iNEMI Reliability and Loss Properties of Copper Foils for 5G Applications

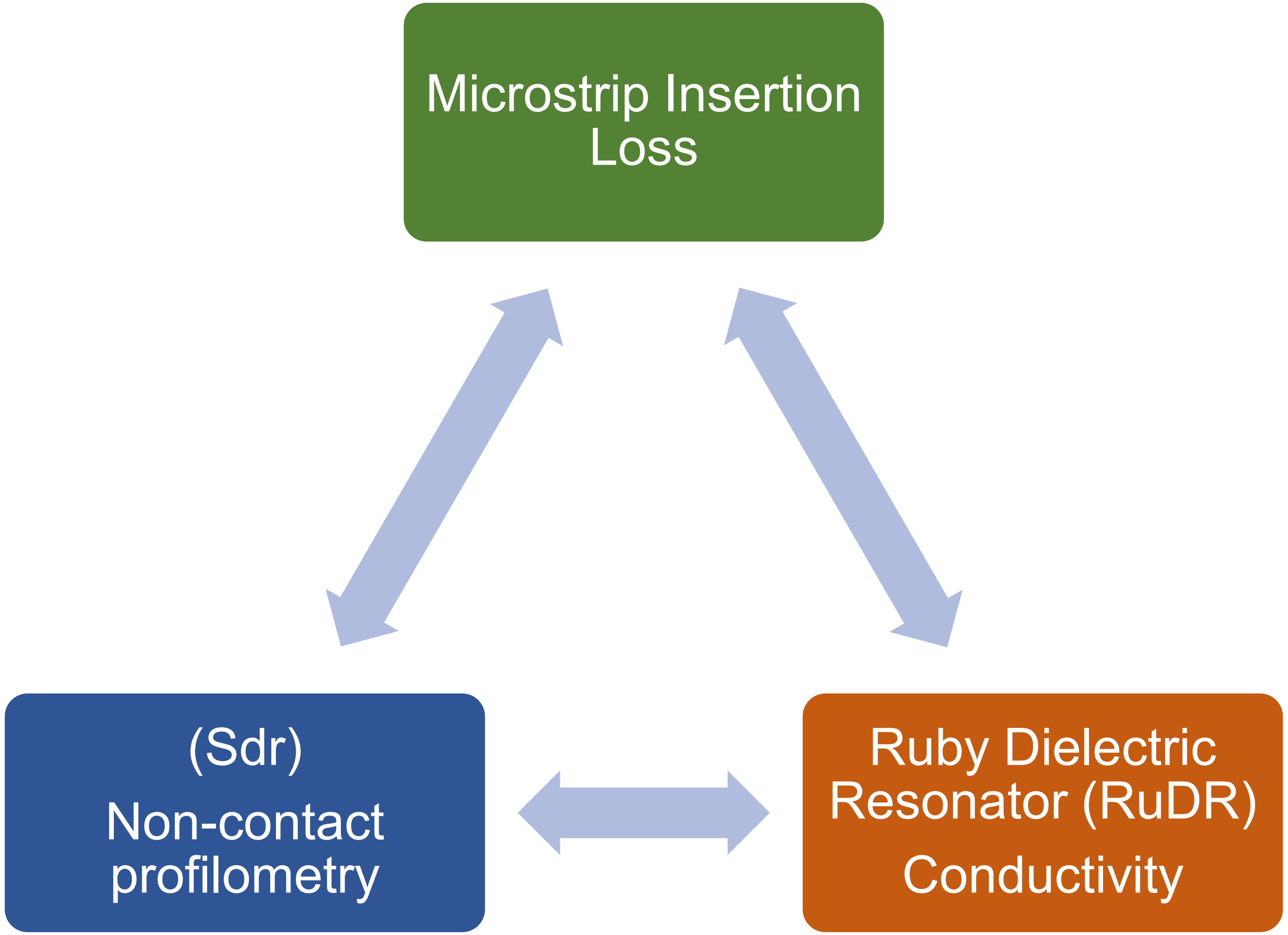
- Correlating high frequency loss with roughness and conductivity of ultra smooth copper foils using alternative oxide treatments.

Abstract - iNEMI Reliability and Loss Properties of Copper Foils for 5G Applications

- High-frequency applications require improved signal integrity.
- Traditional copper foil treatments improve resin adhesion but increase signal loss due to surface roughening.
- Extreme low surface profiles drive the need to correlate foil surface properties with signal integrity
- New methods of assessing the foil-to-low-loss dielectric bond and signal integrity are required.
- This iNEMI project addresses these challenges.

Introduction – Statement of Work

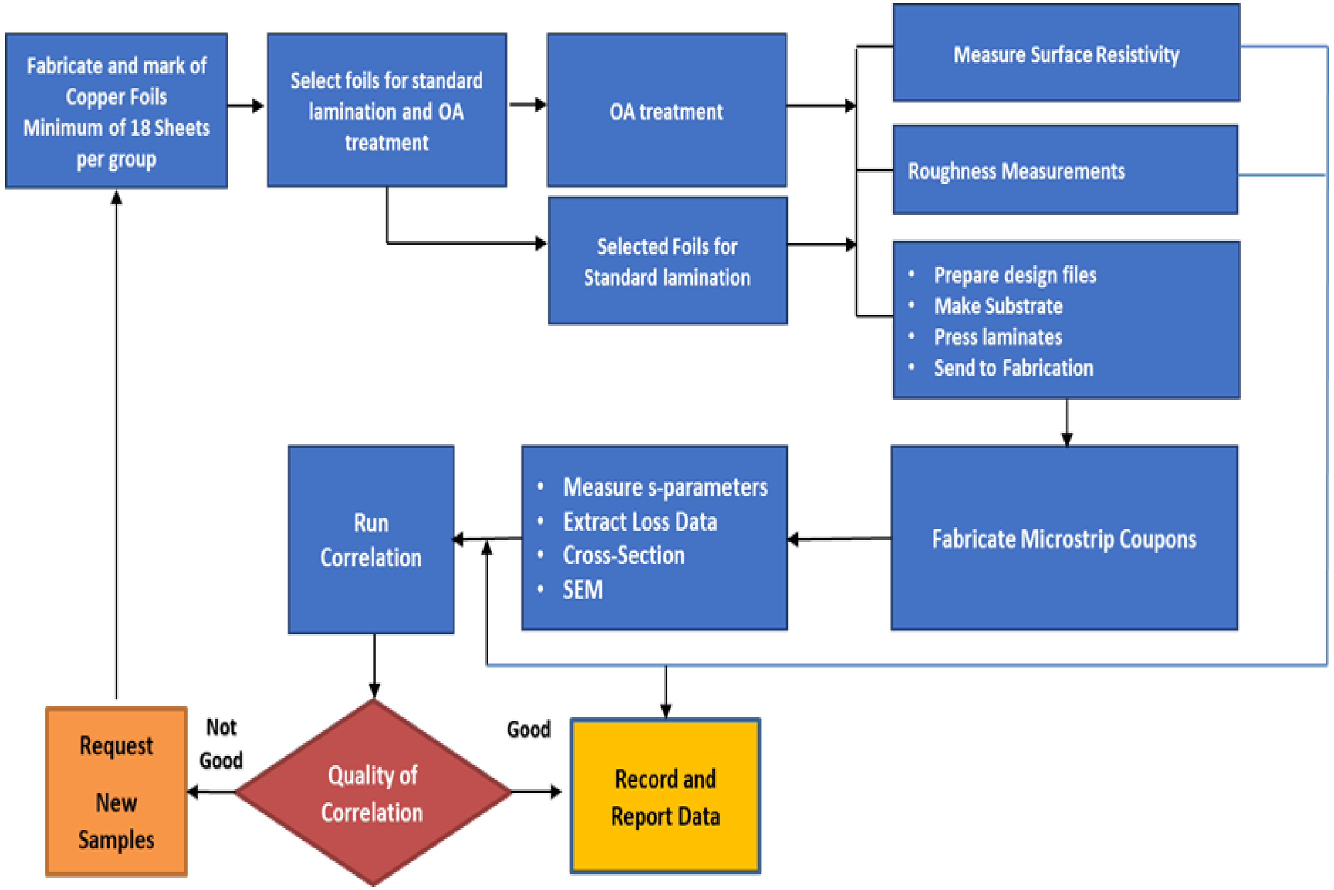
- Non-contact profilometry data, Developed Interfacial Area Ratio (Sdr)
- Preliminary data from a Ruby Dielectric Resonator (RuDR)
- Measuring the effective conductivity of copper foils
- These measurements are then correlated to microstrip insertion loss measurements on 12 sets of foil with oxide alternative treated surfaces.



