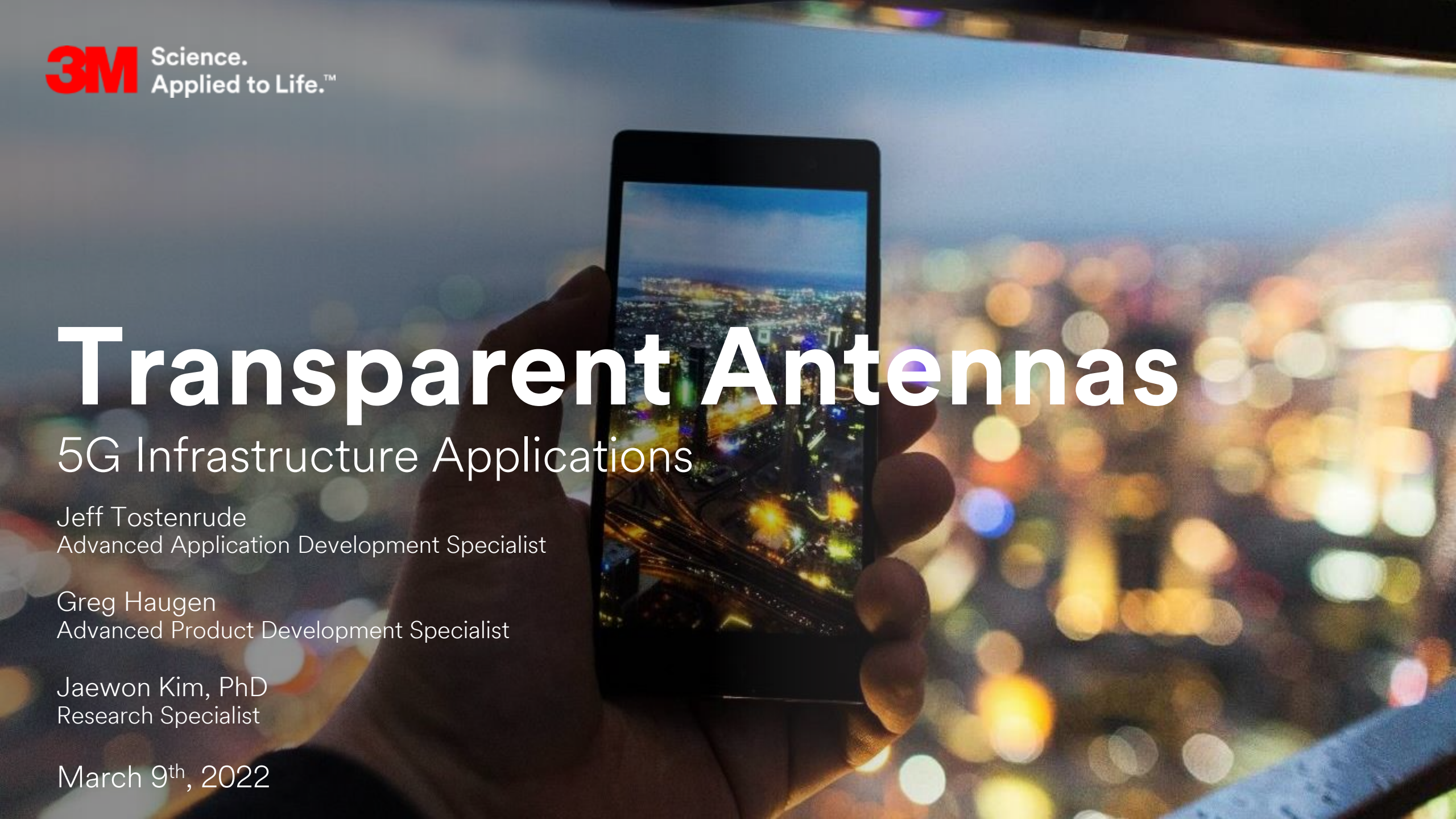


3M Science. Applied to Life.™

Transparent Antennas

5G Infrastructure Applications

Jeff Tostenrude
Advanced Application Development Specialist

Greg Haugen
Advanced Product Development Specialist

Jaewon Kim, PhD
Research Specialist

March 9th, 2022

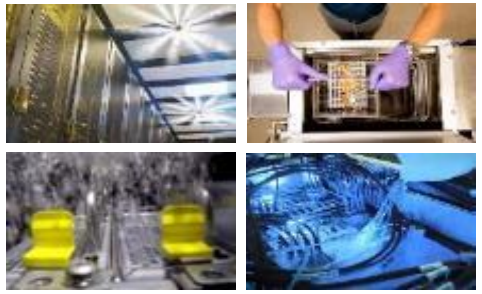
3M at a glance

- Sales in nearly every country
- $32.8 billion in sales
- Four business groups
- 90,000 3Mers globally
- 117,000 patents
- 100+ years of dividends
- One of 30 companies on the Dow Jones Industrial Index

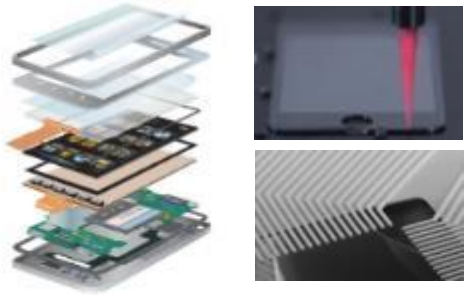
Electronics Materials Solutions Division

What we do

Help enable our customers' next generation of technology



Fluids for sustainable fire protection, cleaning, cooling, coating, formulating, and insulating gases



