DODD-WALLS CENTRE
for Photonic and Quantum Technologies

PhD Scholarship Projects

Theme 1A – Photonic Sensors & Imaging

1a.12) Using nonlinear microscopy to study brain cell and network function in autism spectrum disorder

Nonlinear microscopy is a growing field with an ever-increasing range of applications and its uses include imaging the activity of cells deep inside the brains of live animals. We have recently demonstrated that compact fibre based lasers can be used for nonlinear microscopy as opposed to traditional bulky laser systems. This project aims to further develop fibre based lasers into practical compact sources and then use them to demonstrate improved imaging in brain tissues. The student will begin by testing existing mode-locked fibre sources before designing and building an improved source optimised for imaging. Once the laser and existing multiphoton microscope are optimised these technologies will be applied to image brain cell activity in live animals. Using a mouse model, activity in brain networks will be studied at the synaptic, cellular and network level to reveal how altered activity patterns contribute to the symptoms of autism spectrum disorder.

Contact: *Dr Juliette Cheyne, University of Auckland, j.cheyne@auckland.ac.nz, Dr Frederique Vanholsbeeck, University of Auckland, f.vanholsbeeck@auckland.ac.nz, and Professor Neil Broderick, University of Auckland, n.broderick@auckland.ac.nz.*

1a. 13) Optical Biopsies using Optical Coherence Tomography to detect early signs of chronic diseases.

Optical coherence tomography (OCT) is a real time, non-invasive and non-contact imaging modality for translucent and transparent tissue capable of providing morphological images at the micron scale resolution at more than 1mm depth penetration. First developed in 1991 for measuring the human retina, OCT's fields of application has been extended to a wide variety of tissues and non-biological structures. Conventional OCT is based on measuring the back reflection of light induced by changes of refractive index in the sample. Although the information gain of purely structural images is high, poor contrast can make structures difficult to be identified. Therefore OCT was extended to exploit other light properties for better contrast and quantitative measurements. In this contest, we would like to develop optical biopsies using OCT and new contrast agent such as chromatic dispersion and elastography. The project will have a specific focus on detecting early signs of chronic diseases such age related degeneration (in the eye) and osteoarthritis (in cartilage).

Contact: *Dr. Frederique Vanholsbeeck, University of Auckland, f.vanholsbeeck@auckland.ac.nz*

1a. 14) Resonant Ultrasound Spectroscopy

Resonant ultrasonic spectroscopy fills an important gap between our ultrasonic and seismic research. Together with the PORO lab, we have rock samples to complement laser ultrasound and a host of other petrophysical data with new RUS results.

Contact: *Dr Kasper Van Wijk, Physical Acoustics Lab, University of Auckland, k.vanwijk@auckland.ac.nz*

1a. 15) Laser ultrasonic rock physics under high pressure and/or temperature

The PAL and PORO lab join forces by combining our respective strengths in laser ultrasound and rock physics to improve data quality and quantity. In this project, we are building the expertise to do laser ultrasound in a pressure vessel with optical windows. Source/receiver locations are varied under computer control with an arduino-controlled servo rotational stage.

Contact: *Dr Kasper Van Wijk, Physical Acoustics Lab, University of Auckland, k.vanwijk@auckland.ac.nz*

1a.16) Quality control of timber and fruit products with laser ultrasound

Laser ultrasound can be applied to products of interest to a wide community. Current methods of testing the quality of fruit and timber, for example, can often be described by one or more of the following terms: sparse, contacting, expensive, and often destructive. In this project, we aim to explore the opportunities for laser ultrasound in estimating the quality of fruit and timber in a non-contacting and non-destructive matter.

Contact: *Dr Kasper Van Wijk, Physical Acoustics Lab, University of Auckland, k.vanwijk@auckland.ac.nz*

1a.17) Sensing with THz micro resonators

We have developed thin-walled THz bubble wishpering gallery mode (WGM) resonators where the evanescent field is fairly strong even in the inside of the bubble. The PhD project is about utilising the evanescent field for sensing gases that flow through the bubble. Most polar gases will have strong fundamental (absorption) resonances within the THz range, and these resonances will change the characteristics of the WGM resonances. We expect that it should be possible to measure low concentration of gases down to at least ppm levels. Applications include the detection of green-house gases and poisonous gases emitted by industrial processes.