DoE Process Flow

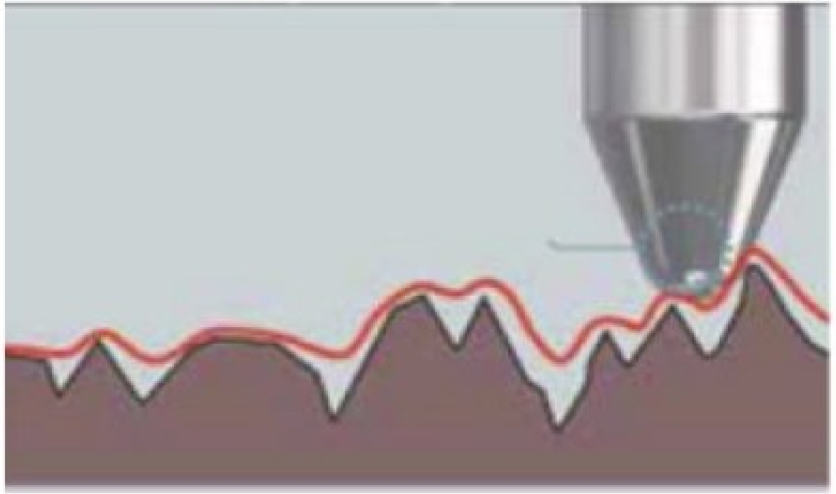
- Six types of copper
- Two types of OAs

Sample Label	Copper Type	Surface Profile	OA Treatment	Treated Side
H1	ED	High	-	Bottom
L1	ED	Low	-	Bottom
H2	ED	High	-	Bottom
L2	ED	Low	-	Bottom
H3	RA	High	-	Bottom
L3	RA	Low	-	Bottom
L1-A	ED	Low	A	Top
L1-B	ED	Low	B	Top
L2-A	ED	Low	A	Top
L2-B	ED	Low	B	Top
L3-A	RA	Low	A	Top
L3-B	RA	Low	B	Top

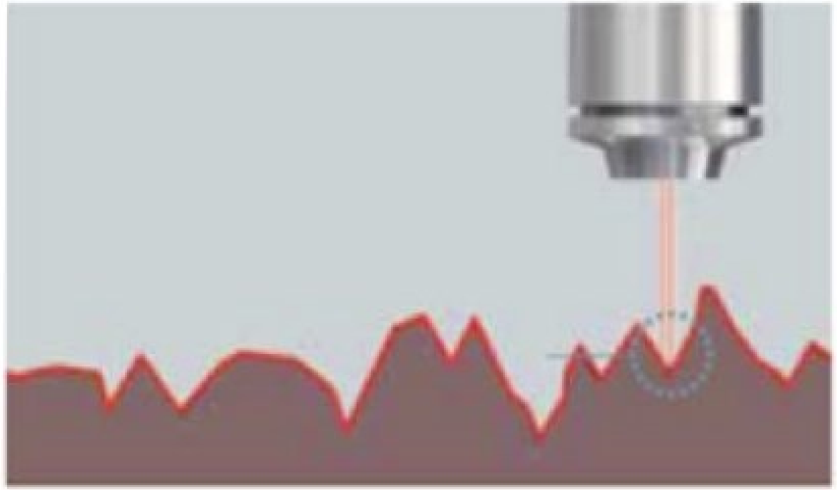


Non-Contact Profilometry

Traditional surface probes do not accurately reflect the micro-roughness of low and ultra-low profile copper foils.



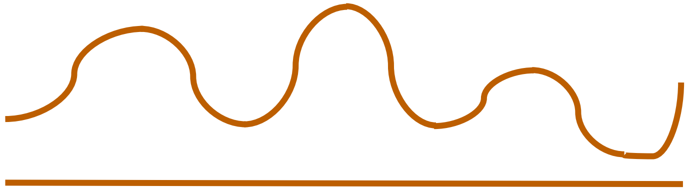
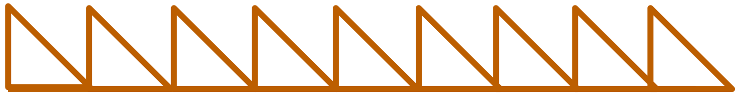
From IPC TM 650 2.2.22

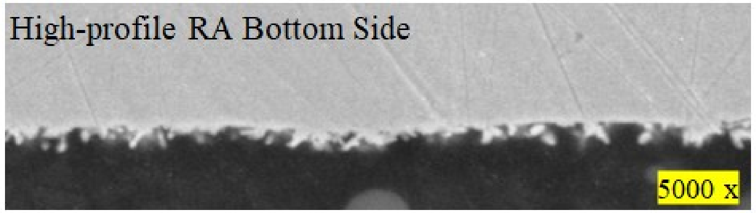


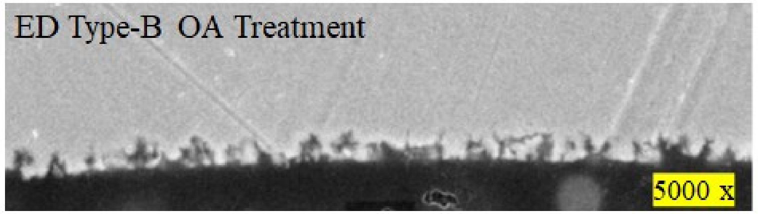
From IPC TM 650 2.2.22

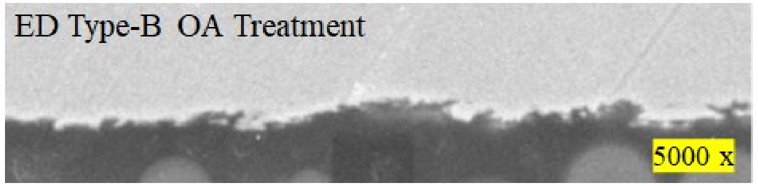
Non-contact profilometry measures differences in the micron range, allowing for proper characterization of these foils.

