Extended Abstract – Center of Excellence (10-year program):

Innovation for Quantum Technologies (I4QT)

Innovation for Quantum Technologies (I4QT) is a ten-year national Center of Excellence committed to reshaping quantum sensing and mid-infrared communication by fusing state-of-the-art integrated frequency-comb lasers with sustainable, nature-derived photonic materials. The programme's scientific heart lies in chip-scale comb sources that oscillate directly across the entire 2–18 μm "molecular-fingerprint" band with near-shot-noise internal coherence, a capability that will enable ultrasensitive trace-gas analysis, neuro-metabolite monitoring in vivo and quantum-secure links far beyond what near-IR platforms can provide today.

The technological roadmap begins with well-established periodically poled lithium-niobate waveguides and advances toward orientation-patterned ZnS and ZnSe thin films, culminating in Cr:ZnS/ZnSe frequency combs heterogeneously integrated on silicon. These platforms support octave-spanning, low-threshold operation and serve as engines for generating nonclassical light—squeezed and entangled states distributed across individual comb modes—to push metrological precision and key-distribution rates beyond classical limits.

A defining feature of I4QT is its commitment to quantum-grade natural materials. Atomically thin clay minerals such as vermiculite and montmorillonite are transferred onto photonic chips, where their nanoconfinement traps enhance mid-IR absorption and provide built-in gas cells without the bulk of conventional multipass cells. We further propose a novel concept of sensor architecture that combines a laser frequency comb with a graphene-based single-electron transistor (SET) coupled to a 2D antiferromagnetic 2D clay. The frequency comb probes molecular absorption lines, while the 2D material acts as a frequency-selective absorber, converting specific optical signals into localized excitations. These excitations are transduced by the SET into electrical signals. The graphene SETs are ultrasensitive to single-electron events and can reach quantum noise limits, operating at or near room temperature. This integrated platform offers a compact, chip-scale solution for broadband molecular sensing with quantum-level precision.

From fast-growing timber and agricultural waste, cellulose nanocrystals and lignin nanoparticles are spin-coated into helicoidal or glassy photonic films that act as chiral resonators, naturally protecting quantum states against back-scattering while slashing the embodied energy of the device stack. Even the quantum emitters themselves draw on biology: vanadyl-substituted chlorophyll radicals extracted from a plant form clock-transition spin qubits that couple directly to the 2.4 μm comb line, offering a biodegradable interface between microwave spin memories and optical photons. A rigorous life-cycle and supply-chain analysis underpins every materials choice, aiming for energy and CO_2 savings well above seventy percent compared with conventional LiNbO3- and III-V-based photonics.

By merging mature photonic integration with these renewable material streams, I4QT will deliver a novel class of compact, field-deployable quantum sensors and mid-IR communication nodes that are not only powerful and scalable, but also environmentally and economically sustainable. Partnerships with international leaders in quantum optics, green chemistry and circular manufacturing ensure that scientific breakthroughs translate swiftly into manufacturable technologies and a resilient, eco-conscious supply chain ready for broad societal impact.

Key objectives

- Develop chip-scale mid-IR frequency-comb lasers whose internal noise approaches the quantum (shot-noise) limit across the 2–18 μm molecular-fingerprint band, using hybrid Cr:ZnS-on-Si and PPLN/OP-ZnSe platforms as the work-horse gain and nonlinear stages.
- Integrate naturally abundant functional materials—atomically thin vermiculite and montmorillonite clays together with spin-coated cellulose- and lignin-based photonic films—to pre-concentrate analytes, tailor dispersion and resonance, and cut the embodied energy of the photonic stack.
- Realise quantum light sources that pair these mid-IR combs with both on-chip $\chi^{(2)}/\chi^{(3)}$ nonlinearities and plant-derived spin defects (e.g., vanadyl-chlorophyll thin films), creating microwave-to-optical transducers and single-photon emitters fully compatible with sustainable processing lines.
- Exploit entangled and squeezed comb modes, enhanced by the strong light–matter overlap inside natural-material resonators linked to the graphene-based single-electron transistors to surpass classical limits in trace-gas sensing, neuro-metabolite spectroscopy and quantum-secure communications.

Selected References:

Bernhardt, B. et al. (2010). "Mid-infrared dual-comb spectroscopy with 2.4 μm Cr^{2+}:ZnSe femtosecond lasers", *Applied Physics B* **100**, 3. (first direct mid-IR dual frequency comb generation)

Sorokin, E. et al. (2007). “Sensitive multiplex spectroscopy in the molecular fingerprint 2.4 μm region with a Cr:ZnSe femtosecond laser”, *Optics Express* **15**, 16540. (unprecedented (200 ppt) sensitivity in molecular fingerprint region)

Lukin, D. et al. (2020). “4H-silicon-carbide-on-insulator for integrated quantum and nonlinear photonics”. *Nature Photonics* **14**, 330. (first hybrid quantum-classical photonic (4H-SiCOI) circuit where quantum emitters and classical nonlinear devices, e.g., waveguides, frequency converters, modulators coexist)

Zhao, R. et al. (2023). “On-chip Ti:sapphire microresonators for quantum photonics”. *Science* **382** (6671), 76. (monolithical integration Ti:sapphire at 0.8 μm —a "gold standard" bulk nonlinear material—into high-performance on-chip microresonators, unlocking a white avenue in quantum photonics)

Reimer, C. et al. (2017). “Generation of multiphoton entangled quantum states by means of integrated frequency combs”. *Science* **351**, 1176. (integrated frequency combs to generate multiphoton entanglement on a chip, merging quantum optics with scalable photonic engineering)

Kues, M. et al. (2019). “Quantum optical microcombs”. *Nature Photonics* **13**, 170. (establishes microcombs as a critical technology for realizing chip-scale quantum networks)

Pacakova B., Fossum J.O. et al. (2025). “Naturally occurring 2D semiconductor with antiferromagnetic ground state.” *npj 2D Materials & Applications* **9**, 56. (vermiculite-based clay nanosheets for photonics and spintronics)

Goswami, S. et al. (2022). “Shot-noise suppression in graphene single-electron transistors at room temperature.” *Nature Nanotechnology* **17,** 143. (room-temperature noise suppression in graphene SETs)

Parker, R. M. et al. (2022). “Cellulose photonic pigments.” *Nature Communications* **13**, 3378. (helicoidal CNC films as chiral mid-IR resonators)

Li, H., Chen, Y. (2025). “Self-assembly of lignin nanoparticles from *Moringa* bark into photonic glasses.” *Green Chemistry* **27**, 2458.

Mullin, K. S. et al. (2024). “Systems-chart approach to the design of spin relaxation times in molecular qubits.” *Dalton Transactions* **53**, 16585. (plant-derived vanadyl- porphyrin spin qubits)

Patel, P. et al. (2023). “Green synthesis of fluorescent carbon dots from *Moringa oleifera* leaves for bio-imaging.” *Journal of Photochemistry & Photobiology B* **245**, 112445.