DC measurement of dressed states in a coupled 100 GHz resonator system using a single quasiparticle transistor as a sensitive microwave detector

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We report on the on-chip detection of microwaves in the frequency range around 100 GHz. For the purpose of detection, we employ a discrete transport channel triggered in a superconducting single-electron transistor by photon-assisted tunneling of quasiparticles. The technique is successfully applied to observe the spectrum of the dressed states of a model cQED system consisting of a superconducting coplanar resonator coupled to a quantum Josephson oscillator. The dressed states appear as typical resonance anticrossing exhibiting, in our case, an unexpectedly wide frequency splitting corresponding to the Jaynes-Cummings coupling strength, \( g/\pi \sim 10 \text{ GHz} \). Due to the high decay rate, \( \gamma \sim 20-40 \text{ GHz} \), in the very transparent Josephson junctions used, the strong coupling limit, \( g \gg \gamma \), which is required for qubit operation, is not achieved, and the photon population in the resonator is low, \( \langle n \rangle < 1 \). Remarkably, the continuous readout of the low population states demonstrates the high microwave sensitivity of the detector.

Strong coupling between a microwave resonator and a quantum oscillator is an important prerequisite for clear observation of circuit/cavity quantum electrodynamics (cQED/CQED) effects [1,2]. One of the significant advantages of superconducting circuit QED systems over cavity QED with real atoms is a much stronger coupling between the components. For example, for a Cooper pair box coupled to a coplanar waveguide (CPW) resonator with a typical length \( l \) of 10 mm to 20 mm and mode frequency \( f_r \) of 5 GHz to 10 GHz, the coupling strength \( g \), which appears in the interaction term of the Jaynes-Cummings Hamiltonian [3], routinely achieves the level \( g \sim 2\pi \times 100 \text{ MHz} \) (see, e.g., Refs. [4,6]).

Even stronger coupling should be expected in shorter resonators, \( l \sim 1 \text{ mm} \), with the coupling strength, \( h g \propto \sqrt{\hbar \omega_r}/2C \propto l^{-1} \) [4,6], increasing linearly with the frequency, \( \omega_r = 2\pi f_r = 1/\sqrt{LC} \propto l^{-1} \) due to the decrease in the effective inductance/capacitance \( L,C \propto l^{-1} \). This could justify an interest in the compact quantum systems operating in an upper microwave frequency range up to 100 GHz. On the other hand, a substantial increase in the loss rate can critically impact the quantum coherence as the result of a stronger capacitive coupling to the electromagnetic environment at elevated frequencies and more intensive generation of non-equilibrium quasiparticles (QP) (cf., e.g., Refs. [7,8]). For example, in a recent experiment [9], a non-coherent model approach was used successfully to describe an Aluminum SQUID array up to the microwave frequencies \( f \sim 100 \text{ GHz} \). In order to access this range, we implement an on-chip test bench, shown in Fig. 1(a), based on Al/AlO_x/Al-junctions and fully controlled via dc signals from room temperature electronics. As a microwave source, we use an overdamped Josephson junction (JJ source), and for the photon detection, we utilize a quasiparticle sensing regime based on a photon-assisted tunneling (PAT) effect in a superconducting single-electron transistor (SSET), shown in Fig. 1(b) (cf. Refs. [12,13]). A significant gain in microwave sensitivity appears in our detection circuit owing to an intrinsic photon-electron multiplying mechanism described below.

The experimental circuit was fabricated using the shadow evaporation technique [14] and studied in a shielded DC setup at \( T = 15 \text{ mK} \) with an integration constant, \( \tau_{\text{int}} \sim 0.5 \text{ s} \), that was sufficiently long for measuring the sub-pA currents. All superconducting components were integrated into a single evaporation mask and included three successive layers of aluminum. Mild (10 min at oxygen pressure 1 Pa) and heavy (15 min, 25 Pa) oxidation steps were performed for the first and the second Al layers, respectively, to form the tunnel junctions for the JJ source/Josephson oscillator and for the high-ohmic SSET device. As a resistive shunt attached to the JJ source (see the right hand part of Fig. 1(a)), we used a finite-loss AuPd coplanar transmission line (TL) with a specific high-frequency impedance of \( Z_s \approx 50 \Omega \). The line was 2.3 mm long and it was terminated at the opposite end by means of a 6 \( \Omega \) section of the AuPd film used as a cold part of the DC biasing circuitry. The full DC load resistance seen by the Josephson junction was \( R_L \sim 25 \Omega \), which was low enough for stabilization of the Josephson voltage, \( V_J = hf_J/2e \), and the base frequency \( f_J \) of the Josephson generation (cf. Ref. [15]).

