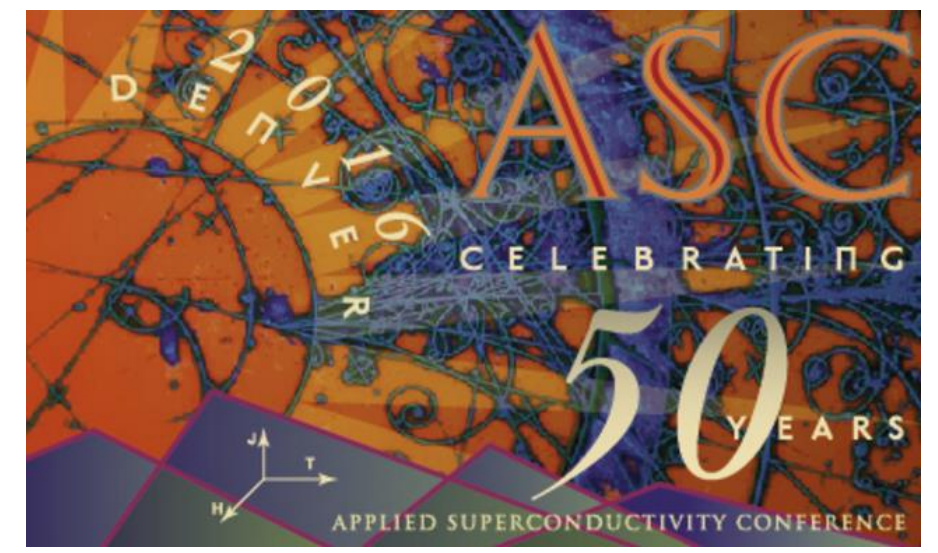


A Cryogenic Waveguide Mount for Microstrip Circuit and Material Characterization

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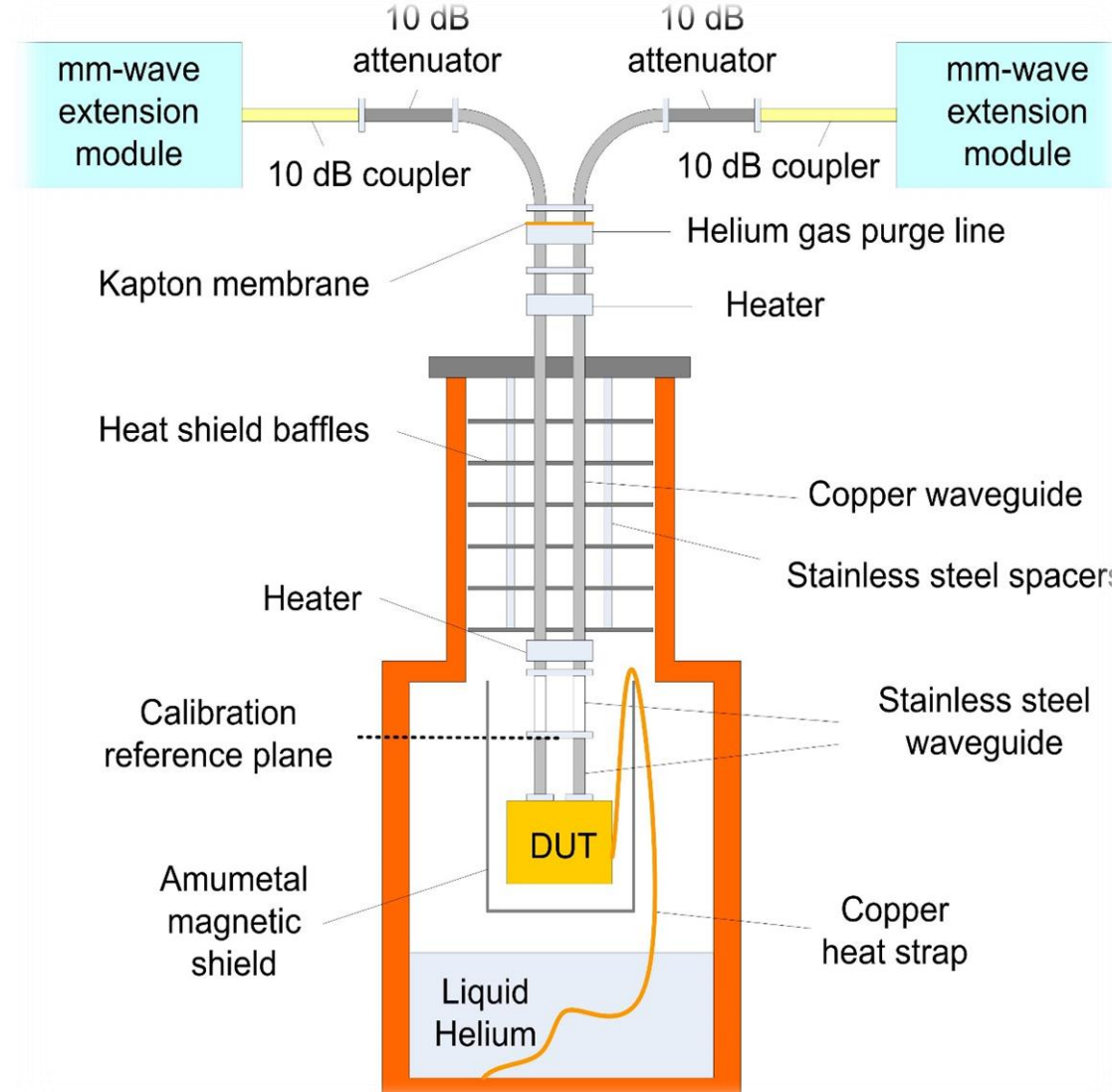
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Abstract