Developed Interfacial Area Ratio (Sdr)

$Sdr = \frac{additional\ surface\ area}{planar\ definition\ area}$	
Sdr = 0	
Sdr = 0.414	







Alternate Measurement Techniques

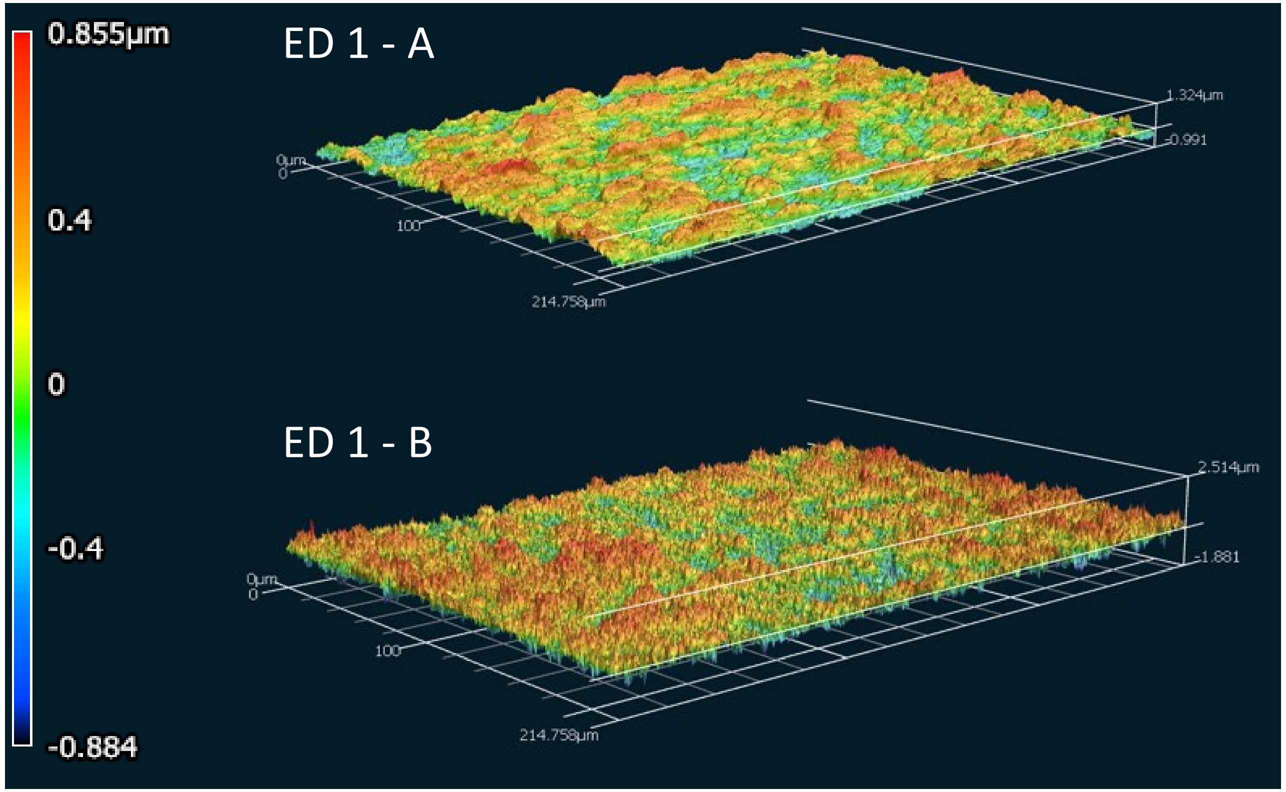
Sa (average absolute mean)
Does not capture or correlate to the surface area being measured.

Sq (root mean square height)
Calculates deviations from an averaged centerline. Better for investigating flatness, rather than a complete roughness profile.

Sz (Σ largest peak height + largest pit depth)
Only captures two points, rather than topography of the entire surface area.

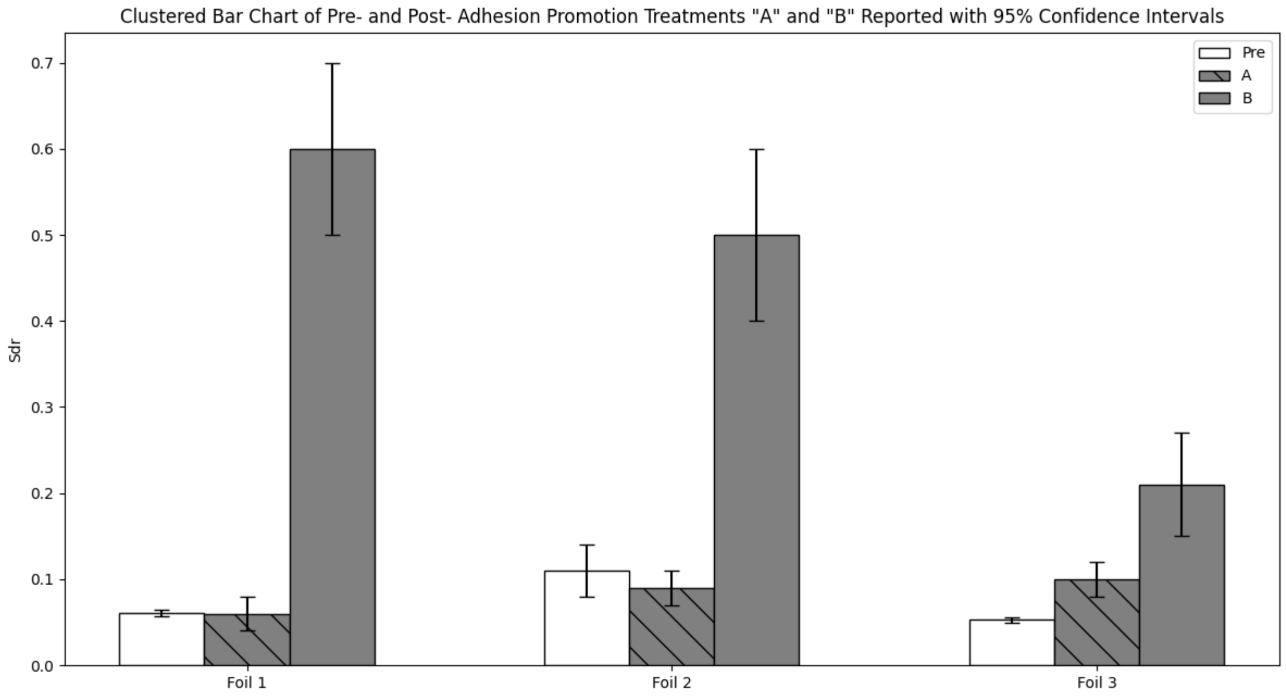
Surface Roughness Test Setup

- 2x1” samples cut from 18x24” sheet
  - 2 samples per foil
  - 5 measurements per sample
- Non-contact laser microscope
- IPC TM-650 2.2.22
  - Noncontact Metallic Foil Surface Topography/Texture



Sdr Results

- Oxide Alternative (OA) “A” had a **less significant** impact on surface roughness compared to OA “B”.
- OA “B” increased Sdr:
  - ED (Foil 1): +163%
  - ED (Foil 2): +128%
  - RA: +119%
- The ED foils had a **greater increase** in Sdr with OA “B” than that of the RA foil.



