Optical Sciences Centre 2023 Physics Honours Projects

1. Advanced Silicon Photonic Integrated Chips

Supervisor(s): Prof. D.J. Moss, Dr. J. Wu
Contact details: jiayangwu@swin.edu.au

Project Description: This project will focus on theoretical designs of high performance optical filters in integrated silicon photonic nanowire resonators[1]. It will use mode interference in formed by zig-zag waveguide coupled Sagnac loop reflectors (ZWC-SLRs), tailored to achieve diverse filtering functions with good performance. These include compact bandpass filters with improved roll-off, optical analogues of Fano resonances with ultrahigh spectral extinction ratios (ERs) and slope rates, and resonance mode splitting with high ERs and low free spectral ranges. The project will verifies the feasibility of multi-functional integrated photonic filters based on ZWC-SLR resonators for flexible spectral engineering in diverse applications.

[1] H.Arianfard, J.Wu, S.Juodkazis,D.J. Moss,"Spectral Shaping based on Integrated Coupled Sagnac Loop Reflectors Formed by a Self-Coupled Wire Waveguide", **IEEE *Photonics Technology Letters* <u>33</u>** (13) 680 (2021).

2. Nonlinear Photonic Chips with 2D Graphene Oxide Films

Supervisor(s): Prof. D.J. Moss, Dr. J. Wu
Contact details: jiayangwu@swin.edu.au

Project Description: This project will investigate enhanced nonlinear optics in complementary metal-oxide-semiconductor (CMOS) compatible photonic platforms through the use of layered two-dimensional (2D) graphene oxide (GO) films [1]. It will investigate the integration of GO films with silicon-on-insulator nanowires (SOI), high index doped silica glass (Hydex) and silicon nitride (SiN) waveguides and ring resonators, to demonstrate an enhanced optical nonlinearity including Kerr nonlinearity and four-wave mixing (FWM). The GO films are integrated using a large-area, transfer-free, layer-by-layer method while the film placement and size are controlled by photolithography. In SOI nanowires we will observe a dramatic enhancement in both the Kerr nonlinearity and nonlinear figure of merit (FOM) due to the highly nonlinear GO films. Self-phase modulation (SPM) measurements will show significant spectral broadening enhancement for SOI nanowires coated with patterned films of GO. The dependence of GO's Kerr nonlinearity on layer number and pulse energy will be investigated to show trends of the layered GO films from 2D to quasi bulk-like behavior. This project will help to demonstrate the strong potential of GO films to improve the nonlinearity of silicon, Hydex and SiN photonic devices.

[1] J. Wu, L. Jia, Y. Zhang, Y. Qu, B. Jia, and D. J. Moss,"Graphene oxide: versatile films for flat optics to nonlinear photonic chips", ***Advanced Materials*** **<u>33</u>** (3) 2006415, pp.1-29 (2021).

3. Applications of Kerr Frequency Microcomb Chips

Supervisor(s): Prof D. Moss
Contact details: dmoss@swin.edu.au

Project Description: Integrated Kerr micro-combs will be investigated as a powerful source of many wavelengths for photonic RF and microwave signal processing as well as optical neural networks [1,2]. They are particularly useful for transversal filter systems and have many advantages including a compact footprint, high versatility, large numbers of wavelengths, and wide bandwidths. This project will investigate photonic RF and microwave high bandwidth temporal signal processing based on Kerr micro-combs with spacings from 49-200GHz. It will consider a range of possible functions from integral and fractional Hilbert transforms, differentiators, integrators as well as optical neural networks. The potential of optical micro-combs for RF photonic applications in terms of functionality and ability to realize integrated solutions will be explored.

[1] M. Tan, X. Xu, J. Wu, R. Morandotti, A. Mitchell, and D. J. Moss, "RF and microwave photonic temporal signal processing with Kerr micro-combs", ***Advances in Physics X*** **6** (1) 1838946 (2021).
[2] X. Xu, M. Tan, B. Corcoran, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, D. G. Hicks, R. Morandotti, A. Mitchell, and D. J. Moss, "11 TOPs photonic convolutional accelerator for optical neural networks", ***Nature*** **589** (7840) 44-51 (2021).

