AltiumLive 2022

CONNECT

Where High Speed Meets High Frequency

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Northwest Engineering Solutions

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Agenda

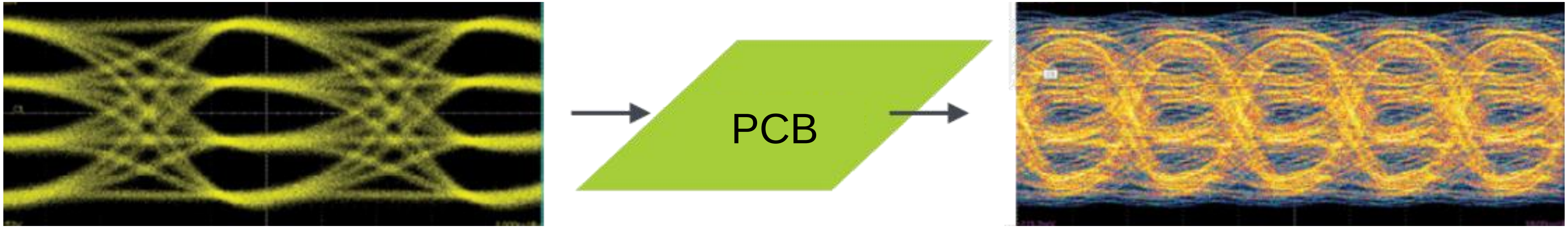
1. Digital vs. analog signals
2. Materials and PCB stackups
3. Impedance and propagation

Digital vs. Analog Signals

DIGITAL	MM-WAVE
Poorly-defined signal bandwidth	Well-defined signal bandwidth
Lower bandwidth limits, but which frequency for analysis?	Bandwidth limit ~ carrier + modulation
Signal level carries information	Carrier + modulating signal
Dispersive losses → **requires wideband analysis**	Dispersive losses → **only worried about narrow bandwidths**

Digital vs. Analog Signals

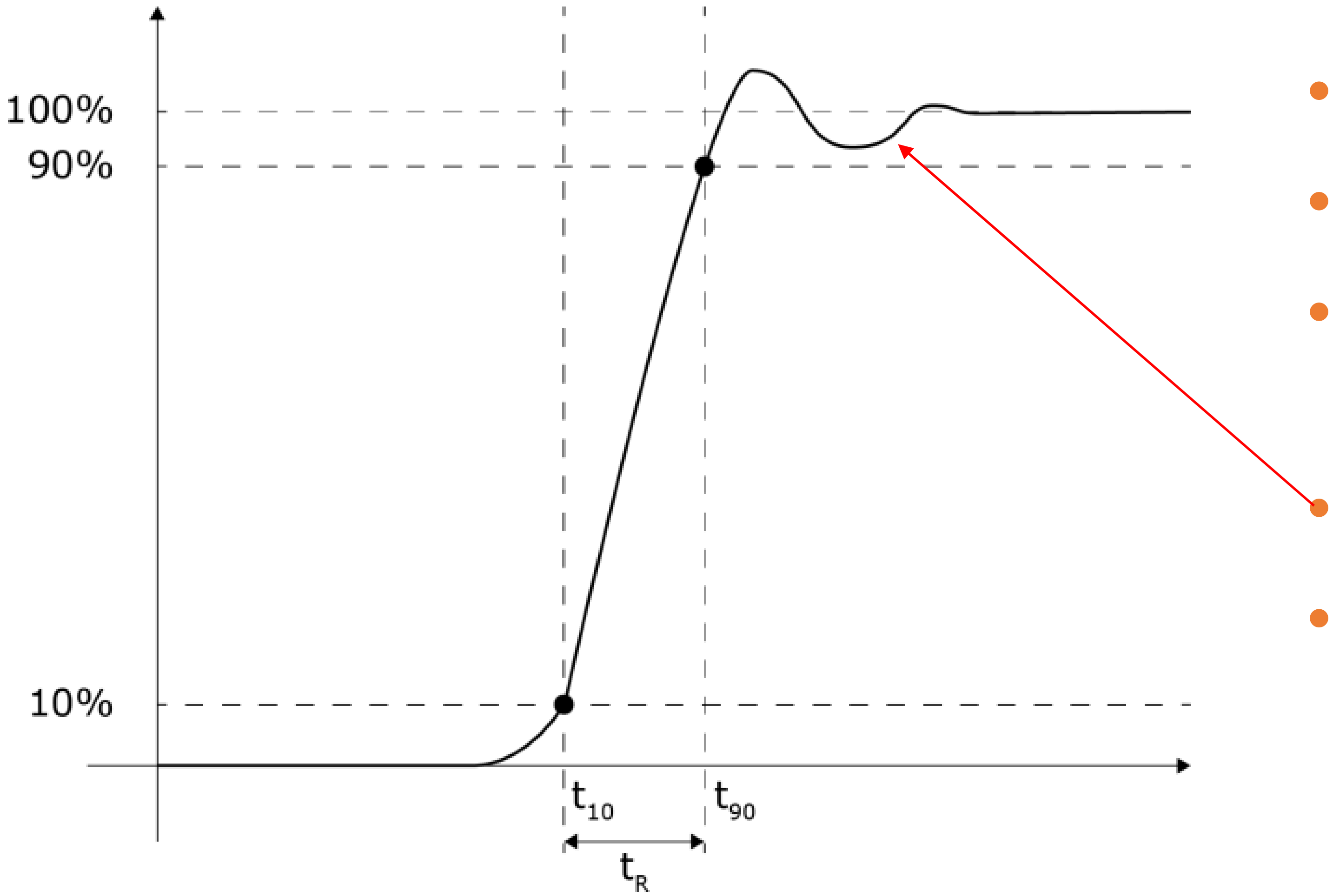
- Signals → Analyzed in the time domain
- Channels → Analyzed in the time or frequency domain
- Metrics: S-parameters, impedance, inter-symbol interference (ISI), insertion loss deviation (ILD), channel operating margin (COM)



PAM4 Signaling in High-Speed Serial Technology: Test, Analysis, and Debug. Tektronix Application Note, July 2018.

Digital vs. Analog Signals

- Signal rise time governs electrical behavior

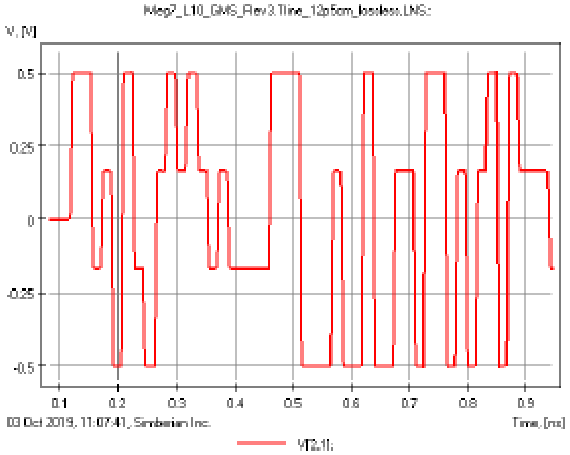


- Crosstalk
- Radiated emissions
- Measurement artifacts (Gibbs)
- Transient phenomena
- Resonant phenomena

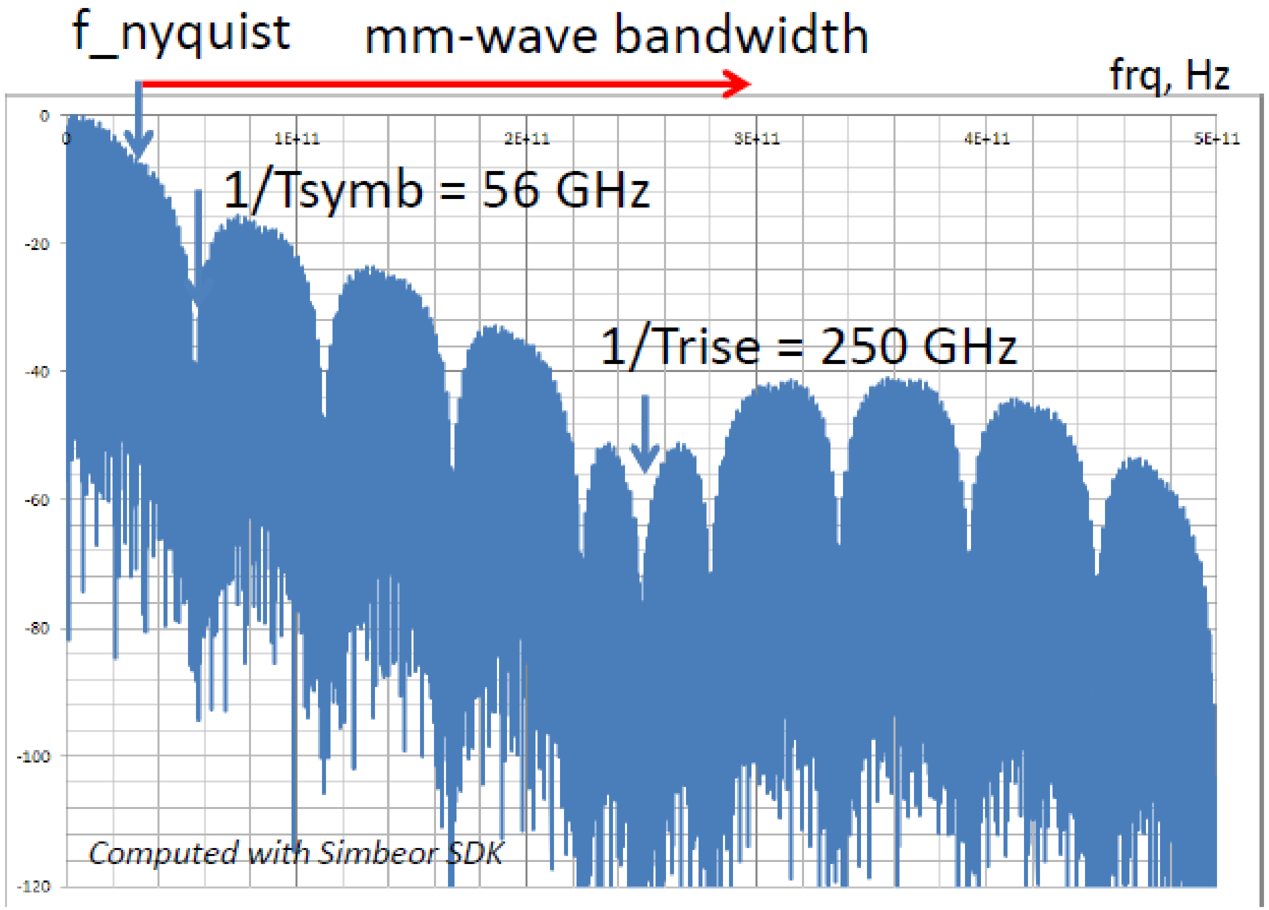
Digital vs. Analog Signals

Example: 112 Gbps PAM4 signaling

112 Gbps: Trise=4ps;
Tsymb=17.8571ps;
f_nyquist = 28 GHz



PSD of
PRBS7



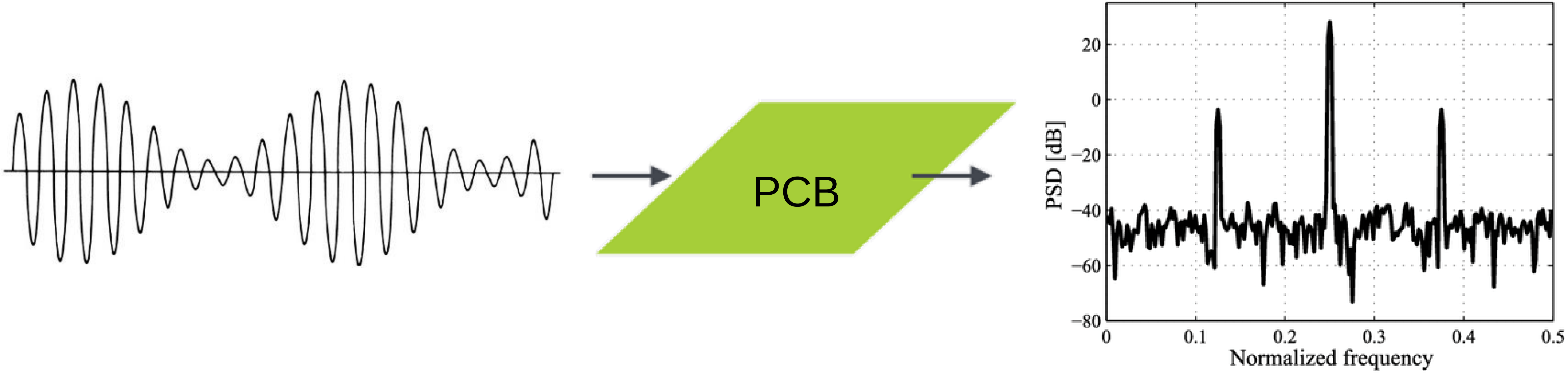
What is the bandwidth?
0.5/Trise looks unrealistic…

Heyfitch, V., and Shlepnev, Y. “Design insights from electromagnetic analysis and measurements of PCB and Package interconnects operating at 6-112 Gbps and beyond.” DesignCon 2020.