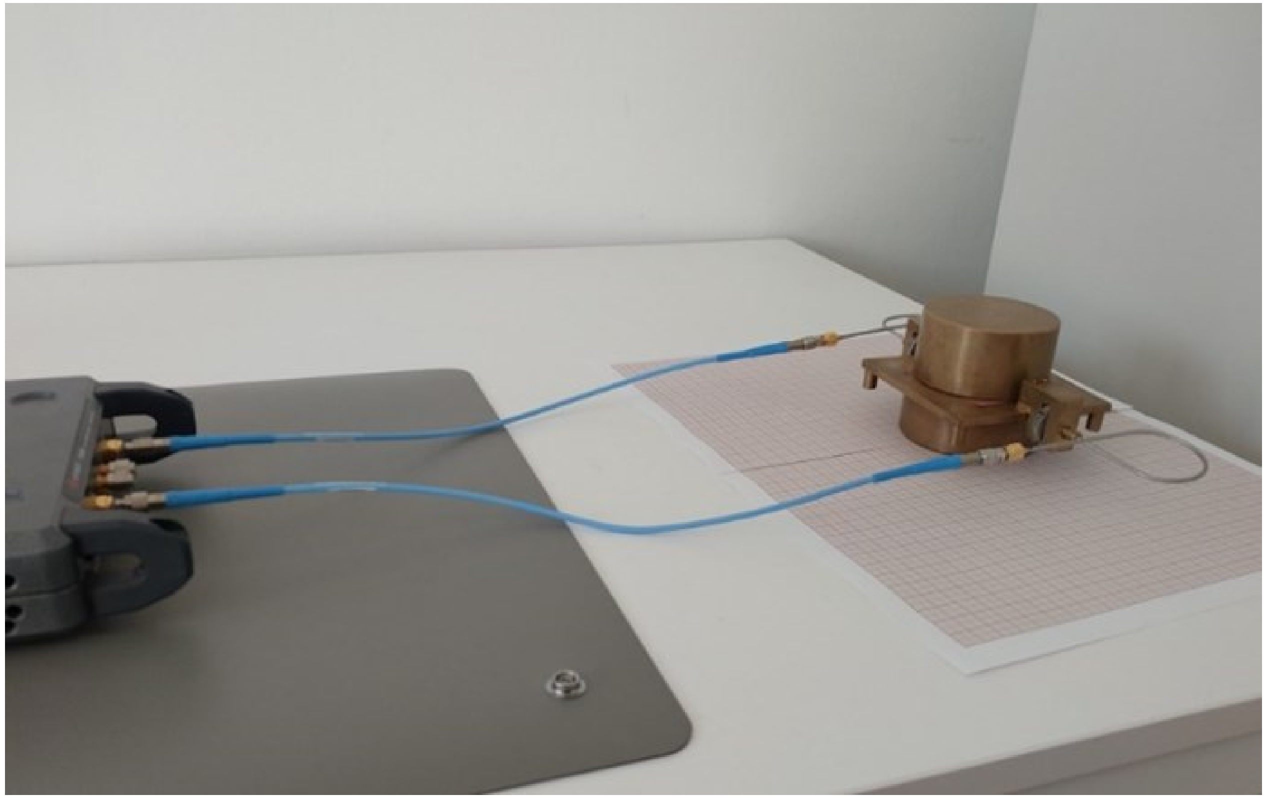
Pre-Adhesion Promotion		Post-Adhesion Promotion	
Foil	Avg Sdr ± Std Dev	Foil-Treatment	Avg Sdr ± Std Dev
1	0.061 ± 0.004	1-A	0.06 ± 0.02
		1-B	0.6 ± 0.1
2	0.11 ± 0.03	2-A	0.09 ± 0.02
		2-B	0.5 ± 0.1
3	0.053 ± 0.003	3-A	0.10 ± 0.02
		3-B	0.21 ± 0.06

Ruby Dielectric Resonator (RuDR)

- Operates at nominal frequencies of **13 GHz** and **21 GHz**.
- Two identical metallic samples are required for measurements.
- The samples should have dimensions of at least **23 mm x 23 mm.**
- The dedicated software calculates material parameters based on the measured data: resonance frequency and Q-factor (extracted through VNA).

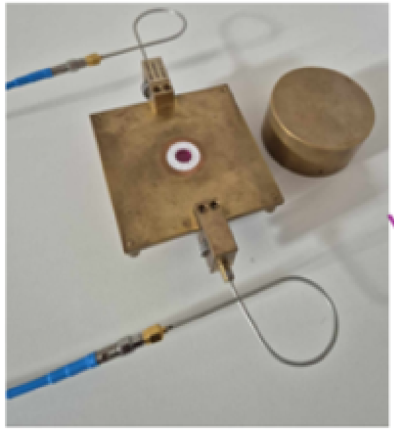
RuDR resonator allows measuring a **copper foil** by itself:

- no need to fabricate a test circuit!
- loss from the foil is separated from any dielectric loss.
- the two sides of foil can be measured separately.



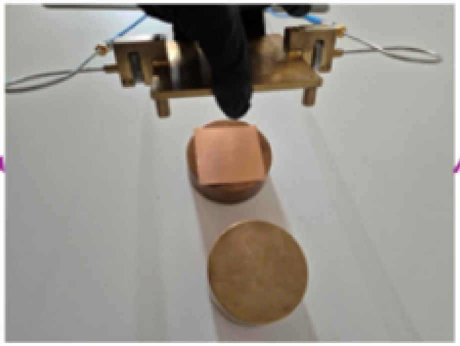
The measurement system consists of a cylindrical RuDR, connected to a VNA through coaxial cables and a laptop with dedicated software.

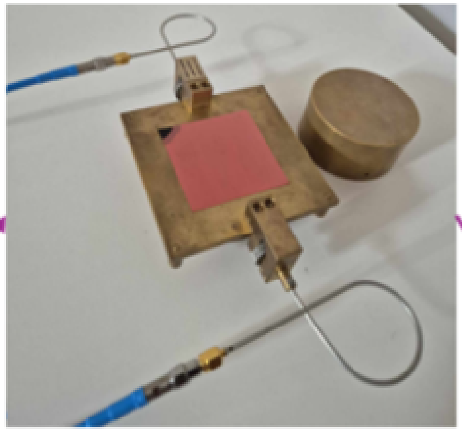
RuDR preparation for copper foil measurement



Empty RuDR

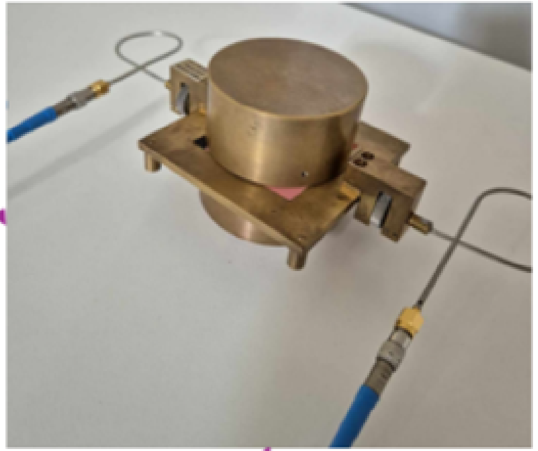
Placing the first sample
under the cavity resonator

