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mm Waves vs. Test Sockets

Gert Hohenwarter
GateWave Northern, Inc.

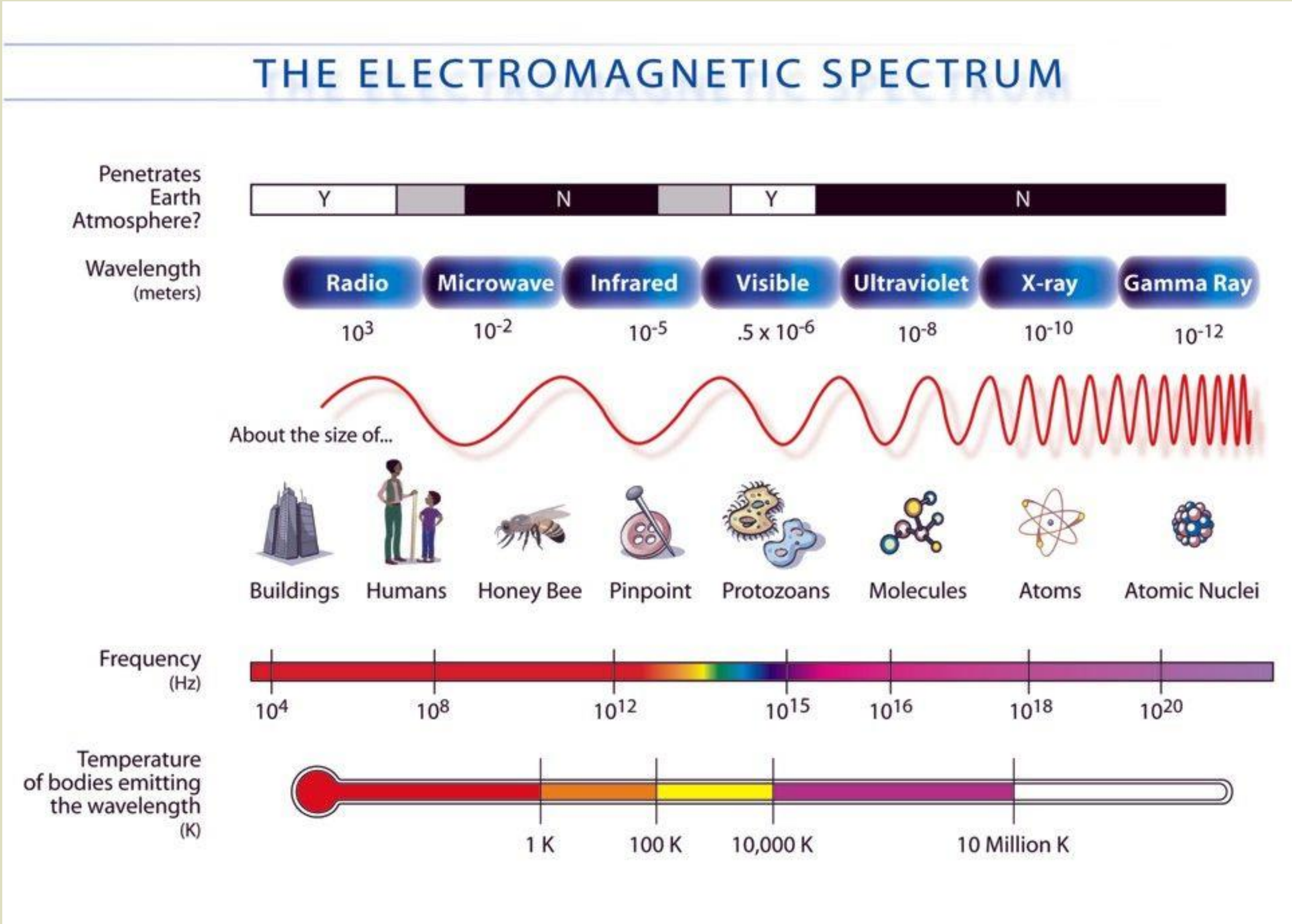
Outline

- Introduction to mm waves
- Material behavior
- Wavelength effects
  - Resonances
  - Transitions
  - Propagation and loss
- Testing

Objective

- A brief look at mm-waves and their unique characteristics is provided first to set the stage
- Material properties for high frequency operation are briefly illuminated
- Once a basic understanding is developed, socket design pitfalls will be addressed
- Why is there a “vs.” in the title ?

Wavelength vs. Frequency Visualized



Source: Luzzilice Luzia Planet Fragile Torus on Pinterest

mm Waves

- What are “mm Waves”?
  - electromagnetic signals with 10 to 1 mm wavelength
  - 30 GHz - 300 GHz
  - Also called EHF (extremely high frequency) or mmW / MMW

- Where are they used ?
  - 5G and short range communications, IoT
  - automotive radar, security scanners
  - Prior to 5G/automotive :
    - Science / radio astronomy / medicine
    - military fire-control radar

mm Waves
Strengths

- Large data rates, video
- Instant response (IoT)
- Good resolution (radar)
- Immunity from interference (short range, directivity)
- Spectrum reuse (short range)
- Small antennas, antenna arrays

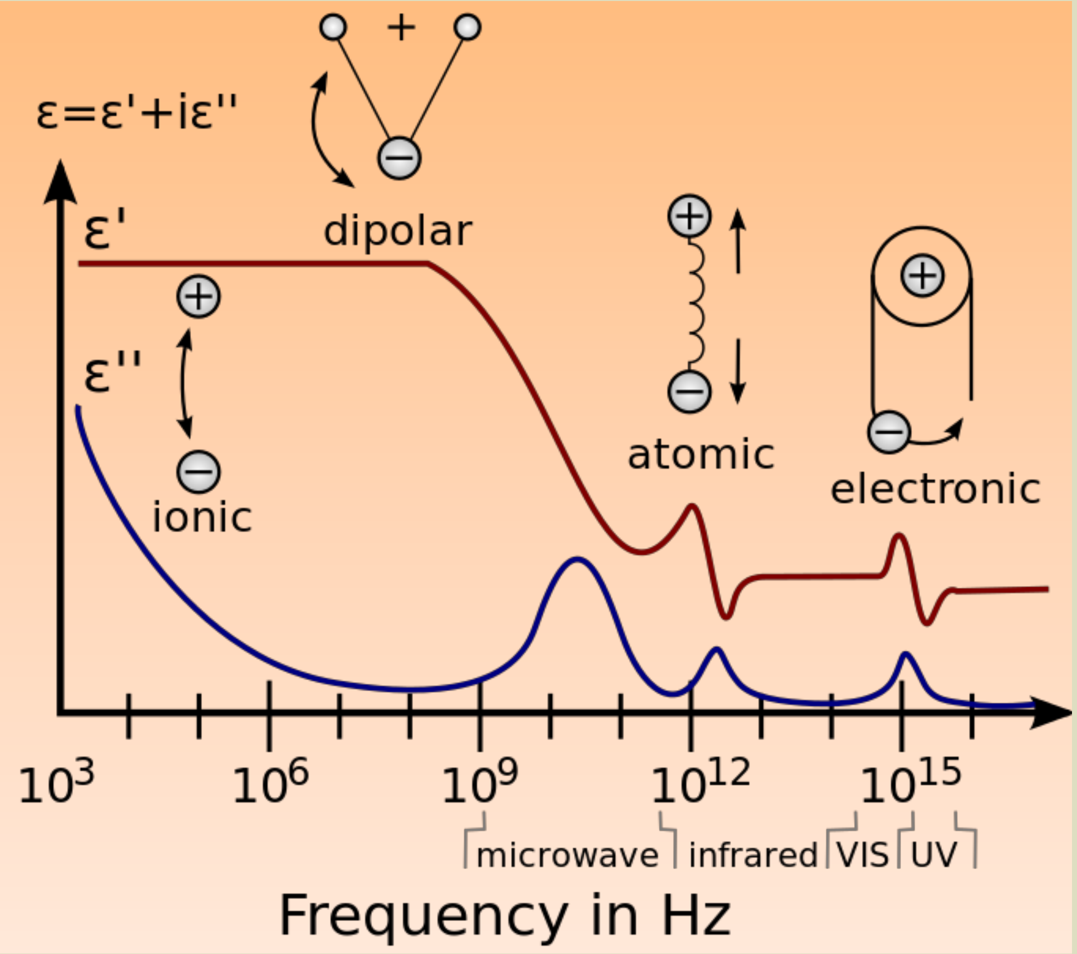
mm Waves
Weaknesses

- Short range (gases, rain drops, humidity)
- No propagation around obstacles
- Loss in traditional circuitry e.g. PCBs, interconnects
- Cost

mm Waves – what changes ?

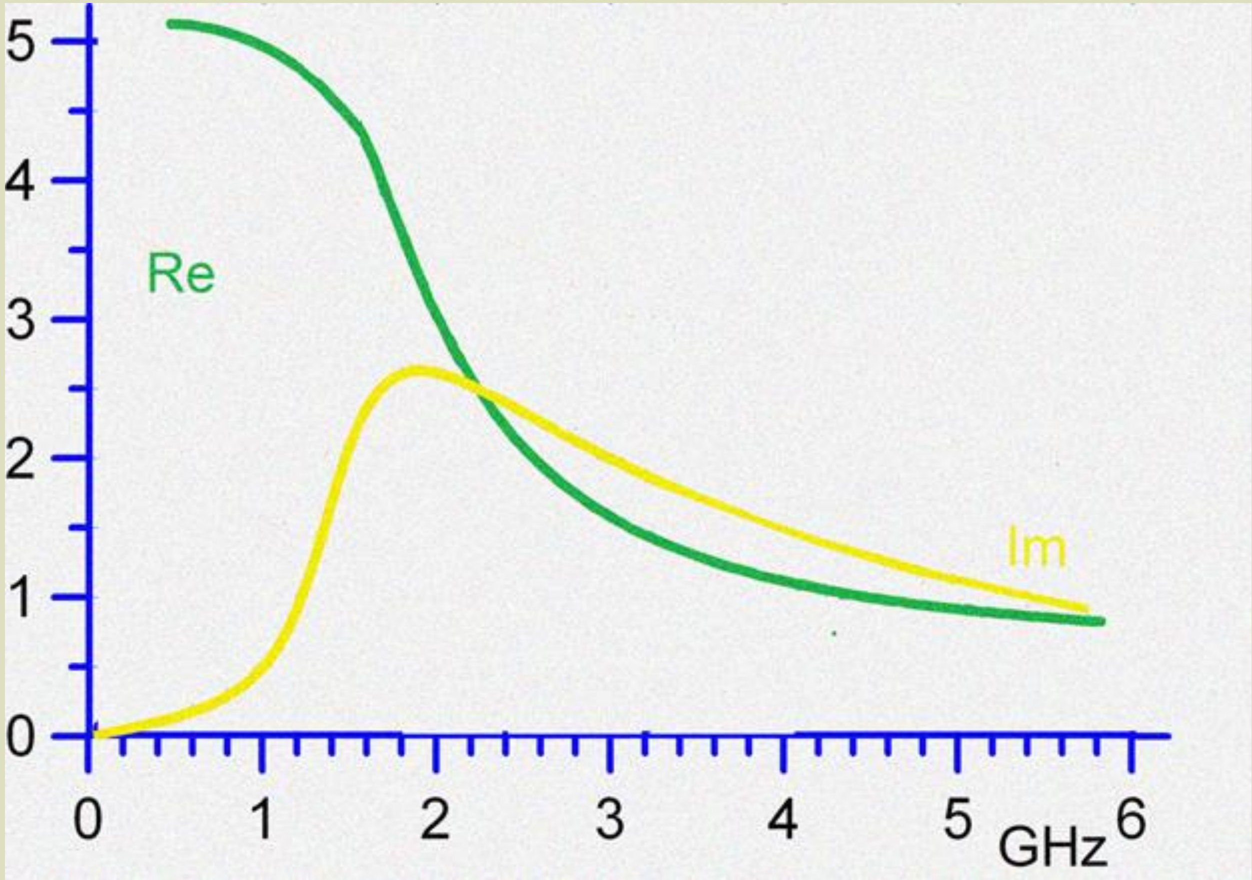
- Lateral dimensions in sockets on the order of significant fractions of wavelength
- Skin depth, roughness, 'detours' into contact, multiple spheres
- Radiation into test environment
- Instrumentation accuracy, *cost*
- Simulation accuracy (component detail, simulation setup, mesh size)
- Material properties often unknown

Permittivity (dielectric constant) and Frequency



Source: Wikimedia File: Dielectric responses.svg

Permeability (response to magnetization) and Frequency



Observation:

Permeability approaches '1' as frequency increases since heavy dipoles cannot respond fast enough to stimulus.

Hence there is no impact to be expected on millimeter wave frequency operation.

Wavelength vs. Frequency

- $\lambda = c / f$ $(c = 3*10^8$ m/s$)$

  (in free space ~air)

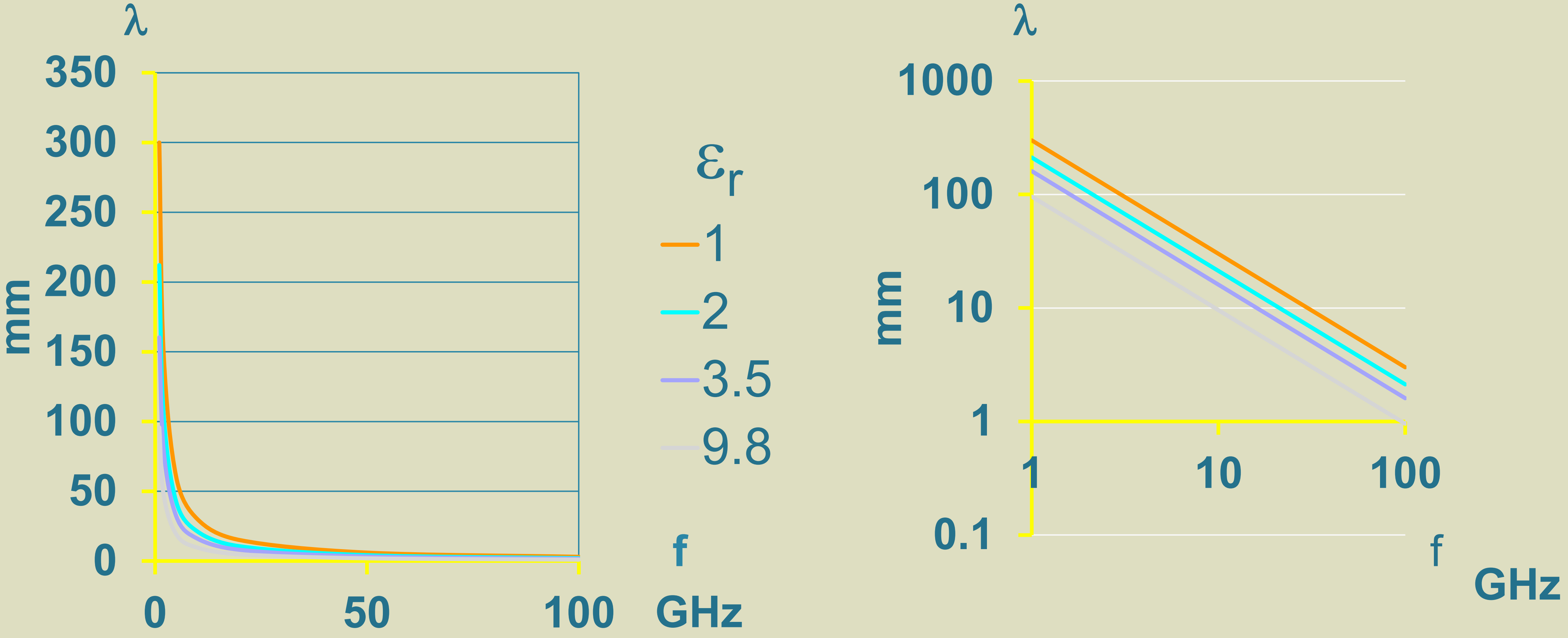
- $c = 1 / \sqrt{(\mu * \varepsilon)}$

  (in matter)