Engineered tapes, adhesives, thermal management, EMI/EMC and cushioning materials for electronic devices

Materials for semiconductor and LED processing, packaging and transport

Fiber optic and copper interconnect for signal management

Market segments served

Electronics industry from semiconductor production and transport, to device assembly and data center

Key 3M Technologies

TODAY & TOMORROW

- Ab — Abrasives
- Ad — Adhesives
- Em — Electronic Materials
- Fi — Films
- Mr — Micro-replication
- Lm — Light Management
- Fl — Fluoro-materials
- Ce — Ceramics
- Es — Electronic Systems
- Ms — Modeling & Simulation

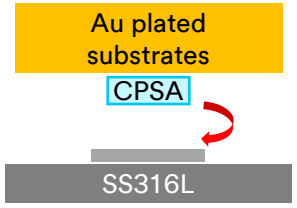
Communications Infrastructure

Developmental materials

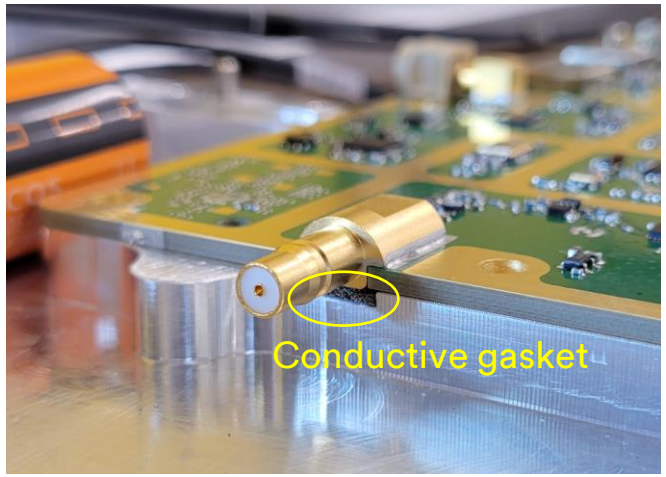
Electrically Conductive Pressure Sensitive Adhesives, Gaskets, and EMI Absorbers

