Program 1. Quantum Sensing - Lead - Kishan Dholakia, University of Adelaide

Project 1.1 – Title: Chip based quantum position navigation & timing devices
Partner Organisation: QuantX
Project lead - Andy Boes (andy.boes@adelaide.edu.au), Deputy lead - Arnan Mitchell
Location – University of Adelaide

The problem: Clocks form the core of most Positioning, Navigation, and Timing (PNT) systems, playing a pivotal role in enabling the precise deployment of both offensive and defensive capabilities in defence systems. They are indispensable for the navigation of autonomous vehicles and play a critical role in various logistics and transportation activities. However, the challenge arises from the fact that the most accurate clocks are large. In response to this issue, the demand for low SWAP (Size, Weight, and Power) in the realm of PNT has become increasingly crucial.

The solution: Leveraging photonic integrated chip technology, create a semiconductor chip advancement capable of reducing a clock from the size of a refrigerator to that of a postage stamp. This project aims to explore and develop on-chip narrow lines with lasers, a key element required for photonic integrated chip clocks, representing a promising avenue for achieving the necessary size reduction for PNT systems.

Project 1.2 – Title: Nitrogen-vacancy centres in diamond and other materials
Partner Organisation: Quandela
Project lead - Brant Gibson (brant.gibson@rmit.edu.au), Deputy lead - Andy Greentree
Location – RMIT

The problem: Solid state magnetometers based on the negatively charged nitrogen-vacancy centre in diamond (NVD) provide an alternative solution for highly sensitive magnetic field detection under ambient conditions. The presence of a natural abundance of 1.1% of 13C in commercial NVD however limits magnetic field sensitivity. Isotopic engineering of diamond can reduce the Optically Detected Magnetic Resonance linewidth and improve measurement contrast and ultimately sensitivity for precision magnetometry applications. A significant factor governing the DC magnetic sensitivity of an NV magnetometer is the T2* decoherence time.

The solution: Optimise modelling and growth to achieve NV ensembles with T2* coherence times longer than commercially available diamond materials. NV dipoles oriented in particular directions will preferentially couple to waveguide structures. To gain control over the NV orientation and coupling of the NV emission into waveguides and optical fibres, diamond growth on (100) and (111) diamond substrates will be explored. Growth on (100) diamond substrates results in NV centres aligned along four distinct orientations which is convenient for vector magnetometry applications. Research has shown that chemical vapour deposition growth on (111) diamond substrates can achieve preferential NV alignment at relatively low NV densities, offering advantages for precision magnetometry applications which will be explored.

Project 1.3 – Title: Single Quantum - Superconducting nanowire single photon detectors
Partner Organisation: Single Quantum
Project lead - Kishan Dholakia (kishan.dholakia@adelaide.edu.au), Deputy lead - Glenn Solomon
Location – University of Adelaide

The problem: Superconducting nanowire single-photon detectors (SNSPD) have revolutionised low-light and single photon detection. There are a few companies in the world marketing these systems, but none in Australia. These detectors work at cryogenic temperatures, typically in the range of 15K, but some as low as sub-1K. While low temperature operation requires additional size, weight, and power, the trade-offs are single photon quantum efficiencies above 90% and jitter as low at 15 ps. They are state-of-the-art. The lack of a national SNSPD technology in Australia is a problem leading to long lead-times bound up in supply chain issues, and reducing changes in flexibility and customisation. An additional problem is the inability to translate these detectors to integrated photonic circuits (IPCs). IPCs are like integrated chips, but optical based. For robustness and scalability quantum technology designers want to integrate optical functionality onto a photonic chip, including the detector. This is unavailable in Australia and in commercial companies world-wide.

The solution: Construct SNSPDs in our cleanroom laboratories on the UoA campus. With guidance from one of the most successful producers of these detectors, we will build NbN superconducting detectors. We will first deposit NbN and optimise its superconducting properties, then fabricate nanowires for single-photon detectors. Detectors will be fabricated for wavelengths associated with biological imaging. Here, the high detection efficiency is useful because the illumination source can be reduced, reducing the damage threshold for live biological imaging. SNSPDs will also be fabricated for a related quantum light source project, Project 3.3. Integration on a simple IPC will also be part of this project. We expect that a successful project will lead to Single Quantum considering a branch in Australia.

Project 1.4 Title: Quantum biosensor development

Project lead - Jiawen Li (jiawen.li01@adelaide.edu.au), Deputy leads - Brant Gibson/Andrew Greentree/Abel Santos

Location – University of Adelaide

The problem: The existing generation of biological sensors has undeniably transformed research, environmental monitoring, and healthcare. However, current sensors often lack the requisite sensitivity, suffer from slow response times, and are optimised for only a single target which limits their efficacy [6].

