Optics of quantum metamaterials

Key Informations

Université de Montpellier
École doctorale I2S - Information, Structures, Systèmes
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Keywords

Quantum optics, electromagnetism, quantum field theory, numerical simulations

Profile and skills required

The candidate holds an MSc or equivalent degree in Physics with knowledge in advanced quantum physics. Knowledge in quantum field theory will be an asset. The candidate must also have an interest in electromagnetism and numerical simulations. PhD student will work in an international competitive context requiring high motivation and intellectual curiosity.

Project description

Metamaterials are composite materials with sub-wavelength structures that give them unusual optical properties. As an example the optical index can be negative, which gives rise to spectacular effects such as negative refraction. Nevertheless their optical properties are fixed by the structuration. Quantum metamaterials [1] will overcome this limitation by providing an external control of the optical properties. Indeed by “quantum metamaterials” we mean that the nanostructures have quantum degrees of freedom that can be externally controlled. For example, it has been shown that a collection of two-level systems inserted into a waveguide give rise to a photonic crystal with a bandgap that oscillates over time at the Rabi frequency of two-level systems [2].

The candidate will be first interested in the superradiant phase transition. This effect has been studied theoretically [3] and predicts a quantum phase transition when the coupling constant between the emitters and the electromagnetic field exceeds a critical value. This phase transition is described by a model, called the Dicke model [4], obtained under the following approximations:

1) The atoms are modeled by dipoles, i.e. the field radiated by the atoms is dominated by the dipolar contribution
2) The diamagnetic term ($A^2$-term in the Hamiltonian) does not contribute to the phase transition
Nevertheless, starting from a Hamiltonian without approximation, a no-go theorem have shown that the superradiant phase transition should not be observed [5]. The proof of the no-go theorem is based on a unitary transformation. We have recently demonstrated that this unitary transformation is not correct in quantum electromagnetism [6].

The first goal of the thesis will be to clarify the results of this no-go theorem by considering a model closer to the experimental reality, i.e. a spherical cavity feeds with atoms. This model will be able to address the strong and ultra-strong coupling regimes.

Results from the first study will lay the foundation to question the theoretical methods usually used to describe the strong and ultra-strong coupling regimes. Indeed it will be questioned whether a perturbative approximation is still valid. If this is not the case, a non-perturbative theory will be considered such as lattice quantum field theory.

This is a theoretical PhD thesis related to experiments [7] taking place in the laboratory. Some objectives of the thesis are to propose experiments in order to highlight the original properties of quantum metamaterials.

References

[1] "Quantum metamaterials in the microwave and optical ranges"  

[2] Quantum metamaterials: Electromagnetic waves in a Josephson qubit line,  

[3] *Chaos and the quantum phase transition in the Dicke model*  


[5] "No-go theorem for the superradiant phase transition without dipole approximation"  

E. Rousseau and D. Felbacq, Scientific Reports 7, 11115 (2017)

[7] "Optical properties of an ensemble of G-centers in silicon"  