Shield Can Lid Tape

Low-PIM Bonding

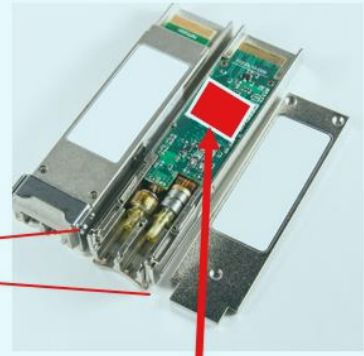


Grounding



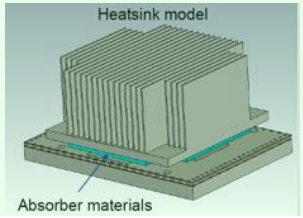
Thermally Conductive mmWave EMI Absorber

Optical Transceivers

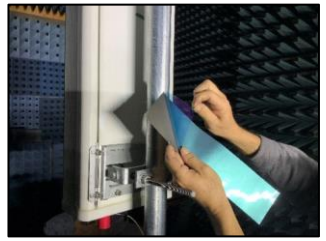


Thermal and EMI control opportunity

Other examples: Under heatsinks, RFIC isolation, etc.



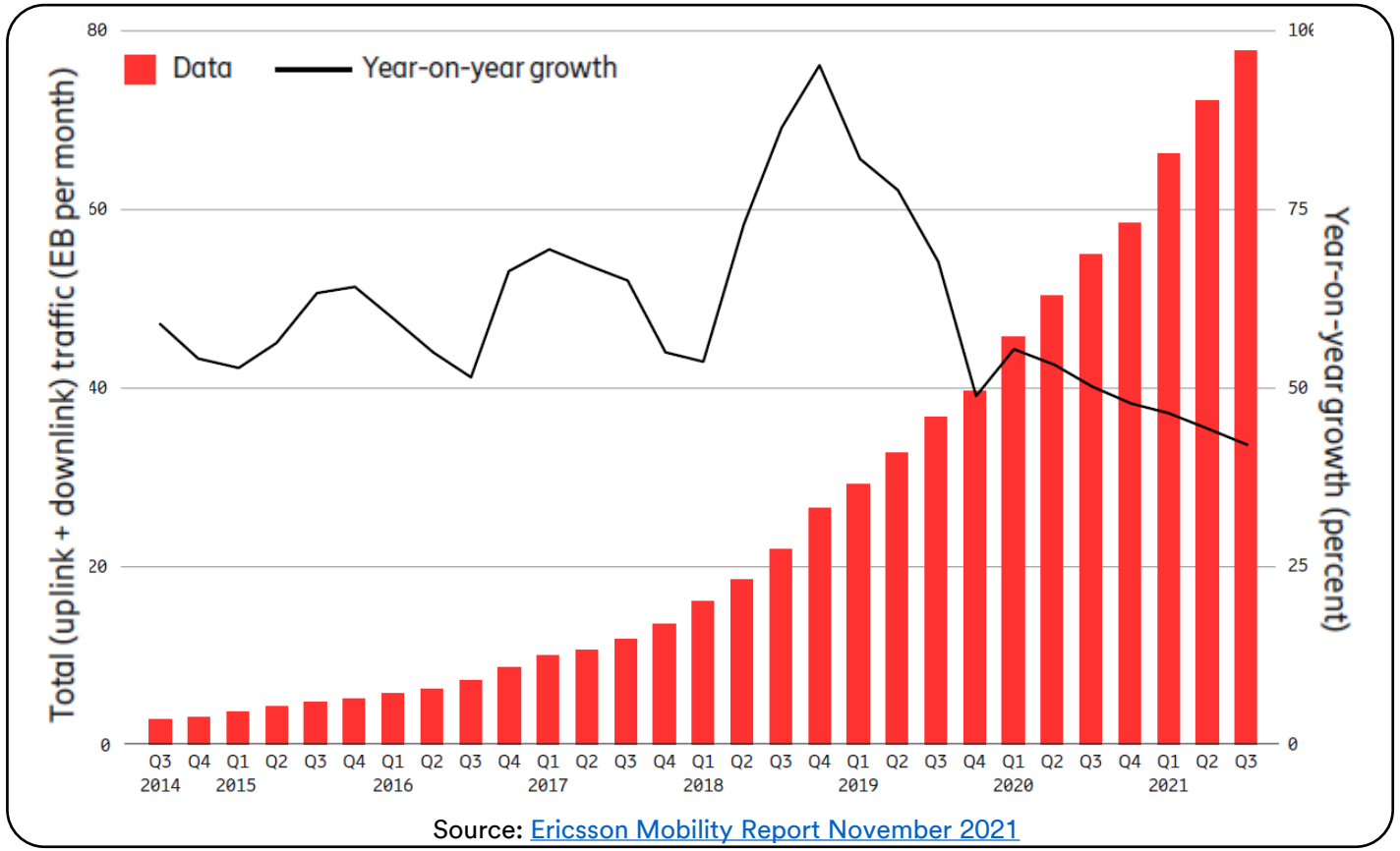
Electrically conductive films and magnetic absorbers for PIM mitigation



