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QUARTER-WAVE RESONATOR WITH THE OPTIMIZED SHAPE FOR QUANTUM INFORMATION SYSTEMS*

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Abstract

Quantum computers (QC), if realized, could disrupt many computationally intense fields of science. The building block element of a QC is a quantum bit (qubit). Qubits enable the use of quantum superposition and multi-state entanglement in QC calculations, allowing a QC to simultaneously perform millions of computations at once. However, quantum states stored in a qubit degrade due to limitations on the qubit lifetime, and due to interactions with the environment. One technical solution to improve qubit lifetime is a circuit comprised of a Josephson junction located inside of a high quality factor (Q-factor; $Q_L > 10^8$ at 6 GHz) superconducting three-dimension (3D) cavity.

RadiaBeam Systems, in collaboration with Argonne National Laboratory and The University of Chicago has developed a superconducting radiofrequency quarter-wave resonant cavity (QWR) for quantum computation. Here a 6 GHz QWR was optimized to include tapering of the inner and outer conductors, a toroidal shape for the resonator shorting plane, and the inner conductor to reduce parasitic capacitance. In this paper, we present the results of the qubit cavity design optimization, fabrication, processing and testing in the single-photon excitation regime at millikelvin temperatures.

INTRODUCTION

Nearly all areas of modern life are influenced by the incredible impact of computational capabilities. A quantum computer, if realized, could disrupt many computationally intense fields of science, including several high-energy physics disciplines: cosmology, quantum field theory, particle interactions, and nuclear physics. The elemental building block of a QC is quantum bit (qubit), which is a two-level system. Qubits enable the use of quantum superposition and entanglement in QC calculations, allowing a QC to simultaneously perform millions of computations at once. Entanglement lets a QC change the state of multiple qubits simultaneously via adjusting the state stored in a single bit, enabling scaling of computational power unachievable with traditional computers [1].

Complex physical problems require powerful machines consisting of many qubits arrayed in a high-speed network. However, the qubit state can degrade rapidly due to spurious interactions with the environment. One technical solution to improve qubit lifetimes is to construct a logical qubit comprised of a Josephson junction [2] located inside of a high Q-factor superconducting 3D cavity. The quantum state excited in the Josephson junction physical qubit is protected from environmental noise and loss by the high-Q resonant cavity.

The coherence time is closely related to the Q-factor of the resonator and its energy dissipation. Current qubit 3D resonators can achieve Q~10^8 and coherence time of several milliseconds [3]. On the other hand, niobium resonators used in particle accelerators can reach quality factors of ~10^{11} [4], potentially enabling storage times approaching seconds if adopted for operation in the quantum regime.

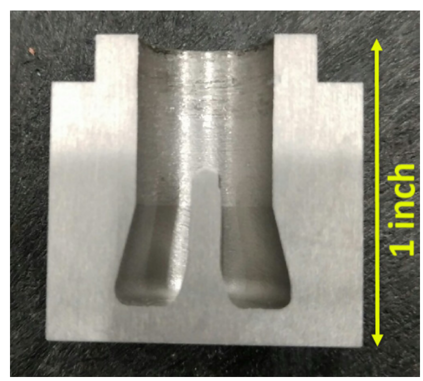

Figure 1: Section of machined niobium qubit 3D resonator with the optimized shape.

In this paper, we will present a 3D Superconducting Radio-Frequency (SRF) Quarter-Wave Resonator (QWR) with shape optimized for operation in the quantum regime [5] (see Fig. 1), developed by RadiaBeam Systems, in collaboration with Argonne National Laboratory and The University of Chicago.

SHAPE OPTIMIZATION

We performed a series of numerical simulations and optimizations to decrease energy dissipation in the QWR. The G-factor parameter was mainly used to measure shape-defined losses since it defines the efficiency of the developed shape. In SRF cavities the unloaded Q-factor can be defined as $Q_0 = \frac{G}{R_S}$. Here, G is the geometric-factor, which ranks the cavity's effectiveness in providing the "useful"

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electric field due to the influence of its shape alone and excludes specific material wall loss. Higher G results in higher Q_0 and thus indicates a better cavity design. R_s is the surface resistance, defined by the material and operating conditions. As a reference model, we used the straight QWR shape adopted by researchers at Yale [4]. During the optimization we also considered the fabrication limits on the cavity dimensions.

First, we adjusted the geometry of the top part of the resonator. For the QWR geometry, this is the region where the major part of the magnetic field is concentrated, thus by modifying this part of the resonator we expect to improve the G-factor. We first simulated geometries with different blending radius for the top part of the cavity. After we explored the outer conductor blending, we optimized the shape of the inner and outer conductors by adding tapering. We further sought to optimize the taper by adjusting the tapering start point for the inner and outer conductors. To increase the qubit-cavity dipole coupling strength, the inner and outer conductor dimensions were also optimized. Optimization started by adjusting the inner conductor radius, followed by simulations to find the optimal width of the gap between the inner conductor tip and outer conductor wall.

