Recent Progress on Flexible Superconducting Integration Technology: Cables and Connectors

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CEC-ICMC 2019

Outline

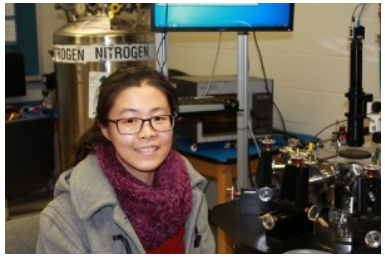
- Intro Comments
- Superconducting Flexible Cables (Stripline)
- Cable-to-Cable Connectors

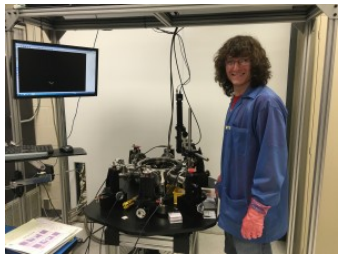
Intro Comments

- AMNSTC – Micro/Nano Fabrication & Technology Center @ Auburn (AL-funded)

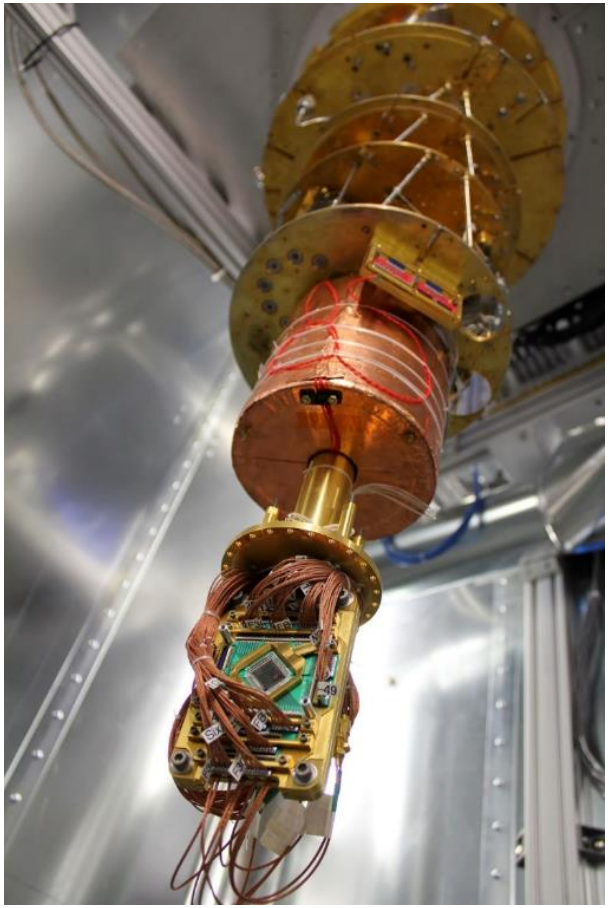
  http://www.eng.auburn.edu/amstc/

- 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), Vaibhav Gupta, Bhargav Yelamanchili, Sherman Peek, Thomas Stegeman, as well as others)
- Majority of work shown here was sponsored by Microsoft, working closely with Dr. David Tuckerman





Motivation ⇒ Cable #'s & Thermal Load



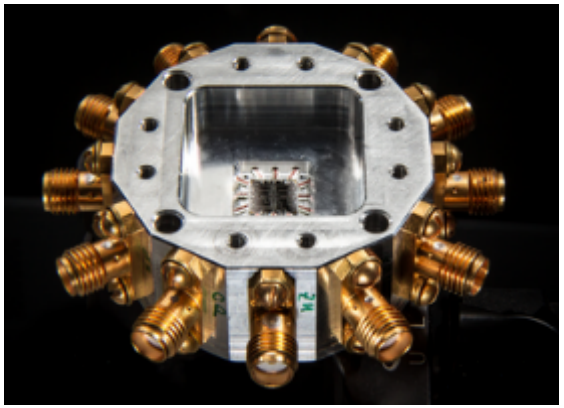
D-Wave processor in a dilution refrigerator (shields removed)

http://www.2physics.com/2013/11/experimental-determination-of-ramsey.html

Janis dilution refrigerator with many cables

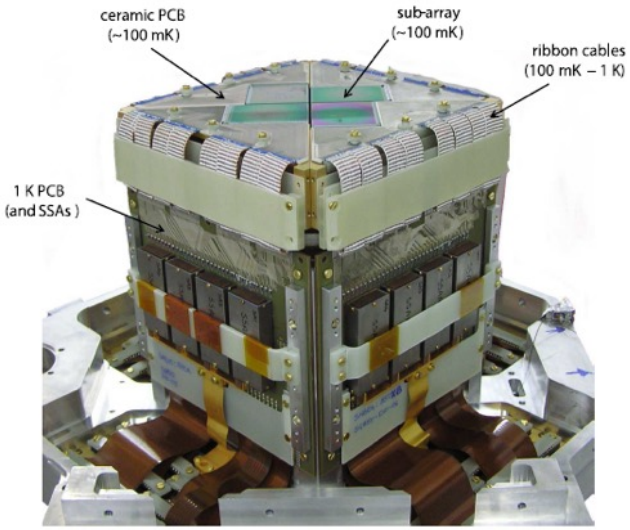
http://www.janis.com/UHVCompatibleDilutionRefrigeratorForSTM_NanoTechWeb.aspx#

Transmon from UCSB (Martinis)



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

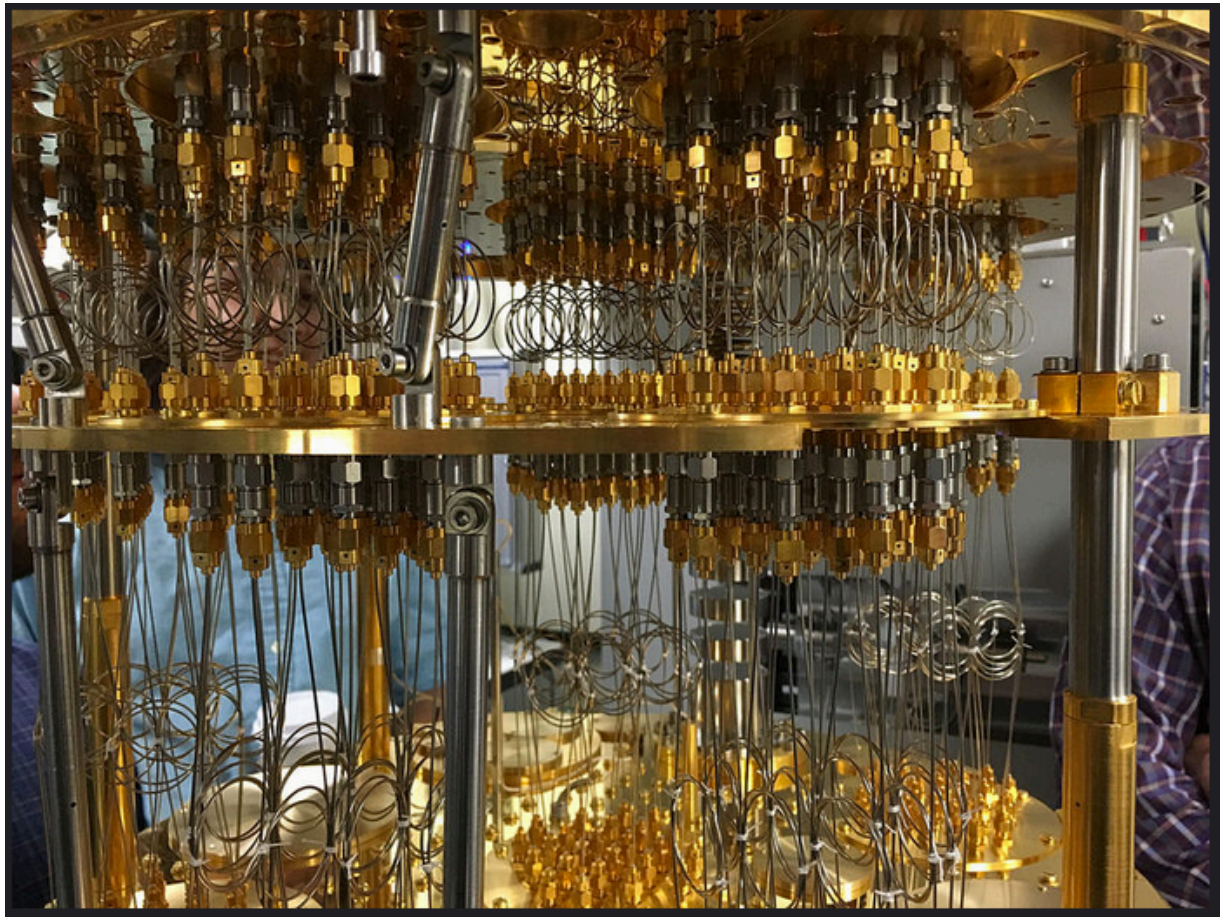
SCUBA-2 Module for the James Clerk Maxwell Telescope



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.

Motivation ⇒ Cable #'s & Thermal Load

Google



IBM

https://venturebeat.com/2019/02/21/googles-new-cryogenic-quantum-controller-uses-less-than-2-milliwatts/

https://www.flickr.com/photos/ibm_research_zurich/26093909563

Motivation ⇒ Cable #'s!

Outline

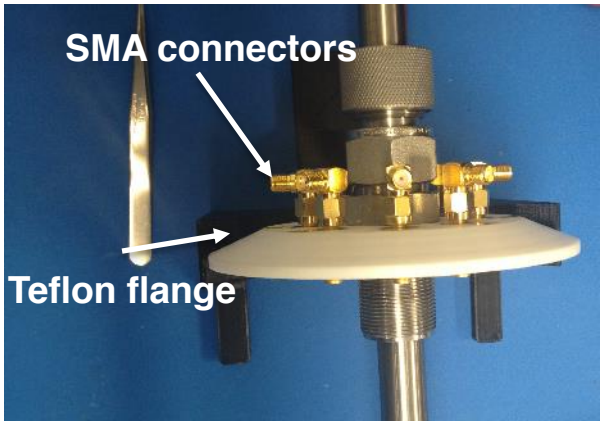
- Intro Comments
- Superconducting Flexible Cables (Stripline)
  - Goal is to develop fabrication and assembly processes for *scalable* stripline transmission line cables (vs. microstrip, coplanar waveguide, …)
  - Desire to be able to predict performance
    - Use SC resonators to characterize microwave properties (ε_r, $\tan\delta$, etc.)
  - Desire most transparent interconnects
  - Impedance match: lower S_{11} & S_{22} is better
    - Ultra-low loss combined with small impedance matches ⇒ many resonances
  - Low insertion loss: higher S_{12} & S_{21} is better
    - Calibration is challenging & important
  - Low cross-talk: lower S_{31}, S_{41}, etc. is better
- Cable-to-Cable Connectors

