PIM in PCBs:
Mechanisms & Mitigation

Outline

- Introduction & Definitions
- PIM Sources & Physical Mechanisms in Communication Systems
- Methods of Measuring PIM
- Sources of PIM in PCBs
- PIM Mitigation & Guidelines for Low PIM in PCBs

Passive Intermodulation (PIM)

- PIM occurs when normally linear components in a communication system (cables, PCBs, connectors, antennas) generate intermodulation products
- These intermodulation products contribute to noise in the communication system & effectively degrade signal-to-noise ratio
- There are many potential contributors to PIM in a wireless communication system
- PIM performance should be specified at the system level, which will result in component-level PIM requirements
- For PCBs, the choice of materials can play a significant role in PIM performance

Passive Intermodulation (PIM)

Inputs → **System (passive, non-linear)** → **Outputs**

F_A, F_B

System Components

- PCB
- High Speed Package
- Antennas
- Cables & Connectors
- …

F_A, 2 F_A, $3F_A$, …
F_B, $2F_B$, $3F_B$, …
$k_AF_A + K_BF_B$
(linear combinations)

Passive intermodulation products are generated when two or more signals are transmitted through a passive system having non-linear characteristics

PIM at the input port is called Reverse PIM
PIM at the output port is called Forward PIM

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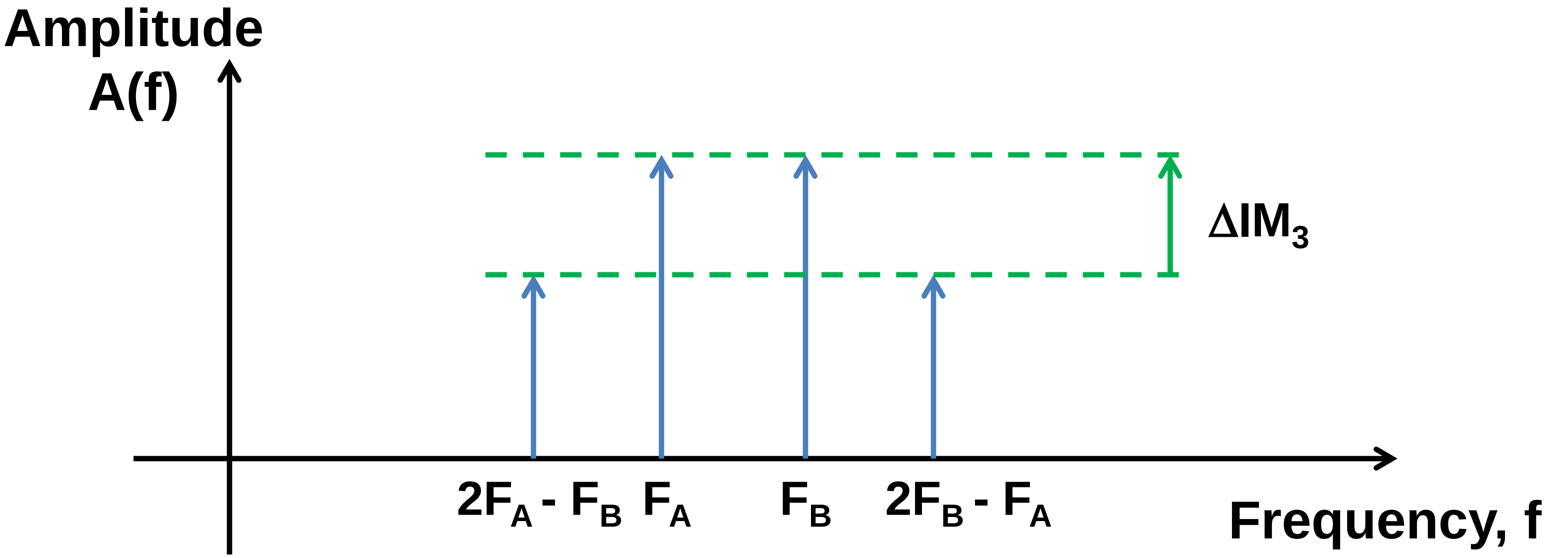
Passive Intermodulation (PIM)



IM_3 = third-order intermodulation product

PIM is measured as the relative difference between the amplitude of the intermodulation product & the amplitude of the carrier

