Narrow-Band Microwave Radiation from a Biased Single-Cooper-Pair Transistor

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We show that a single-Cooper-pair transistor (SCPT) electrometer emits narrow-band microwave radiation when biased in its subgap region. Photoexcitation of quasiparticle tunneling in a nearby SCPT is used to spectroscopically detect this radiation in a configuration that closely mimics a qubit-electrometer integrated circuit. We identify emission lines due to Josephson radiation and radiative transport processes in the electrometer and argue that a dissipative superconducting electrometer can severely disrupt the system it attempts to measure.

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The implementation of a quantum computer in the solid state requires, aside from the quantum bit (qubit) itself, an integrated readout device. It must be fast and sensitive, and it must present the qubit with a minimal source of decoherence. In the Cooper-pair box qubit [1,2], a natural choice for a readout device is the rf single-Cooper-pair transistor (SCPT) electrometer—an rf single-electron transistor (SET) operating in the superconducting state [3–5]. However, there has been growing concern recently that the voltage-biased, and thus dissipative, operation of the superconducting rf-SET electrometer makes it less than ideal in measuring quantum circuits [6–8]. Not only does the electrometer provide a dissipative environment that may relax and dephase the qubit, but the nontrivial back-action noise associated with the various transport mechanisms through the electrometer may also excite the qubit and even lead to a population inversion [9,10]. Despite the availability of new dispersive readout schemes [11–13], the dissipative superconducting rf-SET is still widely used as an electrometer in quantum circuits [14–16]. There is a strong need, therefore, to experimentally determine how the dissipative superconducting electrometer affects the system it measures, and specifically, what are the components of the electrometer’s emission spectrum.

In this Letter, we report on our measurements of the emission spectrum of a biased SCPT. While narrow-band microwave radiation from a biased SCPT has been previously observed using photon-assisted tunneling in a strongly coupled superconductor-insulator-superconductor junction detector [17], those measurements were done in a limited range of the electrometer’s operating point near the Josephson-quasiparticle peak. We spectroscopically measured the radiation emitted from the electrometer as a function of its operating point over a wide range of voltage and charge bias conditions throughout its subgap region. We detected this radiation by photon-assisted quasiparticle (QP) tunneling in a nearby SCPT.

Our experimental setup is shown in Fig. 1(a). The two SCPTs were cofabricated by double-angle Al deposition and were separated by ~6 μm. As in Ref. [8], the islands of the two devices are not coupled directly; their leads, however, provide stray coupling at microwave frequencies [18]. In both devices the charging energy is $E_C = e^2 / 2C \approx 170 \mu$eV (C is the total island capacitance) and the normal state resistance is $R_N \approx 22$ kΩ. We oxygen doped one of the Al layers to increase its superconducting gap [19], $\Delta_1 = 225 \mu$eV (20 nm thick); the other Al film was 40 nm thick with $\Delta_2 = 190 \mu$eV. In the device on the right of Fig. 1(a), which we call the “source,” the island was formed from the film with $\Delta_1$ and the leads had the smaller gap, a configuration that reduces QP trapping on its island. Measurements of the switching current in this device as a function of gate charge, $Q_{\text{src}}$, have shown clean $2e$ periodicity, as expected in the absence of QP trapping. This source device is voltage biased (∼1 kΩ loadline imped-

FIG. 1 (color online). (a) A schematic of the experimental setup. The detector SCPT is embedded in a resonator and measured by rf reflectometry. (b) A cartoon of photon-assisted QP tunneling in the detector, $Q_{\text{det}} = e$. (c) Reflected rf power $P_{\text{ref}}$ vs time at $Q_{\text{det}} = e$. $f = 510$ MHz, $P_{\text{in}} = 3.2$ fW (−115 dBm). (d) Detector even-state probability vs source operating point at $Q_{\text{det}} = e$. Arrows indicate ridges with enhanced even-state probability. No change in $P_{\text{even}}$ was observed for $|V_{\text{src}}| < 100 \mu$V.
In the device on the left of Fig. 1(a) (the “detector”) the film with the lower gap $\Delta_1$ formed the island, and the leads had the higher gap $\Delta_2$. In this configuration the SCPT island can trap QPs far more effectively. We used the QP trapping and untrapping rates, which are very sensitive to electromagnetic noise in the environment and can be photo activated, Fig. 1(b), to detect the radiation emitted by the source.

