Packaging and Interconnect Technologies for Cryogenic & Quantum Systems

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IEEE Silicon Valley / SF Bay Area EPS Chapter
Webinar, April 22nd, 2021

Outline

- **Intro Comments & Overview**
- P&I for Cryogenic Electronics
  - Superconducting resonators
  - Interconnects (Superconducting Flex Cables)
  - Connectors (Cable-to-Cable)
- Moving towards Quantum
  - Very brief intro to “quantum”
  - Challenges
  - Approaches
- Concluding Comments

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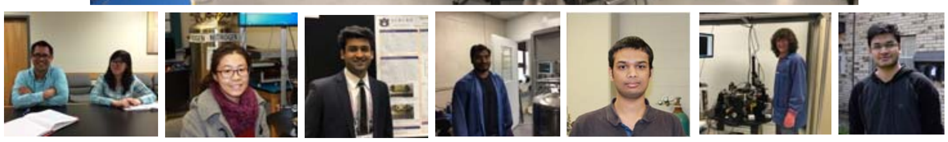
Intro Comments

- AMNSTC – A state-funded Micro/Nano Fab & Tech Center @ Auburn University
- Hamilton Lab @ Auburn University, Auburn, AL (shown below) http://fast.auburn.edu/
  - Work of multiple students (George Hernandez (@ Intel), Rujun Bai (@ Lam), Simin Zou (@ Applied Materials), Uday Goteti (@ UCSD), Vaibhav Gupta, Bhargav Yelamanchili, Sherman Peek, Archit Shah, as well as others)
- Much of the work shown here (for superconducting flex cables and connectors) was sponsored by Microsoft, working closely with Dr. David Tuckerman



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Motivation → Cable (Interconnect) #'s and $\dot{Q}$

D-Wave processor in a dilution refrigerator (shields removed)

https://www.dwavesys.com/press-releases/d-wave-makes-new-lower-noise-quantum-processor-available-leap

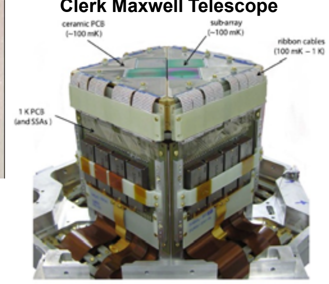
Janis dilution refrigerator with many cables

http://www.janis.com/UHVCompatibleDilutionRefrigeratorForSTM_NanoTechWeb.aspx#

gmon transmon from UCSB (Martinis)

http://web.physics.ucsb.edu/~martinisgroup/photos.shtml

SCUBA-2 Module for the James Clerk Maxwell Telescope



W. S. Holland, et. al., "SCUBA-2: The 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope," *Mon. Not. R. Astron. Soc.*, vol. 430, no. 4, pp. 2513–2533, 2013.

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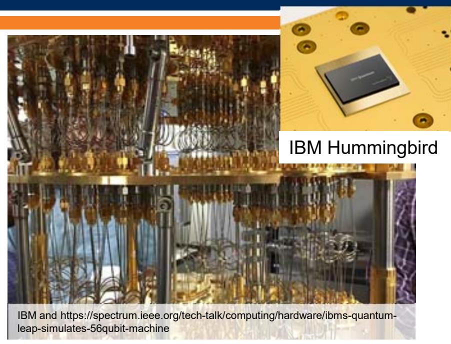
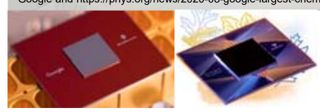
IBM / Google / Intel (among others!)



IBM Hummingbird

IBM and https://spectrum.ieee.org/tech-talk/computing/hardware/ibms-quantum-leap-simulates-56qubit-machine

Google and https://phys.org/news/2020-08-google-largest-chemical-simulation-quantum.html



Google Bristlecone & Sycamore

Intel

Intel Tangle Lake & Horse Ridge II

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Intro / Background

- In much of this work, where possible, we've used superconductors (SC):
  - Ultra-low (but not zero) loss below T_c @ microwave frequencies
  - (Surrounding) dielectric loss (tanδ) important, comparable to SC loss
  - Impedance matching similar to non-SC, but sometimes need to take kinetic inductance (L_k) into account
  - EM simulators (i.e., ADS, HFSS, Sonnet, etc.) with proper SC model
- Example trace density of SC cables*:
  - Single layer of single-ended stripline: 5 μm thick PI, ~ 5 μm wide traces, 5 μm vias, 20 μm space between traces and vias…pitch ~ 50 μm => 200 single-ended / cm (of width) [< 10 nW for 4K-10mK]
  - Need sufficient grounding between signals to reduce crosstalk and allow impedance matching up to very high frequencies (> 100 GHz)
  - Challenge to fan-out/break-out to (available) connectors
  - Working to scale to this level, expand to multi-layer, 2D break-out, etc.

* Not what will be shown today, just for motivating the topic

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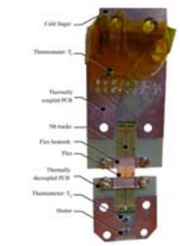
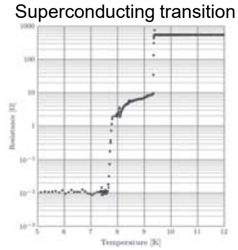
Previous Nb & NbTi Superconducting Flex Cables

- Cables with 19 μm thick PI-2611
- 10 DC traces per cable
- Nb with Ti adhesion
- Ti/Ni/Cu/Au UBM

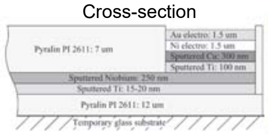
- NbTi foil laminated to Kapton
- Up to 40 cm long and up to 10 traces per cable
- Loss of 2.5 dB and cross-talk of -25 dB obtained at 8 GHz

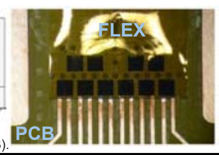


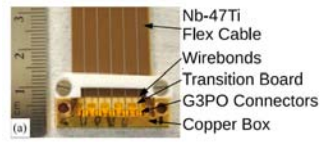
Superconducting transition

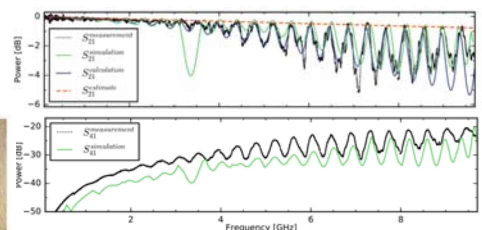


Cross-section









Van Weers et al., *Cryogenics* 55, 1-4 (2013).

Walter et al., *IEEE Trans. Appl. Supercond.*, 28(1), 1-5 (2018).

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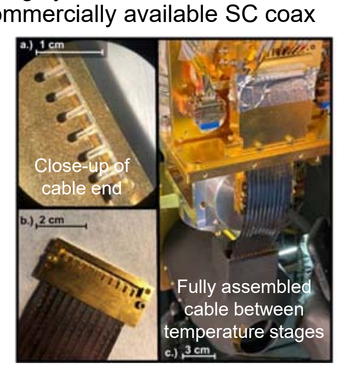
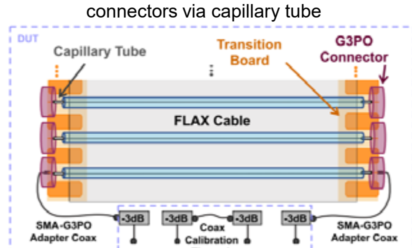
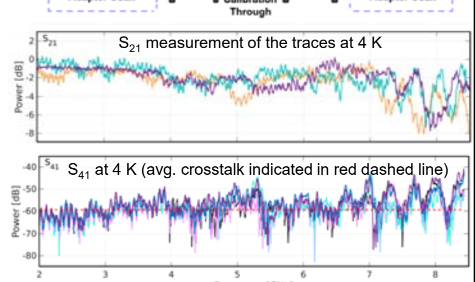
Previous Nb & NbTi Superconducting Flex Cables

- Nb47Ti coaxial ribbon cable terminated with G3PO connectors
- 30 cm long, 1 dB loss at 8 GHz and -60 dB nearest neighbor cross-talk
- Heat load of 20 nW from 1 K to 90 mK – Roughly half the load from the smallest commercially available SC coax



Schematic showing cable attachment to G3PO connectors via capillary tube





Smith et al., *IEEE Transactions on Applied Superconductivity*, *31*(1), 1-5 (2020).

