TERAHERTZ EMITTERS

Lasing from dressed dots

Can a terahertz laser be made using quantum dots? A theoretical analysis of asymmetric dressed quantum dots in a photonic crystal cavity suggests that it should be possible, but will likely require advances in fabrication technology to be realized.

Simone De Liberato

The direct generation of coherent terahertz radiation from solid-state devices is a notoriously challenging endeavour. On one side, electronics struggles with the high frequencies involved. On the other side, standard laser approaches are hindered by the lack of materials with naturally occurring terahertz dipole transitions and the problem of competing fast non-radiative relaxation processes for excited states. While terahertz quantum cascade lasers which exploit transitions between engineered sub-bands in semiconductor heterostructures are a longstanding topic of active technological development [1], their tunability and efficiency remain limited, and many efforts are exploring alternative solutions [2,3,4]. Now, another option has been brought to the table. Writing in *ACS Photonics*, Igor Yu Chestnov and coworkers [5] theoretically investigate the possibility of using dressed asymmetric quantum dots ensembles in a resonator to realise a terahertz laser.

To understand the principle of the proposed device one needs to first review the concepts of electromagnetically dressed states and strong light-matter coupling. When a quantum emitter is resonantly excited by a coherent pump, its energy levels hybridize with the electromagnetic field, giving rise to dressed light-matter states forming a series of AC-Stark split doublets. From a quantum-mechanical point of view one can describe each doublet as formed by the hybridization of two photon and emitter bare states: in one state there is an integer number of pump photons and the emitter is unexcited, while in the other one a photon has been absorbed exciting the emitter. Two consecutive doublets are thus separated by the frequency of a single pump photon, and the two levels composing each doublet are split by an amount known as Rabi frequency, proportional to the pump amplitude (Fig. 1a).

While transitions between different doublets lead to the emission of the Mollow triplet, centred at the pump frequency, transitions between two states belonging to the same doublet would lead to emission at the Rabi frequency (Fig. 1b). In solid-state systems the Rabi frequency can reach well into the terahertz range, making intra-doublet transitions an interesting candidate for the creation of integrated terahertz emitters whose frequency can naturally be tuned by modulating the pump fluency.

Still, such intra-doublet transitions are forbidden in centro-symmetric systems. This forbidden selection rule can be understood by a quantum treatment of the problem, in which dipolar transitions between them can be considered to be akin to difference-frequency-generation processes that do not conserve photon number. Consequently, such intra-doublet transitions obey the standard selection rules of $\chi^{(2)}$ nonlinearities.

In confined solid-state systems the symmetry can be broken by various means such as the application of an external static field, asymmetric confinement, or crystal asymmetry, leading to the appearance of a permanent dipole. Previous proposals have already shown that sizeable THz emission could be obtained from AC-Stark split states using asymmetric quantum wells [6], as well as nitride-based quantum dots [7] in which large strain-induced piezoelectric effect separates electron and hole wavefunctions (Fig. 2).

Now, Chestnov and co-workers [5] have further pushed forward this line of research by theoretically investigating the possibility of exploiting transitions at the Rabi frequency in asymmetric quantum dots ensembles to realise a terahertz laser. The lasing mechanism considered is an extension of the dressed state laser extensively studied in atomic physics [8]. In a dressed-state laser, population inversion between AC-Stark dressed states is reached by cleverly exploiting spontaneous emission. If the pump is slightly blue detuned, the probability of the quantum emitter being in its ground state is larger in the upper dressed state of each doublet than in the lower one. The opposite is true for the probability of the emitter being in its excited state. Spontaneous emission, which causes transitions from the excited to the ground state of the emitter, then translates into a net-excitation transfer toward the upper state of each doublet. With the right parameters this leads to a population inversion in which the upper states of the doublets have a higher population than the lower ones. Chestnov *et al.* expand the standard theory of the dressed state laser to include the effect of a permanent dipole, so that lasing transitions may be considered not between states of different doublets, as usual for atomic physics, but between two terahertz-split states of the same doublet.

Such a theory is then applied to study whether lasing can be achieved with this approach using an ensemble of asymmetric quantum dots coupled to a photonic crystal with a terahertz resonance. Optical devices relying on quantum dots ensembles have to take into account the dots' large inhomogeneous broadening, typically of the order of tens of millielectronvolts, which makes it difficult to obtain large resonant spectral densities. Chestnov and co-workers included the inhomogeneous broadening in their theoretical analysis, showing that indeed only a minute fraction of the dots, of the order of 0.1%, participate in the lasing action, thus making an extremely high dot density necessary to achieve lasing threshold. On the upside, should it be possible to achieve lasing, the gain would in fact cover a very broad frequency range, with the tunability of the laser essentially limited only by the spectral width of the terahertz resonator.

The formula and calculation for the lasing threshold, taking into account the inhomogeneous broadening of the quantum dots is an important result of this paper. The crucial parameters turn out to be the quality factor of the terahertz resonator and the effective number of quantum dots resonant with the intra-doublet transition for a given pump fluency. This is in itself dependent on the total surface density of the dots and by the width of the inhomogeneous broadening.

The critical question is of course if, once realistic parameters are plugged into such a formula, whether the lasing regime turns out to be accessible. The answer is nuanced. While the proposed scheme could be experimentally implemented, reaching the lasing threshold will be challenging, requiring technological improvements over today's state-of-the-art solutions. The authors consider a standard inhomogeneous broadening of few tens of millielectronvolts and a very large quantum dot density of $10^{13} cm^{-2}$, which can be achieved only by stacking hundreds of quantum dot layers, and still lasing turns out to require a terahertz resonator with quality factors larger than 10^{4}. Those quality factors, while already experimentally achieved [9], impose strong constraints on the device design, which also severely limit its effective tunability.

