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#### ABSTRACT

Characterizing superconducting microwave resonators with highly dissipative elements is a technical challenge, but a requirement for implementing and understanding the operation of hybrid quantum devices involving dissipative elements, e.g., for thermal engineering and detection. We present experiments on  $\lambda/4$  superconducting niobium coplanar waveguide resonators, terminating at the antinode by a dissipative copper microstrip via aluminum leads, such that the resonator response is difficult to measure in a typical microwave environment. By measuring the transmission both above and below the superconducting transition of aluminum, we are able to isolate the resonance. We then experimentally verify this method with copper microstrips of increasing thicknesses, from 50 nm to 150 nm, and measure quality factors in the range of 10–67 in a consistent way.

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Superconducting microwave resonators are the cornerstone of much of the current state-of-the art superconducting quantum technologies. Their intrinsic electromagnetic properties routinely enable high quality factors, typically over 10 000,<sup>1</sup> allowing for extremely sensitive measurements, for example, the multiplexed readout of the dispersive shift of a weakly coupled quantum bit,<sup>2–4</sup> a fundamentally important tool for quantum information, or photon absorption of a microwave kinetic inductance detectors (MKIDs),<sup>5–8</sup> a tool widely used in astronomy. On the other hand, dissipative elements added to superconducting microwave circuits are finding increasing applications in the fields of microwave amplification,<sup>9,10</sup> circuit quantum environmental engineering,<sup>11–13</sup> quantum information,<sup>14</sup> and circuit quantum thermodynamics.

In superconducting circuits, normal metal elements can be easily integrated into the existing chip architecture and provide channels for intentional decoherence, such as for quantum bit initialization,<sup>11–13</sup> precise temperature control (electronic heating and cooling),<sup>18,19</sup> and ultrasensitive calorimetry.<sup>20</sup> Notably, these devices are in use as high-speed thermometers and microwave photon sources.<sup>21,22</sup>

Experimentally characterizing such dissipative resonators is challenging by conventional single tone spectroscopy, as the dissipation results in a broad and shallow resonance, often unresolvable from the electronic noise of a cryogenic high electron mobility transistor (HEMT) amplifier and the frequency dependent variations of transmission in the experimental setup. In this report, we present a method for this task utilizing an intermediate superconductor with a lower critical temperature, enabling us to isolate the resonance by performing characterization at differing bath temperatures, with measured quality factors as low as 10.

The method presented is demonstrated here using a structure consisting of two  $\lambda/4$  niobium coplanar waveguide (CPW) resonators, both inductively coupled to a common CPW transmission line, shown in Fig. 1(a), used for multiplexed readout. On the left is a fully super-conducting  $\lambda/4$  CPW resonator to act as a reference. On the right resonator, the voltage node is terminated by an aluminum-copper-aluminum constriction, forming a Nb/Al/Cu/Al/Nb heterostructure, with the copper acting as the dissipative normal metal shown in the micrograph in Fig. 1(b).

Samples are fabricated on a 330  $\mu$ m thick c-plane sapphire substrate using a process described in Ref. 17. The sapphire surface is initially cleaned with an argon ion plasma milling before a 200 nm thick niobium film is deposited by DC magnetron sputtering. The coplanar waveguide resonator patterns are written by electron-beam lithography (EBL) and transferred to the niobium film using an  $SF_6 + O_2$ reactive ion etching process. As the niobium layer is thick, subsequently comparatively thin evaporated aluminum and copper films are fragile and can become discontinuous at the intersection. Therefore, during the EBL exposure, the dose at the interface is incrementally changed, forming a ramp when etched to remove the discontinuity and increase the surface area. The Al/Cu/Al terminations are written by electron-beam lithography onto a bilayer resist and grown using double-angle deposition in an electron-beam evaporator, with the galvanic contact between lithographic layers facilitated by an in situ argon ion plasma milling process removing native oxides on the niobium. At the beginning of deposition, 10 nm of aluminum is evaporated to improve adhesion to the sapphire surface, followed by copper (of variable thickness; 50 nm, 100 nm, and 150 nm for different devices). Finally, two 110 nm thick aluminum contacts to the niobium CPW are deposited. After processing, the substrates are diced with a diamond-embedded resin blade, wire-bonded to the sample stage assembly described in Ref. 23. Finally, the sample is loaded into a cryogen-free dilution refrigerator with a base temperature of 10 mK.