Digital vs. Analog Signals

- Signals and Channels → Analyzed in the frequency domain
- Signals can be modulated → Determines bandwidth

- **Examples:** Quantum computing, 5G/6G, radar, microwave photonics, IEEE 802.11ad (Multiple Gigabit Wireless System, up to 65.88 GHz)



Materials and PCB Stackups

Rogers and Isola very popular, others include Arlon, Megtron, etc…

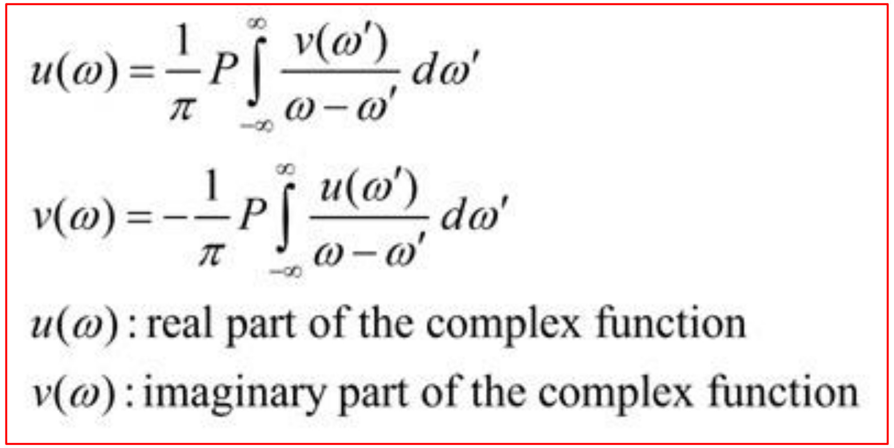
Substrate	T_g (°C)	T_d (°C)	Dk	Loss tangent	Band
FR4	~135	~295	less than 4.4	~0.022 (parasitic conductance ignored)	X-K
Isola MT40	200	360	3.38-3.75	0.0028-0.0035	W
IS680 AG-348	200	360	3.48	0.0029	W
IS680 AG	200	360	3.00-3.48	0.0020-0.0029	W
IS680	200	360	2.80-3.45	0.0025-0.0035	W
Isola MT77	200	360	3.00	0.0017	W
Rogers 3003	NR	500	3.00	0.0013	W
Rogers 3006	NR	500	6.15	0.002	X-Ka
Rogers 4360	greater than 280	407	6.15	0.0038	X-Ka
RT Duroid 6010.2LM	NR	500	10.70	0.0023	X-Ka
RT Druoid 6202	NR	500	2.90	0.0015	X-Ka
RT Druoid 6006	NR	500	6.45	0.0027	X-Ka
RT Druoid 6035	NR	NR	3.5	0.0013	X-Ka

NR: Not reported

Compiled from Isola and Rogers Corp.

Materials and PCB Stackups

- Dispersion: $\varepsilon = \varepsilon_R(\omega) + i\varepsilon_I(\omega)$
- Loss tangent: $tan\delta = \frac{-\omega\varepsilon_I(\omega) - \sigma_{sub}}{\omega\varepsilon_R}$
- Must be causal: obeys a Kramers-Kronig relation



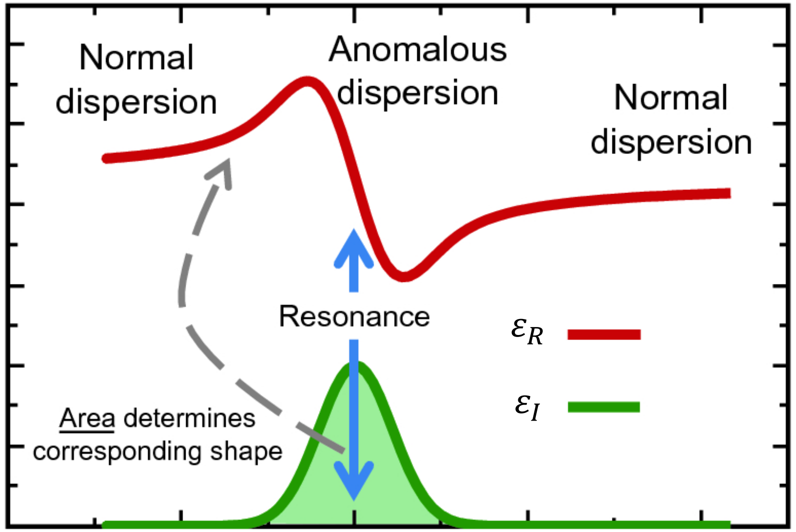
$$u(\omega) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{v(\omega')}{\omega - \omega'} d\omega'$$

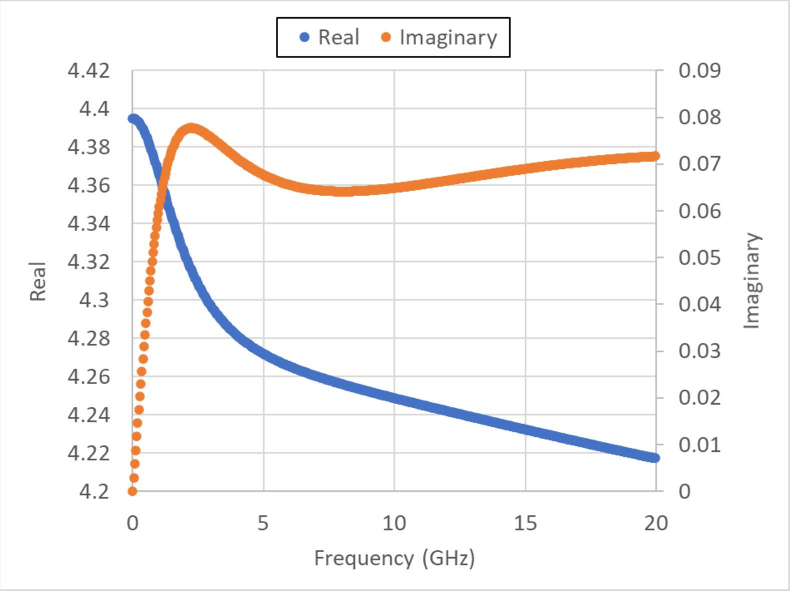
$$v(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{u(\omega')}{\omega - \omega'} d\omega'$$

$u(\omega)$: real part of the complex function

$v(\omega)$: imaginary part of the complex function

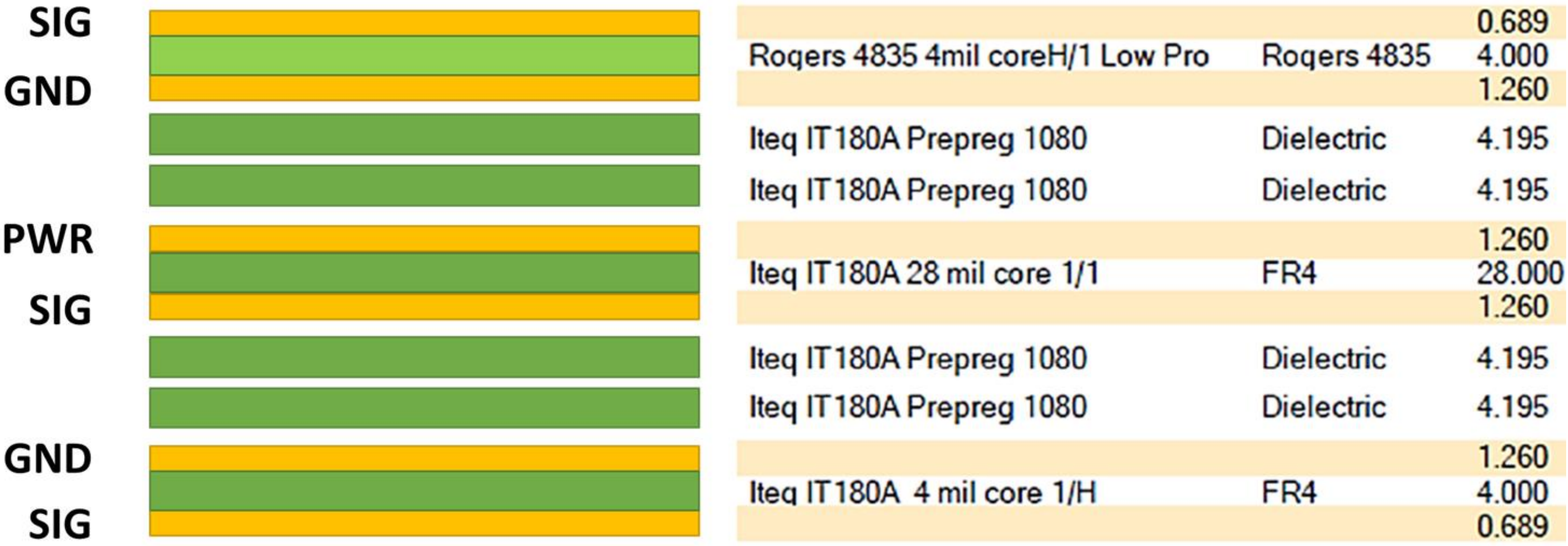
- Wideband-Debye model





Materials and PCB Stackups

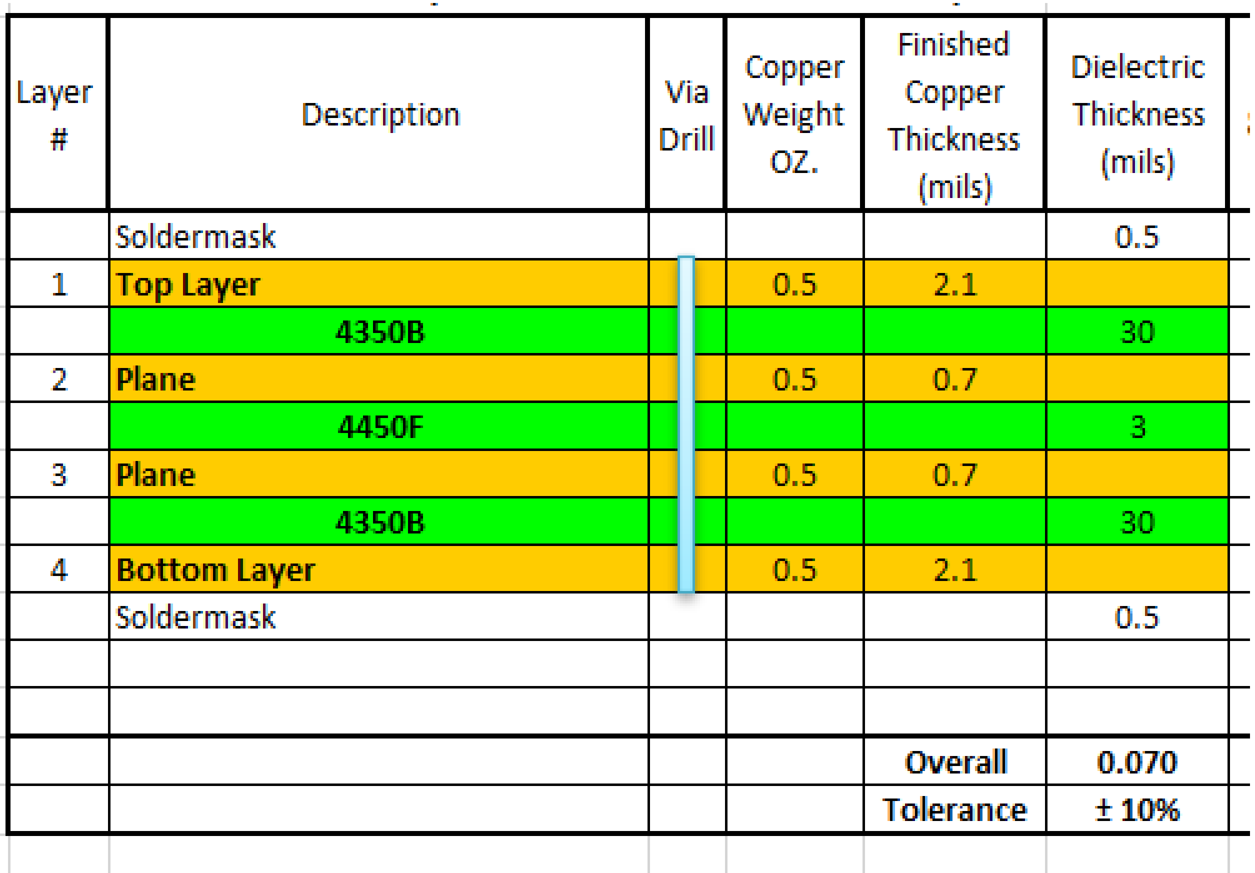
- RF: Hybrid stackup with RF on PTFE layer, all other signals in other layers
- Example for radar board with digital sections



SIG			0.689
	Rogers 4835 4mil coreH/1 Low Pro	Rogers 4835	4.000
GND			1.260
	Iteq IT180A Prepreg 1080	Dielectric	4.195
	Iteq IT180A Prepreg 1080	Dielectric	4.195
PWR			1.260
	Iteq IT180A 28 mil core 1/1	FR4	28.000
SIG			1.260
	Iteq IT180A Prepreg 1080	Dielectric	4.195
	Iteq IT180A Prepreg 1080	Dielectric	4.195
GND			1.260
	Iteq IT180A 4 mil core 1/H	FR4	4.000
SIG			0.689

