Application Note High Throughput Superconducting Microwave Resonator Characterization at mK Temperatures

Applications: Microwave Spectroscopy, Superconducting Qubits, Quantum Processing Units Production

Products: SHFQA+, SHFQC+, kiutra L-Type Rapid

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Abstract

We present the characterization of microwave superconducting resonators with a turnaround time of less than 5 hours. We make this possible by using a kiutra L-Type Rapid cryostat and the Zurich Instruments SHFQA+ Quantum Analyzer. Through an investigation of the internal quality factor as a function of input power and temperature, our work showcases fast and reliable radiofrequency superconducting resonator measurements at millikelvin temperatures.

Introduction

Microwave resonators are an essential building block of superconducting quantum processor units, where they are used for qubit readout. Their characterization is an established method to gauge materials for the fabrication of superconducting qubits and to improve fabrication methods by tracing noise sources and decoherence mechanisms that affect the superconducting qubits, such as two-level-systems (TLS) [1]. The performance of a superconducting microwave resonator is hereby assessed by measuring its internal quality factor (Q_{int}), a measure of how efficiently it stores energy.

Rapid characterization of resonators close to the qubit operating temperature is imperative for fast development cycles in fabrication, and it should serve as a routine step to produce high-quality qubits and superconducting circuits in general, enhancing the efficiency and reliability of quantum computing chips manufacturing. The kiutra L-Type Rapid cryostat in combination with the Zurich Instruments SHFQA+ Quantum Analyzer addresses this demand by realizing fast turnaround times of less than 5 hours for the characterization of superconducting microwave resonators at millikelvin temperatures. If required, the fast and easy temperature control of the L-Type Rapid allows us to add a temperature-dependent measurement for an in-depth investigation of the resonator properties.

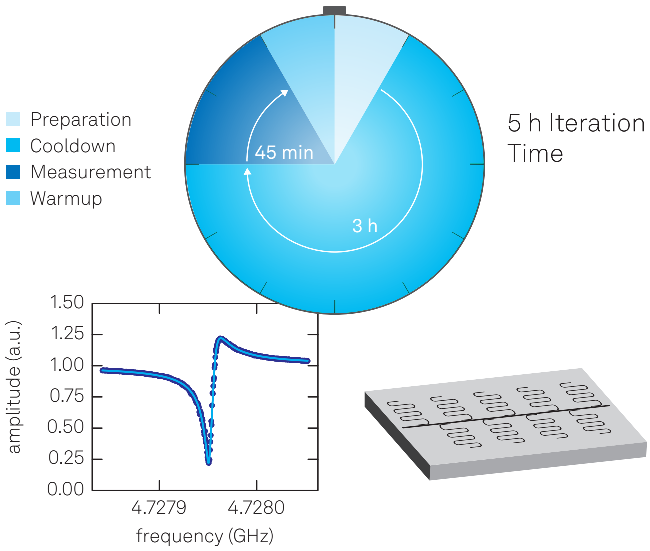

Figure 1. The combination of a kiutra L-Type Rapid cryostat and the Zurich Instruments SHFQA+ Quantum Analyzer enables fast and straightforward characterization of superconducting resonators with a turnaround time of less than 5 hours.

Measurement Plan

In this application note, we examine a sample of nine superconducting aluminium microwave resonators coupled to a common transmission line. The sample is packaged inside a copper box with two SMA connection ports. We mount

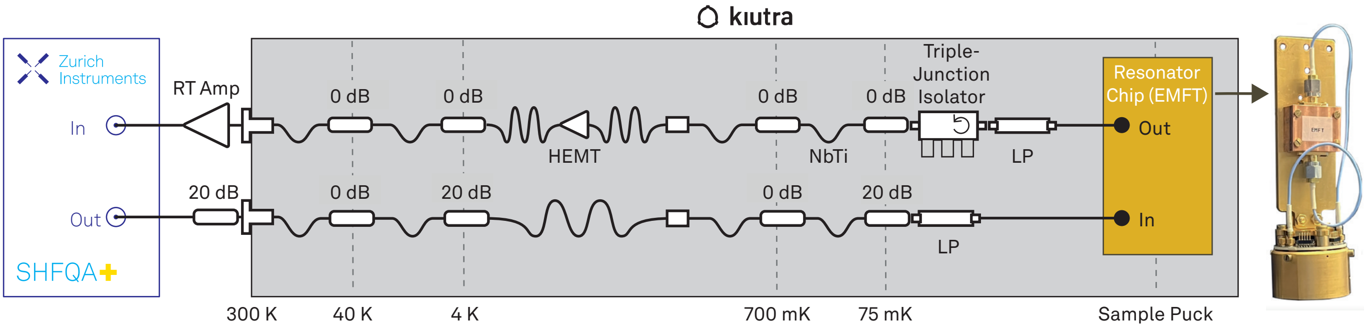

Figure 2. Measurement setup, L-Type Rapid cryostat wire tree and a picture of the resonator sample mounted on a kiutra Puck.

the sample on a custom-made adapter plate and mount it onto a kiutra Puck 36 as shown in Figure 2. Input and output ports of the sample box are connected to the RF lines on the puck, which mate with the internal RF lines upon loading into the cryostat.