4. Satellite Ocean Polariscopy

Supervisors: Dr S. H. Ng (data processing), Prof S. Juodkazis (polariscopy), Dr A. Codoreanu (high performance computing & Earth observation), Prof A. Duffy (high performance computing)
Contact: soonhockng@swin.edu.au

Project description: Observations of ocean waves, their orientation, and height play an important role in the study and modelling of the climate. This information can be used to track the effects of climate change or help with the prediction of severe weather events. This project will investigate adapting a polariscopy method developed for use at the Australian Synchrotron to satellite applications. The method involves taking transmission measurements at 4 different linear polarisations (0°, 45°, 90°, and 135°) and is able to determine orientation of a sample, even when the structures are far below the diffraction limit.

The project will involve processing of currently available altimeter, synthetic aperture radar, and scatterometer satellite data to determine the feasibility of applying this technique to Earth observation and in reflection. It will seek to understand how the low-level data can be processed to extract the required polarisations and if not, how this data can still be utilised. There is the possibility of experimentally validating the method in reflection (subject to easing of restrictions), and future prospects include design and implementation of an instrument for validation in space.

5. Micro-optics for Astro-Photonics (@ Optical and Astronomy Centers)

Supervisors: Dr V. Anand (optical design), Prof K. Glazebrook (astronomy devices), Dr S-H Ng (nanofabrication), Prof S. Juodkazis and T. Katkus (fs laser fab)

Contact: **sjuodkazis@swin.edu.au**

Project description: This project is set up to establish the modeling of micro-optical elements for observational astronomy. Coupling of light from the sky into a fiber-optical element for spectral measurement has to meet stringent constraints for angular light acceptance, collection, high efficiency of light transmission, and simplicity/robustness of design for fabrication of micro-optical elements.

In this 1 year project, we will establish the design and optimize for the collection of light by 5-m-diameter lens into an optical fiber with a 0.5 mm core. What micro-optical element(s) made out of pure silica or sapphire (for high UV-IR transmission) is(are) required will be established. The project will prepare a design that is amenable by femtosecond laser fabrication (3D printing). The optical design or laser fabrication can have the main focus of the project.

6. Silicon nanoparticle fabrication using femtosecond pulsed laser ablation for deep tissue biolabelling

Supervisors: A/Prof. James W. M. Chon, Prof. Saulius Juodkazis

Contact: jchon@swin.edu.au

Project description: Silicon nanoparticles have the ability to pick up magnetic field of visible and near-infrared light. This provides wealth of choice for oscillation modes in the visible and NIR range, which makes silicon nanoparticle attractive for biomedical imaging contrast. It is proposed that these nanoparticles can penetrate deep into tissue for brain and neural network imaging. Recently fabrication methods of silicon nanoparticles have greatly improved with femtosecond pulsed laser irradiation. In this project, we use amplified femtosecond pulsed laser to synthesise silicon magnetic nanoantennas and characterise them using multiphoton microscopy and spectroscopic technique. In particular we utilize dynamic light scattering (DLS) and high-order fluorescence correlation spectroscopy (H-FCS) to characterize the size and shape distribution of nanoparticles produced inside solution and be able to separate monodisperse silicon nanoparticles with controlled sizes from 50 -250 nm. Students are expected learn nonlinear optics, plasmonics, numerical simulation methods and correlation spectroscopies.