Materials and PCB Stackups

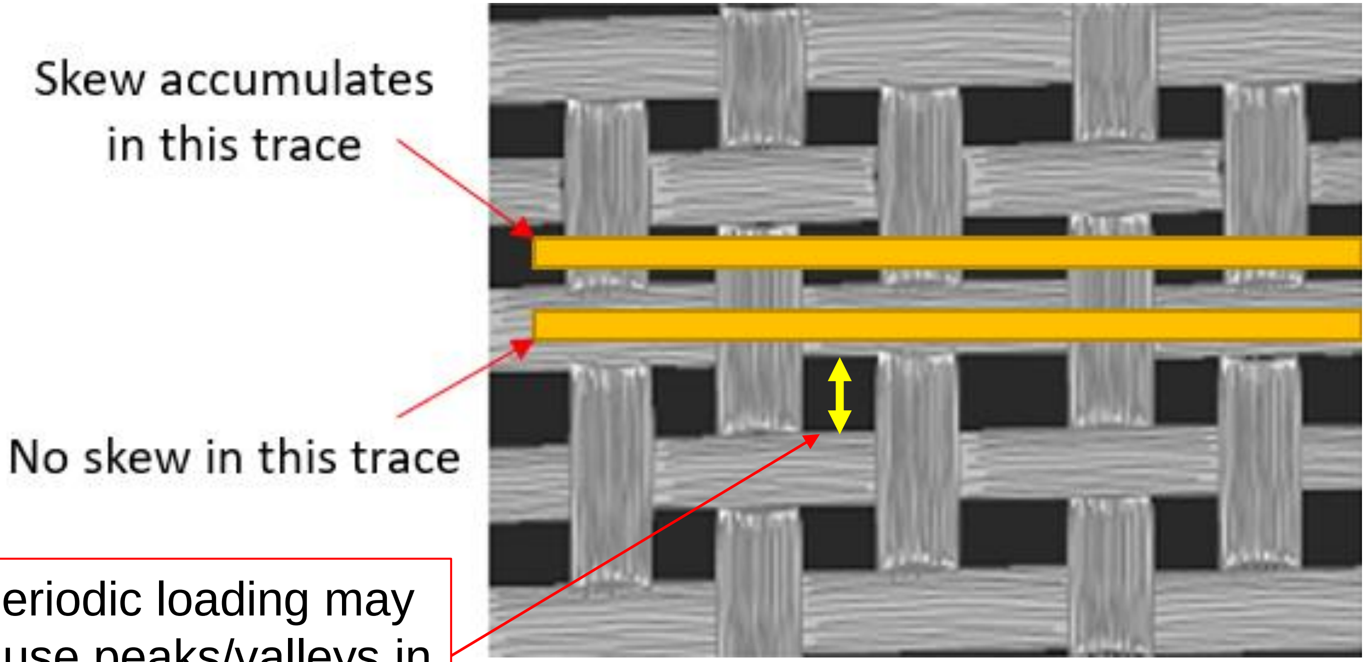
- Layer thicknesses can be inverse of typical digital PCBs
- **Digital:** Thin layers for small, dense trace routing
- **RF:** Thick layers (Low capacitance) → Wide traces (Low inductance, low skin effect)



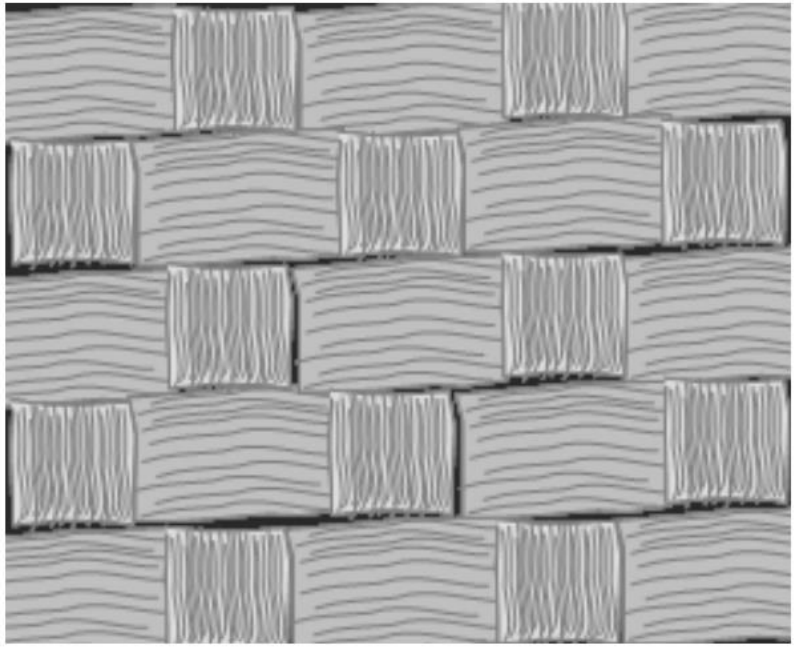
Layer #	Description	Via Drill	Copper Weight OZ.	Finished Copper Thickness (mils)	Dielectric Thickness (mils)
	Soldermask				0.5
1	**Top Layer**		0.5	2.1	
	4350B				30
2	**Plane**		0.5	0.7	
	4450F				3
3	**Plane**		0.5	0.7	
	4350B				30
4	**Bottom Layer**		0.5	2.1	
	Soldermask				0.5
				Overall	**0.070**
				Tolerance	**± 10%**

Materials and PCB Stackups

- **Digital:** Unpredictable skew
- **RF:** Cavities create resonant effects along interconnects at ~50 GHz and higher. $f_n \sim \frac{n\lambda}{2}$ (n = even integer)



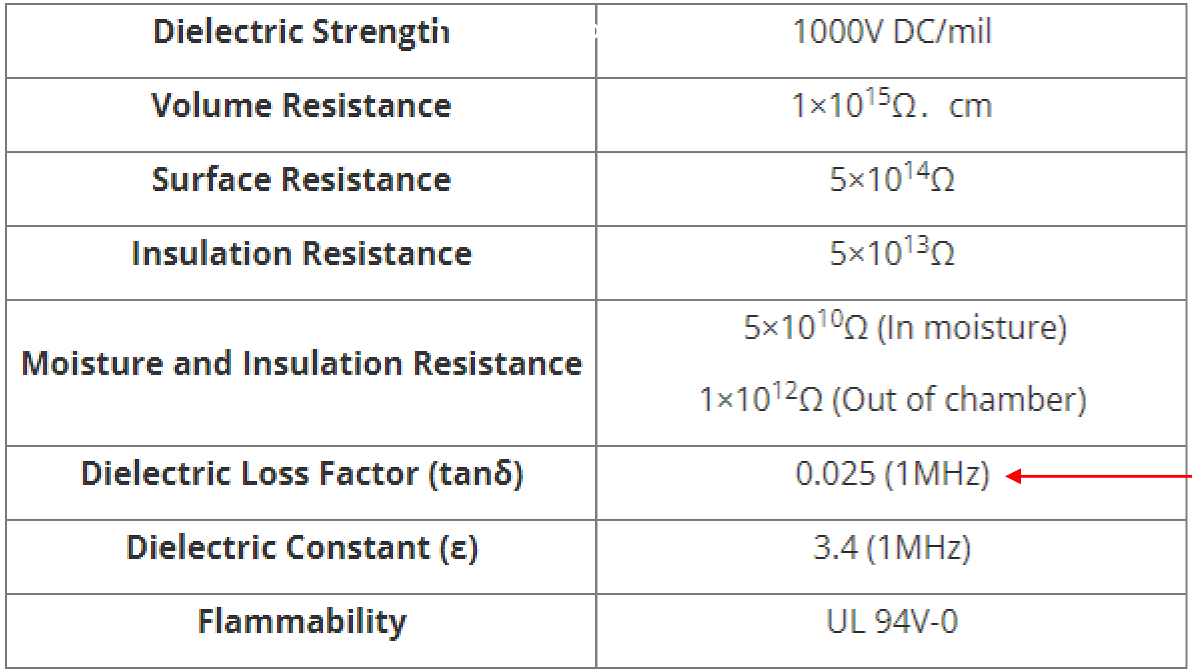
Periodic loading may cause peaks/valleys in return loss spectrum



Materials and PCB Stackups

- Small wavelength → Solder mask matters significantly
- Remove solder mask from emitters and waveguides

Typical LPI values

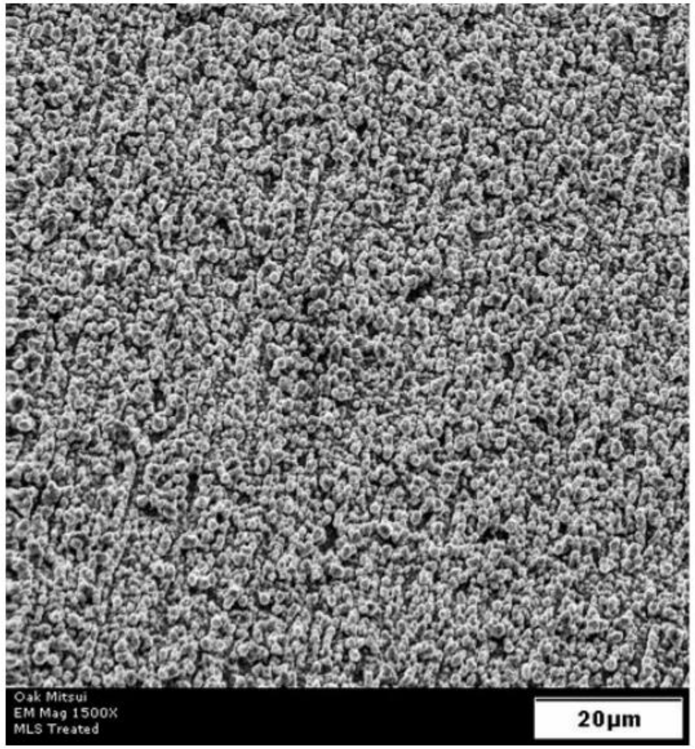


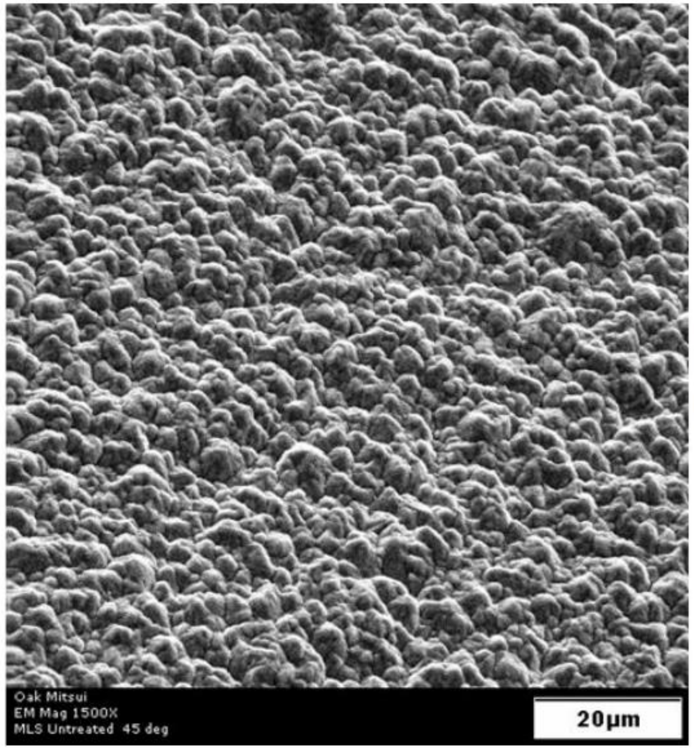
Dielectric Strength	1000V DC/mil
Volume Resistance	1×10^{15}Ω．cm
Surface Resistance	5×10^{14}Ω
Insulation Resistance	5×10^{13}Ω
Moisture and Insulation Resistance	5×10^{10}Ω (In moisture) 1×10^{12}Ω (Out of chamber)
Dielectric Loss Factor (tanδ)	0.025 (1MHz)
Dielectric Constant (ε)	3.4 (1MHz)
Flammability	UL 94V-0

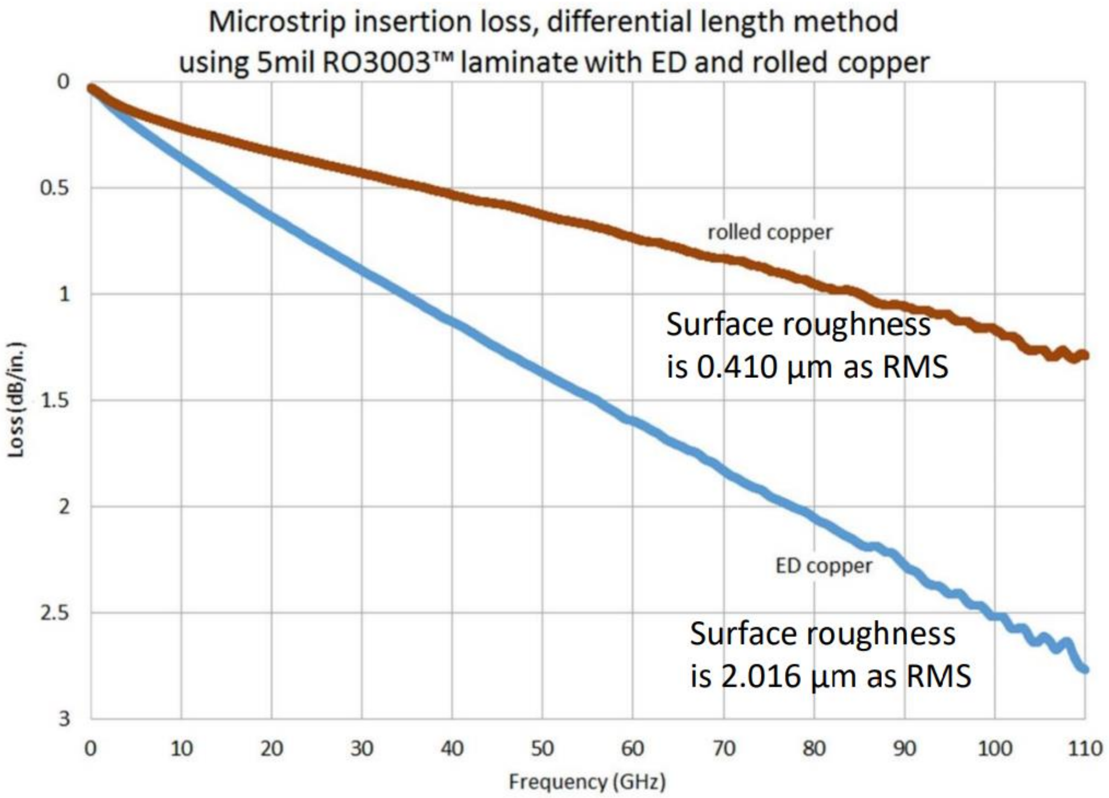
Typically 0.002 for RF substrate materials!

