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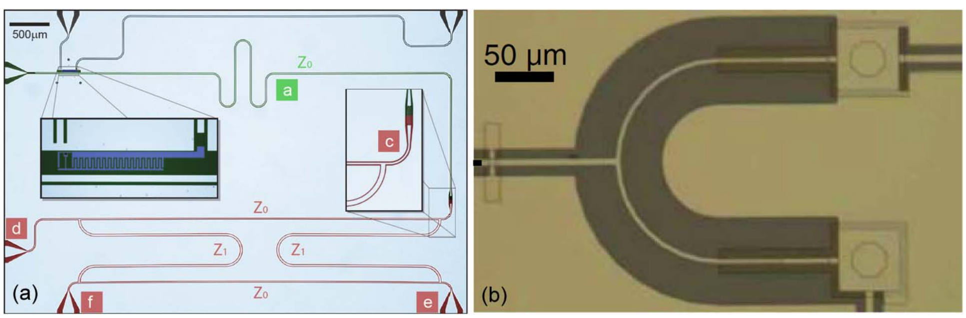

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Breakthroughs in Photonics 2012: Breakthroughs in Microwave Quantum Photonics in Superconducting Circuits

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(Invited Paper)

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Abstract: The latest breakthroughs in microwave quantum photonics in superconducting circuits are presented. Advancing technologies of Josephson junction quantum bits (qubits) have been applied to control and measurement of itinerant microwave fields. Methods to generate nonclassical microwave states such as single-photon states and squeezed states have been developed. Techniques to characterize those nonclassical itinerant states have also been established. They are ready to be combined to demonstrate various quantum protocols, which extend the possibilities of quantum information processing, quantum metrology, and quantum communications using superconducting circuits.

Index Terms: Quantum information science, quantum bit (qubit), artificial atom, superconducting quantum circuits, Josephson junction, quantum optics, microwave, circuit quantum electrodynamics (circuit QED), single-photon source, single-photon detector, Josephson parametric amplifier (JPA), quantum feedback.

In standard microwave-engineering textbooks, the word "photon" is not frequently used. Microwave at 10 GHz has a wavelength of 3 cm in vacuum. This is 20 000 times longer than the optical communication wavelength of 1.5 μm. Accordingly, the energy of the single microwave quantum is far less than that of the infrared one. While the infrared photon energy corresponds to the temperature of 10 000 K, that of a single 10-GHz photon is equivalent to 0.5 K. Naturally, we hardly see any obvious effect of the quantized microwave field at room temperature. Nevertheless, we all know that both "photons" can be treated on equal footing as an energy quantum in electromagnetic degrees of freedom. No physical principle prevents us from speaking of "photonics" in the microwave domain.

Indeed, the last few years have witnessed exciting emergence of microwave quantum photonics in superconducting circuits. The advanced, and still advancing, physics and technology of Josephson junction quantum bits (qubits) have enabled precise manipulation of quantum states in the artificially designed quantum systems. The purpose of this brief review is to introduce the latest breakthroughs in microwave quantum photonics to the readers in the photonics community. Here, we focus on control and measurement of itinerant microwave quantum fields in superconducting circuits. Analogies with photonics in the optical domain should be readily found in those examples.

Superconducting quantum circuits have been developing toward solid-state implementations of quantum information processing [1]. For example, integrated qubits and resonators have already been used to demonstrate simple quantum algorithms including Shor's factorization [2]. Superconductivity offers nearly dissipationless circuits in the microwave domain: Losses in transmission lines are estimated to be as little as in optical fibers, and LC resonator circuits behave as high-Q harmonic oscillators. More importantly, Josephson junction, a tunnel junction between two superconducting electrodes, acts as an inductor with strong nonlinearity. It allows us to construct nonlinear resonator circuits that have nonequidistant discrete energy levels and are often called superconducting qubits or sometimes artificial atoms. We emphasize that they are realized in macroscale electrical circuits with design flexibility and large-scale integrability. Typically they are designed to have excitation energies around 10 GHz and are operated at low temperatures around 10 mK in dilution refrigerators to avoid any thermal excitations. The most significant property of the artificial atoms is their huge dipole moment, either electric or magnetic depending on the designs, due to the macroscopic dimensions of the circuits much larger than that of ordinary atoms. Because of that, and also with a help of the field enhancement in spatially confined modes of the circuits, the artificial atoms interact strongly with electromagnetic fields [3]. In analogy with cavity quantum electrodynamics (cavity QED) developed in quantum optics with atoms, the word "circuit QED" has been coined to the physics of light-"matter" interactions in superconducting quantum circuits in the microwave domain [4].