The surface electric field is the primary source of dissipation in thin dielectric layers which are usually present on the surface of superconducting cavities. In QWR cavities, most of electric field is concentrated on the tip of the inner conductor. Sharp edges of the straight geometry of the central pin are typically the places where the E-field is highly concentrated. We blended this feature to reach a more uniform E-field distribution. We furtherinvestigated dielectric losses [6] by simulating a thin Nb oxide layer on the cavity surface. Prevailing surface oxide in niobium RF cavities is Nb_2O_5 [7]. The results of simulations showed that a 5 nm thick Nb_2O_5 layer limits th Q-factor of the optimized geometry to $5.5 \cdot 10^8$. This is almost two times better than the simulated dielectric Q-factor of $2.8 \cdot 10^8$ for an unoptimized geometry.

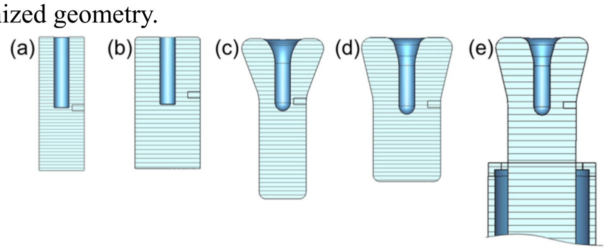

Figure 2: QWR design optimization: reference model (a), optimized straight geometry (b), optimal design not feasible with machining (c), final design optimized for machining fabrication (d) and design with RF choke (e).

We then explored limiting the RF losses in the resonator seam. The surface magnetic field in the region of the weld induces currents flowing across the seam. Lower seam conductivity may introduce additional losses; therefore, we tried to minimize the surface H-field on the seam. One design solution to reduce the seam loss is the introduction of an RF choke. However, an RF chock joint was beyond the scope of this proof-of-principle work.

Table 1: Comparison of RF Parameters of Different Resonator Designs Referred to in Figure 2

Design	a	b	c	d	e
R/Q, Ω	46.8	54	77	55	55
G-factor, Ω	44	57	62	71	71
H-field on seam, A/m	4800	16800	440	14300	7

A comparison of the RF parameters for the different designs (Fig. 2 c-d) is presented in Table 1. Comparing to the reference design, the G-factor is enhanced by 65%.

ENGINEERING AND FABRICATION

The engineering design of the cavity included system integration, thermal management, magnetic shielding, vacuum conductance, and signal acquisition. The final system is shown in Fig. 3. Starting from the inside out, the full-length cavity was truncated to have a separate lower field region made from aluminum, which would also provide connection points for the RF signals through non-magnetic SMA connectors. We then made estimates of thermal conduction and the choice of the fastener materials to assure that any thermal contraction of the fasteners would be large enough to maintain sufficient thermal contact while not deforming the niobium cavity.

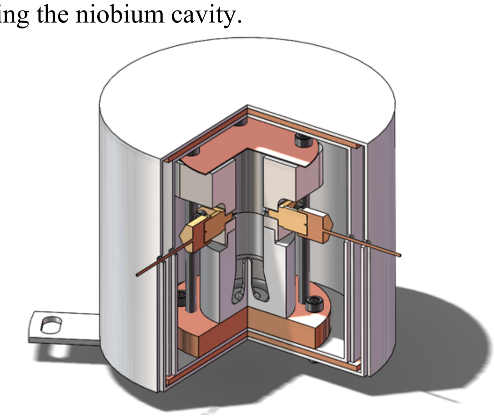

Figure 3: Full assembly with two layers of magnetic shielding, IR shield copper cap, SMA penetrations, and niobium 3D resonator.

The entire fridge is protected by a magnetic shield and the field at the resonator position inside this shield has been measured to be around 1-2 mG. However, due to the circulator placed at 1cm, increasing the fields to maximum 10 mG at the sample position. Additionally, a simple magnetic shield was designed in Cryoperm 10, a unique cryogenically friendly steel alloy that retains functional permeability at cryogenic temperatures more effectively than conventional MuMetal [8]. This magnetic shield uses two separate shielding cans each manufactured from 1mm thick Cryoperm 10 that is separable for assembly of the device under test while permitting small penetrations for SMA cables.

Finally, the full system was re-analyzed to ensure that the additional material did not affect the original assembly's thermal calculations and provisions were made to ensure the full system could be mounted onto the available

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test plate within the University of Chicago dilution refrigerator for 10mK cooldown.

Figure 4: Machined Niobium resonators before (left) and after (right) 1:1:2 buffered chemical polishing at Argonne.