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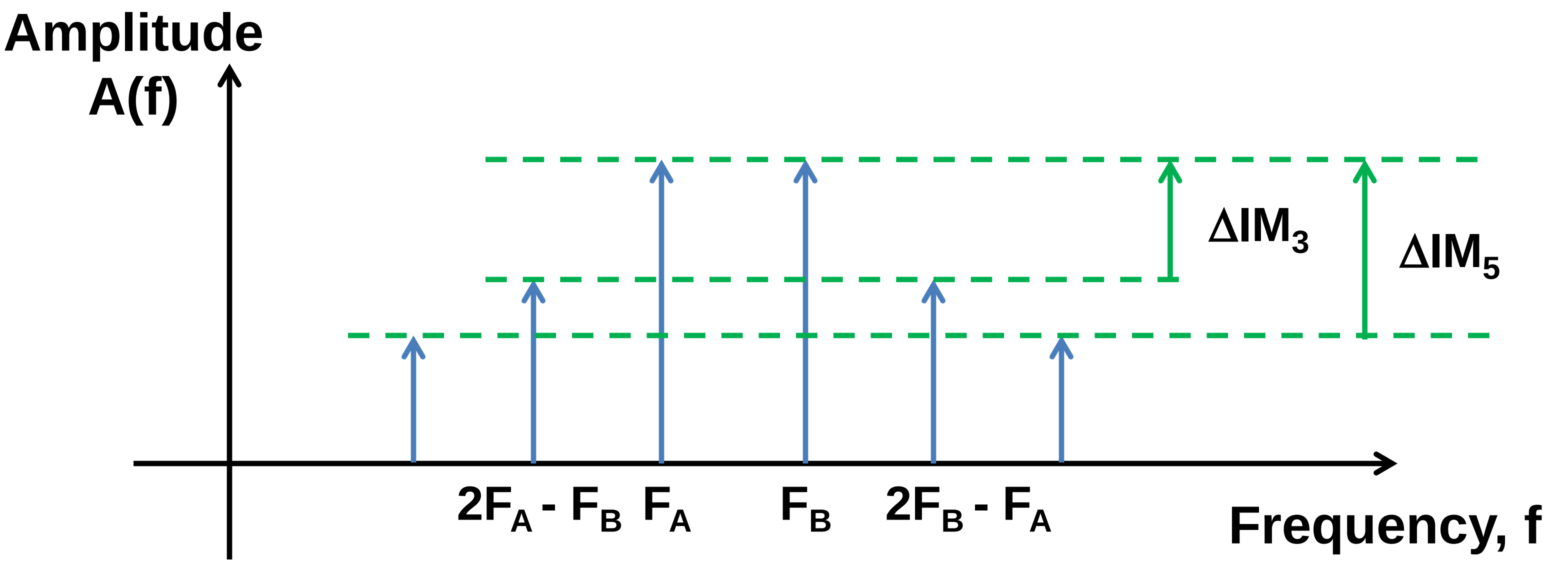
Passive Intermodulation (PIM)