Materials and PCB Stackups

- Roughness depends on process (reverse treated, electrodeposited, rolled copper, additive, etc…)



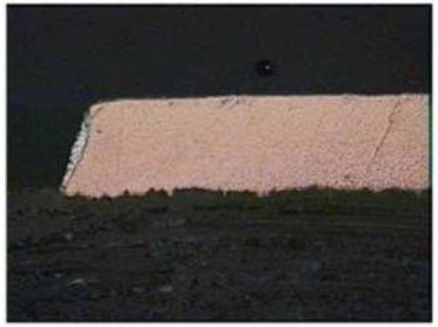




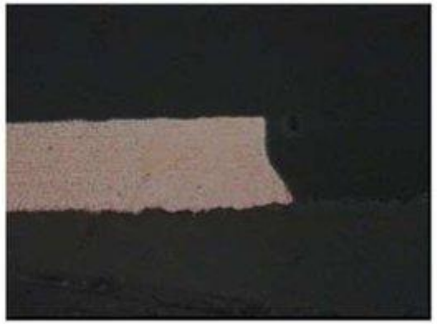
Coonrod, J. “Advancements in Prepreg Enabling New Applications for Millimeter-Wave (mmWave) and High Speed Digital (HSD),” PCB West 2021.
Oak-mitsui, 80 First St, Hoosick Falls, NY, 12090. URL: http://www.oakmitsui.com/pages/company/company.asp

Materials and PCB Stackups

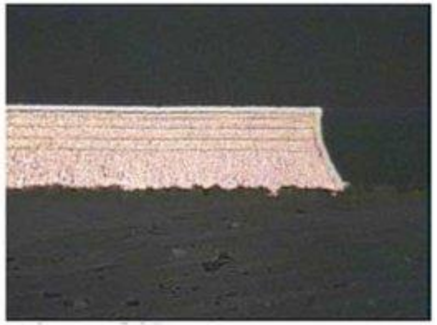
Nickel-based platings can have problems with roughness



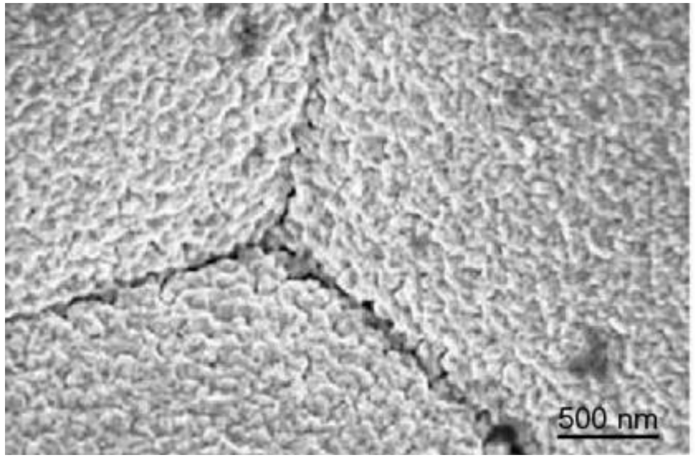
HASL on FR4

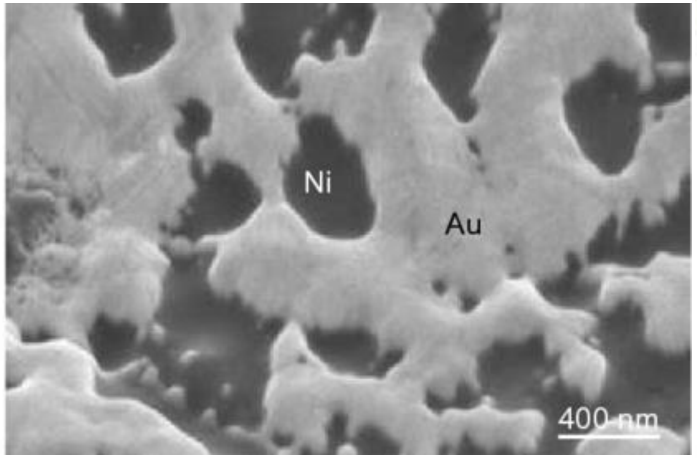


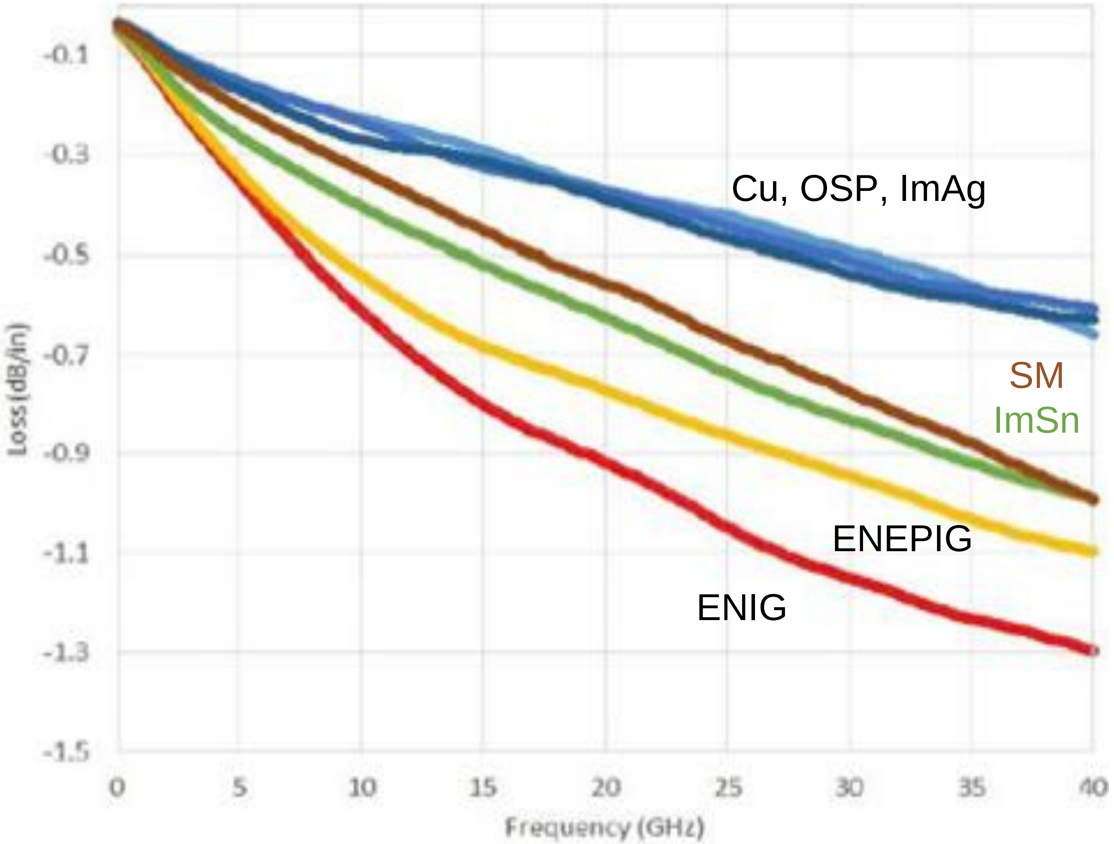
OSP on FR4



ENIG on FR4







Xin, W., et al. "Surface finish effects on high-speed signal degradation." IEEE Transactions on Advanced Packaging ***31****, #1, pp. 182-189 (2008).*

Impedance and Propagation

- Transmission lines: $Z_0 = \sqrt{\frac{R+i\omega L}{G+i\omega C}}$, $\gamma = \sqrt{(R + i\omega L)(G + i\omega C)}$

$$R(\omega) = R_{DC} + \sqrt{\omega} R_s \qquad L(\omega) = L_\infty + {R_s}/{\sqrt{\omega}}$$

Incomplete

$$G(\omega) = \omega C(\omega) \tan\delta\,(\omega) \qquad C(\omega) = K_g \varepsilon_R(\omega) \varepsilon_0$$

- Dielectric constant: $\varepsilon = \varepsilon_R(\omega) + i\varepsilon_I(\omega)$, $tan\delta = \frac{-\omega\varepsilon_I(\omega) - \sigma_{sub}}{\omega\varepsilon_R}$
- Need causal models or data for:

Dielectric constant: $\varepsilon(\omega)$

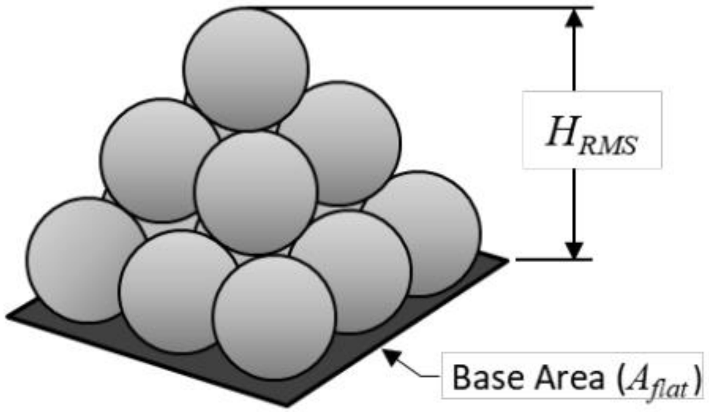
Copper roughness: $K(\omega)$

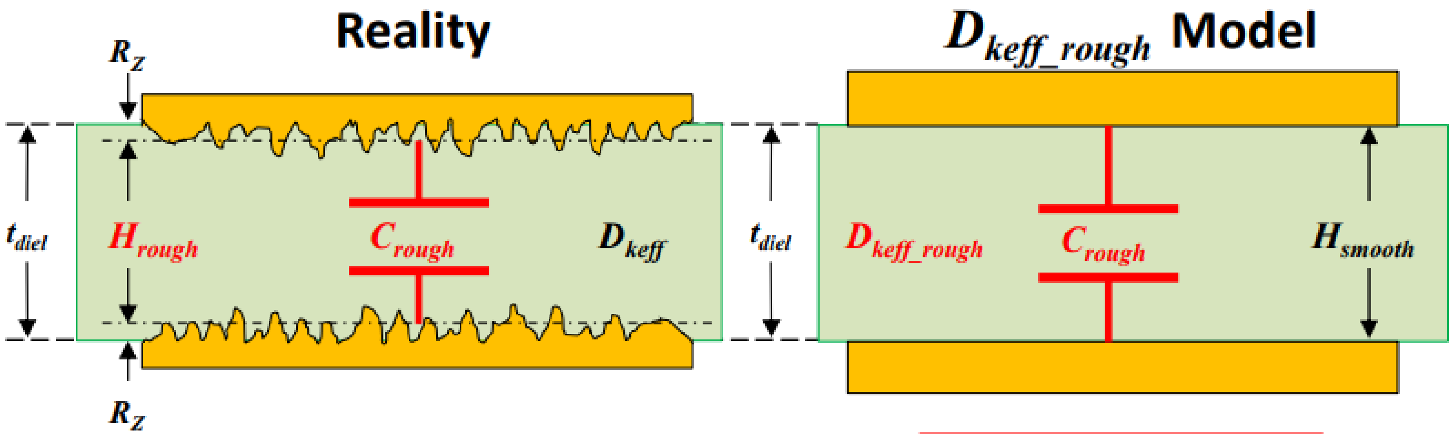
Electrical parameters: $R(\omega), L(\omega)$

Zhang, J., et al. "Causal RLGC(*f*) Models for Transmission Lines From Measured *S*-Parameters," *IEEE Transactions on Electromagnetic Compatibility*, 52(1), pp.189-198 (2009).

Impedance and Propagation

- Cannonball-Huray (Other models: Hammerstad, Snowball Huray, etc.)





$$\boxed{\varepsilon_c(\omega) = \varepsilon(\omega)\frac{t_{diel}}{t_{diel} - 2H_{10}}}$$

$$\boxed{R_s \rightarrow K(\omega)R_s}$$

	Cannonball-Huray
Normalized frequency	$s = i\omega\mu_0\sigma a^2$ (a = cannonball radius)
Correction factor K	$1 + \frac{\sqrt{s}}{1+\sqrt{s}}$

Dmitriev-Zdorov, V. "A Causal Conductor Roughness Model and its Effect on Transmission Line Characteristics," Signal Integrity Journal, November 2018.
Simonovich, B. "PCB Interconnect Modeling Demystified," DesignCon 2019.