Two solid niobium 6.2 GHz quarter wave resonators were machined at RadiaBeam, and then cleaned, etched and high-pressure-rinsed at Argonne National Laboratory. Figure 4 shows the cavities before and after etching. Both cavities were processed according to the following procedure: 1 hour ultrasonic cleaning in 40° C, 4% alconox solution, water rinsed, dried with filtered and de-ionized nitrogen gas, then a 150 minute buffered chemical polish (BCP) in a 1:1:2 (HF:HNO_3:H_3PO_4), followed by 1 hour ultrasonic cleaning, drying, high-pressure water rinse, and final air dry in a class 10 clean room. The finished resonators were triple bagged in the clean room for transfer to the University of Chicago.

RESONATOR TESTS

Two etched resonators, one with the simple and the other with the optimized shape (shapes b and d, as shown in Fig. 2) were delivered to the University of Chicago for the Q-factor measurements in a quantum regime [9] (10 mK temperature at few-photon power levels). We also delivered the aluminum part with SMA connectors, test stand assembly, and the magnetic shielding as shown in Fig. 5.

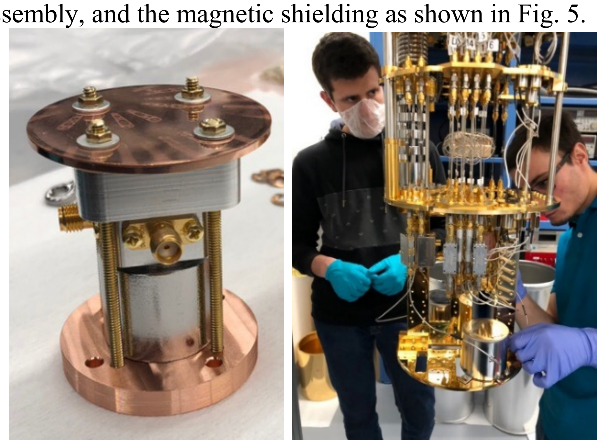

Figure 5: 3D QWR assembly (left), attached to the 10mK stage of the dilution refrigerator at the University of Chicago (right).

We connected the resonators to a microwave setup optimized for superconducting quantum experiments installed inside the dilution refrigerator. The cryostat microwave input line has 20 dB attenuation at 4 K followed by 36 dB attenuation at 10 mK. Unwanted high frequency signals are filtered using a commercial 7.5 GHz low pass filter and a homemade Eccosorb filter [9] at the 10 mK stage. The output signal passes through a second Eccosorb filter followed by two circulators, which protects the resonators from noise emitted by the high electron mobility transistor (HEMT) amplifier located at 4 K. The resonators were then cooled down 10 mK within 24 hours. The resonators remained in the 100-150K region for about 9 hours, long enough to have been potentially affected by "Q-disease" and have their Q-factors reduced [10].

We used several methods to measure loaded Q-factor: reflection (S_{11}), transmission (S_{21}) and ringdown. For the first run, we started with the conservative value of Q_{ext}~10^5 to ensure that we can detect a signal. Then, each other run, we increased Q_{ext} by about an order of magnitude by reducing the coupler lengths.

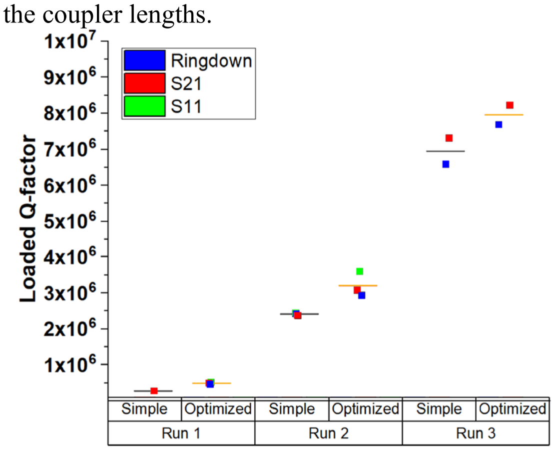

Figure 6: Comparison of measured Q-factors of optimized and non-optimized Nb resonators at 10 mK, measured by different methods in different runs at a single photon level.

All methods demonstrate that the Q-factor of the optimized cavity is ~25% higher than of the unoptimized resonators (see Fig. 6). Due to the project constraints, we had to limit the number of runs to three. In the future we plan on improving our coupler configuration to better couple to QL > 1e9 resonators as has been achieved at Fermi National Accelerator Laboratory for quantum resonators [11].

SUMMARY

RadiaBeam Systems, in collaboration with Argonne National Laboratory and The University of Chicago has developed a 3D QWR with optimized shape to be used as quantum memory in conjunction with a Josephson junction qubit. Thanks to the shape optimization we were able to increase the Q-factor of the resonator by ~25%, which was demonstrated during cryogenic tests at 10 mK and single-photon power levels, while the Q_0-dominated regime has, probably, not been reached. Further improvement of the resonator performance seems possible to achieve with improved surface treatment of the niobium cavity [11].

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