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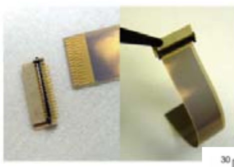
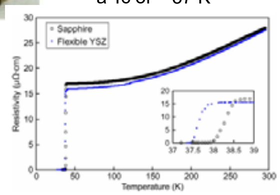
High(er) T_c Superconducting Flexible Cables

- 33 traces, 200 µm wide MgB_2 on flexible YSZ
- Delamination of MgB_2 when exposed to water at RT
  - Improved by using ALD deposited Al_2O_3

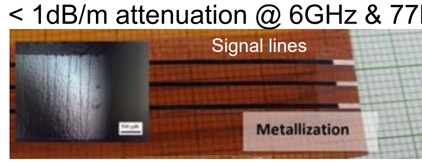


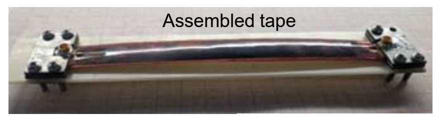
MgB2 FFC before and after mating to a Hirose FFC/FPC connector assembly

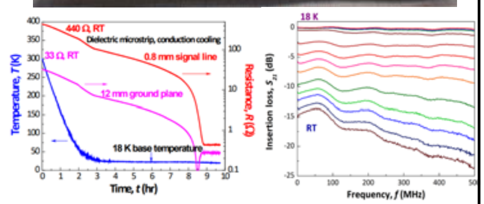
R vs T plot showing a Tc of ~ 37 K



- YBCO films exfoliated and transferred to Kapton
- < 1dB/m attenuation @ 6GHz & 77K







Yung et al., *IEEE Trans. Appl. Supercond.*, *21*(3), 107-110 (2010).

Solovyov et al., No. BNL-220992-2021-JAAM (2021).

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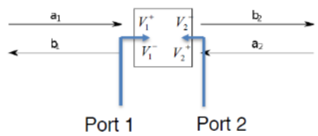
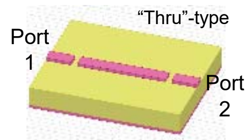
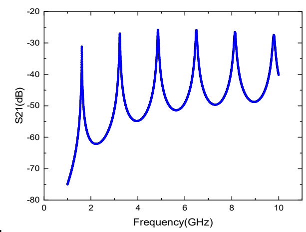
Microstrip Transmission Line Resonators







$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$S_{11} = \frac{b_1}{a_1} = \frac{V_1^-}{V_1^+} \qquad S_{21} = \frac{b_2}{a_1} = \frac{V_2^-}{V_1^+}$$

$$S_{12} = \frac{b_1}{a_2} = \frac{V_1^-}{V_2^+} \qquad S_{22} = \frac{b_2}{a_2} = \frac{V_2^-}{V_2^+}$$

Measure S-parameters with a Network Analyzer

$$\frac{1}{Q_t} = \frac{1}{Q_C} + \frac{1}{Q_d} + \frac{1}{Q_r} + \ldots$$

Q_C Conductor losses…need this to be low! => SC

Q_r Radiation losses…typically negligible

$$Q_d = \frac{1}{\tan\delta}\left(1 + \frac{1-q}{q\varepsilon_r}\right)$$ Dielectric losses (q is microstrip fill factor)

- Assume (design for) very weak coupling, negligible radiation loss, dominated by Q_C and Q_d.
- Use "thru" or "shunt" types of resonators.
- Resonant frequencies related to the real part of dielectric permittivity (ε_r').
- Quality factor related to imaginary part of dielectric permittivity (tanδ).
- Both are needed for microwave design of the SC flex cables based on these dielectrics.

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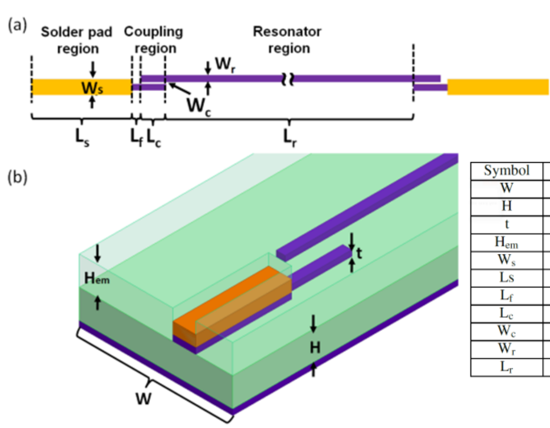
Resonator Design (Including Embedding)

- Half-wavelength microstrip resonator with parallel line coupling capacitor
- Building superconducting flexible cables using an embedded structure is attractive since it has been observed to increase reliability and it is necessary for cables in configurations with reduced cross-talk, such as stripline.



Symbol	Value	Description
W	6 mm	Width of dielectric
H	20 μm	Height of dielectric
t	0.25 μm	Thickness of Nb layer
H_{em}	0, 20 μm	Thickness of HD-4110 encapsulation layer
W_s	120 μm	Width of solder pad
Ls	1200 μm	Length of solder pad
L_f	100 μm	Length of feed line
L_c	300 μm	Length of coupling gap
W_c	20 μm	Width of coupling gap
W_r	47.4 μm	Width of resonator
L_r	46.1 mm	Length of resonator

S. Zou et al., *IEEE Trans. Appl. Supercond.*, vol. 27, no. 7, pp. 1-5 (2017).

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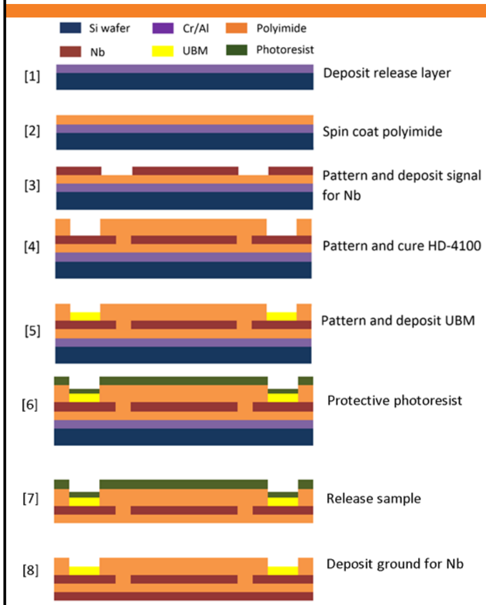
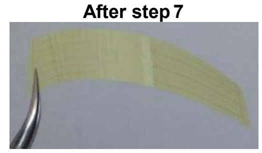
Flexible Microstrip Fabrication Process Flow

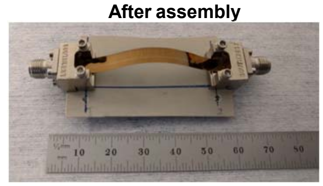


- PI layers ~ 20 µm, Nb layers ~ 250 nm
- Previously used Cr/Al (barrier/sacrificial) layers on top of Si handle wafer, for release of nearly complete sample (then back-side Nb deposition)
- Moved to fused silica wafers and (excimer) laser release (without Cr/Al layers)