All spectroscopic measurements are performed using a vector network analyzer (VNA) at room temperature with the signal reaching



FIG. 1. Device and measurement setup. (a) The image shows two  $\lambda/4$  resonators inductively coupled to a transmission line. The left resonator is a standard  $\lambda/4$ superconducting resonator with one end of the center conductor directly shorted to the ground plane on chip, and the other end is an open circuit to the ground. This resonator acts as a reference. The right side resonator is a copper-terminated (Al-Cu-Al)  $\lambda/4$  resonator. At right and left bottom, four test junctions are made for characterizing the DC electronic properties. (b) Scanning-electron microscopy image of the yellow outlined region of (a), highlighting the AI/Cu/AI junction in contact with the center conductor of the resonator at the right side and with ground at the left side. The image is colored with orange for copper, cyan for aluminum, and purple for niobium. (c) Equivalent lumped circuit for the copper terminated  $\lambda/4$  resonator. The coupled-inductor symbol represents the dominant coupling mechanism between the in/output transmission line and the resonator. The resistance R represents the copper termination. (d) Measurement setup. The microwave signal is introduced from port 1 by a vector network analyzer (VNA) at room temperature and passes through several attenuators distributed at different temperatures to the input of the device at 10 mK. The output microwave is measured at the port 2 of VNA through two isolators and two amplifiers.

the sample via an attenuated microwave line. The attenuation is distributed at various temperature stages of the dilution refrigerator, as shown in Fig. 1(d). This setup reduces Johnson-Nyquist noise from the attenuators at higher temperature stages.<sup>24</sup> The signal leaving the sample is then passed through two circulators at base temperature, to a low noise HEMT amplifier mounted at 4 K, providing 80 dB isolation from the amplifier input. Outside of the dilution refrigerator, the signal is passed through an additional 30 dB amplifier, before it is received by the VNA, capturing both *I* and *Q* quadratures, from which we reconstitute the transmission *S*<sub>21</sub>. The transmission through the system reads

$$S_{21}^{notch} = a e^{i\alpha} e^{-2\pi i f \tau} \left[ 1 - \frac{(Q_l/|Q_c|) e^{i\phi}}{1 + 2iQ_l(f/f_r - 1)} \right].$$
(1)

Here, *a* is the overall amplitude,  $\alpha$  is the phase shift contributed by various components in the circuit,  $\tau$  is the electronic delay caused by the length of the cable and the finite speed of light, and  $\phi$  quantifies the impedance mismatch.<sup>25,26</sup> Parameters f and  $f_r$  denote the probe frequency and the resonance frequency of the resonator, and  $Q_l$  and  $Q_c$ are the loaded quality factor and the coupling quality factor, respectively.<sup>27</sup> The quality factor is the ratio of energy stored in a resonator to average energy lost per cycle. The photon loss rate, inversely proportional to the quality factor, is a linear combination of the internal losses of the resonator and corresponds to the losses arising in the coupling from the resonator to the transmission line. The inverse of the loaded quality factor reads  $1/Q_l = 1/Q_i + 1/Q_c$ . The  $Q_l/Q_c$  ratio determines the depth of the notched transmission and is maximized at  $Q_l \approx Q_c$  at the resonance frequency. In order to increase the measured signal for a lossy resonator, we require  $Q_c \ll Q_i$ , meaning that there are more photons leaving the resonator than dissipated ones.