The detection principle is based on the remarkably high quasiparticle sensitivity of the tunnel current \( I_{\text{SSET}} \) at low bias voltages, \( V_b < 4\Delta/e \), where single-electron tunneling is suppressed. As discussed in Refs. [16,17], in the bias range of 200 \( \mu V \leq V_b \leq 400 \mu V \), a non-vanishing current appears as a time-correlated sequence of single
FIG. 1: (Color online) (a) Electrical circuit diagram of the experimental device. The JJ source junction has an area $S \approx 0.1 \mu m^2$, a critical current $I_C \approx 1.5 \mu A$, and a Stewart-McCumber parameter $\beta_C \approx 0.1$, thus producing microwaves of amplitude $V_A \approx V_C \approx 75 \mu V$, where $V_C = I_C Z_n$ is the Josephson characteristic voltage. In the CPW, the central line (spacing) is $10 \mu m$ (5 $\mu m$) (see text for more layout details). (b) Tilted SEM image of the SSET detector and an example of Cooper pair splitting in advance of the CPE event. The most probable escape persists until the unpaired QP escapes from the island. The density of QPs (and thus the rate of SQPT, $\Gamma_{SQPT}$) depends crucially both on the parity effect (see, e.g., Ref. 18) and on the intensity of the incident or ambient microwaves (see, e.g., Refs. 7, 19–21). The microwave photon energy, $E_{ph}$, must exceed the activation threshold for photon-assisted single-electron tunneling, $E_{ph} \gtrsim E_{PAT} = 2\Delta + E_C(1 + 2n_g + 2m) - eV_b/2$. Here, $n_g \equiv C_g V_g/e$ is the gate charge, $C_g (V_g)$ denotes the gate capacitance (voltage), $E_C \equiv \epsilon^2/2C_\Sigma$ is the charging energy, $C_\Sigma$ is the total capacitance of the central island, and $m$ is an even integer number.

Further details of the detector operation can be illustrated by using the data in Fig. 2 which was obtained for a test sample without a quantum oscillator. Without irradiation, see Fig. 2(a), a clear sub-pA current pattern appears in the odd gate domains, $m + 1/2 \leq n_g \leq m + 3/2$, with one unpaired QP residing in the island most of the time. By contrast, the current landscape is almost suppressed in the even domains, $m - 1/2 \leq n_g \leq m + 1/2$, with all QPs being paired. The current appears at the voltage thresholds $V_b \gtrsim 2E_C(\pm 2n_g - 1 + 2m)/e$, for SQPT, and $V_b \gtrsim [4\Delta + 2E_C(1 + 2n_g + 2m)]/3e$, for the CPE cotunneling. The expectation time $\tau_{CPE}$ of the CPE cotunneling greatly exceeds the time $\tau_{SQPT}$ for SQPT. Indeed, the CPE/CPE cotunneling current, which is on-set in the triangles (color online: red) at the top of the diagram in Fig. 2(a) (see also Ref. 17) and reaches the values $I_{SSET} \approx 10$ pA beyond the diagram scope, provides an estimate $\tau_{CPE} \sim 25$ ns. On the other hand, a much lower CPE/SQPT current measured, $I_{SSET} \approx 0.2-0.5$ pA, corresponds to the cycle period on the scale of a microsecond. This period is obviously limited by the rate of SQPT, $\Gamma_{SQPT}^{-1} = \tau_{SQPT} \approx 0.7-1.6 \mu s$.