Impedance and Propagation

- **Example: Tri-objective problem, e.g., in 100GBase-KR4 or USB 4.0**

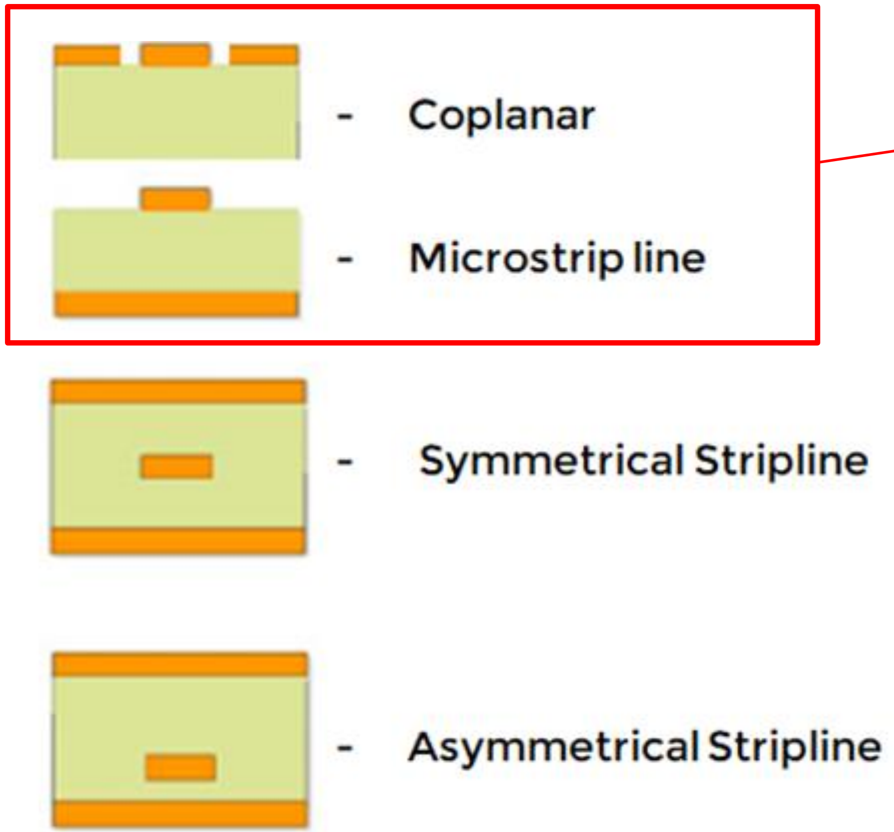
  Uses Multi-port S-parameters for differential interconnect design:

Integrated return loss: $IRL = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 |S_{21}(f)|^2 (|S_{11}(f)|^2 + |S_{22}(f)|^2) df}{\int_0^{fm} |V_{in}(f)|^2 df}}$

Integrated insertion loss: $IIL = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 |S_{21}(f)|^2 df}{\int_0^{fm} |V_{in}(f)|^2 df}}$

Integrated crosstalk: $ITX = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 \sum_{i \neq j} \left|S_{ij}(f)\right|^2 df}{\int_0^{fm} |V_{in}(f)|^2 df}}$

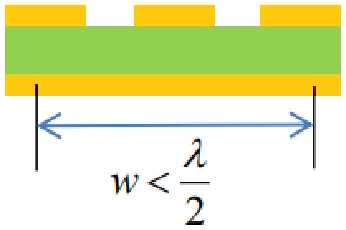
Impedance and Propagation



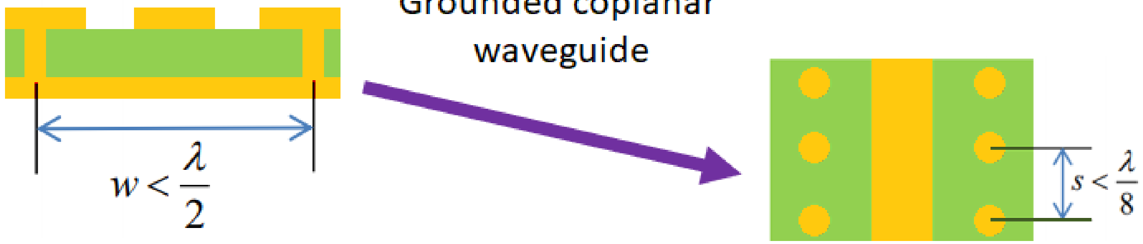
- Coplanar
- Microstrip line
- Symmetrical Stripline
- Asymmetrical Stripline

- Preferred for RF
  - Lower dielectric losses
  - Direct routes between components

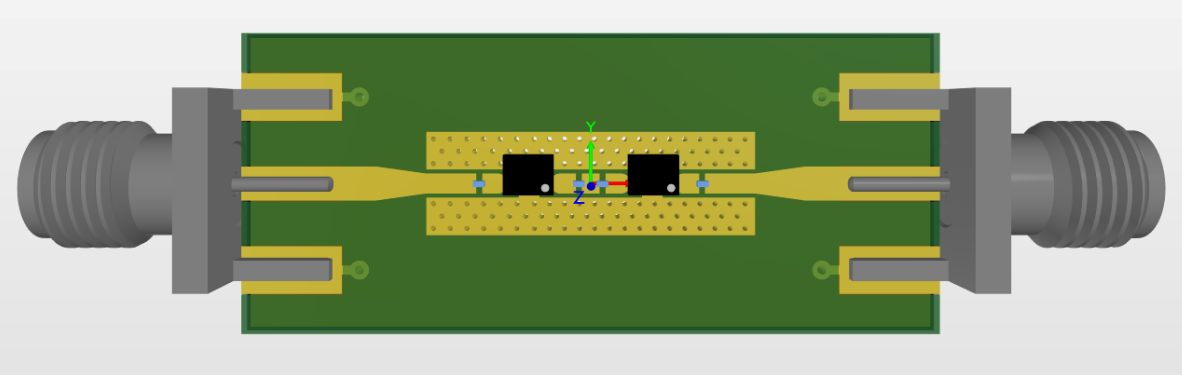
Coplanar waveguide

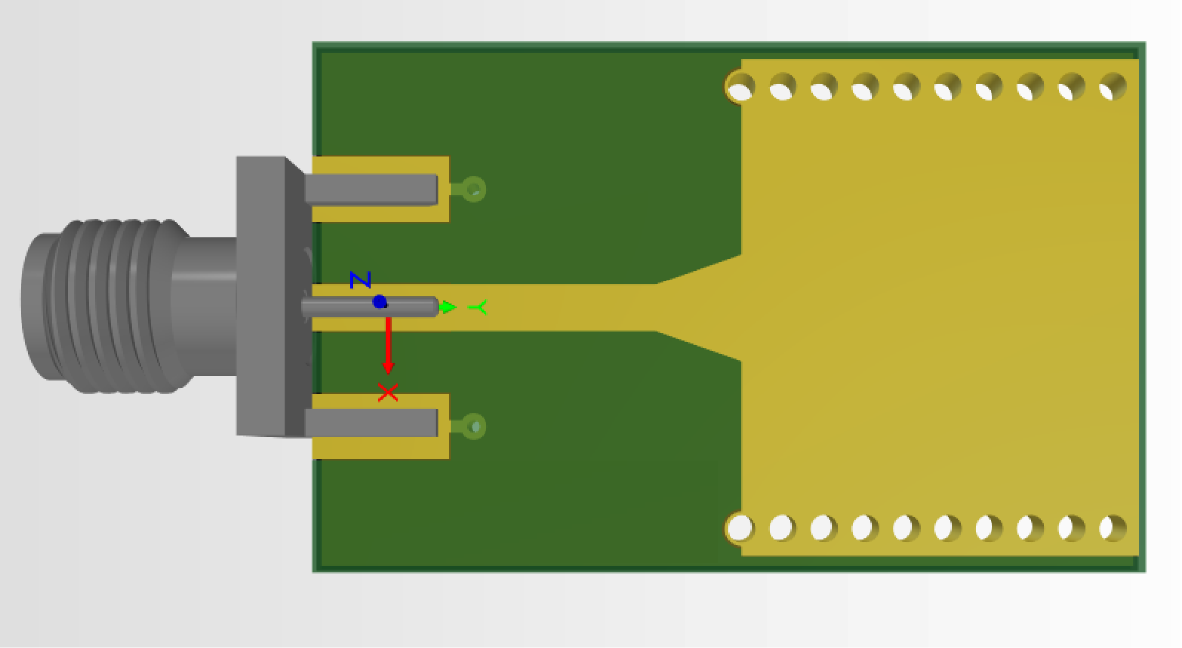


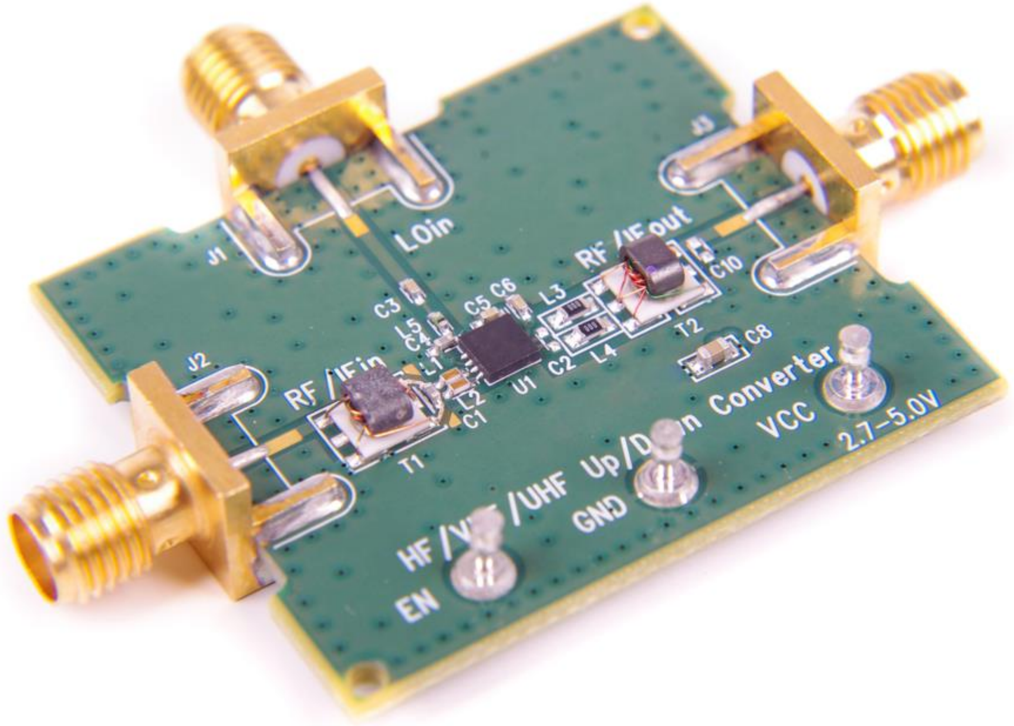
Grounded coplanar waveguide



Impedance and Propagation

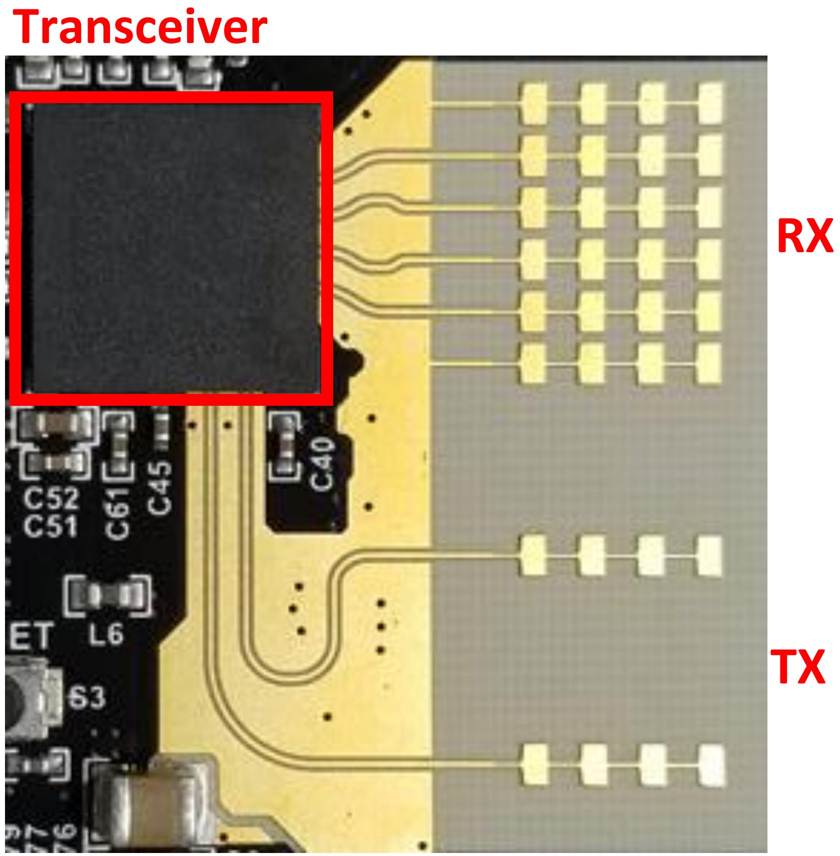


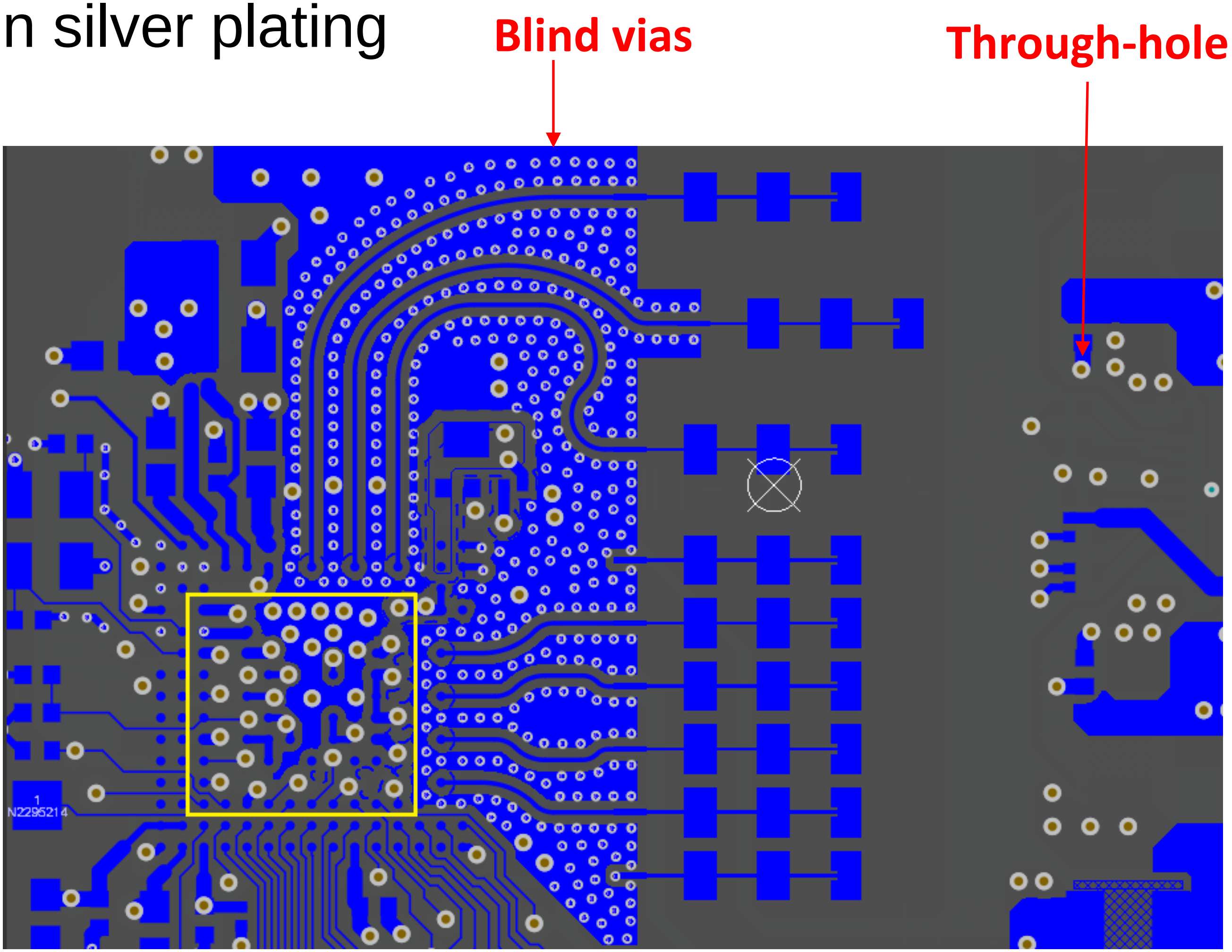




Impedance and Propagation

- Radar example w/ hybrid stackup
- Top layer on Rogers, Immersion silver plating