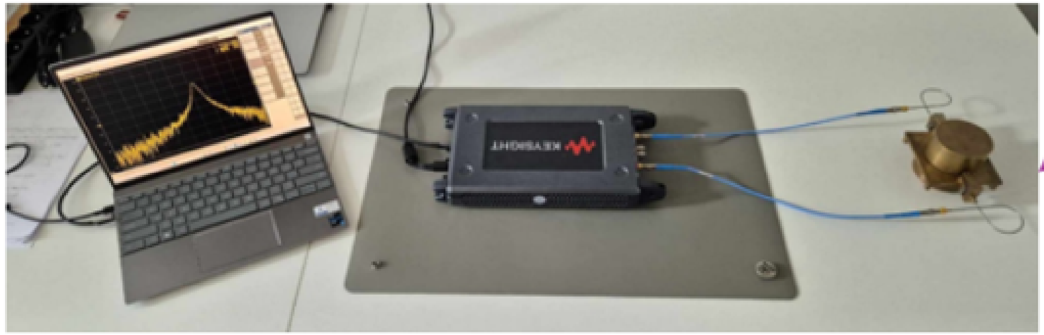




Placing a second identical
sample under the cavity
resonator

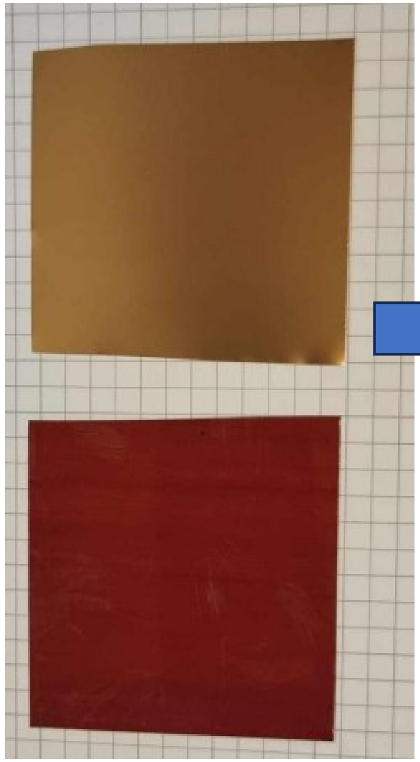
Close the resonator
with samples



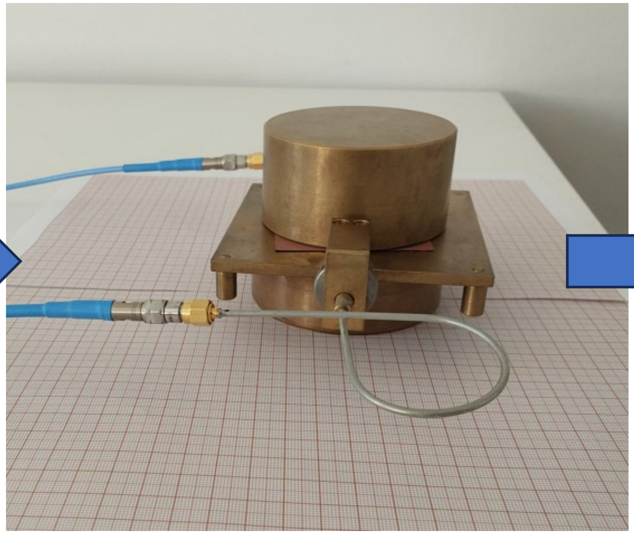


Ready-to-use measurement setup

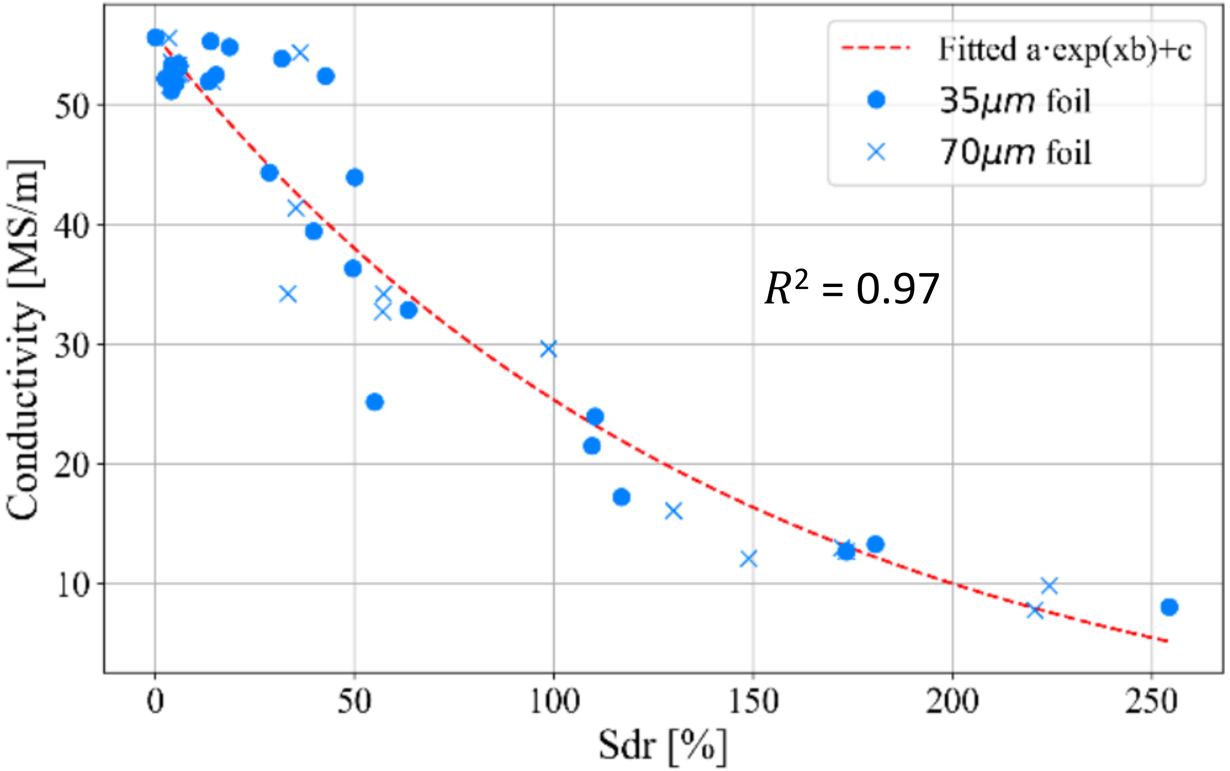
Comparison of conductivity with surface roughness on 13&21 GHz RuDR - Example of work



