High-density HTS interconnects with ultra-low thermal loss

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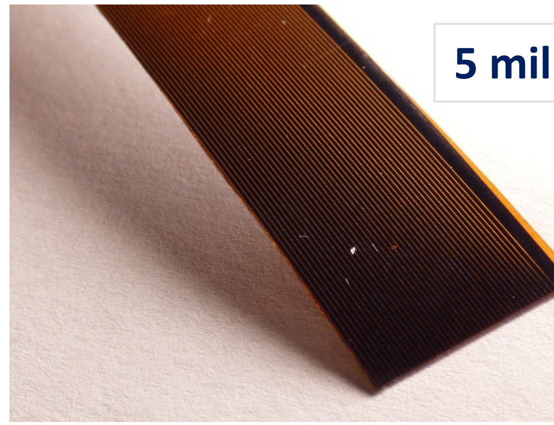
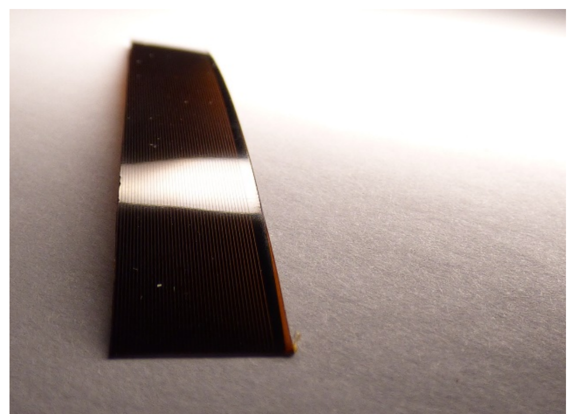
Motivation: practical quantum computers would need 1,000's of interconnects

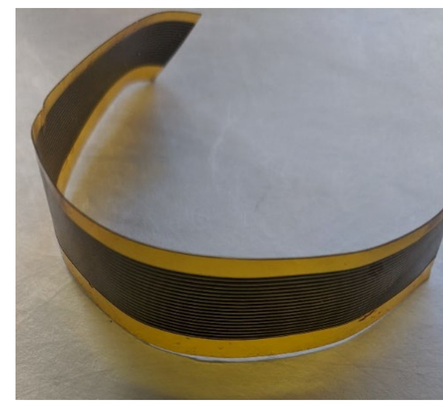
Existing IBM system

Solution: high density superconducting cable
With ultra-low thermal loss



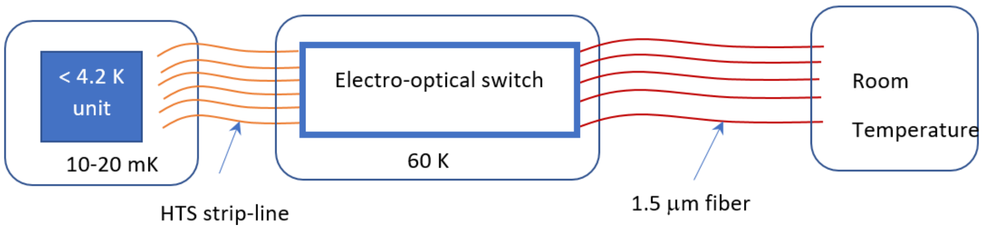
5 mil Kapton

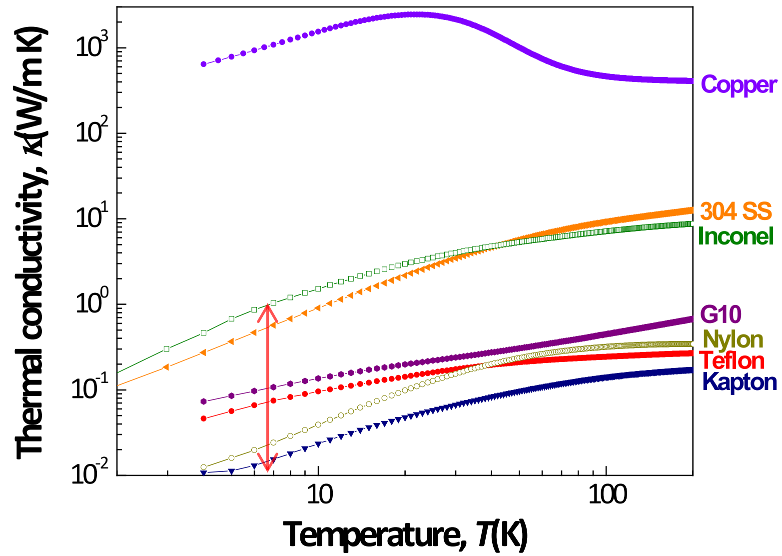




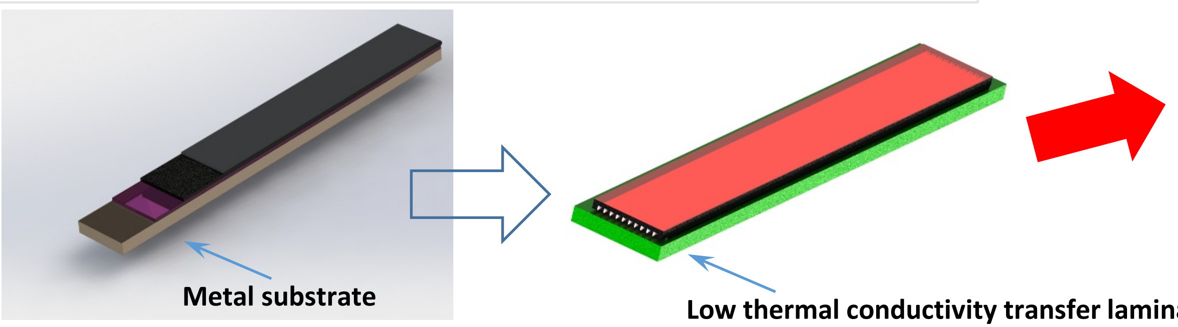
1 mil Kapton

Solution: exfoliated HTS striplies





- HTS can work between 60 K and < 100 mK
- However the substrate (metal) will generate high thermal loss



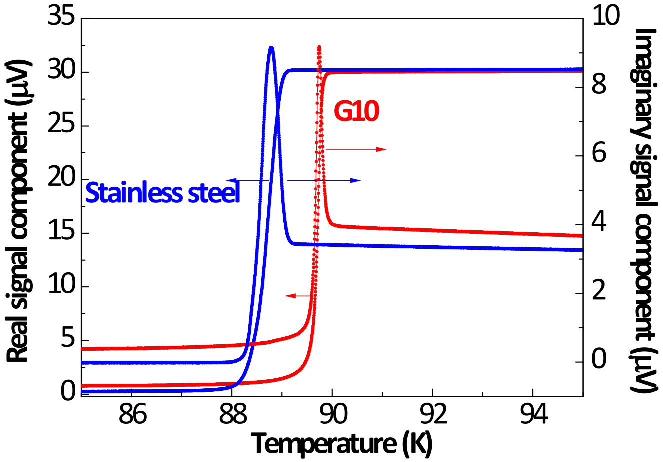
x100 reduction of thermal loss

✓ By transferring epitaxial HTS layer to a low-loss dielectric we reduce the thermal loss by x100, impossible with Wiedemann-Franz metals

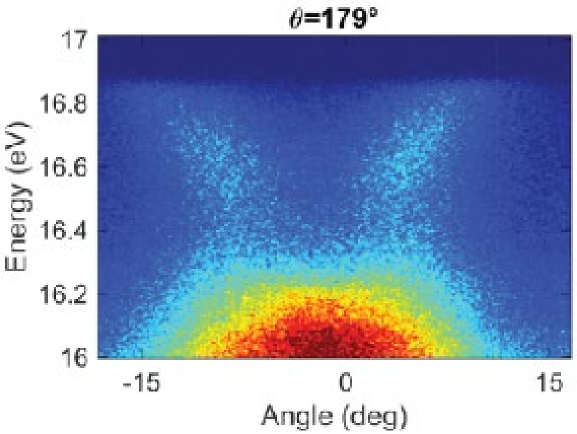
✓ Data transfer from 60-70 K can be efficiently accomplished by off-shelf Si opto-electronics

Advantages of the exfoliated YBCO-Kapton

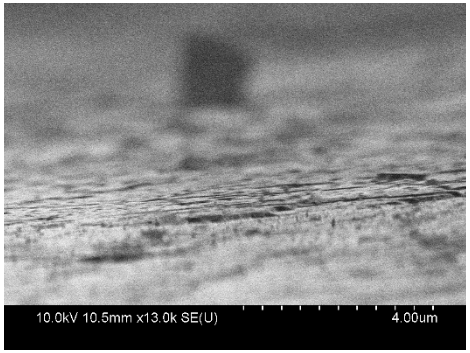
High Tc (due to compression)



High carrier density (substrate side)