Contact: *Dr Rainer Leonhardt, University of Auckland, r.leonhardt@auckland.ac.nz*

1a18) Generating cw THz radiation at 0.57 GHz to be used for a THz hygrometer

The project involves evaluating different methods of generating cw THz radiation around 0.5 THz: i) utilising the nonlinear effect in a two-colour semiconductor laser, ii) reversing the effect of THz detection with high-electron-mobility transistors (HEMTs) to generate THz, iii) using thermally excited H2O gas as THz emitter. After an initial evaluation and preliminary experiments, the most promising method should be further developed to a point where the 0.5THz source can be incorporated into a THz based hygrometer. Collaboration with researchers in Europe ensures access to two-colour lasers and/or HEMT design.

Contact: *Dr Rainer Leonhardt, University of Auckland, r.leonhardt@auckland.ac.nz*

1a.19) Portable THz imaging device

We propose to build a portable terahertz spectral imaging tool that operates in the time-domain. Here, we will use THz pulses to construct 3D images of samples by correlating their return times with the distance they travel. Using existing methods, we can capture an entire THz wave in a 'single shot'

– essential capability for 3D imaging – by using a standard spectrograph to resolve how THz pulses interact with probe pulses in a non-linear optical crystal. In this project, we aim to translate these methods from operating with large amplified lasers, to portable (and less expensive) unamplified lasers from which industrial instruments could be built. Potential applications of such an instrument include primary industries, border security, building materials, and manufacturing production lines. In order to achieve sufficient spectral, temporal, and spatial resolution using weak laser pulses, this project will challenge us to develop new ways of efficiently generating and detecting THz pulses and rapidly processing the data towards real-time applications.

Contact: *Associate Professor Justin Hodgkiss, Victoria University of Wellington*
Justin.Hodgkiss@vuw.ac.nz

1a.20) Bacteria identification using spectroscopic fluorescence

Bacteria are everywhere and are involved in many processes relevant to our everyday life yet it is hard to monitor accurately and in real time bacterial concentration. Recently, the physics department in collaboration with the microbiology department has developed an all-fibre spectroscopic system called the optrode that is able to detect and quantify bacteria. It provides an alternative to the conventional plate count techniques with advantages of portability, sensitivity, near real time measurements and ability to detect a high dynamic range of bacteria concentrations in its natural environment. The next challenge is to be able to identify specific type of bacteria as well as monitoring bacterial processes. One avenue is to immobilise the microorganism using functionalised fibres or microfluidic devices. This work has a strong industry focus in developing This research will be carried out in collaboration with microbiologists who will provide samples and knowledge of microorganisms and bacterial processes.

Contact: *Dr Frederique Vanholsbeeck, University of Auckland* f.vanholsbeeck@auckland.ac.nz

1a.21) High Speed Fruit Scanner

Fruits are evaluated on commercial grading systems by near infrared spectroscopy (NIRS). Infrared radiation is transmitted by the produce, and the spectral response gives an indication of the chemical properties of material. Diffuse optical tomography is a technique, that measures spatially resolved optical properties and can give information on local optical properties. It requires measurement of light modulation phase, light intensity, and optical path length. In this project we propose to combine NIRS and optical tomography to develop a high speed, multiple wavelength device that scans a whole fruit while it is moving and rotating on a commercial grading line. The system will measure the parameters required for diffuse optical tomography reconstruction and will deliver information on the spatial distribution of internal quality parameters. The project is run by the University of Waikato in collaboration with Plant & Food Research and their industry partners.

Contact: *Associate Professor Rainer Künnemeyer, University of Waikato, rainer@waikato.ac.nz.*

1a.22) Optical Method to Determine Storage Breakdown Disorder in Fruit.

