IOP Publishing New J. Phys. 17 (2015) 010201 doi:10.1088/1367-2630/17/1/010201

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

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EDITORIAL

Focus on cavity and circuit quantum electrodynamics in solids

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Abstract

We introduce the works collected in the focus issue on *Cavity and circuit quantum quantum electrodynamics in solids.*

Classically, we visualize light as an electromagnetic wave that interacts with matter through processes such as absorption, reflection and transmission, through concepts such as the refractive index via material polarizability. However, optical energy is carried by photons and the enhanced light–matter interactions arising from resonant recirculation of light in a high-finesse cavity can result in coherent (reversible) interactions at the quantum limit of a single photon and single emitter. This is the regime of strong-coupling cavity quantum electrodynamics (CQED)[11]—a regime that facilitates the preparation, manipulation and investigation of quantum states of light and matter. For the prototype system of ultra-cold trapped atoms or ions trapped in high finesse resonators, experimental advances over the past 35 years have pushed CQED to the forefront of quantum physics. This status was recognized in 2012 by the award of the Nobel prize in physics to Serge Haroche and David Wineland for '*ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems*'.

Beyond the fundamental physics that can be implemented and explored in setups of unwieldy complexity, there is also the urge to derive technological applications from these effects. Whenever applications are involved, the solid state becomes a must, placing the field as one of the main contenders in the quest for a working quantum technology. Today, strong coupling CQED is indeed routinely applied to a plethora of solid-state systems such as quantum dots in dielectric and metallic nanocavities and, most recently, circuit quantum electrodynamics (cQED). A common trend to all the variations of this extremely multidisciplinary field is to bring the physics on-chip to provide devices. At the time of writing, these attempts are still in their infancy, and basic operations such as coupling a quantum emitter to a cavity in various geometries and allowing for a different way to manipulate and observe them in their most fundamental aspects still provide the bulk of the research effort. Whenever an implementation is successful, the problem then turns into that of its scalability. The gains promised by the solid state in this respect, but also in terms of practicality, integration and cost, also come with a serious challenge for quantum applications: the quantum dynamics becomes inherently coupled to a complex environment. This leads to variations from the ideal system, at least in the form of increased dephasing and decoherence, but at a deeper level, also through new types altogether of effects specifics to the solid state. Clearly, there is still a long way before the quantum age of our technology fully turns the page of today's electronics. This, however, only makes the topic more fascinating and pioneering. As should be from any healthy scientific discipline, new physics is continuously being discovered and investigated to put together a field of its own. Solid state CQED and cQED are at the meeting point of quantum optics, condensed matter and solid state physics and

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[11] Note that the acronym 'CQED' is used for 'cavity quantum electrodynamics' while 'cQED' is used for 'circuit quantum electrodynamics'.

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this provides endless opportunities for theorists to combine models, propose new effects or discover new laws of nature.

This ‘focus on’ series collates recent advances in the field of solid-state CQED exploring all these aspects, through 22 original contributions from some of the leaders of the field [1–22]. While the survey of this thriving field is nowhere like complete, there is a good representation of what is shaping the state of the art, involving both theory (about 2/3 of the contributions) and experiments, and covering several topics, overviewed below, in various platforms, mainly related to quantum dots in a microcavity [4, 5, 7–9, 14, 15, 18, 19, 22] and cQED [2, 10–12, 17, 20, 21], but also covering variations on these themes, such as nonlinear photonic crystals [3] and chain or arrays of CQED components [6, 13], as well as other physical platforms, such as nitrogen-vacancy centers in diamond [1] or polariton condensates [16]. The themes explored are now quickly summarized.

Faraon *et al* [1] open the ‘focus on’ series with the successful realization of a solid state quantum appliance. They make one step forward in the implementation of a quantum network in diamond-photonic by demonstrating one of its constituting element in the form of a waveguide coupled to a micro-ring embedding a single NV center. This elementary device, connected to the external world through two grating couplers, demonstrates an efficient coupling between the waveguide and the quantum emitter, now in wait for more NV centers to be coupled and controlled. Their system is shown on the cover of this ‘focus on’ series.

