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Quantum microwaves / Micro-ondes quantiques

Foreword

The microwave domain of the electromagnetic spectrum, compared to the visible optics domain, may initially appear as a bad choice for exploring the quantum properties of electromagnetic fields. A microwave photon of a few GHz indeed corresponds to only of a few μeV, which is more than three orders of magnitude below the thermal energy $k_B T$ at room temperature. In order to observe quantum properties, microwave modes thus need to be cooled down below 100 mK, and conventional room-temperature instruments are ill equipped to detect signals at the single-photon level. In addition, the wavelength of microwaves that sets the typical length of a resonator to several millimeters first appears too large to allow one to observe any quantum phenomenon.

However, as it was realized in the last decades, the low energy of microwave photons comes as an asset as it is compatible with conventional superconductors, so that the microwave fields can be confined into small volumes for very long times. This contrasts with the dielectric confinement, which has to be used at higher frequencies such as for visible photons with energies of a few eV. These small mode volume and long coherence time allow one to reach a regime where an energy quantum can be exchanged coherently between a single microwave mode and an individual quantum object. This is the so-called cavity or circuit quantum electrodynamics (respectively CQED or c-QED) regime, which is harder to reach in any other domain of the electromagnetic spectrum.

1. The rise of quantum microwaves

The manipulation of microwave fields using quantum objects has been used for a long time, for instance with the realization of the maser in 1953 by Townes and coworkers, leading to the 1964 Nobel Prize in Physics awarded to Townes, Basov and Prokhorov. However, the advent of quantum microwaves can be dated back to the end of the 1980s, when *single* quantum objects were successfully coupled with microwave modes and led to the generation of non-classical microwave signals. Two of them, Rydberg atoms and Josephson junctions, now routinely implement C(c-)QED systems.

- Circular Rydberg atoms are alkali atoms in which one electron is in a highly excited orbital. By increasing the principal quantum number, the diameter of the electron orbit increases (up to a tenth of a micron), so that the dipole moment increases, leading to larger couplings with electromagnetic modes. At a principal quantum number of about 50, the transitions between neighboring principal quantum numbers are in the microwave regime and the atom couples with the microwave field. Arguably, the whole field of quantum microwaves started with the realization of the micromaser in 1985 [1], which saw the first coherent exchange of excitation between atom and microwave mode. A review of the field can be found in the 2012 Nobel lecture of Serge Haroche [2] and a recent experiment exploring Quantum Zeno Dynamics is detailed in this dossier (*see chapter by Gleyzes and Raimond*).
- Josephson junctions are tunnel junctions between two superconductors. They behave as lossless inductors whose inductance depends nonlinearly on current. Coupling this nonlinear element with a microwave mode, Yurke and coworkers managed in 1988 to realize quantum squeezing of a microwave mode for the first time [3]. Another important step in the development of quantum microwaves with Josephson junctions came from the direct observation of the various microwave transitions between energy levels of a Josephson junction embedded in a superconducting resonator [4] in 1985. The actual strong coupling (coupling rate larger than decoherence rate) of these levels with a microwave mode in order to prepare it in a non-classical quantum state was first realized in 2004 with the transmon qubit [5]. Such Josephson junction qubits can be coupled even more strongly with microwave modes than Rydberg atoms because they exhibit even larger dipole moments and, as they naturally come with leads, can even be hooked up directly to the host resonator. A review of the field can be found in Ref. [6].

These two architectures have evolved relatively independently since the 1980s with the Rydberg atoms in cavities offering longer coherence times and almost perfectly quantum non-demolition measurement of the field state, while the

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Josephson circuits offer an almost unlimited design flexibility. Recently, these two architectures are converging, with Rydberg atoms even being coupled with superconducting circuits and Josephson qubits being placed in 3D microwave cavities.

Recently, quantum microwaves have been coupled with a variety of physical systems that extend their range of applicability well beyond Rydberg atoms and superconducting circuits. On the one hand, microwaves can be used to probe and use new properties of many quantum systems. On the other hand, this new development could eventually solve one of the biggest challenges for long-distance quantum communication. Quantum microwaves are indeed strongly damped when traveling at room temperature and the quantum information they carry should be converted into the optical domain so that low-loss optical fibers can be used over long distances. Remarkably, many physical systems have recently been successfully embedded in microwave cavities in order to reach the strong coupling regime or at least non-classical microwave field processing. This dossier contains contributions from some of the main players in this recent effort to test new systems.

Among these, impurities in semiconductors such as NV centers in diamond are very promising candidates for a new c-QED architecture. In this case, the microwave field is coupled with a spin degree of freedom of the impurities. This magnetic dipole coupling is several orders of magnitude smaller than in the case of superconducting qubits or Rydberg atoms, which use electric coupling with dipole moments – the ratio between couplings in both cases is given by the fine structure constant, further reduced by material and geometric parameters. Therefore, it has remained elusive so far to directly couple a microwave mode with a single spin and experiments have focused on coupling collective modes of many spins with a microwave resonator. These collective modes are again (almost) linear degrees of freedom, but they hold the promise to preserve quantum coherence much longer than microwave resonators themselves (*see chapter by Grezes et al.*).