7. Acoustic frequency comb generation

Supervisor: Dr Ivan Maksymov

Contact: imaksymov@swin.edu.au

Project description: This project is an excellent opportunity for a student interested in theoretical and numerical modelling to work on the emergent and interdisciplinary topic of acoustic frequency combs. Similar to an optical frequency comb, an acoustic frequency comb is a spectrum consisting of a series of discrete, equally spaced elements that have a well-defined phase relationship between each other. Acoustic combs will benefit marine sciences, underwater positioning and navigation, also opening up novel opportunities for industries using unique properties of liquids, droplets and bubbles (e.g. biomedicine). In this project, we will investigate nonlinear physical phenomena in acoustic, microfluidic and optical systems by developing and using computational codes based on finite-difference methods (FDTD) and other numerical techniques. There would also be opportunities to be involved into experimental research.

Further reading:
PhysicsWorld magazine, https://physicsworld.com/a/acoustic-frequency-comb-measures-up/;
YouTube, "Why you need an optical frequency comb", https://www.youtube.com/watch?v=graq4kpd8-A
FDTD method, https://meep.readthedocs.io/en/latest/Introduction/
https://www.iflscience.com/physics/body-and-ocean-scanning-acoustic-frequency-combs-made-using-fish-tank-bubbles/

8. 2D Fermi Gases near a p-wave Feshbach resonance

Supervisors: Professor Chris Vale, Dr Paul Dyke, Dr Ivan Herrera
Contact: cvale@swin.edu.au

Project description: Ultracold atomic gases can display remarkable quantum behaviours at nanoKelvin temperatures such as superfluidity or flow with zero resistance. In Fermi gases, superfluidity relies on atoms forming pairs and to date only the simplest form pairing (known as s-wave pairing) has been successfully used. In this project you will take steps towards forming p-wave pairs in a 2D Fermi gas. This will involve producing a gas of atoms near a p-wave Feshbach resonance and measuring its lifetime which is predicted to be much longer in 2D. Regardless of the lifetimes, we will study the behaviour of gases following a quench of the interactions near the p-wave Feshbach resonance. We will also investigate the effect of p-wave impurities in cold gases and the p-wave polaron.

9. An ultracold source of Dy atoms

Supervisors: Professor Chris Vale, Dr Sascha Hoinka
Contact: cvale@swin.edu.au

Project description: The Australian Quantum Gas Microscope is a new facility for quantum simulation being constructed at Swinburne for the study of superfluids and quantum materials using ultracold gases of dysprosium atoms. The apparatus is currently being built in a new laboratory and we have various projects available that will contribute to the system. These include the design and testing of lasers and optical layouts for optimal laser cooling, experimental control and imaging systems.

10. Dynamics and interactions of exciton-polaritons in semiconductor microcavities

Supervisors: Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: A polariton is a quasi-particle that is part photon and part exciton (where an exciton is a bound electron-hole pair). These part light – part matter quasi particles arise where there is strong light-matter coupling, such as is the case where 2D materials or quantum wells are incorporated within a light cavity formed by two mirrors. These polariton systems offer great flexibility to control the properties of and interaction between polaritons and form condensed phases of matter that allow for loss-less energy flow. In this project, you will use femtosecond (10^{-15} s) laser pulses and state of the art multidimensional coherent spectroscopy experiments to measure the dynamics and interactions between polaritons and excitons in GaAs quantum wells. This work is part of the Centre of Excellence for Future Low-Energy Electronic Technologies, where we hope to be able to find a way to utilise the unique properties of polaritons for next generation electronics solutions.

11. Coherent Dynamics in High-Temperature Superconductors

Supervisors: Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: Understanding the mechanisms of high-temperature superconductivity has been one of the great challenges in condensed matter physics over the past 30 years since superconductivity was first observed in cuprate materials. In the past 12 months we have been able to successfully realise the first measurements of coherent dynamics in these materials, which we expect will help to provide great insight into the mechanisms responsible for superconductivity in these materials[1]. This project will expand upon that work, measuring the coherent dynamics using femtosecond (10-15 s) laser pulses and state of the art multidimensional coherent spectroscopy experiments.