We configured the detector for rf reflectometry measurement of its charge-dependent Josephson inductance at zero dc bias [11,20] and recorded the temporal variation of the reflected power $P_{\text{ref}}$ which indicates the presence or absence of a single extra QP on the transistor’s island, as shown in Fig. 1(c) (details of the measurement appear in Ref. [20]). The signal was sampled at 100 ns intervals, and the typical time record spans 300 ms. The signal shows telegraph switching between two levels, with the upper level corresponding to the presence of an extra QP on the detector’s island (odd parity state) and the lower one corresponding to its absence (even parity). We operate on the measured telegraph signal with a cumulative likelihood-ratio algorithm [14,21] to discriminate between the two signal levels and find the dwell times of the system in the two states.

Figure 1(d) shows the detector’s even-state probability $P_{\text{even}}$ as we biased the drain-source and gate voltages on the source device. For each point $Q_{\text{src}}, V_{\text{src}}$ in the figure we recorded the statistics of QP tunneling in the detector and determined $P_{\text{even}}$ from the fraction of time spent with no extra quasiparticles on its island. It is immediately clear from the figure that $P_{\text{even}}$ changes significantly in response to the source’s operating point and exhibits a surprisingly intricate structure. $P_{\text{even}}$ changes with $V_{\text{src}}$ both along horizontal lines, independently of $Q_{\text{src}}$, and along sloped lines that are $Q_{\text{src}}$ dependent. In addition, $P_{\text{even}}$ is observed to increase above its $V_{\text{src}} = 0$ value (≈12%) [bright ridges, arrows in Fig. 1(d)], a somewhat counterintuitive result given that QP poisoning is generally assumed to be enhanced in the presence of electromagnetic noise [8]. We observed similar behavior in all four pairs of devices that we measured.

Since $P_{\text{even}}$ depends on both in and out QP tunneling rates, $\gamma_{\text{in}}$ and $\gamma_{\text{out}}$, it does not provide sufficient information to understand the source-detector interactions. However, having access to the QP tunneling dynamics in the time domain allows us to separate $P_{\text{even}} = \gamma_{\text{out}} / (\gamma_{\text{out}} + \gamma_{\text{in}})$ into the constituent rates. Since we know the dwell times of the system in the even and odd states, we can histogram them to reveal the statistics of QP tunneling events into and out of the island, Fig. 2(a). Using a procedure outlined in Ref. [22], we determined the receiver response times $\tau_{\text{out}} = 0.73 \mu$s and $\tau_{\text{in}} = 0.62 \mu$s for the different transitions; using these numbers to account for the finite measurement bandwidth, we extract the actual tunneling rates from the observed lifetime histograms [20,22]. The resulting tunneling rates are shown in Fig. 2(b) and 2(c). Comparing Figs. 2(b) and 2(c) and Fig. 1(d), we see that the observed increase in $P_{\text{even}}$ [arrows in Fig. 1(d)] is due to enhancement of the QP untrapping rate $\gamma_{\text{out}}$ rather than a suppression of $\gamma_{\text{in}}$.

We first discuss the enhancement of the QP escape rate $\gamma_{\text{out}}$ that appears to dominate the detector’s response below $V_{\text{src}} \simeq 200 \mu$V. Figure 2(f) shows the energy band diagram for the detector device. The even parity bands (green) correspond to the ground and first excited states of the transistor, and the odd parity bands (red) are offset by the energy $\Delta_1 - \Delta_2$ that is gained by a QP tunneling from the leads to the island [19]. We identify four possible transitions that, if excited, lead to enhanced QP escape rates. The processes labeled A and B in the figure directly transfer the extra QP from the island to the leads, leaving the SCPT in its ground and first excited state, respectively. Processes C and D do not directly change the parity of the SCPT; rather, they excite the transistor to higher bands, from which the odd QP can escape spontaneously. The energy differences

![Image](227001-2)

FIG. 2 (color). (a) Lifetime histograms in the even (green) and odd (red) states. (b) $\gamma_{\text{in}}$ and (c) $\gamma_{\text{out}}$ vs source operating point at $Q_{\text{det}} = e$. (d) $\gamma_{\text{out}}$ at $Q_{\text{det}} = 0.9e$. (e) Radiative cascades in the source emit microwave radiation that excites interband transitions (f) in the detector. Solid lines in (c), (d) correspond to $\hbar \omega_J = \delta E_{A,B}$ (light blue), $\hbar \omega_J = \delta E_{C,D}$ (dark blue), $\hbar \omega_p = \delta E_{C,D}, n = 3$ (black), $\hbar \omega_p = \delta E_{C,D}, n = 2$ (green). Dashed lines: mixing products with the detector’s self-resonance (see text).
ΔE_{A-D} for transitions A-D depend on the detector charge, so that at different Q_{det} the detector is sensitive to different sets of frequencies.