Smooth surface

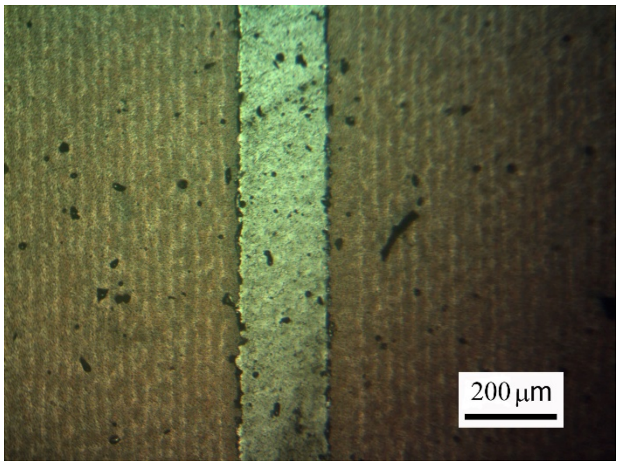


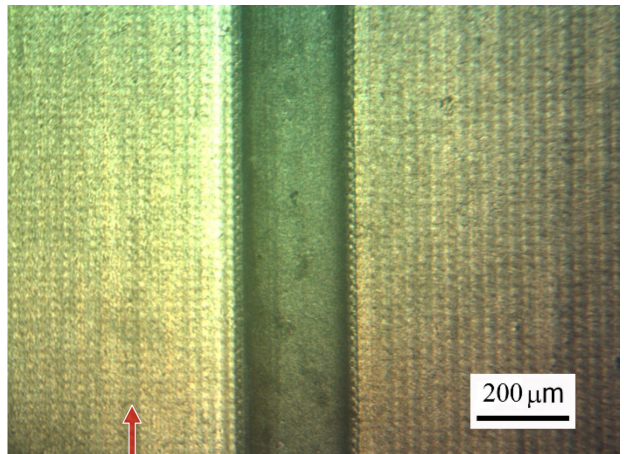
Narrow line patterning for high-density striplines