After step 7



After assembly



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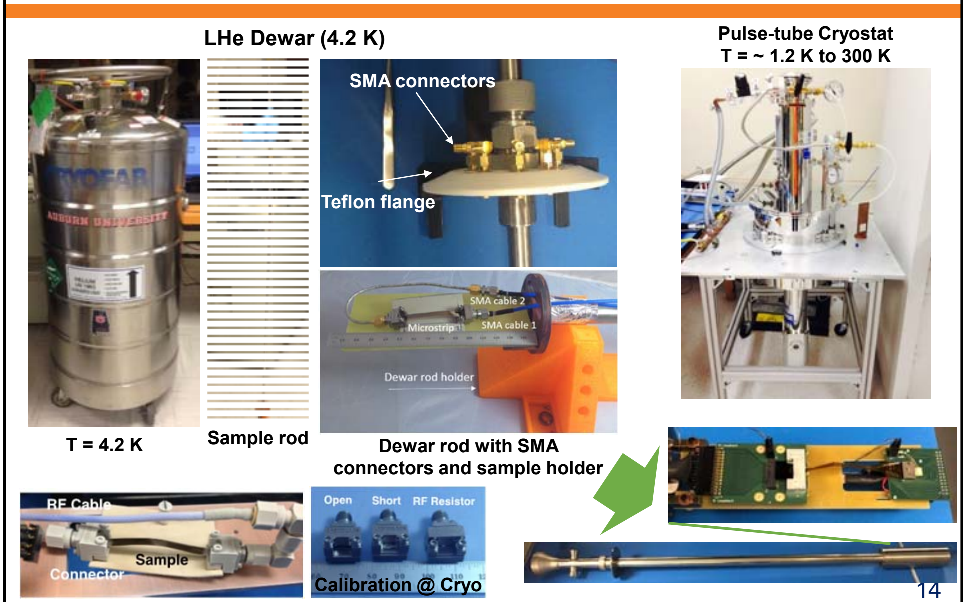
Cryogenic Microwave Measurement Setups



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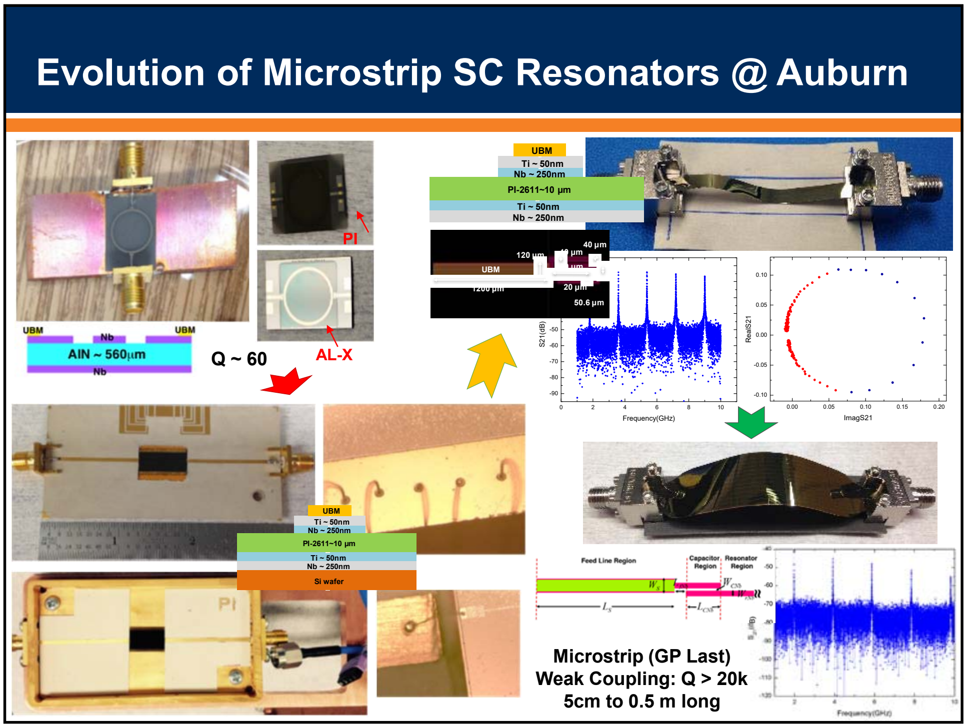
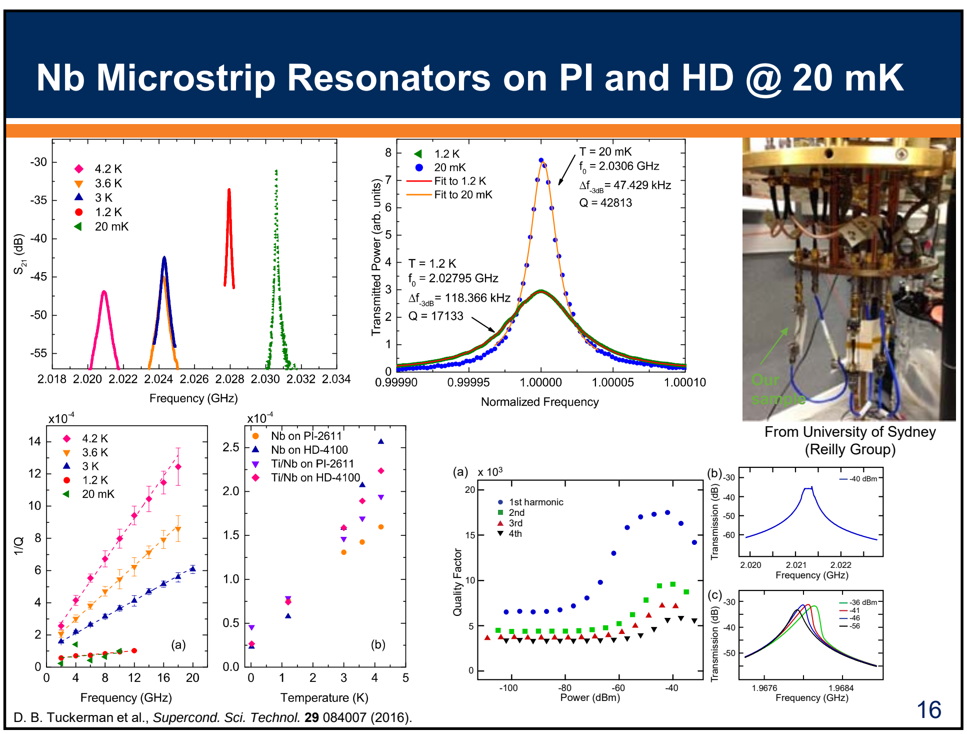

Evolution of Microstrip SC Resonators @ Auburn
UBM
Nb
UBM
AlN ~ 560μm
Nb
Q ~ 60
PI
AL-X
UBM
Ti ~ 50nm
Nb ~ 250nm
PI-2611~10 μm
Ti ~ 50nm
Nb ~ 250nm
Si wafer
Frequency(GHz)
ImagS21
Feed Line Region
Capacitor Region
Resonator Region
Microstrip (GP Last)
Weak Coupling: Q > 20k
5cm to 0.5 m long


Nb Microstrip Resonators on PI and HD @ 20 mK
4.2 K
3.6 K
3 K
1.2 K
20 mK
Frequency (GHz)
T = 20 mK
f0 = 2.0306 GHz
Δf-3dB = 47.429 kHz
Q = 42813
T = 1.2 K
f0 = 2.02795 GHz
Δf-3dB = 118.366 kHz
Q = 17133
Fit to 1.2 K
Fit to 20 mK
Transmitted Power (arb. units)
Normalized Frequency
Our sample
From University of Sydney
(Reilly Group)
Nb on PI-2611
Nb on HD-4100
Ti/Nb on PI-2611
Ti/Nb on HD-4100
Temperature (K)
1st harmonic
2nd
3rd
4th
Quality Factor
Power (dBm)
Transmission (dB)
D. B. Tuckerman et al., Supercond. Sci. Technol. 29 084007 (2016).
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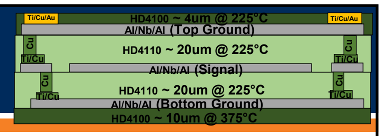
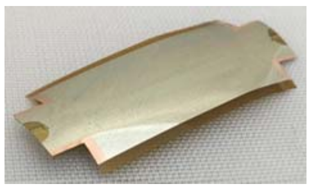
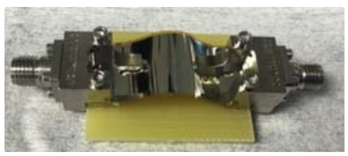
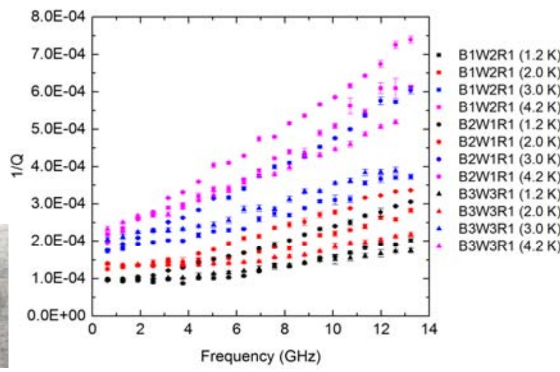
SC Stripline Resonators



- Stripline transmission line resonators from different batches and different wafers.
- Resonators baked in vacuum oven at 90 °C for 2 hrs and then measured in PT cryostat.
- Q for different stripline resonators are relatively comparable and show that the additional fabrication processes can be tolerated (Nb not significantly deteriorated).
- Showed repeatability, process stability and promise for extension to additional signal layers.