The sample is loaded into an L-Type Rapid cryostat equipped with a commonly used microwave I/O chain and a multilayer magnetic shielding. The two RF lines that connect the sample and the relevant RF components are outlined in Figure 2. The lines are calibrated at kiutra with a precision of less than 3 dB before starting the experiments, which allows us to later determine the number of photons based on the input power [2]. To measure, we connect input and output lines from the SMA feedthroughs at the cryostat top plate to the two corresponding SHFQA+ ports.

The quality of the resonator is then determined in three steps. First, the resonances are identified to measure the resonators' center frequencies; second, the power dependence of the internal quality factor is measured for each resonator; third, as an optional step, the internal quality factor is determined as a function of temperature.

Experimental Results

Measurement of Center Frequency

After cooling the sample down to 75 mK, the first step is to find the resonators' center frequencies. To do this, we sweep the input signal frequency and measure its transmission at a fixed temperature. At the center frequency, the resonator exhibits maximum response and can be identified by a sharp dip in the transmission amplitude.

With 1 GHz bandwidth, the Frequency Sweeper Module of the SHFQA+ enables real-time spectroscopy close to the physical limit of the measurement technique. A frequency sweep can be directly programmed on the instrument, where the onboard data averaging and logging functionality significantly reduces the communication overhead during a measurement.

The resonators of the sample under investigation exhibit resonance frequencies distributed between 3.5 GHz and 5.5 GHz. The transmitted signal amplitude as a function of the input frequency is shown in Figures 3a and 3b. The resonance frequencies of all nine resonators are indicated with arrows. We scan this range in multiple segments. In each segment, we sweep the input frequency over 500 MHz with a step size of 50 kHz. Here, we set the input power to a level equivalent to ~1000 photons. Figure 3b shows one single scan from 4.5 to 5.0 GHz. We continue with a finer spectroscopy around each resonance.

Figure 4 shows typical data of the measured transmitted amplitude and phase for input powers equivalent to ~1 and ~1000 photons. We extract Qint from this data using a circle fit technique [3].

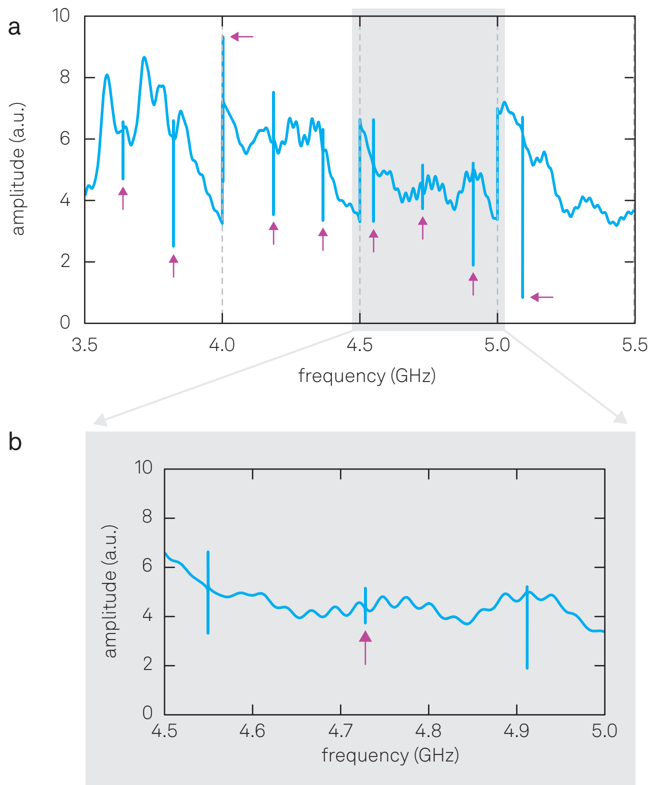

Figure 3. a) Transmitted signal amplitude as a function of the input frequency. The resonance frequencies of all nine resonators are indicated with red arrows. b) Single scan from 4.5 to 5.0 GHz.

