the channel (also using the SLM), placed at random positions throughout the channel. As the BEC moved down the channel, the atoms scattered off the noisy potential, and disorder-induced transport suppression was observed.

Meanwhile, a recent breakthrough in the theoretical description, coined localisation landscape theory [1], predicts that all key localisation properties of a disordered Hamiltonian system may be obtained by solving $Hu = 1$ for the localisation landscape $u$ (Fig. 1 (a)), where $H$ is the Hamiltonian. In 2D, $u(x,y)$ is a surface, and its valleys (anti-watersheds) constitute a network (Fig. 1 (b)) that determines the localisation regions of the eigenstates of $H$ at different energies. In particular, eigenstates are confined by valley lines along which $u < 1/E$ (Fig. 1 (c)), so for higher energies, the network is “cut down”, and the eigenstates occupy a larger area. Furthermore, $W = 1/u$ was shown to act as an effective potential for the system: the valleys of $u$ are the peaks of $W$, causing exponential decay of the wavefunction each time it crosses them (Fig. 1 (d)).

We use localisation landscape theory to gain insight into our noisy dumbbell transmission experiments. The localisation landscape and valley network are computed for each channel geometry and fill factor probed experimentally, and a direct comparison is drawn. We interpret the transmission of the atoms through the noisy channel as the passage of a wavefunction through the potential $W$, where the reduction in transport arises from tunnelling through the peaks of $W$ (the valley network of $u$). This approach to the modelling of the problem is considerably simpler than both exact Schrödinger time evolution and the self-consistent localisation theory, yielding, in addition, a clear and simple physical picture of the experiment.

Figure 1: (a) Localisation landscape with 0.1 fill factor ($\ell = 1.44\mu m$), (b) corresponding valley network (lines), with the velocity field of $u$ as arrows and its extrema as symbols, (c) lowest eigenmode of the Hamiltonian (surface plot) and the “cut down” valley network (lines), (d) the associated effective potential $W = 1/u$.


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CONVERGENCE PROPERTIES OF FOCK-SPACE BASED APPROACHES IN STRONGLY CORRELATED FERMI GASES

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In the description of strongly correlated Fermi system, the exact diagonalization approach is frequently applied in order to achieve reliability and accuracy in theoretical calculations. In this approach, the energies and the wave functions are obtained by diagonalizing the Hamiltonian in a many-body Fock basis. As the size of Hilbert space combinatorially increases with the number of particles and the number of single particle basis functions, most of the calculations are limited for few-body systems at intermediate values of the interaction strength. Therefore, understanding and improving the convergence properties is crucial in order to increase the particle number and the interaction strength.

The rate of convergence of physical observables with increasing basis size is determined, for the most part, by the nature of the particle-particle interaction itself. Usually, in ultracold atoms the interaction potential is modeled by a zero-range pseudopotential. Although it greatly simplifies the complicated dispersion interaction between the atoms, it introduces a singularity in the wave function at the particle-particle coalescence point. This singularity causes painfully slow convergence in one spatial dimension and even leads to pathological behaviour in two and three dimensions.

In this presentation, two alternative approaches will be shown. First, the finite-range Gauss pseudopotential \cite{1} is applied in a harmonic trap in two dimensions. It is smooth potential and hence the wave function is free from any singularity. Though, if the finite basis is not fine enough, the finite-range pseudopotential is indistinguishable from the pathological zero-range potential. We show that the number of the required single particle harmonic oscillator basis functions increases with the inverse fourth power of the characteristic length of the Gaussian potential, which severely limits the usefulness of this approach. Optimizing the unit length of the harmonic-oscillator basis, the dependence can be decreased to quadratic scaling \cite{2}. Even though the applied optimization significantly reduces the numerical efforts, the successful emulation of short-range interactions still remains restricted to a few-particle regime.

As an alternative approach we present the transcorrelated method, where the leading singularity of the wave function is explicitly considered and transformed out of the finite basis set expansion. We will show by the example of the homogenous gas in one dimension that this transformation efficiently improves the convergence rate form $M^{-1}$ to $M^{-3}$, where $M$ is the number of the one-particle basis functions \cite{3}.

References

\begin{itemize}
\item \cite{2} P. Jeszenszki, T. Levy, A. Alavi, and J. Brand, in preparation (2018).
\item \cite{3} P. Jeszenszki, H. Luo, A. Alavi, and J. Brand, “Accelerating the convergence of exact diagonalization with the transcorrelated method: Quantum gas in one dimension with contact interactions” arXiv:1806.11268 (2018).
\end{itemize}

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