The high $\tau_{SQPT}/\tau_{CPE}$ ratio provides the conditions for an intrinsic mechanism of current triggering due to photon absorption. In charge dynamics, the PAT process shown in Fig. 1(b) is followed directly by the charge relaxation act via CPE cotunneling, shown in Fig. 1(c). The resulting state with two unpaired QPs in the island invokes the cyclic SQPT/CPE transport similar to that in the autonomous mode. Accordingly, the tunnel current should consist of the trains of CPE/SQPT pulses, persisting until the unpaired QP escapes from the island in advance of the CPE event. The most probable escape...
FIG. 2: (Color online) Detector current $I_{\text{SET}}$ measured on a test sample without qubit, with a weaker JJ source: $I_C \approx 330$ nA, $V_C \approx 13$ μV, and deviating SSET parameters: $E_C \approx 250$ μeV, and $R_F \approx 185$ kΩ. The diagrams show the current pattern (a) without irradiation and (b) under irradiation from the JJ source tuned to the resonant peak of CPW [the solid line in (c)]. The dotted (dashed) lines indicate the thresholds for CPE cotunneling (SQPT) processes described in the text. (c) Transmission spectrum of the CPW resonator collected via changing the Josephson voltage (frequency) $V_1(f_1)$ in the JJ source and measuring the signal of the detector biased at voltage $V_b = 230$ μV [the solid line in (b)]. The dashed lines are the thresholds of the PAT processes of the kind depicted in Fig. 1(b).

As expected, the detector signal is found to increase significantly (see Fig. 2(b)), due to microwave irradiation arriving at the detector via the CPW resonator. The current diagram appears to be almost 1e-periodic, by exhibiting similar currents in the odd and even domains, which indicates a QP population about unity in the island. The signal dependence on the Josephson frequency (i.e., microwave photon energy), which is shown in Fig. 2(c), confirms a clear resonant peak structure at $f_J \approx 108$ GHz, but also reveals an inferior pattern of stray box resonances and higher Josephson harmonics. Similar to Refs. [12, 13], we roughly estimated the rate of photon-assisted tunneling in SSET irradiated under the conditions of the resonant peak and the gate tuned to the sensitive point, $n_g \approx -0.25$. The obtained value, $\Gamma_{ph} \approx 10^4$ s$^{-1}$, corresponds to an extremely low level of energy dissipation from the CPW into the detector, $W_D = \Gamma_{ph} \times h f_J \approx 0.7$ aW $\approx -151$ dBm. Furthermore, relating $\Gamma_{ph}$ to the signal peak value, $I_{\text{SET}} \approx 0.6$ pA $\sim 4 \times 10^6$ electrons per second, it was possible to obtain a reasonable estimate, $N_p \sim 200$ cycles per photon.

The quantum oscillator coupled to the CPW resonator was designed as a Josephson DC SQUID with a loop of area $A \approx 40 \mu m^2$ and two highly transparent, $0.25 \mu m^2$ Josephson tunnel junctions with a total critical current $I_C(B = 0) = I_{C1} + I_{C2} \approx 8$ μA and a sum tunnel capacitance $C_J \approx 22$ fF (a fitted value, see below). As shown in Fig. 3(a), the magnetic field applied to the SQUID loop periodically modulates the microwave signal transmitted to the detector. The measured period, $\Delta B \approx 14$ μT $< \Phi_0 / A \approx 50$ μT, is smaller than that expected for the loop area presumably due to a flux concentration effect in the slots of the CPW line. On the other hand, the actual flux and field values, $\Phi = B \times A$, can be calibrated directly using the plot periodicity, $\Delta \Phi = \Phi_0$. The plasma frequency of the SQUID, $\omega_p(\Phi) = \sqrt{2 e I_C(\Phi) / h C_J}$, is estimated to vary in a wide range up to $\omega_p(0) \sim 2 \pi \times 170$ GHz and the Josephson-to-charging energy ratio approaches the values, $E_J / E_CJ \sim 4000$, well within the limit of the transmon-type qubits [23].