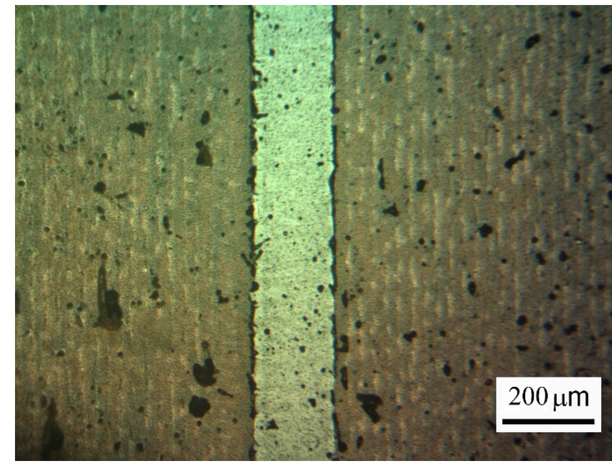
-1 mm

Optimum, in focal plane

+1 mm

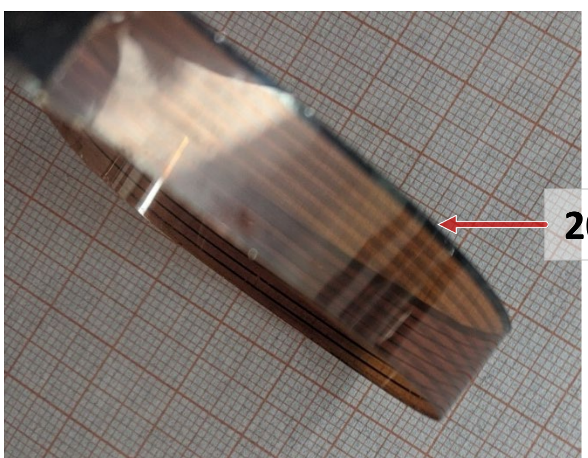






5 mil Kapton

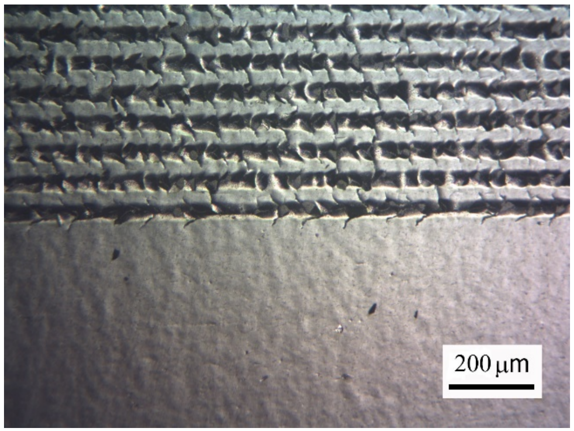
1 µm YBCO



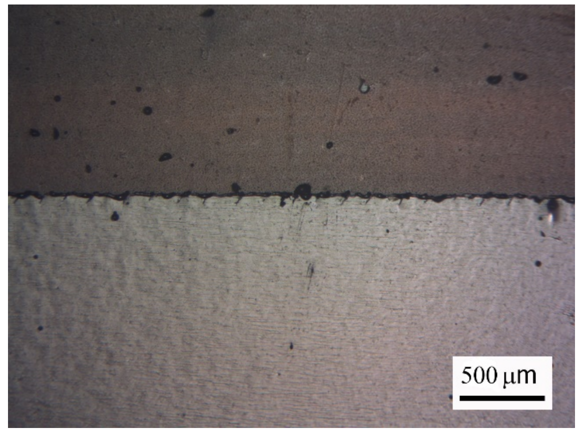
200 µm wide YBCO lines on 5 mil Kapton

Optimization of laser patterning and compression level

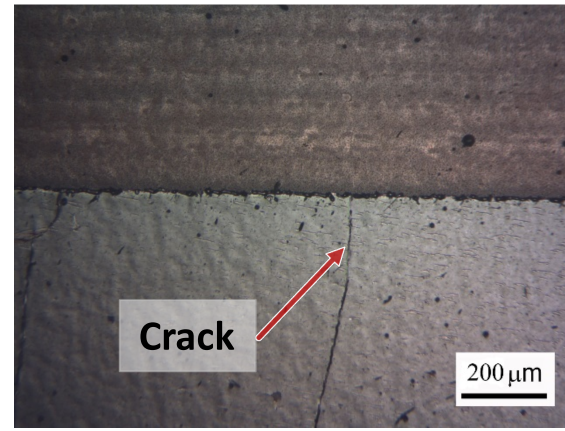
7 W

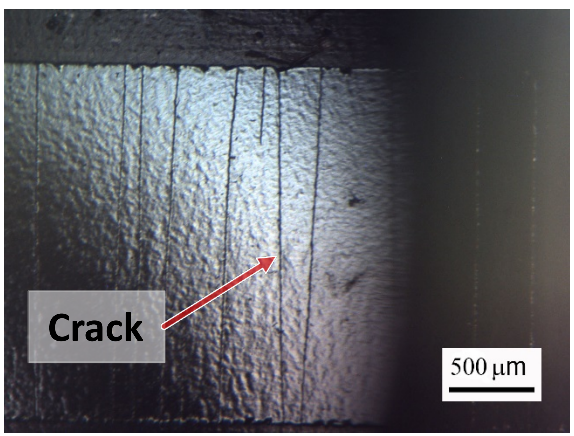


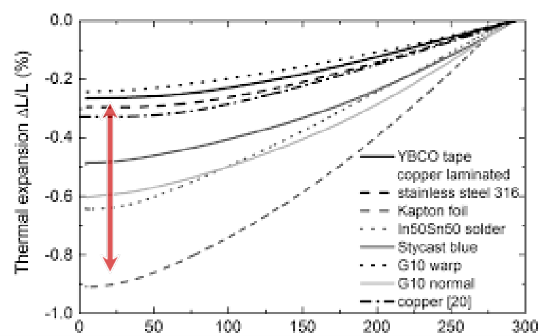
15 W, optimum power



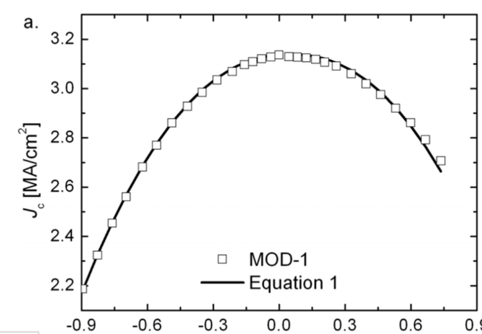
30 W







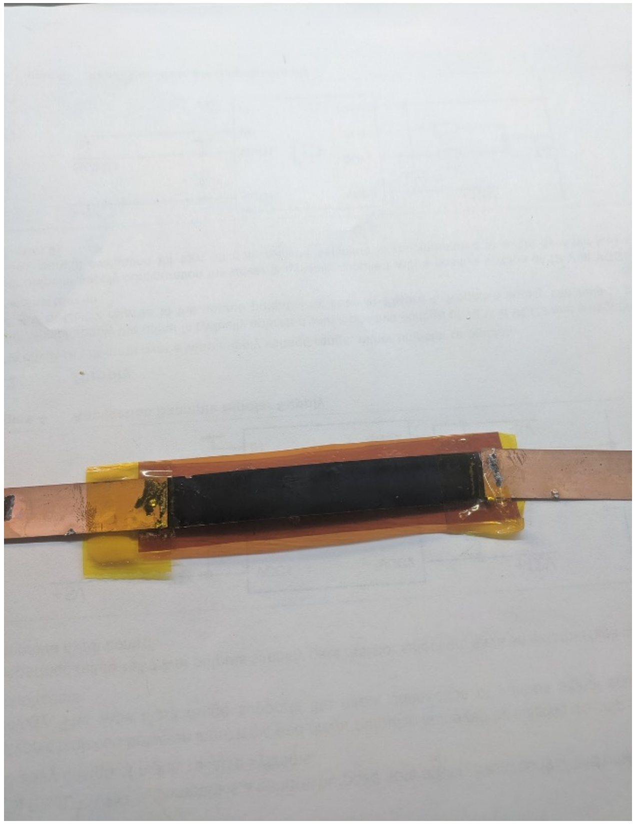
CTE gap between YBCO and Kapton

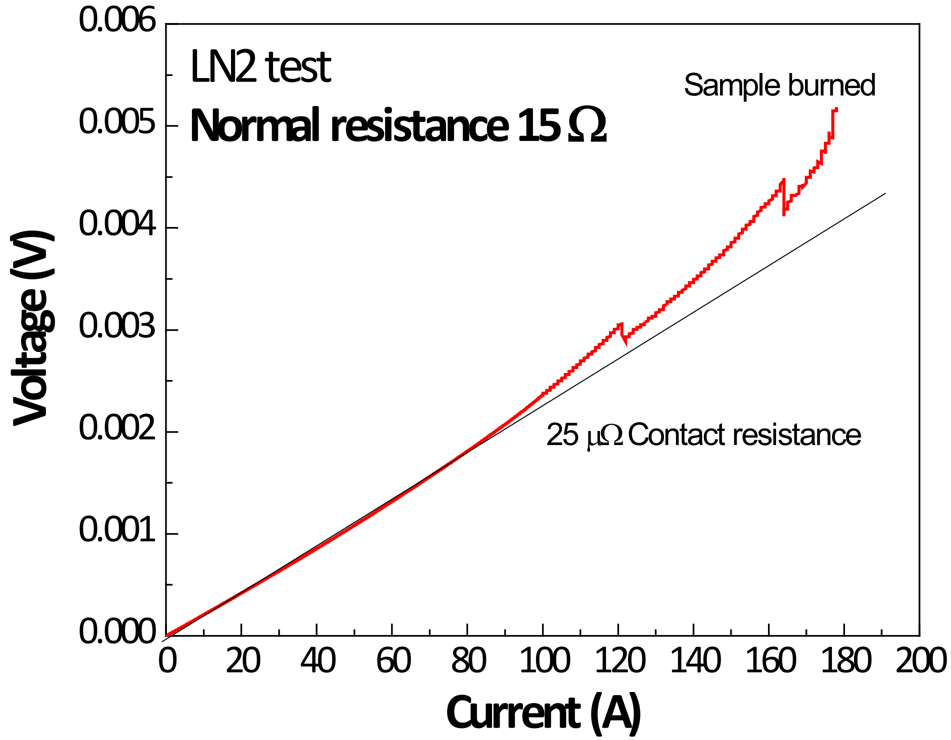


Strain limits for YBCO

✓ **Careful managing of thermal effects level is critical**

Metallization and contact resistance

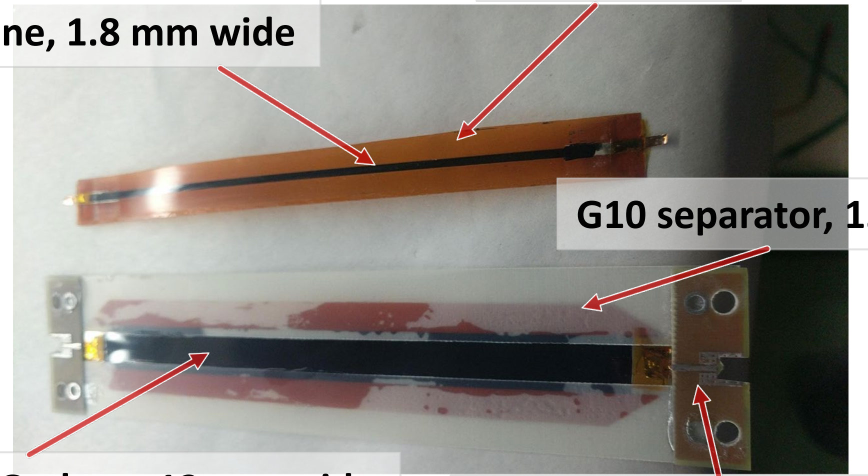




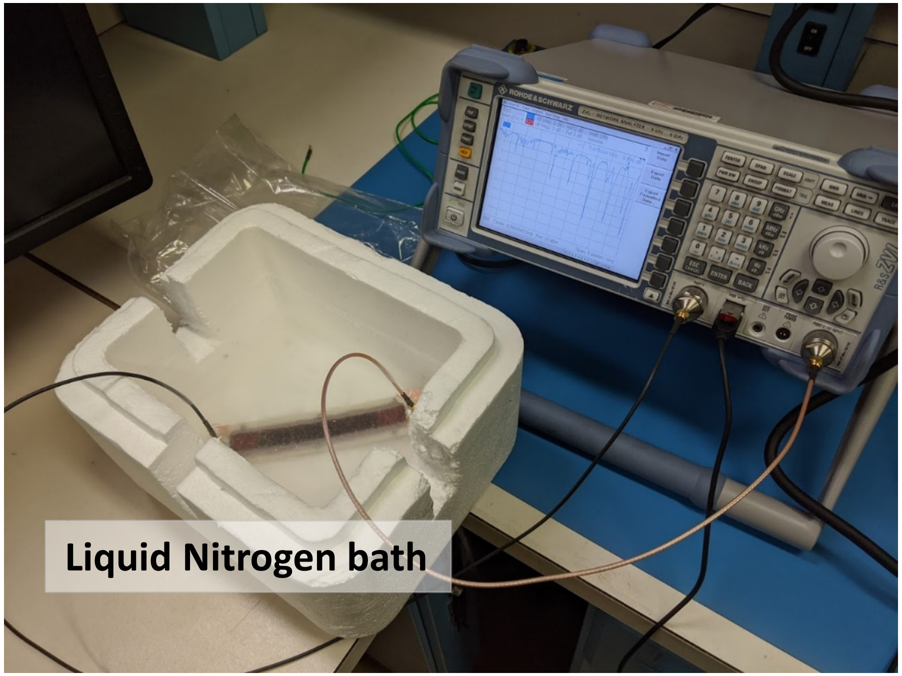
✓ 1×10^{-6} Ω per 1 cm length x 1 cm wide contact resistance demonstrated. Tested up to 200 A in LN2

Air-gapped YBCO-on-Kapton microstrip

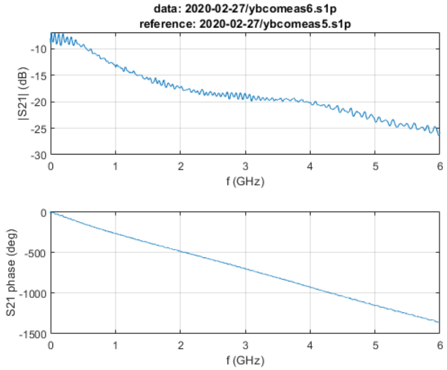
- 0.33 mm air gap, $\varepsilon = 1$
- 15 cm long
- Projected 50 Ω impedance at 1.8 mm
- Ground plane: 32 Ω at RT
- Signal line 149 Ω at RT



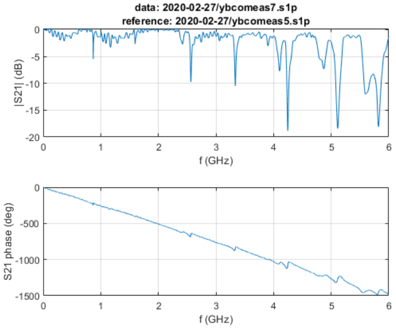
Insertion loss up to 5.5 GHz, the first air-gapped prototype



Room temperature, 25 dB loss



77 K (LN2), < 1 dB loss



- ✓Tested at Brookhaven National Laboratory
- ✓Resonances due to gap size variation in the first prototype