V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

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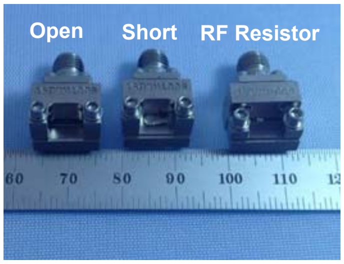
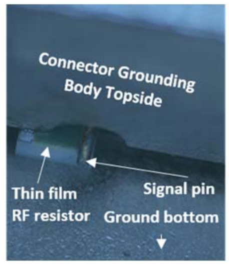
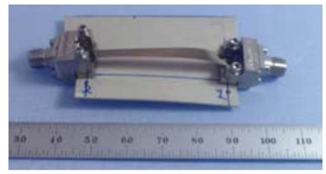
Microwave Calibration at ~ 4 K



Calibration standards based on Southwest Microwave edge launch connectors



Close-up of a 50 Ω Load



Representative thru: sample

- Super low loss expected for SC cables…need excellent calibration.
- SOLR calibration => 4 mechanical standards for Short / Open / Load / Reciprocal-Thru.
- Thru can be any reciprocal thru, including the sample (must be reciprocal).
- Four cool-downs to calibrate two ports.
- Move to RF switches => 1 cool-down.

G. A. Hernandez et al., *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1-4 (2017).

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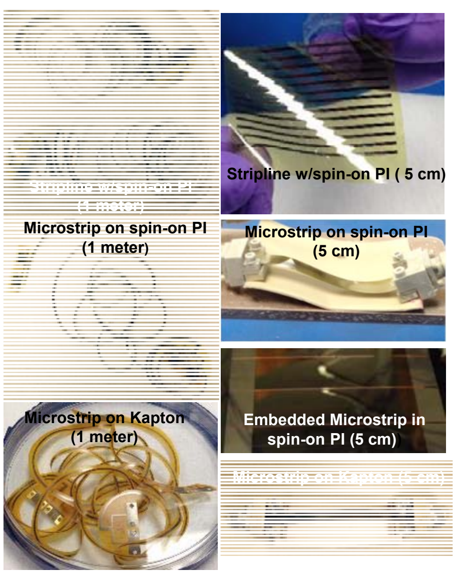
Various Flex Cables Constructed



Name	Length	Material type	Thickness
Stripline	1 m	Spin-on polyimide	20 µm
Stripline	5 cm	Spin-on polyimide	20 µm
Microstrip	1 m	Spin-on polyimide	10 µm
Microstrip	5 cm	Spin-on polyimide	20 µm
Embedded Microstrip	5 cm	Spin-on polyimide	25 µm
Microstrip	1 m	Kapton film	50 µm
Microstrip	5 cm	Kapton film	50 µm

- Family of flex cables fabricated on different flexible substrates.
- Superconducting microstrip, embedded microstrip and stripline versions.
- Significant amount of process development was/is involved…more to do…
- Latest 5 cm long structures (resonators and transmission lines) have excellent yield.

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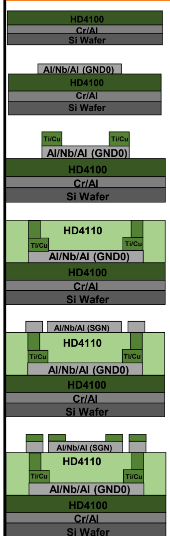
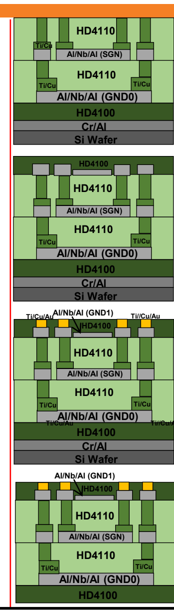
Stripline Transmission Line & Resonator Fabrication Process



- HD4100(10um) cured @ 375°C on Cr/Al deposited wafers
- Al/Nb/Al (bottom ground) patterned and deposited on the cured HD4100
- Ti/Cu seed layer patterned and deposited on bottom ground
- Electroplating on the patterned and cured bottom HD4110(20um) @225°C
- Al/Nb/Al (Signal) patterned and deposited on the cured HD4110
- Ti/Cu seed layer patterned and deposited on top of Signal layer



- Electroplating on the patterned and cured top HD4110(20um) @225°C
- Al/Nb/Al (top ground) patterned and deposited on the cured HD4110
- Top protective polyimide HD4100 (4um) patterned and cured @225°C
- Ti/Au UBM layer patterned and deposited on the cured top protective polyimide
- Release from handle

V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

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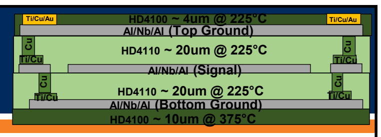
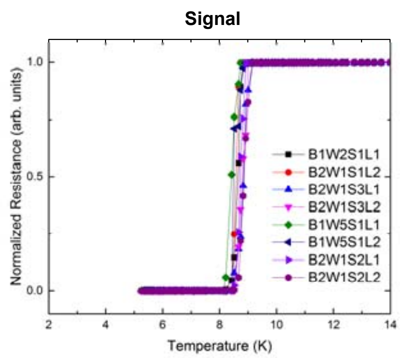
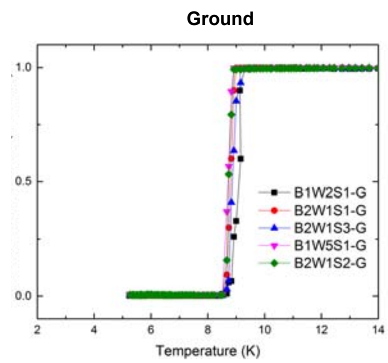
Comparison of T_c for Multiple Stripline Samples







- Transition temps of actual sample structures measured in pulse-tube cryostat
- Comparable T_c obtained from both signal (~ 8.4 K) and ground (~ 8.5 K).
- Measured after the (multiple) polyimide cures on top of the various layers.
  - Al layers "protect" Nb so that it can tolerate elevated process temps
  - Polyimide curing kept below 225 °C as further precaution
  - Also have used Al_2O_3 (deposited with ALD) to protect the Nb

V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

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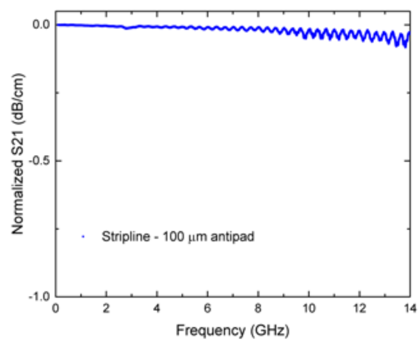
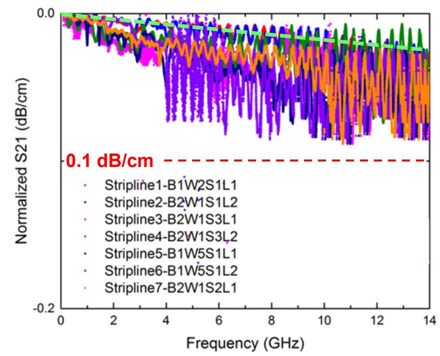
Comparison of Multiple Stripline Samples





- Comparison of normalized insertion loss of multiple stripline samples (loss per unit length).
- Length normalized insertion loss was well less than 0.1 dB/cm for all samples.
- Stripline length was 25 cm (100 μm wide anti-pad)
- "Wiggles" / oscillations in S_{21} due to impedance mis-match…actual loss follows the peaks (top envelope, green dashed line in plot) of S_{21}