A waveguide split-block fixture used in the characterization of thin-film superconducting planar circuitry at millimeter wavelengths is described in detail. The test fixture is realized from a pair of mode converters, which transition from rectangular-waveguide to on-chip microstrip-line signal propagation via a stepped ridge-guide impedance transformer. The observed performance of the W-band package at 4.2K has a maximum in-band transmission ripple of 2dB between 1.53 and 1.89 times the waveguide cutoff frequency. This metrology approach enables the characterization of superconducting microstrip test structures as a function temperature and frequency. The limitations of the method are discussed and representative data for superconducting Nb and NbTiN thin film microstrip resonators on single-crystal Si dielectric substrates are presented.

Measurement Setup



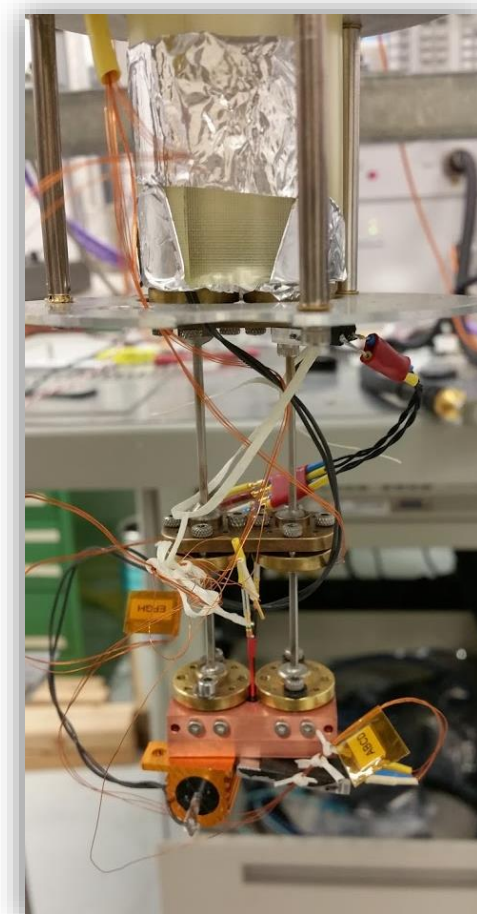
Detail of the experimental setup used for superconducting circuit characterization at W-band frequencies that was connected to a PNA-X vector network analyzer.

To cryogenically test the package a section of thin-walled (thickness $250\mu\text{m}$) stainless steel waveguide was utilized as a thermal break as shown in Fig. 4. The room temperature ends of the waveguide are sealed by a $12\mu\text{m}$ thick Kapton vacuum window and were connected to the WR-10 mm-wave extension modules and the PNA-X vector network analyzer. Helium gas is used to purge excess air from the package and the waveguide sections in cooling the device in the cryostat to 4.2K. A heater is used near the vacuum window interface to prevent cooling below the dew point and accumulation of condensates at this interface. Thermometry is provided by a calibrated (Lakeshore, DT-670) diode attached to the test fixture.