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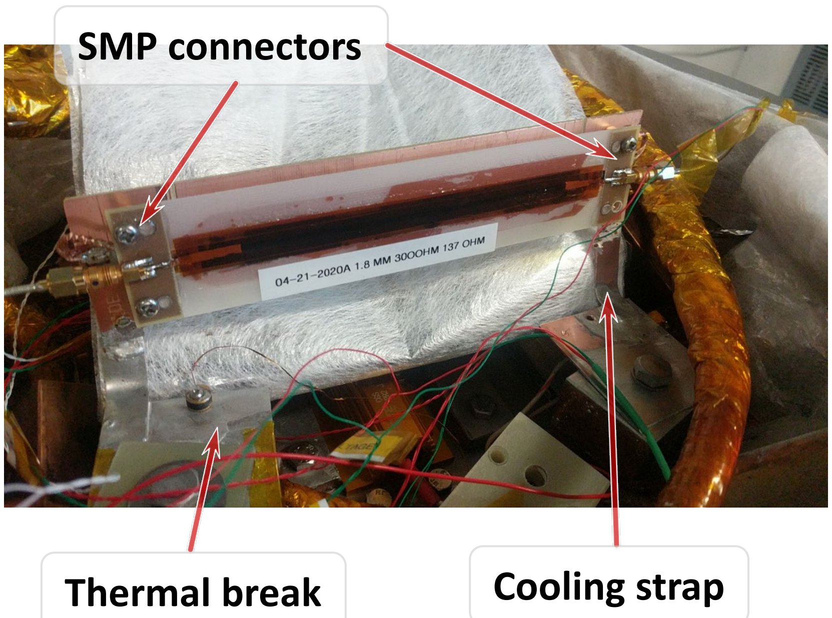
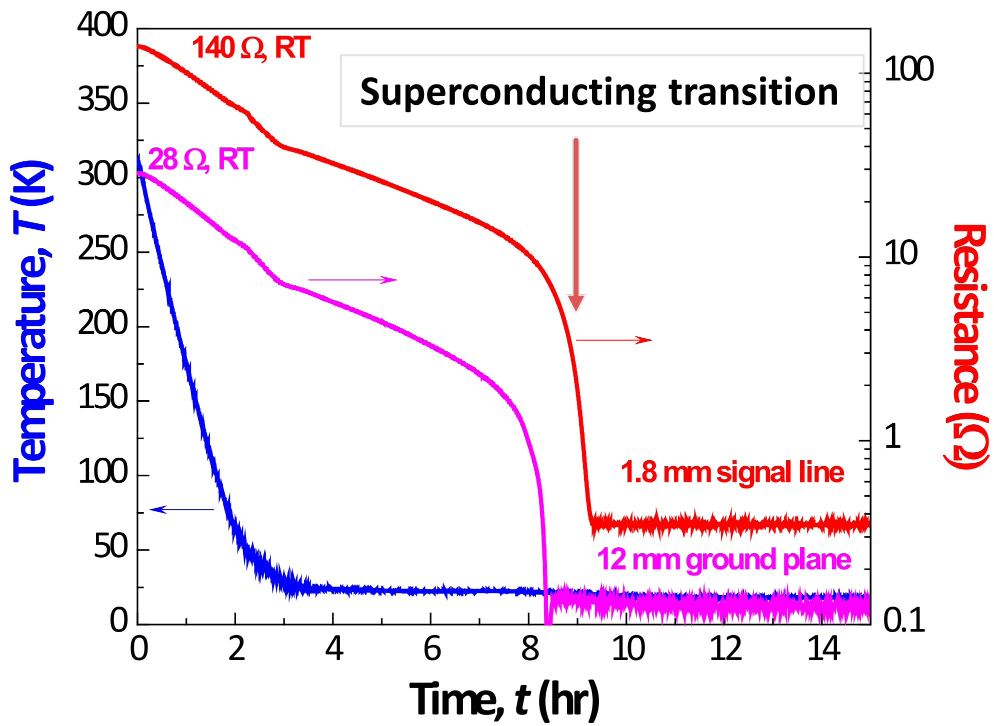
Air-gapped microstrip test, in vacuum conduction cooling





✓ Approx. 3 hours equilibration time

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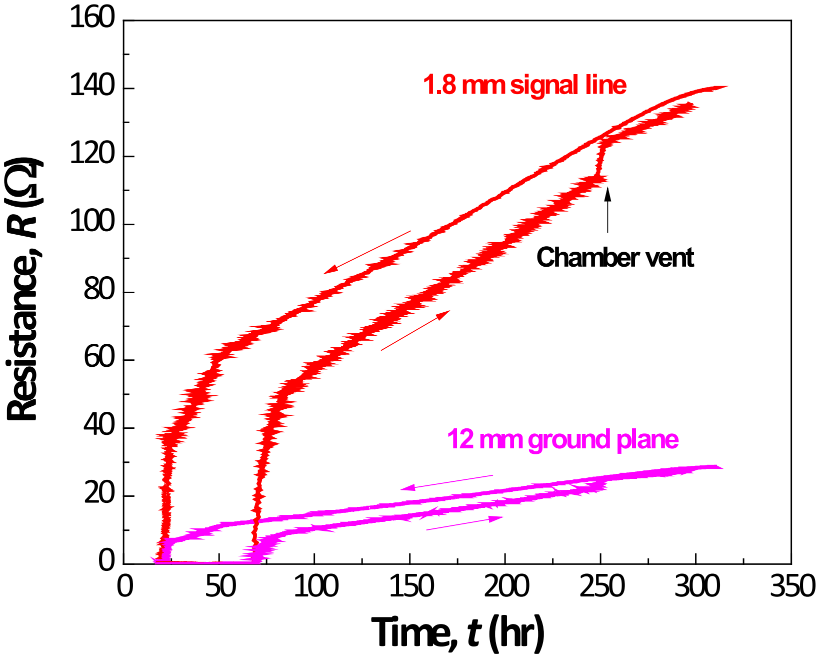
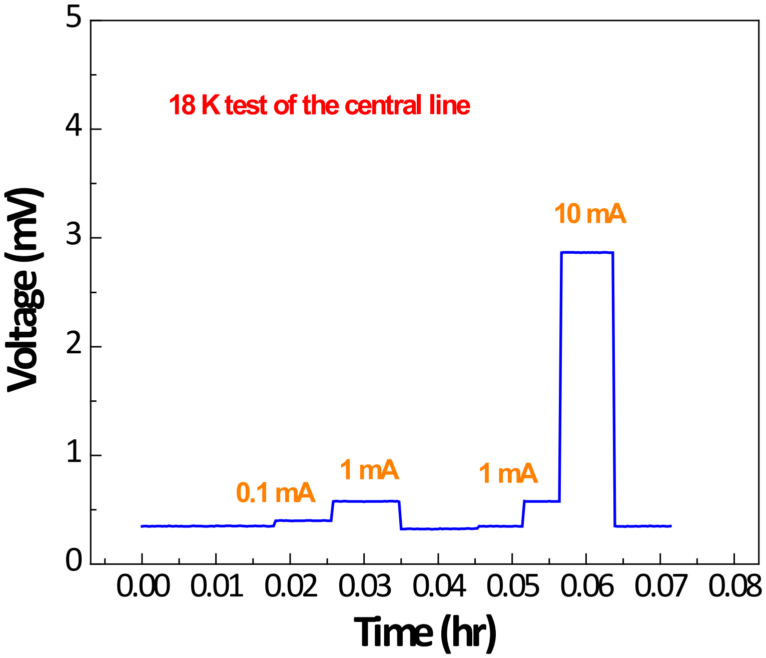
18 K - RT cycling of the air-gapped microstrip



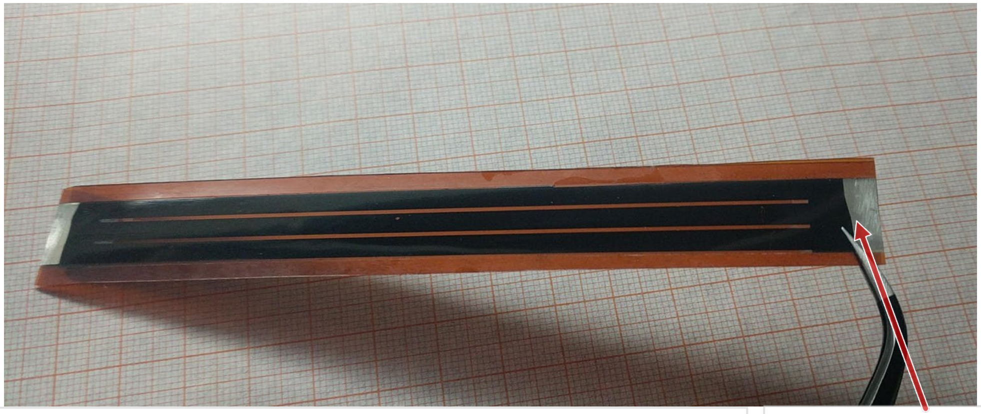


- ✓ The assembly sustained 5 cycles from 18 K to room temperature
- ✓ Central line sustained up to 10 mA current at 18 K

Dielectric YBCO-on-Kapton microstrip

- 0.33 mm thick dielectric, ε = 3.2
- 12 cm long
- Projected 50 Ω impedance at 0.8 mm
- 3 lines 3 mm apart