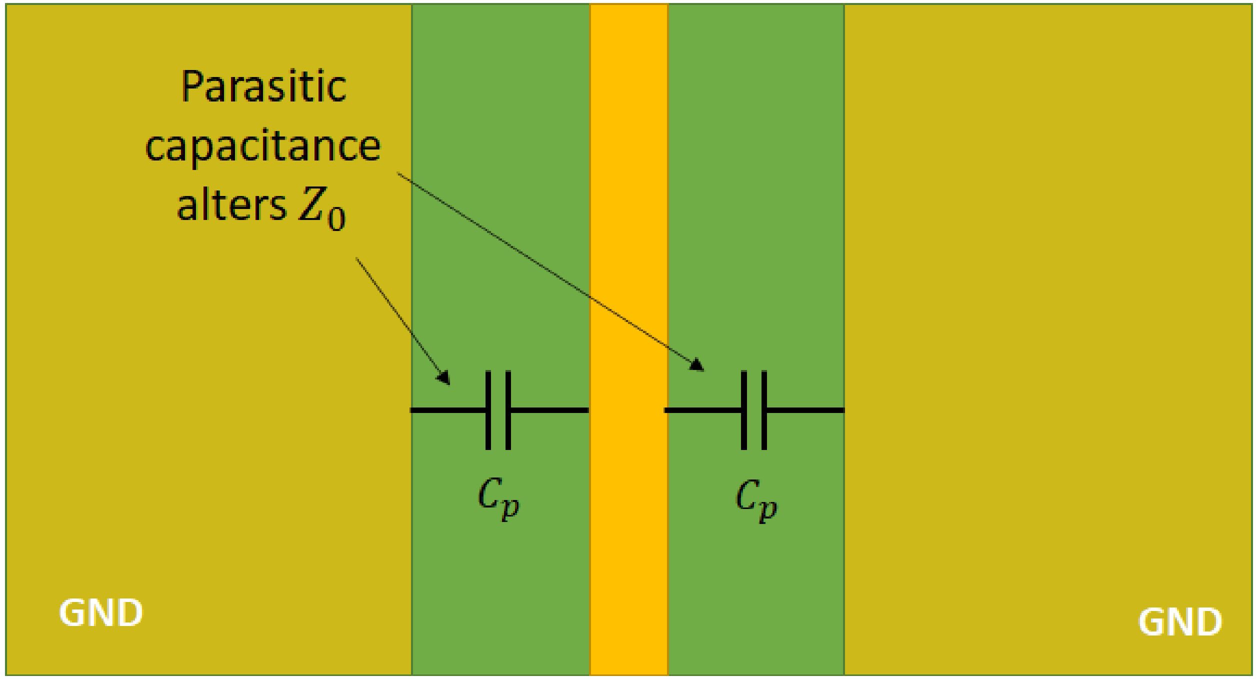




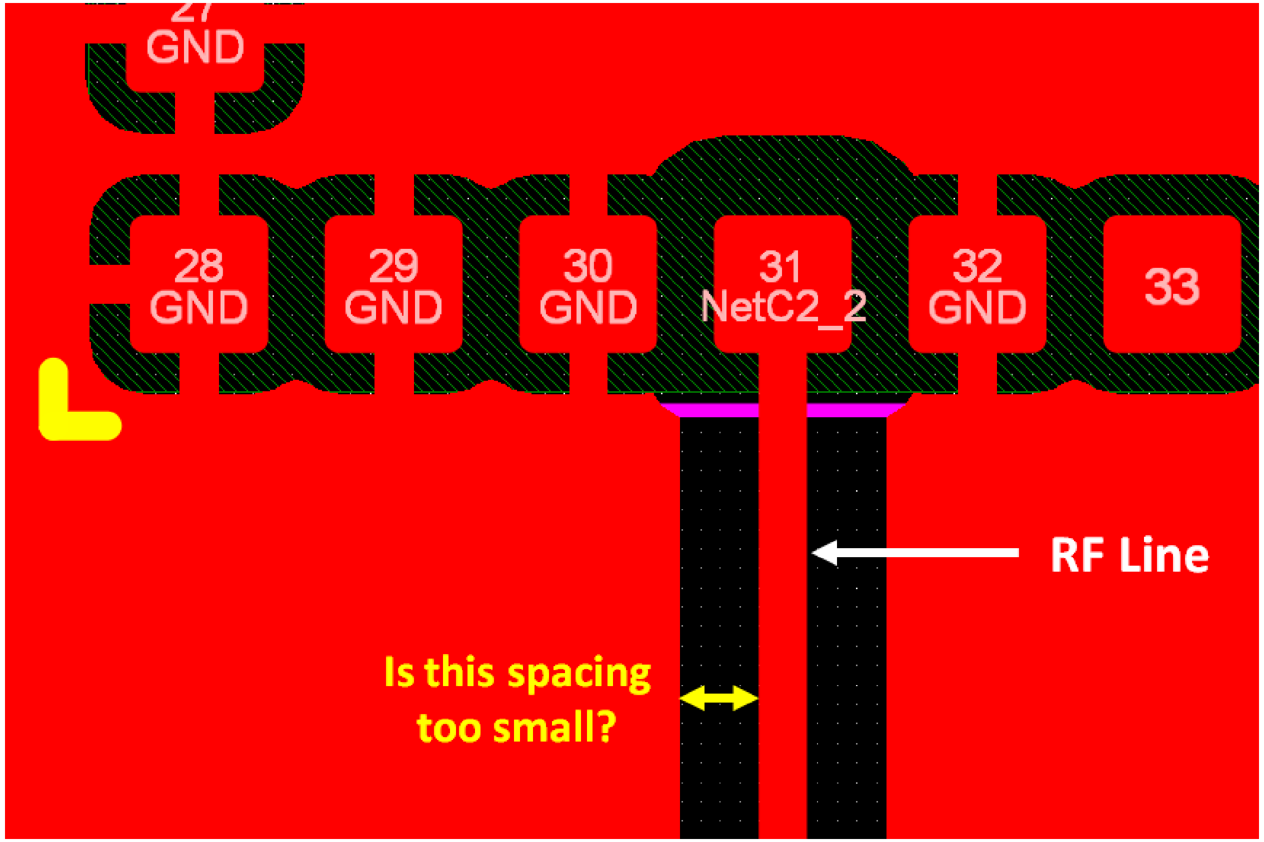
Impedance and Propagation

AltiumLive 2022 CONNECT

- What’s the allowed pour clearance near controlled impedance traces?



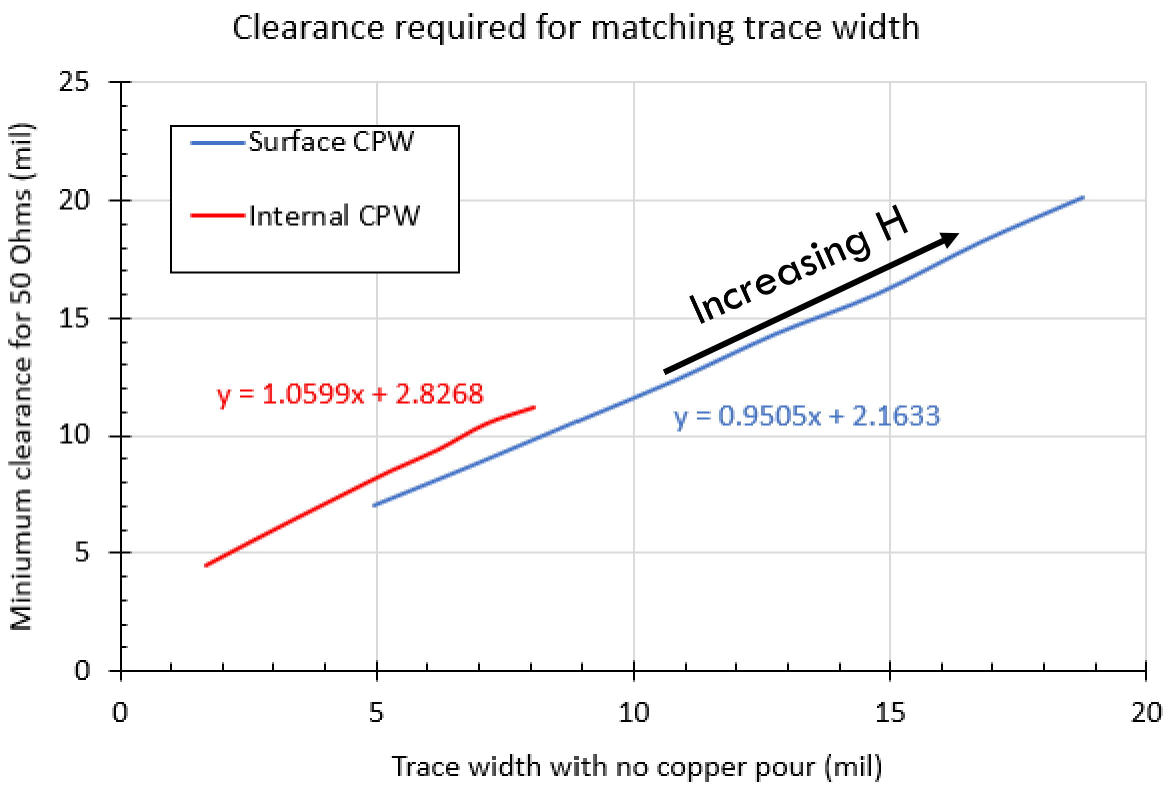
$$Z_0 = \sqrt{\frac{L}{C_{total}}} = \sqrt{\frac{L}{C + 2C_p}}$$