Due to the high detector sensitivity, we succeeded in observing the dressed states $\ket{1,0}$ and $\ket{0,1}$ in the superconducting resonator system as a well-pronounced anticrossing, see Fig. 3(b), between the microwave and qubit resonances. At low detuning, $\delta = |\omega_P - \omega_r| \ll g$. The uncoupled resonant frequencies $\omega_r$ and $\omega_P$ vary along the dashed lines and, on the state diagram in Fig. 3(c), correspond to the resonant transitions from the ground state $|g, 0\rangle$ to the single-photon state $|g, 1\rangle$ or to the lowest excited state of the qubit $|e, 0\rangle$, respectively. The symmetric and antisymmetric dressed states appear for the coupled system as the coherent superpositions, $|\pm\rangle \approx 1/\sqrt{2}(|g, 1\rangle \pm |e, 0\rangle)$ (1/\sqrt{2} is an exact prefactor at $\delta = 0$) and give rise to resonances at $\omega_{\pm} = \omega_P(\Phi) \pm \omega_r \pm \sqrt{4g^2 + [\omega_P(\Phi) - \omega_r]^2 / 2}$, (1) shown by the solid lines in Fig. 3(b). The lines are fitted to the plot by adjusting the values of $C_J$ and...
the SQUID asymmetry factor, \( d = |I_{C1} - I_{C2}|/(I_{C1} + I_{C2}) \approx 0.16 \). The frequency splitting interval, equal to \( g/\pi = e\sqrt{\omega_r}/hC \approx 9.2 \text{ GHz} \), was calculated directly, based on the resonator geometry [24]. The signal peaks, observed at \( \Phi \approx 0.42 \Phi_0 \) and \( \approx 0.58 \Phi_0 \), appear in the vicinity of the zero detuning points, presumably due to the resonant increase in the qubit impedance, causing more efficient matching to the microwave source. Finally, we note that the anticrossing pattern was studied for two different CPW resonators with the microwave parameters summarized in Table I.

| No. | \( l \), mm | \( f_r \), GHz | \( g/2\pi \), GHz | \( \Delta f_j \), GHz | \( \gamma \), GHz | \( \langle n \rangle \) |
|-----|-------------|----------------|-----------------|----------------|-------------|-------|
| 1   | 0.68        | 81             | 4.6             | 7.2            | 43          | 0.2   |
| 2   | 0.8         | 70             | 3.9             | 3.8            | 21          | 0.6   |

As compared to the unloaded test samples, with the detected linewidth of the CPW resonances, \( \Delta f \approx 1.7 \text{ GHz} \), and the Josephson generation linewidth of the source, \( \Delta f_j \approx 0.4 \text{ GHz} \) [25], a significant broadening of the resonance is observed for the samples including the SQUID junctions. We explain this, on a qualitative level, as being the result of a strong quasiparticle subgap leakage due to the high junction transparency (see, e.g., Refs. [23–27]) on the one hand, and the PAT effect [28] on the other hand. The higher-frequency peak exhibits a stronger broadening, thus emphasizing the significance for the leakage current of the photon energy approaching the Cooper pair breaking threshold, \( 2\Delta/h \approx 100 \text{ GHz} \).

Under continuous irradiation, the total loss rate in the coupled CPW-plus-oscillator system, \( \gamma = 2\pi(\Delta f - \Delta f_j) \), is counteracted by the power input from the JJ source, \( P_{in} \approx 0.1 \text{ pW} \). Due to the intensive losses, the average number \( \langle n \rangle \) of photons in our CPW resonator, \( \langle n \rangle = P_{in}/(\gamma h\omega_r) \), is estimated to be lower than unity (see Table I). On the one hand, this may be a detector’s figure of merit, for its clear signal indicates the proper sensitivity of the resonator readout. On the other hand, since the decay rate \( \gamma \) exceeds Rabi frequency \( g/2\pi \), as both are in the GHz-range, no Rabi oscillation can exist under the present conditions. Much lower dissipation (and much more pronounced anharmonicity) can be expected for a SQUID oscillator with sub-100 nm junctions of the same high barrier transparency (and thus of the frequency \( \omega_r > 100 \text{ GHz} \)). Furthermore, a more detailed study is envisaged of the loss rate in a wide range of resonator frequencies.

To conclude, on the basis of a superconducting single-electron transistor, we have developed a highly sensitive on-chip detection technique for microwave frequencies on the scale of 100 GHz. An important element of this technique is a mechanism of photon-activated current triggering that facilitates a batch electron transfer for each absorbed photon. The detection technique was used to observe the two lowest dressed states in a quantum system with a CPW resonator coupled to a Josephson junction oscillator. This observation demonstrated a detector sensitivity down to very low photon populations in the resonator, \( \langle n \rangle < 1 \). Further applications of the detector for on-chip studies of mesoscopic devices are in progress.

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