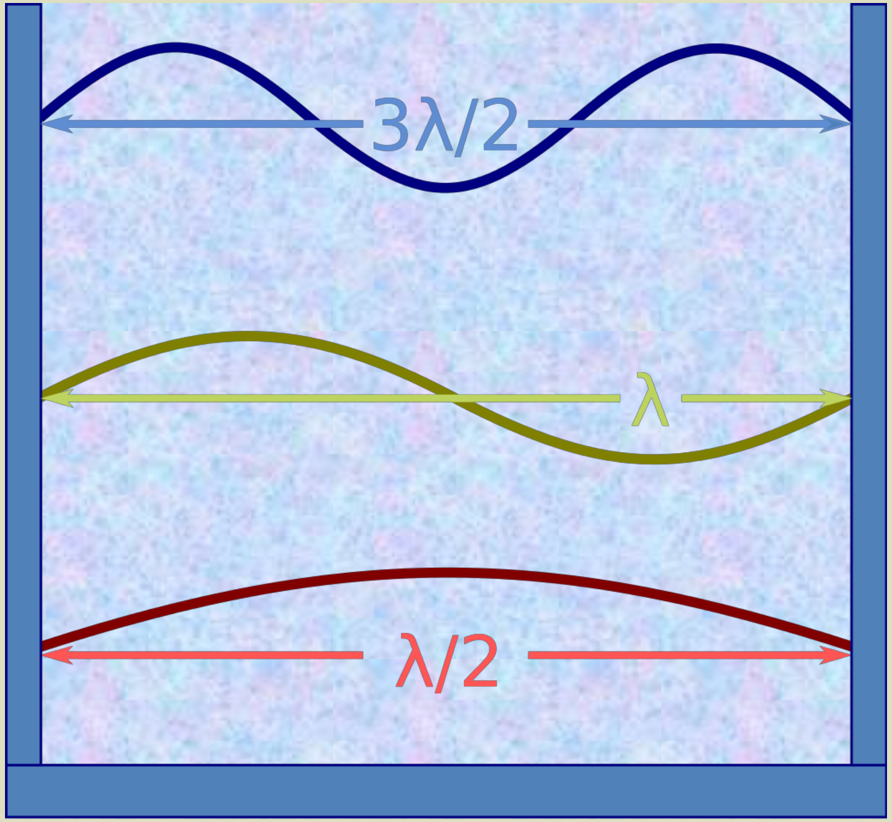
  ε = *permittivity*

  μ = *permeability*

Wavelength vs. Frequency vs. Dielectric Constant



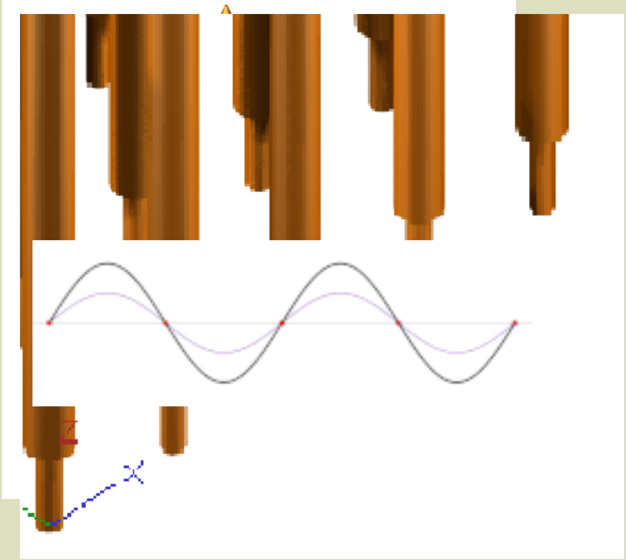
Waves in a Box

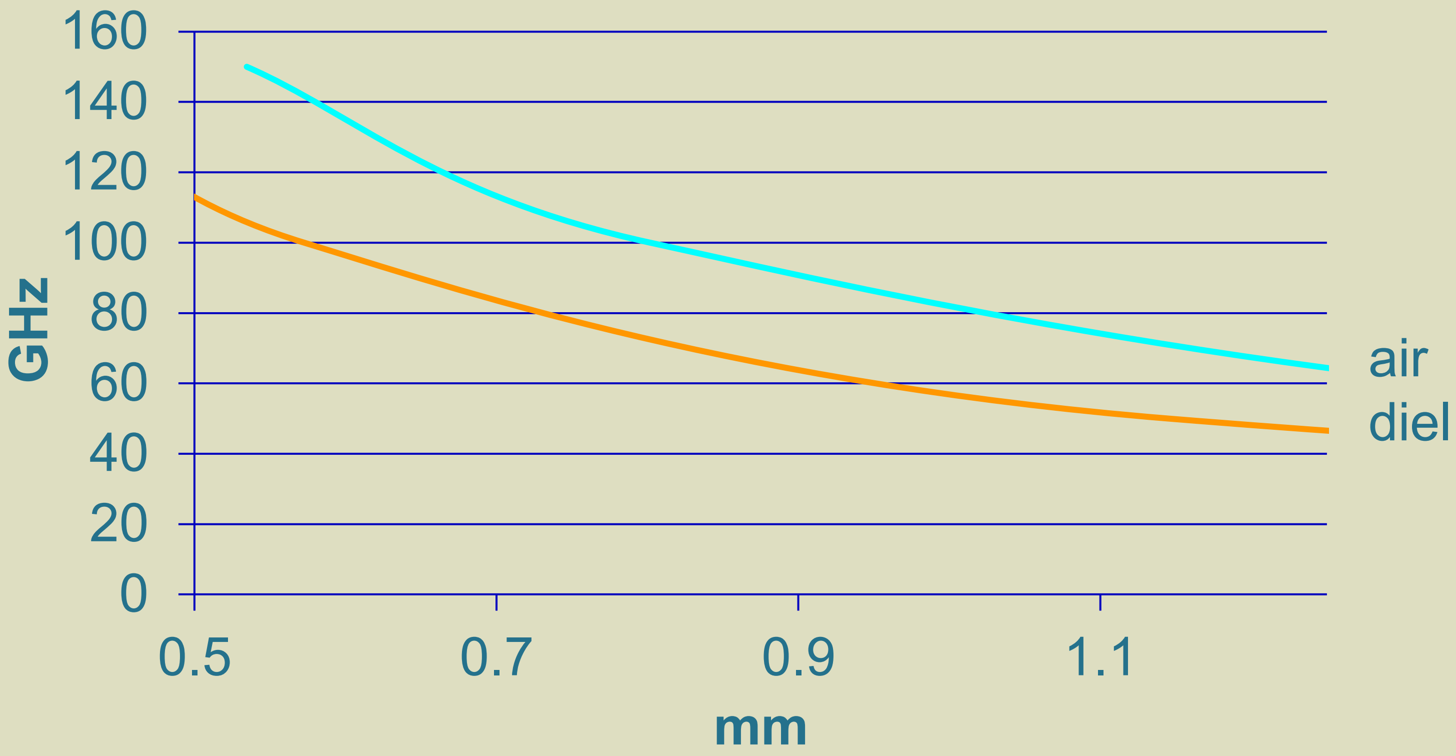


Source: https://commons.wikimedia.org/w/index.php?curid=7115416
Badseed working on a raster by Brews_ohare - Own work

Wavelength vs. Frequency Visualized

mm waves – mm pitch

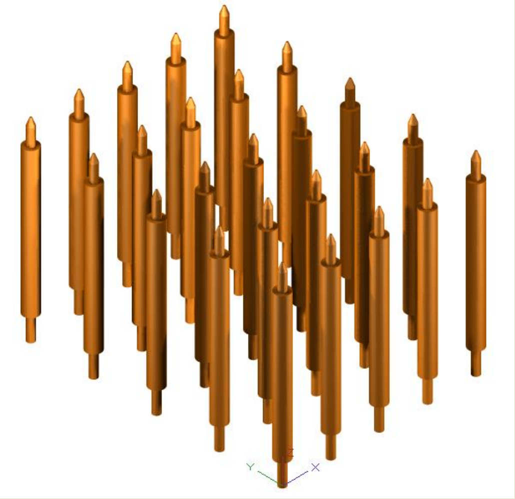


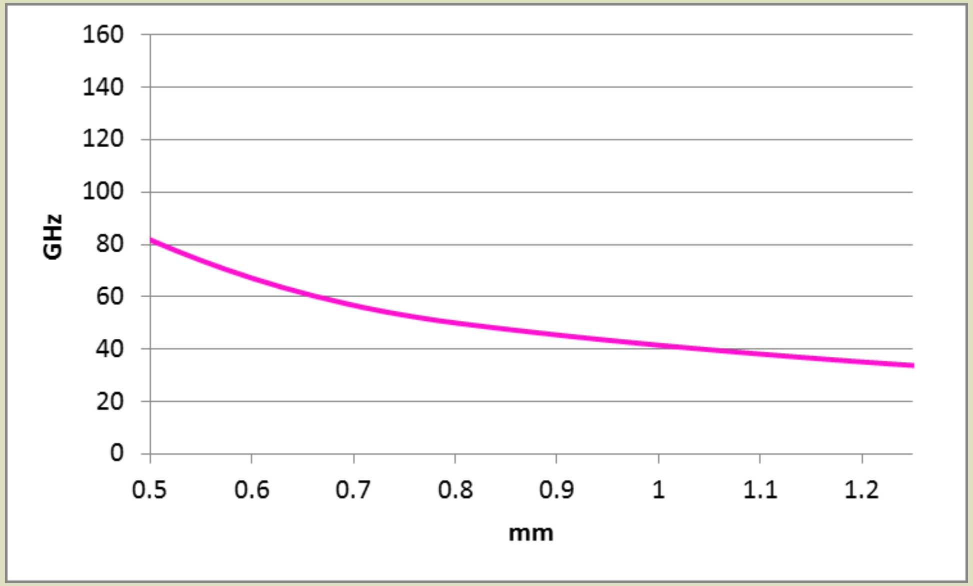


Resonances in the transverse direction (so-called modes) occur at elevated frequencies

Wavelength vs. Frequency Visualized

Length vs. wavelength





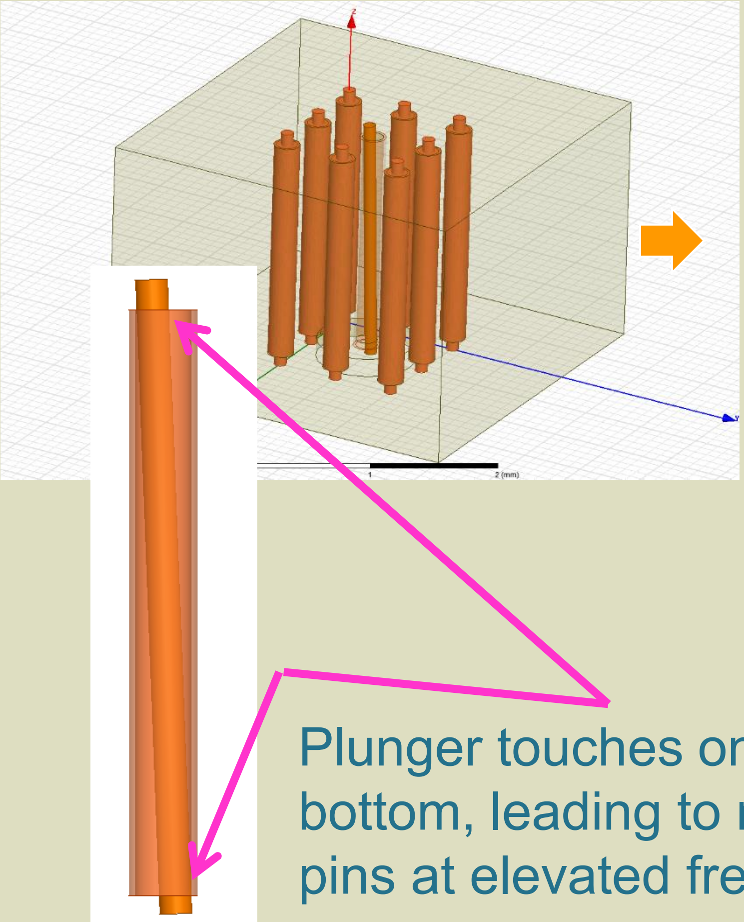
Resonances in the longitudinal direction (so-called modes) occur at elevated frequencies

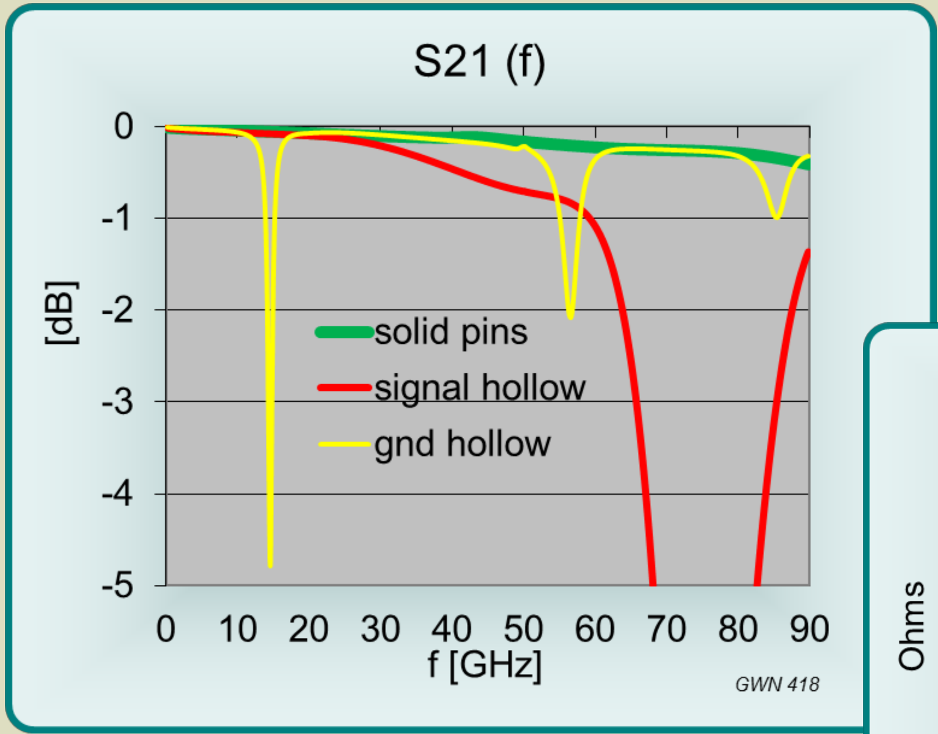
So what are the consequences of using short wavelengths in a test socket environment ?

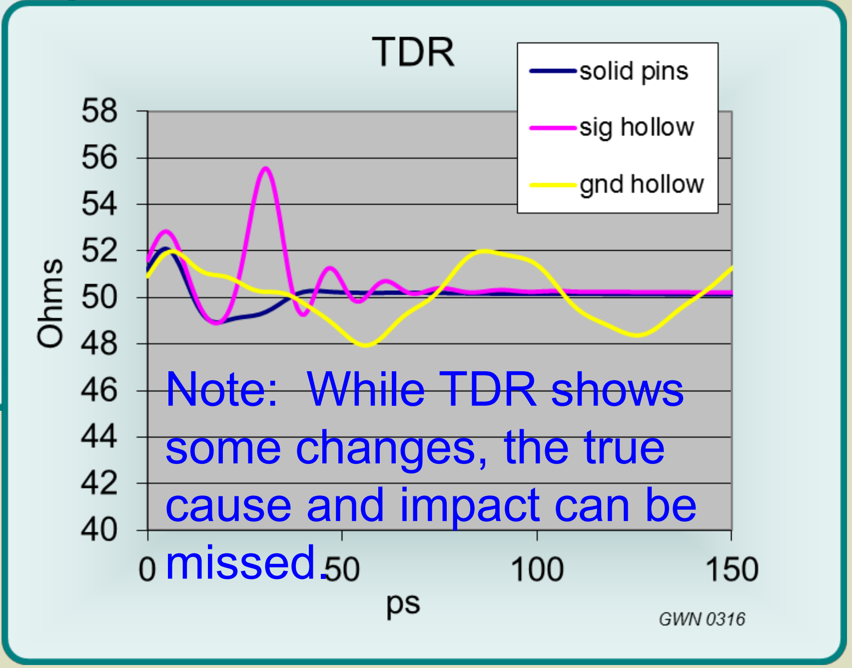
Resonances !

- Smooth transitions needed
- More loss

Internal Pin Resonance Effects

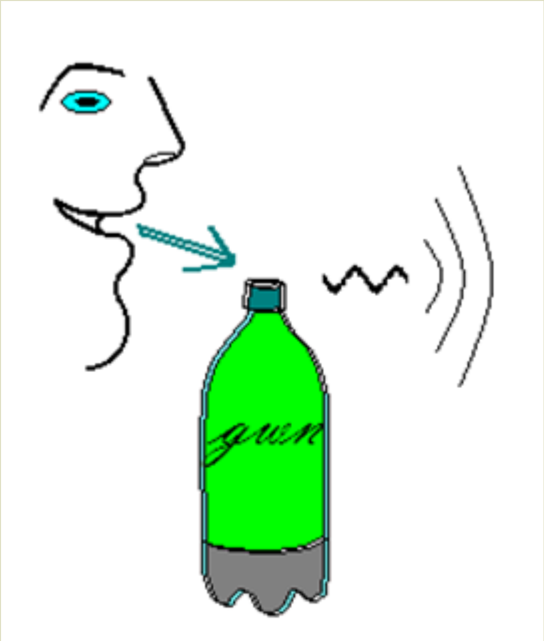


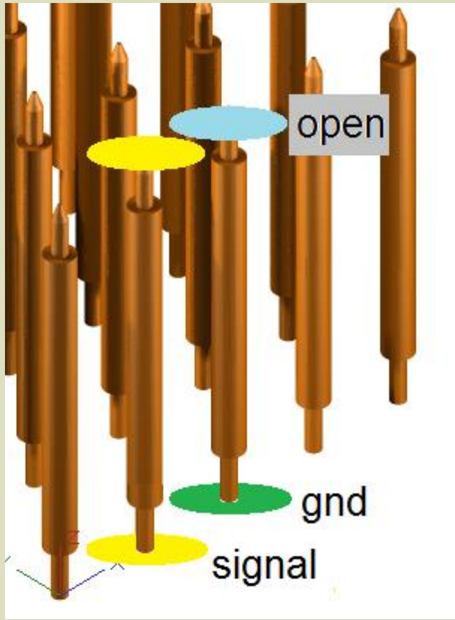


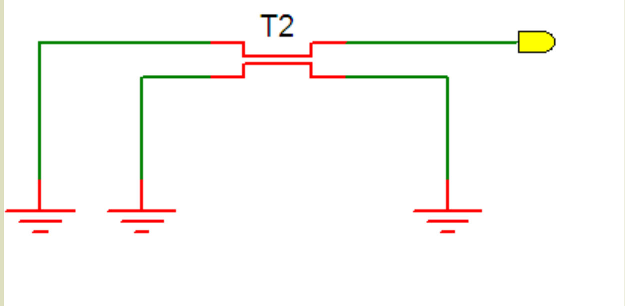


Plunger touches only at top and bottom, leading to resonances inside pins at elevated frequencies.

Adjacent Pin Resonance Effects





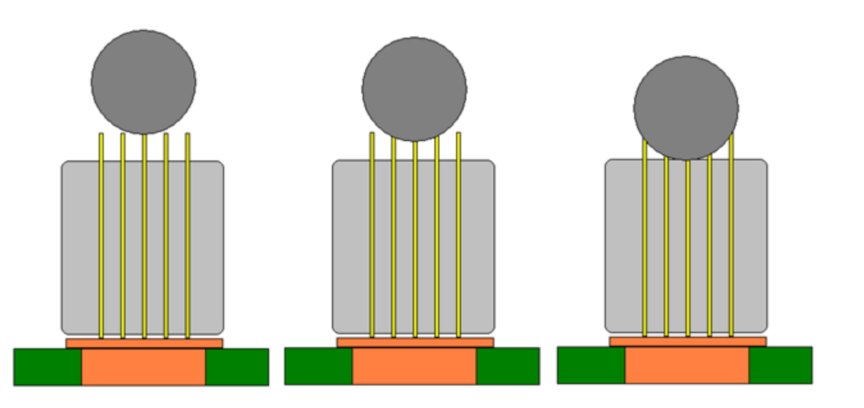


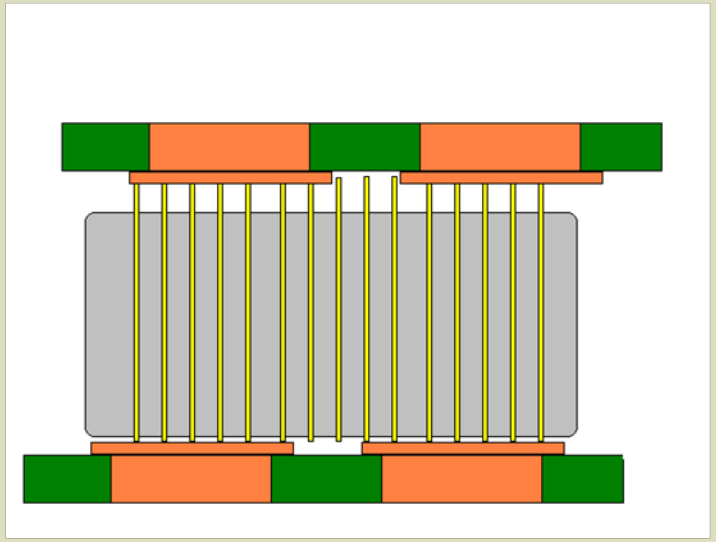
$$f_{res} = \lambda / 4$$

100 GHz ~ 2mm/4 ~ 0.5mm in polyimide

Resonances in ungrounded or partially grounded pins can occur at elevated frequencies