Hoi *et al* [2] bring us to cQED, with superconducting qubits in a microwave resonator. They observe strong-coupling effects from a transmon qubit placed in an open transmission line and illustrate two quantum effects that can power devices: a photon-router that can send single photons in one or any other channels depending on an external pulse, and a photon-number filter that turns a classical (coherent) input field into a single-photon reflected field and a superbunched transmitted one. Strong interactions between the emitter and the open field as well as interferences between the dipole radiation and a weak field exciting show that CQED effect can thus be realized without a cavity!

Ferretti *et al* [3] discuss the popular trend of generating strong quantum features with weakly nonlinear and passive materials, substituting nonlinearities from an active material by destructive quantum interferences, resulting in the generation of single-photon sources. They propose two resonators coupled by tunneling and with a weak Kerr nonlinearity. One of them only is driven coherently and also provides the output. Numerical simulations of a master equation describing this configuration explore the parameter space. The conditions to optimize antibunching are found to be those with unbalanced losses.

Madsen and Lodahl [4] tackle the problem of a quantitative description of the coupling of a quantum dot in a microcavity (both a micro-pillar and a photonic crystal), presenting joint experimental data (in both the spectral and temporal domains) and their theory fit with a master equation. They point at the usually neglected interference term between the cavity and QD electric fields. They find that while the temporal dynamics is well reproduced by a phenomenological model of light–matter coupling, the spectral shape presents disagreements between the theory and experiment.

Bajcsy *et al* [5] bring back the photon blockade effect to its original configuration, namely, with a four-level atom in a cavity. In their theoretical analysis, they confirm by numerical simulation, and support on physical grounds, that a four-level atom provides a stronger blockade than its two-level counterpart. The physical picture is motivated by the transmission for one and two photons in these two cases, with an added blockade mechanism in the case of a four-level atom that also mismatches the frequencies of transmission.

Liew and Savona [6] extend the theme of quantum interferences substituting for strong nonlinearities in the quest of quantum states in the solid state, to the case of multiple cavities. They show, based on a wave-function Monte Carlo approach (backed-up by a master equation for the smaller system), how multipartite entanglement can be created in arrays of weakly interacting and dissipative cavities. Their analysis also highlights the sensibility of continuous variable entanglement on the system’s configuration and parameters, such as the geometry of coupling, excitation and even the relative phase of the exciting lasers.

Poddubny *et al* [7] show how solid-state effects bear on the luminescence of strong-coupling between one or many quantum dots and a microcavity. They specifically address exciton–exciton interactions in large dots and exciton interactions with the reservoir. They find that while the phenomenology is fairly well maintained, such as anticrossing as a manifestation of strong-coupling, important distortions as compared to the linear regime result from interactions of the carriers between themselves or with their environment, with shift, broadening and skewing of the lineshapes, conveniently described in a semi-classical formalism of nonlinear oscillators, easily adjusted to more complex configurations.

del Valle [8] gives a picture of CQED where the cavity acts as a frequency filter of the dynamics of the emitter. In this way, she gives a comprehensive account of the emission from a bare two-level system, its filtering by one or multiple interference filters, its embedding in a cavity and, finally, the combination of filters and cavities. So-called ‘leapfrog processes’, whereby the system undergoes a transition from one state to another by direct two-photon emission (jumping over an intermediate state) are thus identified as the source of strongly-correlated quantum emission. It is shown how, by a process akin to distillation aimed at singling out these processes, one can thus enhance single-photon, two-photon and entangled photon-pair emitters.

Hopfmann *et al* [9] study lasing in the limit of a few optical emitters; in their case, about forty quantum dots in a micropillar cavity. These devices are praised for their low threshold and quantum properties when reaching the micro-lasing configuration of lasing in strong-coupling. While the quantum regime is not yet within reach, the figures of merit reported here are getting close and implement a further control in the form of a controllable feedback. A beam splitter is demonstrated to provide a polarization self-feedback that strongly affects the lasing operation, stabilizing or disrupting coherence and producing revival peaks in the autocorrelation photon statistics.