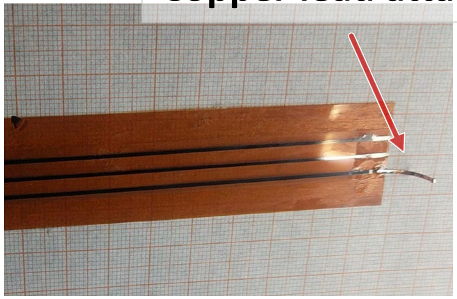
Ground plane side, 33 Ω RT



Signal line side, 0.8 mm wide lines, 500 – 600 Ω RT

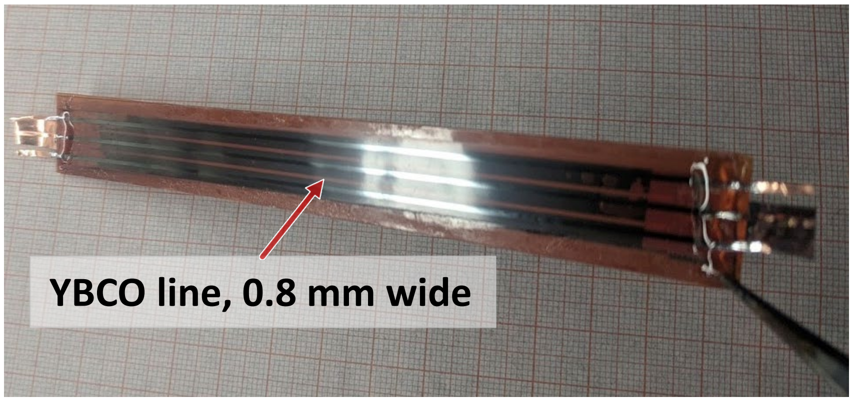
Metallization

Copper lead attached

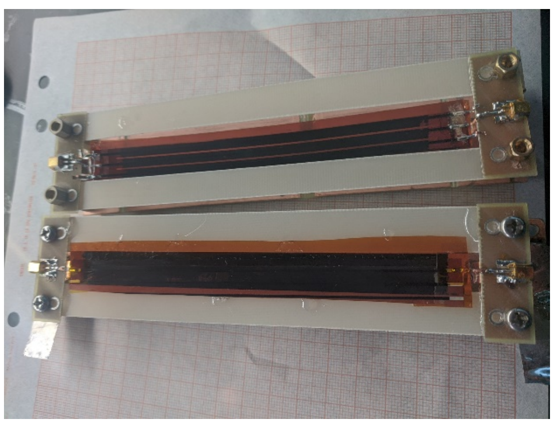


Assembled dielectric YBCO-on-Kapton microstrip

Signal plane side

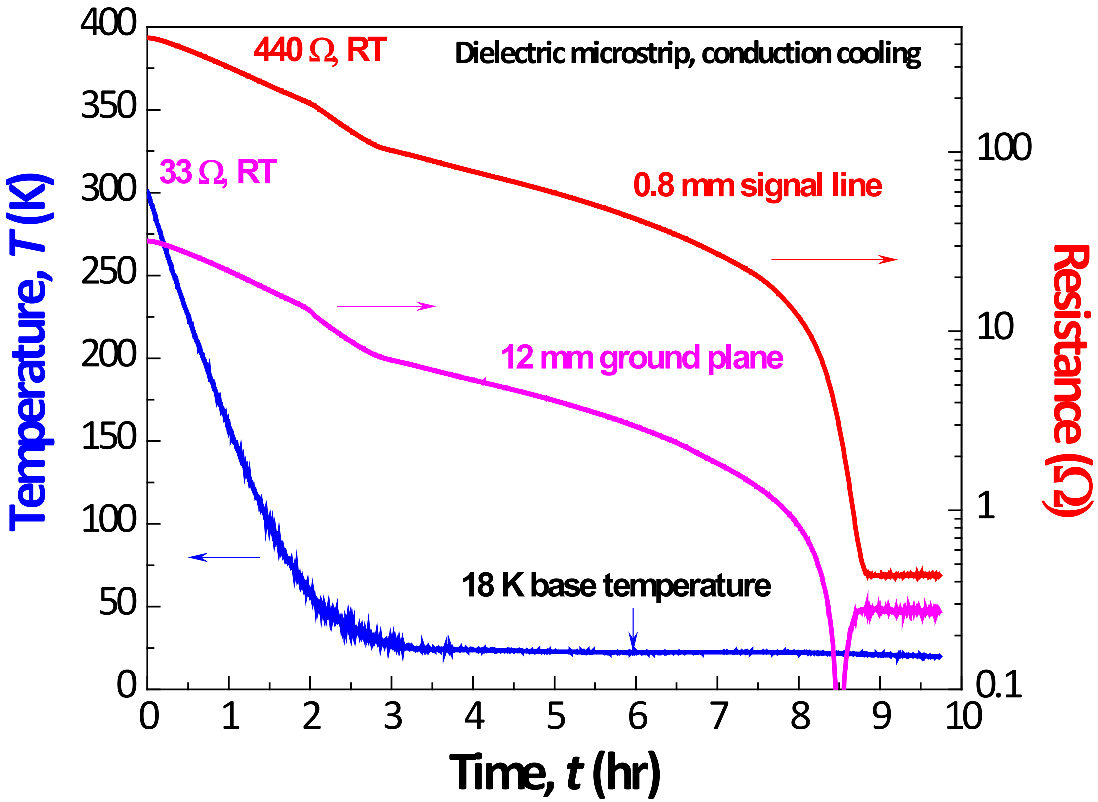


Assembled microstrips



Ground plane side

Conduction cooling test of the dielectric microstrip



- ✓The assembly sustained 5 cycles from 18 K to room temperature
- ✓Central line sustained up to 10 mA current at 18 K

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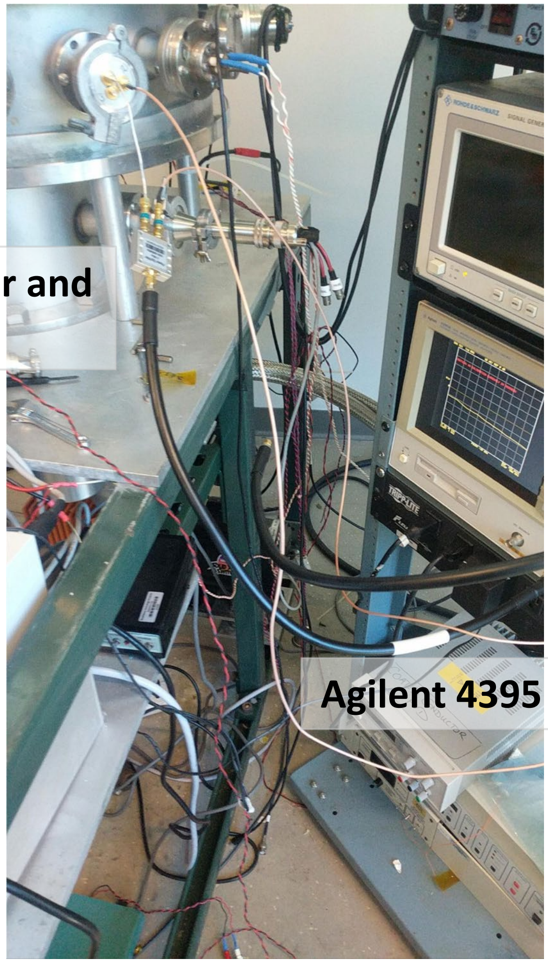
Experiment