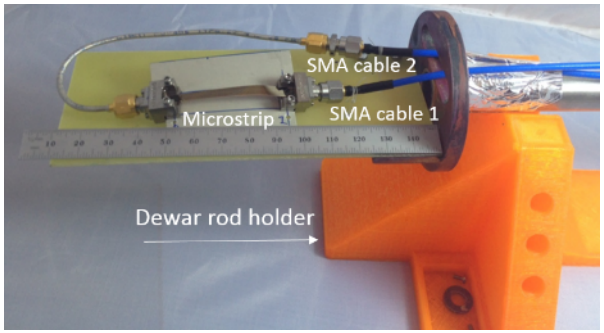
Cryogenic Microwave Measurement Setups

LHe Dewar

T = 4.2 K

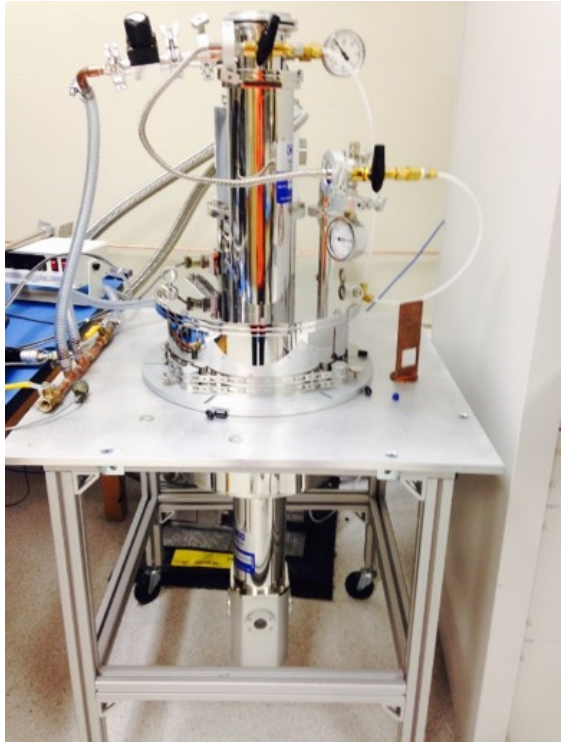
Sample rod

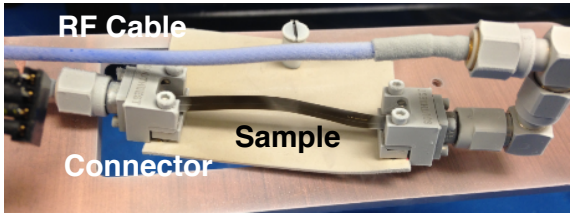




Dewar rod with SMA connectors and sample holder

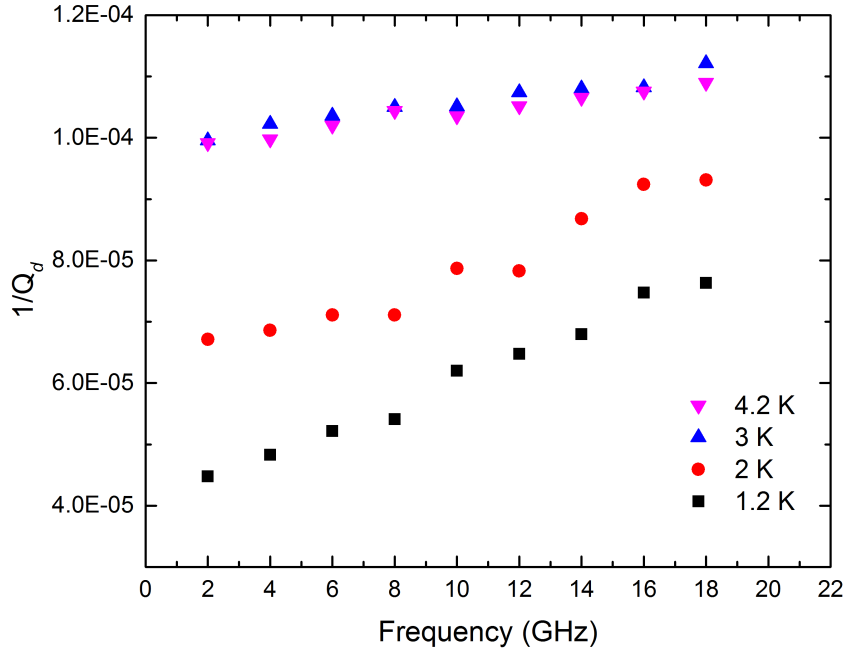
Pulse-tube Cryostat
T = ~ 1.2 K to 300 K

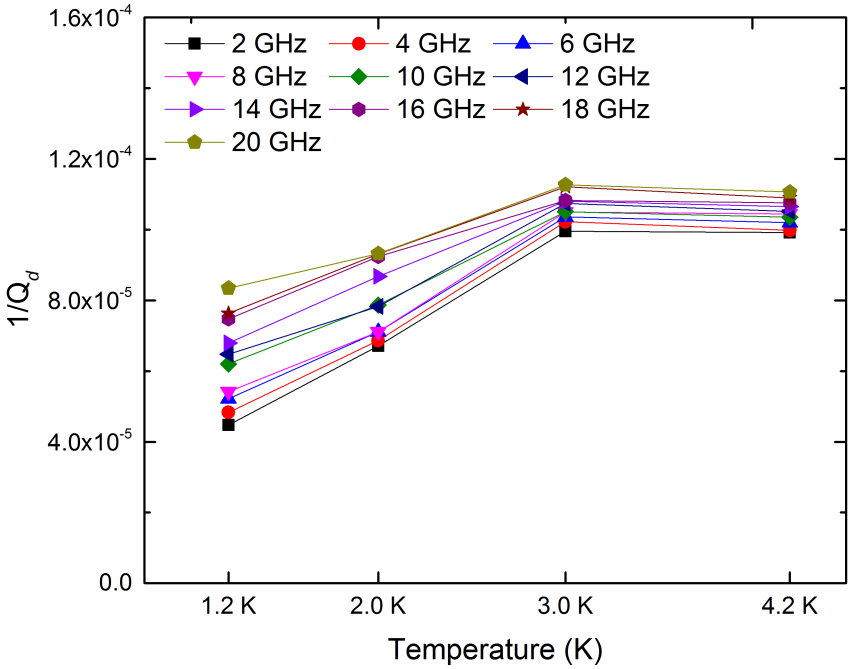




Moving to In bumps and custom connectors

Dielectric Loss ($\tan\delta \sim 1/Q_d$) vs. f & T

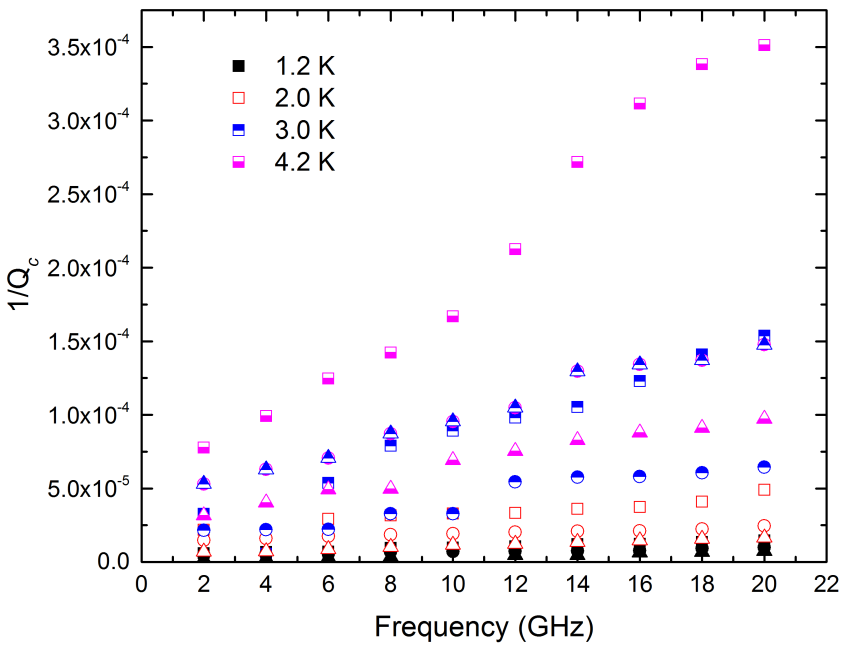


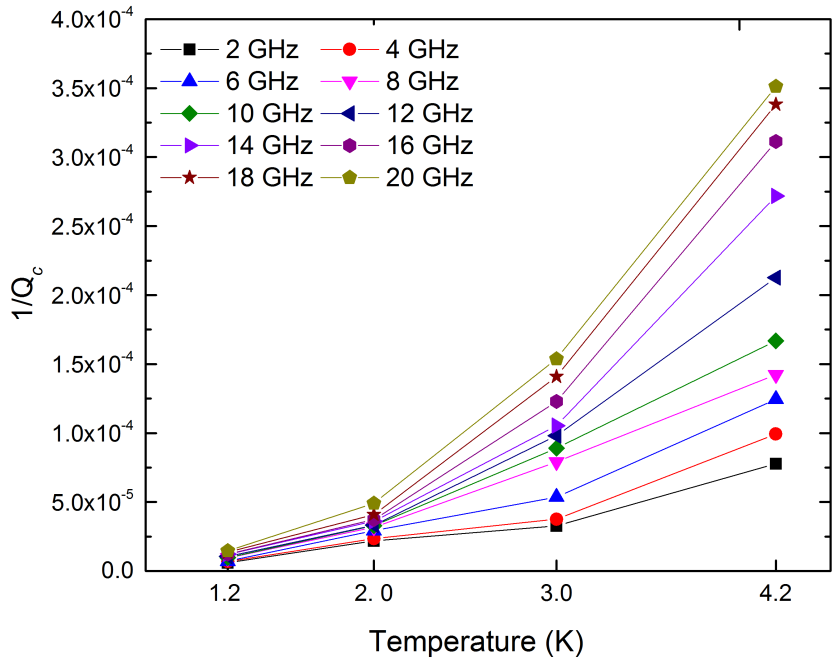


- $1/Q_d$ (i.e., y-intercept of $1/Q_l$ vs. 1/Linewidth) vs. resonant frequency shown for different temperatures. The plot shows a linear trend with frequency.
- $1/Q_d$ (i.e., y-intercept of $1/Q_l$ vs. 1/Linewidth) vs. temperature shown for multiple resonant frequencies. Continues to go down as T is reduced.
- Get $\tan\delta(f, T)$ from Q_d (note: ε_r found from fitting to resonant frequencies)

V. Gupta, B. Yelamanchili, S. Zou, T. Isaacs-Smith, J. A. Sellers, D. B. Tuckerman and M. C. Hamilton, "Distinguishing Dielectric Loss From Superconductor Loss Using Flexible Thin Film Superconducting Resonator Structures," IEEE Trans. Appl. Supercond., vol. 29, no. 5, pp. 1-5 (2019). doi: 10.1109/TASC.2019.2902756

Conductor Loss (~ $1/Q_c$) vs. f & T

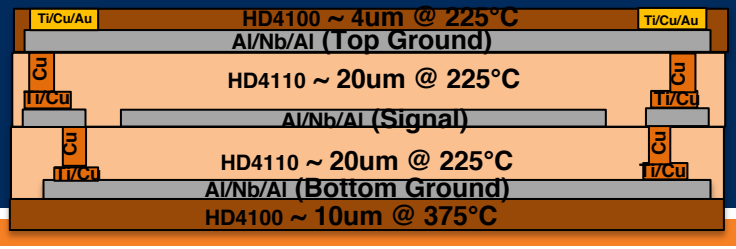




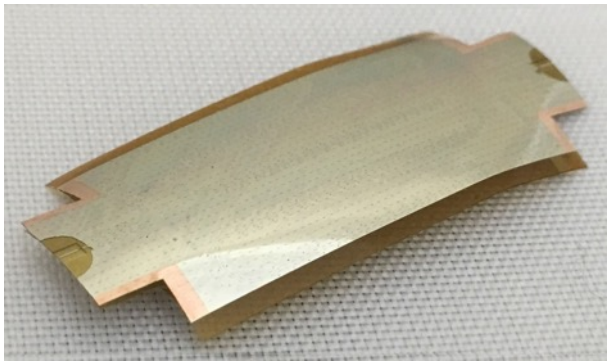
- Remnant loss is (essentially) Q_c
- Extracted $1/Q_c$ vs. frequency for multiple temperatures of different linewidths – 50 µm (square), 100 µm (circle), 150 µm (triangle).
- Extracted $1/Q_c$ vs. temperature at multiple resonant frequencies for 50 µm resonator.