Schmidt *et al* [10] consider the coupling to a microwave resonator of Majorana bound states in the Kitaev model for a nanowire. The prediction that these exotic particles with non-Abelian statistics could be realized in semiconductor nanowires opened the way to take advantage of their topological protection from decoherence for quantum information processing in the solid state. The authors present here the photon–Majorana coupling theory in both a semi-classical and fully quantized way and show how Rabi oscillations between Majorana fermions adjacent to the topologically trivial region can be switched on and off by the cavity field, allowing to implement a qubit rotation.

Jin *et al* [11] consider a hybrid platform with a semiconductor double quantum dot coupled to a superconducting transmission line. Focusing on the micro-lasing regime, they compute with a master equation approach the combined cavity population and transport properties of this system, in two limits of the interdot Coulomb interaction. They find marked features in the current noise spectrum with sub-Poissonian statistics in the lasing state and super-Poissonian statistics before that, a trend also echoed by the cavity field. Weaker interdot coupling is found to provide larger populations and values of the Fano factor.

Peropadre *et al* [12] provide the microscopic derivation for the Hamiltonian describing the interaction between a propagating field and a quantum emitter in one or multiple open transmission lines. That is to say, they consider a continuum of modes rather than a discrete number of isolated ones. They apply their formalism to study the scattering of a propagating coherent field on a transmon, itself described respectively as a two or three-level system. In the former case, there is full-reflection of a weakly incident field while the latter case can display the Autler–Townes effect.

Viehmann *et al* [13] show how to implement a fundamental quantum model—the transverse Ising chain—with a chain of cQED elements (Cooper pair boxes or transmons), coupled to two resonators. In this focus paper they specifically address the effect of disorder, and show that its impact on both the observables and the effects of interest, such as the power spectrum of the resonator or the quenching dynamics, can be tolerated. This makes cQED a platform of choice to experimentally realize the many-body quantum models that support the theories of quantum phase transitions, quantum critically and other non-equilibrium quantum dynamics.

Florian *et al* [14] describe the effect of background emitters in the lasing of a single quantum dot in a microcavity. The semiconductor realization of CQED comes with a so-called cavity feeding mechanism, whereby photons are injected in the system through several factors, of which phonon-assisted processes are singled out here. The authors derive a master equation in the Lindblad form from a microscopic Hamilonian, leading to a quantum-optical type of description but with self-consistently varying system parameters. This provides a more realistic description of solid-state effects such as reflecting the coherent properties of the feeding mechanism when it originates from a gain medium.

Kaer *et al* [15] compute the indinstinguishability of photons emitted by a single quantum dot in a microcavity, both in a quantum-optical formalism in the Lindblad form describing the Markovian case and in a non-Markovian microscopic approach that includes phonons at the same level as the electron–photon system. They find that while the long-time Markovian limit is a good approximation in many experiments, it could fail dramatically to describe indistinguishably, for which both models differ qualitatively. Based on their theory, the authors propose an optimum geometry and configuration of a quantum dot in a micropillar system to realize an efficient solid state single photon source.

Kim *et al* [16] address the physics of Dirac particles in a triangular lattice of exciton-polaritons in a 2D microcavity. They propose the direct observation of the particle dispersion as the most direct evidence for the massless fermions, a measurement for which polaritons are particularly suited by direct angle-resolved spectroscopy. Condensates of polaritons in p orbitals at the Dirac points are characterized through intensity, energy and linewidth in both reciprocal and real spaces. The figures of merit, in particular the too-short polariton lifetime, still make a compelling observation elusive, but all measurements are consistent with the theory and the unique advantages of polaritons to investigate exotic condensed matter phases are clearly demonstrated.