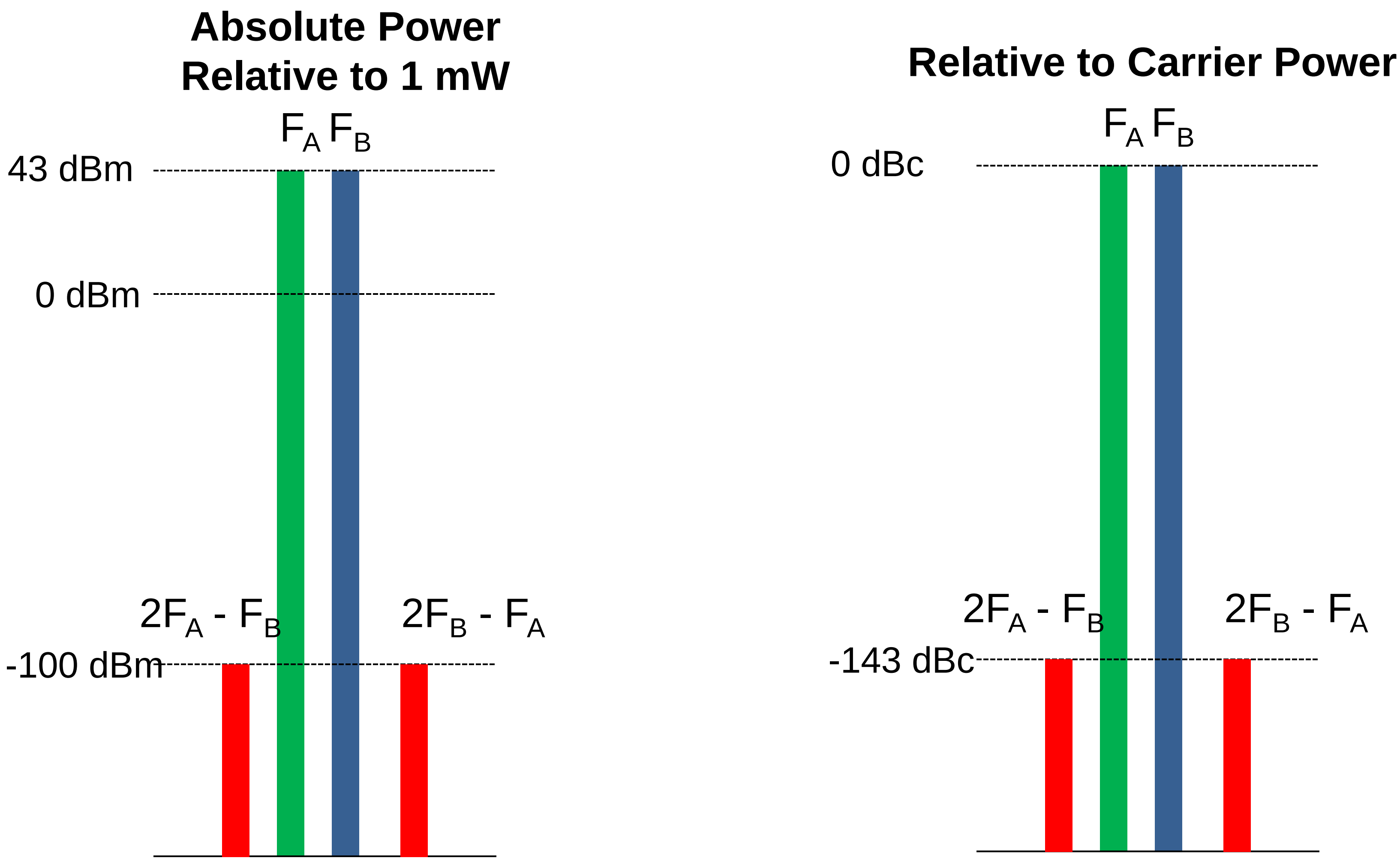


IM_3 = third order intermodulation product

IM_5 = fifth-order intermodulation product

PIM is measured as the relative difference between the amplitude of the intermodulation product & the amplitude of the carrier

PIM Measurement Scales



Units of ΔIM_3 are dBc: If you have a +43 dBm carrier & IM_3 measures -100 dBm, ΔIM_3 is -143 dBc

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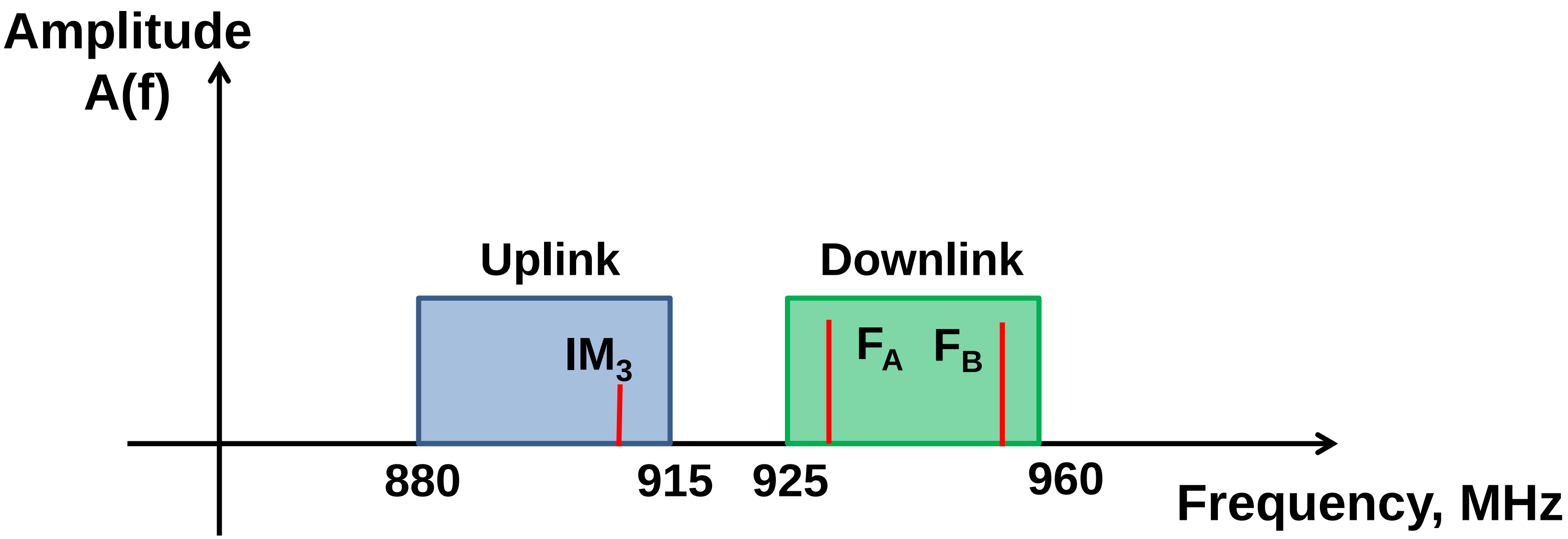
Effect of PIM

- **E-GSM 900 Band as an example**



If $F_A = 930$ & $F_B = 950$, $IM_3 = 910$ MHz is within the uplink band a source of interference

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PIM Bandwidth

- When carriers are modulated, as is the case for spread spectrum, transmitted signals have a finite bandwidth
- Intermodulation products have bandwidths multiplied by their product number—IM_3 has 3x bandwidth of carrier, etc.
- Result is wideband noise rather than isolated effects near the modulation frequency, with contributors (IM_3, IM_5, etc.) overlapping in frequency
- Frequency management prevents some PIM from falling within desired signal band but often is unavoidable