V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

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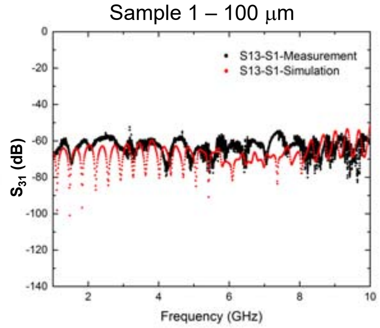
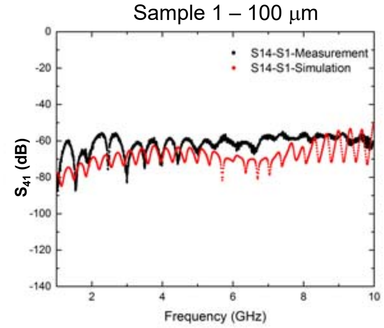
X-talk (S_{13} & S_{14}) Measurement & Simulation

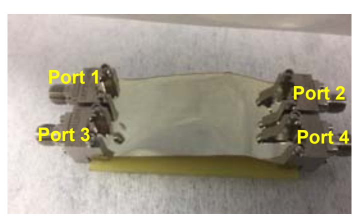
Sample 1 – 100 μm



Sample 1 – 100 μm



- Stripline transmission line designs for characterizing cross-talk (100 μm apart over most of sample length)
- Exhibited promisingly low cross-talk (below ~ -60 dB) and match simulation quite well.



V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

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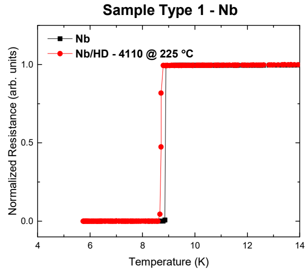
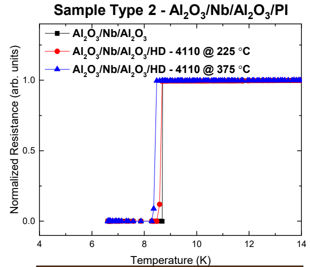
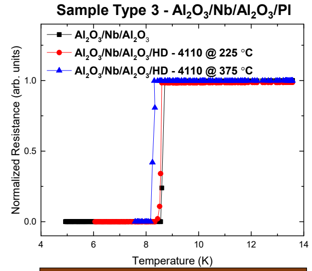
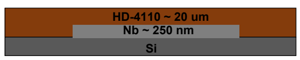
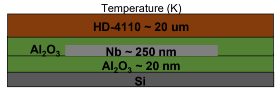
ALD deposited Al_2O_3 Barrier Layers

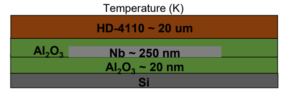












Cross-section of different samples (not to scale)

Test sample (50 μm wide and 250 nm thick Nb patterned on top of Si substrate)

T_c and I_c comparison at 4.2 K for different samples

	Sample 1: Nb		Sample 2: Nb/Al_2O_3		Sample 3: Nb/Al_2O_3	
	T_c (K)	I_c (mA)	T_c (K)	I_c (mA)	T_c (K)	I_c (mA)
Before HD-4110	8.9	186	8.7	250	8.6	222
After HD-4110 (225 ˚C)	8.6	182	8.5	182	8.5	176
After HD-4110 (375 ˚C)	X	X	8.1	75	8.2	65

V. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1-4 (2021).

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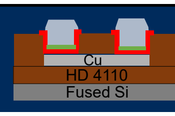
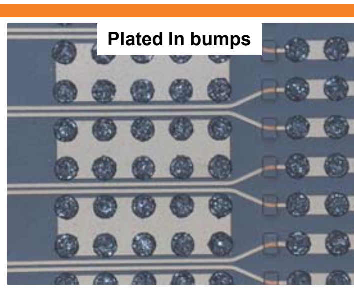
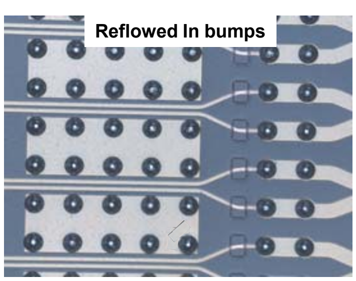
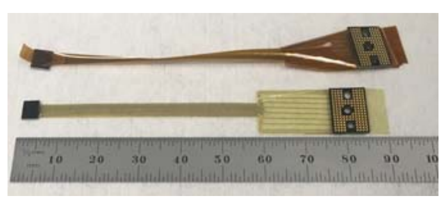
Edge Launch ➞ Indium Bumping



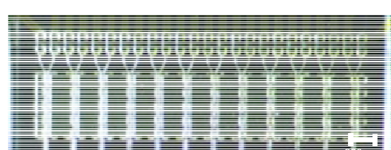




- "Chip"-on-flex bonding for both commercial and custom interconnects
  - SAC-to-indium and indium-to-indium



Custom and commercial "chip-on-flex" attachment of 375 °C cured polyimide cables (top) and 225 °C cured polyimide cables (bottom).



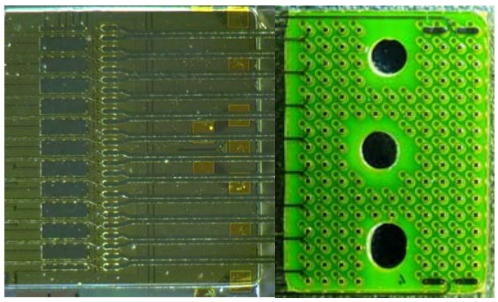
Microscopic image of an indium bump array bonded to indium bump array.

Peek et al, GOMACTech 2021, virtual conference, March 29 – April 1, 2021.

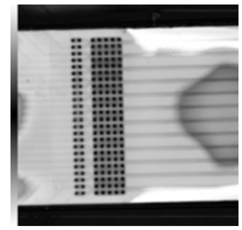
26

Epoxy Underfill Application & Cure

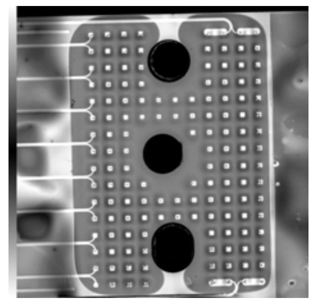
- Epoxy underfill process development used for stability of connection to flex cable and reliable cryogenic thermal cycling.



Microscopic images of
epoxy underfill process



CSAM epoxy underfill example 1



CSAM epoxy underfill example 2

Peek et al, GOMACTech 2021, virtual conference, March 29 – April 1, 2021.

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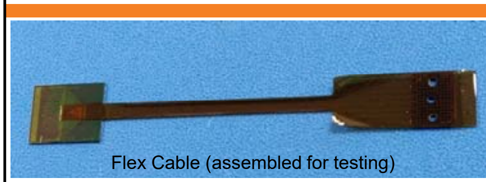
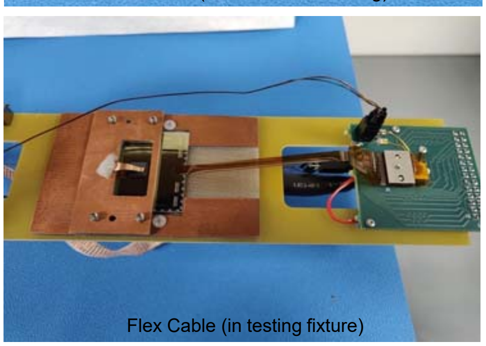
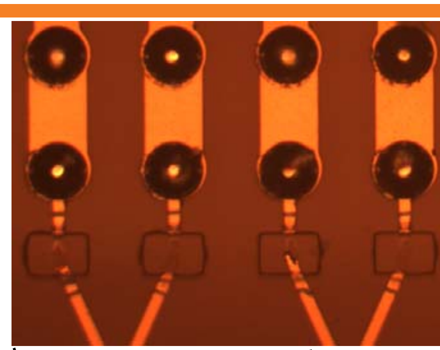
Severing Test Chip and Stubs After Cable Testing

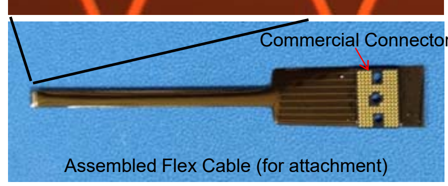


Flex Cable (assembled for testing)



Flex Cable (in testing fixture)





Assembled Flex Cable (for attachment)

- Test chip severed after measurement tests for subsequent bonding.
- Narrow signal lines between primary bump array to a test bump array were cut/removed through opening in PI (DC arc or laser)…signal integrity.