[1] Novelli, Tollerud, Davis Science Advances 6, eaaw9932 (2020), https://doi.org/10.1126/sciadv.aaw9932

12. Floquet Physics in Atomically Thin 2D Semiconductors Supervisors:

Supervisors: Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: The bandstructure of a material plays a major role in describing its properties, and usually doesn't change. Floquet physics provides a pathway to reversibly alter and control the bandstructure of materials through the application of a time-periodic perturbation. In this project you will use the oscillating electromagnetic field of a laser pulse as the periodic perturbation and use it to alter the bands and properties of two-dimensional semiconductors that are one atom thick. With the unique properties of these 2D materials and the control of the bandstructure allowed through Floquet physics it is predicted to be possible to generate exciting new types of quantum materials and switch them on and off. You will probe these states with state-of-the-art coherent multidimensional spectroscopy capabilities developed at Swinburne to reveal coherent dynamics and the physics underlying the switching on and off of the applied field. This project is part of the ARC Centre of Excellence for Future Low-Energy Electronics Technologies (FLEET: www.fleet.org.au), and aims to reveal new physics that can underlie a new paradigm for electronics technologies.

13. Exploring the role of Quantum Coherence and Electronic-Vibrational Coupling in Photosynthesis

Supervisors: Professor Jeffrey Davis
Contact: jdavis@swin.edu.au

Project description: Photosynthesis takes place in the warm, wet environment of biological systems, which at first glance seems an unlikely place to find and explore the clear effects of quantum mechanics. Recent work has identified the presence of long-lived coherences among different molecules within some light-harvesting complexes involved in photosynthesis. Using the techniques developed here at Swinburne, we are able to study directly these quantum mechanical processes in detail. This project will explore the role of quantum coherence and electronic-vibrational coupling in photosynthesis by studying the dynamics of both coherent and classical energy transfer, within the isolated molecules and between the molecules within light-harvesting complexes. The ultimate aim is to develop an in depth understanding of the mechanisms responsible for the efficient energy transfer in photosynthesis.

14. Quantum Turbulence (theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

Project description: Quantum turbulence occurs in superfluids and is associated with chaotic dynamics of quantised vortices. These non-equilibrium quantum systems feature remarkable behaviours such as absolute negative temperature states and large scale Onsager vortex flows. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.

[1] S. Johnstone et al. Evolution of large-scale flow from turbulence in a two-dimensional superfluid, Science 364, 1267 (2019).

15. Superwalkers (experiments/theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

Project description: Millimeter sized droplets can be made to bounce on the surface of a periodically driven fluid. For suitably Floquet engineered parameters these droplets begin to "walk" at speeds exceeding tens of millimeters per second. Furthermore, these curious wave-droplet entities have been shown to mimic the behaviour of various quantum systems. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.
[1] R. Valani et al. Superwalking Droplets, Phys. Rev. Lett. 123, 024503 (2019).

16. Topological Quantum Computation (theory/computation)

Supervisors: A Prof Tapio Simula
Contact: tsimula@swin.edu.au

Project description: The future of computing inevitably involves quantum computers. Topological quantum computation is a novel decoherence resilient way of performing quantum information processing and may be achieved using novel particles called non-Abelian anyons, which are neither bosons or fermions. For recent results in this research topic see reference [1]. A broad range of problems in this space can be tailored to suit the candidates' skills and interests.
[1] B. Field et al. Introduction to topological quantum computation with non-Abelian anyons, Quantum Science and Technology 3, 045004 (2018).

17. Crystallizing Time in a Bose-Einstein Condensate

Supervisors: Prof Peter Hannaford and Prof Andrei Sidorov
Contact: phannaford@swin.edu.au

Project Description: This project involves the creation of a Bose-Einstein condensate of ultracold potassium-39 atoms bouncing under the action of gravity on an atom mirror. The experiment is a forerunner to producing a 'time crystal' of ultracold atoms which is a new form of quantum matter in which a periodically driven many-body system repeats itself in time, rather than in space, with a period longer than the driving period, allowing the periodic structure to resist external perturbations and, in principle, to persist indefinitely in time. Such a time crystal has potential application in condensed matter physics in the time domain, quantum technology and atomic clocks.