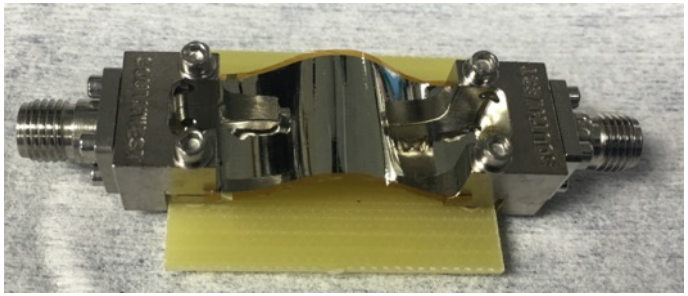
V. Gupta, B. Yelamanchili, S. Zou, T. Isaacs-Smith, J. A. Sellers, D. B. Tuckerman and M. C. Hamilton, "Distinguishing Dielectric Loss From Superconductor Loss Using Flexible Thin Film Superconducting Resonator Structures," IEEE Trans. Appl. Supercond., vol. 29, no. 5, pp. 1-5 (2019). doi: 10.1109/TASC.2019.2902756

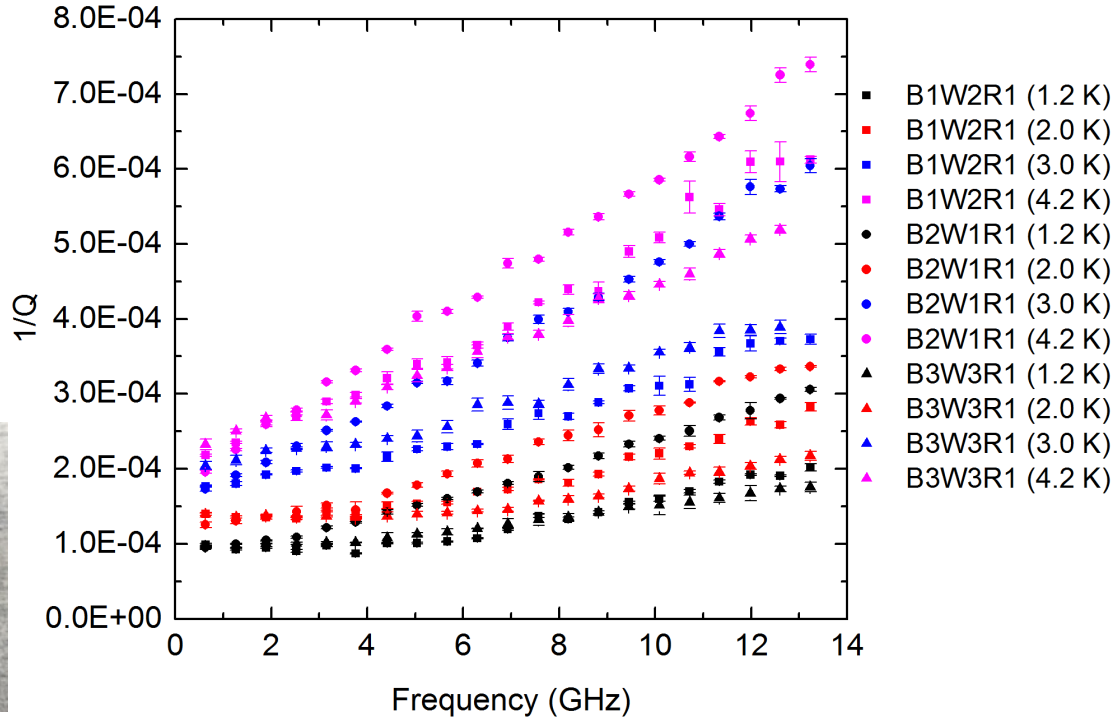
Stripline Resonators



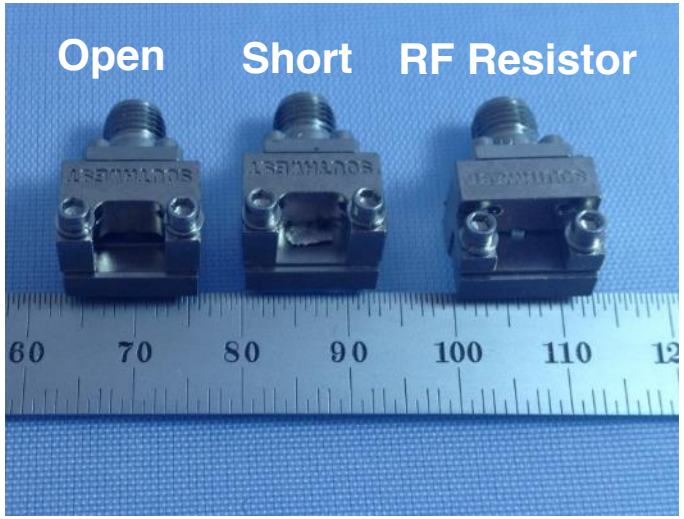
- Similarly-fabricated resonators used to characterize the conductor & dielectric losses.
- Resonators baked in vacuum oven at 90 ^{o}C for 2 hrs and then measured in dewar.
- All the stripline resonators are from different batches and different wafers.
- Q for different stripline resonators are comparable to microstrip resonators and show that the subsequent fabrication processes can be tolerated.
- Shows promise for extension to additional layers…recent work on new ways to "protect" the properties of the superconductor during subsequent fabrication processes (publishing soon).



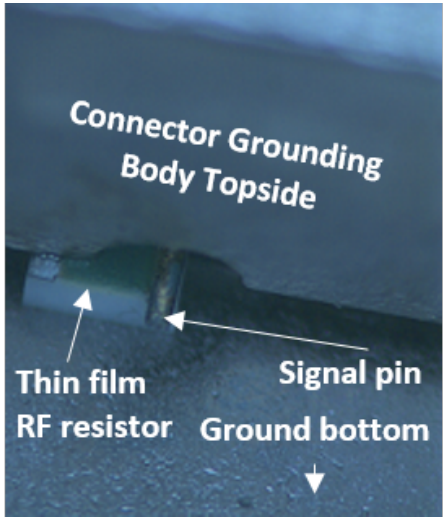




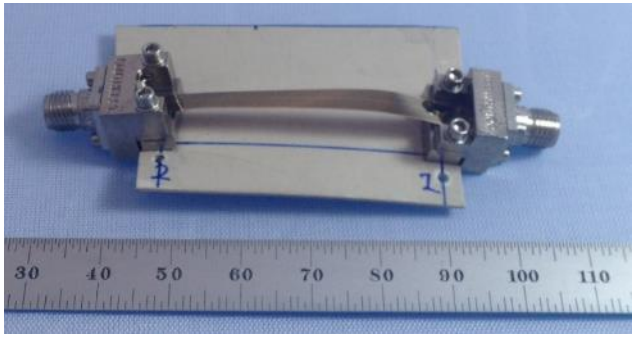
Microwave Calibration at ~ 4 K



Calibration standards based on Southwest Microwave edge launch connectors



Close-up of a 50 Ω Load

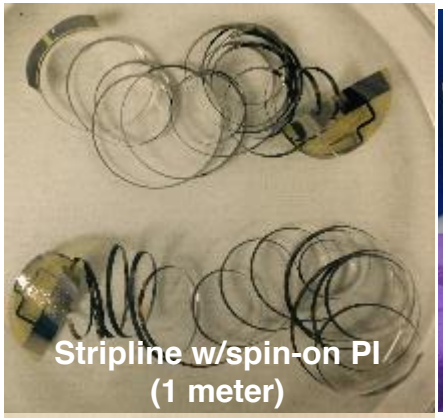


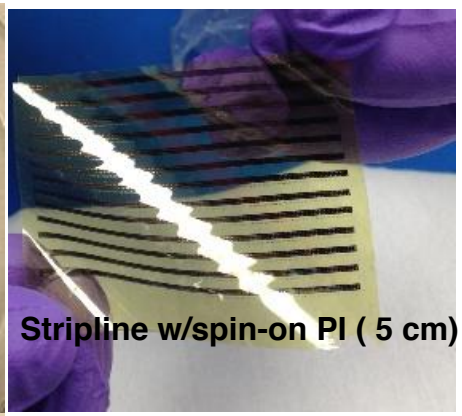
Representative thru: sample

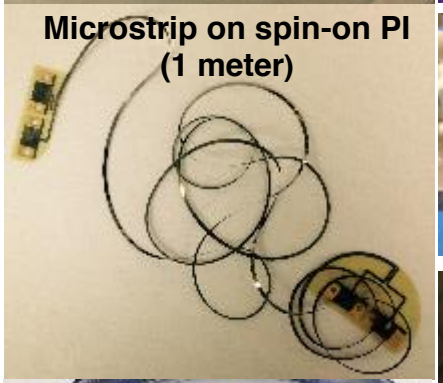
- Super low loss expected for SC cables…need excellent calibration.
- SOLR calibration => 4 mechanical standards for Short / Open / Load / Reciprocal-Thru.
- Thru can be any reciprocal thru, including the sample, as long as it is reciprocal.
- Four cool-downs to calibrate two ports.
- Currently working on use of RF switches => 1 cool-down.

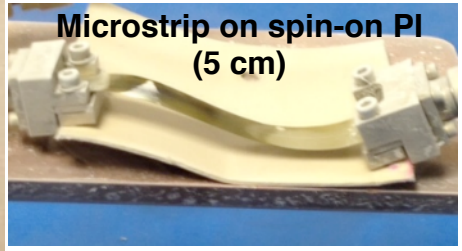
G. A. Hernandez, R. Bai, Y. Cao, J. A. Sellers, C. D. Ellis, D. B. Tuckerman, and M. C. Hamilton, "Microwave Performance Of Niobium/Kapton Superconducting Flexible Cables," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1-4 (2017).