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Outline

- Intro Comments & Overview
- **P&I for Cryogenic Electronics**
  - Superconducting resonators
  - Interconnects (Superconducting Flex Cables)
  - **Connectors (Cable-to-Cable)**
- Moving towards Quantum
  - Very brief intro to “quantum”
  - Challenges
  - Approaches
- Concluding Comments

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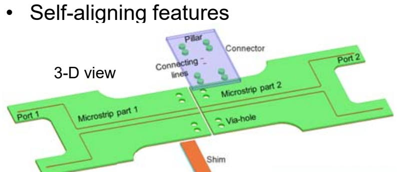
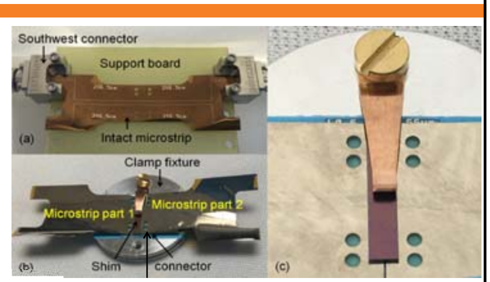
Cable-to-Cable Connection Approach (Bridging)

- Scalable cable-to-cable connector scheme with suitable high frequency performance
- Bridging connector for abutted cables / tapes
- Self-aligning features

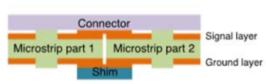


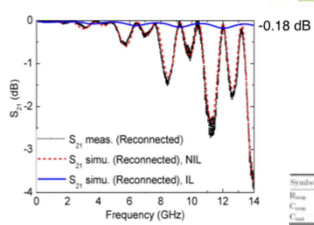


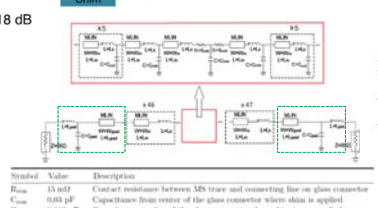
Reconnected microstrip

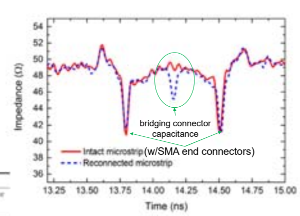
Zoom-in view of reconnected part

Cross section view of connection region:







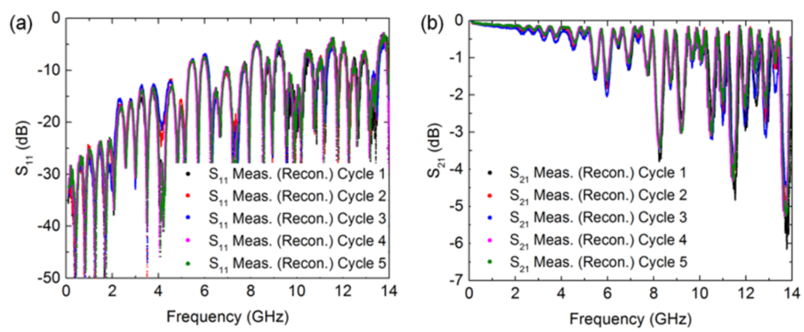


S. Zou et al., *Supercond. Sci. Technol.*, vol. 32, 075006 (2019).

30

Microwave Connector: Thermal Cycle Test

- Testing procedure:
  System calibration → test sample at 4.2 K (cycle 1) → heat up sample to R.T → test sample at 4.2 K (cycle 2) → repeat for 5 times
- Consistent RF performance was observed during different thermal cycles.
- Connector shows encouraging thermal reliability.
- Similar results for disassembly/re-assembly tests.



S. Zou et al., *Supercond. Sci. Technol.*, vol. 32, 075006 (2019).

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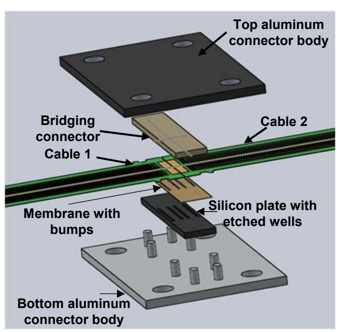
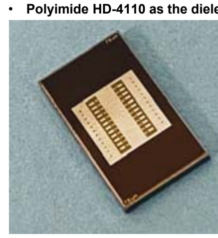
Bridging Connector v2

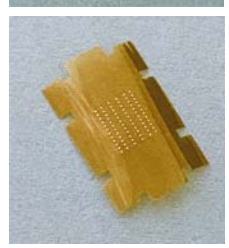
- Multi-component, self-aligned version designed, fabricated and tested
- Included new alignment and clamping mechanisms



Laser released thin-film cable:
- 12 parallel Nb signal lines
- Pitch: 300 µm
- HD 4100 as a protective layer

Bridging connector:
- Stripline structure
- Nb as the conductor
- Polyimide HD-4110 as the dielectric





Si plate w/ wells on bottom Al body:
- Well depth: 20 µm
- Well diameter: 300 µm

Polyimide membrane w/ Cu pillars:
- Pillar height: 10 µm
- Pillar Diameter: 100 µm

A. Shah et al., *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1-6 (2021).

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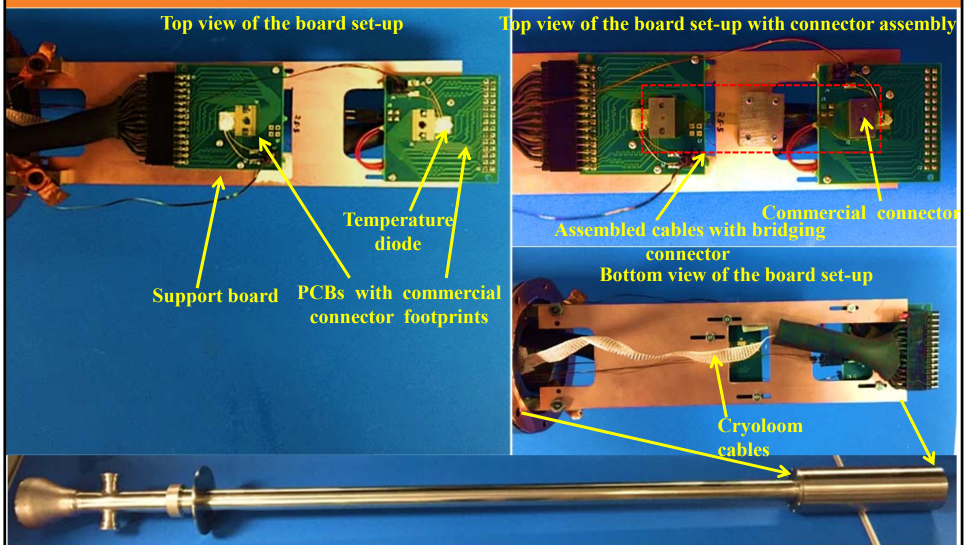
Set-up for Measurement in LN_2 or LHe



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Bridging Connector v2

- Multi-component, self-aligned version designed, fabricated and tested
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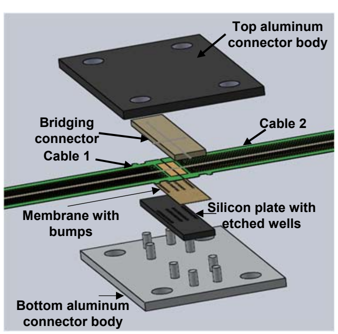