This project seeks to develop a practical method for rapidly and non-destructively determining the presence of storage breakdown disorder (SBD) in fruit. The symptoms of SBD develop with time in a cool store and can currently only be detected when a fruit is cut open. This PhD project will explore the use of NIR spectroscopic methods for both identification of SBD at various storage stages and for providing a better understanding of chilling injury development over time. The spectroscopic methods that will be initially considered include standard NIR methods for whole fruit measurement, which are commonly used in industry. Building on the work of our research group novel methods will be developed to rapidly scan the surface of a fruit at high resolution and measure the transmitted/reflected light at high speed suitable for commercial grading applications. The project is based at the University of Waikato in collaboration with Plant & Food Research and their industry partners.

Contact: *Associate Professor Rainer Künnemeyer, University of Waikato, rainer@waikato.ac.nz.*

1a.23) Virtual Peeling of Produce

Consumers have high expectations of the quality of fruits and vegetables and expect them to be free of any internal defects. Near infrared spectroscopy is a commonly used technique to grade and assess the quality of produce. The spectral response gives an indication of the chemical properties of the surface or the bulk of the material. As defects are usually well below the surface and are often only small, they are difficult to detect with traditional techniques. Furthermore, some produce, such as avocado, has very thick or opaque skin, which dominates the spectral signature and obscures any subtle information from the material below. In this project we seek to develop a method that removes the influence of the skin from measurements but remains fast and is suitable for commercial applications. Expanding the work of our research group, using multiple laser probes novel methods will be developed to rapidly scan a fruit. The project is based at the University of Waikato in collaboration with Plant & Food Research and their industry partners.

Contact: *Associate Professor Rainer Künnemeyer, University of Waikato, rainer@waikato.ac.nz.*

1a24) High Brightness Lanthanide Doped Nanoparticles for Applications in Optical Imaging

This project involves the synthesis and optimisation of highly *stable* and *biologically benign*, alkaline earth fluoride (*e.g*. CaF_2) based core-shell nanoparticles for which the bulk parent crystal is known to exhibit *high order preferential defect clusters* when doped with lanthanide ions. We hypothesise that tuning nanoparticle synthesis conditions will allow to optimize number and type of dopant ions present within a CaF_2 core of controlled size, enforcing spatial proximity, enhancing dopant cluster formation and enabling enhanced energy transfer between the energy donor ion and the accepting ion. Effects of the distribution of the lanthanide ions/clusters (within the nanoparticle core, at the interface between the core and the shell *etc*.) and effects of the shell properties (thickness, crystallinity, chemical functionality at the outermost surface responsible for the interactions with the media *etc*.) will be further investigated. A key goal of this project is to understand the underlying energy transfer processes between lanthanide ions in alkaline earth nanoparticles and utilise that knowledge to optimise the light yield at the desired reporting wavelength.

Contact: *Professor Jon-Paul Wells*, Dr Vladimir Golovko, Professor Mike Reid, University of Canterbury, Christchurch, NZ. Jon-paul.wells@canterbury.ac.nz*

1a25) Frequency Upscaled Ring Laser Gyroscopes

This project involves the development of a large scale, mechanically stabilised, He-Ne ring laser gyroscope *which will be the first to operate* on the 543.3 nm neon ($3s_2 \rightarrow 2p_{10}$) transition. This will effectively upscale the ring laser utilising the shorter wavelength transition without the additional mechanical instabilities associated with very large laser structures. Having characterised and understood 'green gyroscopic' operation it is then proposed to implement next generation supermirrors having multiple stop bands i.e. the intra-cavity mirrors will be designed to allow simultaneous laser oscillation at two wavelengths, 632.8 and 543.3 nm, with mode locking used to stabilise against mode competition. The cavity is intended to be actively stabilised by placing piezeoactuators under two of the mirror mounts themselves and using a comparison of the 632.8 nm output against an iodine stabilised He-Ne offset laser - using the beat frequency between the ring and the reference laser (disciplined by GPS derived standard frequencies) to maintain the perimeter stability. *This first of its kind* laser has the potential to rotation sense at both wavelengths on different laser output ports with the primary (high frequency) Sagnac time-series obtained at 543.3 nm.

