Strong light-matter coupling in nanostructures and quantum neural networks

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Description of many-body light-matter interactions in the regime of strong-light matter coupling is usually presented within the framework of the seminal work of Hopfield, where the concept of polariton was introduced [1]. However, this description has several drawbacks that limit its applicability. The picture of several well-defined modes of light and matter modes interacting with each other is correct as long as the shapes of eigenmodes are not substantially modified by the interaction. Plane-wave description of polariton modes is far from reality in confined systems, while dissipative effects can lead to substantial corrections. This may lead to incompatibility of theoretical descriptions and physical realizations. To date, there is no systematic way to determine a quantum model in the form of a master equation, for a given physical nanostructure, that would take into account all its physical features.

We present a systematic method for obtaining precise form of quantum master equation from first principles, under the assumption of small size of emitters (such as excitons) compared to the wavelength of light, which are strongly coupled to light in a dielectric structure. The method is based on Bogoliubov transformation [2], [3] in the conservative case and on the concept of third quantization [4] in the dissipative case. The procedure involves finding eigenmodes of Maxwell equations coupled to macroscopic polarization field in the classical limit, which can be performed by any solver of choice. We propose that this method can be used for engineering many-body nonlocal interactions between polariton modes in carefully designed structures. In one example, we design a semiconductor structure characterized by high nonlocality of interactions which leads to substantial quantum correlations between modes of emitted light (see Fig. 1). The polariton non-Hermitian eigenmodes are conveniently obtained using the extended Photonic Lasers Simulation Kit (PLaSK), which allows to treat the light-matter coupling in the strong coupling regime.

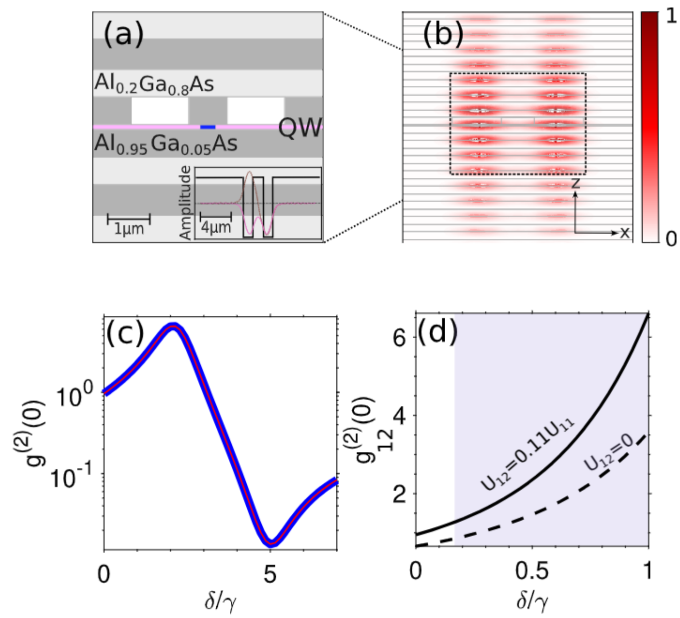

Fig. 1. (a) An example of an engineered semiconductor structure hosting exciton-polariton modes with nonlocal interactions. (b) Electric field intensity in the symmetric eigenmode. (c) second-order correlation function of emitted light in function of detuning. (d) cross-correlation showing enhancement of cross-mode correlations due to nonlocal interactions.

We demonstrate how the strong interactions resulting from exciton and photon confinement in polaritonic nanostructures can be used to realize a photonic quantum neural network. The concept relies on the idea of quantum reservoir computing [5], which is a special type of recurrent quantum neural network where recurrent node connections do not have to be tuned in the training phase. The training consists of modifications of the output layer connections, which has several important computational advantages. We show how polariton networks can be used in this configuration to realize tasks on quantum inputs, such as quantum feature detection, quantum tomography, and quantum state generation.

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