Polariton lattices: a solid-state platform for quantum simulations of correlated and topological states (InterPol)

The aim of this project is to implement polariton lattices as a photonic-based solid-state platform for quantum simulation. We plan to reach the quantum-correlated regime, in which single polariton interactions overcome the optical losses, and develop simulators of strongly correlated phases and topological protection.

Project aim
The development of quantum simulation lacks compact on-chip scalable platforms. The recent demonstrations of polariton lattices in semiconductor microcavities, in combination with their extraordinary nonlinearities, place polaritons as one of the most promising candidates to achieve this goal. The aim of this project is to implement polariton lattices in semiconductor microcavities as a photonic-based solid-state platform for quantum simulations.

We will combine the expertise in semiconductor physics and technology of four experimental groups and the input of three theoretical groups to push polariton nonlinearities into the strongly interacting regime.

Main objectives
- Development of two novel complementary types of lattices – tunable and static. We will combine experimental approaches developed by the partners:
  1) deep-etched lattices of micropillars
  2) open-access microcavities (MC)
  3) lattices based on strain induced by surface acoustic waves (SAW)
- Optimization of polariton lattices to reach the quantum regime.
  Observation of photon antibunching and photon fermionisation in few lattice sites. Complementary techniques will be used to reach the quantum regime via deeper confinement in smaller volume, and by reducing the losses.
- Simulating correlated and topological phases
  1) Superfluid to Mott quantum phase transition
  2) 1D SSH model and topologically protected edge states
  3) Tonks-Girardeau phases
  4) Haldane insulator
  5) Topological protection in strongly correlated systems
  6) Fractional quantum Hall effect in the presence of dissipation
- Theoretical methods for dissipative quantum many body systems
  1) Extension of phase-space methods to account for quantum correlations
  2) Matrix-Product-States (MPS) and time-dependent Density-Matrix-Renormalization-Group (tDMRG) including drive and losses out of equilibrium

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Work Package 1: Static quantum lattices (C2N/PDI)
Fabricate micropillars with adiabatic mirrors, to reduce the lateral dimension of polariton modes (enhancing interactions) while keeping or enhancing the Q-factor (reducing losses). We expect to achieve $U/\gamma \sim 5-10$.

Work Package 2: Tunable quantum lattices (C2N/PDI/USFD, Oxford)
Tunability will be achieved by using lattices of hemispherical mirrors in open microcavities of variable cavity length, and combining with short-wavelength SAWs enabling realization of different superlattice geometries.

Work Package 3: Static quantum lattices (C2N/PDI)
Load strongly interacting polaritons into the flat bands of Lieb and Kagome lattices to achieve correlated phases akin to Fractional Quantum Hall states. Photon correlation measurements between different lattice sites will be performed using homodyne detection techniques.

Work Package 4: Topologically protected states
Study of topological properties in the quantum (and/or non-linear) regime. In 1D lattices and arrays of coupled 1D chains, we will address the SSH model and Haldane insulators. In 2D honeycomb lattices we will implement a Z topological insulator.

Work Package 5: Methods for non-equilibrium systems
Many-body methods for driven-dissipative non-equilibrium polariton systems in quantum correlated regime based on: (a) extension of MPS and tDMRG to driven-dissipative systems (b) stochastic phase-space methods to account for quantum correlations

The polariton platform will allow for the engineering of the lattice geometry and site-to-site hoping, state preparation and detection in individual sites, sensitivity to magnetic fields, and scalability due to the low value of disorder. The driven-dissipative nature of the system opens the exciting possibility of studying out-of-equilibrium strongly correlated phases, and calls for new theoretical methods. This project will provide the first quantum simulation platform using scalable lattices at optical wavelengths.