Contact: *Professor Jon-Paul Wells, University of Canterbury, Christchurch, NZ. Jon-paul.wells@canterbury.ac.nz*

1a.26) Spectroscopy and Modelling of Rare-Earth Ions in Quantum-Information Candidate Materials

Single crystals doped with rare-earth ions are candidates for a number of quantum-information applications. Recent use of the ZEFOZ (Zero First Order Zeeman) technique has enabled coherence to be stored for up to six hours. Searching for the ZEFOZ point requires a detailed knowledge of the Hamiltonian for the particular magnetic-hyperfine splitting of the electronic states of interest, which in turn entails exhaustive spectroscopic studies, and non-trivial parameter fitting. In previous work we have used the predictive ability of crystal-field theory to calculate magnetic-hyperfine spin Hamiltonians. This PhD project will extend previous work on Er^{3+} ions in YSO to other ions. Literature data for Pr^{3+}, Eu^{3+}, and Yb^{3+} will be analysed using our fitting techniques, and additional data will be obtained for Nd^{3+} and Ho^{3+} using a variety of laser spectroscopy techniques. With a consistent set of parameters across the rare-earth series it will be possible to identify potential ZEFOZ points in a variety of ions, which may then be investigated experimentally.

Supervisors: *Professor Jon-Paul Wells* and Professor Michael Reid, University of Canterbury, Christchurch, NZ and Associate Professor Jevon Longdell, University of Otago, Dunedin, NZ. Jon-paul.wells@otago.ac.nz*

1a.27) Resonant enhanced sensing (experimental)

We aim at establishing a new type of resonant enhanced sensing by utilizing high quality optical resonators. Our group fabricates some of the world's best crystalline optical resonators. These resonators allow us to translate a number of environmental changes (such as pressure, chemical reactions, electric field potential, etc.) into frequency changes, which can be very precisely detected. The Resonant Optics group at the University of Otago is newly established and equipped with a state-of-the-art laboratory and we are looking for an engaging PhD student to take on this challenging and potentially highly rewarding task.

Contact: *Dr Harald Schwefel (harald.schwefel@otago.ac.nz), University of Otago*

1a.28) Light Matter Interactions, particularly on the very short time (sub-50 ps) timescales

When light is absorbed by a molecule or a material, it is converted by that matter into other forms of energy: lower energy light, vibrational excitation, chemical reaction, molecular rotation, proton or electron transfer, etc. Our laboratory studies the fundamental aspects of this conversion process - how does the structure (nuclear & electronic) affect how the system "decides" what to do with the energy it absorbs in the form of light? And how can we control that "decision-making" process. One key target is to design (using quantum and classical chemical physics), construct (through collaboration with synthetic chemists) and test (via ultrafast laser spectroscopy) a molecular dragon system.

Contact: Professor Cather Simpson, Photon Factory, University of Auckland
c.simpson@auckland.ac.nz

1a.29) Integrated optical sensors to predict food product quality

Optical sensors including, but not limited to, Optical Coherence Tomography, Raman Spectroscopy and Hyperspectral Imaging can be used to measure various meat product quality characteristics from data captured on raw meat products via calibration equations. Calibration is achieved by elucidating the correlations between the spectral absorption/scatting effects and product quality characteristics using multivariate statistical approaches known as chemometrics. This PhD project will seek to develop novel approaches to calibrating optical sensors by integrating data from multiple sources into common prediction models for different meat quality parameters. Key meat product quality parameters of interest are Texture, Fat Content and pH. This project is a unique opportunity to be part of a multidisciplinary team with expertise in meat science, photonics, bio-physical modelling and meat industry commercialisation working to develop a technology platform based on optical sensors to enable real-time measurement of meat product quality at an industrial scale. We seek applications from highly motivated individuals with a passion for applied research in the food industry to join our project team as a PhD student.