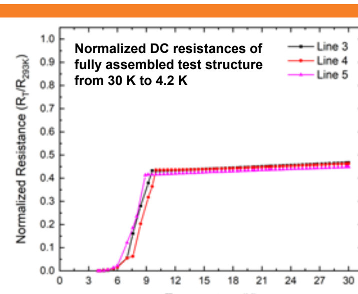

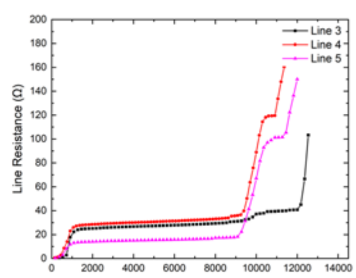

A. Shah et al., *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1-6 (2021).

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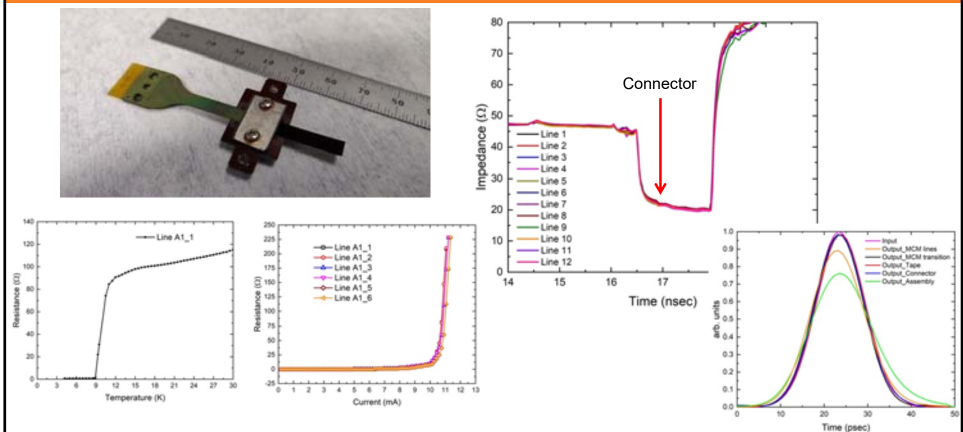
Face-to-Face Connection



- DC test
- Representative line with a T_c of ~ 9.0 K
- All lines in the assembly gave a critical current I_c of ~ 10 mA
- Survives thermal cycles

- TDR response of 12 SC striplines @ 4K
- Results show very small dip in impedance at the connector region
- Simulation of pulse transmission using time-domain response

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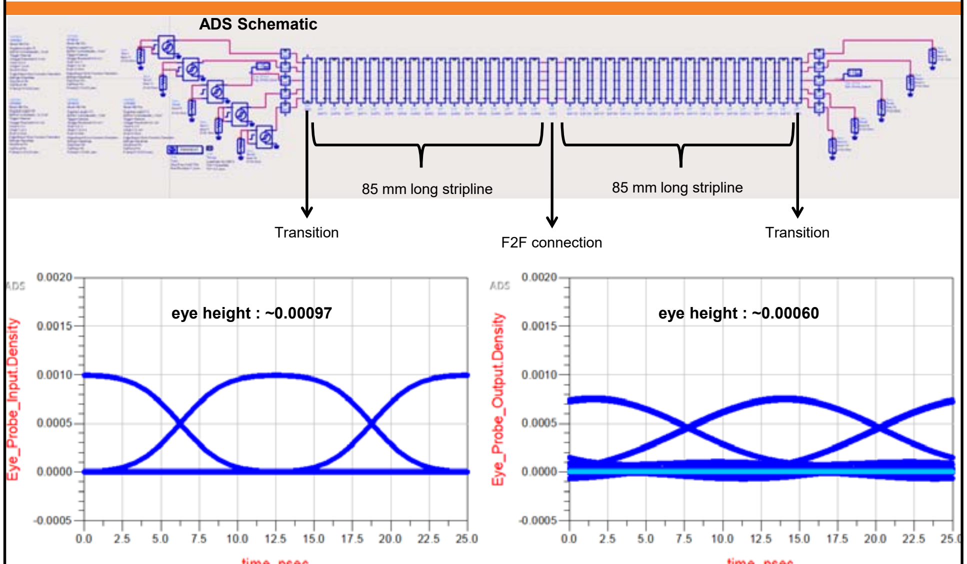
Signal Integrity Simulations in Keysight ADS



"Eye" Diagrams of Guassian Pulses to Represent Single Flux Quanta (SFQ)

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Additional Comments

- Other considerations:
  - Mechanical reliability (repetitive flexing, cooling in flexed configuration, …)
  - Environmental stability (impact of humidity, barrier layers, …)
  - Thermal cycle reliability (fabrication at elevated temps, then use @ / cycle to/from < 4 K, …)
  - Maintain positioning when cooled (fiber alignment, …)
- New packaging & integration technologies:
  - Alternative MCM substrates and construction (for better CTE match)
  - Suitable materials for die attach and underfill (re-workability?)
  - Connectors

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  - **Very brief intro to "quantum"**
  - **Challenges**
  - **Approaches**
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Classical vs. Quantum

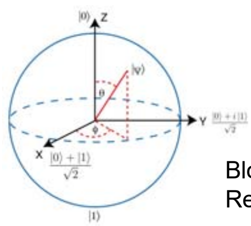
- Classical: 0 or 1

Switch ON or OFF

Capacitor / Node Charged to V Or Not Charged

- Quantum: $|0\rangle$ and $|1\rangle$

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



Superposition & Entanglement

Bloch Sphere Representation

https://www.quantum-inspire.com/kbase/bloch-sphere/

- Historically, many different device structures and materials systems were (are still being) explored
- Exponential growth once CMOS and materials were settled upon
- Si vs. other semi., clean SiO_2, etc.
- Continued materials advances to support continued growth

- Many similarities (regarding technology & materials status)
- Currently, multiple different qubit types/structures and materials are being explored (with massive scaling in mind)
- Beginning (hoping) to see sustained growth (exponential?)
- Tremendous number of materials studies and advances are needed (expected)

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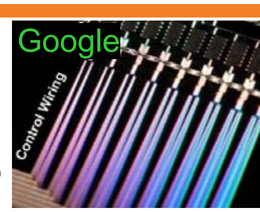
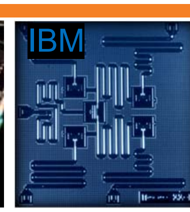
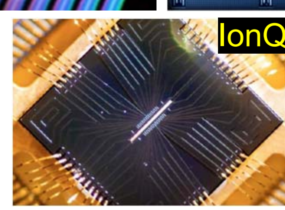
A Few Examples of Qubit Approaches

- Superconducting microwave qubits (cQED)
  - Single microwave photon < 10 GHz (superconducting JJ-based circuit coupled to a superconducting cavity)
  - Cooled to ~ 10 mK in dilution fridge
- Ion qubits:
  - Electronic states of trapped ions and collective ion motion
  - Trapped, laser cooled
- Photonic / Optical qubits (Linear or Nonlinear Optical QC):
  - Spin or orbital angular momentum components (modes) of photons
  - Squeezed systems or cluster states
- …







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Quantum Challenges

- Quantum states are (usually) delicate:
  - Preserve coherence to maintain superposition / entanglement
  - Allow unitary operations to manipulate / interact qubits
- Trade-off between ***control*** and ***coherence***.
  - "Control" includes manipulation, interaction, movement, measurement
  - Higher isolation from "environment", longer coherence
- Visualize noise as smearing of location on Bloch sphere
  - Decoherence - destroys quantum information in qubit
- Can think of situation as quality factor of resonator:
  - Q's of loss mechanisms sum as inverse (i.e., $1/Q_a + 1/Q_b + \ldots$) and overall Q dominated by lowest Q process
  - (Or a bucket with water & holes)
- This is the situation we're in now, exploring what and where the "holes" / loss processes are to reduce the leaks to a level acceptable for quantum error correction. ➞ Scaling!