24 types of copper foils
3 samples each give
-> **72 measured samples**



13&21 GHz RuDR test-fixture

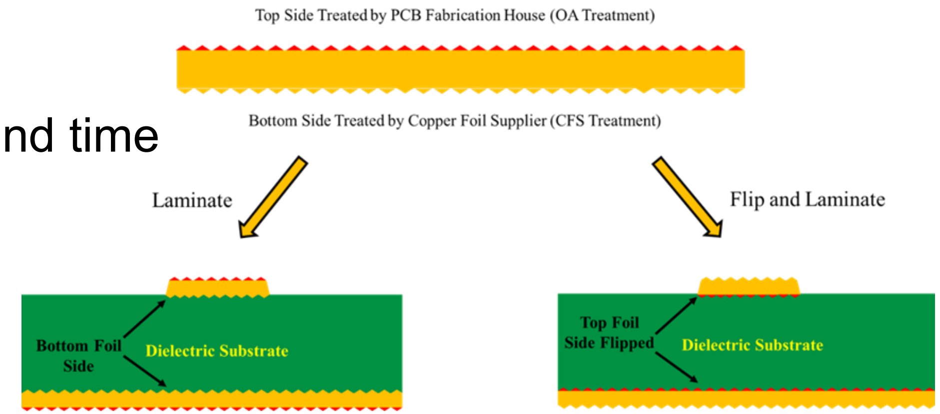


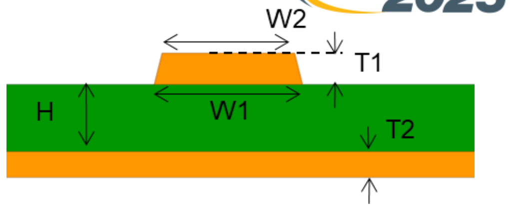
Correlation between effective conductivity (measured at 13 GHz in the RuDR) and surface roughness parameter Sdr (measured with laser interferometry).

M. Celuch, T. Devahif, T. Nalecz, J. Rudnicki, "A Systematic Study of Correlation between Surface Roughness and Microwave Effective Conductivity of Copper Foils for Ultra-Low-Loss Applications", 25th International Microwave and Radar Conference MIKON, **1-3 July 2024**, Wroclaw, Poland

Microstrip TL Test Setup

- Why Microstrip TL:
  - reduced fabrication turnaround time
  - cost-effective
  - ease of preparation
  - straightforward testing





Geometry	Design Value
Trace Width (W1)	0.0115 in
Copper Weight (T1)	½ oz + Plating
Substrate thickness (H)	0.005 in
Panel Size	18 in x 24 in
Dk/Df	3.33/0.0018

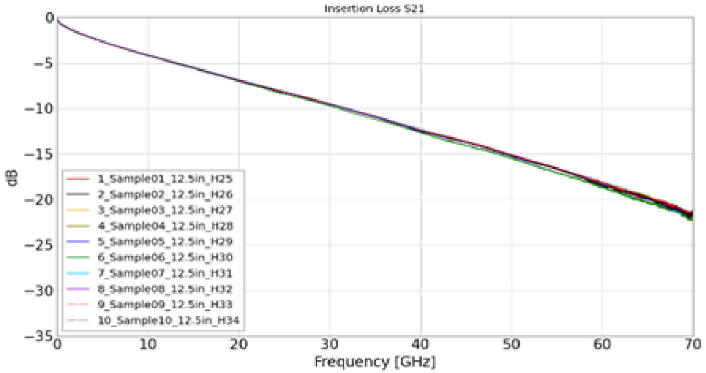
- Ten sets of microstrip coupons are prepared and tested for each type of copper and surface treatment.
  - Each set consists of a 1-inch trace and 12.5-inch traces.

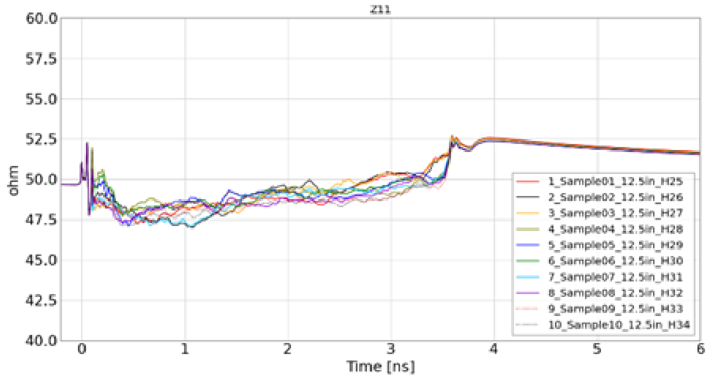
1-inch Coupon

12.5-inch Coupon

- Testing up to 70GHz using VNA.

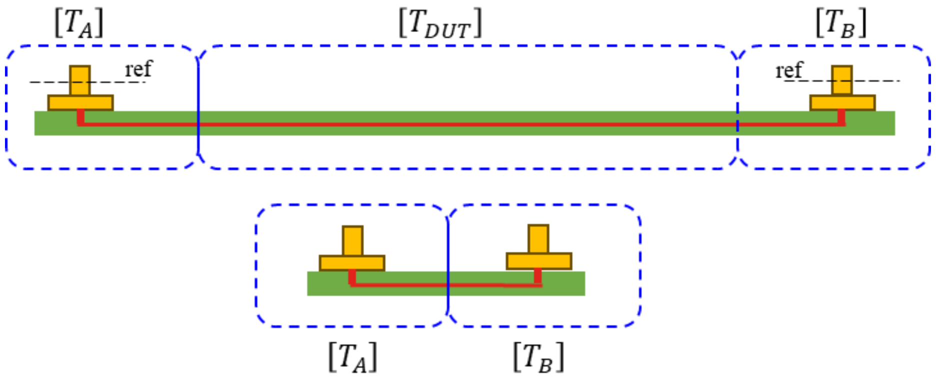
- Cables are de-embedded using 70GHz AutoCal.



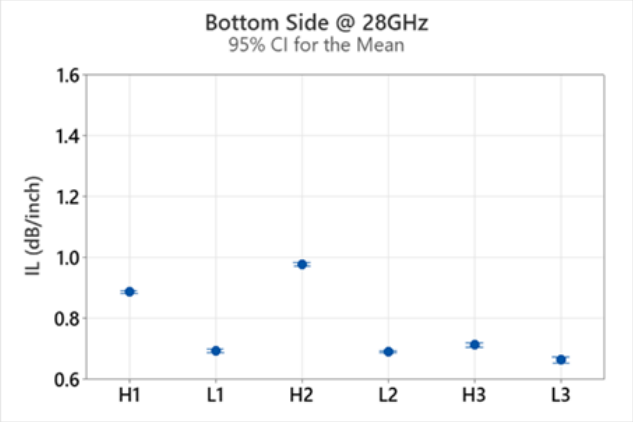


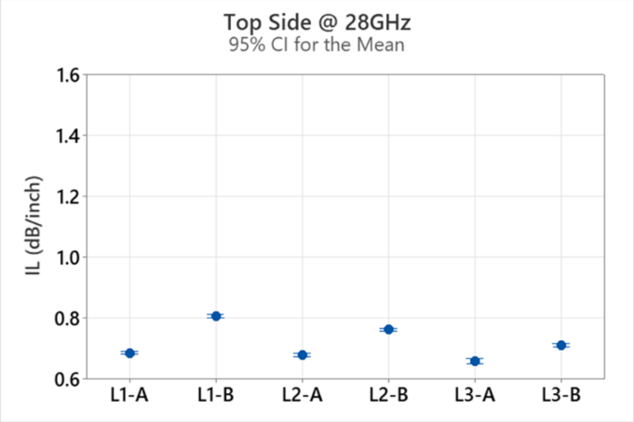
Attenuation Loss (dB/in)

