Revealing coherence of single emitters with photonic nanostructures

Physicists usually associate coherence with macroscopic interference patterns, as observed for example in the famous experiment where light waves are passed through a double-slit. Astonishingly, interference is also generated when photons are launched one-by-one, as if they were capable of going through both slits at the same time. This can only be explained by acknowledging that individual photons go through a double-slit in a quantum superposition state. Such states, carrying microscopic coherence – that seem so bizarre and hidden to our "common sense" – are ubiquitous in the quantum realm. The example of the laser, which exploits macroscopic coherence, indicates that it would be not only exciting, but also useful to harness microscopic coherence. So how can we reveal it?

Accessing and manipulating coherence of single quantum objects – like photons, atoms, molecules, or emitters embedded in solids – is at the forefront of physics, especially at the intersection of quantum optics, condensed matter and information processing. The key to accomplish such advanced tasks is to conceive a robust interface between our clumsy detection apparatus and the object studied.

Take, for example, emitters in a solid. One can produce these at low temperature by shining light on a semiconductor and exciting a cloud of electrons and holes attracting each other. We have learnt over the last two decades to trap and isolate a single electron-hole pair within a nanoscale "Quantum Dot" (QD) inside the semiconductor. As the trapped electron-hole pair possesses a dipole moment, it strongly interacts with light and annihilates, sending out a photon approximately every nano-second. A great deal of research has been devoted to study such emission, now resulting in innovative commercial products such as quantum dot displays. Rather more at the development stage, quantum dots are becoming a leading resource for high repetition rate, single photons – a crucial asset in future quantum technologies that will exploit entanglement and indistinguishability of photons.

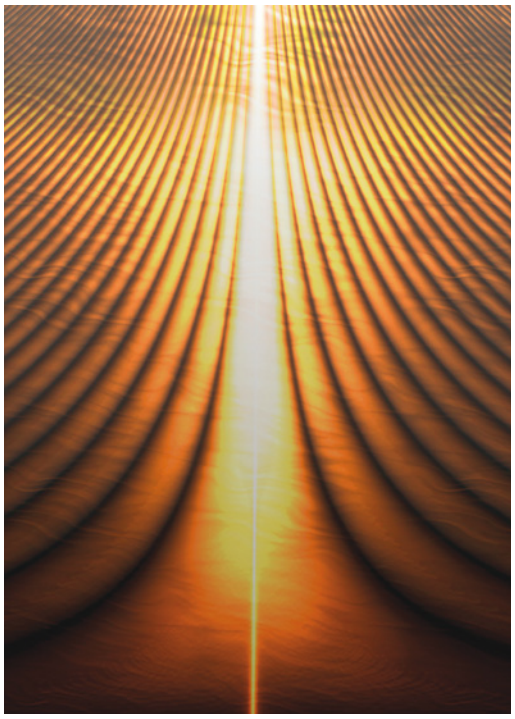

***Fig. 1**: Graphical representation of our multi-wave, coherent-manipulation scheme, as applied to an individual exciton (an electron-hole pair) confined in an Indium Arsenide quantum dot. In this colour-coded map, the horizontal axis displays the four-wave mixing spectrum of a single quantum dot. The vertical axis is the delay between a control pulse and the four-wave mixing signal. The control pulse stops the four-wave mixing transient, inducing shaping of the four-wave mixing spectrum. (Figure credit: Florence Fernandez, Institut NÉEL.)*

While observing the emission from a quantum dot has become an easy task, detecting the dot's absorption – which holds information about the coherence of the resident quantum dipole – is arduous. In our experiment, we use 100 femto-second (10^{-13} sec) laser pulses, centred at the wavelength of the expected optical absorption (which is around 1000 nanometres for our Indium Arsenide/Gallium Arsenide QDs). The pulses are so short that the uncertainty principle intervenes and they undergo spectral broadening by several nanometres. Thus, the pulses constitute an equivalent "white light" source for measurements of the quantum dot's picometre (10^{-12} m) wide absorption band. Using a microscope we focus the laser beams onto the quantum dot and observe the spectrum of the reflected light, where we look for an absorption dip.

The huge difficulty in this experiment is that the "white light" laser intensity dominates the dot's response by typically 12-15 orders of magnitude – it is as if one were trying to observe sunspots by gazing at the sun with a naked eye (which is strongly discouraged!).

Rejection of this overwhelming background is the key aspect of our technique. It is accomplished in a three-fold manner. Firstly, instead of one we use three laser pulse trains and modulate their relative phases. Thus, the resulting third-order absorption – called four-wave mixing – within the QD is also modulated, and we simply demodulate it as in an old-fashioned radio. Secondly, the signal is detected via interfering it with yet another laser beam, improving the detection sensitivity.

Finally, specially for this project, which involved eight French and European teams, our colleagues have conceived novel "nanophotonic" structures with embedded quantum dots, specifically semiconductor microcavities, photonic-waveguide antennas and microlenses. With these devices we can amplify the electromagnetic field locally around the dot to penetrate efficiently across the vacuum-dielectric boundary. This drastically decreases the "white light" background and improves the signal-collection efficiency, increasing the sensitivity for retrieving the single emitter coherence by four orders of magnitude.

This experiment then provides unprecedented insight into the dynamics and the control of the optical coherence of single emitters in solids. In ongoing research, we have introduced a spatial separation between the three beams. The beams now selectively excite a pair of emitters embedded in a photonic waveguide, to induce their non-local coupling, mediated by the microscopic coherence.

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FURTHER READING...

"Harvesting, coupling and control of single exciton coherences in photonic waveguide antennas"
Q. Mermillod, T. Jakubczyk, V. Delmonte, A. Delga, E. Peinke, J.-M. Gérard, J. Claudon and J. Kasprzak
***Physical Review Letters* 116**, 163903 (2016).

"Multi-Wave Coherent Control of a Solid State Single Emitter"
F. Fras, Q. Mermillod, G. Nogues, C. Hoarau, C. Schneider, M. Kamp, S. Höfling, W. Langbein and J. Kasprzak
***Nature Photonics* 10**, 155 (2016).

"Dynamics of excitons in individual InAs quantum dots revealed in four-wave mixing spectroscopy"
Q. Mermillod, *et al.*
***Optica* 3**, 377 (2016).