In the samples measured, a quality factor of 20 was desired corresponding to favorable operation of the envisioned device, the quantum heat engine.<sup>16,17</sup> The quality factor of our samples can be estimated by a simple model which terminates the center conductor of the CPW transmission line and the ground through a lumped resistance *R* at the voltage node and capacitively to the ground at the current node. The impedance of our  $\lambda/4$  transmission line, shown in Fig. 1(c), is given near this resonance by  $Z = -i\pi Z_{\infty}(f/f_r - f_r/f)/4$ , where  $Z_{\infty} = 50 \Omega$  is the characteristic impedance of an infinite transmission line. Power injected to the termination at the half-power points  $f = f_r \pm \Delta f/2$  can be written as  $P \simeq V^2/(R(1 + (\pi Z_{\infty}/4R)^2(\Delta f/f_r)^2))) = V^2/2R$ , where  $\Delta f$  is the width of the resonance peak. By definition, the internal quality factor  $Q_i$  of the resistively terminated resonator can be written as

$$Q_i = \frac{\pi Z_\infty}{4R}.$$
 (2)

To measure the low  $Q_i$  coupling should be increased  $(Q_c \ll Q_i)$ ,<sup>28</sup> in order to maximize the measurable signal. For us, however, even though the coupler covers half of the cavity length to achieve the strong coupling regime,  $Q_i$  is still dominated by  $Q_i$ . Due to the low overall quality factor, the depth of the notch in  $S_{21}$  is of order 1 dB, which typically cannot be resolved within the background of the microwave setup. To isolate the resonator, the method presented here is based on measuring the spectrum above and below the critical temperature of aluminum  $T_{c,Al}$ . The lower quality factor  $Q_i$  of the resonator above  $T_{c,Al}$  suppresses the resonance. Under these high temperature conditions, the transmittance can be regarded as a reference measurement for the background. The transmission through the CPW line is shown in Fig. 2(b), with the red and blue traces measured at different temperatures  $T_H$  and  $T_L$ , above and below the critical temperature of the aluminum  $T_{c,Al}$ , respectively, yet staying sufficiently below the critical temperature  $T_{c,Nb}$  of the niobium transmission line. Here,  $T_{c,Al}$  and  $T_{c,Nb}$  can be determined by the resistance-temperature characteristic of a coprocess sample shown in the inset of Fig. 2(a). A narrow band of  $S_{21}(T_L)$  is shown in the right inset of Fig. 2(b), emphasizing the narrow bandwidth of the standard reference resonator. Here,  $f_0$  is extracted as 7.246 GHz with a corresponding 5 MHz shift with temperature, as the kinetic inductance increases with decreasing temperature.<sup>29,30</sup> The dissipative resonator is not clearly visible in either trace. We observe, however, that as expected, due to lower operating temperature and thus more ideal superconducting characteristics of the CPW transmission line, the blue trace is consistently higher than the red trace, except in the region highlighted in yellow, centered around the design frequency of the dissipative resonator. By taking the ratio of the two  $S_{21}$  measured at  $T_L$  and  $T_H$ , one can isolate the resonance of the dissipative resonator. This ratio is shown in Fig. 2(b). Fitting a standard notched resonator model<sup>27</sup> to the trace, the parameters  $f_{i2}$   $Q_{i2}$  and  $Q_i$  can be extracted, with data for different samples (with variable thicknesses of copper) presented in Table I.



**FIG. 2.** (a) Transmittance spectra of the device with 100 nm thick copper termination. The red and blue curves are measured at  $T_H = 2$  K and  $T_L = 10$  mK, respectively, as indicated by arrows in the inset. Here,  $T_L$  and  $T_H$  satisfy  $T_L \ll T_{c,AI} < T_H < T_{c,Nb}$ . The inset shows resistance-temperature characteristics of a nominally identical coprocess dissipative element, demonstrating three plateaus corresponding to the superconducting transitions of aluminum and niobium, respectively. The yellow region demonstrates the frequency range of the resistively terminated superconducting resonator. We present in the right inset of (b) the quality factor of 2.8 × 10<sup>4</sup> at resonant frequency  $f_0 = 7.246$  GHz of the reference resonator. (b) The amplitude of  $S_{21}(T_L)/S_{21}(T_H)$  and the phase in the left inset. Within the yellow highlighted frequency region, we see the resonance of the dissipative resonator. Here, we extracted  $f_r$  and  $Q_i$  as 6.71 GHz and 45 corresponding to the green dashed fitting line.