The solution: Quantum biosensors offer a revolutionary solution to the challenges of biological monitoring. By leveraging the principles of quantum mechanics, these biosensors provide unparalleled sensitivity, enabling the precise identification of biomolecules even at extremely low concentrations. The real-time monitoring capabilities of quantum biosensors and the portability of these sensors supports point-of-care testing, particularly in resource-limited areas. Also, quantum biosensors play a crucial role in environmental monitoring and advance biological research, offering insights into molecular processes and aiding drug development for more effective healthcare solutions.

Project 1.5 Title: Quantum chemical sensor development

Project lead - Abel Santos (abel.santos@adelaide.edu.au), Deputy lead - Brant Gibson

Location – University of Adelaide

The problem: Traditional sensors struggle to achieve highly sensitive, real time and accurate detection of a wide range of chemical substances. Whilst lab-based systems can perform these analyses, there a wide range of scenarios that demand small, inexpensive sensors with these capabilities.

The solution: Quantum chemical sensors represent a ground-breaking advancement in sensing technology, harnessing the principles of quantum mechanics to achieve unparalleled precision in detecting and analysing chemical substances. These sensors leverage the unique properties of quantum systems, such as superposition and entanglement, to enhance their sensitivity and accuracy. By exploiting quantum phenomena, quantum chemical sensors can detect subtle changes in molecular structures and electronic configurations, allowing for the identification of specific chemicals even at extremely low concentrations. This level of sensitivity holds tremendous potential across various fields, including environmental monitoring, medical diagnostics, and industrial safety.

Program 2. Quantum Computation - Lead – Jared Cole, RMIT

Project 2.1 Title: Superconducting quantum circuit design
Partner Organisation: AQC
Project lead - Jared Cole (jared.cole@rmit.edu.au), Deputy lead - Giuseppe Tettamanzi
Location – RMIT

The problem: Microwave circulators are key to a range of superconducting electronics as they allow routing of control and noise signals into and out of low noise devices. Conventional circulators are bulky devices using magnetic materials. AQC aims to develop on-chip circulators which are integrated into superconducting electronics, providing better performance in a much smaller volume. A significant limitation of current on-chip circulator designs is the stability and movement of quasi-particles generated externally and within the chip, which reduce circulator performance.
The solution: Using advanced theoretical and computational modelling techniques, this project will study the dynamics of quasi-particles in superconducting circuits. The aim will be to characterise and understand existing designs, and then propose and analyse new designs which will control quasi-particle dynamics. Improved materials and designs will then be tested both at UoA and AQC to calibrate and validate the theoretical models.

Project 2.2 Title: Optical quantum computing
Partner Organisation: Quandela
Project lead - Jacqui Romero (m.romero@uq.edu.au), Deputy lead - Andrew White
Location – University of Queensland

The problem: The transverse mode and frequency of photons are alternative degrees of freedom for encoding classical or quantum information using light—these can be used as dits, or qudit. Applications include high-bandwidth communication and computation technologies such as short- or long-haul optical interconnects, optical neural networks, and quantum communication and computation. However, the design of individual components is challenging because of the individual control necessary for each mode - this is often nontrivial.
The solution: To overcome the issues faced when designing and fabricating traditional multimode devices, we will develop inverse design and nanofabrication methods which enable us to demonstrate multimode photonic components with broadband operation, improved fabrication robustness, and compact footprint. Our technology will enable the next generation of large-scale photonic circuits which leverage multimode waveguides to improve the performance of short- or long-haul optical interconnects, optical neural networks and quantum communication and computation applications.

Project 2.3 Title: Quantum tools
Partner Organisation: MOGLabs
Project lead - Arnan Mitchell (arnan.mitchell@rmit.edu.au), Deputy lead - Halina Rubensztein-Dunlop
Location – RMIT

The problem: Many quantum sensors (and some forms of quantum computers) can be achieved using atoms such as rubidium or cesium with exceptional spectral properties. Robust and compact vapour cells containing these atoms can be made relatively cheaply in high volumes creating the possibility of inexpensive and deployable quantum sensors for applications in navigation, precision timing and magnetic field sensing to name just a few. This is the business of our partner Infleqtion. To read such a sensor, you need a very sophisticated laser system (such as those made by MOGLabs) which can be large, fragile and expensive. While well suited for laboratory experiments, these laser systems could not be deployed in applications such as self-driving cars or autonomous robots for advanced manufacturing.

The solution: Recently there have been major advances in photonic integrated circuits. Hybrid integration has made it possible to combine the semiconductor materials required for lasers, with waveguide circuits and high-speed modulators to make these lasers precise and tunable - all the functionalities required to read quantum sensors. This project will explore interfacing the semiconductor materials made by Centre Director Solomon and interface them with CI Mitchell's photonic integrated circuit platforms to make an integrated tunable laser that can be used to read Infleqtion's quantum sensors with PI Rabeau. We will coordinate with CI Rubenstein-Dunlop and PI Scholten from MOGLabs to ensure these chips complement high-end laboratory grade quantum lasers and systems, expanding the Australian made quantum sensing ecosystem.