The 10dB fixed attenuators are used to limit reflections and present an appropriate power level for the device under test (DUT). The test system was calibrated at room temperature using custom-made Thru-Reflect-Line (TRL) calibration standards at the fixture's input interface. The packaged device was enclosed in a magnetic shield to suppress interactions between the Earth's magnetic field and the superconducting test device.

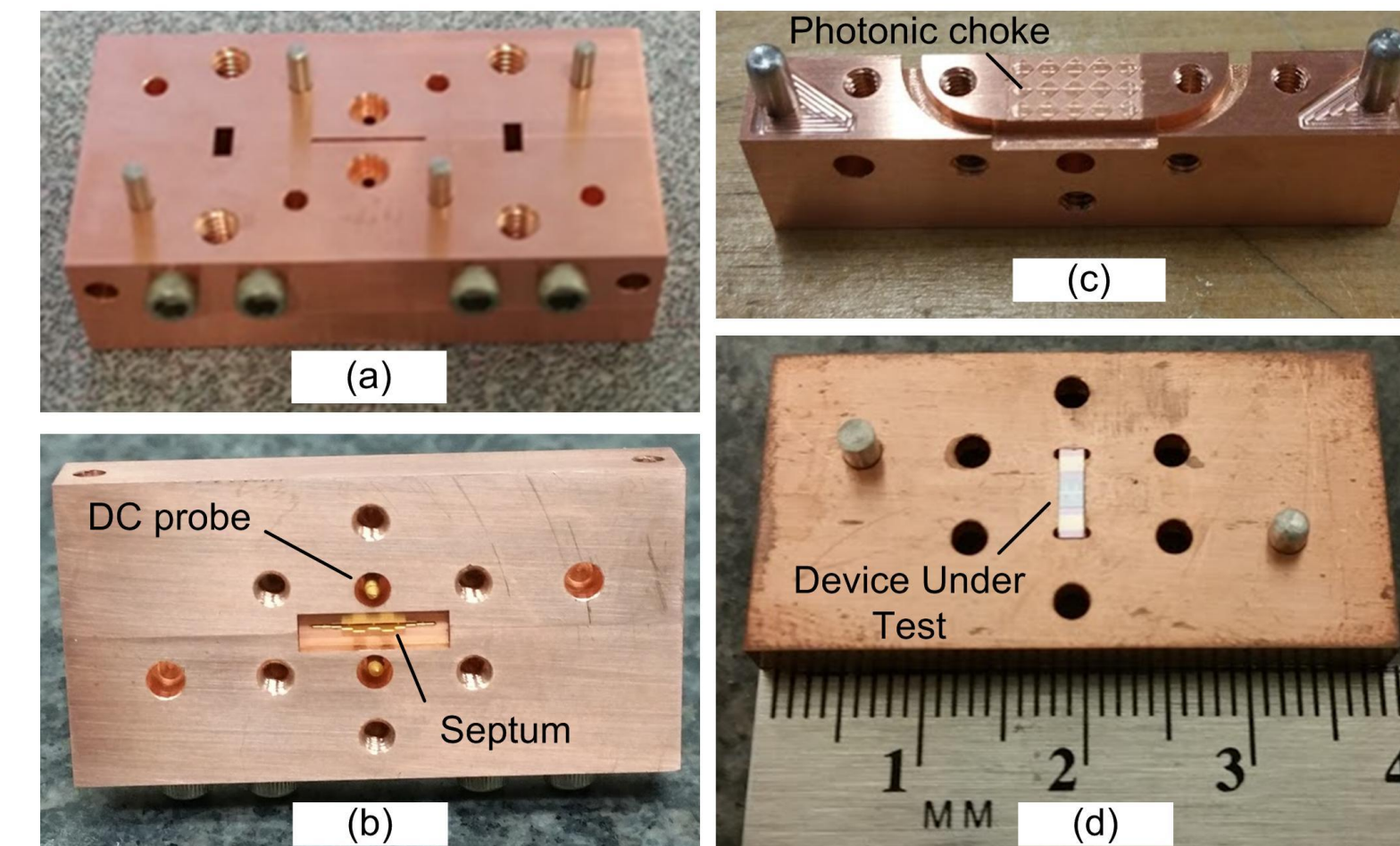