In order to gain access to the nonlinearity of a single spin, effort is made to optimize the superconducting circuit in order to sufficiently enhance magnetic coupling. It would then be possible to reach the strong coupling regime between a single dopant spin and the microwave mode, where an excitation can be exchanged before coherence is lost. Another approach to reaching the strong coupling regime is to interpose a charge degree of freedom between the spin and the microwave mode. This is possible with semiconductor quantum dots: an electron that is confined in a quantum dot has a large electric dipole moment, which allows for very strong coupling with the microwave mode. This orbital degree of freedom can then be coupled with the electron spin via spin–orbit coupling. The downside of this approach is that hybridizing the spin degree of freedom with the charge degree of freedom of the electron via spin–orbit coupling strongly reduces the spin coherence time, but this could be circumvented by dynamically switching the dot between configurations with strong and weak spin–orbit coupling to, respectively, exchange and store information (*see chapter by Viennot et al.*).

Single spins, in NV centers or quantum dots, can still be modeled as artificial atoms that can interact with microwave modes in the quantum regime. In fact, even simple tunnel junctions between normal metals can generate non-classical microwave fields. This is surprising because the current–voltage characteristics of such a junction is linear. But due to the quantum-probabilistic character of the transmission of electrons of charge e through the tunnel barrier, a junction biased at a dc voltage V presents quantum current fluctuations called shot noise, which can generate photons in the electromagnetic environment of the junction. Shot noise photons at a frequency ν can only be generated if a tunneling electron provides sufficient energy i.e. if $e|V| > h\nu$. Therefore, the noise–voltage characteristic of a tunnel junction is non-linear even though the current–voltage characteristic is linear. By applying a pump tone on top of the dc bias, this non-linear response can be exploited to generate single-mode or two-mode squeezing (*see chapter by Forgues et al.*).

Despite the considerable ease of creation and manipulation of non-classical states of microwave radiation, a faithful transducing platform to optical photons seems instrumental for long-distance communication, due to their larger energy than $k_B T$ at room temperature and low-loss propagation properties. Owing to their magneto-optical properties, magnons in materials such as yttrium iron garnet appear to be very promising for realizing such a transducer. This architecture indeed reaches the strong coupling regime between a microwave cavity and magnon modes and has the added benefit of coupling magnons with optical modes. Recently, magnons were shown to couple with superconducting qubits, hence definitely entering the quantum regime (*see chapter by Tabuchi et al.*).

The coupling of other systems with quantum microwave modes is currently explored, for example the modes of mechanical resonators [7,8] or surface acoustic waves [9], which should also provide an interface between quantum microwaves and quantum optics.

2. Measuring microwave fields at the quantum level

In several of the recently explored physical systems, the microwave fields are used to sensitively probe quantum properties that are out of reach with other detection techniques. This is made possible by the tremendous progress in the detection of microwave fields since the end of the 1980s. On the one hand, microwave signals have become incredibly easy to measure and control because of the developments driven by telecommunication, spatial and radar technologies. On the other hand, this is only valid for large signals, and quantum microwave fields of only a few photons need to be amplified without being overwhelmed by noise. State-of-the-art room-temperature amplifiers now add about 100 photons of noise to signals, making measurements at the level of single quanta almost impossible. A significant improvement in that respect came from the development of cryogenic HEMT amplifiers for astronomy in the 1980s and operating at 4 K, which have reduced the noise level by approximately two orders of magnitude compared to the best room-temperature amplifiers at the time [10]. The best ones now operate in the range of 4 to 8 GHz and their noise is less than 10 photons when referred to a device that is anchored at the base temperature of a dilution refrigerator. This noise level is already sufficient to perform quantum tomography of a propagating microwave field at the single photon level in a reasonable amount of time [11,12] by carefully subtracting out the noise of the amplifiers. Yet their noise level remains much higher than zero-point fluctuations, hence preventing one to use quantum measurement backaction as a resource for quantum control.

With revisiting the pioneering work of Yurke et al. from the 1980's [13] using recent microwave and nanofabrication techniques, the last decade saw the advent of parametric amplifiers based on Josephson junctions, which have now reduced the noise level of microwave measurements by one more order of magnitude and add a noise of the order of vacuum fluctuations only. A variety of these amplifiers have now been developed and are used routinely in labs over the world (*see chapter*[1] *by Devoret and Roy*).

A direct application of Josephson amplifiers consists in generating non-classical Gaussian states of microwave light. This was done using phase preserving microwave amplifiers that produced single-mode squeezing with microwaves, first in the 1980s by Yurke et al. [3] and more recently with much stronger squeezing [11]. An important development was the realization of two-mode squeezing on a single transmission line [14] and then entanglement between two distant microwave modes [15,16].