Inadvertent Adjacent Pin Resonances

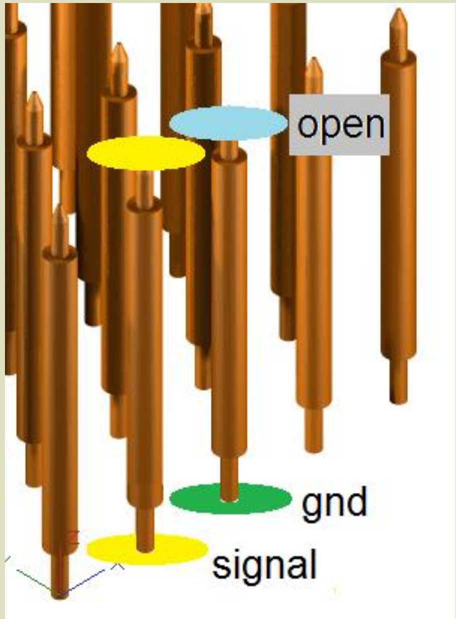


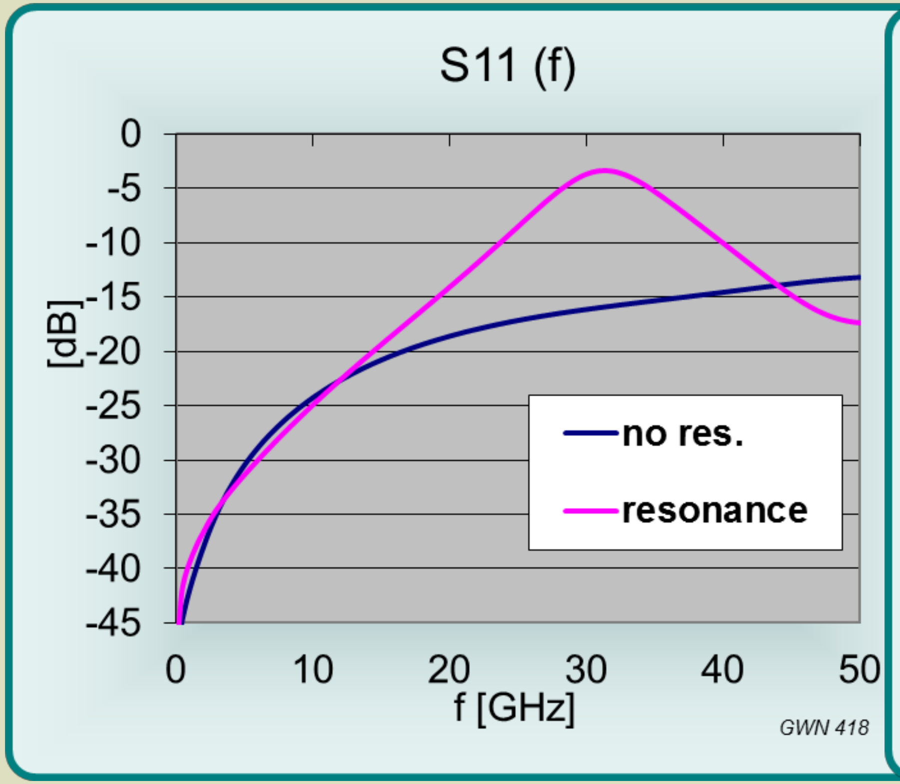


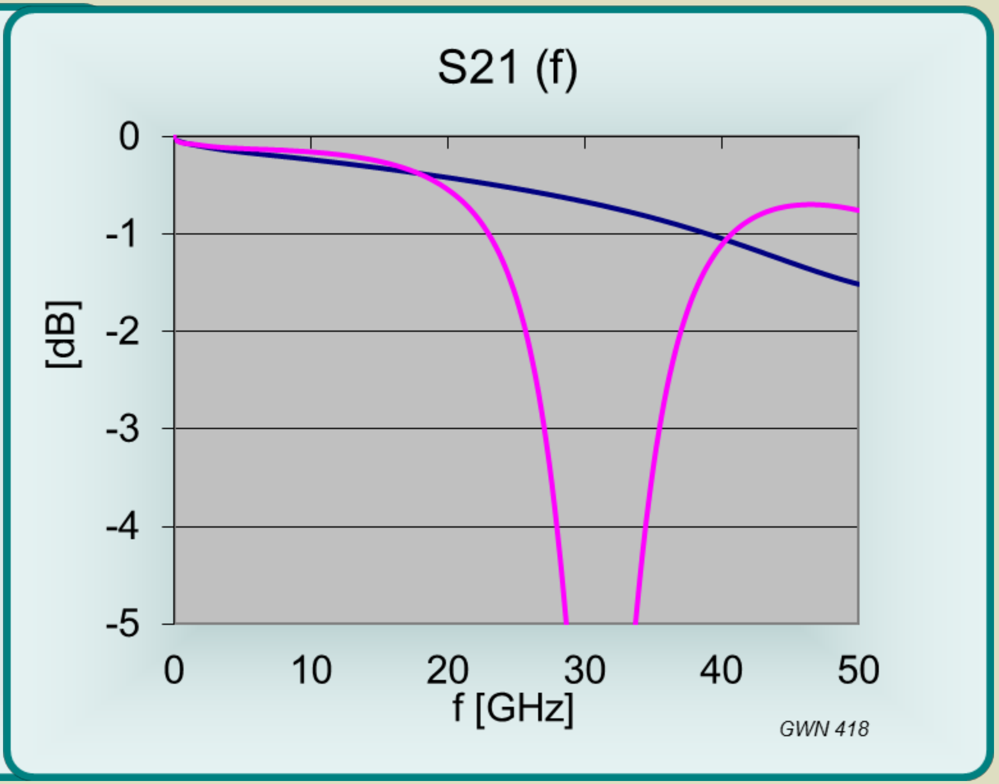
If not properly configured parallel conductors can contribute to resonances

Insertion loss measured for 3 different displacements

Adjacent Pin Resonance Effects

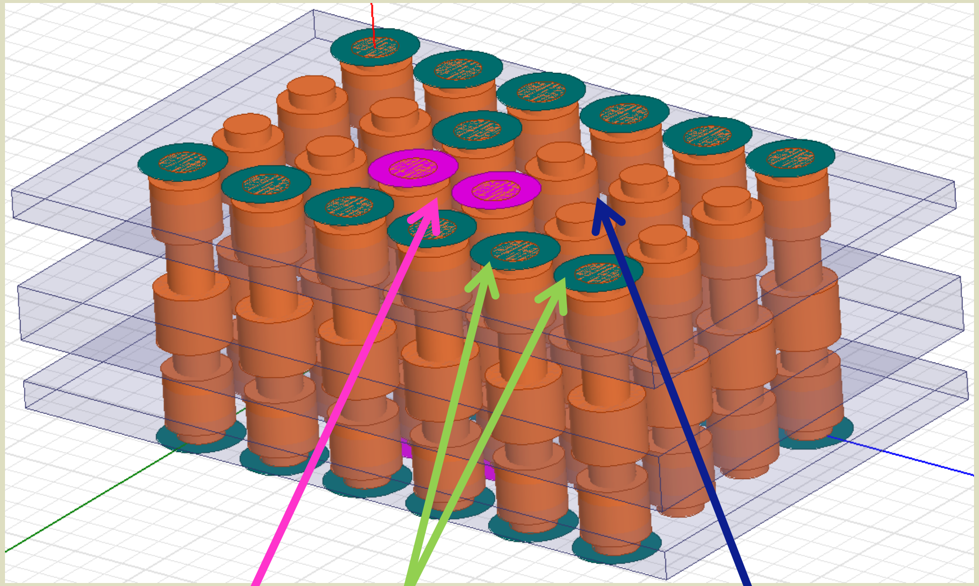


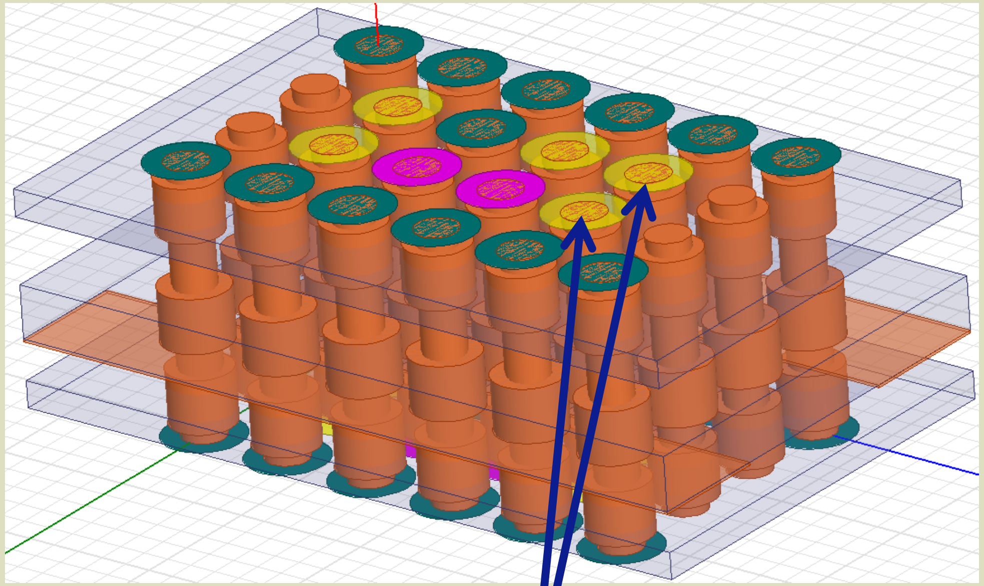




Resonances in ungrounded or partially grounded pins can occur at elevated frequencies

External Pin Resonance Effects





Ground (all green)

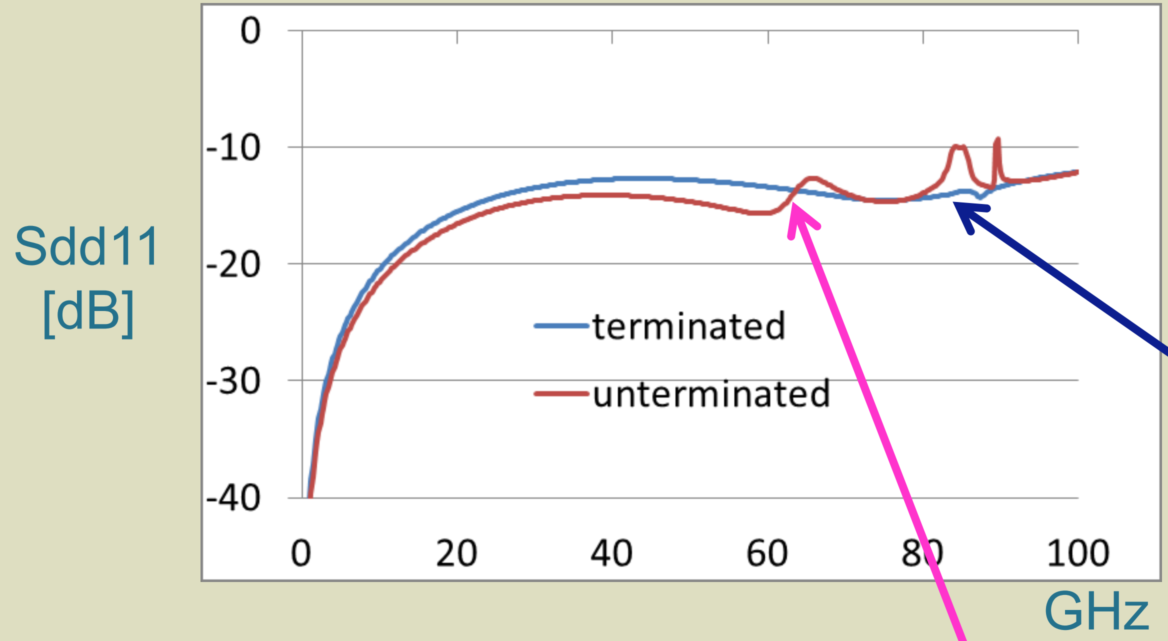
Differential signals

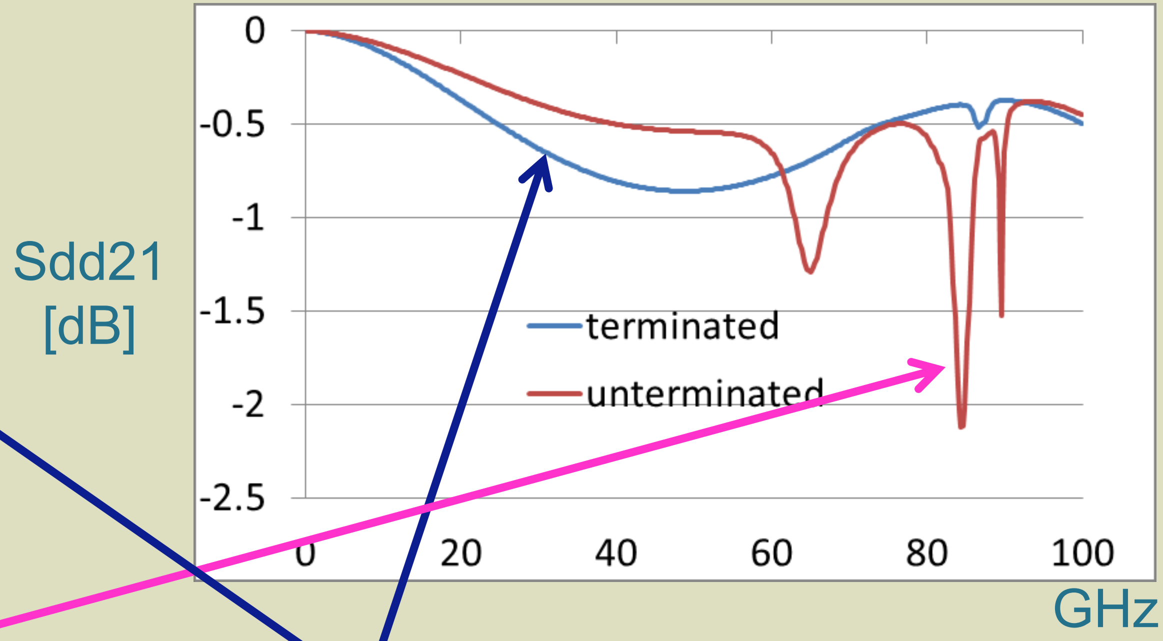
Design has 'floating' or otherwise not matched impedance pins near signals

Design has controlled impedance pins near signals (all yellow)

Thickness = 1mm
Pitch =0.35mm

External Pin Resonance Effects



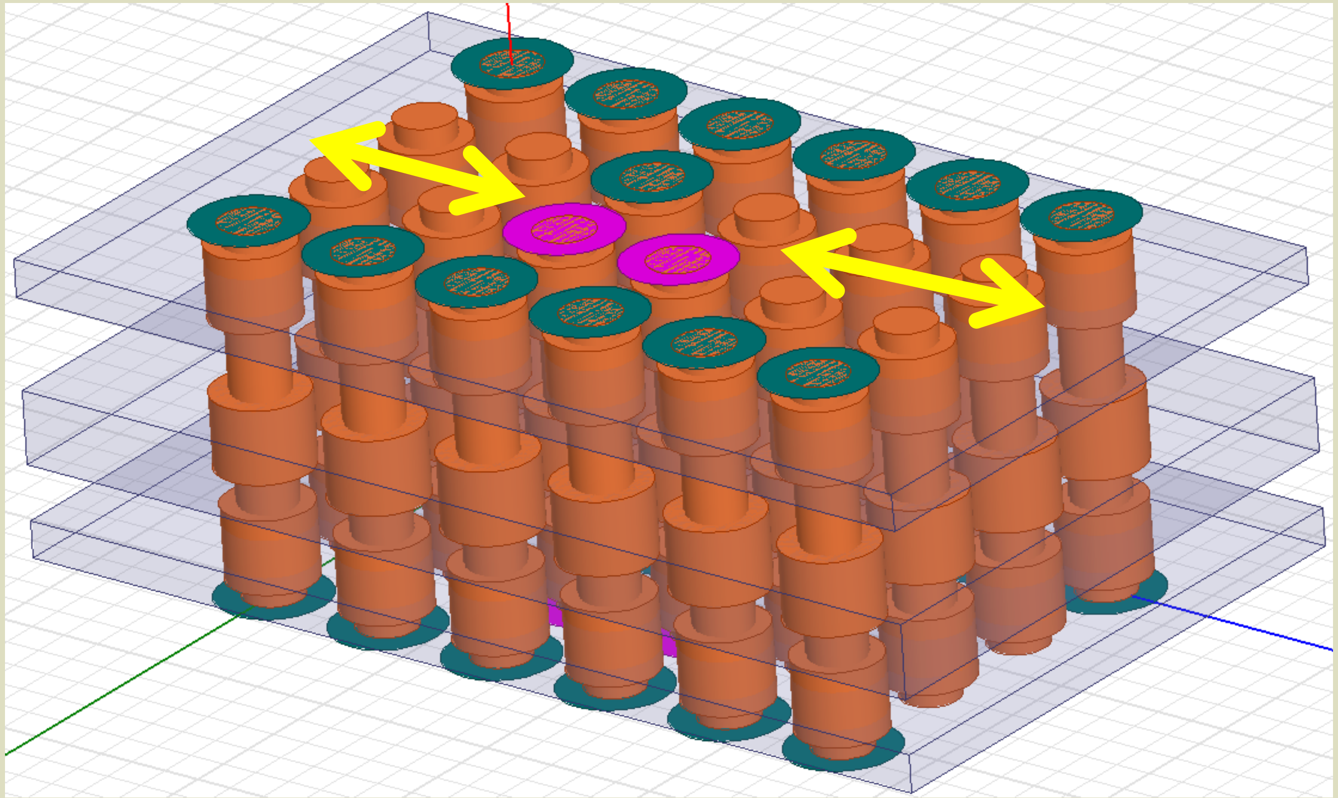


Design has 'floating' or otherwise connected pins near signals

Design has controlled impedance pins near signals (all yellow)

In general: Resonances appear when wavelength drops below twice pin length, but length here is only 1mm !!