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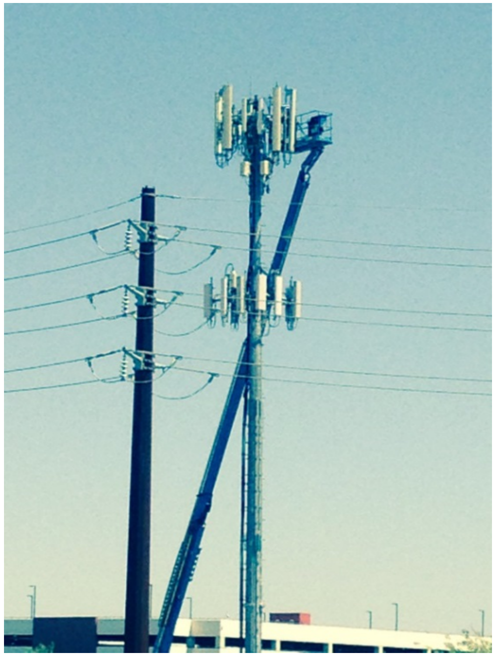
Implications of PIM

- **PIM produces signals in cell receive band, which will raise noise floor & increase the BER—resulting in reduction of cell coverage area & quality of service (dropped calls, slower data downloads)**
- **Field measurements show download speed decreased by 18% when PIM increased from -125 dBm to -105 dBm**
- **PIM can cause receiver blocking, effectively shutting down a sector**

PIM Sources & Physical Mechanisms in Communication Systems

PIM Producing Components

- Antennas
- Cables
- Connectors
- RF Components: Filters, duplexers, diplexers, circulators, TMAs
- Printed Circuit Boards
- Environmental Surroundings: Antenna support structure, nearby buildings



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PIM Sources

- Ferromagnetic materials (ferrites, nickel, steel, etc.) due to Hysteresis effect
- Contaminates including dirt, moisture or oxides on electrically conducting surfaces
- Inconsistent metal-to-metal contact
- Unmatched (galvanically) metals in contact
- Multipath with oxidized metal structures
- Stray metal particles from component installation of cable fabrication
- In PCBs, non-linear trace resistance & non-linear dielectric properties

Connectors

- Proper connector choice & care of connects is essential for good PIM performance
- Most common connector type is DIN 7/16 connector followed by Type N
- For low PIM, connectors must use non-ferrous materials
- Connectors degrade as a result of tightening & loosening & cause elevated PIM
- Impurities at connector mating surfaces degrade performance
- Improper torque results in elevated PIM—
  as much as 10-15 dB higher has been reported
- Metal-to-metal contact effects are the main sources of PIM

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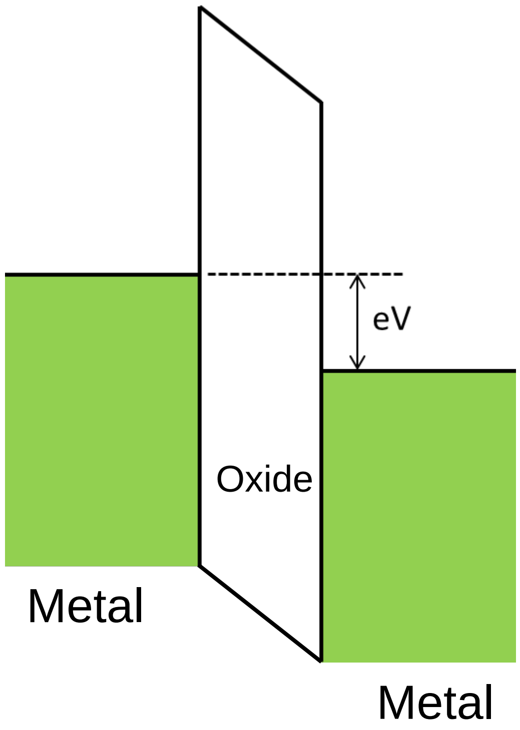
PIM Physical Mechanisms

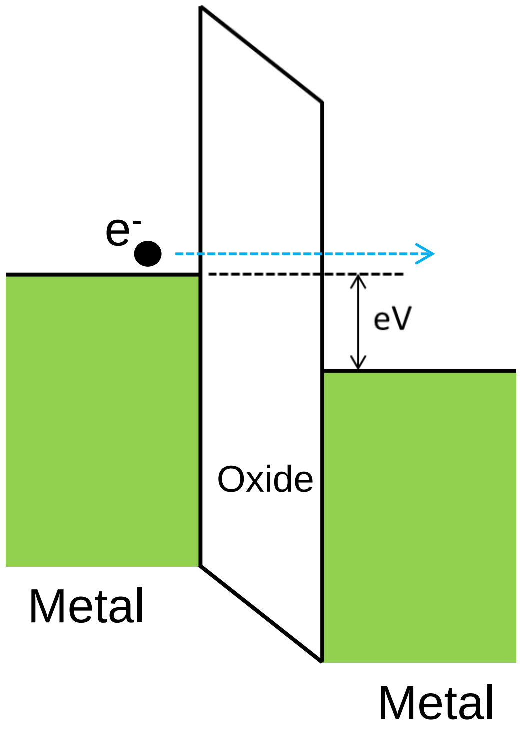
Metal to Metal Contact

- **Metals in "contact" are generally separated from each another by an oxide**
- **This oxide presents a potential barrier to electrons traveling from one side to the other**
- **Two mechanisms enable electrons to overcome the barrier**
  - Schottky Emission
  - Tunneling