Contact: *Dr Frederique Vanholsbeeck f.vanholsbeeck@auckland.ac.nz University of Auckland and Dr Cameron Craigie Cameron.craigie@agresearch.co.nz AgResearch*

Theme 1B – Photonic Sources & Components

1b.11) Period Doubling, Chaos and Stability in Mode-locked Lasers

The dynamics of light propagation in a mode-locked laser is a treasure trove of interesting effects from stable pulsing (producing the world's most accurate clocks) to chaotic behaviour with applications in cryptography and everything in between. In this project we will use a variety of mathematical models to study the behaviour of both semi-conductor and fibre lasers looking at the properties of both. This work will involve working closely with experimentalists in Paris, Zurich and Auckland and is expected to lead to optimised designs that can be demonstrated experimentally.

Contact: *Professor Neil Broderick, Department of Physics, University of Auckland and Professor Bernd Krauskopf, Department of Mathematics, University of Auckland.*
n.broderick@auckland.ac.nz.
This project is suitable for students with an undergraduate degree majoring in Mathematics.

1b.12) Coupled Cavity Dynamics in Photonic Crystals

Passively driven optical cavities such as micro-resonators, fibre loops or photonic crystal cavities all display a wide range of dynamical behaviour due to the interplay of nonlinearity, loss and linear coupling.

In this project we will model the behaviour of two coupled cavities passively driven by a single source demonstrating the existence of chaotic dynamics as well as stable pulsing regimes. This work is done in collaboration with experimentalists in Paris and will lead to new understanding of their current experiments and well as potentially leading the way for new experiments in quantum chaos.

Contact: *Professor Neil Broderick, Department of Physics, University of Auckland and Professor Bernd Krauskopf, Department of Mathematics, University of Auckland.*
n.broderick@auckland.ac.nz.
This project is suitable for students with an undergraduate degree majoring in Mathematics.

1b.13) Advanced Mode-locked Fibre Lasers

We will design, build and test new passively mode-locked fibre lasers suitable for high-power applications. This work will extend previous designs working at 1 micron to go to new wavelengths using novel Bismuth doped fibres as well as making dynamically switchable laser cavities by including active elements inside the laser cavity. These lasers will be amplified up to high powers and used for micro-machining experiments.

Contact: *Professor Neil Broderick, Department of Physics, University of Auckland*
n.broderick@auckland.ac.nz.

1b.14) Light Matter Interactions, particularly on the very short time (sub-50 ps) timescales

When light is absorbed by a molecule or a material, it is converted by that matter into other forms of energy: lower energy light, vibrational excitation, chemical reaction, molecular rotation, proton or electron transfer, etc. Our laboratory studies the fundamental aspects of this conversion process - how does the structure (nuclear & electronic) affect how the system "decides" what to do with the energy it absorbs in the form of light? And how can we control that "decision-making" process. One key target is to design (using quantum and classical chemical physics), construct (through collaboration with synthetic chemists) and test (via ultrafast laser spectroscopy) a molecular dragon system.

Contact: *Professor Cather Simpson, Photon Factory, University of Auckland c.simpson@auckland.ac.nz*

Theme 2A – Quantum Fluid and Gases

2a.9) Atomtronics experiments

New technological developments have created the possibility to create the elements of a common electrical circuit for ultra cold atoms. This emphasises the quantum nature of the propagation of the atoms through such circuits. At the University of Auckland we do such experiments using ultra cold rubidium atoms, trapped in a thin film. This directly maps to nanoscale electronic circuits in two dimensions. The project will focus on generating the elements of common electronic circuits, such as transistors and diodes, in addition to already available resistors and capacitors using ultra cold rubidium atoms from a Bose-Einstein Condensate.

Contact: *Dr Maarten Hoogerland, (m.hoogerland@auckland.ac.nz), University of Auckland*

2a.10) Josephson vortices for atomtronics (theory)

Atomtronics is a field that aims at developing components, circuits, or devices based on ultra-cold atom physics that mimic the operation of counterparts in electronics. In close collaboration with the experimental ultra-cold atom group at the University of Auckland, this project will develop the theoretical description to understand the underlying physical principles related to the operation of atomtronic components based on atomic Josephson vortices, the quantum-gas analog of vortices in tunnel junctions between superconductors that have already found interesting applications in the world of electronics. The project is a collaboration between Massey University, Victoria University, and the University of Auckland, and the candidate could be based either in Auckland or Wellington.