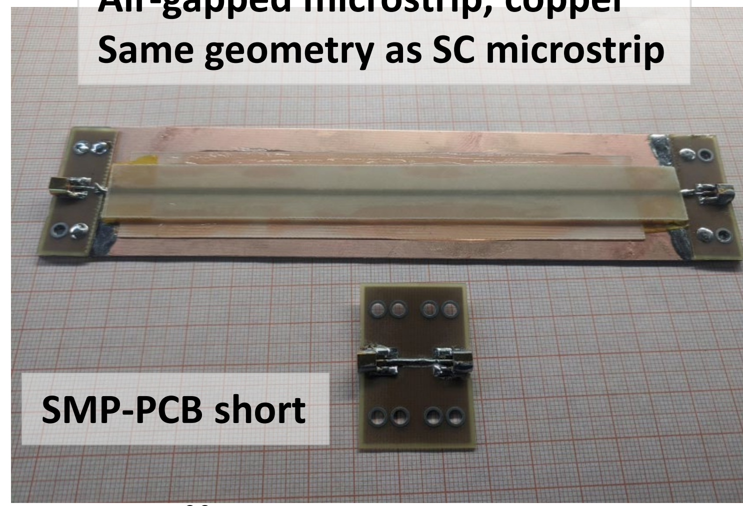
Cryochamber

Power splitter and attenuators

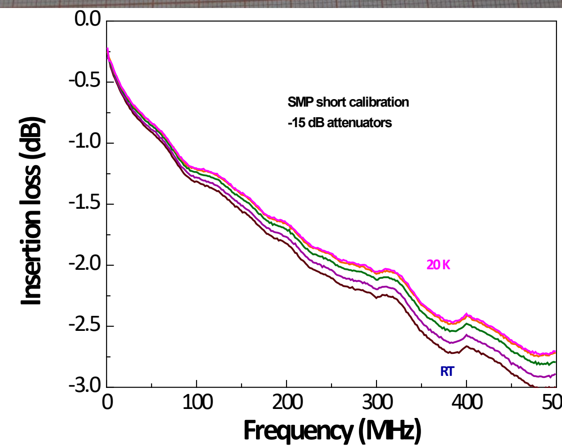


Agilent 4395 A VNA

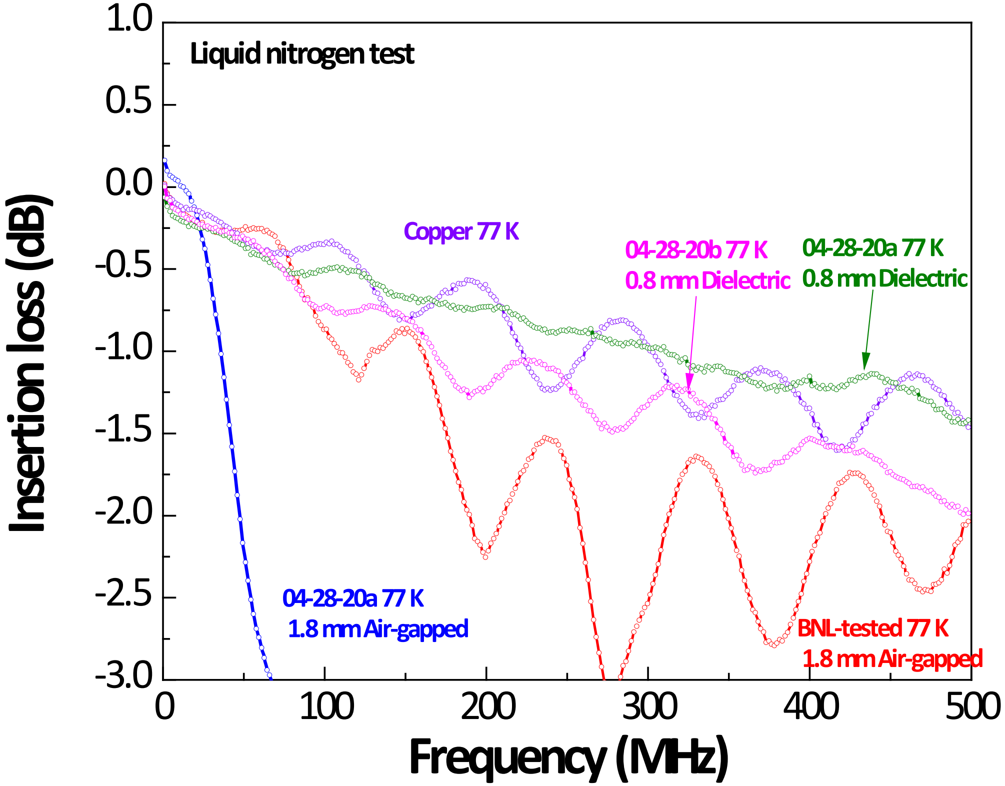
Air-gapped microstrip, copper
Same geometry as SC microstrip



