Josephson squelch filter for quantum nanocircuits

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We fabricated and tested a squelch circuit consisting of a copper powder filter with an embedded Josephson junction connected to ground. For small signals (squelch ON), the small junction inductance attenuates strongly from dc to at least 1 GHz, while for higher frequencies dissipation in the copper powder increases the attenuation exponentially with frequency. For large signals (squelch OFF), the circuit behaves as a regular metal powder filter. The measured ON/OFF ratio is larger than 50 dB up to 50 MHz. This squelch can be applied in low temperature measurement and control circuitry for quantum nanostructures, such as superconducting qubits and quantum dots.

Quantum nanocircuits, such as superconducting qubits or semiconductor quantum dots, are nonlinear systems that are adversely influenced by noise. External noise sources are unavoidably introduced by connection lines for electrical or magnetic bias, operational signals, and measuring devices. Commonly these lines are permanently coupled to the quantum circuit. Low temperature filtering is used, but that leads to signal loss. We have developed a squelch circuit, a nonlinear filter that shorts all low amplitude signals from dc to high frequencies but transmits with low loss when a stronger signal is applied. It consists of a Josephson junction that acts as a nondissipative short for any current below its critical current.

FIG. 1. (Color online) The Josephson squelch circuit. (a) Printed circuit board with the chip containing the Josephson junction. The brownish areas to the left and right is the copper loaded epoxy containing the meandering signal wires. (b) Two complete filters with SMA connectors, built side by side. The total length is 11 cm containing 80 cm of thin Cu wire. (c) Scanning electron micrograph of a Josephson junction. The junction is fabricated using electron beam lithography and double angle shadow mask evaporation. The area is $1 \times 0.2 \, \mu m^2$ and the critical current density $j_c=15 \, \mu A/\mu m^2$. (d) Schematic of the Josephson squelch between a source of impedance $R_0$ and a load $R_L$. The Josephson junction is represented by a cross. (e) Transmission of the Josephson squelch. For low frequencies the Josephson junction acts like an inductive short, with transmission $\sim \omega$. For frequencies higher than the cutoff frequency of the copper powder filter $f > f_{\text{corr}}$, the absorption of the incoming noise increases exponentially with frequency.
$I_C\approx 2.9 \mu A$, yields $L_J=110$ pH and $R_c=110 \Omega$. Experimentally we measure a copper powder filter cutoff frequency of 80 MHz (see below); for this frequency one calculates $A'\approx 0.001$ or 60 dB for the small-signal attenuation by the junction inductance. The overall small-signal attenuation is smallest at 200 MHz, with $A\approx 50$ dB, shown as the maximum in Fig. 1(e). Beyond $f_c$, we measure that the filter attenuation increases by approximately 65 dB/decade.

The metal powder filter is built by using a two-component epoxy$^9$ loaded with copper powder. A thin (~0.1 mm) copper wire of 80 cm is meandered with a fixed spacing inside the epoxy-powder mixture so that the impedance is uniform along the filter wire. The Josephson junction is made of a 40 nm film of aluminum, fabricated using electron beam lithography and double angle shadow mask evaporation [Fig. 1(c)]. The junction sits on a 404 µm thick thermally oxidized silicon substrate and is placed on a printed circuit board (PCB) in a gap left in the center of the copper powder filter. The PCB is attached to the housing of the copper powder filter with bolts to allow for good thermal anchoring and electrical grounding. Then it is soldered to the pins that connect to the copper wire and the chip with mal anchoring and electrical grounding. Then it is soldered [see Fig. 1(a)]. Finally a metallic lid is tightly screwed onto the filter housing, preventing signal leakage.

The $S$-parameters of the Josephson squelch were measured with a HP-8753C Network Analyzer at room temperature and at 4 K. In the transmission $S_{21}$, the ~3 dB point was seen at 80 MHz at room temperature, increasing to 100 MHz at 4 K. Beyond this frequency the transmission dropped steadily down by 50 dB at 600 MHz. The reflection $S_{11}$ was seen to be ~20 dB up to 2 GHz, corresponding to an impedance of 60 Ω.

To characterize the performance of the Josephson squelch, we mounted it on the mixing chamber of a cryogenic dilution refrigerator with a base temperature of 15 mK. In the transmission $S_{22}$, the ~3 dB point was seen at 80 MHz at room temperature, increasing to 100 MHz at 4 K. Beyond this frequency the transmission dropped steadily down by 50 dB at 600 MHz. The reflection $S_{11}$ was seen to be ~20 dB up to 2 GHz, corresponding to an impedance of 60 Ω.

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We first used the Josephson junction to probe the attenuation of the copper powder at different frequencies. We ramped a current $I_{dc}$ through the Josephson junction to monitor its $I-V$ characteristic [Fig. 2(b)]. For this particular junction, we observed a critical current of 2.9 $\mu A$. On top of the ramping current, we added a high frequency signal $I_{ac}$ of small amplitude, $I_{\text{total}}=I_{dc}+I_{ac}$. The ac signal reaching the junction experienced the attenuation of half the copper powder, which is frequency dependent. Signals of frequency $f\gg 2f_{\text{co}}$, with $f_{\text{co}}\approx 100$ MHz being the cutoff of the copper powder filter, were strongly damped and did not affect the $I-V$ characteristic [green curve in Fig. 2(b)]. As the frequency was decreased below $f_{\text{co}}$, the signals reaching the Josephson junction had increasing amplitude that was added to the slow current ramp, so that less $I_{dc}$ was needed to reach $I_C$. As a result, the critical current of the Josephson junction appeared to effectively decrease [as seen progressively in the brown, red, and black traces in Fig. 2(b)].

The squelch action was probed by applying a signal of small amplitude from the network analyzer (much smaller than $I_C$) and then adding a dc bias $I_{dc}$. In this measurement we used a Josephson junction with a critical current $I_C=1$ $\mu A$. As can be seen in Fig. 3, for $I_{dc}<0.8$ $\mu A$ no signal beyond the noise floor was observed through the Josephson squelch. When the full current approached the critical current $I_{dc}+I_{ac} \approx I_C$, we measured a progressive increase on the voltage acquired by the amplifier. This is a direct proof of the performance of a Josephson junction used as a controllable squelch. When $I_{dc}=1.2$ $\mu A$, the Josephson junction was in
its dissipative state and the signal saturated. In an actual quantum circuit application [see Fig. 1(d)], when a load $R_L$ is employed behind the Josephson squelch, the pulse that probes the load needs to have a large enough amplitude so as to switch the junction to the voltage-carrying state.

When the applied power was low enough, only the noise coming from the amplifier was observed. Taking the difference between the traces at 0 $\mu$A and at 1.2 $\mu$A in Fig. 3, the ON/OFF ratio was seen to be at least 50 dB up to 50 MHz, where a resonance in some part of the circuit was observed.

In summary, we have developed a squelch circuit that integrates a high frequency low-pass copper powder filter with a Josephson junction that acts as the signal-level-dependent element. The squelch operates from dc to more than 50 MHz with an ON/OFF ratio of more than 50 dB. The Josephson squelch is highly attractive for the operation of quantum nanocircuits, where the interaction between instrumentation and nanocircuit needs to be active only during specific short periods while optimal isolation is required at all other times. In particular, dephasing due to low frequency noise in control and measurement lines can be strongly suppressed.

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9. Epoxy Bison, Cu powder 10 $\mu$m average diameter. Mixing ratio epoxy/copper 30/70 (by weight).