SQOD final report

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The SQOD (Solid-state Quantum Optical Devices) project aimed at integrating an experimental group (that of Prof. J.J. Finley, scientist in charge) from a theorist perspective to support experimental findings on the one hand and suggest directions on the other hand. The field was semiconductor optics; the research was conducted in Garching bei München, in Germany.

The main objectives as listed in the project were:[1]

1. Observe or evidence the Jaynes-Cummings $\pm(\sqrt{n+1}\pm\sqrt{n})$ nonlinearities.
2. Develop the theory of colored photon-counting and account quantitatively for relevant quantum correlations in the experiment.
3. Develop the theory to describe the quantum dynamics of strongly-coupled semiconductor quantum dots under incoherent pumping, taking into account the spin degree of freedom and Coulomb interaction of carriers, and match it to (or guide it with) the experiment.
4. Model theoretically and assist the experimental realization of elementary but working and usable quantum devices, such as single-photon sources and entangled-photons pair emitter.

In this final report on the two years of activities devoted to the above-mentionned points, I will discuss the achieved results in layman terms and list the academic outputs of the project in terms of publications and presentations in conferences, which are the main measure of success for a theoretical effort. In advance, I can say that the project has been largely successful. It allowed me to be ranked first in my discipline for a tenure-track position in Spain (Ramón y Cajal fellowship).

1 Completion of the declared objectives

1.1 Observe or evidence quantum nonlinearities

The quantum-nonlinear regime is difficult to achieve in semiconductors because of the large dissipation in these systems. To better understand the interplay of the coherent and incoherent dynamics, I have refined the theoretical understanding of light-matter coupling under incoherent pumping in the nonlinear regime [5], obtaining semi-analytical solutions allowing to conveniently characterize various regimes of operations for a given system. According to these results, the figures of merits of the samples then available at the host institution did not allow an explicit observation of quantum nonlinearities. This situation changed only recently with new samples under production and characterization. In the meantime, I have proposed a configuration allowing to explicitly demonstrate such nonlinearities even in strongly dissipative systems, such as those of the WSI, relying on a particular configuration, namely, coherent excitation of the quantum emitter detuned from the cavity mode and measurement of the cavity-photons statistics [15]. I have shown how strong, clear and robust (to dephasing, lifetime, etc.) resonances appear at precisely the anharmonic frequencies characteristic of this system, not in the form $\pm(\sqrt{n+1}\pm\sqrt{n})$ but in the related form of $\sqrt{n}/n$. The scheme presents a few technical difficulties for an experimental implementation, as quantum statistics is difficult to acquire and the coherent excitation of the emitter is not-standard (it is also less adapated to the sort of samples grown in Munich, so-called photonic crystal; other implementation, so-called micro-pillars grown elsewhere present a better geometry for the proposed experiment). The theory has been, however, as successful as could have been by identifying a clear manifestation of quantum nonlinearities even in systems with very high dissipations. It is expected that experiments will one day realize this scheme or a variation of it useful as quantum devices [18]. The theoretical investigations also led to a new definition of lasing in strong coupling [12] by identifying a regime where an ideal thresholdless laser with no threshold in the characteristic curve for the intensity or the statistics of the emitted light is almost realized as a function of the pumping power, modulo a deviation caused by a fundamental property of Bose particles: the indistinguishability of two photons. Apart from this interesting twist (due to quantum nonlinearities), we have motivated why the single-atom laser is the one that maximises strong-coupling rather than the one that minimises spontaneous emission of the emitter.

[1] Cf. page 19 of part B of the proposal.