ARTICLE

Thickness	50 nm		100 nm		150 nm	100 nm <sup>a</sup>	
Sample	A-1	B-1	B-2	B-3	C-1	D-1	D-2
$f_r$ (GHz)	6.54	6.74	6.69	6.70	6.53	6.67	6.67
Q <sub>c</sub>	330	340	200	250	320	150	460
$Q_i$	10.3	45.3	53.2	44.7	66.3	20.4	26.5
$Q_{i,err}$	0.5	0.5	0.9	0.3	1.3	0.2	0.8

<sup>a</sup>Samples with increased contact resistance between the niobium and aluminum layers.

In order to investigate how the  $Q_i$  of the resistively terminated superconducting resonator depends on its resistance R, the coprocess samples with identical termination elements [see the red dashed frame in Fig. 1(a)] are measured in a current biased four probe configuration at a 50 mK bath temperature. A measured IV curve is shown for the 150 nm thick copper termination in Fig. 3(a). By ramping the bias current up through the termination, we observe first the superconducting energy gap and then two resistive branches at higher bias. The superconducting state exists by virtue of the proximity effect in the superconductor-normal metal-superconductor (SNS) Josephson junction induced by the Al/Cu/Al structure,<sup>31,32</sup> and the termination switches to the first dissipative branch at current  $I_{sw1} = 5.6 \ \mu A$  with normal state resistance  $R = 0.87 \Omega$ . The normal resistance R due to the copper wire and the imperfect contact between the aluminum and the copper layers determines the quality factor of the resonator in the microwave measurement at  $T_L$ . Continually increasing the current, the resistance increases at  $I_{sw2} = 43.3 \ \mu\text{A}$  with resistance  $R_{>} = 4.83 \ \Omega$  when the current exceeds the critical current of aluminum. R> consists of R, the normal state resistance of aluminum wire and the Al/Nb contact. All the measured parameters  $I_{sw1}$ ,  $I_{sw2}$ , R, and  $R_{>}$  extracted from IV measurement are given in Table II.

The presence of supercurrent in SNS junctions is due to the wellknown proximity effect.<sup>33–36</sup> Based on the ratio of the Thouless energy  $E_T = \hbar D/L^2$  to the superconducting gap of aluminum  $\Delta$ , the junction is in the long junction regime, when  $E_T \Delta \ll 1$  and the zero temperature  $eRI_c$  is found to be proportional to  $E_T$  in this limit. Here, L is the length of the junction,  $D = v_F l_e/3$  is the diffusion constant of the N metal,  $v_F$  is the Fermi velocity,  $I_c$  is the critical current of the junction, and  $l_e$  is the elastic mean free path of electrons. In Table II,  $eRI_{sw1}$  is smaller than 5  $\mu$ eV, indicating a long junction limit.

The N lead between S superconductors of the resonator is an ideal element to localize heat. The small volume of normal metal enhances the temperature of the element at fixed transferred power, whereas the S

TABLE II. DC properties of Nb/Al/Cu/Al/Nb junctions.

Thickness	50 nm		100 nm		150 nm		100 nm <sup>a</sup>	
Sample	A-2	A-3	B-4	B-5	C-2	C-3	D-3	D-4
I <sub>sw1</sub> (μΑ)	0.2	0.3	2.1	1.8	5.6	2.6	0.74	1.0
I <sub>sw2</sub> (μΑ)	19.6	22.8	39.0	40.0	43.3	42.0	21.0	21.1
$R(\Omega)$	5.3	4.3	1.7	1.6	0.9	1.3	3.3	2.8
$R_{>}(\Omega)$	21.5	16.0	8.2	7.9	4.8	5.2	19.4	19.5

<sup>a</sup>Samples with increased contact resistance between the niobium and aluminum layers.

forms a Cooper pair while injecting an electron from N and reflects a hole known as Andreev reflection that drops the temperature at the interface and localizes the heat efficiently in the N.<sup>37</sup> Depending on the application and operation regime, the quality factor  $Q_i$  of the resistively terminated resonator can be designed merely by the resistance of the N element in the long junction regime. In Ref. 17,  $f_r/Q_i$  is identified as the coupling between the copper heat bath and the resonator.