Although not likely implementable with today's off-the-shelf technology, the proposal by Chestnov and co-workers clearly highlights an interesting venue for future research. Technological advances in quantum dot fabrication could in fact pave the way for both the reduction of the inhomogeneous broadening, and an increase in the surface density. This, together with improvements in the design of broadband, ultra-high quality factor THz resonators, could turn this proposal into a groundbreaking viable device.

Moreover, the theory of asymmetric and inhomogeneously-broadened dressed state laser here developed for quantum dots, could now be applied to investigate different non-centrosymmetric systems, both molecular and solid-state, in which larger dipole densities and smaller broadenings could possibly allow to achieve terahertz lasing with less stringent parameters.

Simone De Liberato is in the Department of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK
E-mail S.De-Liberato@soton.ac.uk

[1] Williams, B.S. Nature Photon. 1, 517 (2007)
[2] Kavokin A.V. et al., Phys. Rev. Lett. 108, 197401 (2012)
[3] Liew T.C. et al., Phys. Rev. Lett. 110, 047402 (2013)
[4] Barachati, F., De Liberato, S & Kéna-Cohen, S. Phys. Rev. A 92, 033828 (2015)
[5] Yu. Chestnov I. et al., ACS Phot. 10.1021/acsphotonics.7b00575
[6] Shammah, N., Phillips, C.C. & De Liberato, S. Phys. Rev. B 89, 235309 (2014)
[7] Kibis, O.V., Slepyan, G.Y., Maksimenko S.A. & Hoffmann, A. Phys. Rev. Lett. 102, 023601 (2009)
[8] Zakrzewski, J. Lewenstein, M. & Mossberg, T.W. Phys. Rev. A 44, 7717 (1991)
[9] Campa A. et al., Optics Express 23, 3751 (2015)

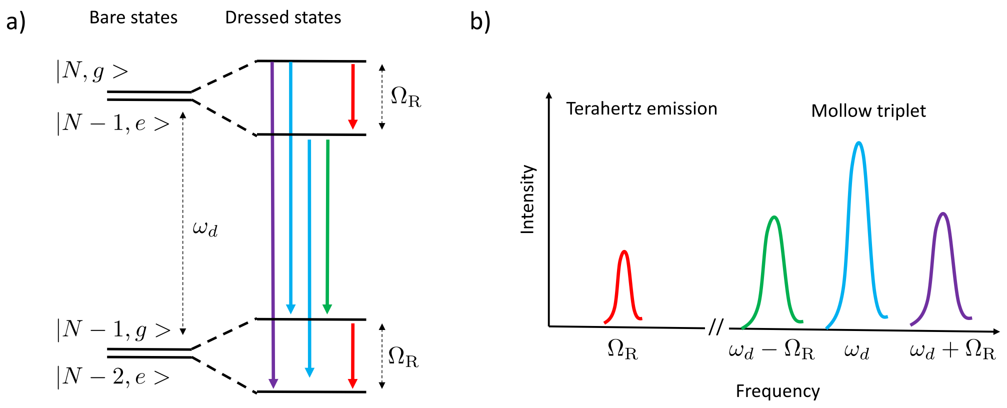

Fig 1. Concept of a laser based on asymmetric dressed quantum emitter. (a) Level scheme of a two-level quantum emitter under resonant pumping, formed of a ladder of doublets split by the Rabi frequency Ω_R and separated by the pump photon frequency ω_d. Each doublet is created by the interaction of the pump in a state with N photons and the emitter which can absorb a photon jumping from its ground (g) to its excited (e) state. Coloured arrows highlight different possible radiative transitions, with the terahertz emission indicated in red. (b) Fluorescence spectrum, showing the inter-doublet Mollow triplet and the intra-doublet terahertz emission.

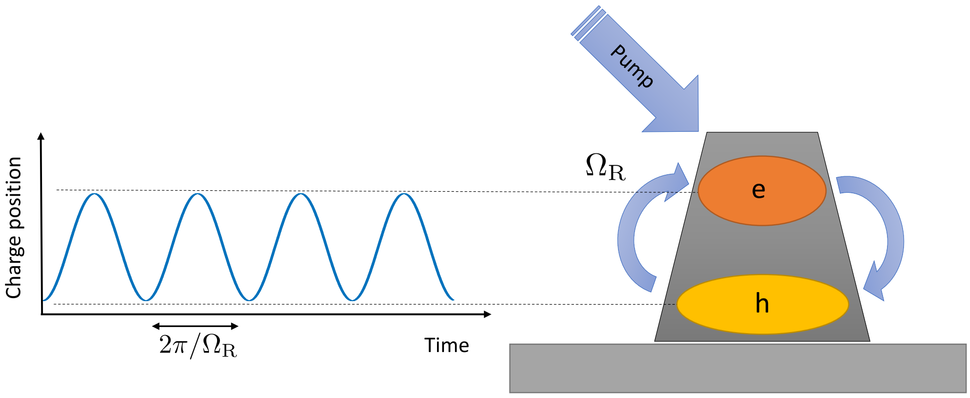

Fig 2. Oscillating dipole in an asymmetric dot. Different confining potentials for electrons and holes in a quantum dot lead to a spatial separation of their respective wavefunctions and center of mass. Under optical pumping transitions between the two states thus create a spatial charge oscillation at the Rabi frequency.