Photograph of the measurement setup for superconducting film characterizations

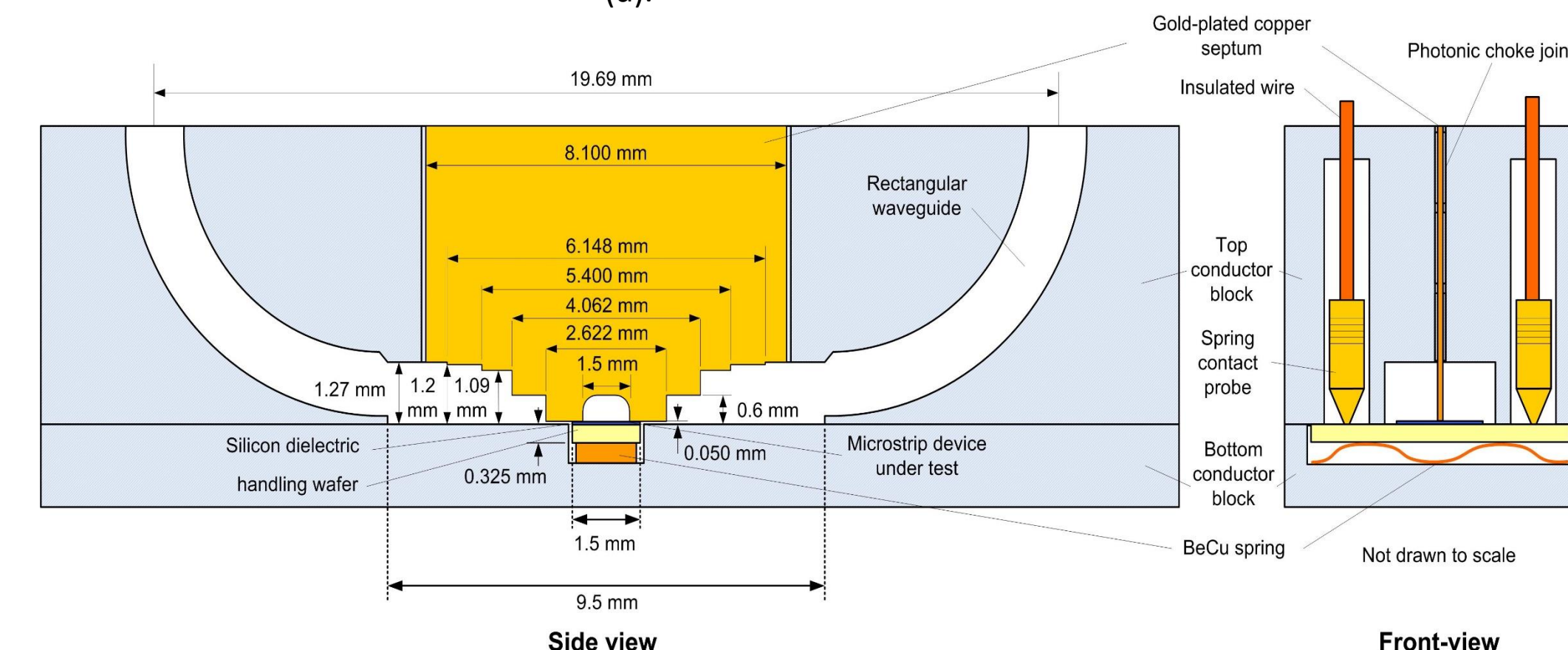


Photograph of the test fixture installed inside the cryogenic dewar (without Amumetal magnetic shield)

Package Design



Test fixture used for characterizing thin-film superconductor microstrip resonators (a) with gold-plated copper septum and DC probes when viewed from the bottom (b). The top-half containing waveguide channel and photonic choke (c). The bottom-half of the package contains chip alignment features (d).