The strong interaction with itinerant microwave field readily manifests in the scattering of coherent-state microwave by a single superconducting qubit coupled with an on-chip waveguide. Nearly perfect extinction of the transmission at the resonance has indicated its high cooperativity [5], [6]: Due to the strong coupling, almost all the scattered field by the artificial atom is guided into the propagation mode. One-dimensionality of the mode leads to perfect spatial-mode matching, which results in destructive (constructive) interference in the forward (backward) scattering and consequently to perfect reflection. With increasing the probe microwave power, resonance fluorescence also manifests as a Mollow triplet in the inelastic scattering spectrum [5]. Nonclassical nature of the scattered microwave has been measured [7], [8]. Moreover, a strong drive at the transition to an auxiliary excited state causes energy-level splitting (Autler–Townes splitting) between the dressed states, and the probe transmission recovers at the qubit resonant frequency. This induced transparency can be used as a compact and fast microwave switch or router [6], [9]. The three-level artificial atom can also be pumped to create population inversion and demonstrate microwave amplification by stimulated emission of radiation (MASER) [10], a single-atom analog of fiber amplifiers in optics.

Further progress has been accelerated by development of novel techniques for characterizing itinerant microwave fields. In optics experiments, in order to characterize an itinerant light field, single-photon detection and counting are commonly used. In the microwave domain, however, because of the smallness of the single-photon energy, single-photon detectors had been elusive until very recently. Nevertheless, it has been shown that it is still possible to measure the field correlations by using linear detectors [11]–[13]. Simultaneous homodyne measurements at two output ports of a "beam splitter" (a hybrid coupler in microwave engineering) allow full characterization of the correlation functions of the input field [Fig. 1(a)]. This has been applied in a series of experiments performing quantum state tomography of nonclassical microwave fields [14], [15]. In parallel, a single-photon detector using a current-biased Josephson junction has been proposed and demonstrated recently [16]–[18]. The Josephson junction works as an effective three-level system with a Λ-type configuration. Placed at the end of a transmission line, the Λ-system absorbs an incoming photon most efficiently when the excited state has equal relaxation rates for the two decay channels. A pair of such detectors has been used in a Hanbury–Brown–Twiss experiment, revealing photon bunching in a microwave thermal field [Fig. 1(b)] [17]. Microwave photon counting with number resolutio would be the next challenge.

Generation of nonclassical microwave fields has also been a hot research topic. Single-photon sources producing itinerant single-photon pulses have been widely studied in optics. In the microwave domain, a superconducting qubit coupled with a resonator plays a role of the emitter

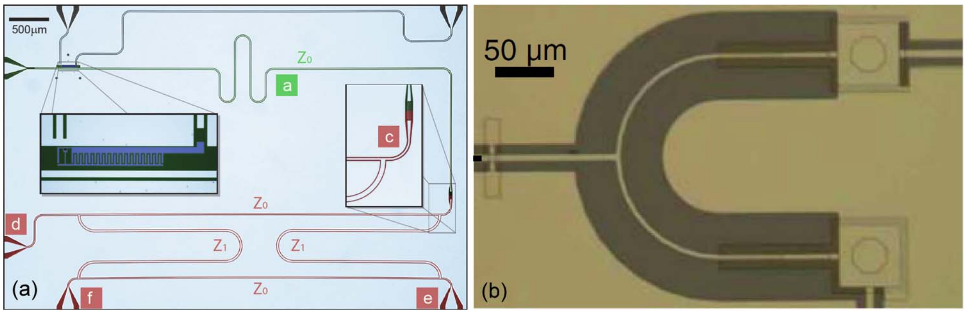

Fig. 1. Examples of microwave quantum photonic devices. (a) Single-photon source and beam splitter built in superconducting coplanar-waveguide circuits (reprinted from [13] with permission from Macmillan Publishers). A superconducting qubit (blue: left inset) coupled with a transmission-line resonator "a" emits single photons through an output capacitor "c" (right inset). The ports "e" and "f" after the "beam splitter" (a quadrature hybrid coupler with the branch characteristic impedances Z_0 and Z_1) are used for the photon correlation measurements. (b) Single-photon detector (reprinted from [17] with permission from APS). Incoming microwave signals from left are split at the T-junction divider, and the photon coincidence is detected by the two circular-shape current-biased Josephson junctions.

[13], [15], [19]. Precise control of the qubit and its strong coupling to the transmission line realize a high-fidelity on-demand single-photon source with a negligible multiple-photon emission probability. Moreover, time-dependent control of the coupling to the output mode has enabled pulse shaping of the emitted microwave photons [19]. This is a key technology for quantum state transfer using itinerant microwave photons between remote quantum nodes [20], where temporal mode matching between the sender and the receiver is crucial. More recently, indistinguishability of microwave photons generated by two separate single-photon sources has been confirmed in a Hong–Ou–Mandel interference experiment [21]. This is a first step toward microwave quantum photonic circuits with synchronized multiple single-photon sources.