SMP-PCB short



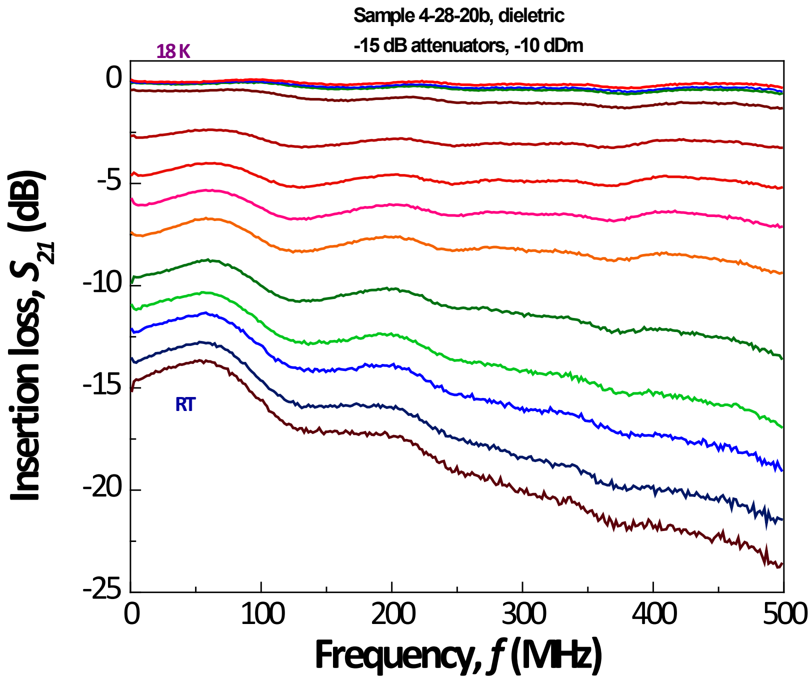
Liquid Nitrogen test

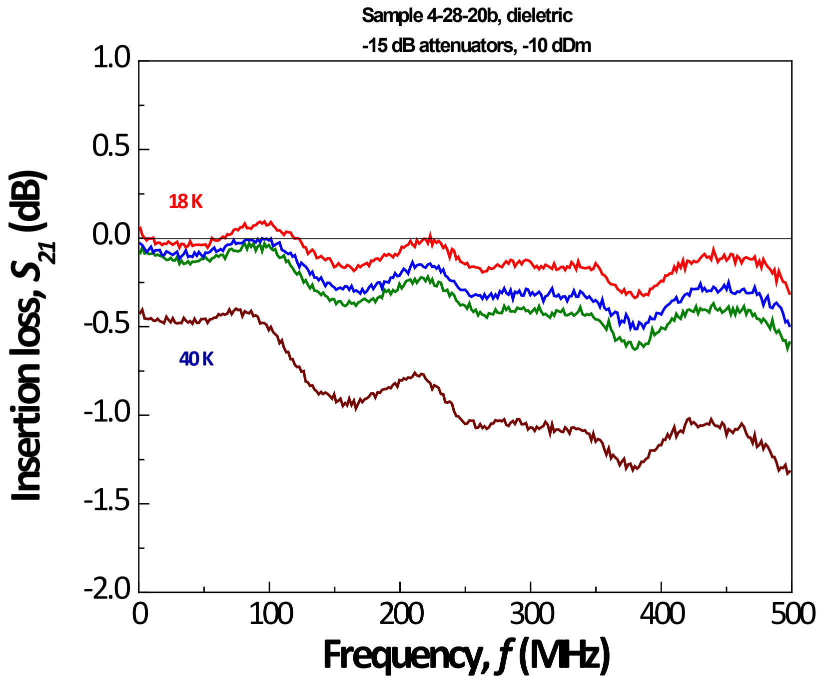


Extra solder

✓ **Possibly extra solder in the gap caused high losses > 50 MHz**

Successful conduction cooled test: dielectric microstrip





✓ **Insertion loss ≈ 0.1 dB at 500 MHz at 18 K**

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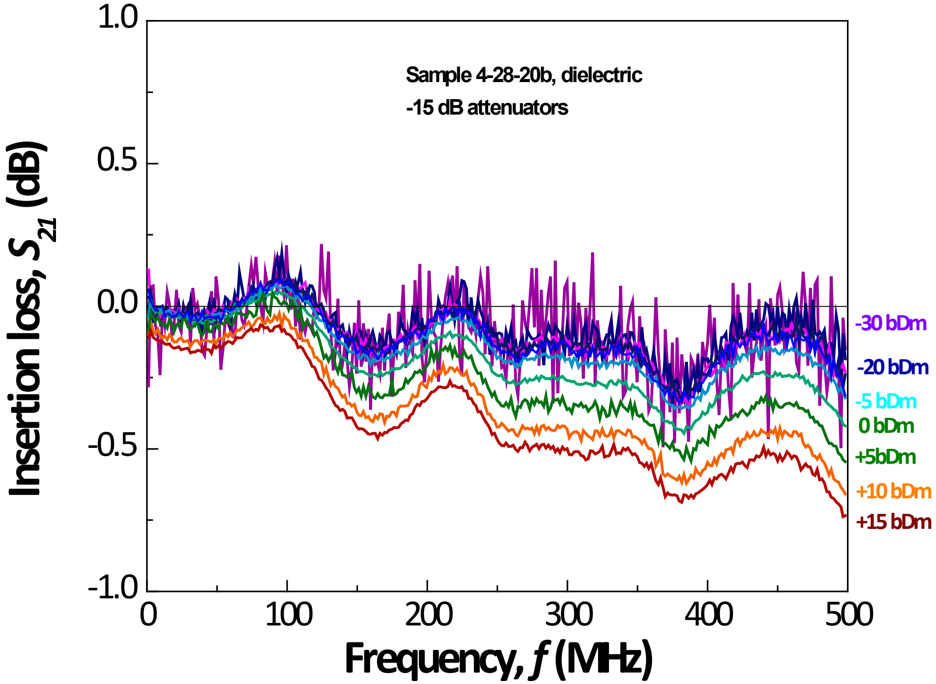
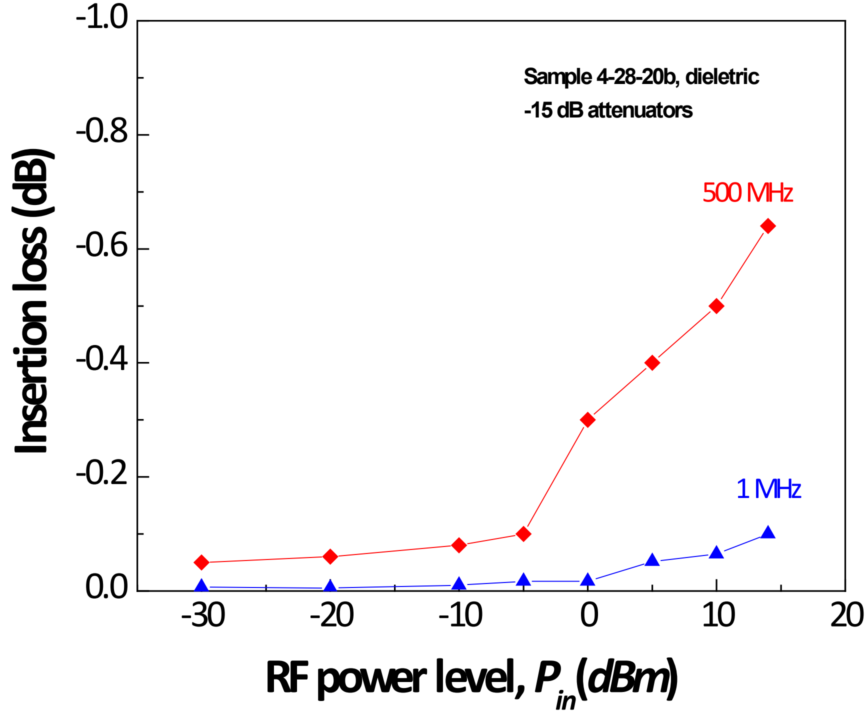
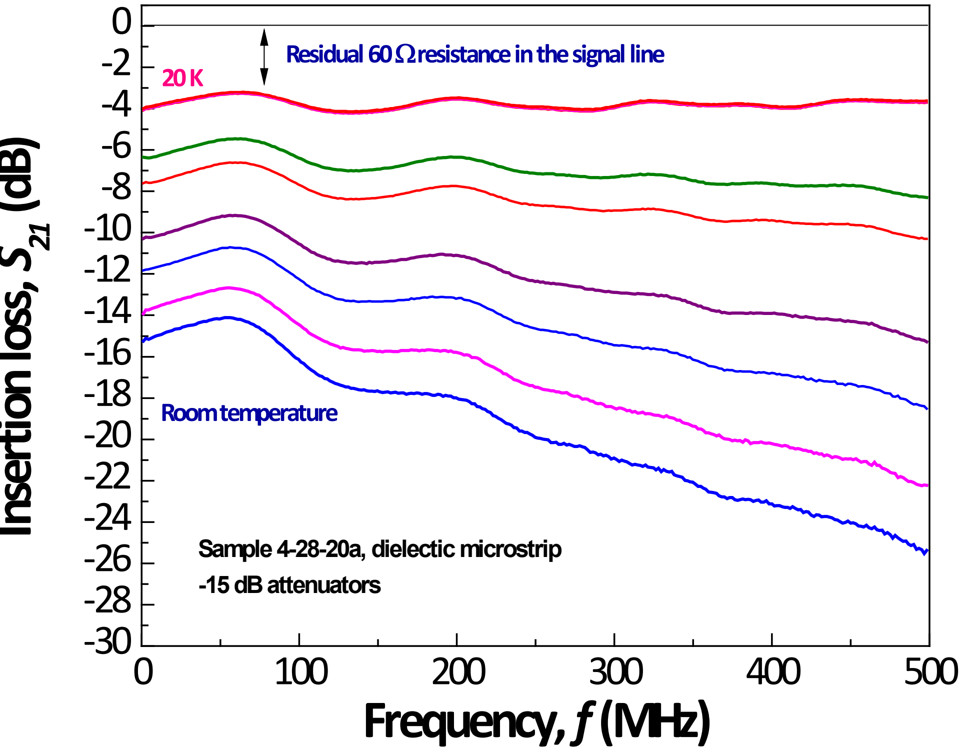
Power dependence of the loss

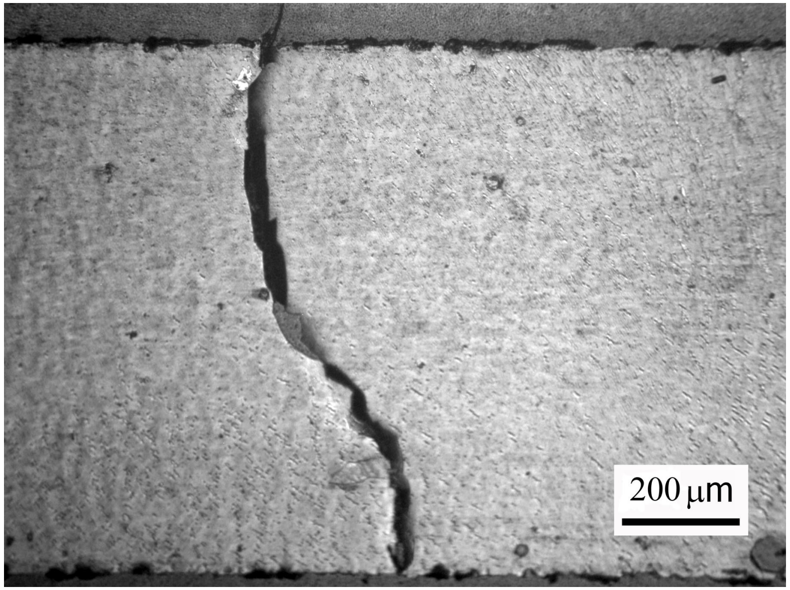




✓ **Mechanism of the power dependence needs to be further investigated**

Failed dielectric microstrip: residual resistance





✓ Signal line failed probably due to mechanical damage

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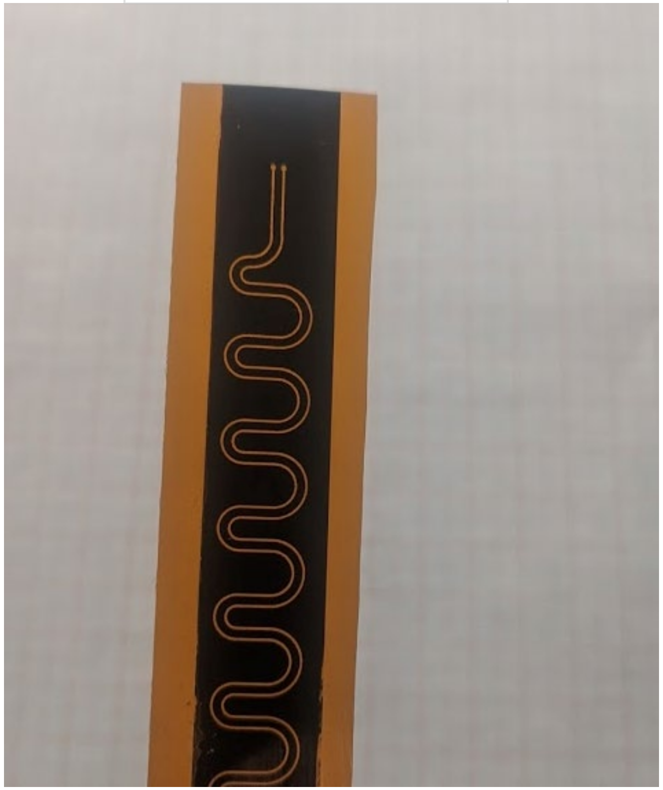
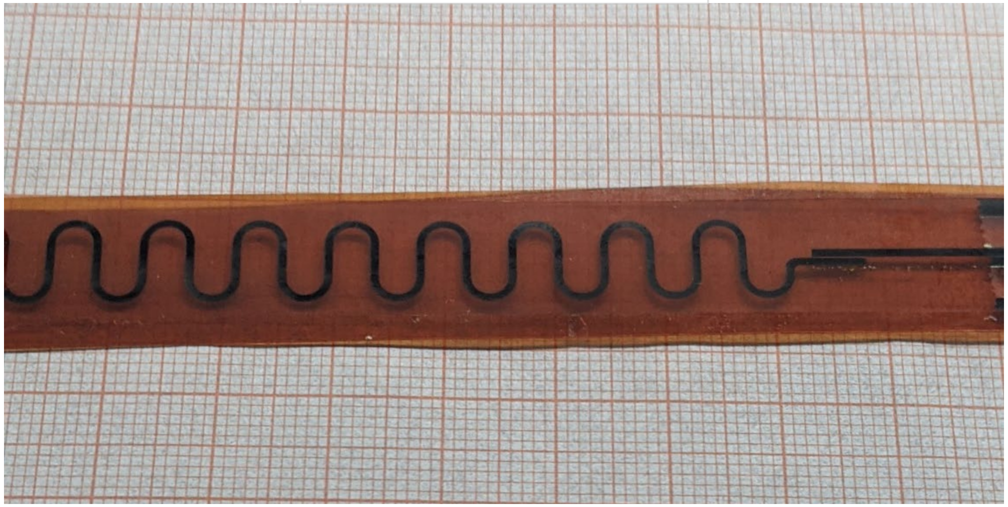
Future work: quality factor of resonator