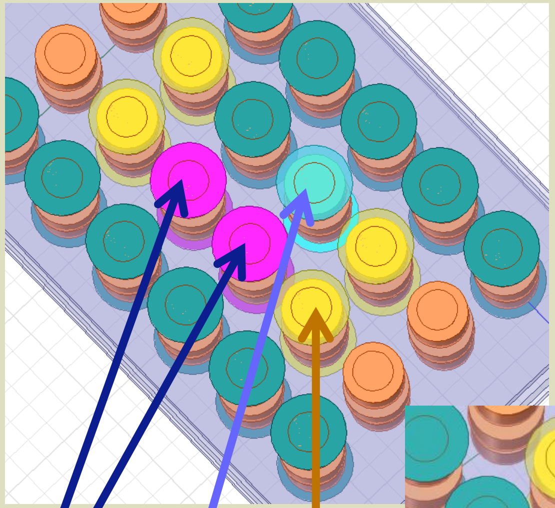
External Pin Resonance Effects

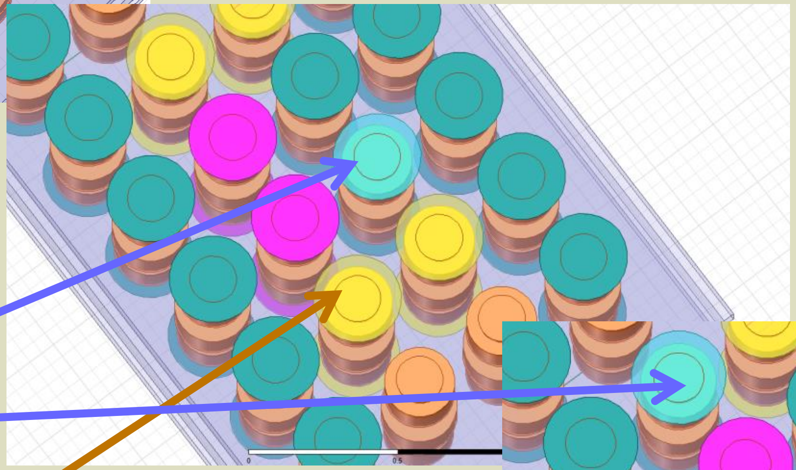


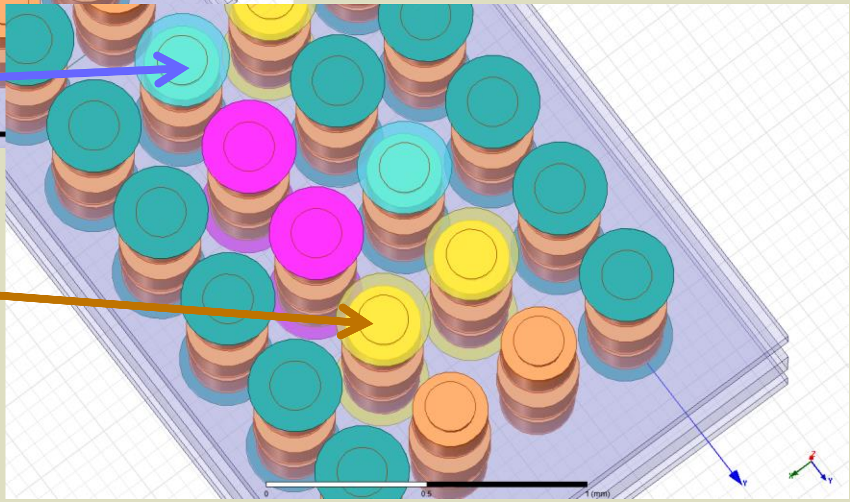
Resonances in this case occur orthogonal to arrangement as indicated and depend on pin configuration and socket boundaries

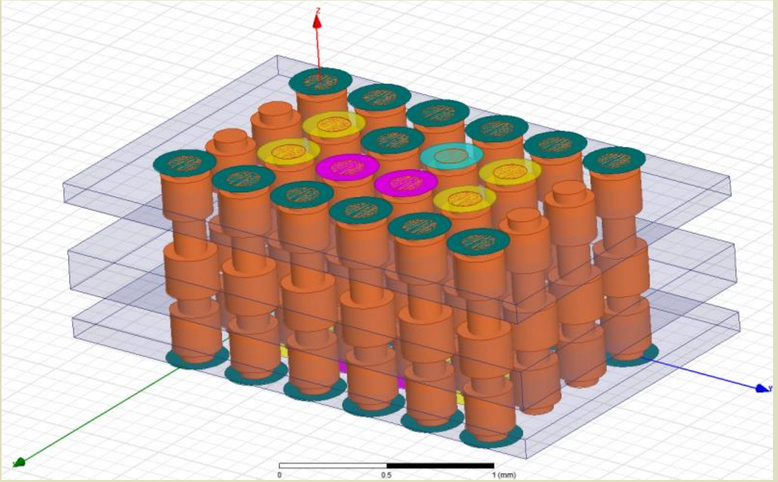
Partially terminated pins

Thickness = 1mm
Pitch =0.35mm







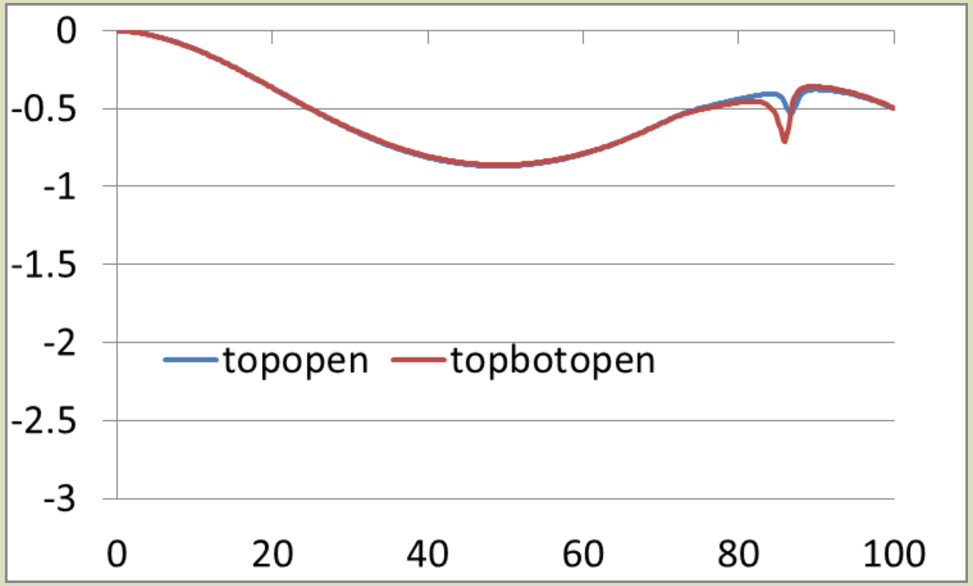


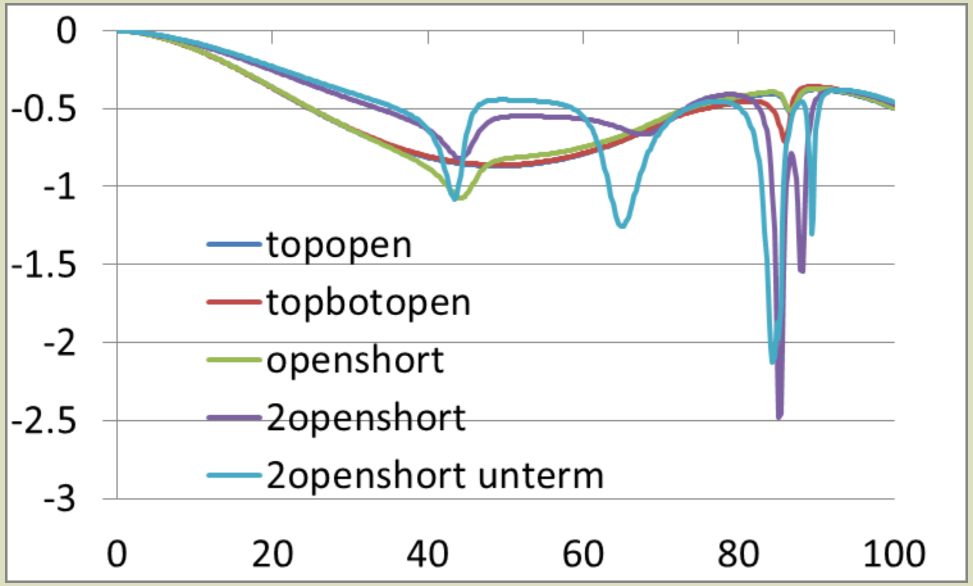
Diff signals (pink)

Open contact (blue)

Terminated contacts (yellow)

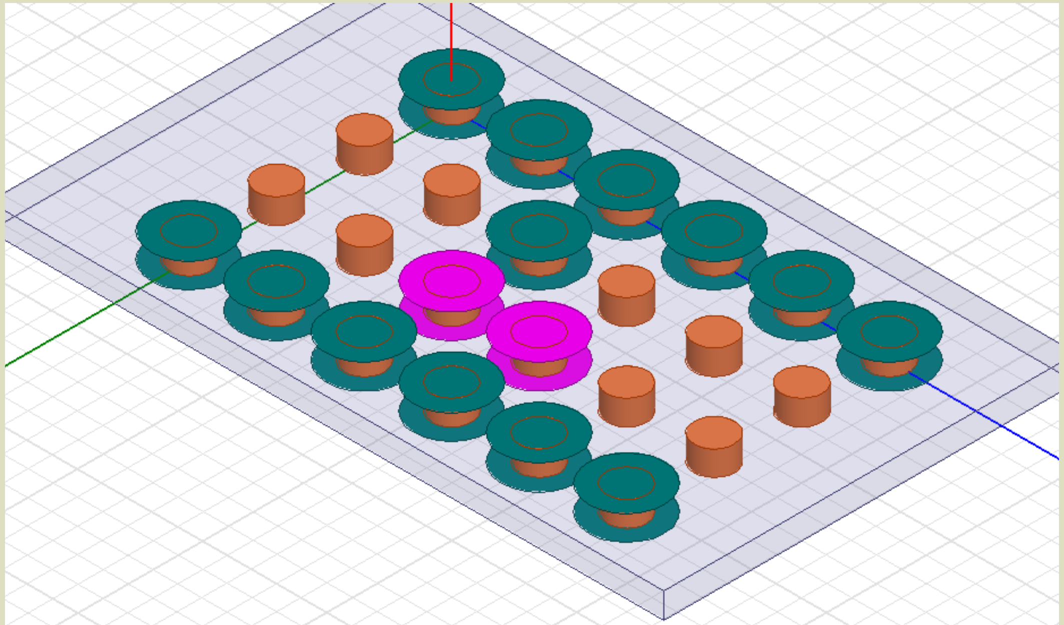
Partially terminated pins





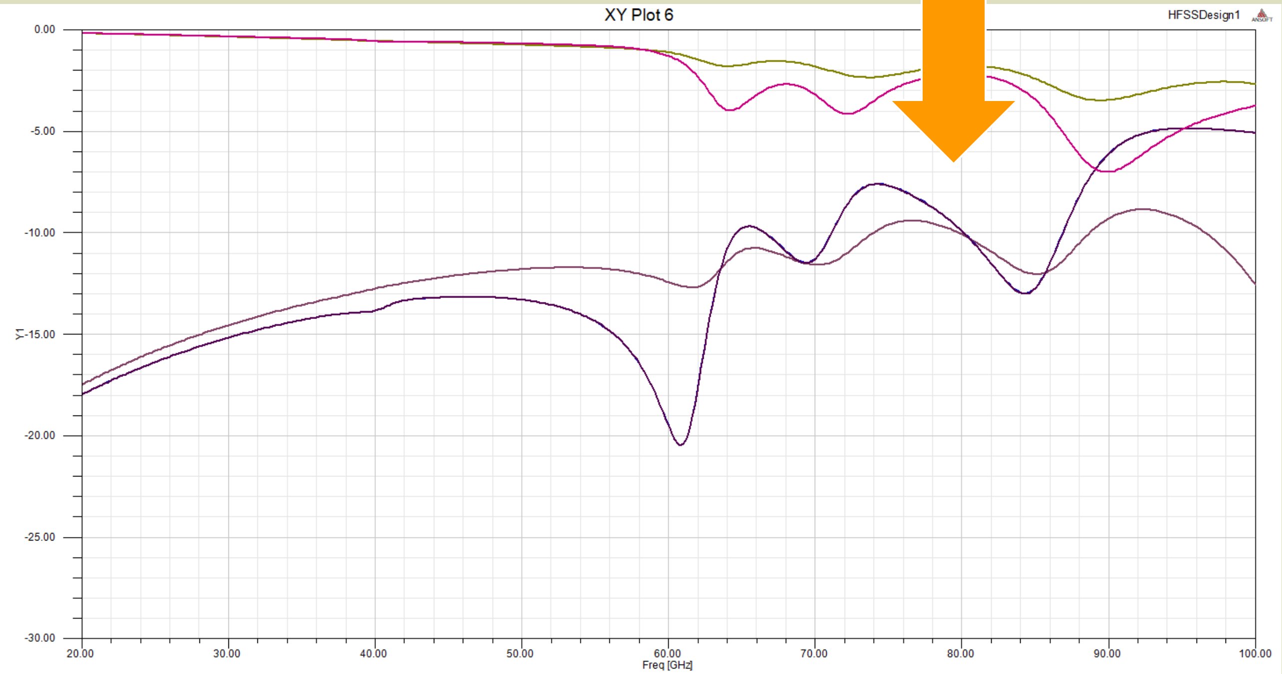
While a single open circuited contact may be ok (left), insertion loss (S21) shows problems in the presence of only a few improperly terminated contacts

Ultra-thin interface



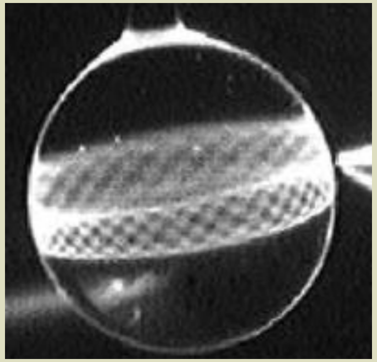
0.1 mm thick
0.65 mm pitch

"It" can (and will) still happen, just at higher frequencies



Other resonance effects

- Dielectric resonator



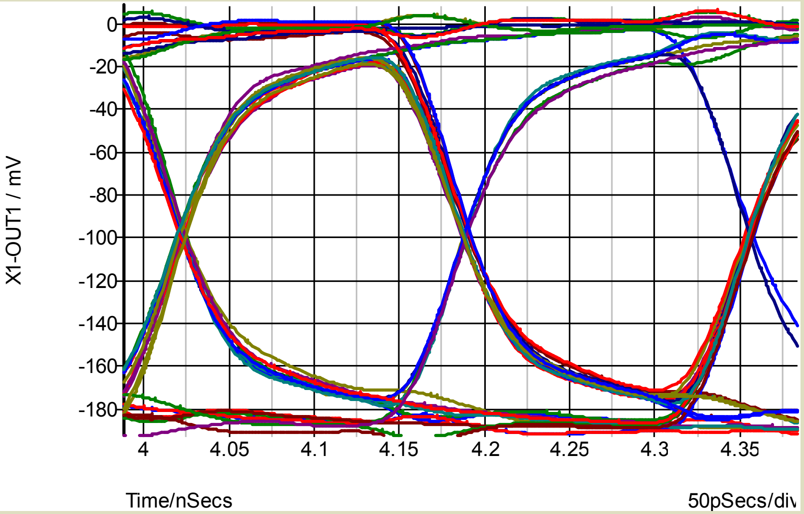
Source: Wikimedia - File:Whispering gallery modes sphere.png

- Whispering gallery modes

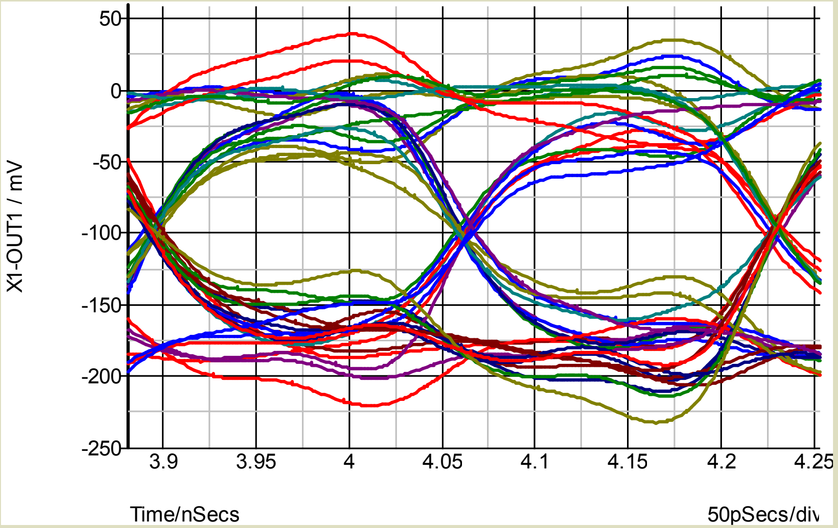
Source: Wikimedia - File:St Paul's Cathedral Whispering Gallery.jpg

Eye Diagram in the Presence of Resonances

Measured insertion loss S21 of a load board with a parasitic resonance



no resonance



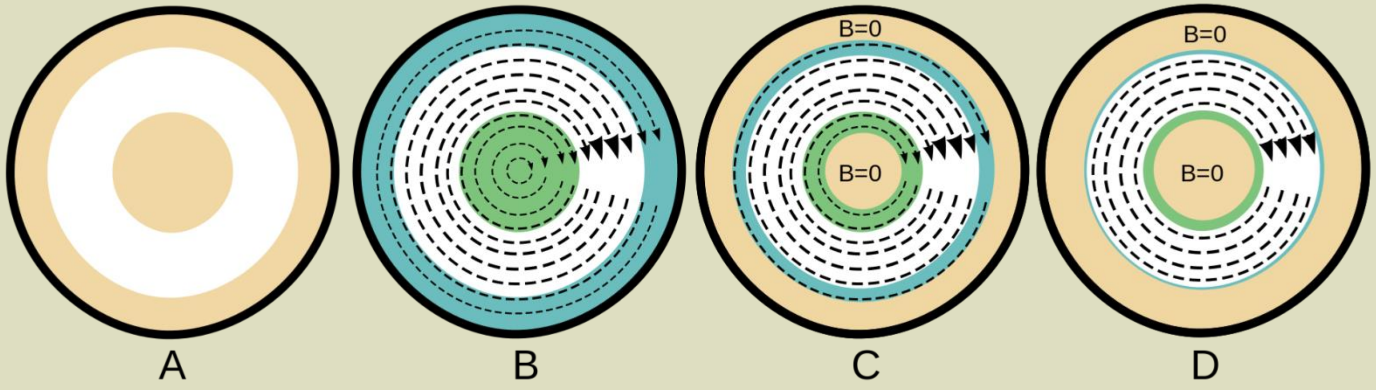
resonance

Noticeable degradation of load board eye diagram (6Gbps) from a 3 GHz resonance

Wave propagation at mm waves

What other considerations must be applied for sending mm-wave signals through PCBs and sockets?

