Quantum Emitters Coupled to Subwavelength Hyperbolic Phonon Polaritons

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Project Type: Bachelor, Master Semester project (or a combination or all)

Context: The coupling of infrared optical phonons with electromagnetic fields in anisotropic polar materials gives rise to hybrid excitations known as hyperbolic phonon polaritons (HPhPs). In materials such as hexagonal boron nitride (hBN) and α-MoO_3, HPhPs can propagate with very large wavevectors (Figure 1b), resulting in electromagnetic fields confined to dimensions far below the free-space diffraction limit [1,2]. This extreme field confinement makes HPhP-based structures promising platforms for controlling light at the nanoscale. Their propagation direction, dispersion and field distribution can be engineered through the material geometry and nanostructure design (Figure 1a). More importantly, the large local density of optical states supported by HPhPs can substantially enhance the interaction between confined electromagnetic fields and localized quantum emitters (Figure 1c). These properties create opportunities for studying enhanced spontaneous emission, strong light–matter coupling, and collective quantum-emitter dynamics in highly confined nanophotonic environments.

Project overview: This project investigates the interaction between quantum emitters and hyperbolic phonon polaritons supported by anisotropic nanophotonic structures. The project will combine classical electromagnetic simulations with quantum-optical modelling. The first objective is to simulate the propagation and spatial confinement of HPhPs in selected material platforms, such as thin crystalline slabs or patterned structures. The student will study quantities including the electromagnetic field distribution, polariton wavelength, propagation direction, and material losses. The simulated electromagnetic response will then be used to calculate how the nanophotonic environment modifies the properties of a nearby quantum emitter. In particular, the student will firstly investigate the Purcell effect, which describes the enhancement or suppression of spontaneous emission caused by the surrounding electromagnetic structure. At a later stage, the project will examine parameter regimes in which the interaction between emitters and a confined polariton mode becomes sufficiently strong to produce coherent energy exchange. The analysis may be extended to multiple emitters in order to investigate HPhP-mediated interactions and the emergence of collective superradiant and subradiant states.

What the student will do: The student will conduct theoretical and computational research at the interface of nanophotonics, electromagnetism, and quantum optics. The project will begin with a focused literature review on hyperbolic phonon polaritons and nanoscale light–matter interactions. The student will then reproduce selected published results in order to become familiar with the relevant physical concepts and numerical methods. Using COMSOL Multiphysics, the student will construct and simulate representative HPhP-supporting structures. They will investigate the dispersion, propagation and spatial confinement of hyperbolic phonon polaritons, while examining the influence of geometry, material anisotropy and optical losses on the electromagnetic response. The student will then quantify the Purcell enhancement experienced by nearby quantum emitters and compare the performance of HPhP-based platforms with alternative nanophotonic architectures. Finally, they will extract the relevant electromagnetic quantities required for quantum-optical modelling and analyse the resulting simulation data. The student should have a solid foundation in electromagnetism, classical optics or photonics. Previous experience with numerical electromagnetic simulations is useful but not required. The main simulations will be performed using the graphical interface of COMSOL Multiphysics. Familiarity with Python or another programming language is strongly recommended for data analysis and visualisation. No formal background in quantum optics is required.

Benefits: The project provides hands-on training in the numerical modelling of advanced nanophotonic systems. The student will gain practical experience with COMSOL Multiphysics and develop transferable skills in electromagnetic simulation and numerical analysis. A central feature of the project is the connection between classical electromagnetic simulations and quantum-optical models. The student will learn how quantities obtained from Maxwell-equation solvers can be used to predict spontaneous-emission enhancement, coherent coupling, and collective emitter dynamics. The student will work closely with a doctoral assistant and will have opportunities to interact with experimental researchers. This will provide experience in interpreting numerical results, evaluating the feasibility of physical designs and connecting theoretical predictions with experimentally relevant structures.

References:

1. Caldwell J. D. et al. Photonics with hexagonal boron nitride. Nat Rev Mater 4, 552–567 (2019)
2. D. N. Basov et al. Polaritons in van der Waals materials, Science 354, aag1992 (2016)
3. Novotny L. and Hecht B. Principles of nano-optics, 2nd ed. Cambridge University Press (2012)

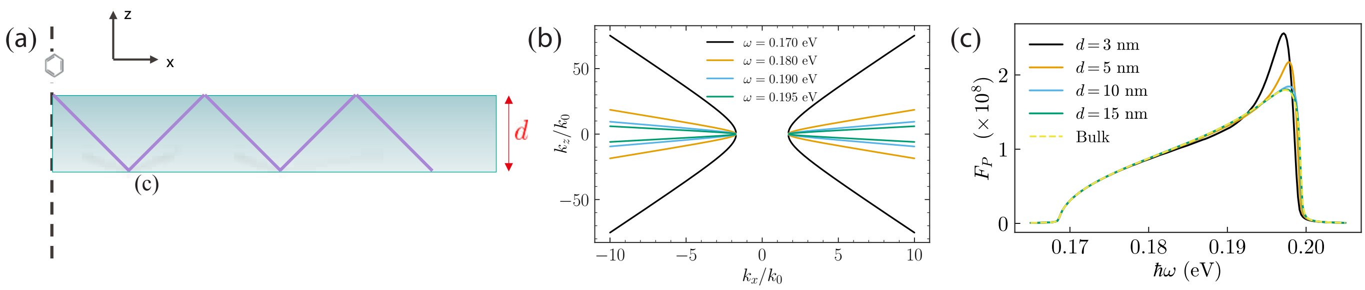

Figure 1. (a) Schematic of a molecular quantum emitter interacting with hyperbolic rays in a planar configuration. (b) Iso-frequency curves for hyperbolic phonon polaritons in hBN. (c) Purcell factor calculated at 1 nm from the interface.