1.2 Theory of colored photon-counting

One of the ambitious goals of the project was to develop a theory of frequency-filtered photon correlations. Quantum optics is mostly concerned with measuring correlations between photons, typically in their arrival time: natural light exhibits bunching (photons arrive together), lasers emit uncorrelated photons while quantum sources emit a given number of photons at a given time. While the theoretical formalism to compute such correlations is well known since the work of Glauber (that earned him the Nobel prize in 2005), experimentalists increasingly supplement the time information with the energy of the photons. In this case, however, the theory needs to be revisited at a fundamental level since frequency and time are conjugate variables. A formalism has been successfully developped in the late seventies but consisted in an extremely awkward integral formulation with an exponential complexity of computation. This made actual computations impossible but for the simplest cases. With theorist co-workers from a nearby (Physik Department in Garching) and my present (Universidad Autonóma de Madrid) institution, we have developped a formalism able to compute such time and frequency-resolved correlations for arbitrary systems and for any number of photons [16]. While all previous works since the 1970s have been limited to two-photon correlations for a single atom, we computed up to four-photon correlations for a vastly more complicated system: an atom in a cavity (the Jaynes-Cummings model). This is a tremendous progress on the state of the art related to an important and increasingly popular experimental scheme. The results now available have already identified new types of emission in cavity QED (e.g., so-called "leap-frog processes" whereby the system emits simultaneously pairs of photons by jumping over intermediate rungs of the ladder of dressed states, resulting in strongly correlated emission at energies specified by our theory). The difficulty of the task made this result arrive too late to be implemented experimentally by the host, at least during the project itself, but setting up such a theory that is both efficient and practical is a complete and likely to be resounding success of this project.

1.3 Cavity QED theory and experiments

One chief goal of the project was to interact strongly with experimentalists. The project planned to favour cavity QED. The situation with samples, however, has not been ideal at the same time as the leader of such experiments (Arne Laucht) was moving to Sydney. As a result, few exciting results emerged from the lab with the available samples while better ones started to arrive when the project was already drawing near its end. Results have remained purely theoretical, with investigations of coupling with more than oen emitter [2] or of the effect of Coulomb interaction as well as study of alternative schemes of excitation, such as pump-and-probe experiments [14].

A better collaboration with the experiments was obtained with the work of N. Hauke *et al.* [8], who studied the emission of Germanium islands in photonic crystals, using the latter to enhance the emission efficiency (by the Purcell effect that accelerates the emission rate and collection and redirection of the photons by the cavity). They observed an a-priori unexpected result that better cavities (higher Q factor) resulted in smaller intensity of emission; exactly the opposite trend as the one motivating their experiment. I have shown how an interesting regime of cavity QED precisely results in the observed phenomenology. However, the range of parameters clearly did not allow this regime to be reached and it was left for a more mundane interpretation (through absorption) to explain the result. Therefore, although the collaboration has been successful in understanding the observation itself, it turned out to be of limited intrinsic interest.

The best results in connection with experimental observations have been obtained in another type of experiments, with no cavity. In the coherent excitation of a quantum dot (resp. of a quantum dot molecule), V. Jovanov (resp. K. Müller) observed an unexpected sharp and intense luminescence line, that was initially supposed to be a coherent feature arising from an elastic scattering. It took us a large chunk of the project, combining theory and experimental efforts, to identify its true nature: a Fluctuation Induced Luminescence (FIL) due—not to a coherent response of the system—but to fluctuations. The difficulty in such an identification came from the nature of such fluctuations, namely, scalefree fluctuations, characterized by arbitrarily large deviations from the median that, combined with the large absorption of their system, realize so-called Black Swan events: extremely rare occurences that have a very strong impact (a new luminescence line in their case). Beside reporting a new and peculiar type of luminescence, the observation could have applications in the sampling of fat-tail distributions, a problem of notorious difficulty. This work is currently under review for publication in a prestigious journal (Nanoletters) [17].