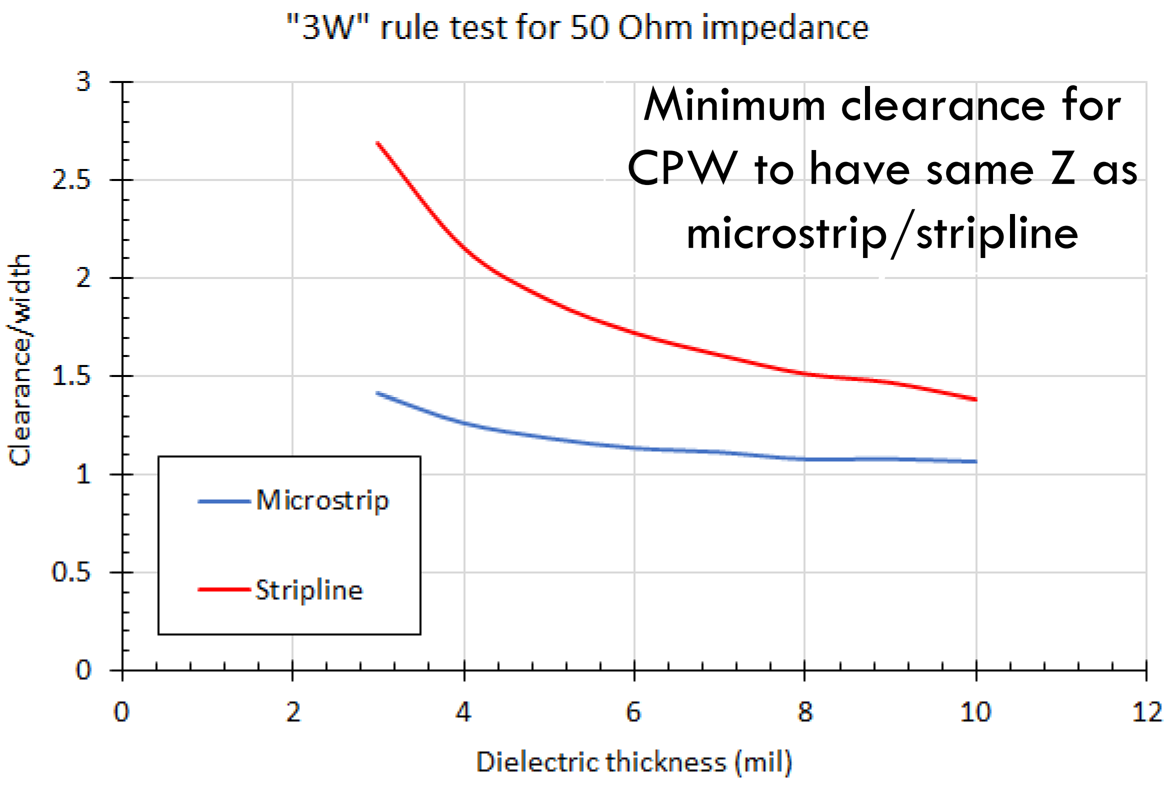


Impedance and Propagation

AltiumLive 2022 CONNECT

- We can easily violate the “3W” clearance rule without affecting impedance

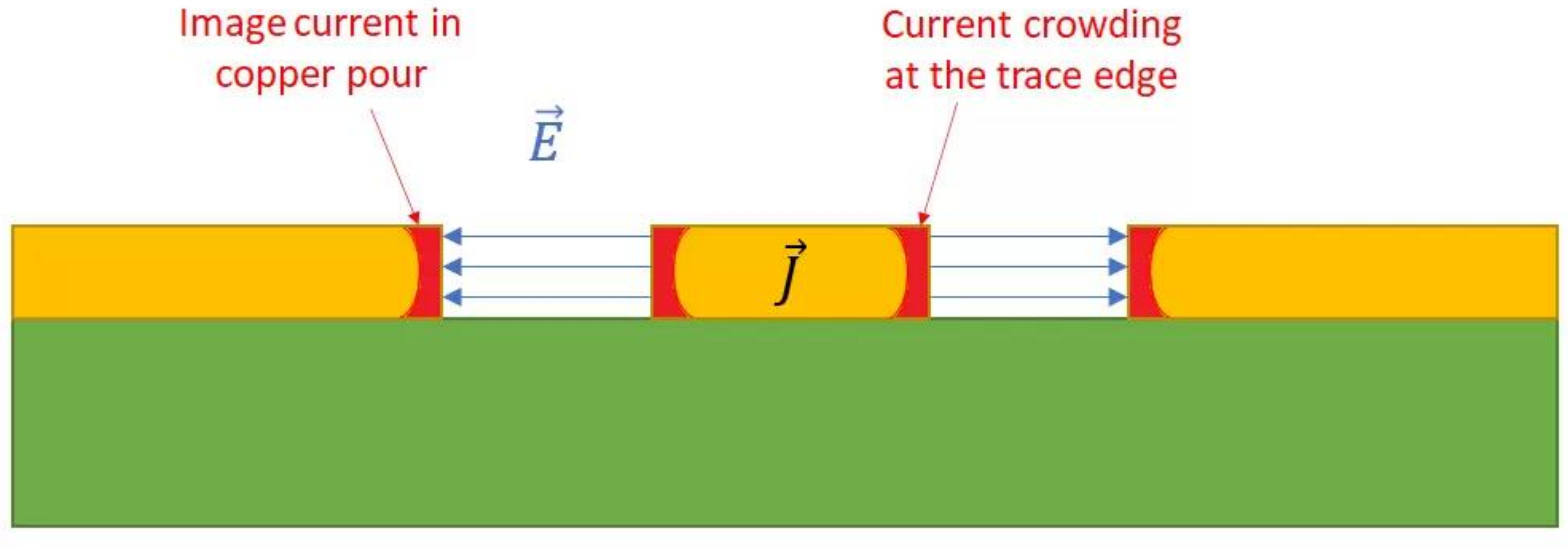




Minimum clearance for CPW to have same Z as microstrip/stripline

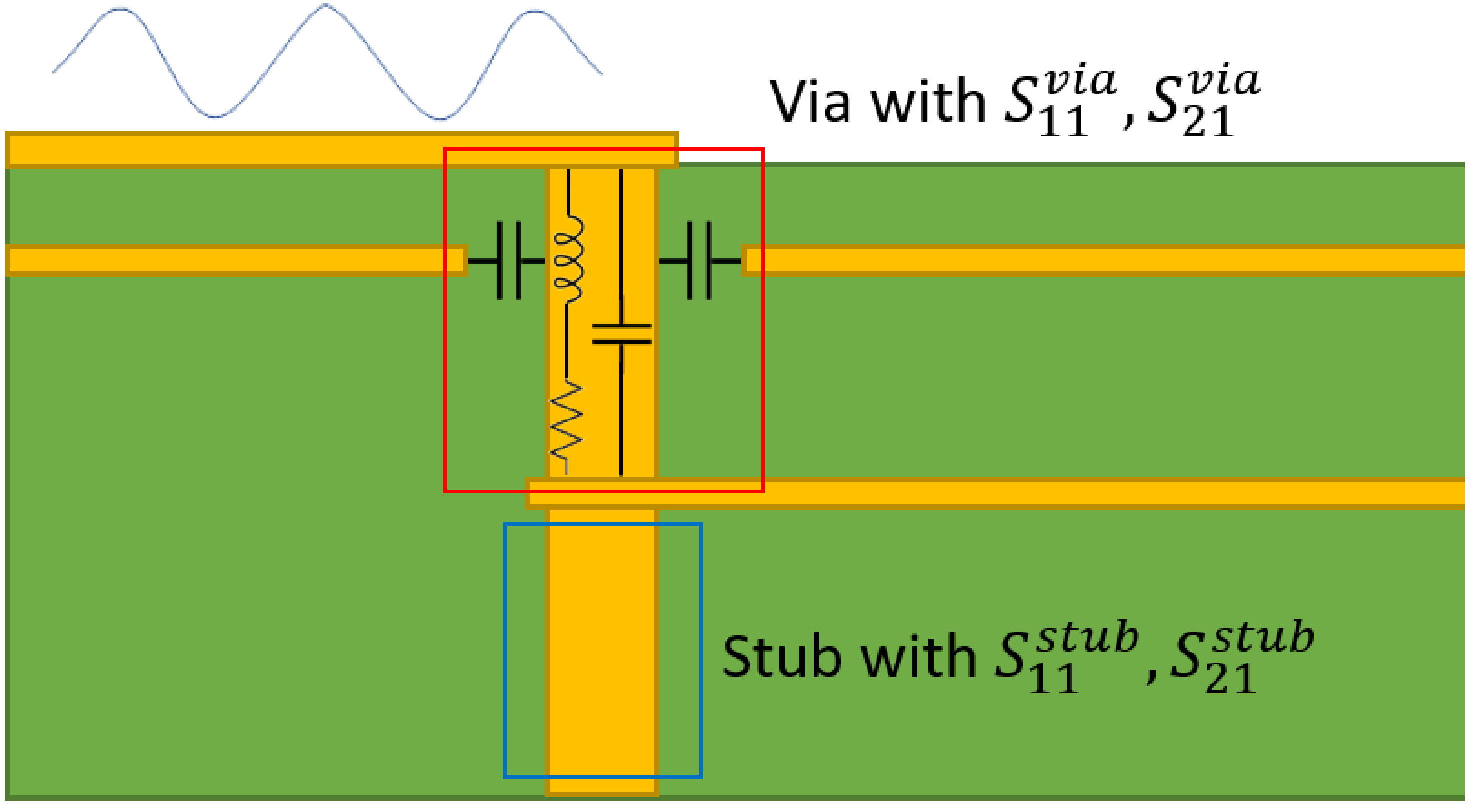
Impedance and Propagation

- Smaller spacing → Field concentration → Greater skin resistance



- *Losses reduced with smoother plating (OSP or immersion Ag)*

Impedance and Propagation

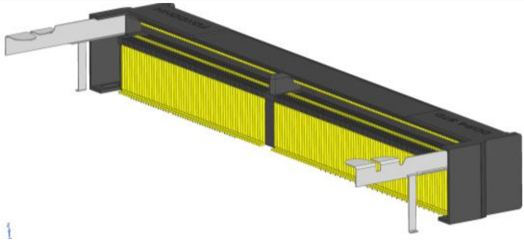


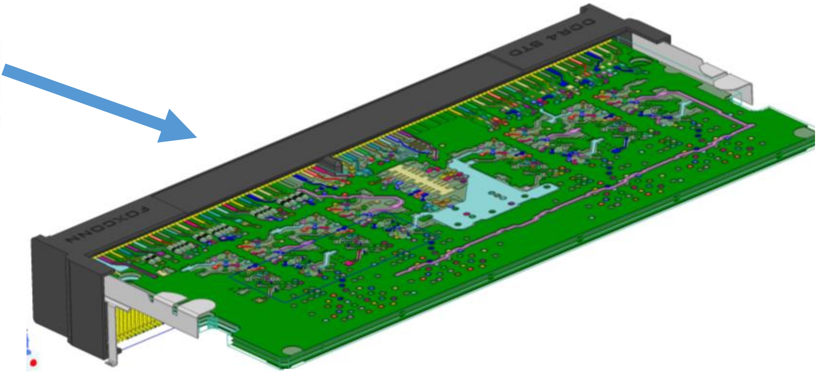
Low f $Z_{via} \approx i\omega L + R_{DC} + \sqrt{\omega}(1+i)K(\omega)R_{skin}$

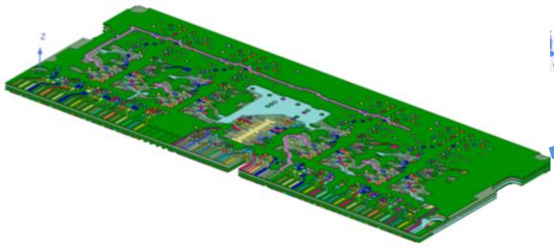
High f: Treat as a resonator (next slide), use input impedance

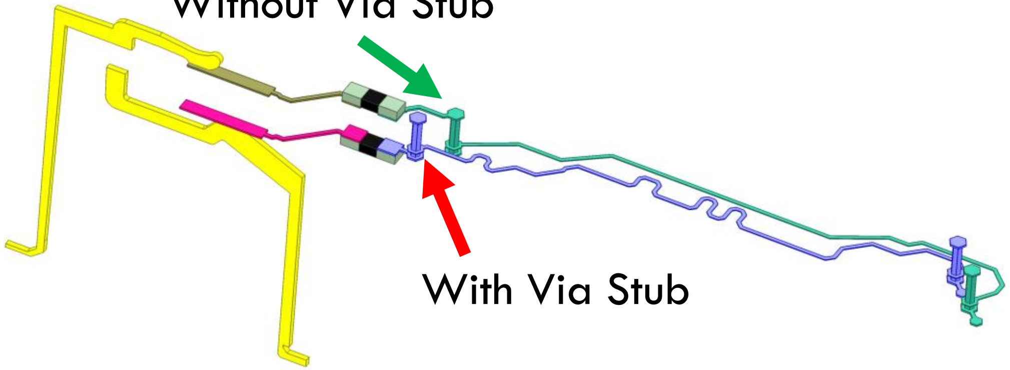
0.1 mm stub length: okay for signals up to roughly 150 GHz (typical FR4 substrate)