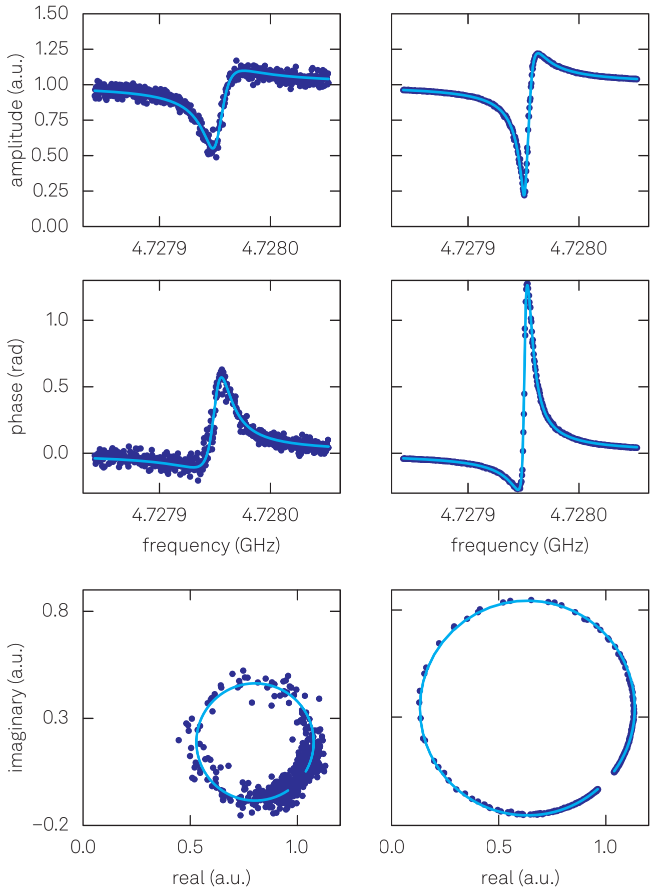

Figure 4. Transmitted amplitude and phase for input powers equivalent to ~1 photon (left column) and ~1000 photons (right column) around the resonance at 4.72795 GHz. We extract Qint from this data using a circle fit technique in the complex plane.

Power Dependence

To further characterize the resonator, we vary the input power and measure the corresponding change of Q_{int} (Figure 5a). The large power dynamic range of the SHFQA+ allows us to measure all resonators from single photon to saturation (> 106 photons) without using additional amplification or attenuation on the input line. Thanks to the real-time frequency sweeping and result logging, the measurement time per resonator and input power is on the order of tens of seconds (< 10 seconds for higher powers, 48 seconds for the lowest power). We observe that the input power influences the resonator's Q_{int}, as expected because of power-induced nonlinear effects and saturation of quasiparticles [4]. We fit our measurement results with a kiutra Python library for post-processing superconducting microwave resonator data, which uses a model based on Ref. [5]. The fit matches the data at lower and intermediate input powers very well, which allows us to assess the functionality of these devices, as low input power is used in typical quantum computing applications. At high power, Qint is influenced by material-specific loss mechanisms not included in the model.

Millikelvin Temperature Dependence

Finally, we measure Q_{int} for different temperatures ranging from 75 mK to 350 mK in steps of 10 mK (Figure 5a). The input power is kept constant at the single photon limit. Each temperature step needs only a few minutes to stabilize due to the efficient temperature control of the L-Type Rapid. Each frequency sweep takes 48 seconds (501 frequency points, 6 averages with 0.016 s integration time per point) at single photon input power level. As shown in Figure 5b, we observe an initial rise of Qint for increasing temperature, followed by a decrease towards higher temperatures. This behavior is expected, and the data can be fitted using a kiutra Python library that makes use of a model based on Ref. [6].

Conclusions and Outlook

We have combined technologies and products provided by kiutra and Zurich Instruments to realize a comprehensive characterization cycle of a superconducting microwave resonator in less than 5 hours. The full characterization cycle is shown in Figure 6. We have demonstrated that we can significantly reduce the time required for millikelvin temperature characterization compared to the combination of commonly used dilution refrigerators and vector network analyzers.

The measurements are fast and straightforward, thanks to the combination of the user-friendly L- Type Rapid cryostat