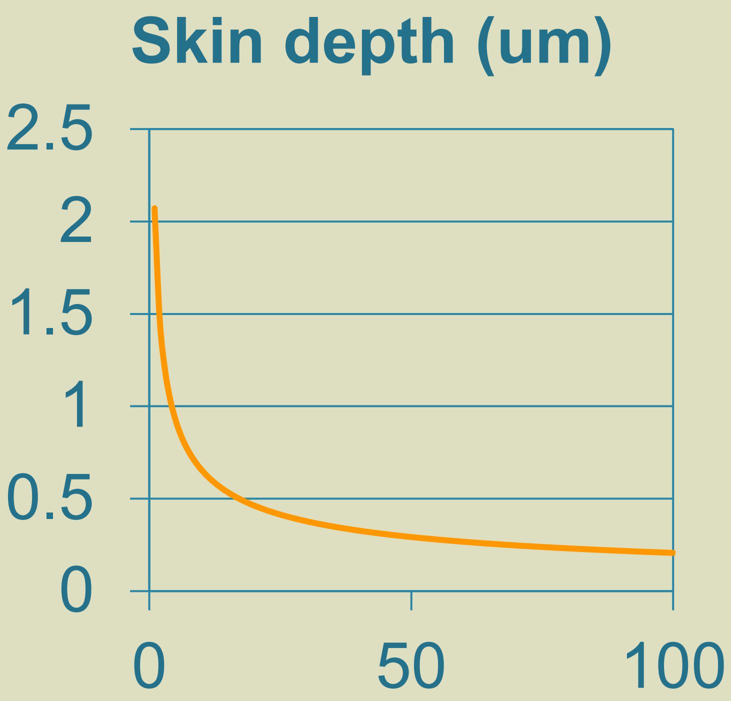
RF current flow



With progressively increasing frequency the RF current penetrates the conductors less and less

Source: Wikimedia - File:Coax and Skin depth.png, CC0, https://commons.wikimedia.org/w/index.php?curid=14208109

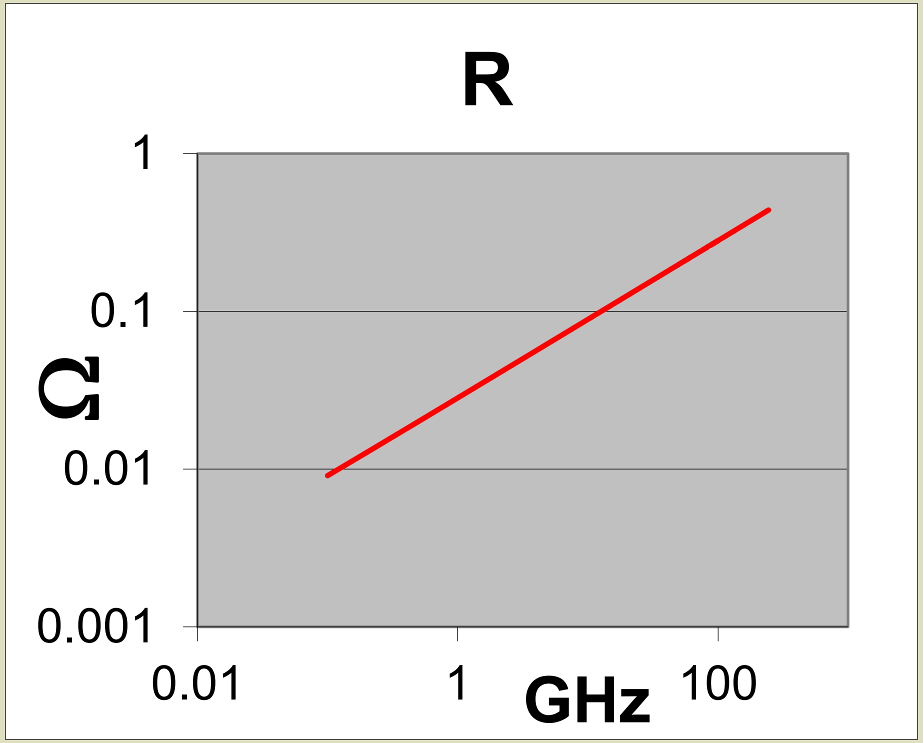
Skin depth

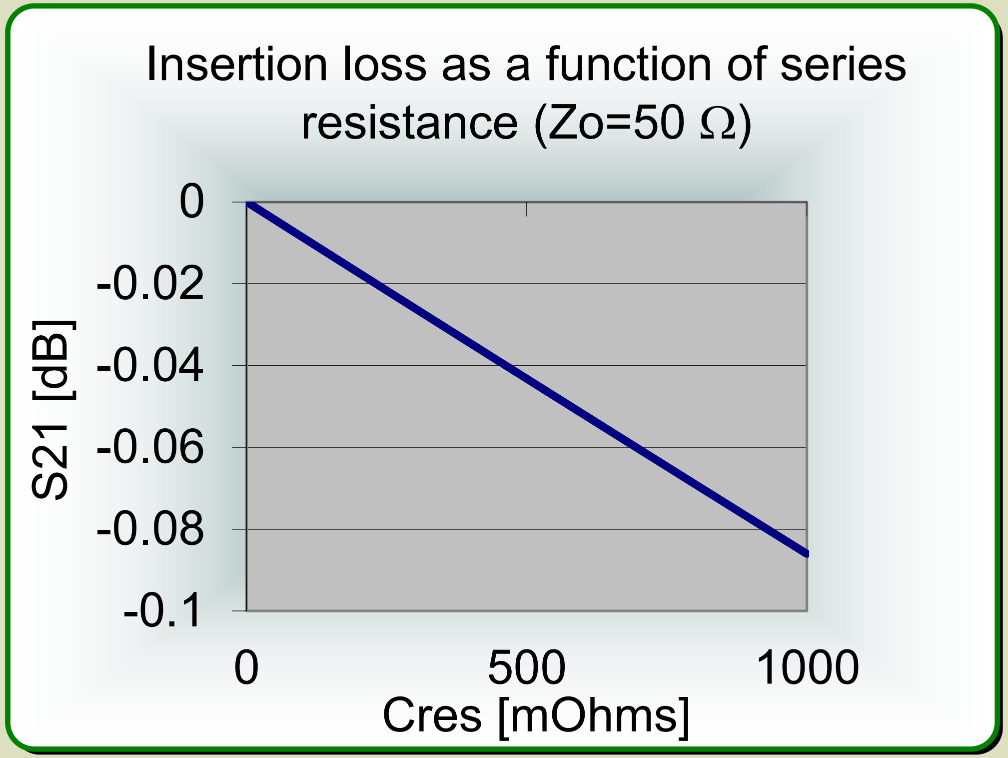


$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

$$R = \frac{\rho}{\delta}\left(\frac{L}{\pi(D-\delta)}\right) \approx \frac{\rho}{\delta}\left(\frac{L}{\pi D}\right)$$

Effective Resistance as a Function of Frequency





This illustrates the drastic change of effective resistance due to the skin effect (single piece contact, 3mm long).

However, for short contacts this is of little consequence (example is for a typical one piece contact).

Surface Roughness Illustration

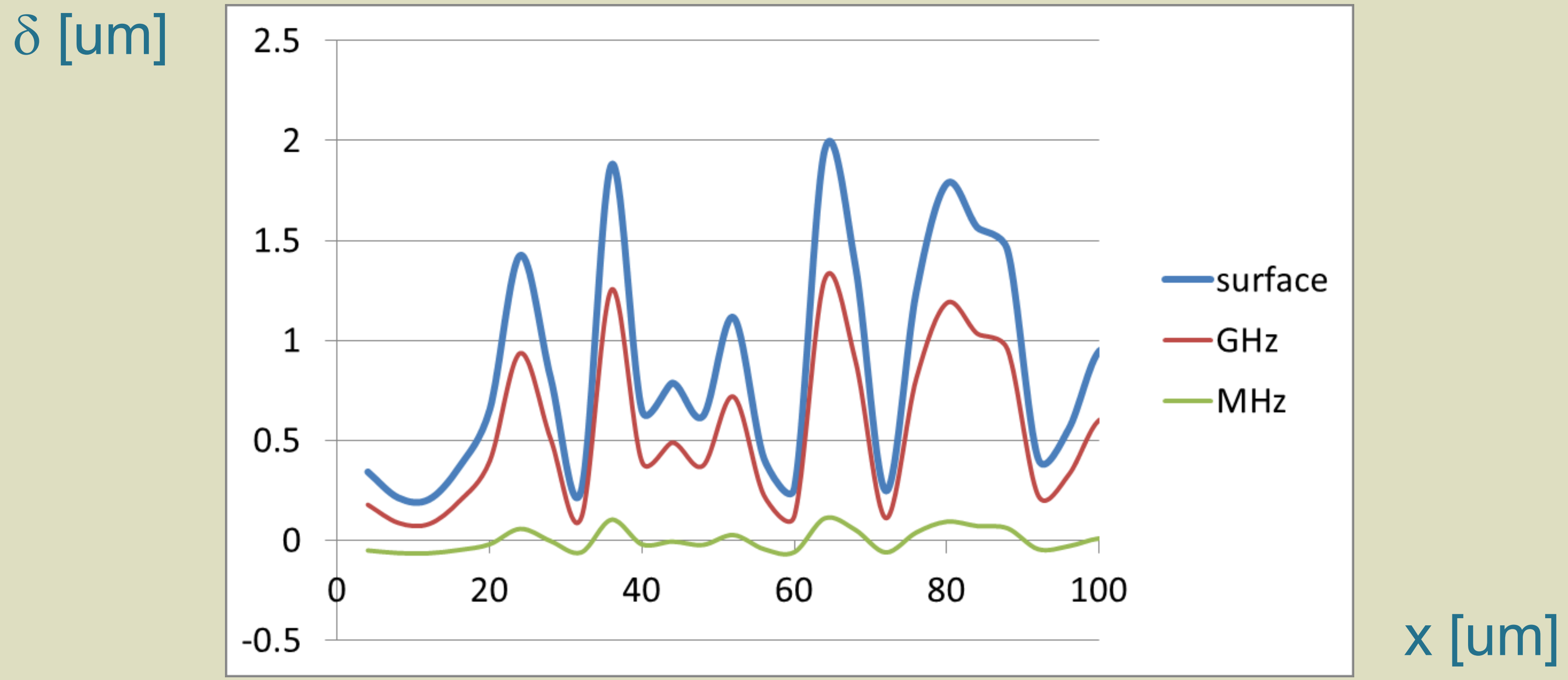
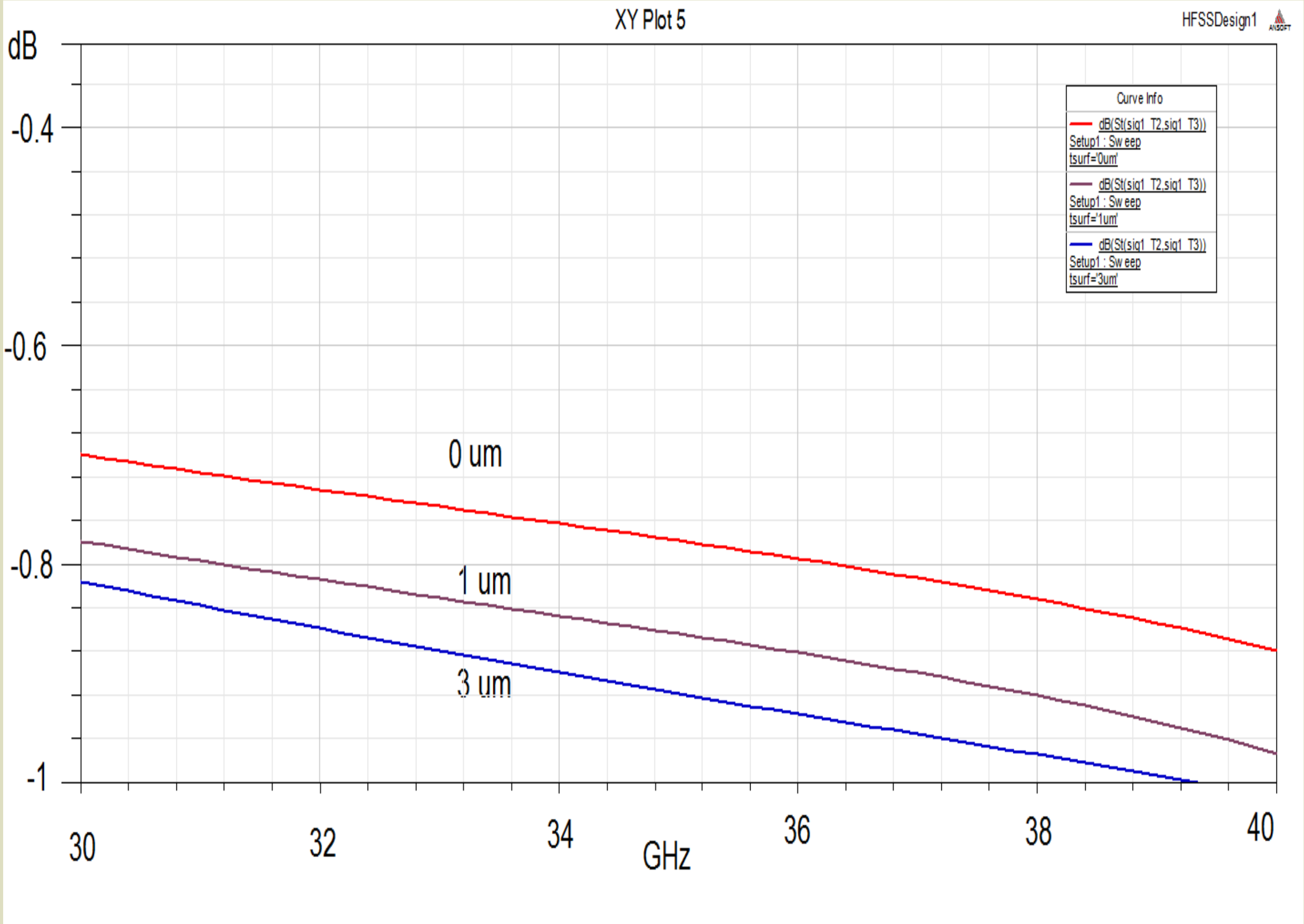


Illustration of approximate paths for different frequency RF signals
additional path length here is only approximately 2% for small skin depth

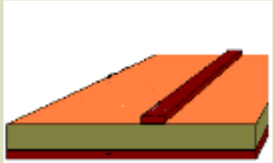
Coax Loss vs. Surface Roughness



Loss of a 100 mm long coax as a function of surface roughness

Moving mm waves

- PCB transmission lines (short)

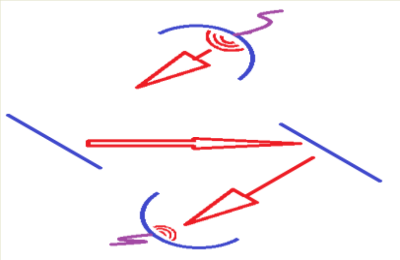


- Coax (semi-rigid preferred)

- Waveguide

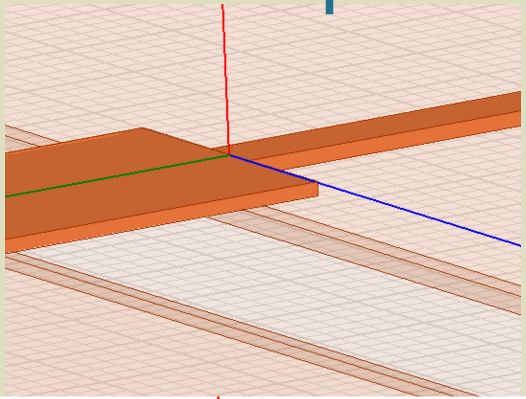
Source: Wikimedia
File:Sound-waveguide-drain.jpg

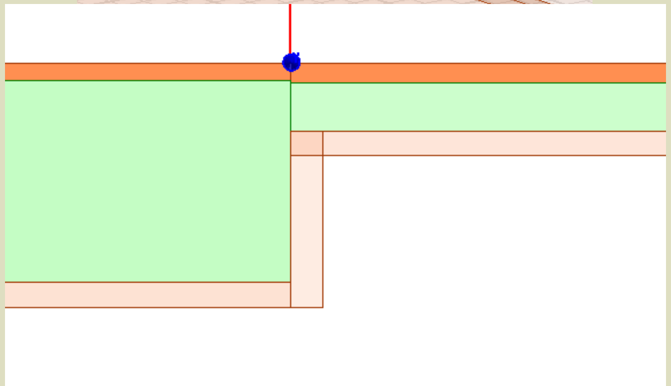
- Beam waveguide



Moving mm waves across boundaries

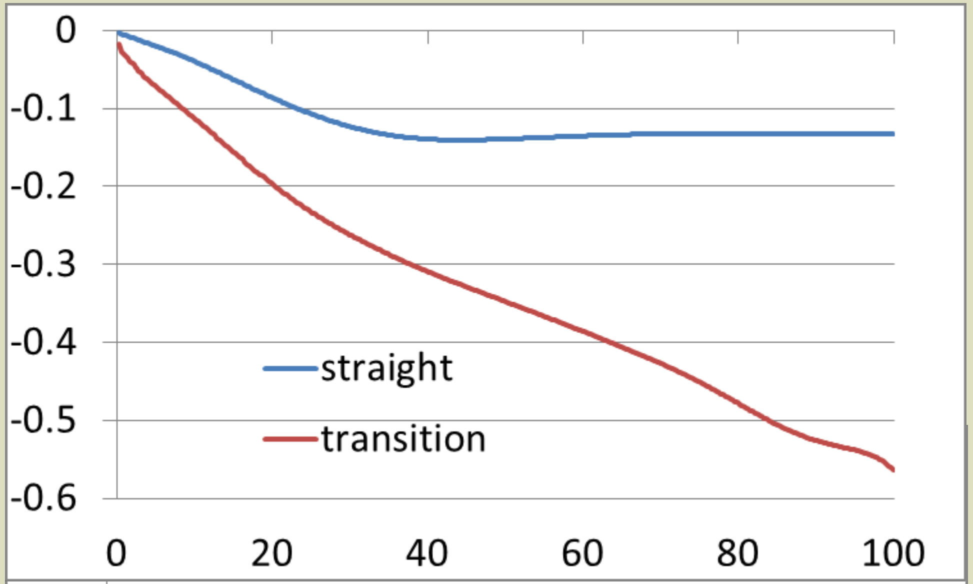
Transition smoothness becomes important:



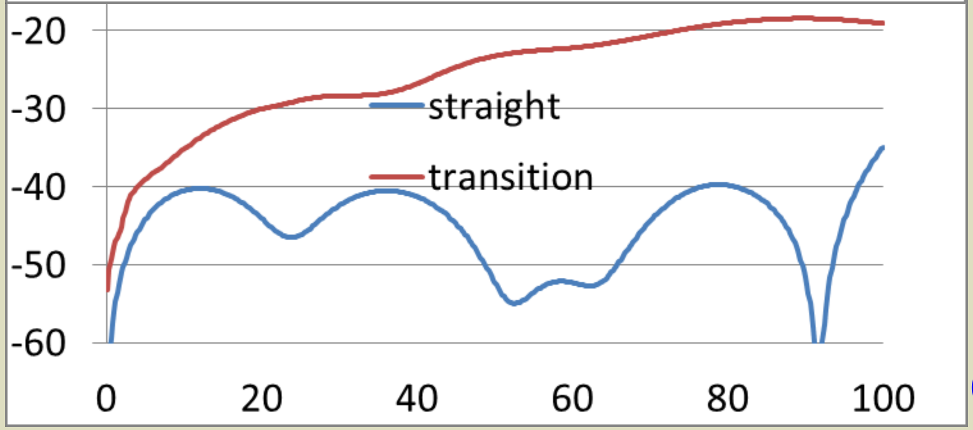


S21

dB



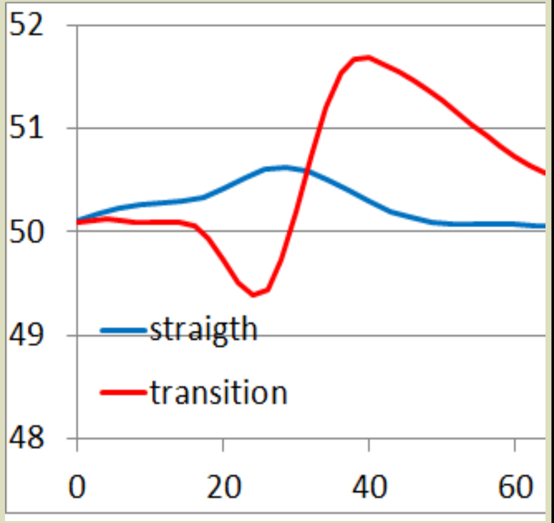
S11



GHz

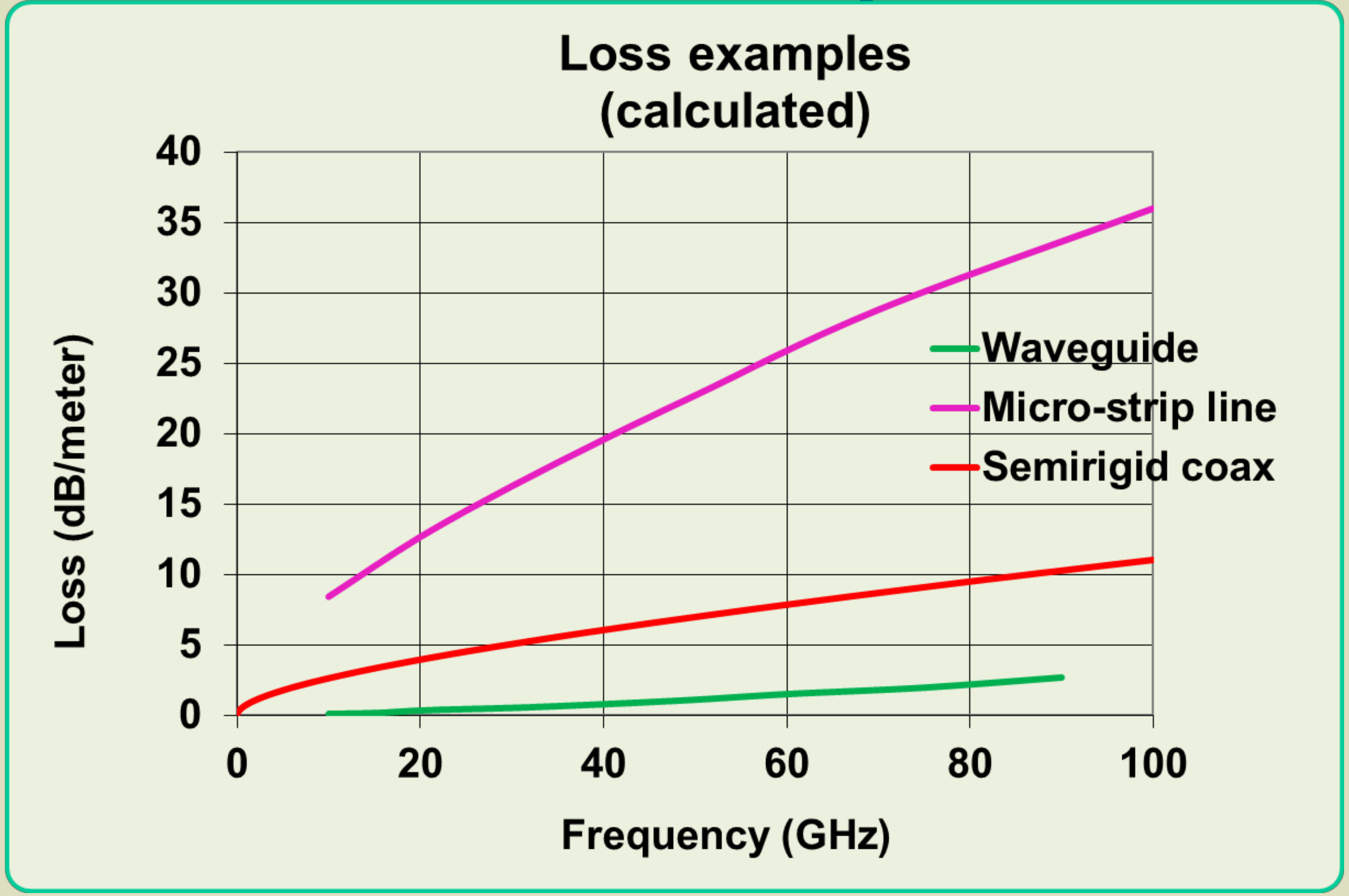
TDR

Ohm



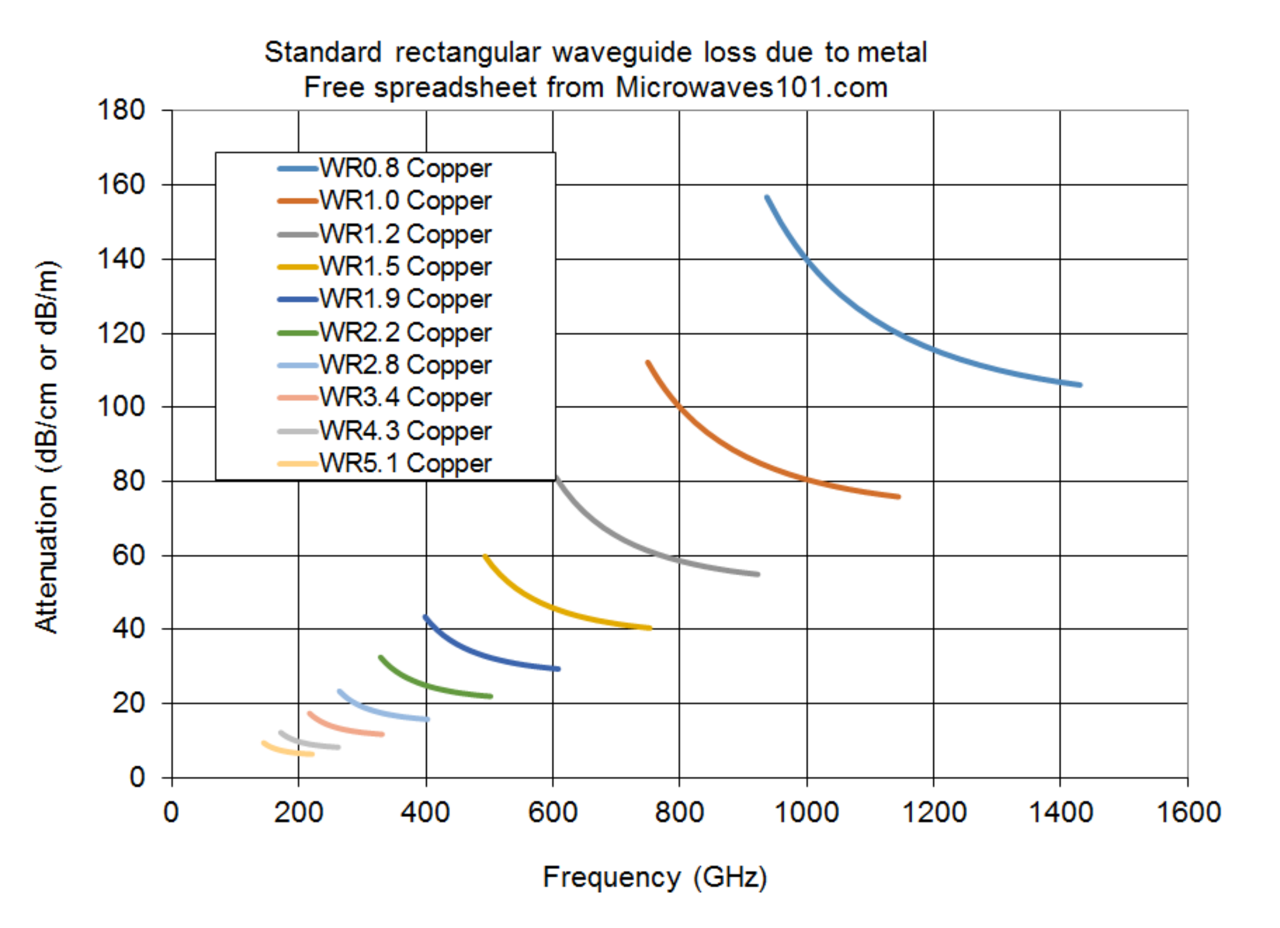
ps

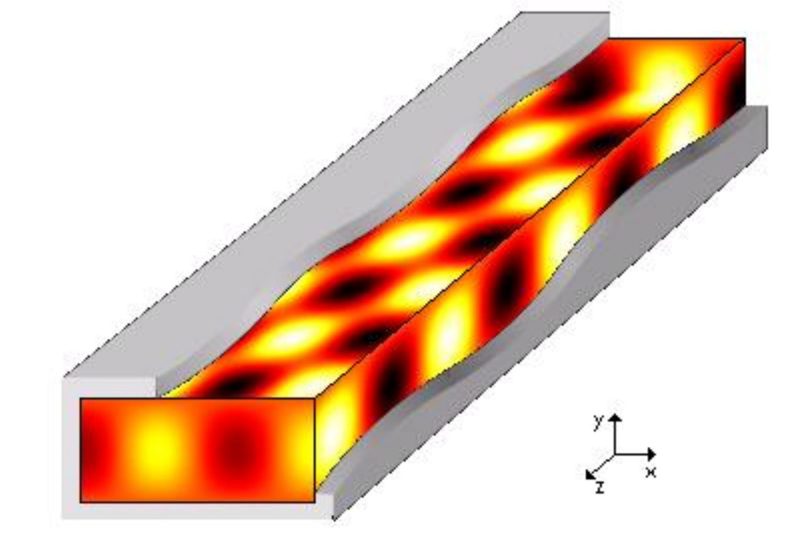
Loss examples



Loss examples for typical semi-rigid coax, waveguide and microstrip lines

Waveguide Bands and Loss

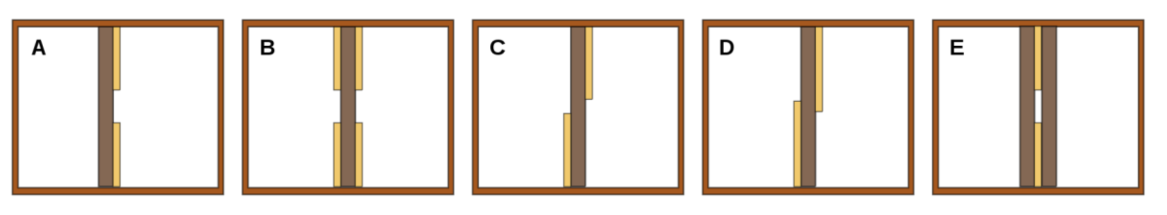




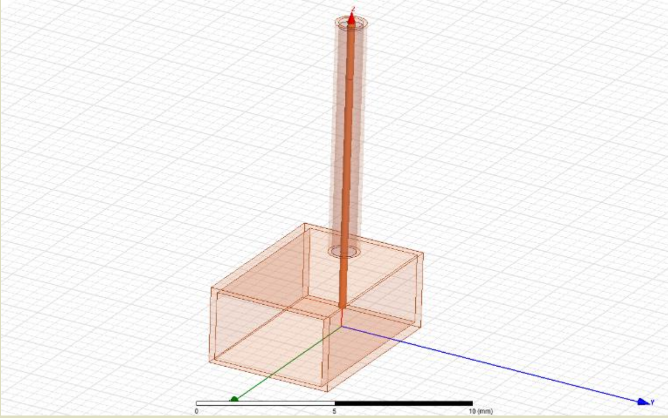
Source: https://commons.wikimedia.org/wiki/File:Waveguide_x_EM_rect_TE31.gif

Source: https://www.microwaves101.com/encyclopedias/waveguide-loss

Waveguide Interface Examples

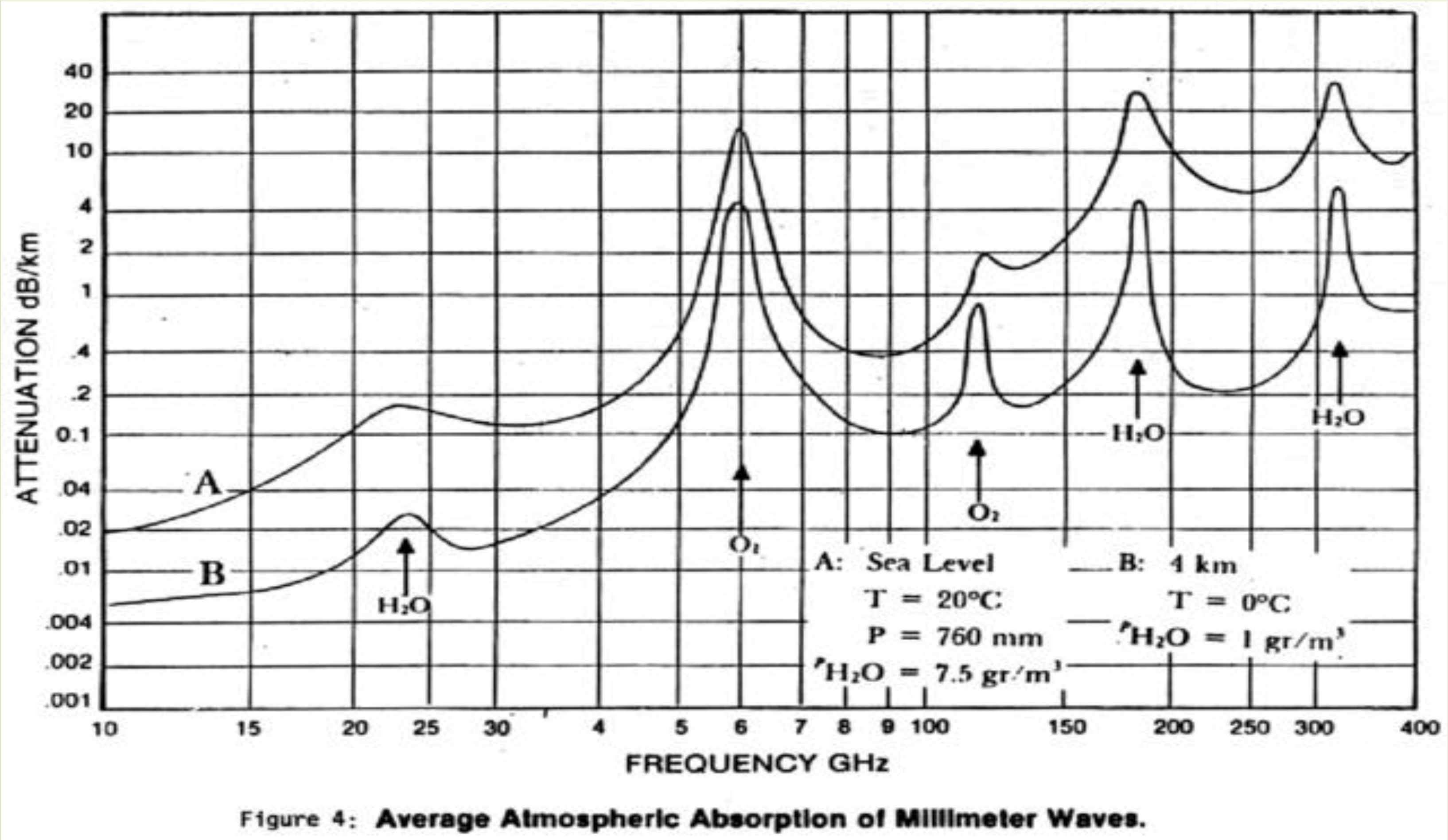


Finline
(extends out from
waveguide onto PCB)



Waveguide post
(extends out from
waveguide into coax)

Atmospheric Loss



Source: Wikimedia - File:Millimeter waves atmospheric loss.png

Wave propagation through air has vastly lower loss than in coax/PCB traces.

Frequency windows of higher absorption exists, however.

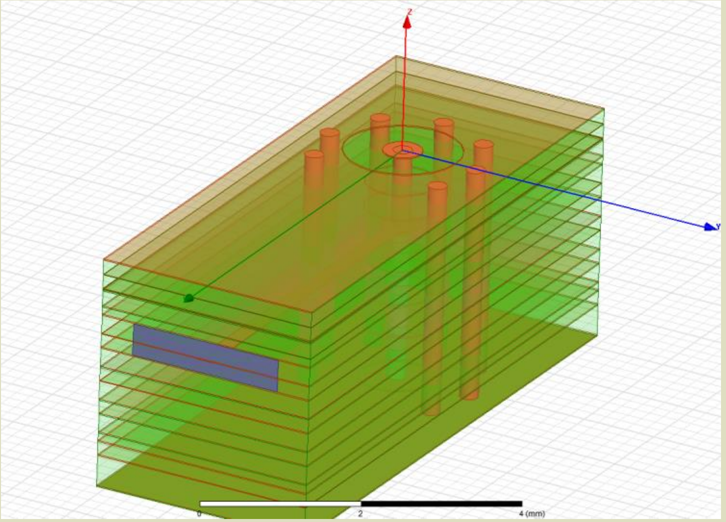
Some mm-wave Socket Design Considerations

- A good design for lower frequency sockets can be used as a point of departure:
  - Scaling (all 3 dimensions) is possible if pitch is also scaled, e.g. a very good 0.8 mm socket design will likely at least yield a reasonable 0.4 mm pitch design for higher frequency operation.
  - Materials that work well to 40 GHz will likely do so to higher frequencies.
  - Plating thicknesses need not be scaled.
  - The design must be verified since interface parasitics (e.g. L, C) will not necessarily scale as desired.

Some mm-wave Socket Design Considerations

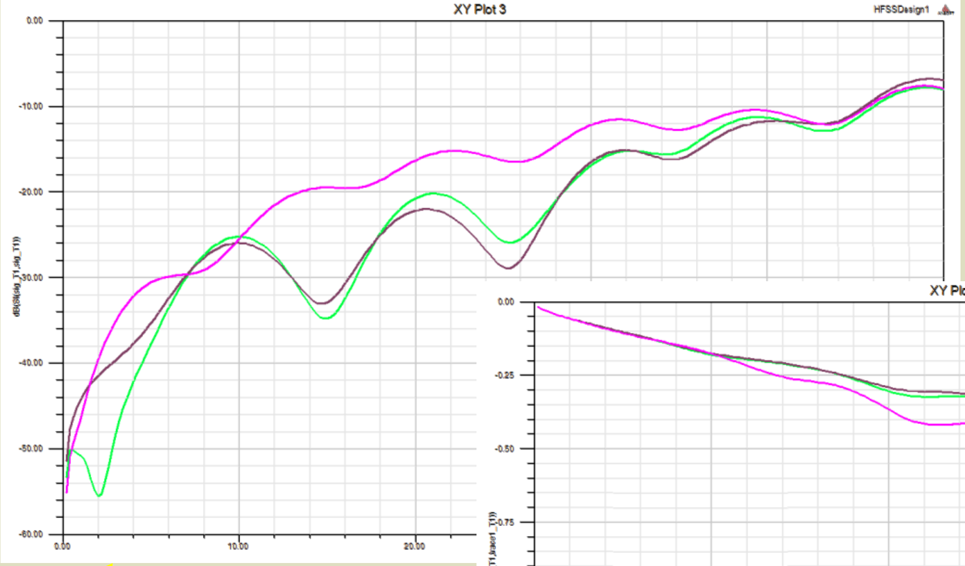
- PAM – 4 operation requires good crosstalk and good return loss performance
  - Return loss will be best if socket is designed to be 100 Ohms differential characteristic impedance
    (50 Ohms if signals are single-ended)
  - This design will generally NOT be equivalent to an optimal single-ended 50 Ohms impedance case
  - It is risky to generalize design advice for minimal differential crosstalk since unexpected results can and will be encountered. Designs must be verified via simulation in each specific case.
  - The PCB design (via and pad/antipad diameters as well as locations ***must be*** optimized for the intended socket.

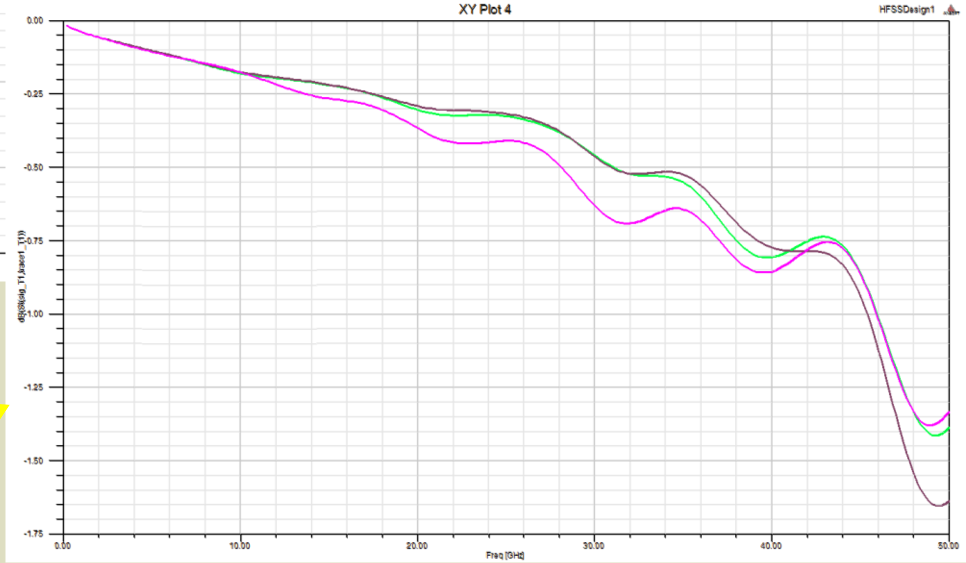
PCB Interface – Insertion and Return loss



Example: Coaxial feed structure

(3 different parameter choices shown)



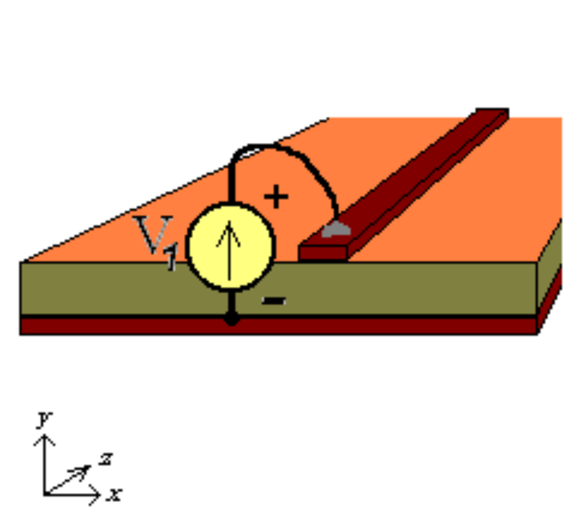


Return loss S11 and insertion loss S21 depend on the internal construction of the PCB.