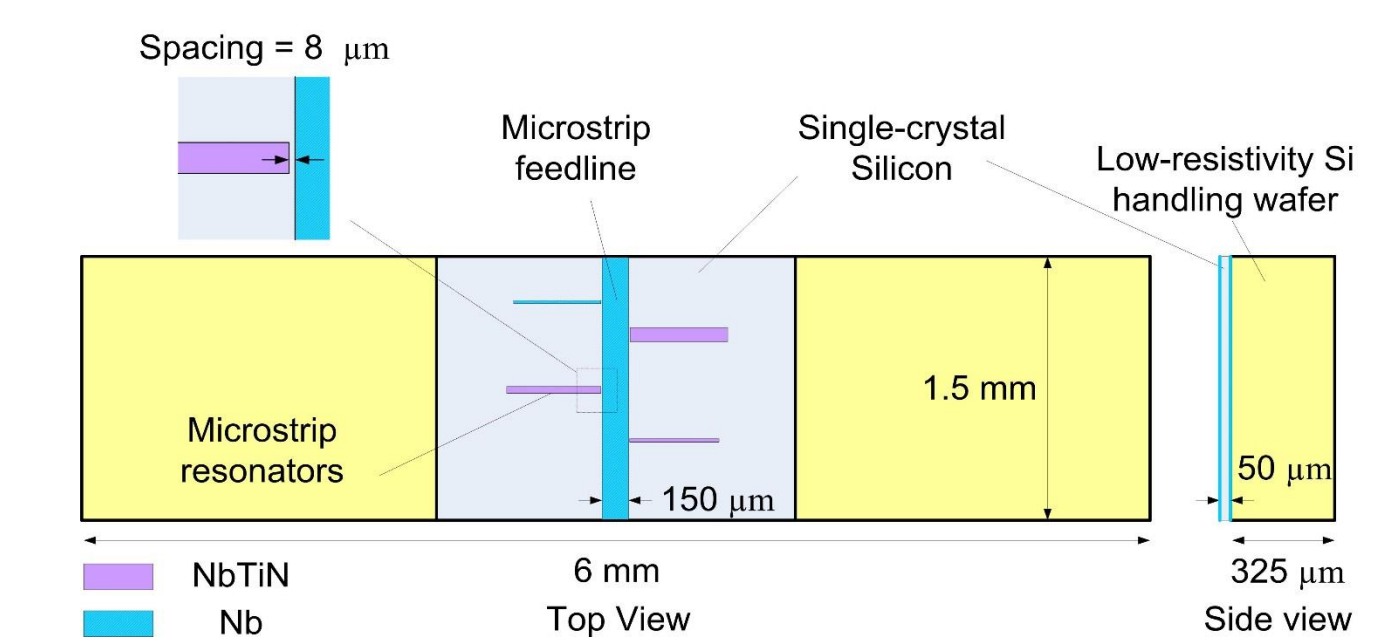


Cross-sectional view of the waveguide-to-microstrip transition employed for thin-film circuit and material characterization.

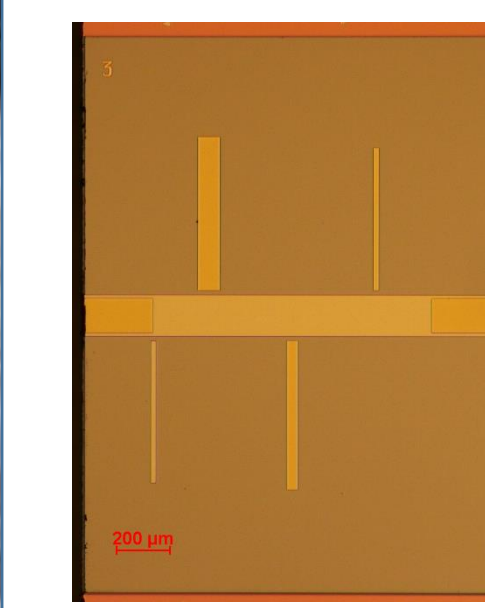
The E-plane split-block package was made from three copper pieces by direct CNC machining. The waveguide septum was realized from a gold-plated $100\text{-}\mu\text{m}$ thick BeCu sheet fabricated using photo-chemical etching. Two of the copper blocks form the waveguide housing while the third is used to align and secure the microstrip test wafer in the fixture. The test device is pressed against the waveguide septum and with a physical contact force by a BeCu spring residing under the chip. Features machined into the split-block define the chip alignment with respect to the package housing. Alignment pins in the copper blocks are used to facilitate device assembly.

In practice – the outer surfaces of the split-block housing are used as a reference to align the package elements with a precision machinist vice before tightening the housing fasteners.