Demand for Transparent Antennas

- 4G/5G network densification
- Increasing spectrum allocations
- Increasing data utilization
- Antenna concealment requirements

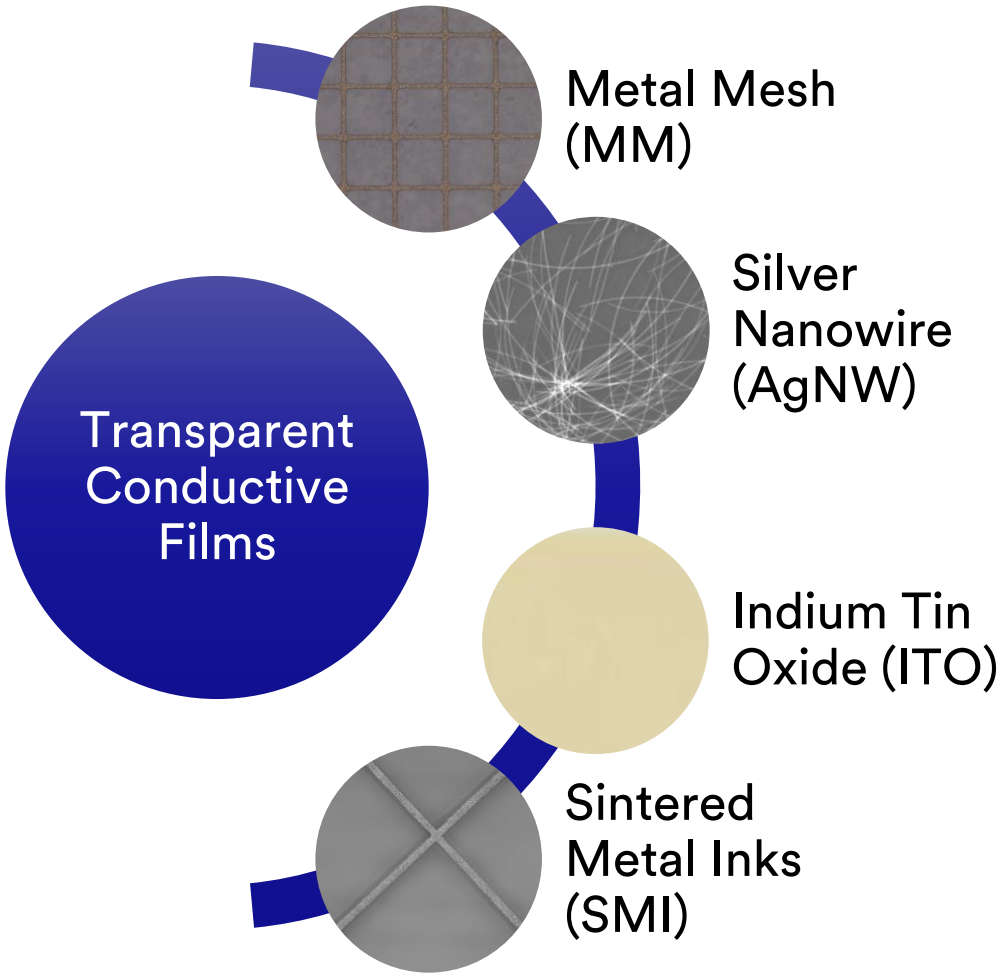
<u>More antennas will be required,</u>
<u>but must be inconspicuous</u>