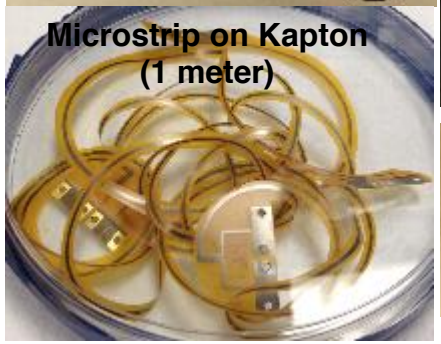
Various SC Flex Cables Fabricated

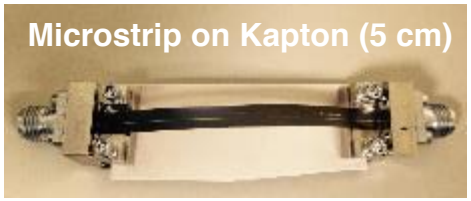








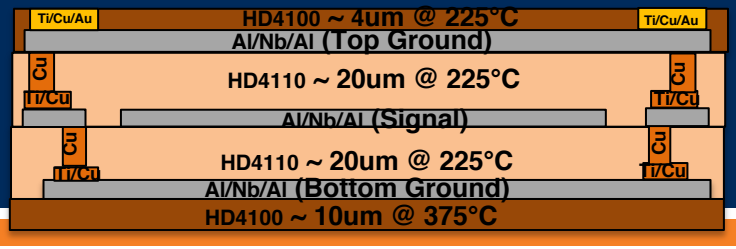


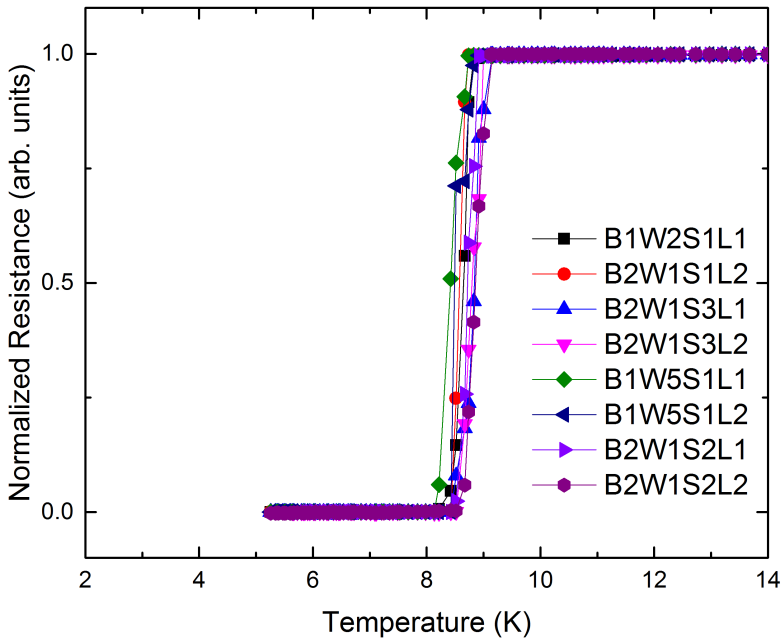


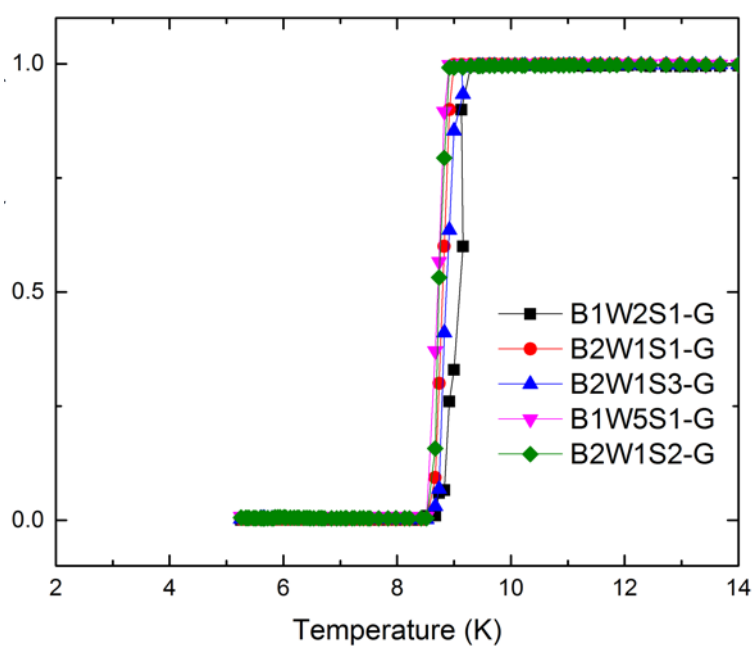
Name	Length	Material type	Thickness
Stripline	1 m	Spin-on polyimide	20 µm
Stripline	5 cm	Spin-on polyimide	20 µm
Microstrip	1 m	Spin-on polyimide	10 µm
Microstrip	5 cm	Spin-on polyimide	20 µm
Embedded Microstrip	5 cm	Spin-on polyimide	25 µm
Microstrip	1 m	Kapton film	50 µm
Microstrip	5 cm	Kapton film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

- Family of flex cables fabricated on different flexible substrates.
- Superconducting microstrip, embedded microstrip and stripline versions, of various lengths.
- Latest structures (resonators and transmission lines) have excellent yield.

Comparison of T_c for Multiple Stripline Samples



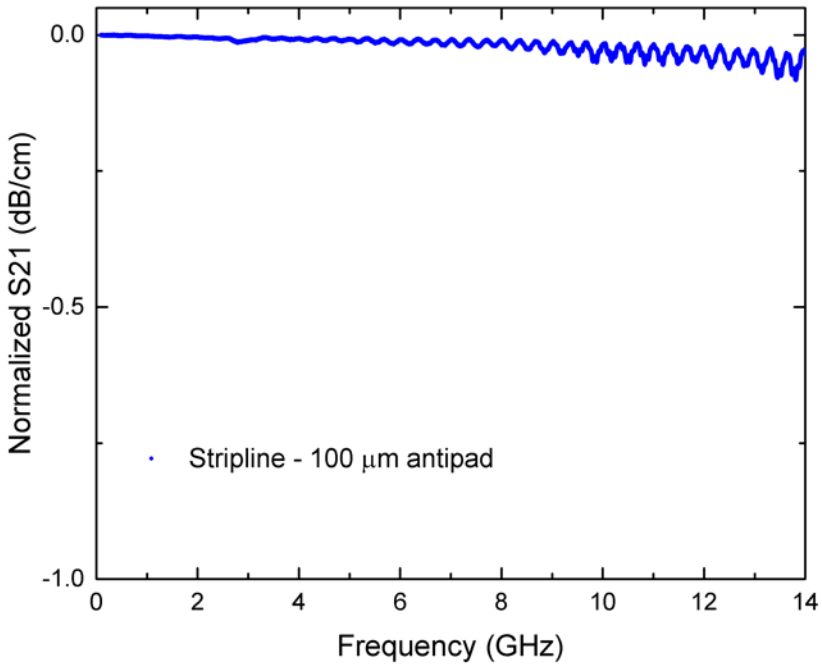


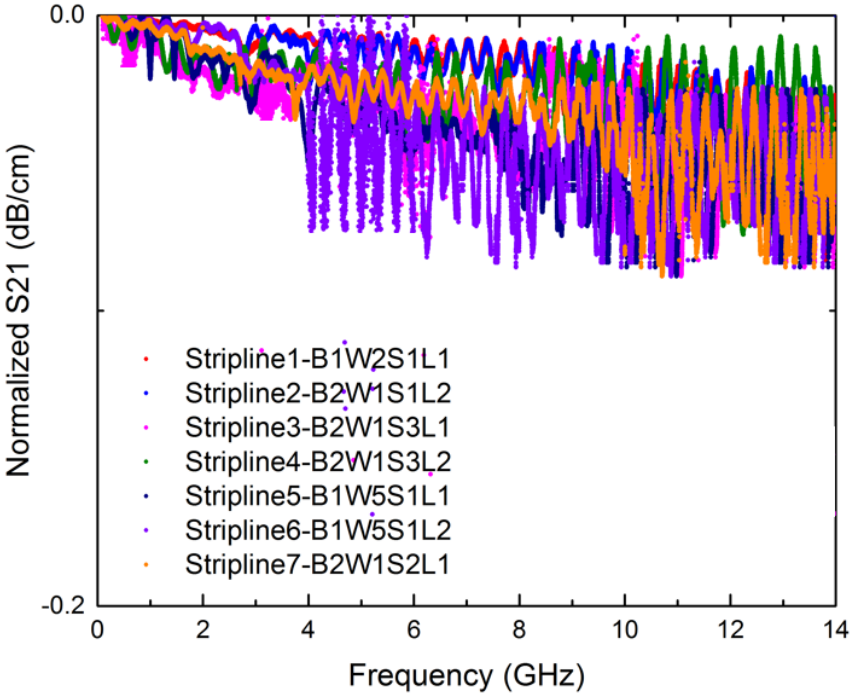


- Transition temps of actual structures (not test structures) measured in cryostat.
- Comparable T_c obtained from both signal (~ 8.4 K) and ground (~ 8.5 K).
- This is for after the (multiple) polyimide cures on top of the various layers.
  - Al layers ”protect” Nb
  - Polyimide curing kept below 225 ^{o}C

V. Gupta, B. Yelamanchili, S. Zou, T. Isaacs-Smith, J. A. Sellers, D. B. Tuckerman and M. C. Hamilton, “Thin-Film Nb/Polyimide Superconducting Stripline Flexible Cables,” *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-5 (2019).

