Surprises in the modeling of quantum metamaterials

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Fig. 1: Illustration of the behavior of a metamaterial. The metamaterial is heterogeneous, structured at a scale small compared to the wavelength of the incoming light. Nevertheless, it behaves as an homogeneous materials exhibiting unusual optical properties such as negative refraction.

Optical metamaterials are man-made materials exhibiting unusual optical properties. They behave as homogeneous materials (at least from some frequency ranges) whereas their optical properties arise from multiple scattering events i.e. from collective effects. This is illustrated in the Fig.1.

It has been suggested recently to introduce quantum emitters into metamaterials structures [1,2] in order to benefit from quantum effects to manipulate the propagation of light. As an example, quantum metamaterials could realized a photonics crystal with a band-gap that oscillates in time with the Rabi frequency of the quantum emitters[2].

Modeling quantum metamaterials starts with the choice of a hamiltonian that describes the quantum dynamics of the emitters and the electromagnetic field (modeled as a quantum object too). Although this seems as old as the quantum-optics theory itself, I will show that the choice of a hamiltonian to start with is not free of “surprises”. I will explain that a result as old as the Power-Zienau-Woolley hamiltonian[3], intensively used to model the interaction of the quantum electromagnetic-field with matter, is actually not correct [4]. Indeed, I will show that it breaks the gauge-independence of the electromagnetic field and explain the consequences at the quantum level of the breaking of the gauge-independence.

References