Schwarz *et al* [17] enhance a type of superconducting qubit, namely the flux qubit which, despite being problematic in fabrication and fragile against decoherence, comes with strong advantages of its own, such as strong anharmonicity and good coupling to the resonator. To overcome its weaknesses, the authors implement a design for the flux qubit whereby one of the Josephson junctions that define its standard architecture is upgraded to a SQUID, making it gap tunable. A comprehensive characterization is made by spectroscopy, with excellent agreement to a Hamiltonian model for the qubit, showing the great level of control and accuracy provided by cQED platforms.

Miguel-Sánchez *et al* [18] present a novel approach in semiconductor CQED by mounting a fiber optic as one end of the microcavity, allowing for unpaired flexibility and control in these systems, starting with the possibility to optimize jointly the spectral and spatial alignment between the dot and the now tunable and positionable cavity, which is one of the central fabrication problems. The system can be both excited and observed through the same fiber (for photoluminescence) or collected at the bottom of the sample (for transmission). Both techniques are demonstrated with a dot at the onset of strong-coupling, making future improved versions of this setup promising candidates to evidence quantum features in the deeper strong coupling.

Kasprzak *et al* [19] climb the Jaynes–Cummings ladder in the quantum dot-microcavity architecture by pump probe experiments. Semiconductor architectures suffer considerably more from decoherence and dissipation than, e.g., cQED and manifestations from higher rungs are therefore difficult. The authors show how four-wave mixing and post-selection measurements give access to the lower or higher manifolds of the Jaynes–Cummings model depending on the sign of the temporal delay between pump and probe. This allows them to evidence the characteristic anharmonic response of the quantum regime, otherwise unreachable by incoherent excitation despite a clear vacuum Rabi splitting. Increasing power, they also demonstrate the fully quantized CQED Mollow triplet, realized in the quantum-to-classical transition.

Pedernales *et al* [20] show how to implement a quantum simulator in cQED, here the 1D Dirac equation simulated by the Jaynes–Cumming model with three driving fields. The Dirac wavefunction is encoded in the joint cavity-emitter wavefunction allowing them to prepare various states with spinor components attached to the qubit levels and position/momentum to the cavity quadratures. For instance, normal Schrödinger diffusion of a Gaussian wavepacket is read in the simulator as a coherent state evolving into a squeezed one. Relativistic effects bring the resonator field into complex states with negative Wigner functions. Various masses recover various limits of wavepackets propagation and simulate two famous effects: the Zitterbewegung (oscillatory motion due to spinor admixtures) and Klein paradox (tunneling in infinite barriers).

DiVincenzo and Solgun [21] propose a scheme in cQED to measure directly, i.e., without a quantum gate, the parity of a set of qubits. Relying on quantum nondemolition (dispersive regime of the Jaynes–Cummings model) and quantum erasing, they present two protocols for three and four qubits, respectively, that can be scaled up. In the former case, two cavities of slightly different frequencies coupled to the qubits encode their parity in a phase shift of a scattering probe. In the latter case, the scheme is similar but requires three cavities, also with slight resonance imbalance. A 3D geometry is discussed to accommodate for the multiple resonances needed and meet the constraints imposed on the protocols, in particular equal coupling of all qubits to the cavities.

Carmele *et al* [22], in the closing contribution, illustrate how the coupling to an environment, usually regarded as an adverse component of the solid state realization, can on the other hand provide more interesting quantum effects. Namely, they show how the celebrated Cummings collapses, and how revivals of the emitter population, caused by the anharmonic frequencies in the light–matter quantum coupling, can be stabilized by a phonon bath. The non-Markovian dephasing it causes leads to some damping of the revival but also to a stabilization allowing multiple and well-defined revivals even at low photon numbers, unlike the atomic case.