Contact: *Prof. Joachim Brand (j.brand@massey.ac.nz), Massey University Auckland and Prof. Uli Zuelicke (uli.zuelicke@vuw.ac.nz), Victoria University Wellington, Dr. Maarten Hoogerland (M.Hoogerland@auckland.ac.nz), University of Auckland*

2a.11) Topological phases and excitations in quantum gases (theory)

Solitons and vortices are nonlinear waves with exceptional stability properties that have been observed in atomic Bose-Einstein condensates and superfluid Fermi gases. The purpose of this project is to investigate the dynamics of these waves under the influence of artificial gauge fields, which have become available to ultra-cold gas experiments in recent years. In Fermi gases with spin-orbit coupling there is, in particular, the possibility to enter the phase of a topological superfluid, where solitons and vortices can carry Majorana fermion quasiparticles, which have interesting potential applications in topological quantum computing.

We seek a PhD candidate with a strong background in theoretical physics or applied mathematics to investigate the problem in hydrodynamics/nonlinear field theory. The project is a collaboration between Massey and Victoria University and the candidate could be based either in Auckland or Wellington.

Contact: *Prof. Joachim Brand (j.brand@massey.ac.nz), Massey University Auckland and Prof. Uli Zuelicke (uli.zuelicke@vuw.ac.nz), Victoria University Wellington*

Theme 2B – Quantum Manipulation and Information

2b.10) Making microwaves visible (experimental)

The first generation of quantum computers will most likely be based on superconducting microwave circuits. Within these devices the quantum information is encoded in a microwave field. In order to connect such devices to a future quantum communication network based on optical fibres these microwave photons need to be converted into the optical domain. We have realized a first step in this direction within a highly nonlinear optical resonator and are looking for an excellent PhD student to push the boundaries of the experiment to realize efficient quantum state bi-directional transfer between the optical and microwave domain.

Contact: *Dr Harald Schwefel (harald.schwefel@otago.ac.nz), University of Otago*

2b.11) Cavity QED experiments with optical nano fibres

The interaction of a single photon with single atoms has long captured the imagination of scientist everywhere. It promises to allow quantum information stored in the state of this atom to be mapped to the state of a photon. The latter can now be transmitted to a distant other system, where its quantum state can be mapped back onto an atomic state. This subject has long been dominated by experiments involving very high quality free-space cavities. A new technology, using optical nano fibres, is now used at the University of Auckland to interface atoms to photons. This project will take the next step towards turning this into a quantum network, where quantum information is shared between a number of simple 'nodes'.

Contact: *Dr Maarten Hoogerland (m.hoogerland@auckland.ac.nz), University of Auckland*

2b.12) Measurements conditioned dynamics: monitored quantum jumps do not "jump"

The idea of a quantum jump entered physics in the early 20th century with the atomic model of Niels Bohr: in essence, considering its restriction to discrete energy levels, any change of state under illumination by electromagnetic radiation must take the form of instantaneous jump from one energy level to another. While the arrival of Schroedinger's wave equation did bring the quantum jump idea under attack, the notion nevertheless persisted, and in the mid-1980's quantum jumps were reported to be experimentally observed [W. Nagourney, et al., Phys. Rev. Lett., 56, 2797 (1986); T. Sauter et al., Phys. Rev. Lett. 57, 1696 (1986); J. Bergquist et al., Phys. Rev. Lett. 57,1699 (1986)]. This project will revisit these experimental observations and ask: in what sense are the observed quantum jumps in fact "jumps"? It will use the theory of a conditional quantum evolution (stochastic quantum trajectories of monitored quantum systems) to explore the possibility of interrogating the "jump" dynamic in closer detail using the technology now available through advances in circuit QED [see, e.g., R. J. Schoelkopf and S. M. Girvin, Nature 451, 665 (2008); M. H. Devoret and R. J. Schoelkopf, Science 339, 1169 (2013)].

Contact: *Professor Howard Carmichael (h.carmichael@auckland.ac.nz), University of Auckland*