Program 3. Quantum Photonics - Lead – Andrew White, UQ

Project 3.1 Title: Laser development
Partner Organisation: MOGLabs
Project lead – Glenn Solomon (glenn.solomon@adelaide.edu.au), Deputy lead – Arnan Mitchell
Location – University of Adelaide
The problem: MOGLabs make constant power (cw) tuneable lasers for a variety of applications in Defence, communication testing, physics, and metrology. The heart of their systems is an edge-emitting semiconductor diode laser, but unfortunately there is no Australian supplier of these. Thus, MOGLabs is at the mercy of supply-chain variabilities and national interests abroad to obtain the critical components of their tuneable lasers. This becomes more of a problem because their order size is not large, further diminishing their leverage. In addition, MOGLabs would like to assess a small but fast turn-around time on semiconductor diode lasers to investigate new products.
The solution: This project will use molecular-beam epitaxy (MBE) and cleanroom a fabrication process to produce edge-emitting diode lasers at various wavelengths. These lasers will be characterised to insure they meet MOGLabs specifications. Once the lasers have been fabricated and tested to meet specification, they will be sent to RMIT to be mounted and enclosed in rugged mounts.

Project 3.2 Title: Bacterial sterilisation using quantum light
Project lead - Katharina Richter (katharina.richter@adelaide.edu.au), Deputy lead - Andy Greentree
Location – University of Adelaide
The problem: Superbugs, or antibiotic-resistant bacteria, pose a significant problem due to their ability to withstand the effects of traditional antibiotics, rendering these medications less effective or entirely ineffective. This resistance arises through the overuse or misuse of antibiotics, creating an environment where only the most resilient bacteria survive and reproduce. New methods to kill these bacteria are required to prevent serious economic and health impacts.
The solution: Mid-infrared Light-Emitting Diodes (LEDs) of specific wavelengths hold significant promise in combating superbugs, representing a cutting-edge approach in the field of antibacterial technology. These LEDs operate within the mid-infrared spectrum, allowing for targeted interactions with bacterial cells. The unique wavelength characteristics of mid-infrared light, enable it to penetrate bacterial membranes, disrupting cellular structures and functions. By harnessing this technology, researchers and scientists can explore innovative methods to address antibiotic-resistant superbugs, which pose a growing threat to public health. This project will develop LEDs of novel wavelengths and test their efficiency against a wide range of critical bacteria.

Project 3.3 Title: Quantum light sources
Partner Organisation: Quandela
Project lead - Andrew White (andrew.white@uq.edu.au), Deputy lead - Yan Jiao
Location – University of Queensland

The problem: Quantum dots are fast becoming the dominate discrete single and entangled photon source. They have high quantum efficiency, meaning they produce nearly one photon per pumping clock cycle. They also have fast decay rates so that the single or entangled photon emission rate can be in the GHz regime. They can be inserted into micrometre-scale optical cavities to focus photon emission into an optical that can be easily coupled into optical fibres or a free-space system. The problem is the coherence time of the spin in the ground state of the quantum dot system. Its coherence time is reduced because of the strain distribution across the quantum dot due to the indium content of the quantum dot.

The solution: Choose a quantum dot and surround material that is strain-free. This has been shown to drastically improve the spin coherence time in the quantum dot, allowing for longer quantum memory time and larger photon entanglement. This project will construct a GaAs quantum dot instead of InAs, in a host material of AlGaAs so that no strain is produced. Metallic aluminium will be used to etch nanometre-scale hole regions in the AlGaAs layer, after which GaAs will be added to fill the holes. Once these quantum dots have been developed and characterised, optical cavities will be constructed around the quantum dots to enhance their outcoupling.

Project 3.4 Title: Compact hybrid optical-atom-chip traps
Project lead - Tyler Neely (t.neely@uq.edu.au), Deputy Leads - Kishan Dholakia/Halina Rubensztein-Dunlop, Location – University of Queensland

The problem: Atom chips have enabled real-world applications of ultracold atom technology by reducing the SWAP requirements of relatively complex laboratory-based experiments. This has resulted in compact apparatus, such as the Cold Atoms Laboratory, flying on the International Space Station. While these approaches have reached a high degree of refinement, the most powerful and precise techniques for trapping ultracold atoms are instead based on tailored optical traps, formed from precisely shaped and focused laser beams. The advantages of optical traps are rapid reconfigurability and increased dynamic control of the cold atom system, essential for applications such as trapped and/or guided atom interferometry for inertial navigation or mass sensing. However, combining these two trapping technologies has proved challenging due to the optical access being restricted by the opaque atom chip, making the integration of optical elements clunky and challenging.

The solution: Combine key aspects of magnetic trapping on atom chips, via integrated electrodes, with integrated photonic elements. This will enable additional optical trapping, based on both evanescently coupled optical fields to surface etched features (such as ring structures), and via direct projection through the backside of a transparent atom chip. This project will develop new atom chip approaches, including traps based on transparent conducting films on transparent substrates. Key aspects will include optical design and wavefront control to enable high-resolution aberration-corrected imaging through the substrate structures.