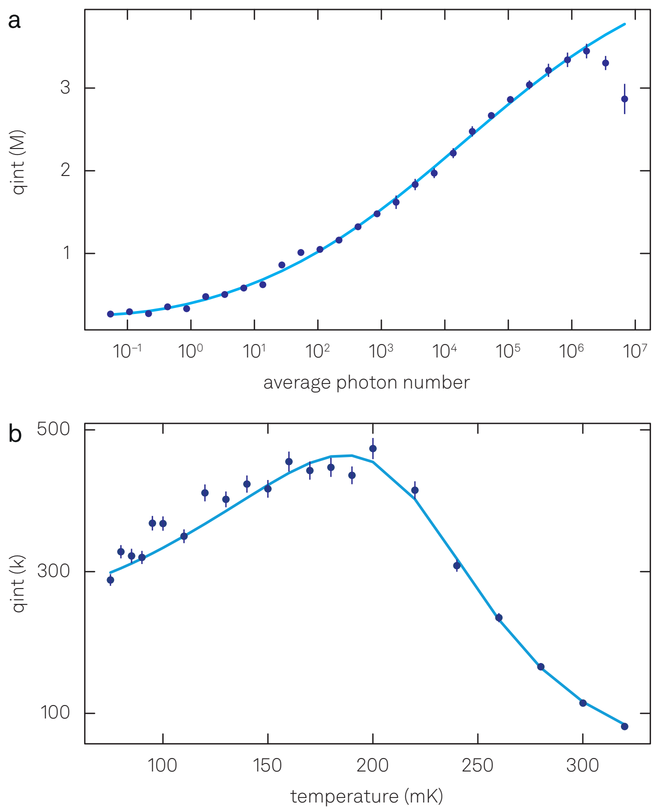

Figure 5. a) Measured Qint as a function of input power. b) Measured Qint at the single photon limit for varying temperatures.

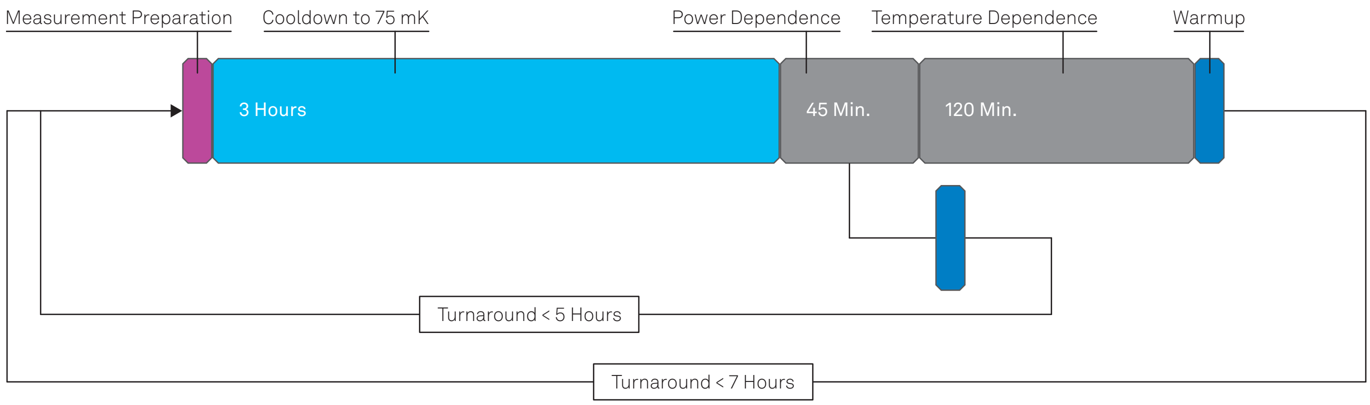

Figure 6. Turnaround time for the characterization of 9 superconducting resonators. The total measurement time including resonance frequency detection and power dependence of Q_{int} is less than 45 min, and another 120 min to measure the temperature dependence of Q_{int} for each resonator.

and the efficient measurement solutions provided by the Zurich Instruments SHFQA+. By automating key processes such as sample loading, cooldown, and temperature control, the L-Type Rapid minimizes manual effort and ensures consistent and repeatable results. Its sample exchange system with a transfer cage also makes consecutive device loadings easy. This level of efficiency and automation makes the L-Type Rapid an ideal solution to be integrated into fabrication environments and shared research facilities.

Looking ahead, the ability to rapidly characterize superconducting microwave resonators and investigate their performance as a function of input power and temperatures will be increasingly valuable as quantum technologies advance. Simplifying the full characterization chain, as shown here, will help researchers to fabricate superconducting radiofrequency devices much faster, reducing time and effort in the process.

Acknowledgements

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About Us

kiutra is a pioneering cryogenics company headquartered in Munich, Germany. We want to turn cooling from a bottleneck into a key enabler for quantum science and technology. We do this by providing simplified, fast and modular cooling solutions as well as services at ultra-low temperatures.

Zurich Instruments makes cutting-edge instrumentation for scientists and technologists in advanced laboratories. We have revolutionized instrumentation with fully digital lock-in amplifiers and the first commercial quantum computing control system. By combining excellent hardware, signal generation, and signal analysis in the frequency-domain and time-domain within single products, we help to reduce the complexity of laboratory setups and support innovative measurements in the DC to Gigahertz range.

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