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CRYOGENIC PROBE STATION AT OLD DOMINION UNIVERSITY CENTER FOR ACCELERATOR SCIENCE*

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Abstract

With a growing effort in research and development of an alternative material to bulk Nb for a superconducting radiofrequency (SRF) cavity, it is important to have a cost effective method to benchmark new materials of choice. At Old Dominion University's Center for Accelerator Science, a cryogenic probe station (CPS) will be used to measure the response of superconductor samples under RF fields. The setup consists of a closed-cycle refrigerator for cooling a sample wafer to the cryogenic temperature, a superconducting magnet providing a field parallel to the sample, and DC probes in addition to RF probes. The RF probes will extract a quality factor from a sample patterned in a coplanar waveguide resonator structure on a 2in wafer. From the measured quality factor, the surface resistance and the penetration depth as a function of temperature and magnetic field will be calculated. This paper will discuss the design and measurement procedures of the current CPS setup.

INTRODUCTION

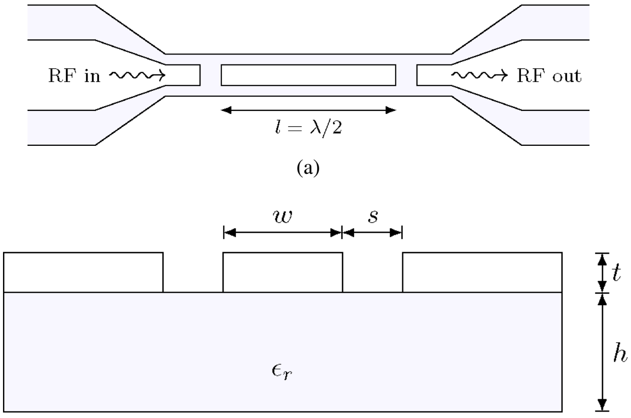
Over the decades of developmental efforts, there have been reported instances of Nb cavities operating at their theoretical limits. In order to meet the increasing demands of future accelerator performance and cost requirements, significant efforts have been made into research and development of new materials alternative to a bulk Nb. Some of the new innovations include nitrogen doped and infused niobium cavities [1–3], multi-layer coatings consisting of thin dielectric layers sandwiched between superconducting layers [4], a thin film niobium over copper [5], and cavities made with other materials such as MgB_2 and Nb_3Sn [6, 7].

This paper will discuss a closed-cycle cryogenic probe station at Old Dominion University that will be used as part of an R&D effort for benchmarking such new SRF materials. A sample will be fabricated into a planar transmission line resonator, and the CPS will be used to extract superconducting surface resistance and penetration depth under an RF field with varying DC parallel magnetic field. The obtained information would give insight into how the SRF cavities would perform using those new materials.

EXPERIMENTAL SETUP

Sample

A sample that will be prepared for the measurements are a series of superconducting half-wavelength coplanar waveguide (CPW) resonators designed on top of a dielectric substrate as shown in Fig 1. Because it is only necessary to deposit the superconducting film on one side of the substrate, the CPW structure provides an affordable method for a sample fabrication compared to other transmission line structures which requires a ground plane and a conducting strip on both sides of the substrate. The CPW resonators are patterned by photolithography after a film is deposited onto a dielectric substrate. A single 2in wafer can contain multiple resonators given that they are spread enough so that any cross coupling of power between adjacent resonators is negligible.



(a)

(b)

Figure 1: (a) A schematic diagram showing the top view of half-wave CPW resonator capacitively coupled to the RF input and output and (b) the side view with the center conductor width w, gap s, and a substrate with a dielectric constant ϵ_r and thickness h.