While the field quadratures can be amplified and measured efficiently using Josephson amplifiers, the ideal detection of single photons needs the development of another kind of device. Photocounters are the working horse of quantum optics, but are still missing in the microwave domain.[2] There are various ways to implement such single-photon detectors in the microwave domain, including by quantum non-demolition measurements (*see chapter by Sathyamoorthy, Stace, and Johansson*).

With good microwave detectors at hand, a quantum object does not necessarily have to be in a high-quality factor cavity to couple with quantum microwaves. One can even omit the cavity entirely and directly couple the quantum object with a wave guide. In such a setup the quantum state of interest is not the state of the quantum object itself, or of a cavity, but the field propagating along a transmission line, and such setups have been dubbed 'waveguide-qed'. They can be used to pick single photons out of an incoming coherent state to generate single-photon states or to route photons depending on a control field at another frequency [19–21].

3. Quantum microwaves for quantum information

Given the exquisite level of control of microwave modes in the quantum regime, they are one of the most promising candidates for quantum information processing.

With quantum limited amplifiers, it is now possible to intercept and analyze most of the information that would normally leak out from a quantum system into its environment. It thus allows the observer to follow the evolution of a quantum system in real time, conditioned on the continuous flow of information that is recorded. The inherent backaction of a quantum measurement can thus be observed directly. These experiments enable to access the single-shot quantum trajectories of a system and compute their statistics (*see chapter by Weber et al.*).

Besides observing these quantum trajectories in an open-loop configuration, the efficiency of Josephson amplifiers allows quantum engineers to implement feedback schemes that act back on the quantum system based on the measurement outcome. In the simplest case of Markovian feedback, the output of the amplified measurement record is fed to a controller that drives the system depending on the instantaneous measurement alone. The permanent stabilization of quantum trajectories of a single qubit was demonstrated based on quantum non-demolition measurement [22–24] or fluorescence measurement [25] and for two qubits also [26]. More elaborate schemes were also demonstrated [27–29], where both the instantaneous amplified microwave signals and a real-time estimation of the system state are used. Measurement-based feedback schemes can stabilize not only a single quantum state, but also manifolds of quantum states, which makes them promising for implementing quantum error-correction algorithms.

Being able to implement a scalable quantum error correction scheme is indeed the current decisive missing step for realizing quantum computers that surpass their classical counterparts [30]. Superconducting microwave circuits currently appear as the most promising candidates to build such scalable quantum error correction schemes, and there are several proposals to do this. Most of them are based on superconducting qubits as building blocks, the most successful at the moment being the so-called 'transmon' qubit. The coherence times of these qubits are so far below a millisecond, while gates that modify the state of a qubit or couple qubits take of the order of 10 to 100 ns. This leads to a so-called gate fidelity, the probability that no error is made during a gate operation on a qubit to currently 0.999 to 0.9999 in the best cases. This fidelity is large enough to reach the so-called fault tolerant threshold and hope for a quantum error corrected architecture.

There are several schemes for combining physical qubits into decoherence-protected logical qubits with various tradeoffs between the minimum required fidelity of the physical qubits and the needed number of them to form logical qubits. The scheme currently believed to be the most straightforward (but very challenging!) is the 'surface code' where qubits are arranged in a grid with half of the qubits being used to measure the errors of their nearest neighbors [31]. Single physical qubit errors then lead to specific error syndromes in these parity measurements, which can be corrected. Currently, these codes have been able to realize a protected quantum memory, but not yet quantum operations on a protected logical qubit.

[1] This chapter is also a good reference to understand the notion of microwave photons.
[2] Very recent experiments have now demonstrated such detectors [17,18].

While in such surface codes, quantum microwaves play a crucial role in the measurement of qubits and in the feedback to correct for errors, other schemes directly use the large number states in a microwave mode instead of a qubit register to provide the redundancy needed to encode collectively a logical qubit. A single electromagnetic mode indeed already has a Hilbert space with an infinite number of states corresponding to every possible photon number. This hardware-efficient architecture provides an interesting shortcut to quantum computing (*see chapter by Mirrahimi*). In the so-called 'cat codes', superpositions of coherent states (Schrödinger cat states) are used to encode a logical qubit. With this promising scheme, a recent experiment has realized for the first time a logical quantum bit that exhibits longer coherence times than any of its constituents [32].

It is very likely that quantum machines going beyond accessible calculations by classical computers will be realized before a universal quantum computer exists. In this direction, quantum microwaves have already been used to realize quantum simulations [33] and machine learning tasks [34].

Microwaves in the quantum regime have come a long way over the last 25 years. Starting from the cavity QED regime, they have now accessed most of the regimes that can be reached with visible light and many experiments that are very difficult or even impossible in the optical domain have now been performed in the microwave domain. It is therefore certainly justified to now speak of the field of 'Quantum Microwaves' in the same way as one talks of Quantum Optics. This dossier aims at providing a snapshot of the current state-of-the-art in this blooming field of research.

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