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Quantum Packaging & Integration (Q-P&I)

- At least three phases for Q-P&I:
  - I. Previous phase:
    - Many different experimental and some small number of "operational" quantum computing / QIP systems
    - < ~ 100 qubits, integrated onto one "chip" in one "package"
  - II. Current phase: "NISQ" or noise intermediate scale quantum[1]
    - ~ 100 qubits, most likely still integrated onto/into one chip/package
    - Increasing challenge to add comm/control/I/O electronics to external systems
    - Beginning to see those electronics move closer to the quantum hardware
    - Quantum state transduction (QST) to (noisily) move Q info between systems
    - Opportunity to deeply explore P&I materials and structures to learn about impact on quantumness (see recent Science article [2])
    - Use qubits to sense the "defects"
  - III. Following phase(s) (post-NISQ):
    - > $10^3 \ldots 10^6$…and more, not necessarily on/in one chip/package
    - Incorporating quantum error correction (QEC) (move from physical to logical qubits)
    - Need for quantum capable / transparent interfaces
    - Need understanding of how materials & interfaces affect Q info (decoherence) and need ability to control / remove those effects

[1] Preskill, John. "Quantum Computing in the NISQ era and beyond." *Quantum* 2 (2018): 79.
[2] de Leon et al. "Materials challenges and opportunities for quantum computing hardware." *Science* 372, no. 6539 (2021).

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Q-P&I Challenges for Superconducting Qubits

- Superconducting microwave qubits:
  - 5 GHz photon: 20 μeV
  - Thermal noise @ RT (290 K): 25,000 μeV ~ -174 dBm/Hz
  - Thermal noise @ 4 K: 345 μeV ~ -193 dBm/Hz
  - Thermal noise @ 10 mK: 0.9 μeV ~ -219 dBm/Hz
- Potentially millions of interconnects*, with high density
- Impedance matching: not necessarily 50 Ω systems, no reflections
- Control crosstalk and scattering (resonance/mode control in packages)
- High thermal isolation, reduced thermal load, thermalization, attenuation
- Reliability and stability (thermal-cycle)
- Need to eliminate loss into unknown or unclear loss processes through interaction with states in dielectrics (two level system, or TLS), such as surface oxidation or interface states…difficult to passivate.

* Bardin, IEEE MTT-S Webinar, April 13th, 2021.

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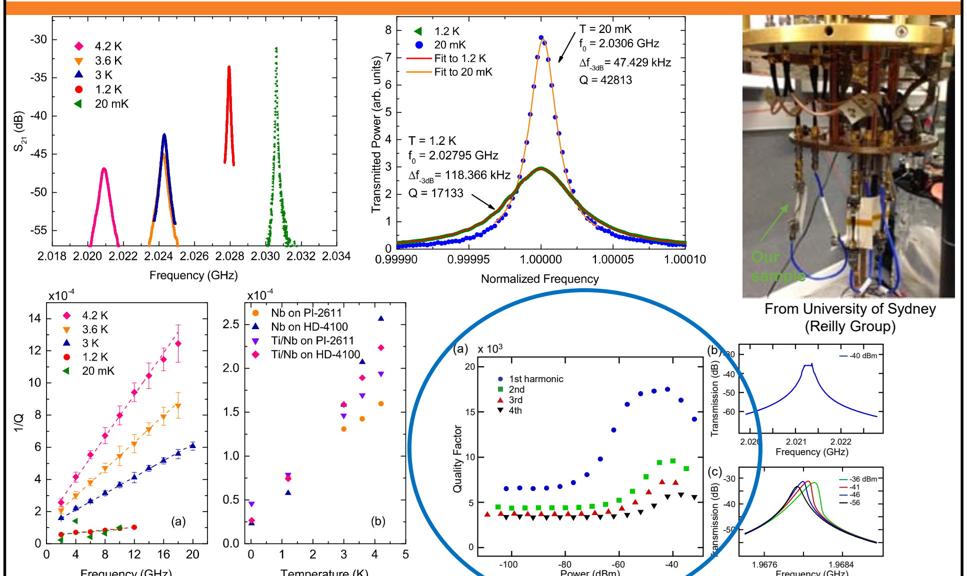
Nb Microstrip Resonators on PI and HD @ 20 mK



D. B. Tuckerman et al., *Supercond. Sci. Technol.* **29** 084007 (2016).

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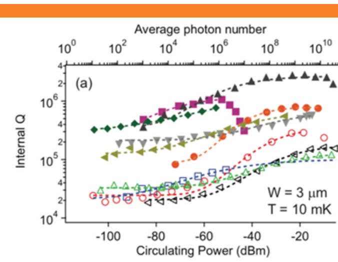
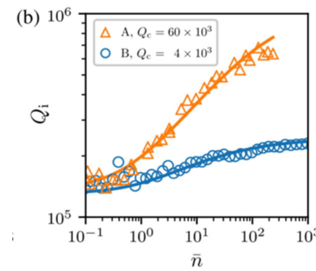
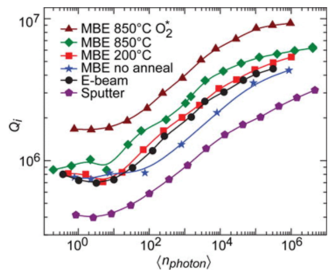
Loss at Low Microwave Power (Low ⟨n_{photon}⟩)



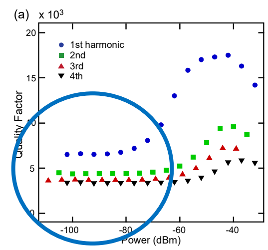
Sage et al., *Journal of Applied Physics* 109, no. 6 (2011): 063915.



Grünhaupt et al., *Physical review letters* 121, no. 11 (2018): 117001.



Megrant et al., *Applied Physics Letters* 100, no. 11 (2012): 113510.



D. B. Tuckerman et al., *Supercond. Sci. Technol.* **29** 084007 (2016).

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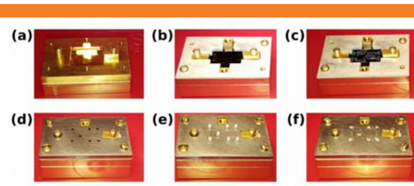
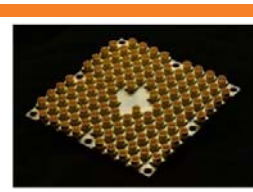
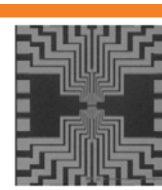
Active Area of Research (Small Sample)



Bronn et al., “High coherence plane breaking packaging for superconducting qubits” 2018 Quantum Sci. Technol. 3 024007



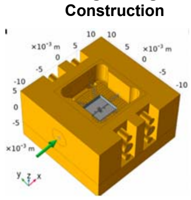
Intel’s Tangle Lake SC quantum processor: 49 qubits & 108 RF connections to the outside world.



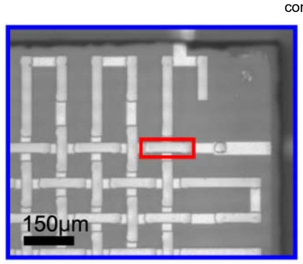
Intel’s 3 Si spin qubit chip, defined by 7 gates. Ratio of control wires to qubits is >>1.

J. S. Clarke, "Quantum Computing and the Importance of Interconnects," *2018 IEEE IITC*.

Package Design & Construction

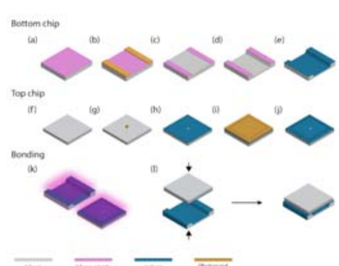


Lienhard et al., "Microwave Packaging for Superconducting Qubits," 2019 IEEE MTT-S International Microwave Symposium (IMS).



Multi-layer In interconnects (stacked-chips)

Foxen et al., “Qubit compatible superconducting interconnects”, *Quantum Science and Technology*, 3(1), 014005 (2017).



Lei et al., "High coherence superconducting microwave cavities with indium bump bonding," *Applied Physics Letters* 116.15 (2020): 154002.

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Closing Comments

- Packaging & integration for cryogenic electronics
  - Growing number of applications (space, quantum, etc.)
  - SC resonators for materials exploration
  - Various types of superconducting flexible cables with very high performance (ultra-low loss, low cross-sections)
  - Multiple types of connectors with suitable performance, but still room for improvement
- Moving towards quantum systems
  - Many opportunities for materials and P&I structure exploration
  - + many challenges

- Thank You!

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