Tunneling Effects

- **Electrons with insufficient energy to overcome the potential barrier can tunnel through**
- **Electron tunneling occurs with a finite probability, generating current**
- **This current is non-linear in nature & is a source of PIM**
- **Greater number of metal-insulator-metal sites implies higher PIM**



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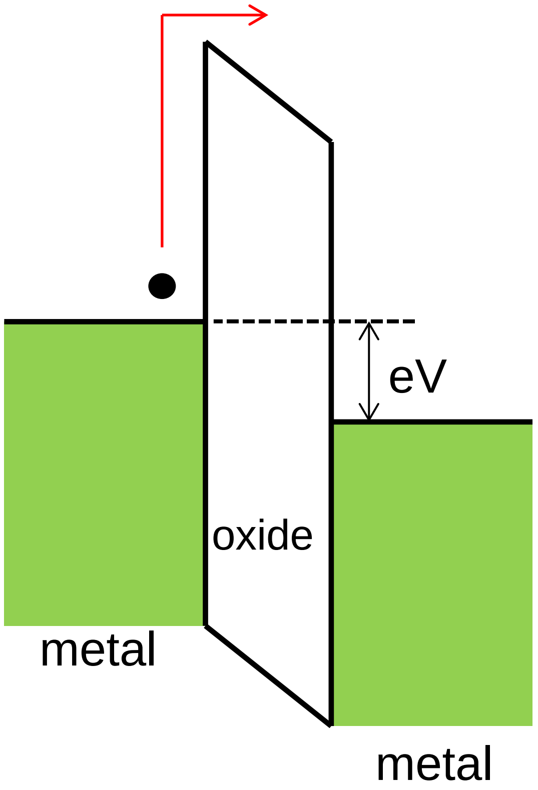
Schottky Emission

- **Schottky emission takes place when thermally activated electrons are injected over the potential barrier**
- **Presence of an electric field lowers the potential barrier**
- **The result is an increase in the current flow vs unbiased conditions**
- **This current is also nonlinear in nature contributing to PIM**



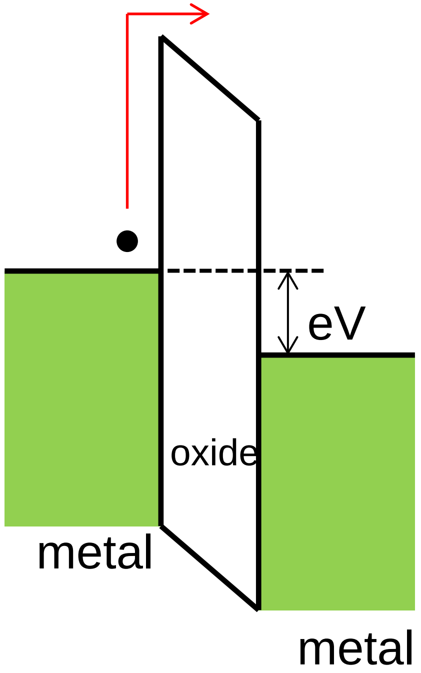
Schottky Emission

Current is described by modified Richardson Equation

$$J(E,T,W) = A_g T^2 e^{-(W-\Delta W)/kT}$$

$$\Delta W = (e^3 E/(4\pi\varepsilon_0))^{1/2}$$

E = electric Field
T = temperature
W = metal work function
K = Boltzman constant
A_g = Richardson constant*



Here, W replaced by (W- ΔW)

Electric field lowers the surface barrier by amount ΔW & increases the emission current

Constriction Resistance

- Constriction resistance results when current flows through a limited area between two metallic contacts
- Localized heating occurs as a result of the current bunching & changes the resistance
- The change in resistance is a non-linear effect & contributes to PIM

PIM Testing

Measurements

- **IEC 62037 is the PIM measurement standard**
- **Two tones at 43 dBm (20W) each are injected into the device under test & magnitudes of IM products are measured**
- **Measurements are typically performed in shielded enclosure to prevent interference but are also done in the field on cell towers**
- **Equipment**
  - Kaelus (Summitek) Instruments PIM analyzer
  - Anritsu PIM Master
- **High quality coax to microstrip transitions are required to evaluate PIM performance of PCB laminates**
- **On the same PCB Reverse PIM can vary by 10dB based on the transition type – cable launch vs edge connector**
- **Near-field field-probe is alternate test method**