Overall, we hope that this ‘focus on’ series will have succeeded in conveying the prosperous and growing activity that drives solid state CQED. Much effort is still devoted to designing, engineering and enhancing the basic physical objects [1, 17, 18] to attain the extremely demanding figures of merit at the degree required for applications. When this falls short of the required standard, tremendous benefits can still be found for classical applications, with unfading classics such as the physics of lasers [9, 11, 14] constantly being improved and brought to the edge. Nevertheless, a genuine nonlinear quantum regime has been experimentally demonstrated in all the platforms, including the noisiest one of semiconductors [19]. In platforms with better figures of merit, actual devices performing basic but nontrivial quantum operations are already a reality [2] and proposals abound as for their applications [5, 10, 13, 21] in a greatly multidisciplinary context, e.g., to explore the Dirac equation [16, 20]. Concepts from CQED have been applied to optimize quantum properties by distillation with frequency filtering [8]. The peculiarities of the solid state have been emphasized [4, 7], sometimes requiring dedicated formalisms breaking with the textbook case of atomic optics [15] but, excitingly, offering opportunities rather than hindrance [15, 22]. Finally, it has been discussed how, more often than not, CQED effects take place without a cavity [2, 8] or on the contrary with cavities only [3, 6]. This illustrates that the paradigm of cavity QED with a resonator enclosing a quantum emitter is just one specific implementation of a wider theme, which is that of light–matter interaction at its quantum limit.

References

[1] Faraon A, Santori C, Huang Z, Fu K M C, Acosta V M, Fattal D and Beausoleil R G 2013 *New J. Phys.* **15** 025010

[2] Hoi I, Wilson C M, Johansson G, Lindkvist J, Peropadre B, Palomaki T and Delsing P 2013 *New J. Phys.* **15** 025011

[3] Ferretti S, Savona V and Gerace D 2013 *New J. Phys.* **15** 025012

[4] Madsen K and Lodahl P 2013 *New J. Phys.* **15** 025013

[5] Bajcsy M, Majumdar A, Rundquist A and Vučković J 2013 *New J. Phys.* **15** 025014

[6] Liew T and Savona V 2013 *New J. Phys.* **15** 025015

[7] Poddubny A N, Glazov M M and Averkiev N S 2013 *New J. Phys.* **15** 025016

[8] del Valle E 2013 *New J. Phys.* **15** 025019

[9] Hopfmann C, Albert F, Schneider C, Höfling S, Kamp M, Forchel A, Kanter I and Reitzenstein S 2013 *New J. Phys.* **15** 025030

[10] Schmidt T, Nunnenkamp A and Bruder C 2013 *New J. Phys.* **15** 025043

[11] Jin J, Marthaler M, Jin P, Golubev D and Schön G 2013 *New J. Phys.* **15** 025044

[12] Peropadre B, Lindkvist J, Hoi I, Wilson C M, adn P Delsing J G R and Johansson G 2013 *New J. Phys.* **15** 035009

[13] Viehmann O, Delft J and Marquardt F 2013 *New J. Phys.* **15** 035013

[14] Florian M, Gartner P, Gies C and Jahnke F 2013 *New J. Phys.* **15** 035019

[15] Kaer P, Gregersen N and Mork J 2013 *New J. Phys.* **15** 035027

[16] Kim N Y, Kusudo K, Löffler A, Höfling S, Forchel A and Yamamoto Y 2013 *New J. Phys.* **15** 035032

[17] Schwarz M J, Goetz J, Jiang Z, Niemczyk T, Deppe F, Marx A and Gross R 2013 *New J. Phys.* **15** 045001

[18] Miguel-Sánchez J, Reinhard A, Togan E, Volz T, Imamoglu A, Besga B, Reichel J and Estve J 2013 *New J. Phys.* **15** 045002

[19] Kasprzak J, Sivalertporn K, Albert F, Schneider C, Höfling S, Kamp M, Forchel A, Reitzenstein S, Muljarov E A and Langbein W 2013 *New J. Phys.* **15** 045013

[20] Pedernales J S, Di Candia R, Ballester D and Solano E 2013 *New J. Phys.* **15** 055008

[21] DiVincenzo D P and Solgun F 2013 *New J. Phys.* **15** 075001

[22] Carmele A, Knorr A and Milde F 2013 *New J. Phys.* **15** 105024