Comparison of Multiple Stripline T-Lines

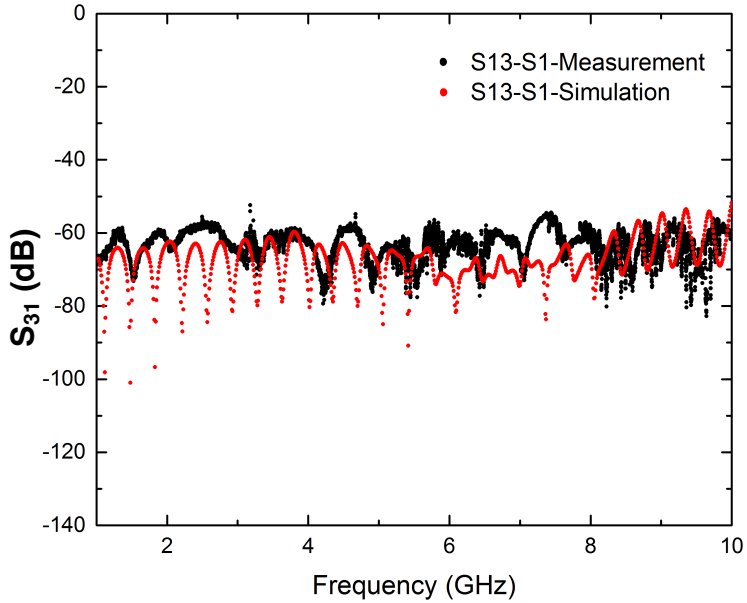


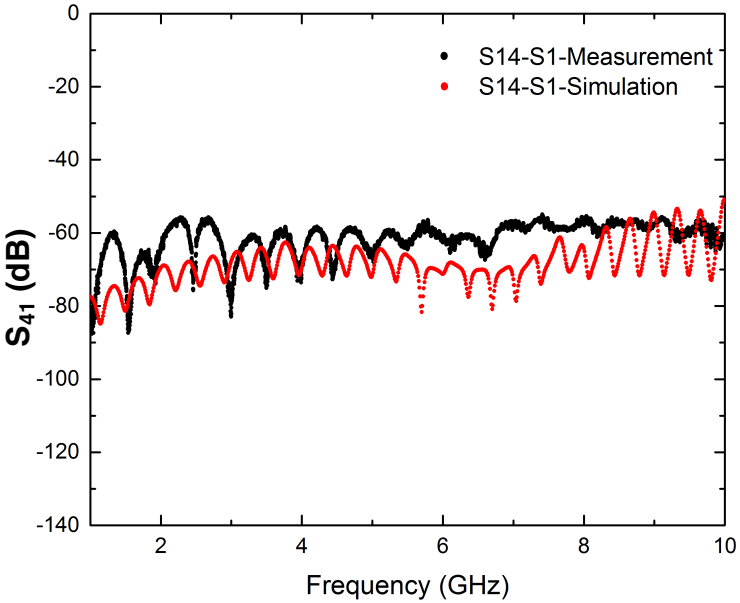


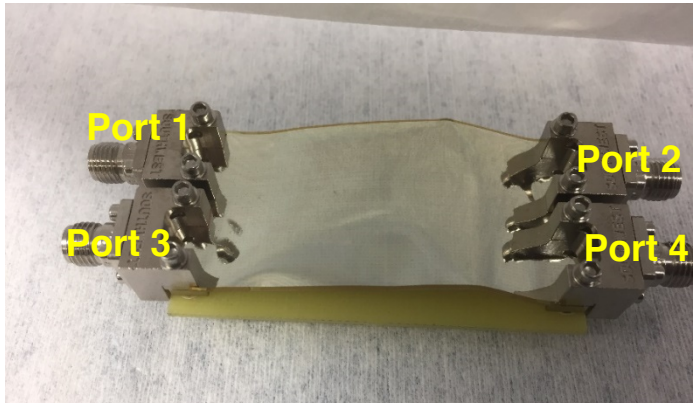
- Comparison of normalized insertion loss of multiple stripline samples.
- Normalized insertion loss is above – 0.1 dB/cm for all samples.
- Stripline length is 25 cm (100 μm wide anti-pad)
- Stripline designs:
  - 1 & 2 – 200 μm pitch
  - 3 & 4 – 100 μm pitch
  - 5 & 6 – 200 μm pitch
  - 7 – 200 μm pitch with vias in between traces

X-talk (S_{31} & S_{41}) Measurement & Simulation

Stripline with trace separation = 100 μm

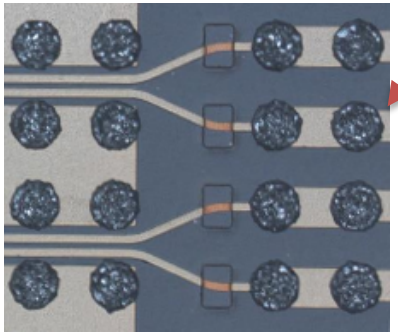




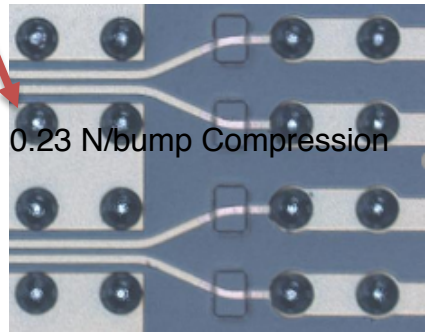


In bumps

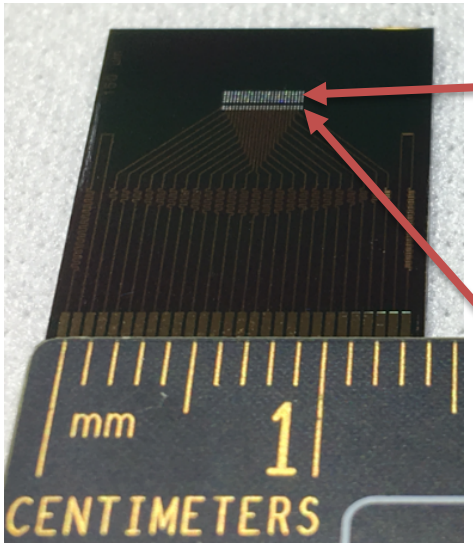
In Bumps



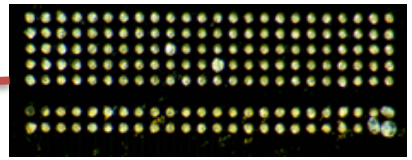
Before Reflow & Cleaning



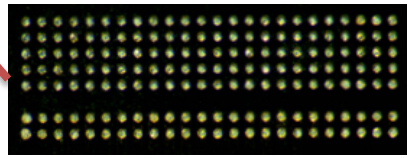
After Reflow & Cleaning
0.15 N/bump Compression



Si Test Chip



0.23 N/bump Compression

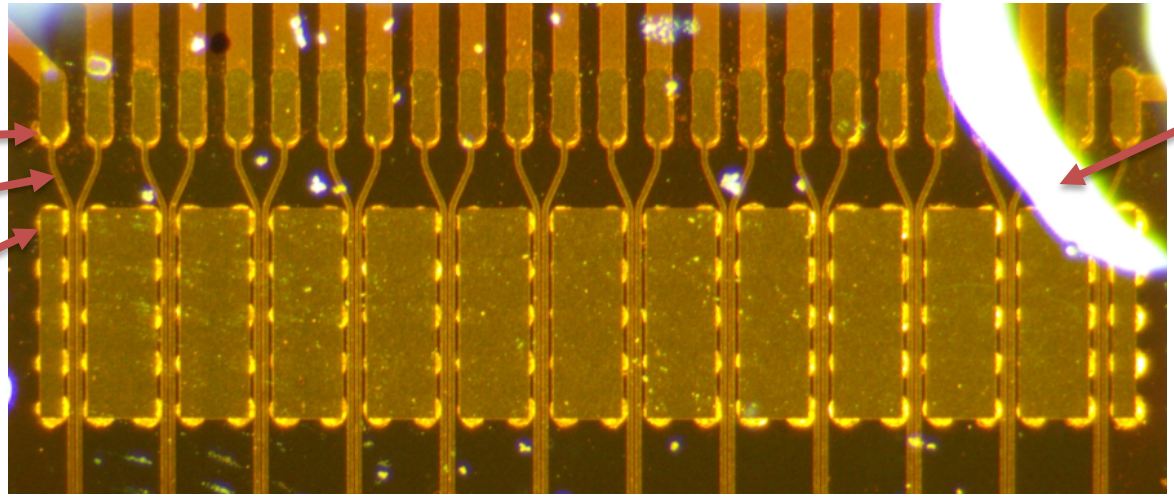


0.15 N/bump Compression

Signal In Bumps

Signal Lines

Mechanical In Bumps



Light Reflection

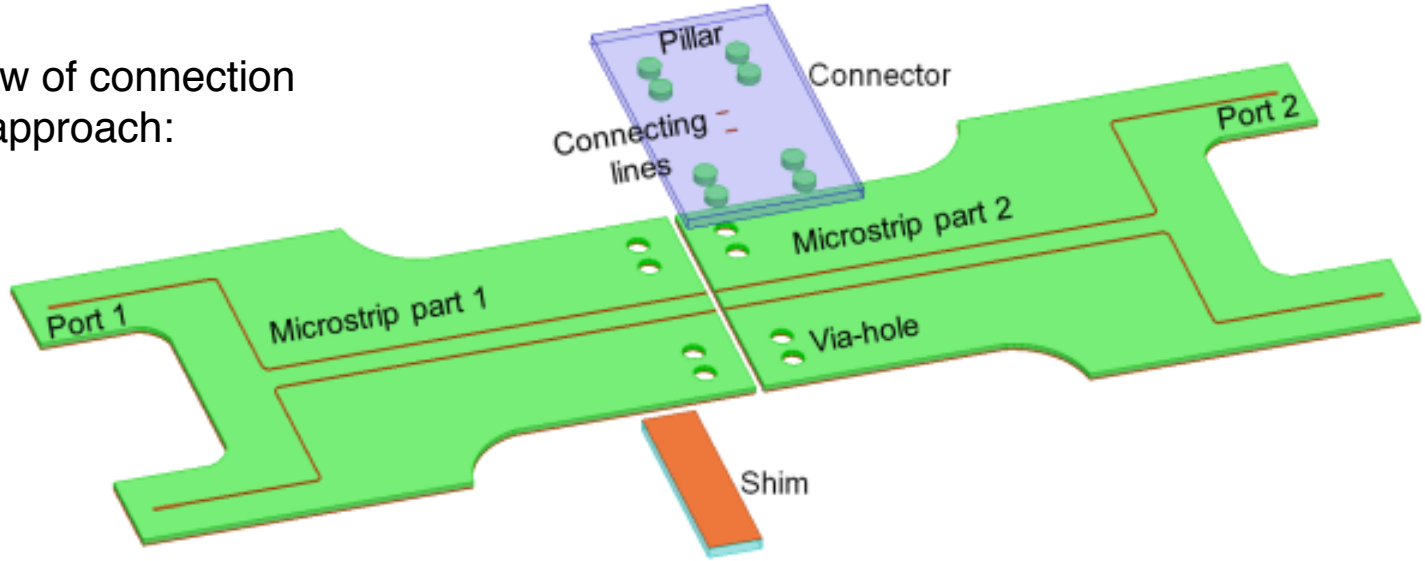
S. Peek, V. Gupta, B. Yelamanchili, T. Stegeman, T. Isaacs-Smith, J. Sellers, D. Tuckerman, M. Hamilton, “Fabrication and Assembly Processes for Custom and Commercial Flip-Chip Connections to Fine Pitch Indium Bump Arrays,” IMAPS DPC 2019, Fountain Hills, AZ.

Outline

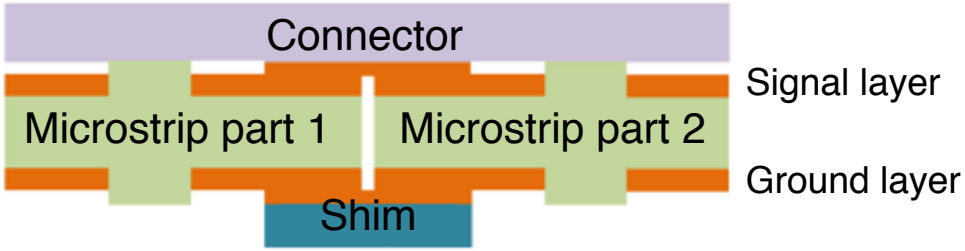
- Intro Comments
- Superconducting Flexible Cables (Stripline)
- Cable-to-Cable Connectors
  - Goal is to create a useful connector technology for flexible superconducting cables.
  - Similar signal integrity considerations as cables: desire most transparent interconnect, sufficient impedance match, lowest loss, need to consider cross-talk!
  - Also, desire a technology that is useful in the “field”…easily installed/deinstalled/reinstalled.