The design of the CPW resonator is chosen to achieve desirable resonant frequencies and also to minimize losses. Main components of the CPW resonator consist of a center conductor, ground planes separated by a gap S, coupling capacitors and contact pads where the RF probes make contacts. The ratio between the center conductor width W and the gap S are determined such that the characteristic impedance of the transmission line is approximately 50 Ω for maximum power transfer. A first sample that will be measured here will contain Nb resonators with two different center width: W = 10 µm and 15 µm and the gaps S = 6.15 µm and 8.77 µm in order to experiment with different geometric factors. The thickness of the film will be 200 nm or approximately five times the penetration depth λ. The lengths of the straight resonators are l = 17 mm, 20 mm, and 24 mm corresponding to the resonant frequencies of 2.5 GHz, 3.0 GHz, and 3.5 GHz respectively. Due to the space limitation, the lowest frequency achievable using a straight resonator is 2.5 GHz;

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however, it is possible to construct a meander-shaped resonators to test at lower resonant frequencies, for example at around 1.0 GHz to 1.5 GHz, relevant to SRF cavities. The RF power is delivered to the CPW from the network analyzer by touching the Ground-Signal-Ground probes to the contact pads.

It is essential to minimize all sources of dissipation in order to isolate internal quality factor from the measured loaded quality factor. Other than the conductor loss, two main sources of dissipation come from dielectric and radiation. Reduction of dielectric loss can be readily achievable by using a dielectric substrate with low loss tangent. For example, using Al_2O_3 with $\epsilon_r = 11.5$, the dielectric loss quality factor $Q_d \approx 10^5$ can be attained. As for the radiation loss, it may be suppressed by using a micro-scale feature size of the CPW. Any radiation produced from a current flowing in the center conductor is nearly canceled by the radiation from the current of opposite polarity in the ground planes [8]. Therefore, minimizing the geometries of the CPW to the extent allowed by a current photolithography technique helps keep power dissipation small. By making an analogy with field patterns of a slot antenna, Zmuidzinas [8] estimated the radiation quality factor to be

$$Q_{rad} \approx 5 \times 10^{-3} \left(\frac{\lambda_0}{W}\right)^2 \tag{1}$$

where λ_0 is the wavelength at the operating frequency in the free space and W is the center conductor width. For a structure with W=10 µm at $f_r = 2.5$ GHz and 3.5 GHz, the radiation quality factor would be roughly $Q_{rad} \approx 7.2 \times 10^5$ and 4.0×10^5 according to Eq. (1). By carefully choosing the dielectric substrate, minimizing the CPW structure, and operating at low frequencies, potential sources of dissipation may be reduced.

Cyogenic Probe Station

The CPS is housed in a vacuum chamber rated at 10^{-5}mbar at a room temperature. To dampen vibration of the system to less than 1 µm, it is stationed on top of air suspension legs. The precise placement of the RF probes onto the CPW resonators are achieved using probe arms with translation resolution better than 10 µm, and by inspecting through an optical microscope placed on top of a glass window above the sample. The system has two additional probe arms perpendicular to the RF probes for applying DC current to the sample. Shown in Fig. 2 is the CPS vacuum chamber with its lid off.

The sample is cooled to cryogenic temperature using a two-stage cryocooler (RDK-415D2, Sumitomo Heavy Industries, Ltd.) for conductive cooling of the sample. The temperature of the first stage is 39.60 K with 45.0 W of heat load, and the second stage temperature is as low as 3.99 K with 1.50 W of the applied heat load. The first stage is responsible for cooling a thermal shield surrounding the sample, and the second stage is connected to a sample holder and a superconducting magnet via copper braids extending inside the shield. The sample holder is made of a gold plated, oxygen-free coper and can hold a sample as large as 2 inches in diameter, and the superconducting magnet can produce field up to one Tesla parallel to the sample. The shield component is supported by a six-servomotor system which can be operated to fine adjust the field orientation to within 10 degrees in all three directions. Finally, surrounding the shield are three pairs of Helmholtz coils to suppress Earth's stray magnetic fields from affecting the sample. It is essential to eliminate any fields during the cool down to avoid any vortex trappings inside the superconductor.

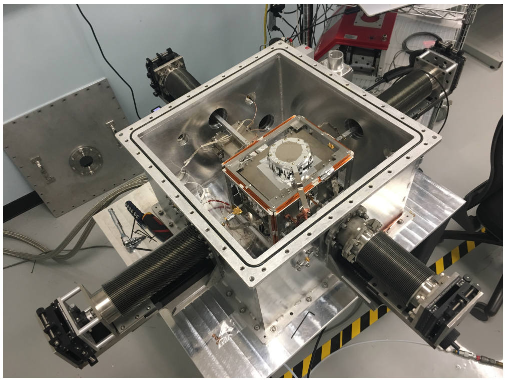

Figure 2: A CPS vacuum chamber with four probe arms. Two of the probes are used for RF probing and the other two are for sending in DC current. Inside the chamber is a shield housing a sample and a superconducting magnet. Three pairs of Helmholtz coils are wrapped around the shield.