Chip Design



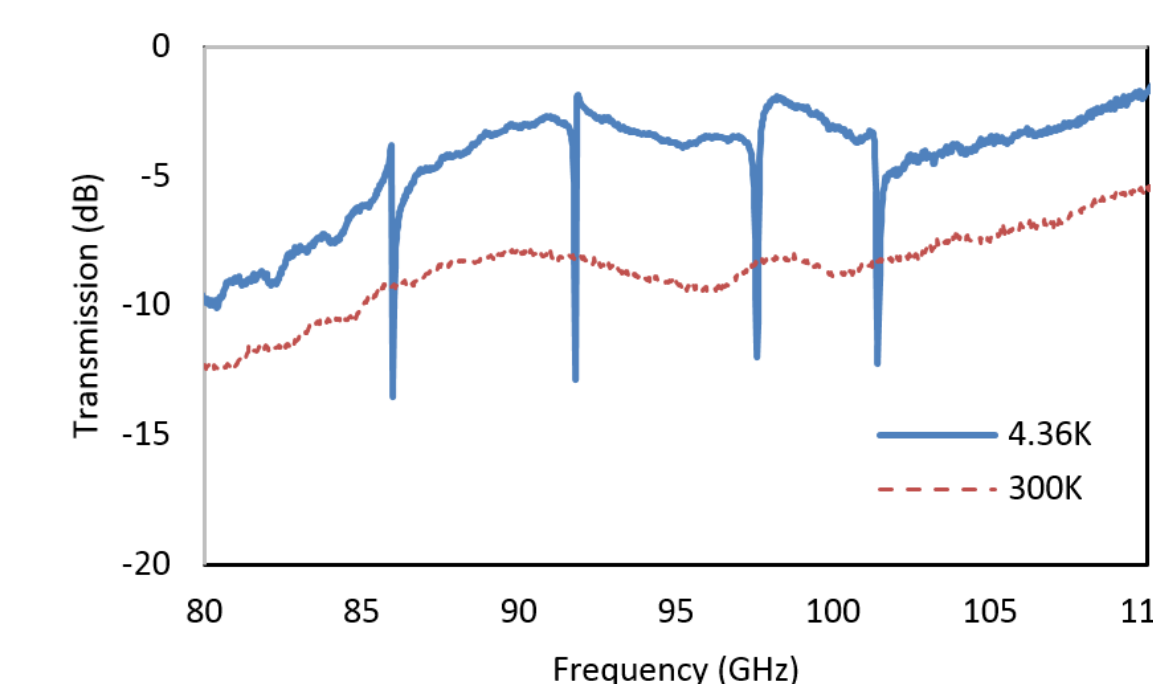
Device under test contained Nb and NbTiN microstrip resonators. The NbTiN resonator microstrip line width 80, 40 and $20\mu\text{m}$ and lengths are 550, 534, $510\mu\text{m}$, respectively. The Nb resonator is $20\mu\text{m}$ wide and $510\mu\text{m}$ long. The resonators are placed at $8\mu\text{m}$ away from the feed line, respectively to define the microstrip resonator coupling.



Photograph of the WR10 waveguide band resonator chip

Test devices for cryogenic material characterization were fabricated, which contain three niobium titanium nitride (NbTiN) and one niobium (Nb) half-wavelength resonators coupled to a Nb microstrip feed line. The test chip ground plane is realized from $0.5\mu\text{m}$ thick Nb. This configuration enables the test package transmission as well as loss to be evaluated in the superconducting film through quality factor measurement

Measurement Results and Discussions



Complex transmission (left) and power transmission (right) model and data at $T=4.5\text{K}$. A Qi of 2,671 and Qc of 3,542 and $f_0=96.24\text{GHz}$ are derived.

The measurement results show relatively uniform transmission between 90 GHz and 110 GHz. The Nb resonator was used to determine the dielectric loss of the substrate through the measurement of its quality factor and serves as a reference for the NbTiN resonators to determine the kinetic inductance. The kinetic inductance can be extracted by comparing the measured resonance frequency with that simulated using with surface impedance model on the trace and ground plane and using SONNET electromagnetic simulation software.

These simulations indicate kinetic inductance values of $\sim 0.81\text{ pH/square}$ for NbTiN and $\sim 0.097\text{ pH/square}$ for Nb films, respectively, at 4.36K. These values are in agreement with the analytical model for NbTiN derived from numerical integration of the Mattis-Bardeen integrals computed based on the measured sheet thickness of 150 nm, critical temperature of 15K, and normal-state sheet resistivity of $79.4\mu\Omega\text{-cm}$.

Conclusions

A waveguide split-block fixture was designed and fabricated for thin-film circuit and material characterization at W-band frequencies. Although demonstrated in a wet cryogen dewar, the approach is more generally applicable in cryo-cooled systems with appropriately defined thermal isolation. Superconducting film phase velocity and dielectric loss measurements are demonstrated at millimeter wavelengths through the characterization of the transmission of half-wavelength niobium resonators in a reusable-mounting fixture.

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