In Fig. 3(c), we plot the measured  $Q_i$  from Table I as blue dots. The theoretically expected  $Q_i$  is shown as an orange line. The expected slope by Eq. (2) is shown with  $Z_{\infty}$  set to 50  $\Omega$ . For a more general analysis of the internal quality factor, a model that takes into account the nonvanishing quality factor above the aluminum superconducting transition temperature can be used to simulate the measurement technique by inserting  $R_>$  into Eq. (2) to obtain  $Q_i(T_H)$ .  $Q_i(T_L)$  and  $Q_i(T_H)$  are independent dissipation channels with  $1/Q_l = 1/Q_i$  $+1/Q_c$ , which are then inserted into Eq. (1) to obtain the general two temperature model,  $S_{21}(T_L)/S_{21}(T_H)$ . Here,  $Q_i(T_L)$  is extracted from



**FIG. 3.** (a) and (b) *VI* measurement for the termination element of Nb/Al/Cu/Al/Nb of the 150 nm thick copper.  $I_{sw1}$  is the critical current of the SNS junction and  $I_{sw2}$  denotes the critical current of aluminum. Applying current below  $I_{sw2}$  and over  $I_{sw1}$  leads to the slope marked with a light blue dashed line originating from the resistance *R* of copper wire and the Cu/Al contact resistance. At a bias current exceeding the critical current of the aluminum wire, the copper, aluminum, Cu/Al contact resistance, and Nb/Al contact resistance all contribute to the total resistance  $R_{>}$ . (c)  $Q_i$  extracted by fitting two models, notch  $S_{21}$  and divided notch  $S_{21}/S_{21}(R_{>})$  vs the reciprocal measured termination resistance *R* in blue dots and green hollow circles, respectively. The orange solid line denotes theoretical  $Q_i$  as a function of reciprocal termination resistance.

the model and plotted as green hollow circles. The slopes of extracted  $Q_i$  vs 1/R from the two models differ by less than 12%, which places the values within the uncertainty of the fitting algorithm. According to Table II,  $R_{>}$  decreases while the thickness of the copper increases. The lower  $R_{>}$  in the thicker samples yields a broader resonance when aluminum undergoes the transition to normal state, which explains the difference of extracted  $Q_i$  for the thicker Cu films. However, the measured  $Q_i$  is approximately double the expected value. The plausible origin of the discrepancy with respect to Eq. (2) is that the admittance of the SNS junction is composed of parallel dissipative (real) and reactive (imaginary) components,  $Y_R$  and  $Y_L$ , respectively.<sup>38</sup> In this case, the actual quality factor  $Q_i$  is enhanced with respect to Eq. (2) by a factor  $(Y_R^2 + Y_I^2)/Y_R^2$ , and while the contribution of the phase is challenging to measure, based on the  $I_{sw1}$  and R values presented in Table II, we estimate that this can lead to an enhancement of approximately factor 2, which would explain the discrepancy.

In conclusion, we have presented a technique for isolating the resonance of low-quality dissipative superconducting resonators based on the transition temperature of an intermediate superconductor with a lower energy gap as compared to that of the superconducting resonator. We have verified this method by characterizing a series of resistively terminated  $\lambda/4$  superconducting CPW resonators. From microwave measurements, we have extracted extremely low quality factors of 10-67 for resonators with different resistances of the copper termination element. While similar characterization exploiting the superconducting transition could be achieved by supplying sufficient power to the resonator in excess of the critical current of aluminum or bypassed completely by using a microwave switch to measure a background reference, we believe the technique presented here is more versatile, applicable also in highly attenuated microwave input lines, such as those being used in circuit quantum electrodynamics and thermodynamics experiments and more accurately measuring the microwave background closer to the device being characterized.

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