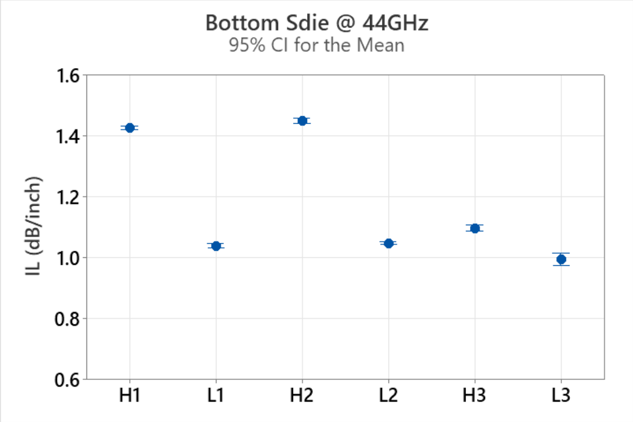
- The loss is extracted using the eigenvalue de-embedding method.
- Frequencies of 28 GHz and 44 GHz are selected to match the RuDR.

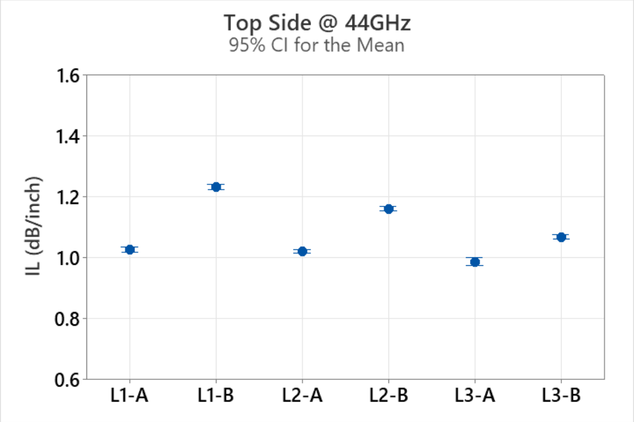


$$[T_{L1}] = [T_A] \times [T_B]$$
$$[T_{L2}] = [T_A] \times [T_{DUT}] \times [T_B]$$
$$[T_{L2}] \times [T_{L1}^{-1}] = [T_A] \times [T_{DUT}] \times [T_A^{-1}] \text{ …., Similar to } [T_{DUT}]$$





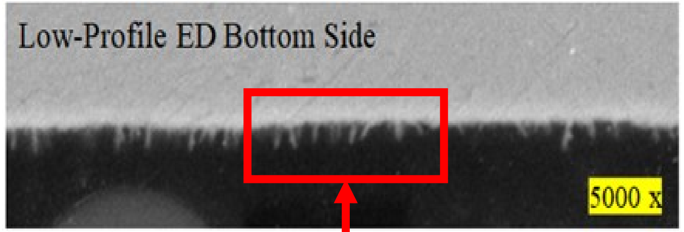




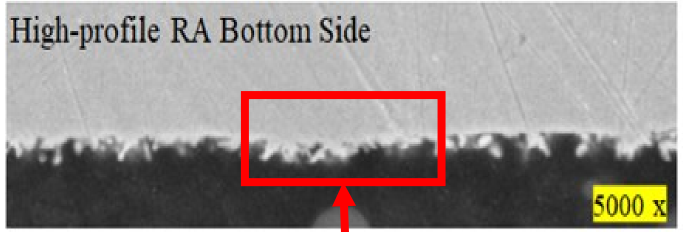
- **Bottom side** refers to the laminate (core) side.
- **Top side** refers to the effect of OA on the resist (prepreg) side.

Surface Topology (via SEM)

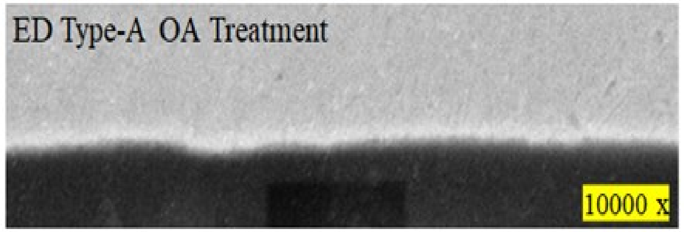
- Scanning Electron Microscopy (SEM) was used to characterize the surface topology of the copper through cross-sectional analysis.
- Bottom Side
  - Significant differences in tooth height, width, shape, and concentration.
- Top Side (OA Treated)
  - OA "A" results in a smoother surface than type "B"
  - A key difference is the **shape of the dendrites**.
- Bottom side of the high-profile and the top side of the low-profile treated with type B oxide exhibit rough surfaces, the shape of the dendrites differs considerably.

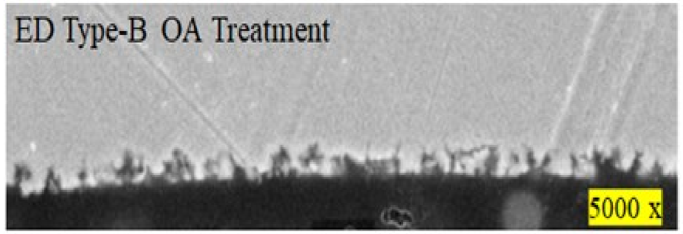


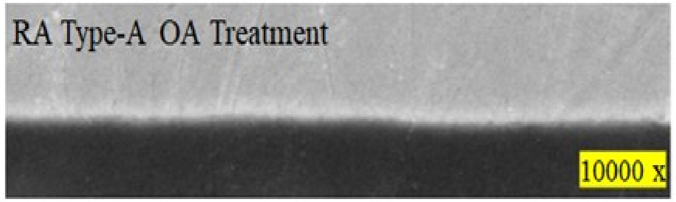
Dendrites are **smaller**, **narrower**, **less condensed**, and predominantly grow in a **uniform** direction.

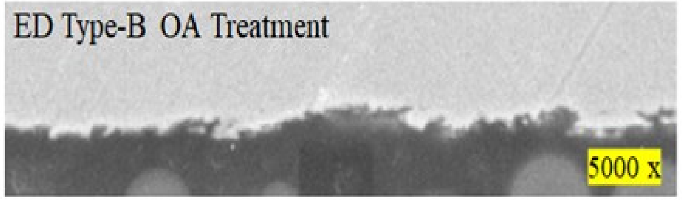


Dendrites in the high-profile trace are **longer**, **wider**, **denser**, and exhibit a more **random** growth pattern.