A good socket design can be "ruined" by a poor PCB design.

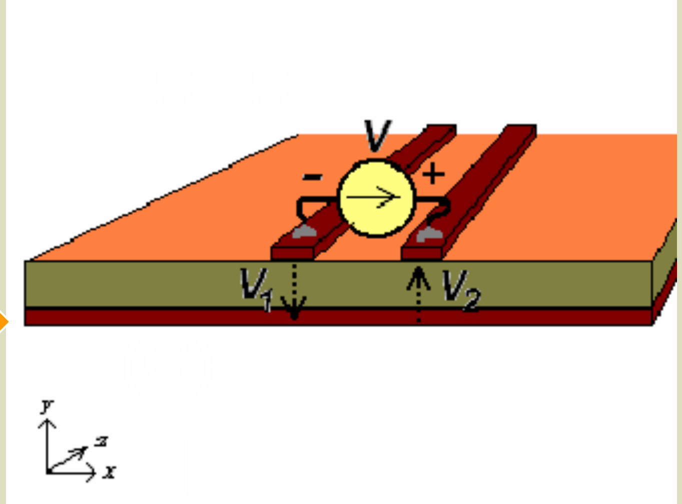
Single Ended vs. Differential Signaling

SE



Differential

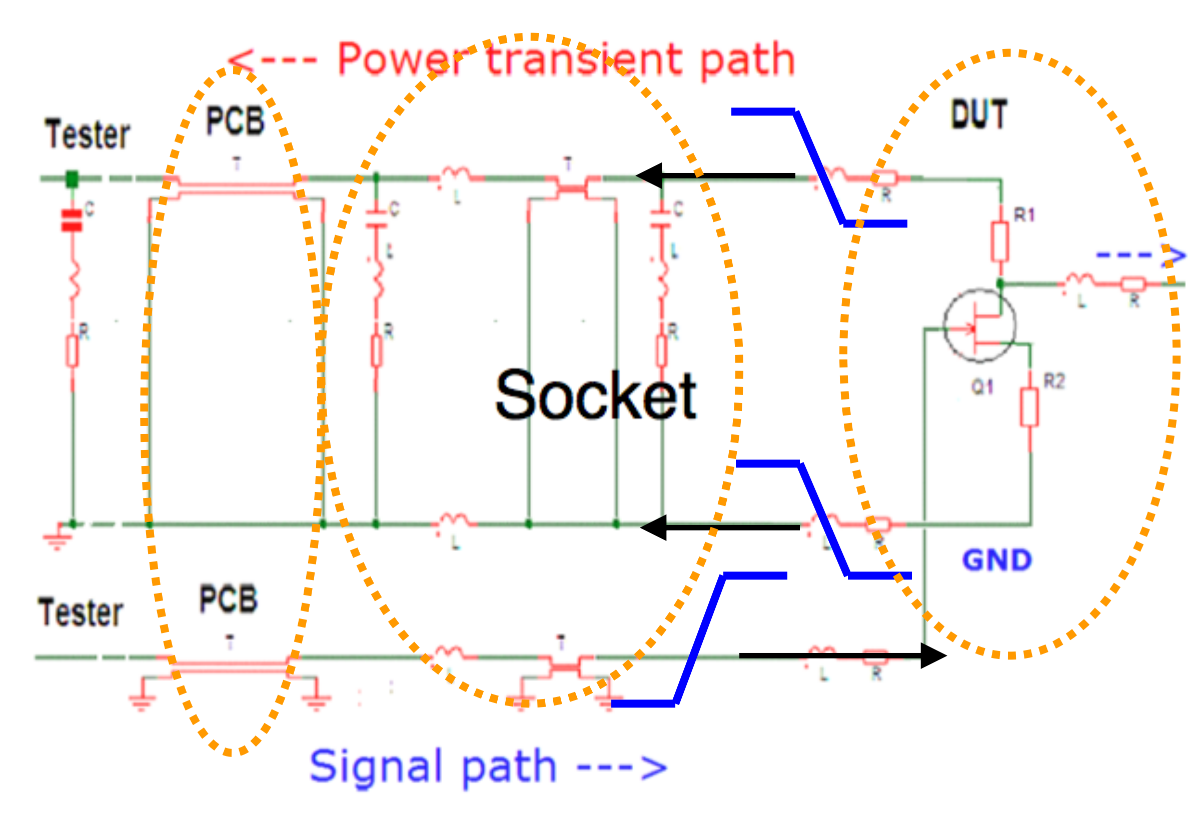
(GND) →



A voltage is established between a signal line and ground.

A voltage is established between two signal lines. The ground (underside of the circuit board) serves merely as a reference. Thus differential signaling is much less affected by what surrounds the signal path. But…

Signal and Power Paths



At mm-wave frequencies it is imperative to consider not only the signal flow but also ground return and power delivery paths

Socket SI Parameters

- Impedance Z_o
- Delay t_d
- Capacitance C
- Inductance L
- Mutual elements C_m, L_m

Example of relevant socket parameters

Relevant Socket Parameters

- Ground locations
- Pitch
- Contact length
- Contact lateral dimensions
- Housing construction (metal vs. dielectric)
- Housing material, e.g. dielectric constant

Only major parameters that affect SI are listed

Trend tables: Electrical vs. mechanical characteristics

	Mechanical parameters			Properties	
Electrical characteristics	diameter	length	pitch	conductivity	dielectric constant
L	vvv	^^	^^	--	--
C	^^^	^^	vv	--	^^
Lm	vv	^^	vv	--	--
Cm	vv	^^	vv	--	^^
Cres	vv	^^	--	vv	--
Zo	vvv	--	^^	--	vv
td	--	^^	--	--	^

Legend:

An increase of the table parameter results in the following change ---->

^^^	strong increase
^^	increase
--	neutral
vv	decrease
vvv	strong decrease
v^	either way

What is most important for mm-wave socket:

Trend tables: Physical characteristics vs. SI/PI performance

	Mechanical parameters			Properties	
Performance parameters	diameter	length	pitch	conductivity	dielectric constant
S11	v^	^	v^	--	v^
S21	v^	^	v^	--	v^
S41	v^	^	v^	--	v^
didt	v	^	^	--	--
Zpds	v	^	^	--	--
Rdc	v	^	--	v	--
Qdot	v	^	v	v	--

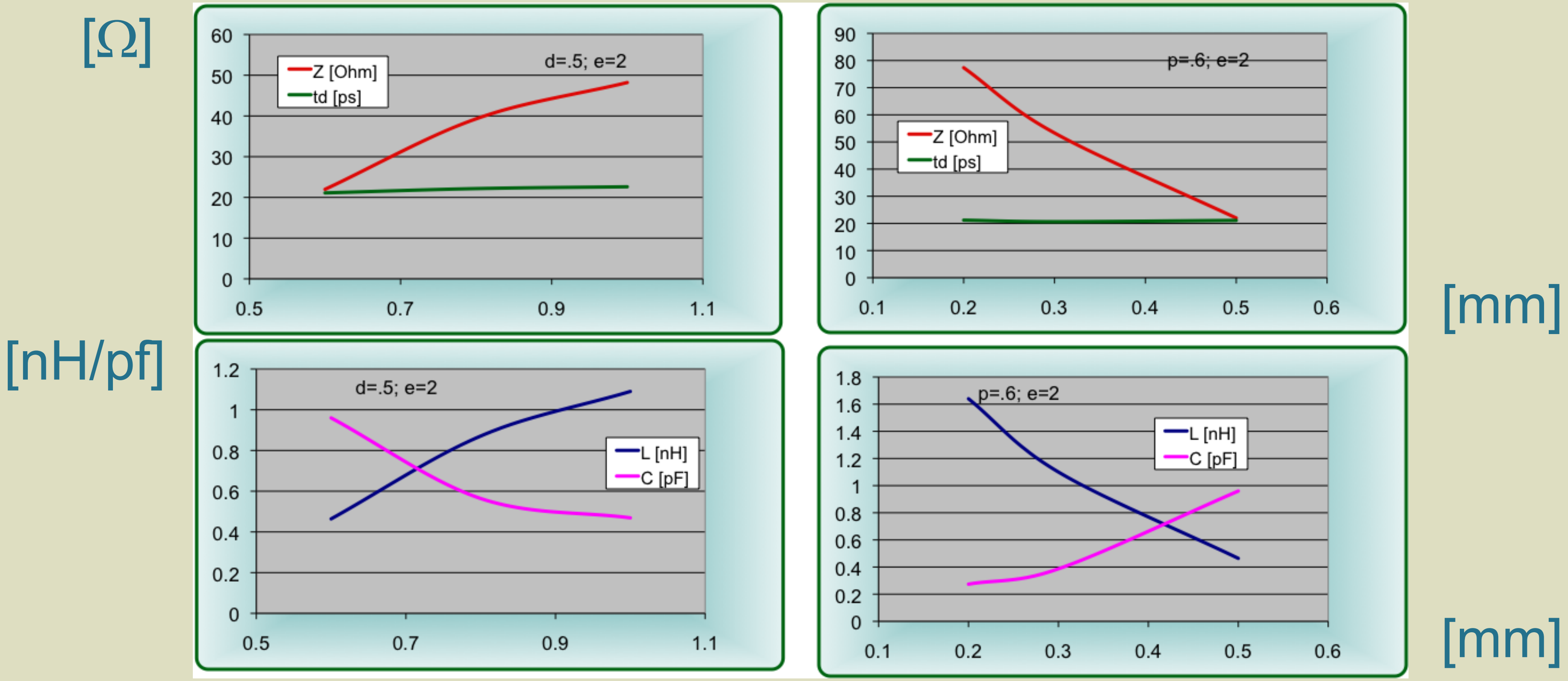
Tables are based on basic mathematical relations and frequently observed responses- they are only meant to serve as a guide.

What is most important for mm-wave socket:

Dimensions vs. SI/PI parameters

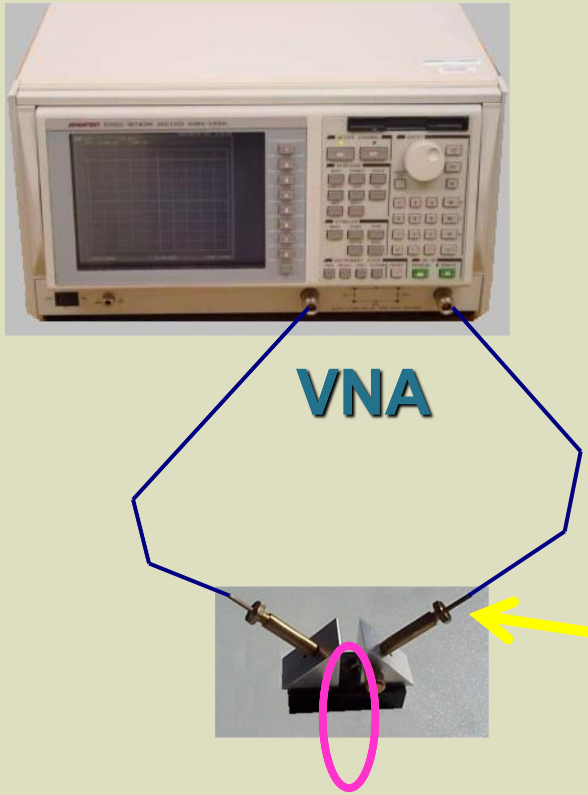
Pitch

Diameter



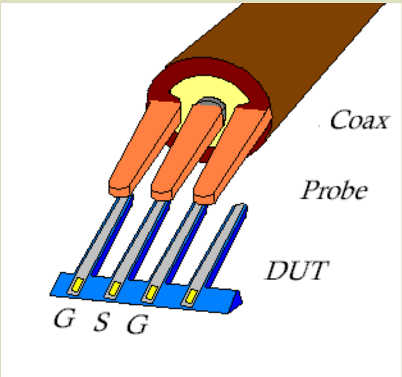
Mutual inductance and capacitance will change significantly, too

Test Methodology for EHF Socket Measurements

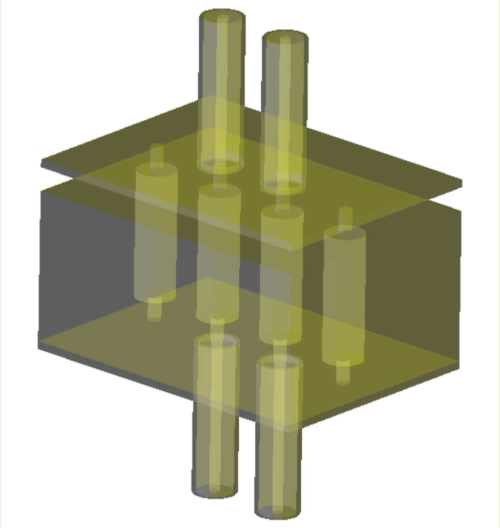


VNA

DUT



Probes



G-S-S-G test arrangement with coax feeds

Test Methodology for EHF Socket Measurements

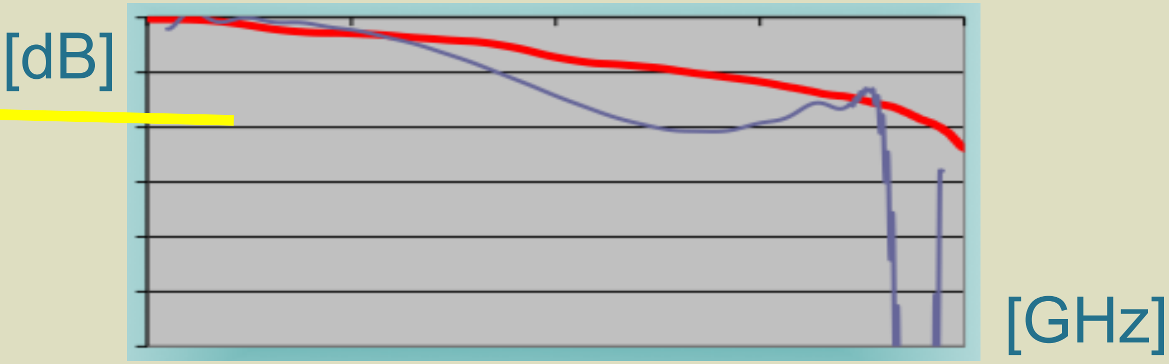
De-embedding (Fixture removal):

A process of calibration and data processing that moves the so-called reference planes right up to the device to be tested. This effectively removes all contributions from coax cables, probes and fixturing. It leaves only the data that are associated with the device under test (DUT) itself.

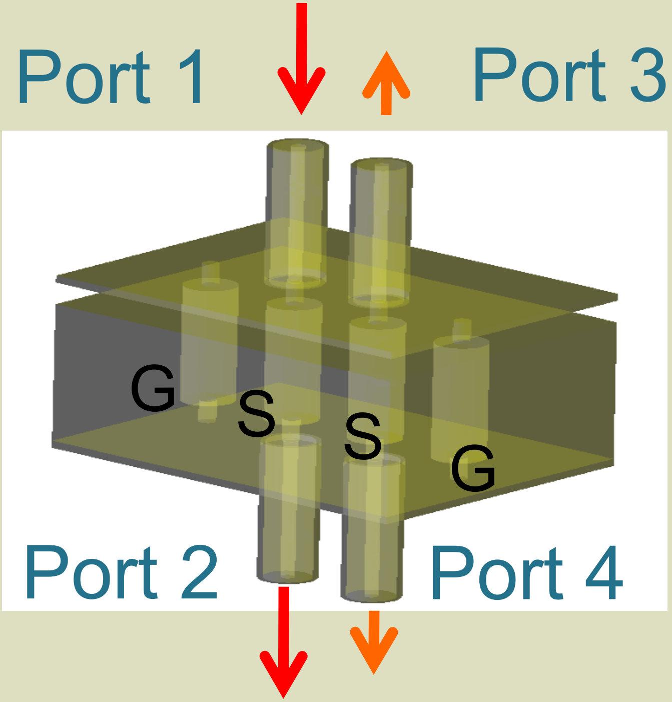
Socket Test:

… performance parameters vs. electrical characteristics …

- Insertion loss (S21)
- Return loss (S11)
- Crosstalk (S31, S41)



Simulated performance (blue) is not always better than measured (red)



- Impedance $Z_o \sim = \sqrt{L / C}$
- Delay t_d
- Capacitance C
- Inductance L
- Mutual elements C_m, L_m

Typical Test Equipment for EHF Socket Measurements

- *Network analyzers*
  - *Scalar network analyzer*

    (generate only amplitude response e.g. insertion loss)

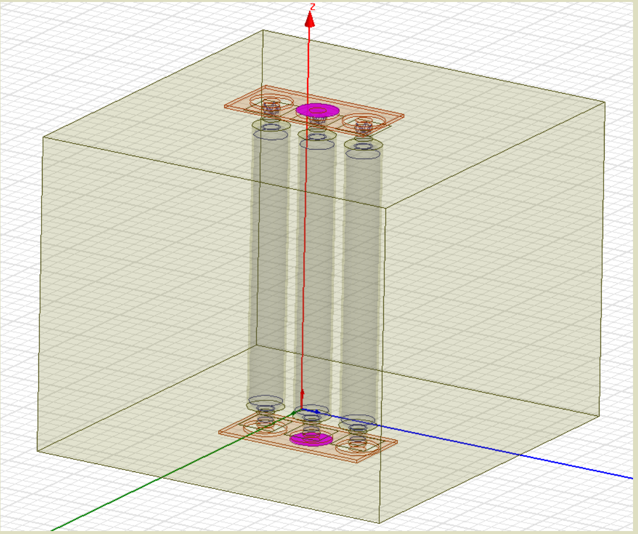
  - *Vector network analyzer*

    (generate full datasets with phase information that can be used in system performance simulations