1.4 Design of working and usable quantum devices

The project concluded with two proposals for quantum devices, both photon sources, one as a two-photon emitter [6, 13], the other as a more versatile N-photon emitter, N any integer (starting from 1) [18] (this latter work is not yet submitted). The former relies on a bi-exciton in a microcavity, with twice the cavity-photon energy matching the bi-exciton energy but the single cavity-photon being detuned from the single-exciton thanks to the bi-exciton binding energy. The latter is a variation of the scheme to evidence Jaynes–Cummings nonlinearities [15] in a case of large detuning and weak-coupling of the bottom rungs of the ladder of dressed states. Through the theoretical analysis of such cavity QED dynamics with dissipation, I came to the realization that an efficient quantum emission can be obtained through a strong Purcell enhancement of the quantum dynamics, that is, one first has to isolate in a pure Hamiltonian picture a process with a large quantum amplitude, and place it in a strongly dissipative environment. This has several advantages: first is that Hamiltonian dynamics is easier to deal with, theoretically. Second is that in this worldview, dissipation suddenly becomes an asset whereas, when we started, it was regarded as a disadvantage spoiling the quantum features. What happens is that the system does not, indeed, develop a quantum dynamics of its own. It directly outputs quantum states to the outside world. But this is precisely what one seeks in many applications. The N-photon emitter relies on a system where I have shown one can, in a fully Hamiltonian picture, creates quantum states of the type $\frac{1}{\sqrt{2}}(|0,\mathrm{g}\rangle \pm |N,\mathrm{e}\rangle)$, i.e., quantum superposition of N photons and the excited-state of the emitter with no-photon and the groudn state of the emitter. These are extremely peculiar states (only the case $N = 1$ is familiar, namely, the so-called "polaritons") that can be locked in the system by a driving laser at particular energies in a detuned system which the theory provides. When the Q factor is now reduced from infinity (lossless cavity) to a number small enough, the system does not Rabi-oscillate but emits bursts of N photons. The experimental realization of such a behaviour, even at the proof-of-principle level, would represent a tremendous advance both in the fundamental physics of light-matter interactions and for applications.

2 Conclusions, future works and outcomes expected from this project

In conclusions, the project has been very successful from the theory point of view, which was its main angle, fulfilling completely its objectives in particular on the difficult question of the time- and frequency-resolved photon correlations, where it surpassed expectations as only two-photon correlations were discussed in the proposal and the work turned out to be general in the number of photons.

The project has also been mainly successful in proposing experiments as it resulted in various schemes to bring to the laboratory, including two proposal for quantum devices. Their experimental confirmation or infirmation is only a question of time.

A similar qualification can be attributed for the support of existing experiments as it provided theoretical interpretations of the results for the two works with which I have been involved, culminating with an interesting and novel effect (FIL) which, being of a completely unexpected nature, will require time and consideration from other groups to assess the level of interest it ultimately presents.

3 Publications

The project resulted in a total of 18 manuscripts, 14 published, 2 in press, 1 under review and 1 still under preparation at the time of writing. This includes 2 papers in Phys. Rev. Lett., 4 in high impact-factor (> 3) journals (Phys. Rev. or New J. Phys.), 2 chapters in books and a revised and extended edition of the book "Microcavities" (Oxford University Press). The complete list appears below.

3.1 Published papers

[1] Mollow triplet under incoherent pumping. E. del Valle and F. P. Laussy. Phys. Rev. Lett. 105, 233601 (2010).

[2] Luminescence spectra of quantum dots in microcavities. III. multiple quantum dots. F. Laussy, A. Laucht, E. del Valle, J. J. Finley and J. M. Villas-Bôas. Phys. Rev. B 84, 195313 (2011).

[3] Phase-space of strong coupling of two bosonic modes. F. P. Laussy and E. del Valle. AIP Conf. Proc. 1399, 585 (2011).

[4] Microcavities, A. Kavokin, J. J. Baumberg, G. Malpuech and F. P. Laussy, Oxford University Press, revised and extended edition (2011).

[5] Regimes of strong light-matter coupling under incoherent excitation. E. del Valle and F. P. Laussy. Phys. Rev. A 84, 043816 (2011).

[6] Generation of a two-photon state from a quantum dot in a microcavity. E. del Valle, A. Gonzalez-Tudela, E. Cancellieri, F. P. Laussy and C. Tejedor. New J. Phys. 13, 113014 (2011).

[7] Dephasing of strong coupling in the non-linear regime. A. Gonzalez-Tudela, E. del Valle, E. Cancellieri, C. Tejedor, D. Sanvitto and F. P. Laussy. AIP Conf. Proc. 1399, 975 (2011).

[8] Correlation between emission intensity of self-assembled germanium islands and quality factor of silicon photonic crystal nanocavities. N. Hauke, S. Lichtmannecker, T. Zabel, F. P. Laussy, A. Laucht, M. Kaniber, D. Bougeard, G. Abstreiter, J. J. Finley and Y. Arakawa. Phys. Rev. B 84, 085320 (2011).