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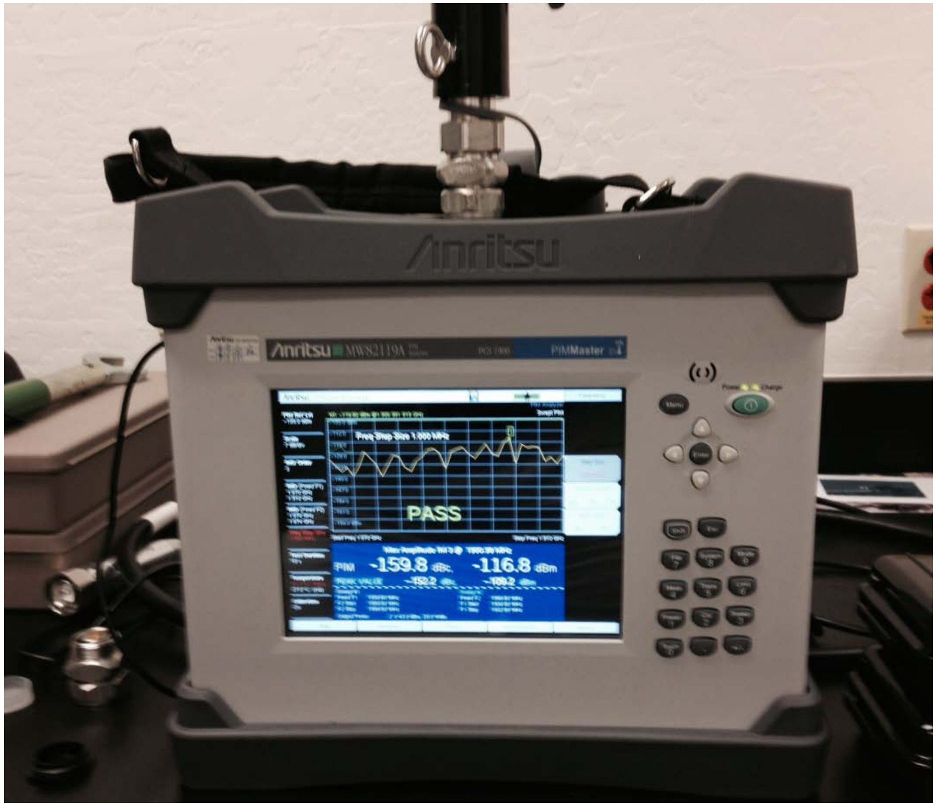
PIM Test Equipment

- **Anritsu PIM Master portable analyzer**
- **Provides swept PIM results**
- **Identifies PIM sources with Distance-to-PIM feature**



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Reverse PIM Testing

- For reverse PIM testing, two signals are sent to antenna & PIM levels are measured at same test port
- Most commonly, one of two signals is swept in frequency to avoid signal cancellation at a single frequency
- In the field, care must be taken with swept measurements so interference with service subscribers doesn’t occur
- This is the most common PIM testing

Forward PIM Testing

- **For forward PIM, signals are transmitted through antenna system & receive antenna & spectrum analyzer are used**
- **For improved accuracy & isolation tests on antennas are often performed in anechoic chamber**
- **Forward PIM measurements are not susceptible to cancellation when done in controlled environment**
- **Forward PIM not typically measured for installed antenna systems in field such as base station**
- **Forward PIM is also performed using a high rejection filter network on the output of the device under test to separate out PIM components**
- **Forward PIM tests are used to characterize PCB features responsible for PIM**

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Sources of PIM in PCBs

PIM in PCBs

- **Many technical papers have been published since the 1990s**
- **Yet, the mechanisms of PIM in PCBs are only partially understood**
  - Inconsistent measurements
  - Measurement-induced errors
  - Insufficient measurement device sensitivity
  - Incomplete PIM prediction models
- **General conclusions can be drawn from research to date**

General Conclusions

- **Forward PIM in PCBs is considered a distributed non-linearity and is cumulative**
  - Magnitude monotonically increases with transmission line length
- **Forward PIM decreases with increasing trace width**
  - Decrease in current density is believed responsible for this effect
- **Reverse PIM unaffected by line length and trace width but affected by input/output transmission line mismatch**
  - Results of cable launch vs DIN 7/16 connectors illustrate effect
- **Reverse PIM is generally lower than forward PIM**
- **PIM performance can be traced to physical characteristics of PCBs elements**

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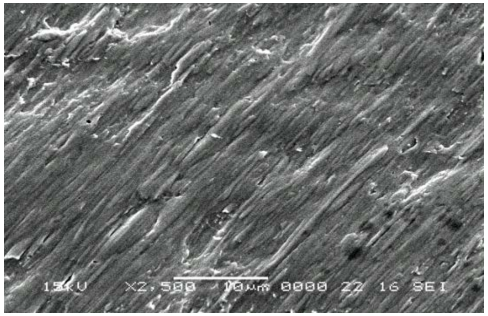
PIM in PCBs