Cable-to-Cable Connection Approach

3-D view of connection approach:

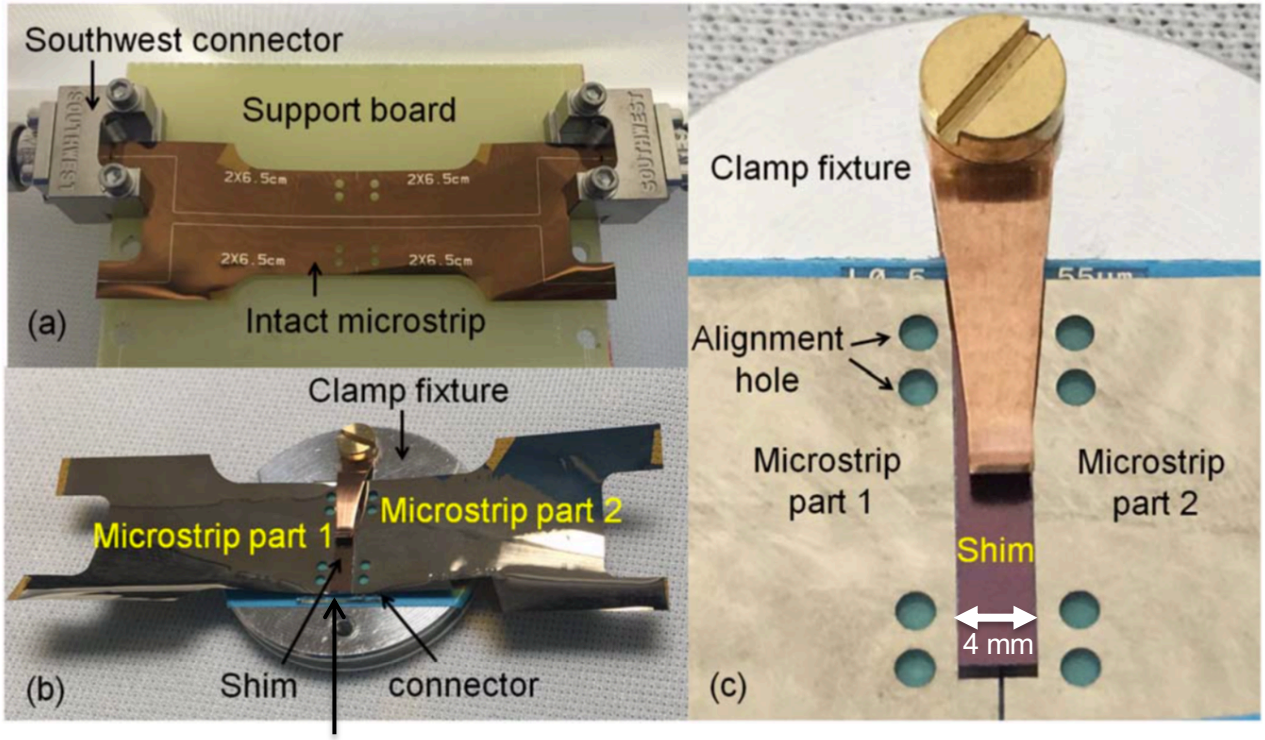


Cross section view of connection region:



S. Zou, B. Yelamanchili, V. Gupta, J. A. Sellers, T. Isaacs-Smith, D. B. Tuckerman, and M. C. Hamilton, "Low-Loss Cable-to-Cable Parallel Connection Method for Thin-Film Superconducting Flexible Microwave Transmission Lines," *Supercond. Sci. Technol.* (2019). doi: 10.1088/1361-6668/ab1825

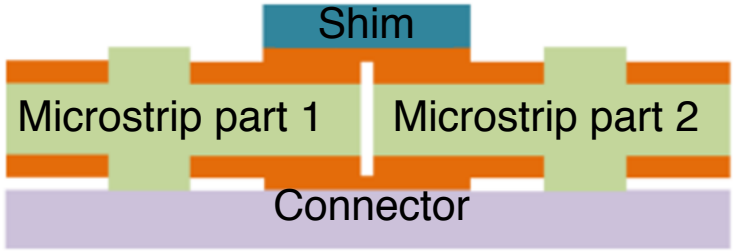
Sample Assembly



Reconnected microstrip

Zoom-in view of reconnection

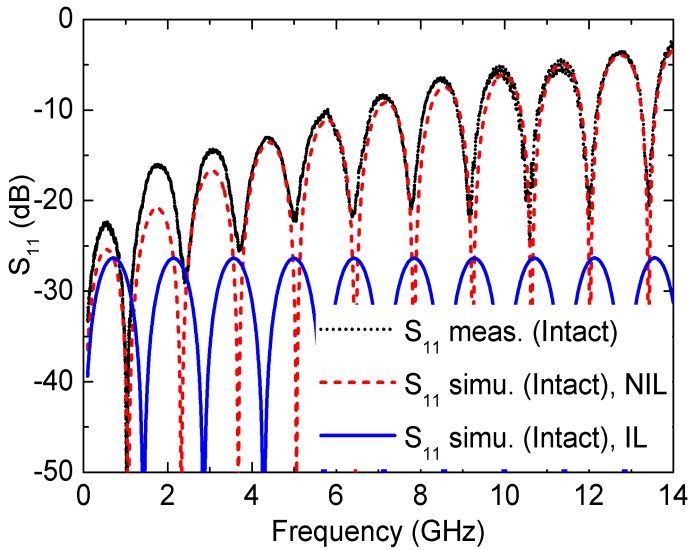
Schematic cross section of reconnected region:

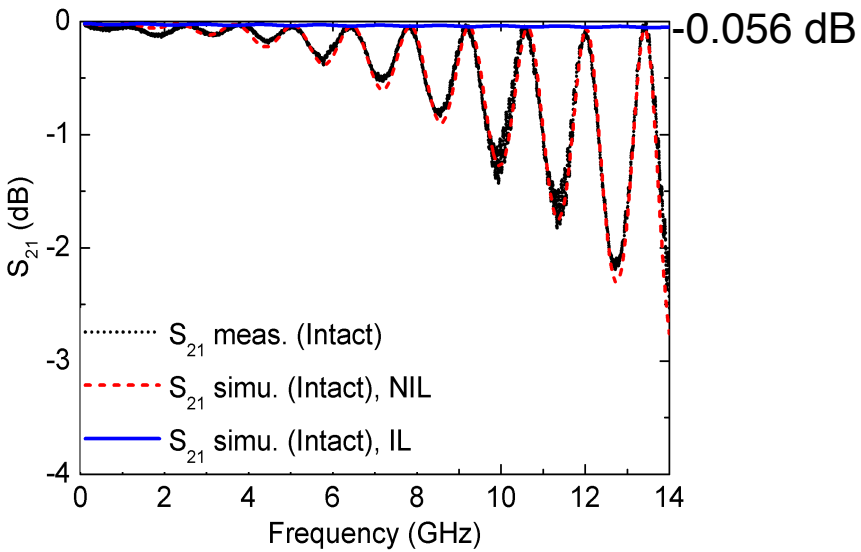


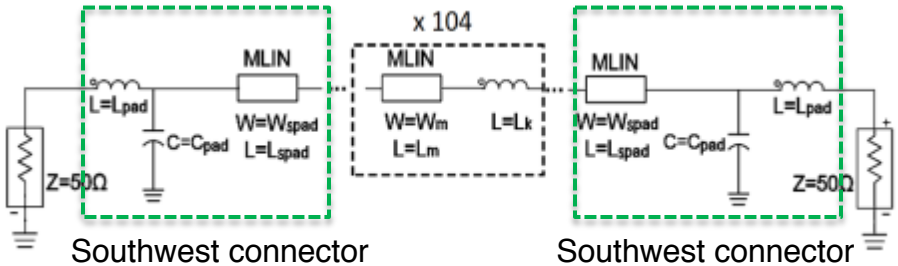
S. Zou, B. Yelamanchili, V. Gupta, J. A. Sellers, T. Isaacs-Smith, D. B. Tuckerman, and M. C. Hamilton, "Low-Loss Cable-to-Cable Parallel Connection Method for Thin-Film Superconducting Flexible Microwave Transmission Lines," *Supercond. Sci. Technol.* (2019). doi: 10.1088/1361-6668/ab1825

Measurement & Simulation of Intact Microstrip

- Length of signal trace is 6.5 cm-long.
- DC measurement at 4.2 K: Signal resistance = ~ 30 mΩ, ground resistance = ~ 3 mΩ.
- Non-ideal launch (NIL) simulation results matched well with measurement results.
- With ideal launch (IL), intact microstrip intrinsic loss is less than 0.056 dB (0.85 dB/m).