What emission processes in the source SCPT drive these transitions? It is convenient to represent the voltage-biased source by the states |n, k⟩, where n is the number of charges on the island, k is the number of charges that have passed through the device, and the energy of the state |n, k⟩ is given by E_{n,k} = E_{C}(n - Q_{src}/e) - keV_{src} [23,24], as shown in Fig. 2(e). As Cooper pairs are transported through the device under voltage bias, the system cascades down the energy ladder, emitting microwave radiation into the environment; the linewidth of this radiation is set by voltage fluctuations across the device. The processes labeled J in the figure correspond to a transfer of a Cooper-pair (CP) across the whole device, producing the usual Josephson process.

The individual rates become immeasurably fast when the source is biased above its superconducting gap V_{gap} ~ 400 μV. The individual rates become immeasurably fast when the source is biased above its superconducting gap edge; this was also observed in Ref. [8].

While our model for the source-detector interactions does not explain all the features seen in Fig. 2(b)–2(d), it does account for the positions of the most prominent ones with good agreement and with no adjustable parameters. We emphasize that although our experiment is sensitive only to radiation at the relatively high frequencies of CP transitions, much lower frequencies approaching those of a typical qubit level splitting can be produced at electrometer bias points close to resonant CP tunneling lines. The intensity of the emitted radiation can be calculated, in principle, by solving the master equation for the biased transistor [23].

We further tested our interpretation of the data by studying the response of the detector to radiation with known frequency, applied by an external microwave generator. We spectroscopically mapped the transition frequencies of the detector by finding Q_{det} at which the CP escape rate was enhanced for a given frequency f_{μw} of the generator. The inset in Fig. 3(a) shows a histogram of the reflected probe signal over a 20 ms window at Q_{det} = 1; the two peaks correspond to the two telegraph levels of the signal in the even and odd states. The intensity plot in the main panel of Fig. 3(a) represents a stack of these histograms, acquired at different Q_{det} values in the absence of radiation. A similar plot is shown in Fig. 3(b) but with external radiation applied at f_{μw} = 44.75 GHz. At this frequency the weight in the histogram shifts from the odd to the even peak at a particular Q_{det}^0 = 0.76e. This shift in weight [dip in Fig. 3(c)], essentially an increase in P_{even}, occurs at different values of Q_{det}^0 for different frequencies f_{μw}, as shown in Fig. 3(d). These values are symmetric about odd-integer gate charges and are 2e periodic. We found that the CP escape rate γ_{out} at Q_{det}^0 grows linearly with microwave power (not shown), as expected from perturbation theory for photon-assisted tunneling.

If we now generate radiation by voltage biasing the source SCPT in place of the external generator and repeat the above measurements, the enhancement of the detector even-state probability should follow the same Q_{det}^0(f_{μw}) dependence of Fig. 3(d), where now the microwave fre-
The inset in (a) shows the histogram at $Q_{\text{det}} = e$. (b) Comparison of the time-averaged reflected probe signal, relative to the "dark" response, for a set of source voltages we have plotted the time-averaged reflected probe signal, the time-averaged reflected power ($P_{\text{ref}}$), and the radiation emitted by a voltage-biased SCPT electrometer. (c) Location of the dip in $\delta(P_{\text{ref}})$ vs microwave frequency $f_{\mu w}$. (d) The frequency $f_{\mu w} = 2eV_{\text{dc}}$ at $Q_{\text{det}} = 0.5e$ (offset for clarity). Diamonds: $Q_{\text{det}}^0(f_{\mu w})$ data of panel (d).

The inset in (a) shows the histogram at $Q_{\text{det}} = e$. (c) Difference between the devices. We thank K. W. Lehnert for valuable discussions.

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