[9] Quantum Dynamics of Polariton Condensates, F. Laussy, Chap. 1 in Exciton-polaritons in microcavities, vol. 172, p.1-42, Springer Berlin Heidelberg (2012).

[10] Luminescence spectra of quantum dots in microcavities, F. P. Laussy, E. del Valle, A. Laucht, A. Gonzalez-Tudela, M. Kaniber, J. J. Finley and C. Tejedor, Chap. 9 in Quantum optics with semiconductor nanostructures, Woodhead Publishing, (2012).

[11] Superconductivity with excitons and polaritons: review and extension. F. P. Laussy, T. Taylor, I. A. Shelykh and A. V. Kavokin. J. Nanophoton. 6, 064502 (2012).

[12] Universal signatures of lasing in the strong coupling regime. F. Laussy, E. del Valle and J. Finley. Proc. SPIE 8255, 82551G (2012)

[13] Generation of a two-photon state from a quantum dot in a microcavity under incoherent and coherent continuous excitation. E. del Valle, A. Gonzalez-Tudela and F. P. Laussy. Proc. SPIE 8255, 825505 (2012)

[14] Quantum dynamics of damped and driven anharmonic oscillators. M. Schrapp, E. del Valle, J. J. Finley and F. P. Laussy. Phys. Stat. Sol. C 9, 1296 (2012).

3.2 Papers in press

[15] Climbing the Jaynes-Cummings ladder by photon counting, F. P. Laussy, E. del Valle, M. Schrapp, A. Laucht and J. J. Finley, arXiv:1104.3564 to appear in the Journal of Nanophotonics.

[16] Theory of frequency-filtered and time-resolved N-photon correlations, Elena del Valle, Alejandro Gonzalez-Tudela, Fabrice P. Laussy, Carlos Tejedor, Michael J. Hartmann, arXiv:1203.6016 to appear in Phys. Rev. Lett.

3.3 Papers under review

[17] Fluctuation induced luminescence sidebands in the emission spectra of resonantly driven quantum dots, F. P. Laussy, V. Jovanov, E. del Valle, A. Bechtold, S. Kapfinger, K. Müller, S. Koch, A. Laucht, T. Eissfeller, M. Bichler, G. Abstreiter, J. J. Finley arXiv:1207.6952

3.4 Papers under preparation

[18] A *N*-photon gun based on a quantum-dot in a microcavity, F.P. Laussy, E. del Valle, S. Lichtmannecker, A. Büse and J. J. Finley.

4 Talks

4.1 Invited Talks in conferences

1. MIFP March meeting 2011, 18 March (2011).
2. MIFP March meeting 2012, 23 March (2012).
3. XXXV Encontro Nacional de Física da Matéria Condensada (ENFMC 2012) in Águas de Lindóia, May 2012. (A lecture and a talk, both Invited).

4.2 Invited Seminars

1. Arbeitsgruppe Theoretische Festkörperphysik seminar of Universität Bremen, Bremen (Germany) 9 November (2010).
2. SFB 787 Halbleiter-Nanophotonik seminar of the Technische Universität Berlin, Berlin (Germany) December (2010).

4.3 Contributed Talks in conferences

1. Contributed Talks 18th International Symposium NANOSTRUCTURES: Physics and Technology, Saint Petersburg (Russia), June 2010.
2. ICPS30, Seoul (Korea), July 2010.
3. SOLID workshop in Garching (Germany), October 2010.
4. PLMCN11 conference in Berlin (Germany), April 2011.
5. LASE SPIE Photonics West in San Francisco (United States), January 2012.
6. DPG Spring Meeting in Stuttgart (Germany) in the Q9: Quanteneffekte: Interferenz und Korrelationen session, March 2012.
7. PLMCN12 conference in Hangzhou (China) June 2012.
8. ICPS 2012 in Zurich (Switzerland), August 2012.

4.4 Posters

1. PLMCN11 conference in Berlin (Germany), April 2011.
2. NanoTUM workshop in Garching (Germany), 1st June 2011.
3. ICPS12 in Zurich (Switzerland), August 2012.