PhD PROJECT PROPOSAL

## **PhD Project Title**

## Coupling of light to vibrations in quantum materials

## **PhD Supervisory Team**

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## **Project Abstract**

How to confine and enhance the coupling of light to atoms and molecules? This is a fundamental question in the field of nanophotonics that deals with the interaction of light with matter at the nanoscale. One can improve these interactions by using specialized nanoarchitectures and create new mixed states that are part-light and part-matter in nature. By utilizing quantum materials, specifically the vibrations in them, this project will investigate their coupling to light in the terahertz (THz) frequencies. The goal is to create an efficient detector system that will have several applications in molecular sensing and spectroscopy, medical diagnostics, and quantum technologies.

## **Detailed Project Description**

The interaction of light and matter at nanoscale offers unprecedented opportunities to manipulate the dynamics of nanoscale objects such as atoms and molecules. While there have been advancements in boosting the coupling of visible light to matter all the way down to single-molecule levels, the lack of suitable materials has limited the manipulation of light with THz frequencies. 1-10 THz range of the electromagnetic spectrum harbours spectral signatures of ions, atoms, and molecules that are central to our understanding of the composition and origin of the solar system and galaxies.

This project will explore the coupling of THz light to vibrations in quantum materials. The ultimate aim will be to develop an efficient THz light detection scheme by upconverting the invisible THz light to visible light. This demonstration will have tremendous applications in molecular sensing, medical diagnostics, security, and quantum technologies.

When THz light interacts with a material, it results in weak oscillatory vibrations in the atomic bonds of the material. This interaction, however, is severely hampered by the thermally populated incoherent vibrations. On the contrary, electronic states in materials with transition energies in the visible regime have a negligible thermal occupation. Therefore, the direct detection of visible light is much more efficient, down to the single-photon level.

When it comes to nanoscale materials, the electronic and vibrational transitions are coupled, and this coupling governs the electron/ heat transport through molecules. In complex nanoarchitectures such as those in devices, electronic and vibrational coupling is significantly modified, affecting the device performance. Yet, no methods exist to coherently manipulate the vibrations in materials. THz detection scheme developed in this project will provide a unique way to coherently control vibrations in quantum materials and ‘see’ the electronic-vibrational coupling.



To enable this, optical cavities will be utilized to trap light in confined volumes. By constructing robust plasmonic optical nanocavities, one can trap light in extremely small gaps. This allows us to ‘see’ the nano-world and enables strong light-matter coupling; the reason being the negative permittivity of metals allowing collective oscillation of free electrons on metal surfaces called surface plasmons. The effective optical volume in a metal (plasmonic) nanocavity is a million times lower than the diffraction limit (Fig.1). This enables room temperature measurements otherwise reserved for cryogenics at high vacuum. This way, one could perform quantum experiments at ambient conditions.

To demonstrate coherent coupling of vibrations to optical cavities at ambient conditions, the PhD student will (i) fabricate, assemble, and develop optical nanocavities with quantum materials having intense and tuneable vibrational signatures, (ii) couple THz modes in nanocavities which involves optical and THz characterization methods, and (iii) demonstrate upconversion of THz signals to visible light which involves the development of new spectroscopy and microscopy techniques. The aim is to have a resultant detection scheme that has an ultrafast response, single-photon efficiency, and low noise.

The student is also expected to perform simple numerical simulations using standard commercial software packages to optimize the geometrical parameters of quantum materials and nanocavities and to elucidate the light-matter coupling scenarios.

The student will regularly be interacting and discussing with collaborators in the Metamaterials Research Centre as well as from other departments and institutions to enable knowledge transfer and dissemination.

The concept of this project radically departs from the existing THz light detection methods that are slow and often need cooling to very low temperatures. By developing a novel concept of converting invisible THz light to visible light using coupled vibrational and electronic states in quantum materials assembled into nanoscale plasmonic optical cavities, this project is expected to bridge the gap between fundamental research and applications, driving forward technological developments in THz light detection.