Source: Ericsson Mobility Report November 2021

The proliferation of antennas is driven by these factors
Solution ➔ Transparent antennas

Transparent Conductive Films



Key Characteristics

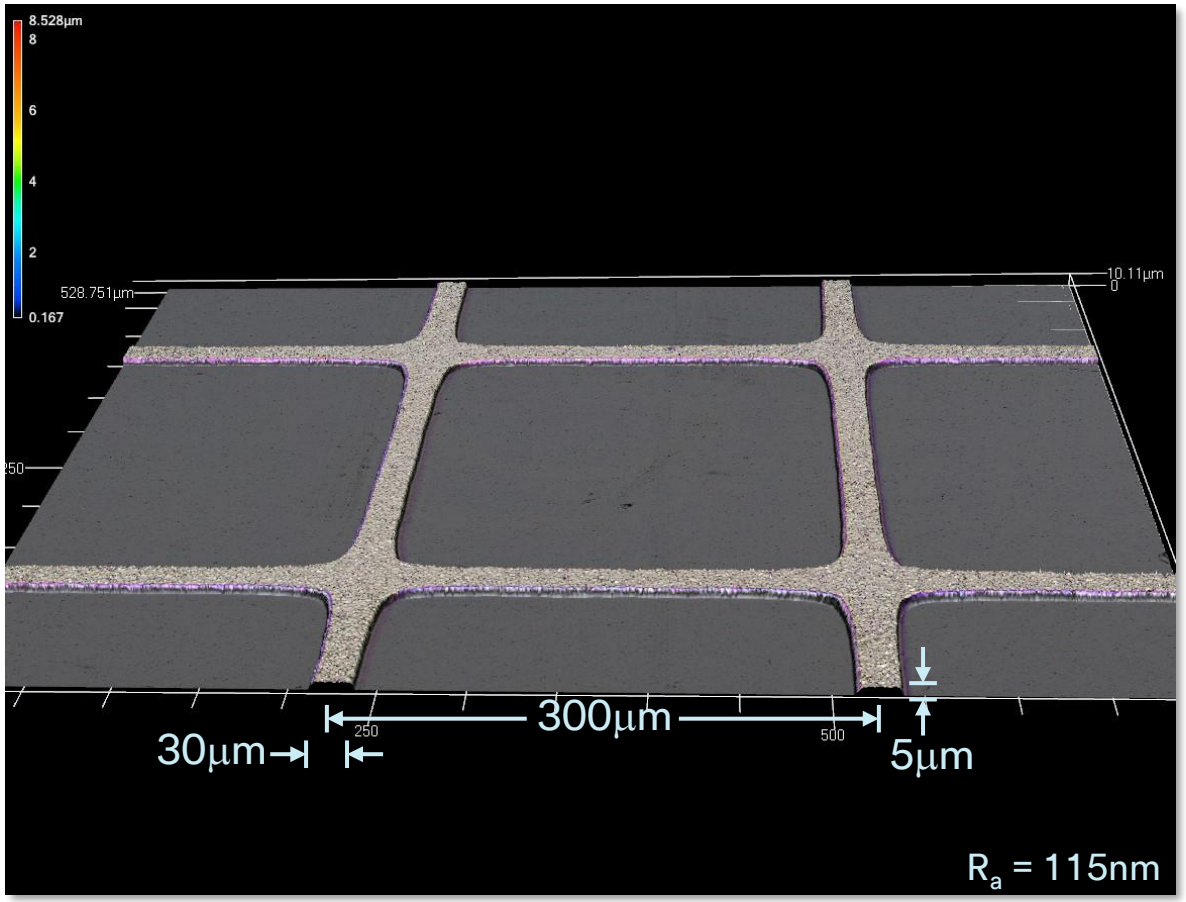
Property	MM	AgNW	ITO	SMI
Sheet resistance				
PIM				
VLT				
Power				
Haze				
Color				