Impedance and Propagation



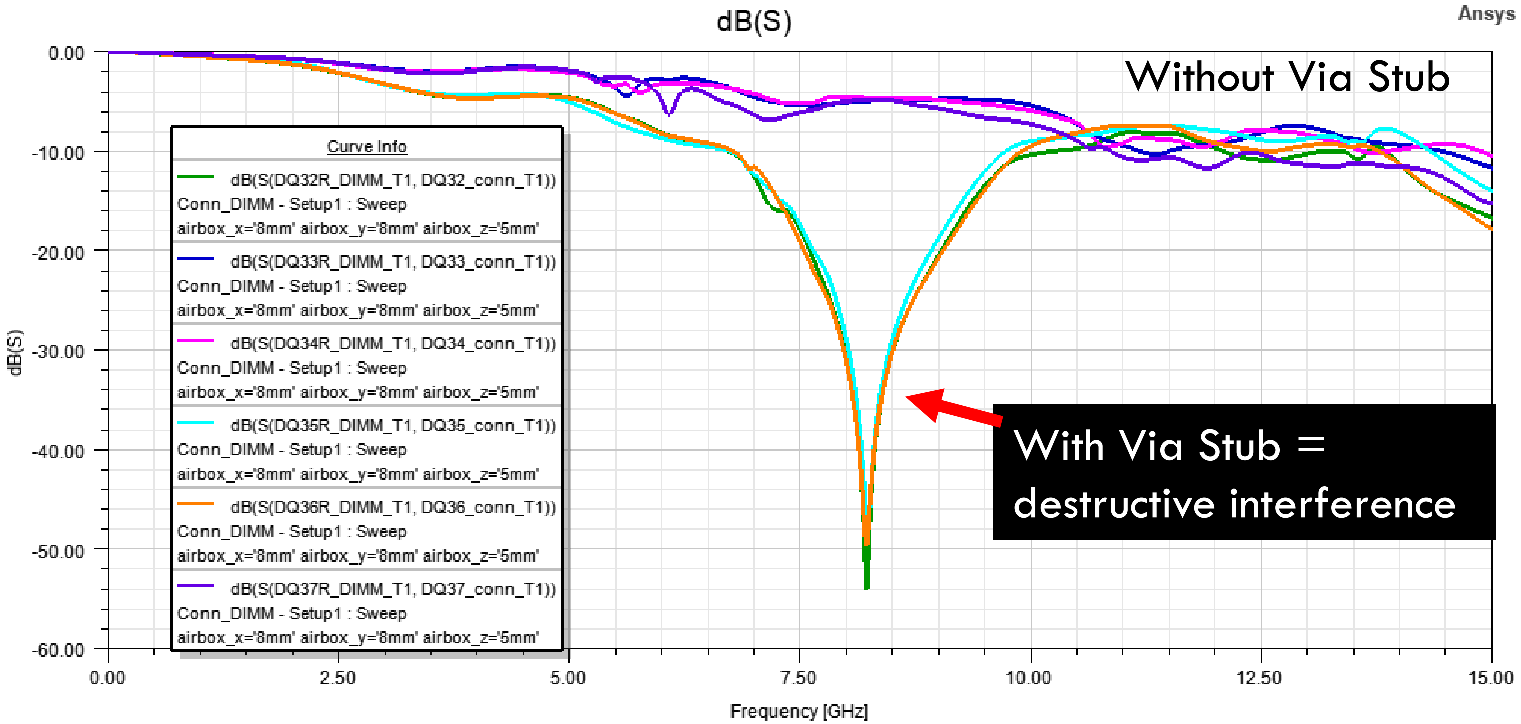






Without Via Stub

With Via Stub

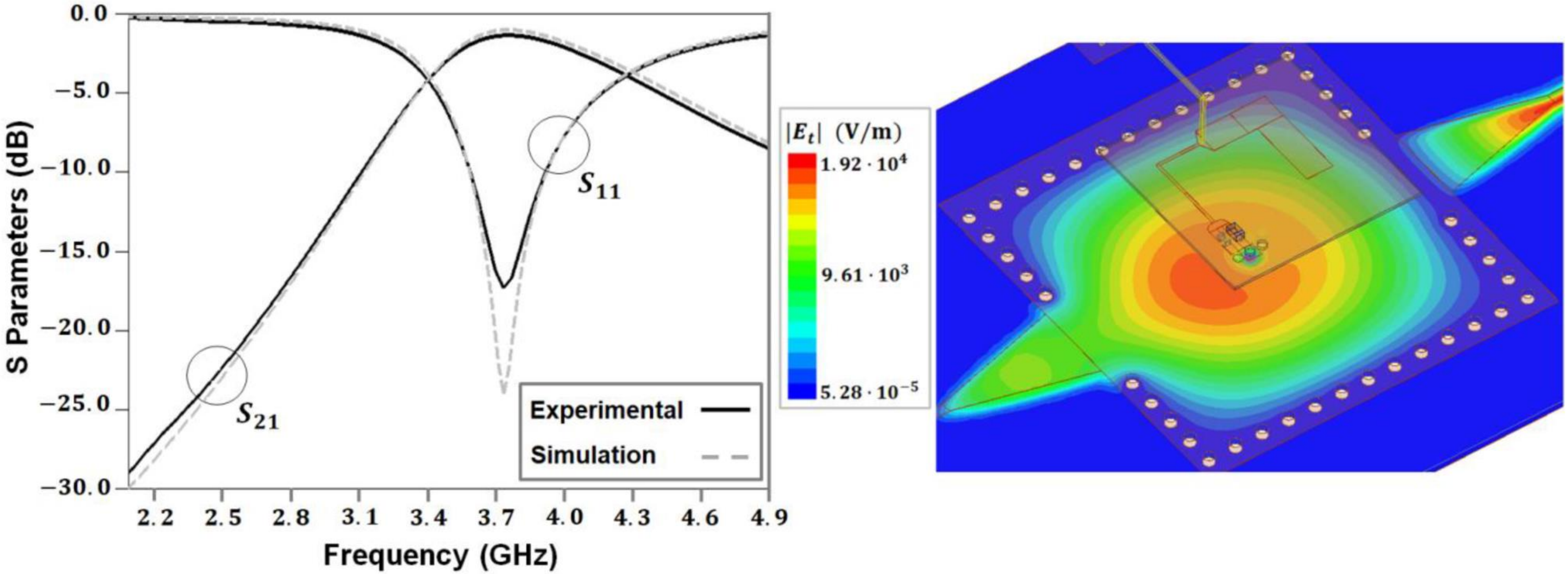


Without Via Stub

With Via Stub = destructive interference

Impedance and Propagation

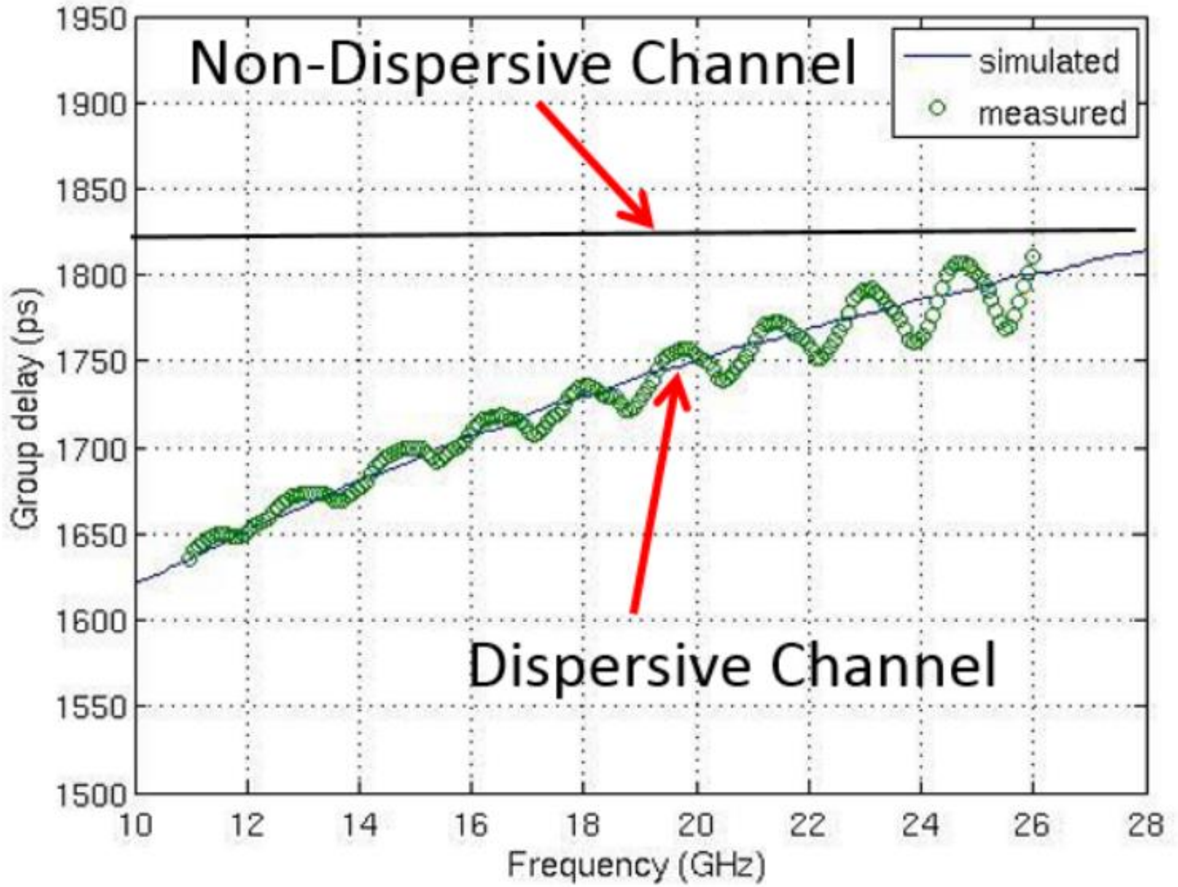
- **Unintentional resonators:** Structure of the PCB, stitching vias, plane pairs
- **Intentional resonators:** Antennas, waveguides, unique printed circuits

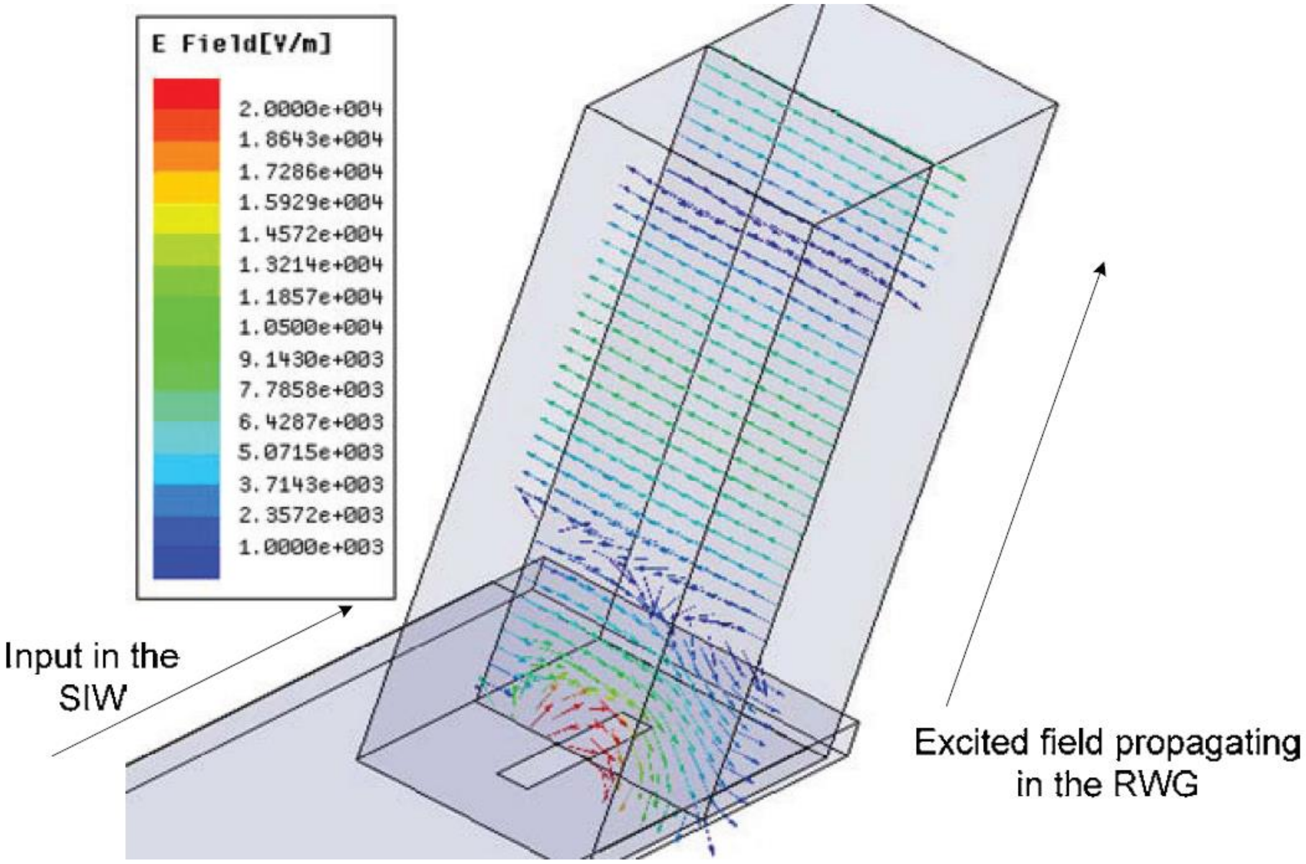


Caleffo, R., and Correra, F. "3.4/4.0 GHz tunable resonant cavity in SIW technology using metal post and PIN diode on a low-cost biasing network for 5G applications." Journal of Microwaves, Optoelectronics and Electromagnetic Applications ***19,*** *pp. 94-105 (2020).*

Impedance and Propagation

- Dispersion and phase response affect coupling

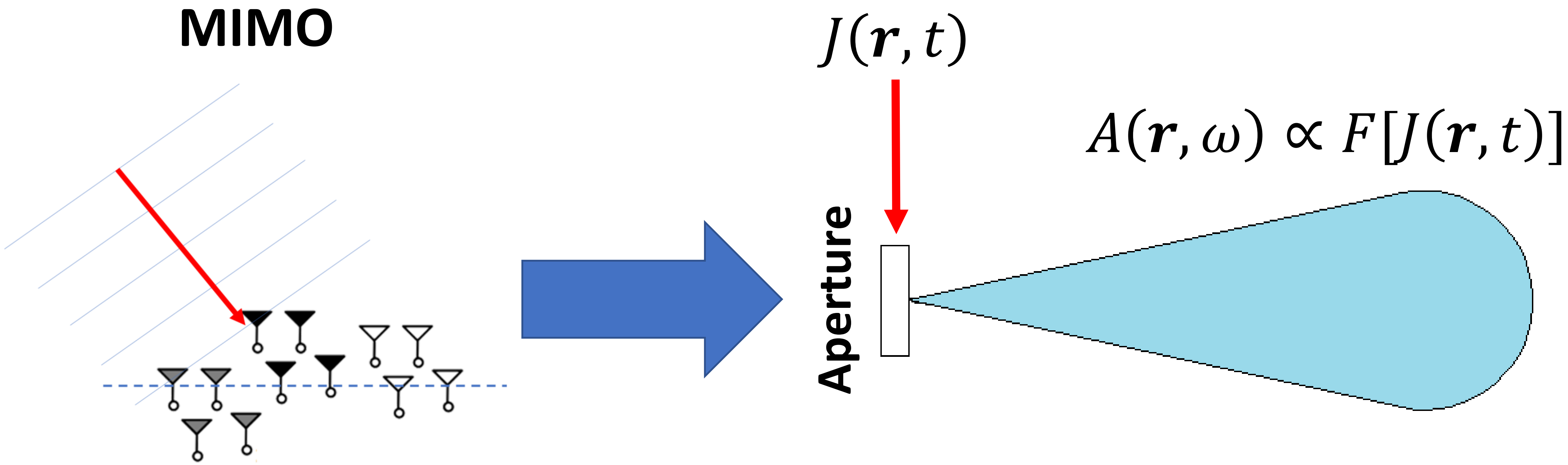




Li, L., et al. "A transition from substrate integrated waveguide (SIW) to rectangular waveguide." In *2009 Asia Pacific Microwave Conference*, pp. 2605-2608. IEEE, 2009.

Impedance and Propagation

- Aperture engineering: MIMO behavior without MIMO antenna array.
- Can we do this on a PCB?



MIMO

$$J(\boldsymbol{r}, t)$$

$$A(\boldsymbol{r}, \omega) \propto F[J(\boldsymbol{r}, t)]$$

Thank You!

Please send me questions on LinkedIn.