Polariton lattices: a solid-state platform for quantum simulations of correlated and topological states — PhD project-area description

M. H. Szymanska*

Ever since the original proposal for the idea of quantum simulations, the search for suitable physical platforms and their improvement has been one of the most active and successful branches of Quantum Technologies. Proposed platforms range from cold atoms and ions, nuclear and electronic spin, superconducting circuits, electrons on liquid helium to photonic systems. The applications are wide-ranging and aimed at understanding the most difficult condensed matter problems: Hubbard and spin models, quantum phase transitions, disordered and frustrated systems, spin glasses, superconductivity, topological order and open quantum systems as well as questions in high-energy, nuclear physics and cosmology. Although some effects have already been demonstrated, there are several obstacles tampering a smooth evolution of this field such as difficulty to dissipate energy (or remove entropy) in order to reach a ground state for low-energy problems (cold atoms), scalability, disorder, access to information etc...

The aim of our research in collaboration with three leading experimental groups (in Sheffield, Paris and Berlin) is to explore the recently emerged new solid-state platform, that of polariton lattices [1–3], and to optimize it for the holly grails of quantum simulations: **quantum-correlated regime** and **topological protection**. From the experimental side three different routes will be followed: the open cavities, the micropillars and the lattices induced by Surface Acustic Waves (SAW). The three different experimental groups are world leaders in their respective platforms, and we aim to combine theirs and our expertise to design a platform or platforms, where strong correlations and topological protections can be achieved.

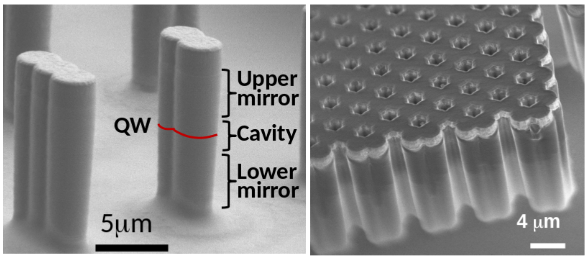

FIG. 1: Left: set of two and three deeply etched coupled micropillars. Right: honeycomb lattice of micropillars.

Microcavity polaritons are mixed light-matter quasiparticles with extraordinary nonlinear properties, which can be easily accessed in photoluminescence experiments. Due to their very light effective mass, of the order of 10^{-5} of an electron mass, quantum effects can persist to higher, even room temperatures. Photon polarisation gives rise to new types of spin-orbit coupling effects when combined with lattice geometries. Additionally, either by using their nonlinear character, or their sensitivity to magnetic fields, polaritons in a lattice could give rise to chiral edge states with topologically protected transport [4, 5]. Thanks to angle and energy resolved detection we have access not only to the ground state but to the whole excitation spectrum. Spatially resolved measurements are possible with a single site resolution which enables to study hidden orders such as, for example, Haldane insulator. On one hand we can study conservative dynamics within polariton lifetime after excitation. On the other hand we can explore driven-dissipative steady-states — a simulator of correlated and topological states in the conditions of dissipation and non-equilibrium. At the moment the theoretical methods such as Matrix-Product States or DMRG methods are only in the process of being generalised to non-equilibrium driven/dissipative systems. So polariton lattices, which can be easily studied in a condition of dissipative-driven steady-state, can be used as simulator of non-equilibrium phase transition to compare with outcomes from such methods, and help to develop them.

The aim of a PhD project in this area will be to develop techniques suitable to study correlated and topological effects in conditions of drive, dissipation and non-equilibrium, directly relevant to those light-matter systems in close collaboration with experimental groups. This could follow one (or more) of the following lines:

- Adopting stochastic methods [6], existing in our group, to lattice geometries and calculating correlations within and between lattice sites. These methods will work well in approach to quantum regime but can also be generalised to include quantum corrections, and so to work in the correlated regime.
- Study correlation between two (or a few) lattice sites using exact quantum optics method (Master equations, quantum jumps and stochastic Schroedinger eqns).
- Analytical methods: mean-field approximation, Keldysh Field theory, Renormalisation Group.
- Developing Matrix-Product States codes for 1D system including drive and dissipation characteristic for light-matter setting.

---

[1] Exciton-polaritons in lattices: A non-linear photonic simulator A. Amo and J. Bloch, C. R.Physique 17 (2016) 934945.
[2] D. Tanese et al., Nat. Commun. 4, 1749 (2013).
[3] M. Abbarchi et al., Nat. Phys. 9, 275 (2013).
[4] M. Milievi et al., Phys. Rev. Lett. (2017).
[5] F. Baboux et al., arXiv:1607.03813 (2016).
[6] G. Dagvadorj et al., Phys. Rev. X 5, 041028 (2015).

*Electronic address: m.szymanska@ucl.ac.uk