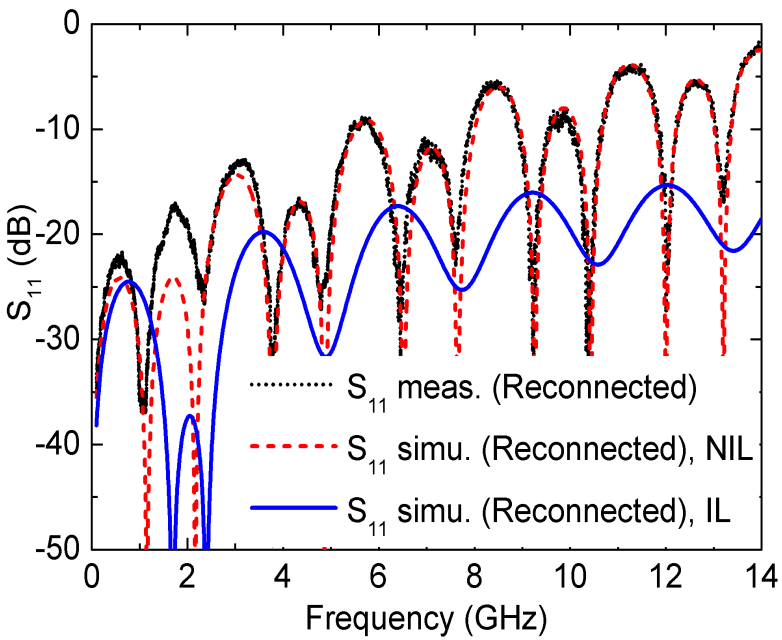
Southwest connector model

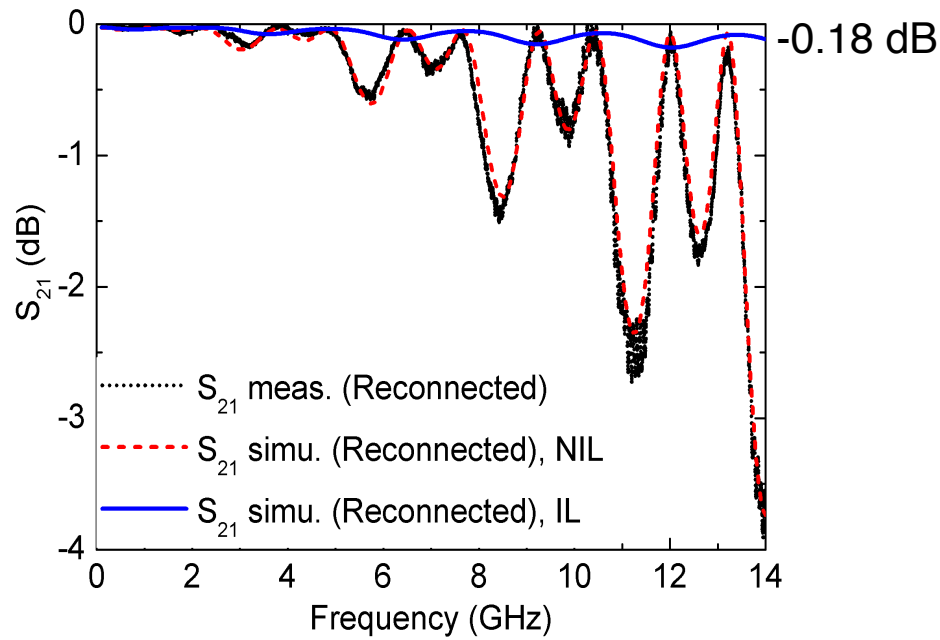
Southwest connector model

Symbol	Value	Description
W_m	52.3 µm	Width of MS unit
L_m	0.625 mm	Length of MS unit
W_{spad}	122 µm	Width of solder pad
L_{spad}	1.1 mm	Length of solder pad
L_{pad}	0.3 nH	Inductance introduced by the non-ideal launch
C_{pad}	0.09 pF	Capacitance introduced by the non-ideal launch
L_k	3.5 pF	Kinetic inductance of the Nb of each MS unit

Measurement & Simulation of Reconnected Microstrip (2 Reconnection Points)

- DC measurement: Signal resistance = ~ 60 mΩ, ground resistance = ~ 3 mΩ.
- Non-ideal launch (NIL) simulation results matched well with measurement results.
- With ideal launch (IL), microwave connector insertion loss is less than 0.18 dB.





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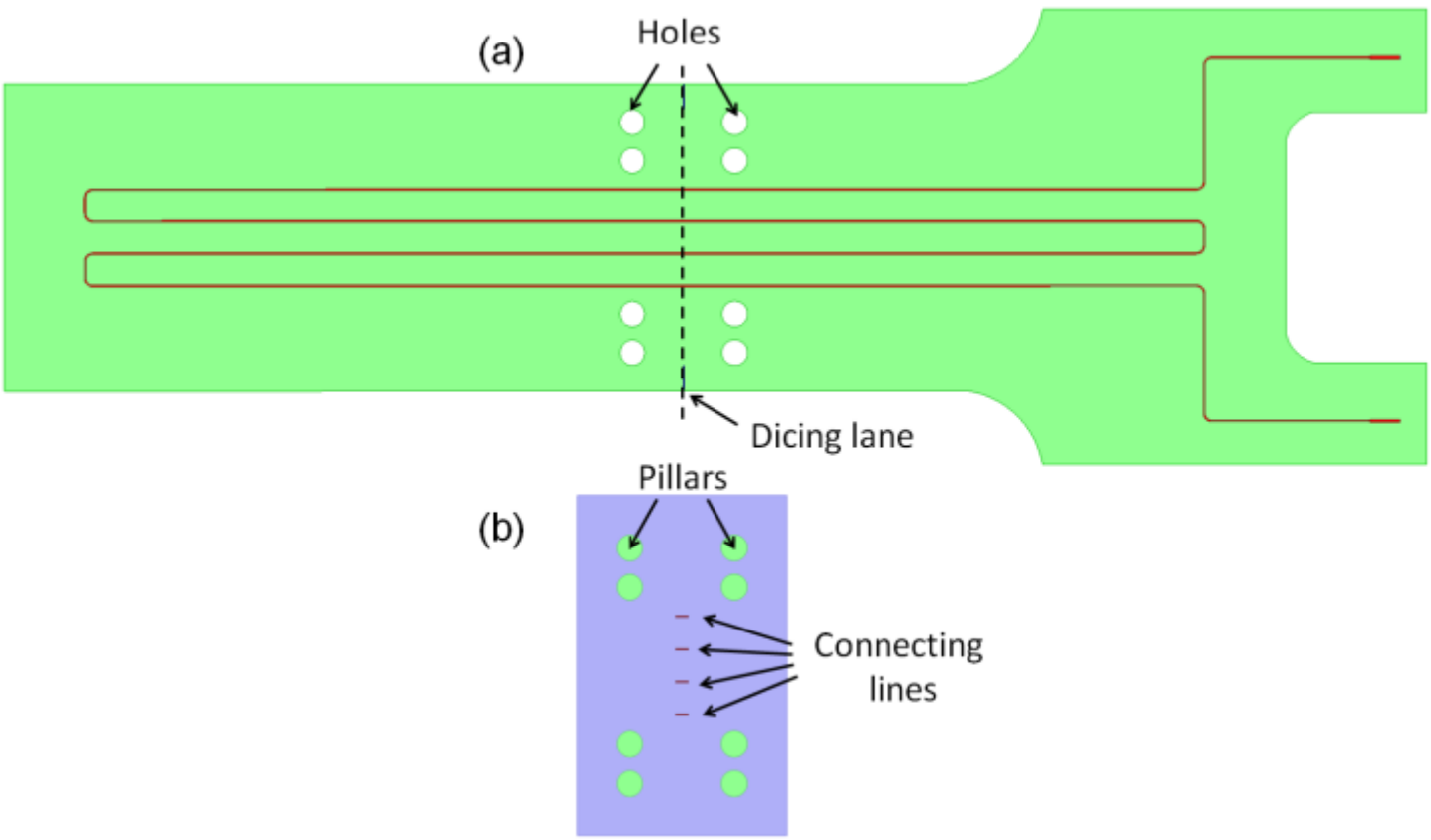
Microstrip with Four Reconnections

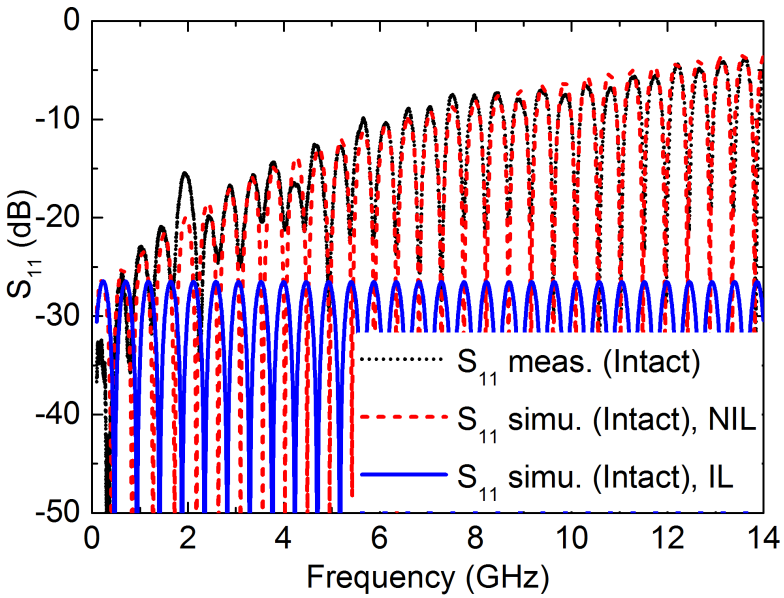
- To demonstrate “scalability” & extension to connections over larger areas.
- Length of signal trace is 20 cm-long.
- During reconnection testing, there are four reconnections in the cable.

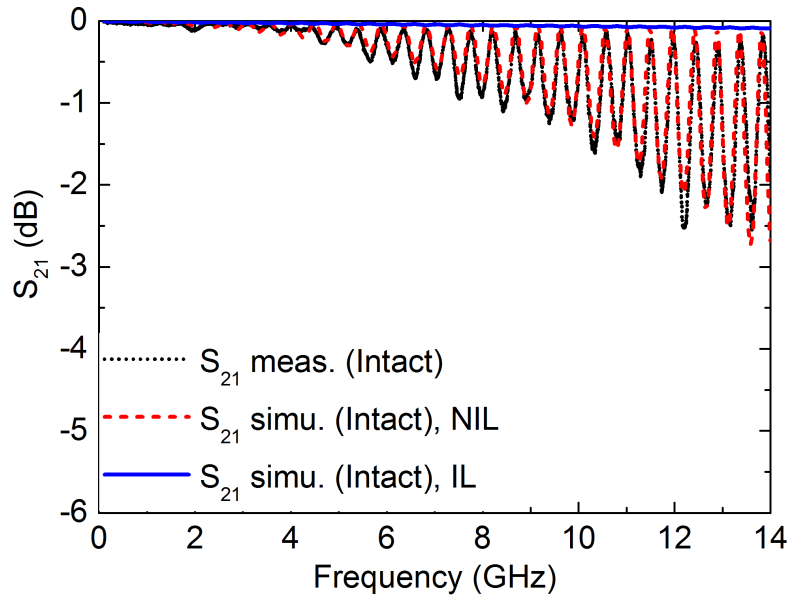


S. Zou, B. Yelamanchili, V. Gupta, J. A. Sellers, T. Isaacs-Smith, D. B. Tuckerman, and M. C. Hamilton, “Low-Loss Cable-to-Cable Parallel Connection Method for Thin-Film Superconducting Flexible Microwave Transmission Lines,” *Supercond. Sci. Technol.* (2019). doi: 10.1088/1361-6668/ab1825

Measurement & Simulation of Intact Microstrip

- Non-ideal launch (NIL) simulation results matched well with measurement results.
- With ideal launch (IL), intact microstrip intrinsic loss is less than 0.095 dB (0.48 dB/m).