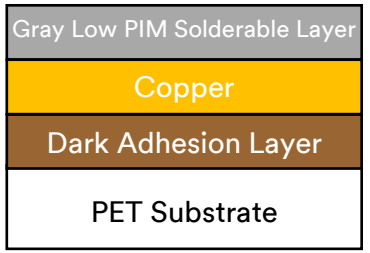
Excellent Poor Unacceptable

Metal mesh film exhibits properties that are advantageous for antenna applications

3M Transparent Conductor Film Properties

Typical configuration



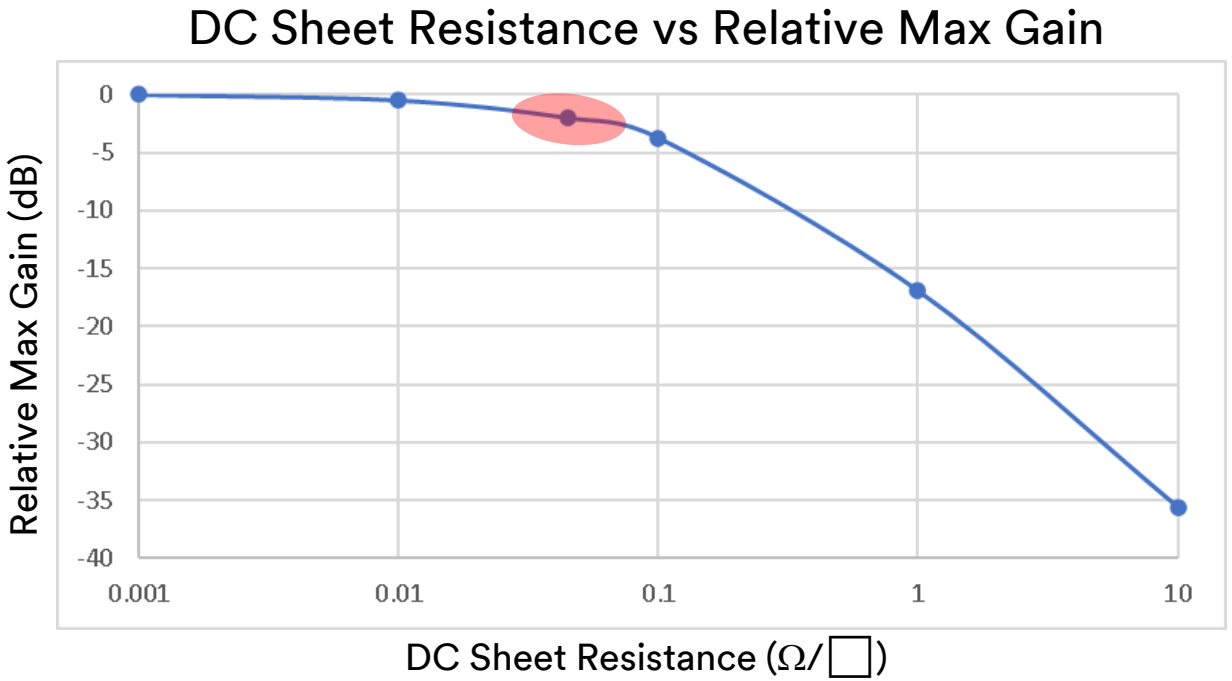


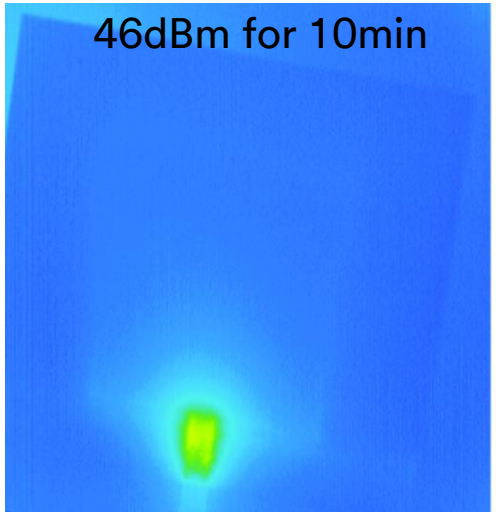
Not to scale

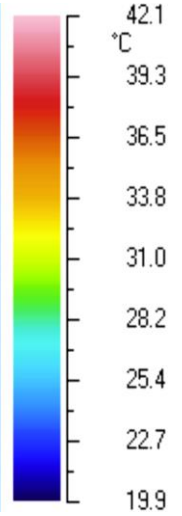
Property (typical)	Value