MEASUREMENT ANALYSIS

The network analyzer will measure the complex transmission coefficient S_{21} of the CPW resonator sample, from which a loaded quality factor is extracted. The measured quality factor takes the form

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} + \frac{1}{Q_d} + \frac{1}{Q_{rad}}, \tag{2}$$

where Q_0 is the internal quality factor of the superconducting resonator, and Q_{ext} is the coupling quality factor. In general we need Q_d and Q_{rad} to be at least an order of magnitude greater than the Q_0 so that the effect of such dissipation may be neglected. From Q_0, the surface resistance R_s and λ are extracted using a numerical technique developed for a strip transmission line by Sheen [9] and later applied to a CPW resonator by Porch [10].

In this method, a cross-section of the CPW geometry is divided into N smaller patches, with higher concentration of patches near edges of the conductors where the current varies rapidly, as shown in Fig. 3. On each patch, currents are assumed to be constant, and the sum of all the currents, including the ones on the ground planes, are set to zero. The patches can then be treated as a system of parallel N-coupled transmission line. The current distributions are calculated

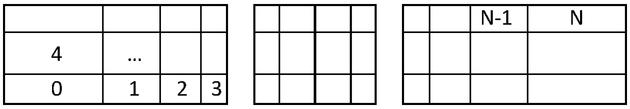

Figure 3: A cross section of a CPW divided into N patches. Smaller patches are located along the edges where the current varies over the penetration depth.

by solving the system of transmission line equations:

$$-\frac{\partial v_n}{\partial z} = \sum_{m=1}^{N} (r_{mn} + j\omega l_{mn})\, i_m \tag{3}$$

where v_n and i_m are the voltage and current on each patch. The resistance matrix r_{mn} is given by

$$r_{mn} = \Re\mathrm{e}\left(\frac{1}{\sigma A_0} + \delta_{mn}\frac{1}{\sigma A_n}\right) \tag{4}$$

with A_n the cross-sectional area of the nth patch and $\sigma = \sigma_1 - j\sigma_2$ the complex conductivity of a superconductor. The inductance matrix l_{mn} is the sum of an internal and external inductance. The internal inductance arises due to kinetic energy of Meissner currents and is given by

$$l_{mn(internal)} = \Im\mathrm{m}\,\frac{1}{\omega}\left(\frac{1}{\sigma A_0} + \delta_{mn}\frac{1}{\sigma A_n}\right) \tag{5}$$

An expression for the external inductance can be obtained by calculating the mutual inductance between each pair of transmission lines and is only a function of the geometry. Therefore, given two unknowns, σ_1 and σ_2, the current distribution within the CPW is solved by taking an inverse of Eq. (3). Once the current distribution is calculated, the total resistance R and inductance L of the system is solved by

$$R = \frac{1}{I_{tot}^2}\sum_n i_n^2 R_n \tag{6}$$

$$L = \frac{1}{I_{tot}^2}\sum_{mn} i_m i_n L_n \tag{7}$$

The internal quality factor can then be predicted to be

$$Q_0 = \omega\frac{L}{R}. \tag{8}$$

By comparing this analytical value with the measured Q_0's from two CPW resonators differing only in geometries, σ_1 and σ_2 can be extracted. Finally, the surface resistance of the superconductor is calculated by

$$R_s = \frac{1}{2}\mu_0^2\omega_0^2\sigma_1\lambda_L^3 \tag{9}$$

where λ_L is extracted from

$$\frac{1}{\sigma_2} = \mu_0\lambda_L^2\omega_0. \tag{10}$$

CONCLUSION

The closed-cycle cryogenic probe station will be used at Old Dominion University to benchmark new materials for SRF cavities. The superconducting CPW resonators will be measured for extracting surface resistance under an RF field, and the penetration depth as a function of applied DC parallel magnetic field will be analyzed. The system will provide a low cost way to study new superconducting materials and understand their performance in SRF cavities.

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