Nonclassical states in continuous microwave have been investigated as well. When the boundary condition of an electromagnetic vacuum, e.g., the position of a mirror, is modulated at a speed comparable to that of light, pairs of photons are spontaneously generated with certain correlations in a wide frequency range; this is the prediction of the dynamical Casimir effect but has never been observed in the optical domain. This effect has been demonstrated in a microwave transmission line terminated by a SQUID [22], [23]. The boundary condition is modulated by driving the SQUID magnetic flux bias at a pump frequency. The resulting two-mode squeezing between different frequency modes has been confirmed [23]. Josephson parametric amplifier (JPA) is a circuit that works similarly but only in a narrow frequency band defined by an additional resonator [24], [25]. When the boundary condition is modulated at twice the resonator frequency, i.e., in the degenerate-mode operation, phase-sensitive parametric amplification takes place. For a vacuum input, the output is a squeezed vacuum. State reconstruction of a squeezed vacuum thus generated has been achieved [26], [27]. Most recently, it has been observed that the transverse decay rate of a qubit irradiated with a squeezed vacuum is enhanced or reduced, depending on the relative phase of the quadrature squeezing [28]. We emphasize that JPA is not only a good squeezed vacuum source but is also useful as a low-noise amplifier. Being a phase-sensitive amplifier, JPA can in principle be a noiseless amplifier that does not add any additional quantum noise to the input signal. In the field of microwave quantum photonics, it is now commonly used as a low-noise preamplifier in front of a broadband HEMT amplifier used at 4 K. Striking improvement of signal-to-noise ratio has been seen in many experiments. Josephson ring modulator is yet another nonlinear circuit that can be used as a frequency converter or a phase-preserving parametric amplifier depending on the operation modes [29]. The bridgelike symmetric design of the circuit cancels unwanted nonlinear interactions between relevant modes, leaving only the necessary terms. Recent experiments have demonstrated excellent properties of the circuit in agreement with the theory [30]–[32]. As a resource for quantum information processing using itinerant microwave fields, entanglements between spatially separated modes have been generated and quantified. Entanglements between two itinerant microwave modes have been achieved either at the same frequency [27] or between the different frequencies [33]. In the single-photon source circuit, the qubit in the resonator and the emitted photon have been entangled [34].

Given the progress on the sources and detectors discussed above, interests are rising in the integrations of those key elements for realizing more advanced microwave quantum photonics circuits. While simple assemblies can be made with commercial microwave connectors and components, larger scale high-fidelity quantum circuits require on-chip monolithic integrations. All aspects of the circuits, such as material, surface, shielding, design, etc., have to be engineered carefully for quantitative improvements of the fidelities of the circuits. On-chip microwave couplers corresponding to optical beam splitters have already been used in experiments [13], [21]. *In situ*, hopefully dynamical, tunability of couplers as well as phase shifters would be useful for constructing programmable and adjustable interferometry circuits. Also, attractive for such control may be integration with superconducting digital logic circuits [known as single-flux quanta (SFQ) circuits], which operate at extreme high speed and low power in cryogenic environment. An important element still missing is a nonreciprocal component, such as a circulator and an isolator. When itinerant microwave interacts with a local quantum node, it is important to spatially separate input and output modes so that all the quantum information carried by the output field is guided to the following node, not returned to the preceding ones. It is also useful for isolating the output of JPA from the input. Schemes based on Josephson junctions, without using ferromagnets, have been proposed both in passive [35] and active circuits [36]. Additionally, the recent success in the integration of superconducting qubits in 3-D cavity resonators [37] has suggested a route toward 3-D integrations of microwave quantum photonics circuits.

The itinerant quantum states of microwave are expected to be exploited in various quantum technologies. Entangled states between two modes can be used in quantum teleportation. As a primitive for remote quantum gates, it can be applied to quantum state transfer, quantum error correction, and so on. Squeezed vacuum can enhance the measurement precision below the standard quantum limit set by the uncertainty principle, as has already been applied in experiments. Autonomous stabilizations of quantum states are targeted in quantum feedback control. Recently, it has been implemented by using a coherent-state microwave signal from a weak measurement of a qubit [38]. The signal was coherently amplified and fed back to the qubit for sustaining its Rabi oscillations. Coherent feedback has also been demonstrated in coupled nonlinear superconducting resonators [39].

Finally, a Holy Grail of microwave quantum photonics is fusion with quantum photonics in the optical domain. Microwave is good for quantum operations and measurements in superconducting circuits inside a refrigerator, but certainly not for long-distance communications at ambient temperature. For quantum communication and quantum networking between local cryogenic nodes, quantum interfaces between microwave and optical domains are necessary. However, superconducting circuits have an upper limit in the operation energy scale: Above their superconducting gap energy, the circuits become highly dissipative due to Cooper pair breaking. Therefore, in order to overcome the energy mismatch between microwave and optics, quantum interface using hybrid quantum systems—combinations of superconducting circuits with other types of quantum systems—have been pursued. The candidates include, for example, hybridizations with spin ensembles in solids or atoms, semiconductor quantum dots and nanowires, and nanomechanical systems. The last has been intensively explored recently as electro- and optomechanical systems [40]. Quantum state transfer between itinerant microwave field in superconducting circuits and a mechanical oscillator has been reported [41].

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