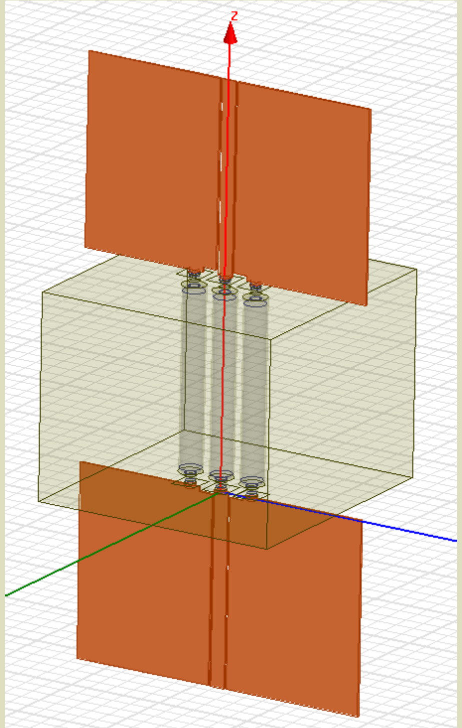
- *(Time domain reflectometers)*

- *Custom built analyzers*

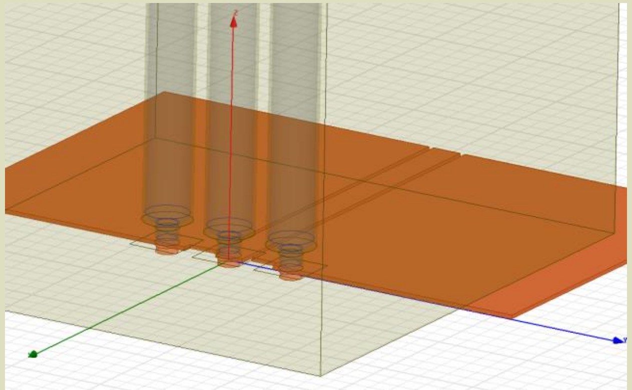
Socket Test Interfaces



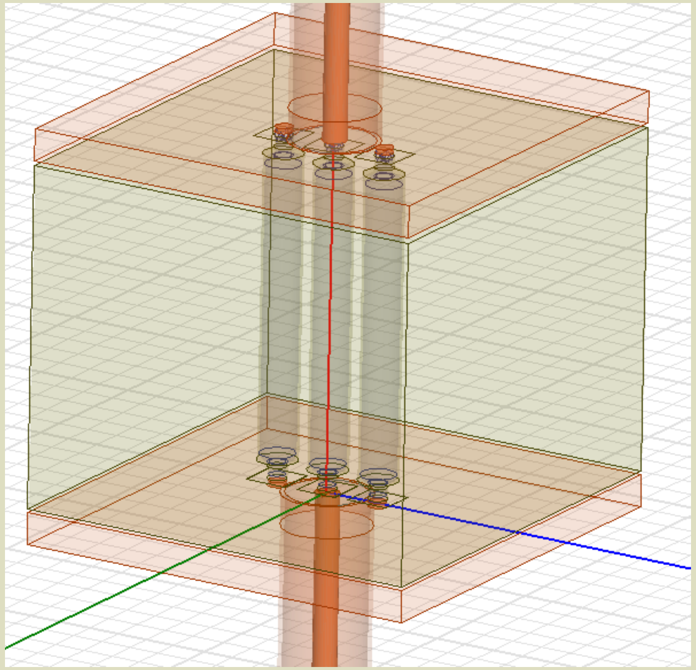
GSG with direct feed



- CPW probes

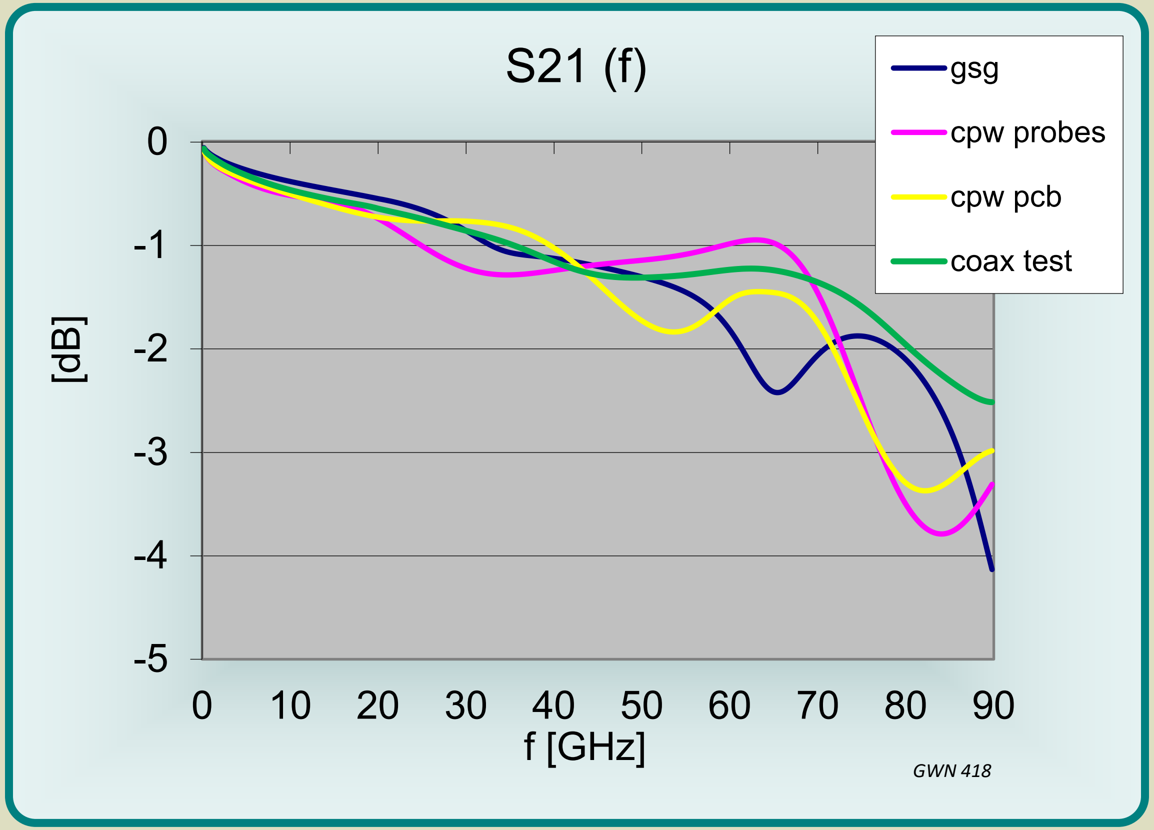


- CPW on PCB



- Test configuration

Socket Test Results – Insertion loss

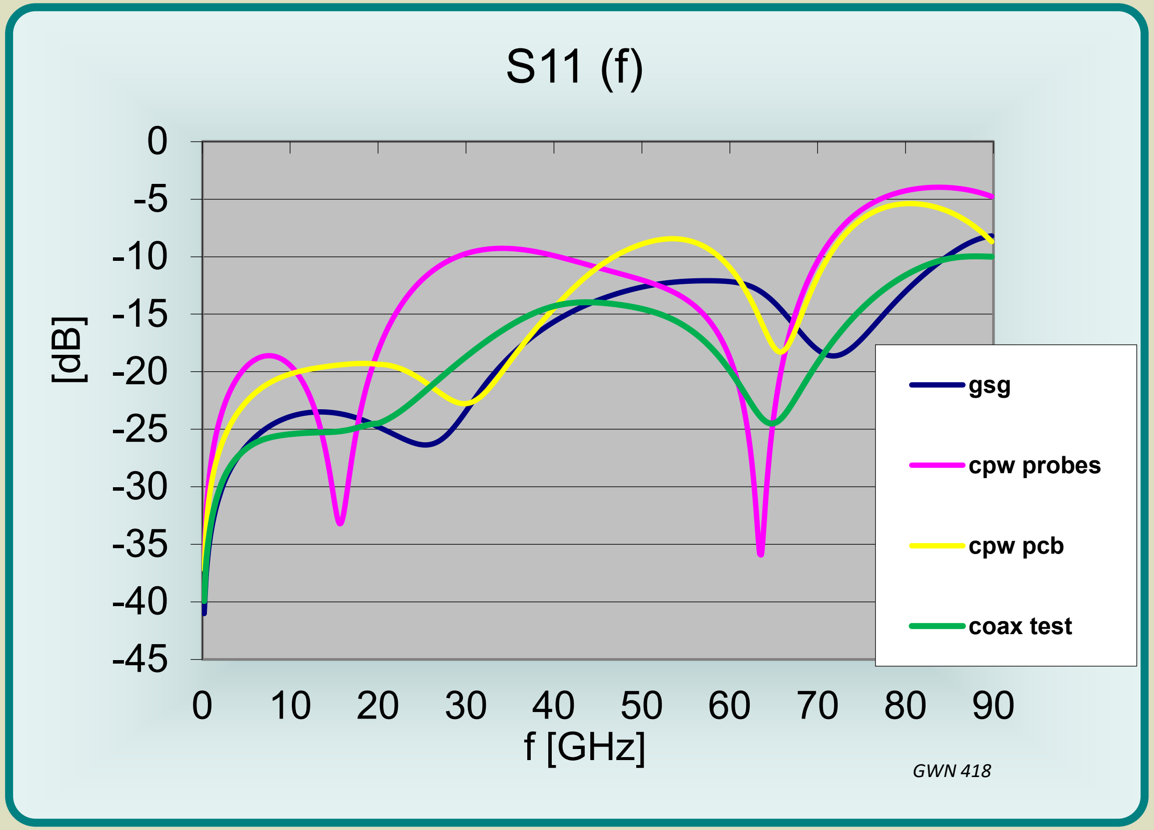


Insertion loss for different feed structures

(example socket here has 0.35 mm pitch)

Insertion loss begins to depend on feed structure for f > 20 GHz. A coax test configuration in this case provides consistent good performance beyond 90 GHz.

Socket Test Results – Return loss



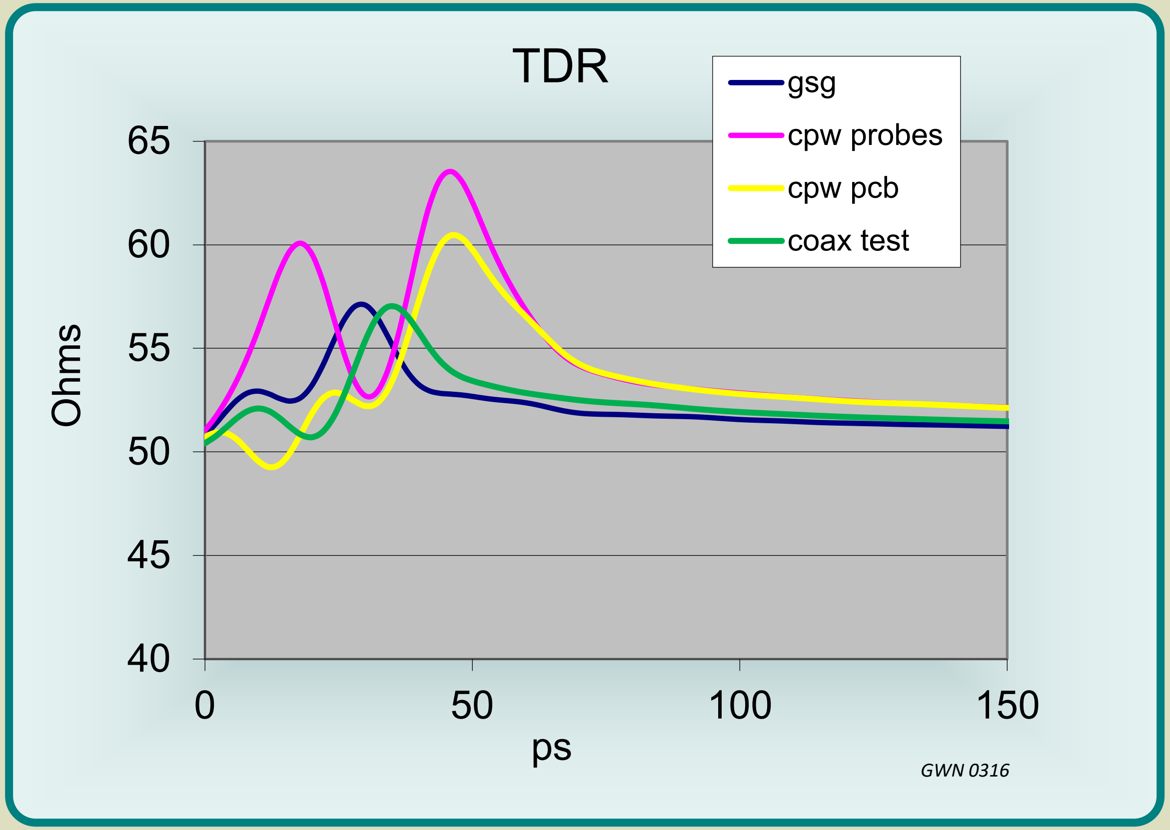
Insertion loss for different feed structures

(example has 0.35 mm pitch)

Return loss depends on feed structure.

Coax test configuration in this case provides comparable performance to direct GSG feed.

Socket Test Results – Impedance



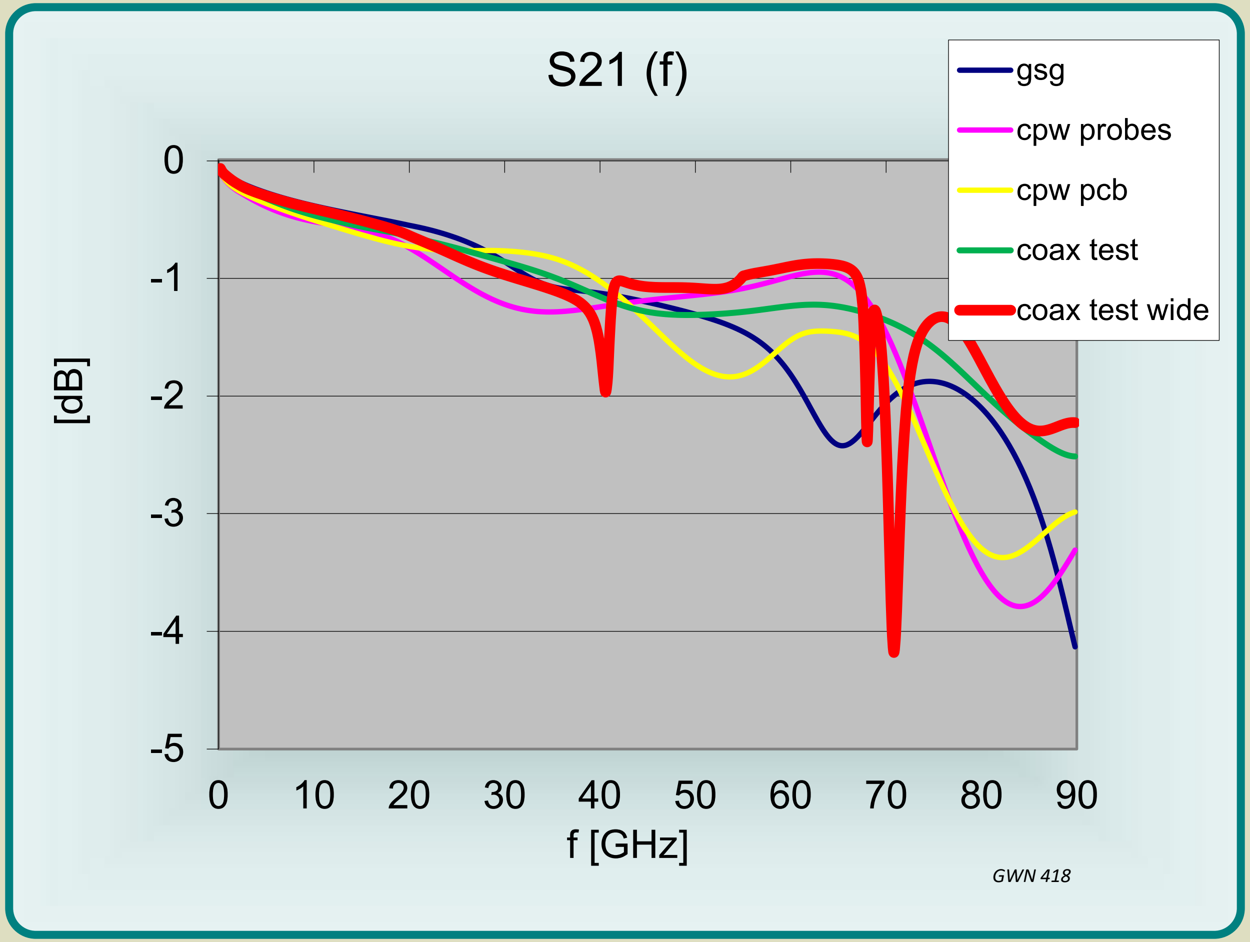
Insertion loss for different feed structures

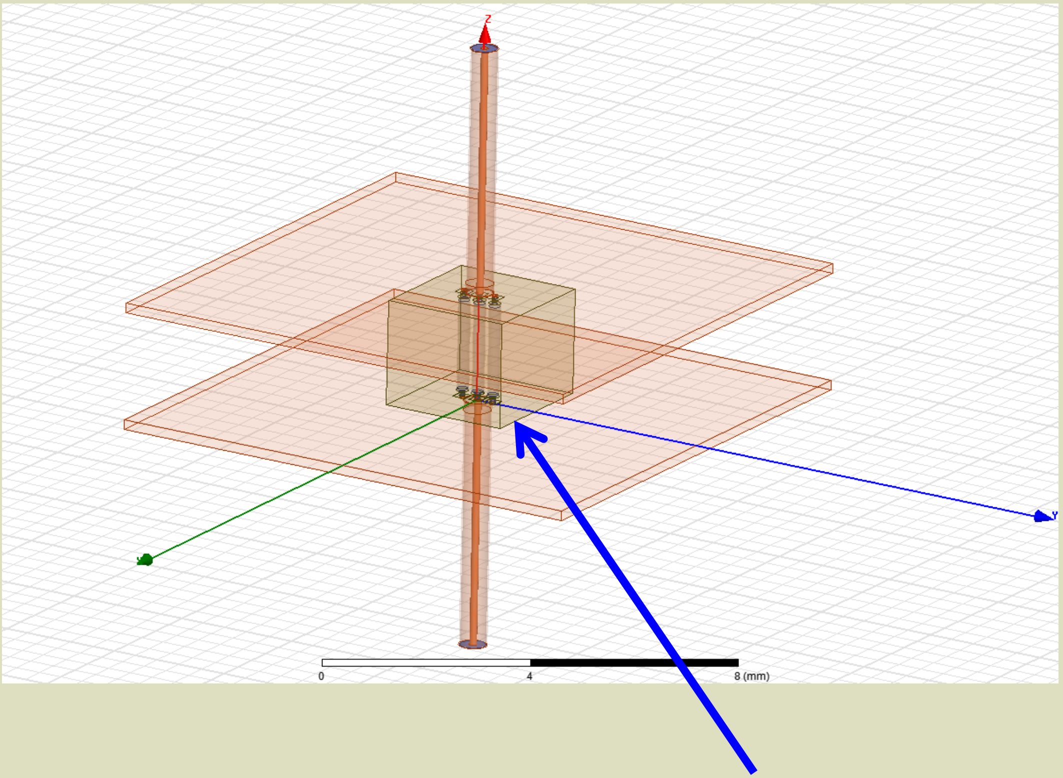
(example has 0.35 mm pitch)

Observed impedance discontinuities exist depending on feed structure.

Coax test configuration in this case provides comparable performance to direct GSG feed.

Socket Test Results – Insertion loss





Feed structure with extended bases shows resonances (modes in dielectric)

Conclusion

- Resonance and interface effects become a major issue at mm-wave frequencies.
- A PCB design optimization must accompany socket design/application.
- Use of sockets in mm-wave applications requires a good grasp of what may happen when wavelength approaches contact size and pitch dimensions.