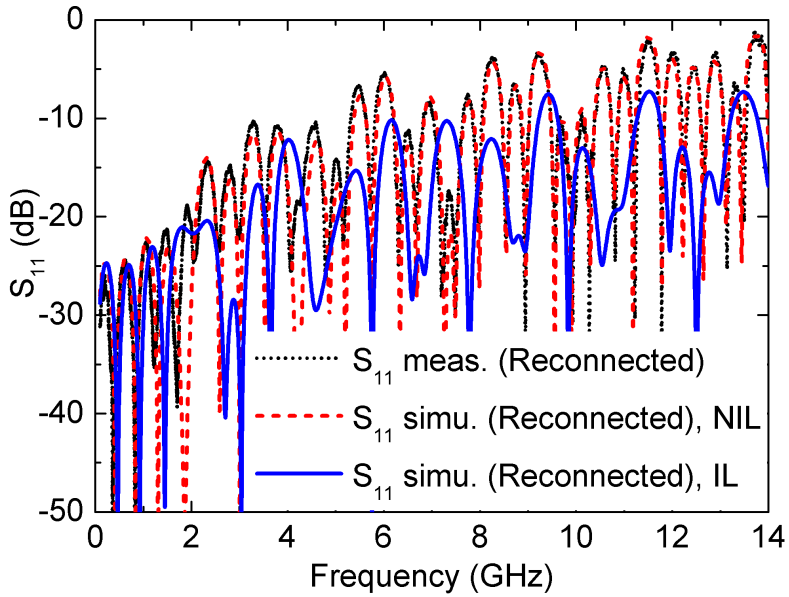


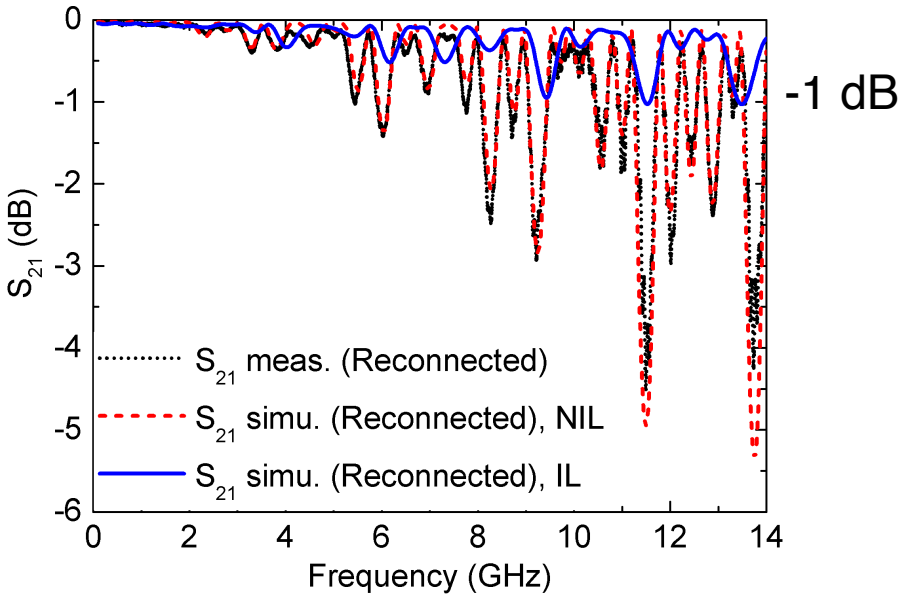
-0.095 dB

S. Zou, B. Yelamanchili, V. Gupta, J. A. Sellers, T. Isaacs-Smith, D. B. Tuckerman, and M. C. Hamilton, "Low-Loss Cable-to-Cable Parallel Connection Method for Thin-Film Superconducting Flexible Microwave Transmission Lines," *Supercond. Sci. Technol.* (2019). doi: 10.1088/1361-6668/ab1825

Measurement & Simulation of Reconnected Microstrip (8 Reconnection Points)

- Non-ideal launch (NIL) simulation results matched well with measurement results.
- With ideal launch (IL) and four reconnections, microwave connector insertion loss is less than 1 dB.





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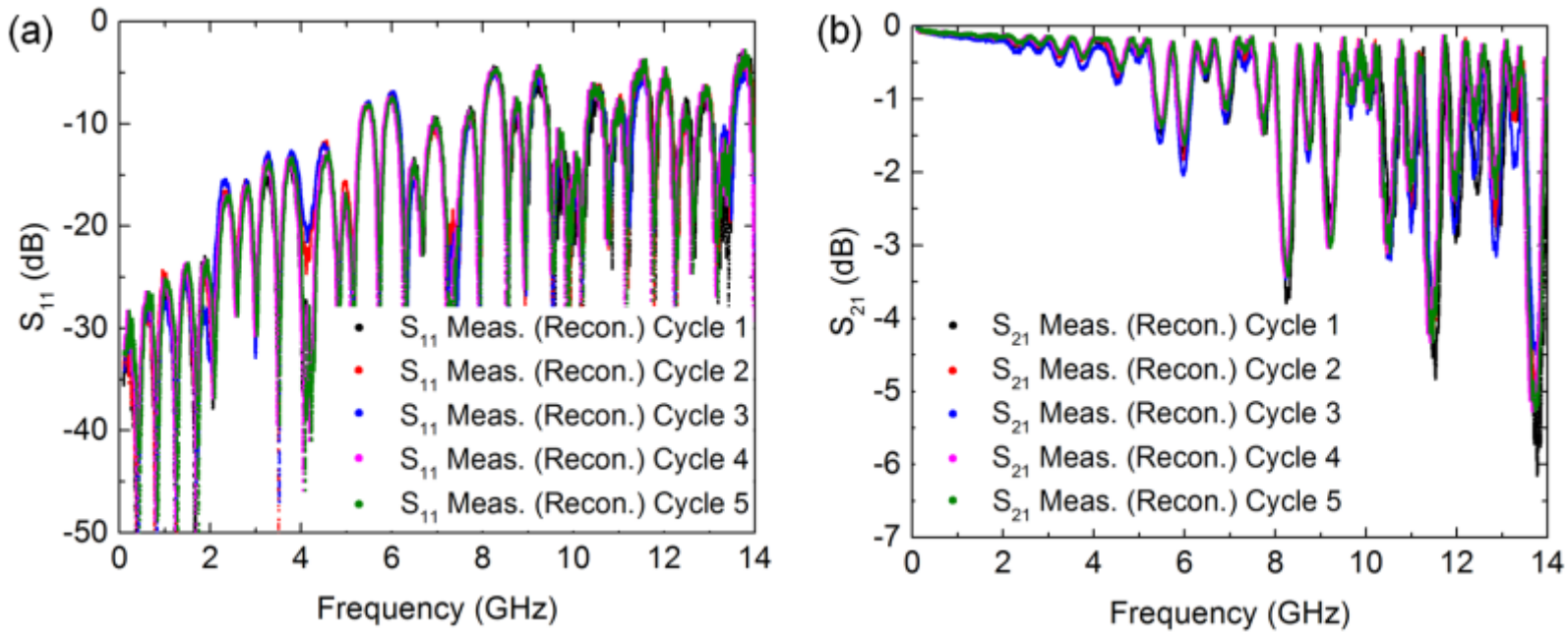
Microwave Connector Thermal Reliability Test

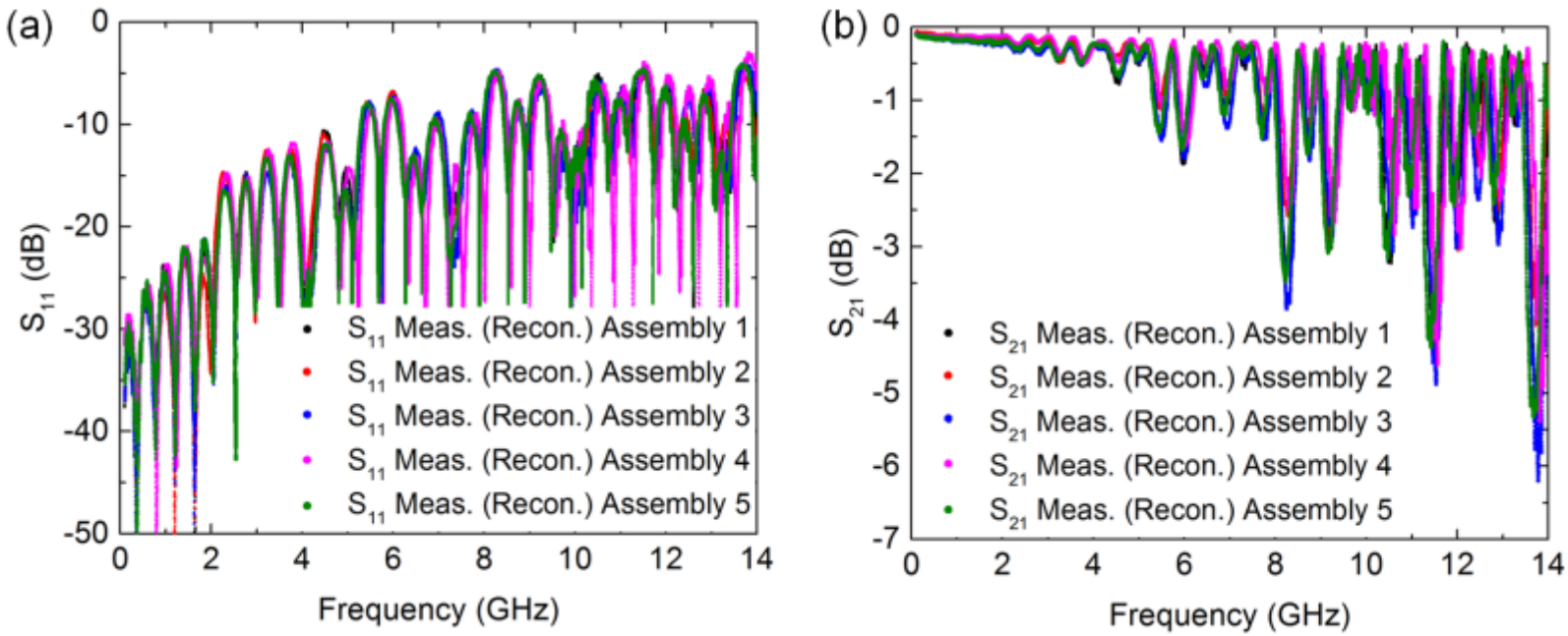
- Thermal cycle testing procedure:
  System calibration → test sample at 4.2 K (cycle 1) → heat up sample to R.T → test sample at 4.2 K (cycle 2) → repeat for 5 times
- Consistent RF performance was observed over (limited number) of different thermal cycles.
- Connector shows encouraging thermal reliability.



S. Zou, B. Yelamanchili, V. Gupta, J. A. Sellers, T. Isaacs-Smith, D. B. Tuckerman, and M. C. Hamilton, "Low-Loss Cable-to-Cable Parallel Connection Method for Thin-Film Superconducting Flexible Microwave Transmission Lines," *Supercond. Sci. Technol.* (2019). doi: 10.1088/1361-6668/ab1825

Microwave Connector Re-assembly Reliability Test

- Testing procedure:
  System calibration → test sample at 4.2 K (assembly 1) → heat up sample to R.T, dis-assemble and re-assemble the sample → test sample at 4.2 K (assembly 2) → repeat for 5 times
- Consistent RF performance was observed over (limited number) of different thermal cycles.
- Connector shows promising re-assembly reliability.



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Conclusion

- Much progress has been made in our group on Nb-based superconducting flexible stripline cables along with superconducting cable-to-cable connectors…interconnect technologies suitable for use in densely-integrated cryogenic electronics systems down to < 4 K.
- Superconducting resonators to characterize loss properties of relevant materials (made using relevant fabrication processes).
- Stripline cables exhibit intrinsic insertion loss < 0.1 dB/cm up to > 14 GHz and better than -60 dB cross-talk for densely-integrated lines.
- Cable-to-cable connector technology developed that exhibits an insertion loss of better than 0.2 dB for two connections…though this needs more work to be more “user-friendly” for assembly.
- Many possibilities here: other SCs (higher L_k), integration of normal conductors for attenuators, patterned structures for impedance control / filtering, …

Thank you