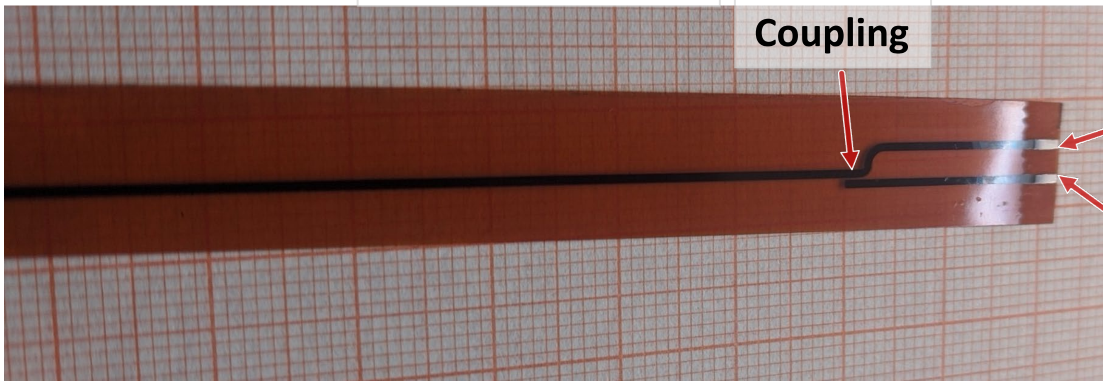
Coplanar resonator

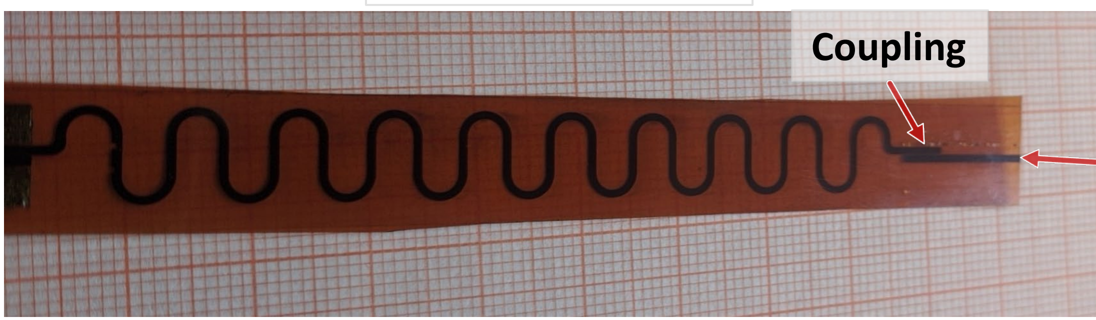


Microstrip resonator

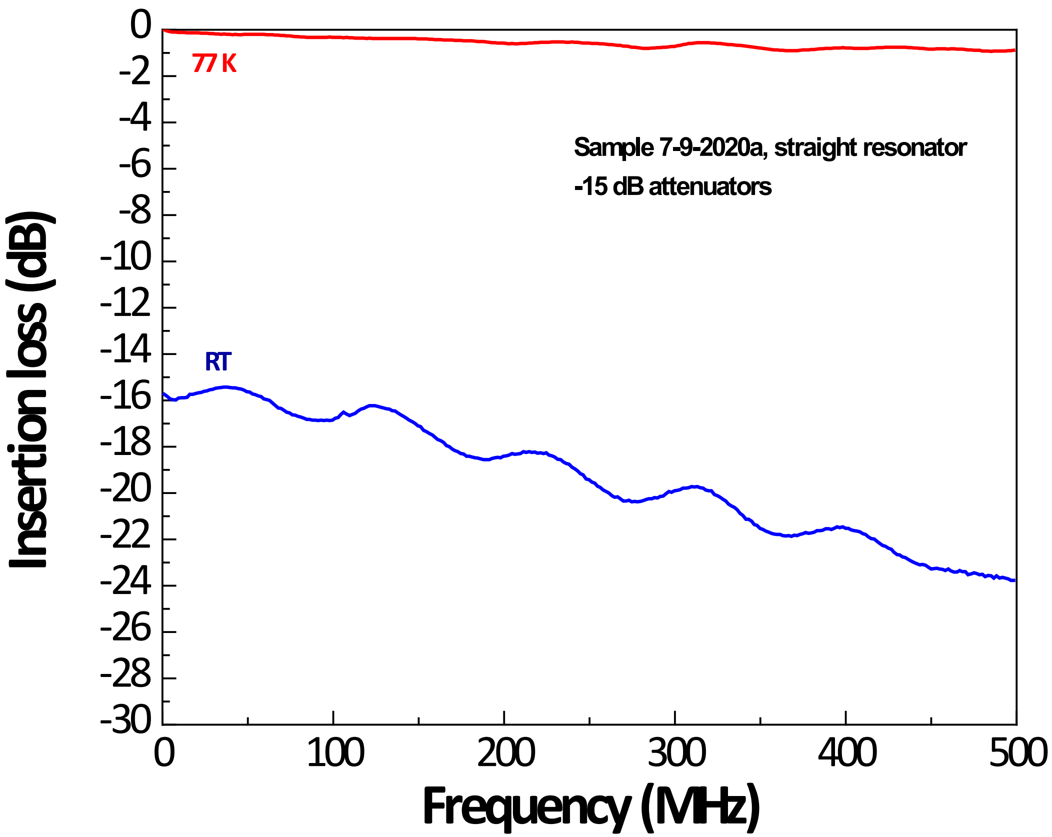


Resonator design

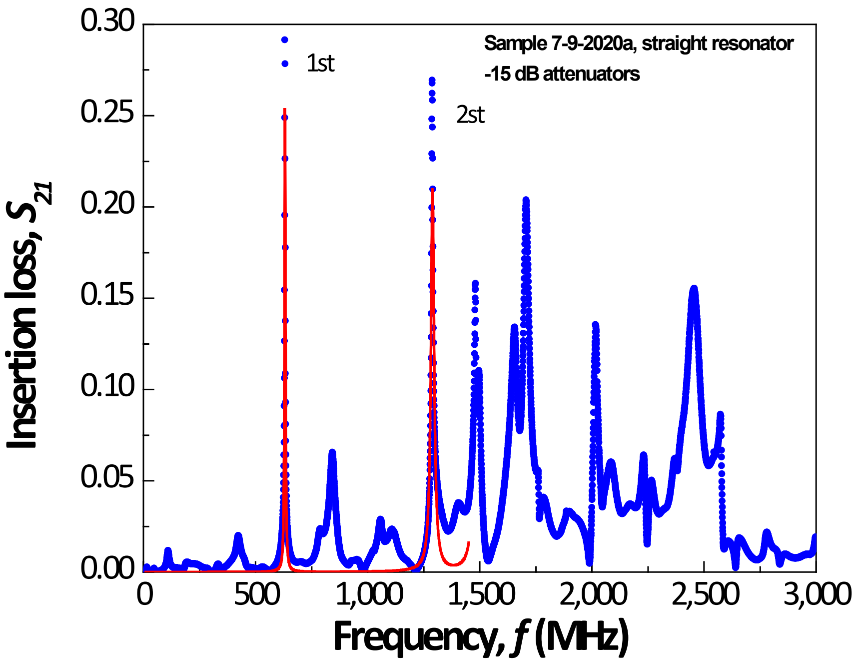


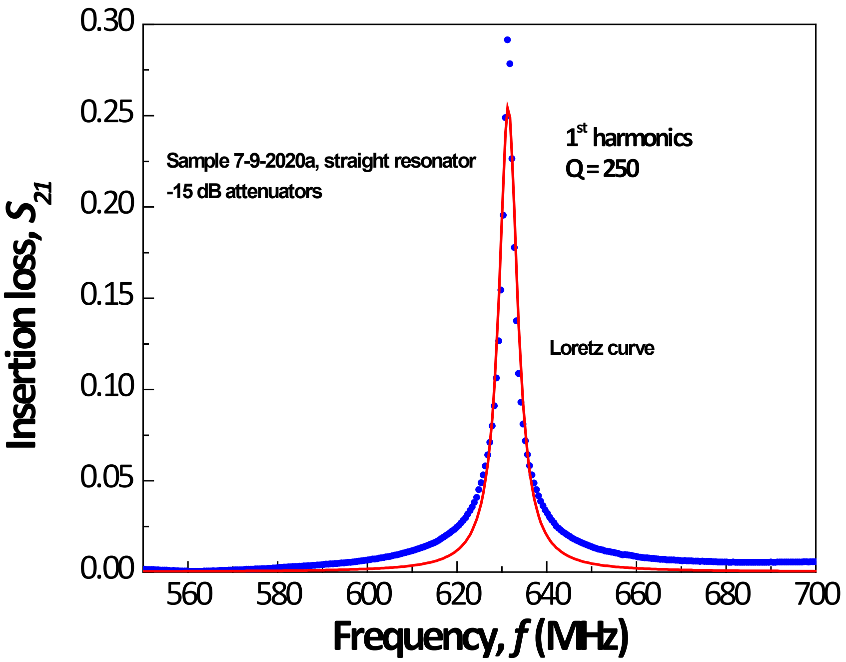


The signal line diagnostics



Straight resonator





Summary

- Manufactured air-gapped and dielectric 3-filament microstrips
- Demonstrated superconducting transition in conduction-cooled mode
- Detailed insertion loss measurements up to 500 MHz at 18 K, conduction cooled
- Air-gapped microstrips exhibited high loss > 50 MHz, possibly due to excessive solder in the gap
- Dielectric microstrips demonstrates 0.1 dB at 500 MHz at 18 K