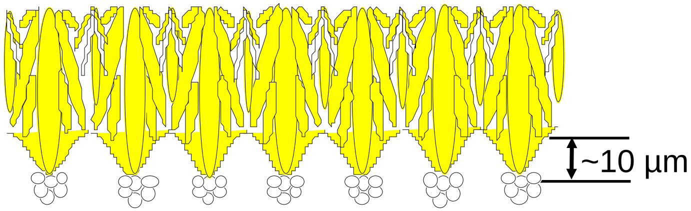
- **Quality of Copper**
- **Etched Trace Quality and Uniformity**
- **Dielectric Composition**

Copper Surface Roughness

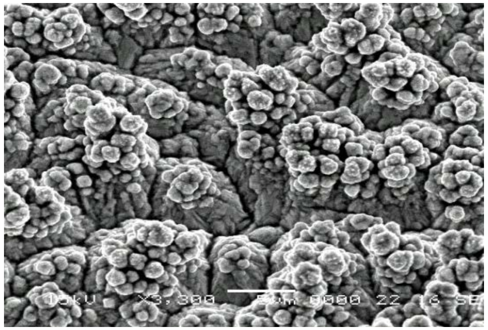
Resist side



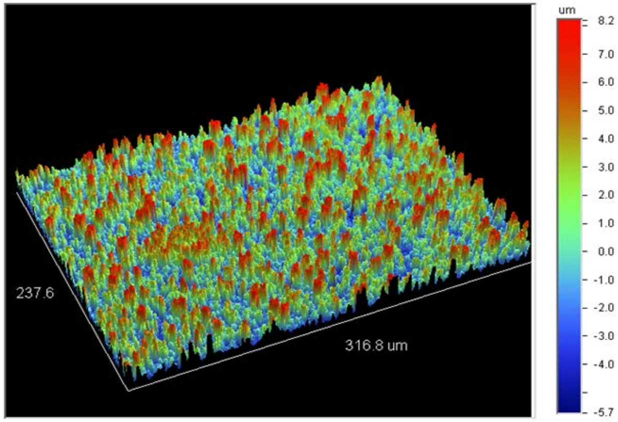
Standard foil



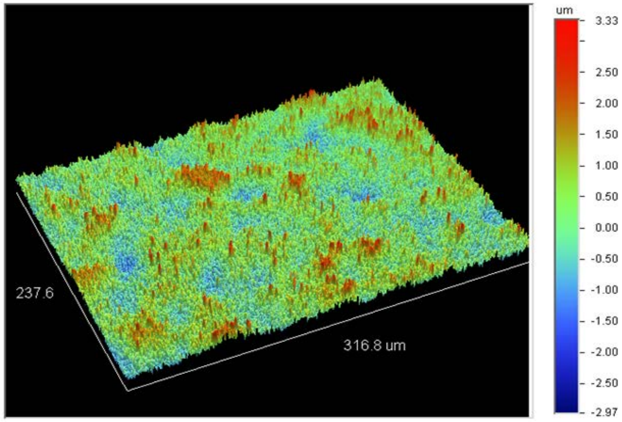
Bonding side



RTF: Rq=2.6 um, RF=1.85



VLP: Rq=0.68 um, RF=1.3



For PIM performance, copper quality means low-profile, fine crystalline structure and absence of impurities

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Etched Trace Quality

- Quality of etching strongly affects PIM performance
- Rough and fractured edges of a trace can create sites for contamination
- Poor quality edges create voids and can degrade the finish coating
- Trace width variations can increase non-linear thermo-resistance effects

