Cavity quantum electrodynamics in a solid by nonlinear spectroscopy

Milestone achievements in cavity quantum electrodynamics (cQED) were honoured recently by the award of the 2012 Nobel Prize in Physics to Serge Haroche and David J. Wineland. Their explorations of the interaction between electromagnetic radiation and matter at the most fundamental quantum level were done in microwave cavities on individual atoms. Similar cQED effects can now be observed in nanostructured semiconductor objects, which will be better suited for miniaturization and commercialization. Furthermore, employing optical transitions in semi-conductor nanostructures, one can operate at optical wavelengths compatible with glass fibre communications.

Individual modes for radiation and matter can be realized, on the one hand by confining photons in solid state resonant cavities and, on the other hand, by confining an electron and a hole in a semiconductor Quantum Dot (QD), so as to obtain an atom-like species called an exciton. When these two kinds of excitations are matched in frequency and space, the photon-exciton coupling is radically enhanced. The unison of light and matter is then achieved in the "strong-coupling" regime, where single portions of excitation are reversibly exchanged between the photons trapped in a cavity mode and a QD exciton.

The quantum and nonlinear character of the light-matter interaction is particularly pronounced at low photon occupation number. In this regime of strong coupling, described theoretically in 1963 by Jaynes and Cummings, the transfer of excitation from photon to exciton and back to photon – a kind of temporal "ping-pong" known as Rabi oscillation – shortens in discrete steps when increasing the number of optical excitation quanta. Going from one to two (or n) photons carried by the cavity mode, the period of the Rabi oscillation is reduced by a factor $\sqrt{2}$ (or $\sqrt{n}$). This non-intuitive "Jaynes-Cummings nonlinearity" can be pictured as if two tennis players (one player being a photon, the other an exciton, and a ball being an excitation) exchanged faster and faster, while putting more and more balls into the game.

Following initial studies in 2010, we have directly demonstrated Jaynes-Cummings nonlinearity in a solid, in the framework of a collaboration between Cardiff University (UK), Würzburg University (Germany) and the Institut NEEL. We have employed a tiny cylindrical pillar, as depicted in Fig. 1, precisely sculpted in a pair of interference mirrors that sandwich a layer of Quantum Dots. The pillar provides a cavity of effective volume 0.3 microns^3 that can host near-infrared photons of wavelength 930 nm for about 10 picosec (10^{-11} sec). We inject individual photons into the pillar using a pulsed laser. During its trapping time a cavity photon can be absorbed by a Quantum Dot matched to the cavity wavelength, generating an exciton in the dot. The exciton subsequently decays emitting a photon, which feeds back into the cavity mode to once again excite the dot: the coupled exciton-photon system survives several periods of these Rabi oscillations, before the photon escapes to the outside world via leakage out of the top facet of the pillar.

Until now, the photon lifetime, still rather short in state-of-the-art solid-state optical resonators of this kind, has hampered demonstration of Jaynes-Cummings nonlinearity. To tackle this issue we have applied nonlinear spectroscopy methods capable of probing phenomena occurring at the pico-second timescale. We were able to inject either just one or just two photons into the pillar and, by measuring an optical signal called Four-Wave Mixing (FWM), we observed a speed up of Rabi oscillations by $\sqrt{2}$, as predicted by the theory of Jaynes and Cummings.

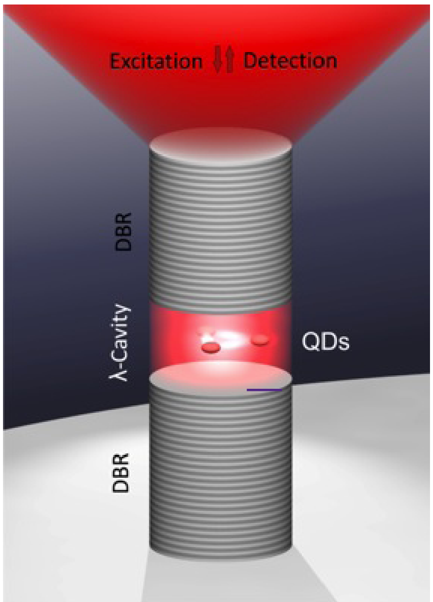

Figure 1: The semiconductor microcavity including the light coupling from the top facet. The sample, shaped into a 2 micron diameter pillar, consists of two GaAs/Aluminium Gallium Arsenide DBR's (Distributed Bragg Reflectors), and a one wavelength thickness GaAs spacer (the cavity) hosting a layer of Indium Gallium Arsenide quantum dots (QDs).

Most recently, we have used this FWM technique to probe the radiative coupling between excitons in separate QDs. This type of coupling is a central issue in many research areas, ranging from biology (where it is essential for understanding photosynthesis) to quantum information science (where the "quantum bus" technology aims at constructing long-range coupling channels between distant quantum bits). We have measured subtle dynamics of radiative coupling in a trio of spatially distant Quantum Dot excitons, having nearly identical energy, mediated via the photon mode of a pillar operating in the strong coupling regime. Here, a tentative analogy from the macroscopic world could be a tennis game, where three of the players (on one side!) are excitons, while the fourth player is a cavity mode.

Experiments are being undertaken at Institut NEEL and elsewhere to exploit such radiative coupling mechanism to "wire up" distant emitters that are embedded in waveguides or networks of photonic-crystal cavities, to enable a long-range coupling, and thus to implement "quantum bus" technology in semiconductors.

CONTACT
Jacek KASPRZAK
jacek.kasprzak@neel.cnrs.fr

FURTHER READING

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