Sheet resistance	<0.05Ω/□
Substrate material	PET
Substrate permittivity, ε', ε'' (@1GHz)	3.22, 0.021
Open area for light transmission	80%
Haze	<2%
Minimum Bend Radius	10mm
Temperature Range	-40 to +100 °C
Antenna Example:	
Supported Frequency Range	3GPP FR1
PIM (2 x 43dBm)	<-153dBc
Max Power Demonstrated	50W cont.

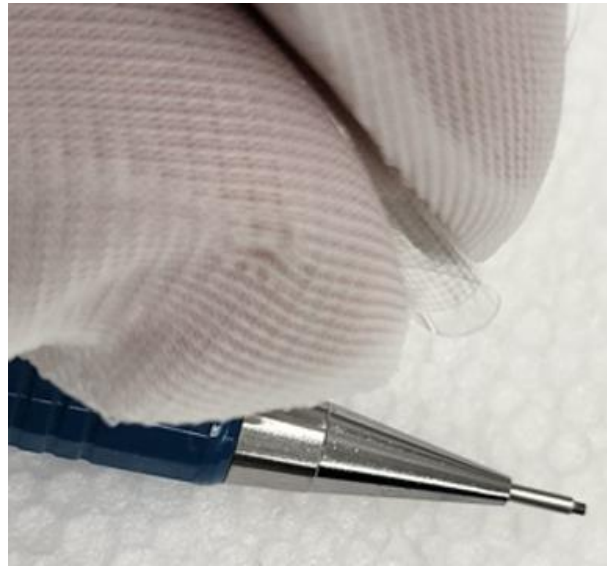
3M Transparent Conductor Film Performance