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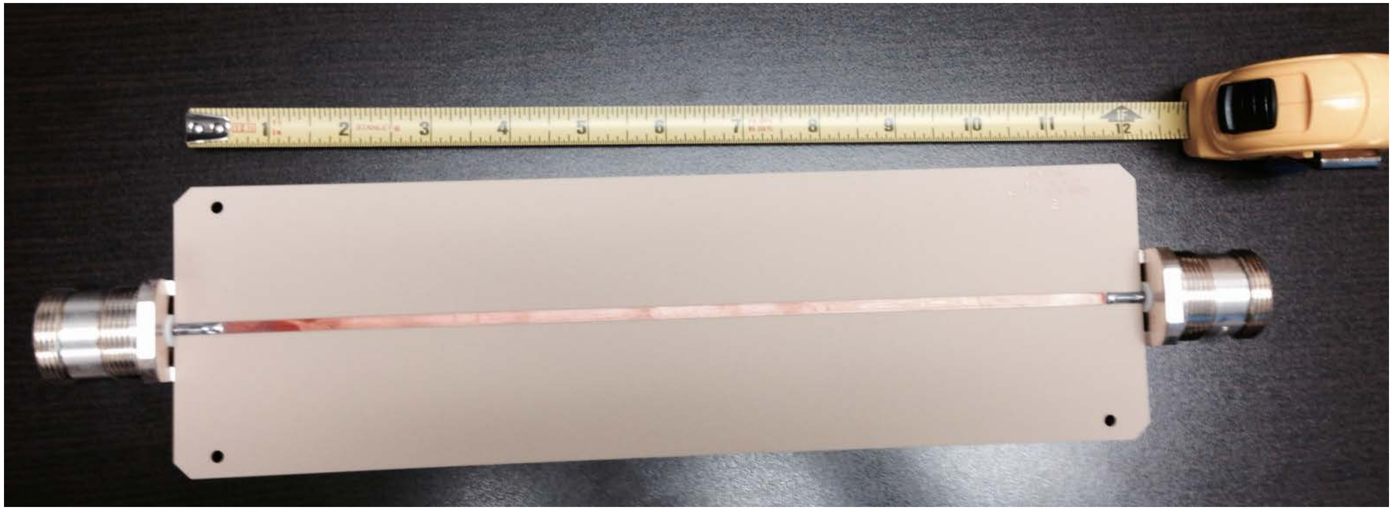
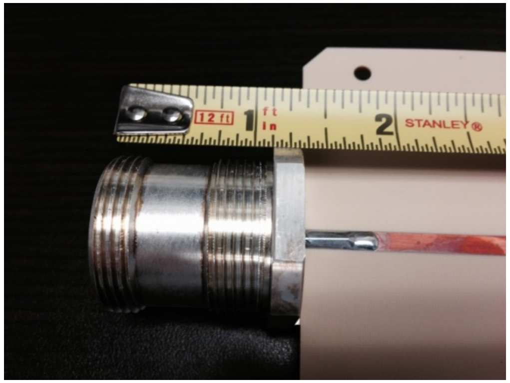
Dielectric Composition

- **Materials of various compositions and ranges of Dk, Df have been measured to assess impact on PIM**
- **General conclusions from research indicate**
  - Materials with high moisture absorption have worse PIM performance
  - Presence of fillers can increase PIM
  - Dielectric materials with lower Df tend to have lower PIM but is more of a secondary effect vs the effects of copper traces
  - Change in crystallinity associated with PTFE-based laminates is bad for PIM stability over time

PIM Test Board





Typical single-trace PIM test board using DIN 7/16 connectors

PIM Mitigation in PCBs

Mitigating PIM in PCBs

- **Choose low-profile copper**
  - Rough copper is more prone to defect trapping & non-linear thermo-electric effects
- **Use thicker copper than you might ordinarily use while maintaining low profile**
  - Better thermal performance, fewer non-linear thermal resistive effects
- **Use laminates with low dielectric loss & those without ceramic fillers—some are ferroelectric**
- **Use "PIM-friendly" finish coating such as immersion tin**
- **To achieve good PIM performance over time, avoid PTFE-based products**
- **Optimize circuit layout to minimize PIM generation**
  - Minimize sharp bends in traces and features causing current to concentrate

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Fabrication Concerns

- **Using the same base materials, different fabricators can yield circuit boards having vastly different PIM performance**
- **There are two major contributors to the differences seen**
  - Etch quality of lines
  - Introduction of impurities
- **These risks can be mitigated through proper quality control**

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References

- "Understanding PIM Application Note", Anritsu, http://www.anritsu.com/en-US/Products-Solutions/Solution/Understanding-PIM.aspx
- Nash, Adrian, "Intermodulation Distortion Problems at UMTS Cell Sites", Aeroflex Wireless Test Solutions, Burnham
- Jargon, Jeffrey A., DeGroot, Donald C., Reed, Kristopher L., "NIST Passive Intermodulation Measurement Comparison for Wireless Base Station Equipment", 52nd ARFTG Conf. Digest, pp. 128-139, Rohnert Park, CA, Dec 3-4, 1998.
- Shitvov, A., Olson, T., Schuchinsky, A., "Current Progress in Phenomenology & Experimental Characterization of Passive Intermodulation in Printed Circuits"
- Shitvov, A., Olson, T., Schuchinsky, A., "Effect of Laminate Properties on Passive Intermodulation Generation"
- Shitvov, A., Zelenchuk, D., Olson, T., Schuchinsky, A., "Transmission/Reflection Measurements & Near-Field Mapping Techniques for Passive Intermodulation Characterization of Printed Lines"
- Shitvov, A., Zelenchuk, D., Schuchinsky, A., Fusco, V., "Passive Intermodulation in Printed Lines: Effects of Trace Dimensions & Substrate", IET Microw. & Antennas Propag., 2009, Vol. 3, Iss 2, pp. 260-268
- Crowell, C. R. (1965). "The Richardson constant for thermionic emission in Schottky barrier diodes". Solid-State Electronics 8 (4): 395–399. Bibcode:1965SSEle...8..395C. doi:10.1016/0038-1101(65)90116-4.
- Orloff, J. (2008). "Schottky emission". Handbook of Charged Particle Optics (2nd ed.). CRC Press. pp. 5–6. ISBN 978-1-4200-4554-3.

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