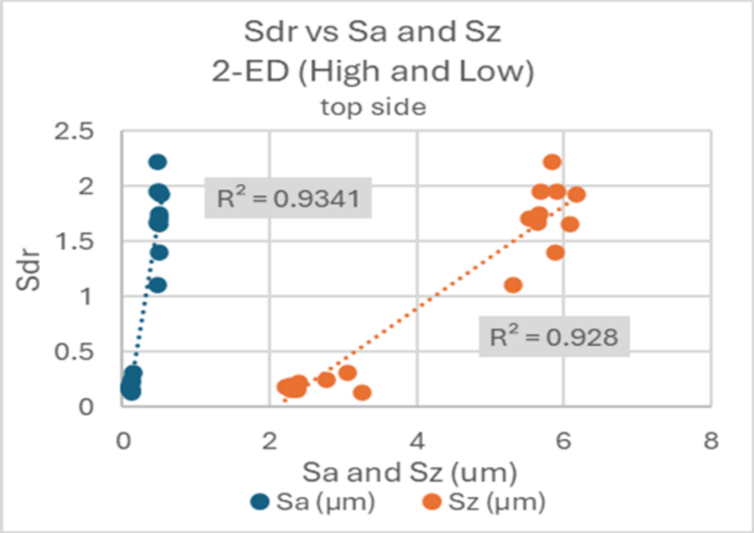


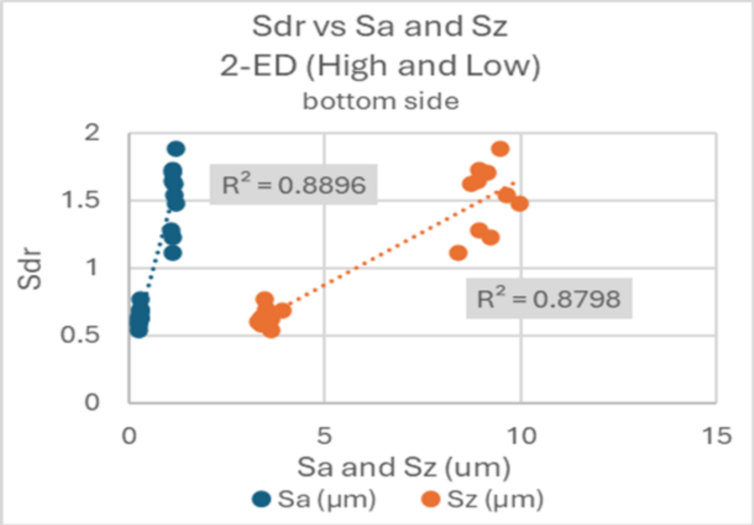


OA is applied exclusively to **low-profile** copper.

Summary

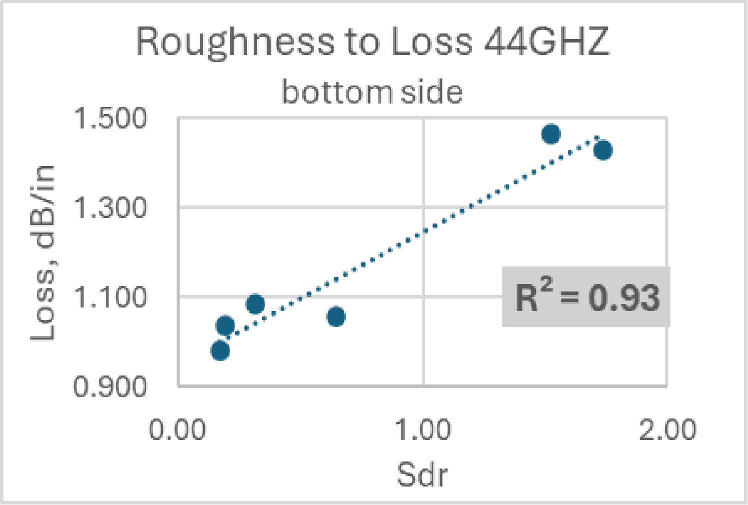
- 3 copper vendors each supplied foils with 2 levels of roughness on the bottom side
  - 2 electrodeposited (ED)
  - 1 rolled annealed (RA)
- 2 oxide alternative (OA) processes with different roughness levels were applied to the top side, measured for roughness, and bonded to the dielectric for microstrip testing
- Total measurements across all parameters **exceeded 5,000**
- Sdr, Sz and Sa were measured on all samples and assessed for correlation
  - **ED top side R^2 values were >90%; bottom side R^2 values were just below 90%**
  - **RA foils exhibited a narrower range of roughness values**

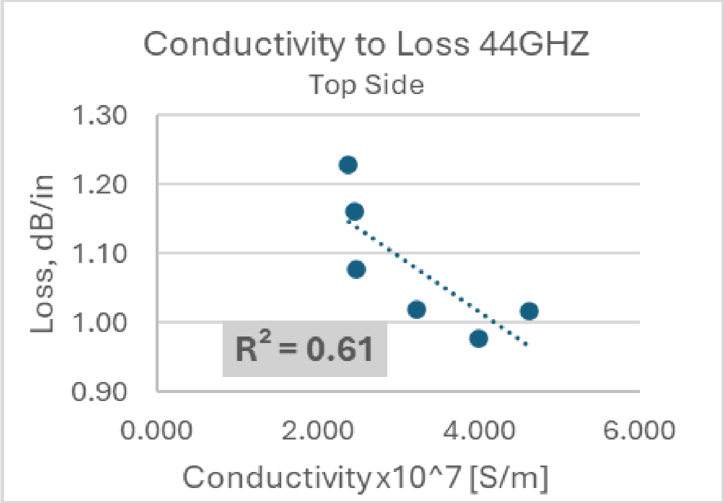


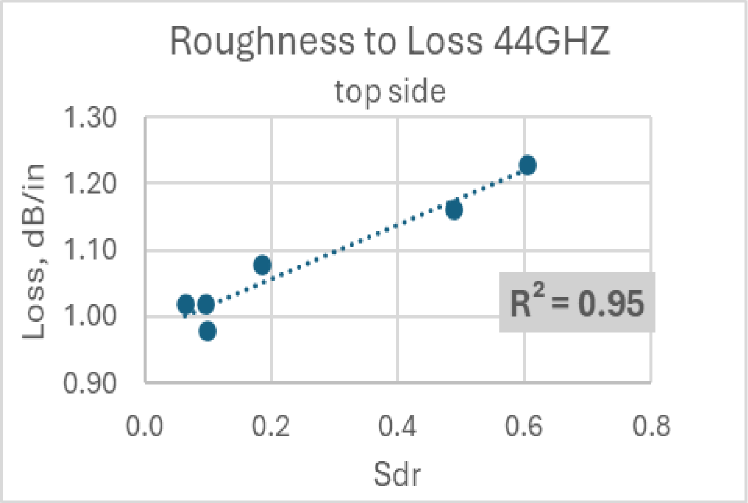


Summary (continued)

- 28 & 44 GHz were chosen for correlation of loss and conductivity
  - 44 GHz correlations presented here
- Roughness values correlated well with loss measurements on both the top & bottom side of all samples with **R^2 above 90%**
- Conductivity measurements correlate well with roughness on the non-oxide alternative bottom side of all samples with **R^2 in the 90% range**
  - Higher roughness consistently showed lower conductivity
- Conductivity also correlates well with loss on the bottom side samples, with **R^2 above 90%**
- Top side samples did not show good correlation of conductivity with loss or roughness
  - Previous studies of conductivity and roughness exhibit higher correlation
  - These results may have been influenced by the range of different copper types & OA processes
  - Future work will investigate this further







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