Low sheet resistance is required to achieve high gain





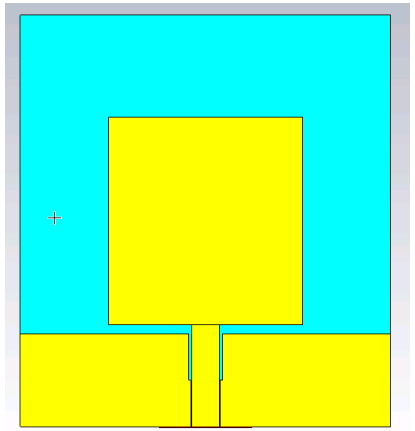


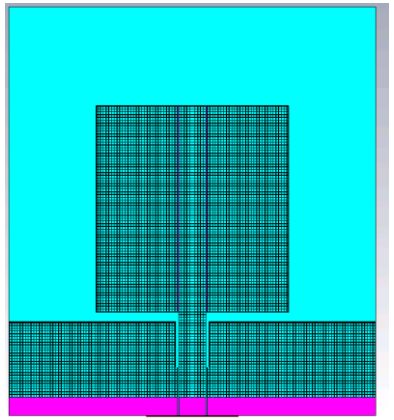


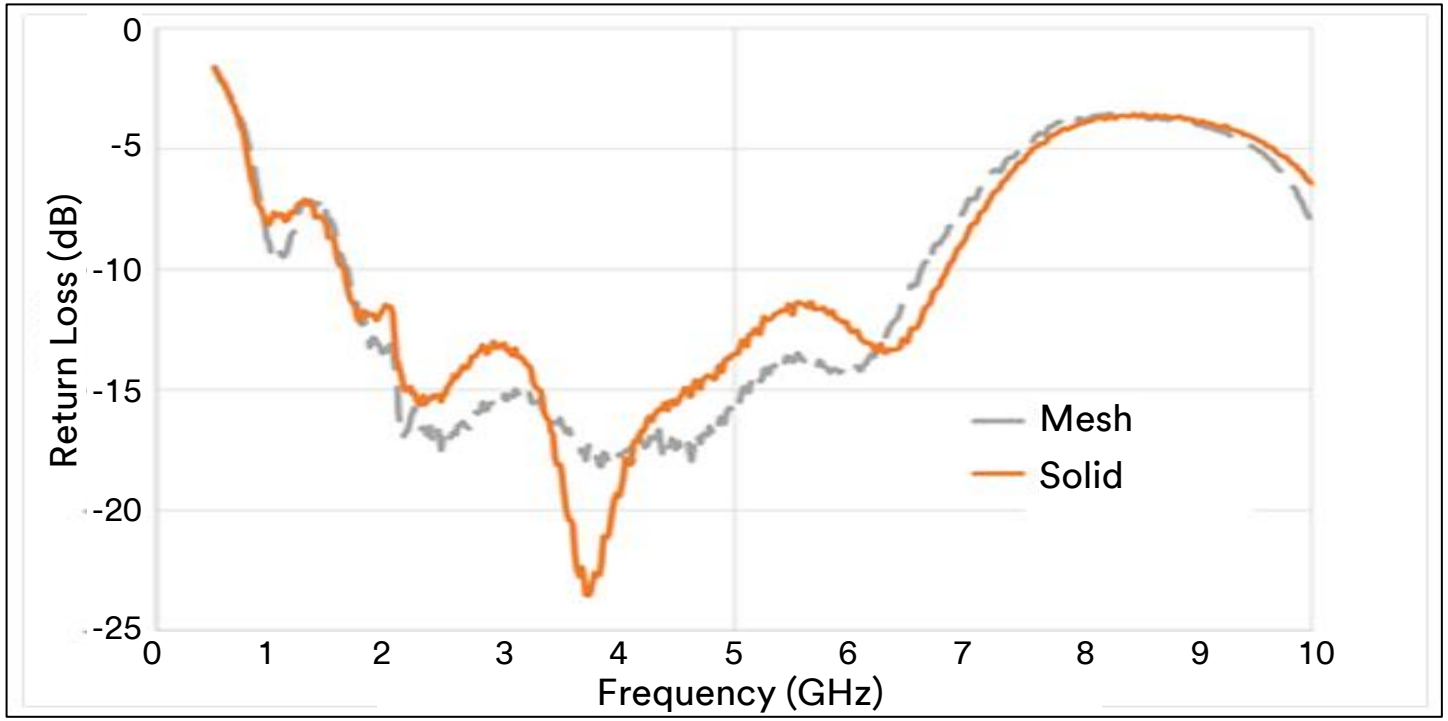
- Performance data for specific antenna designs included in later slides

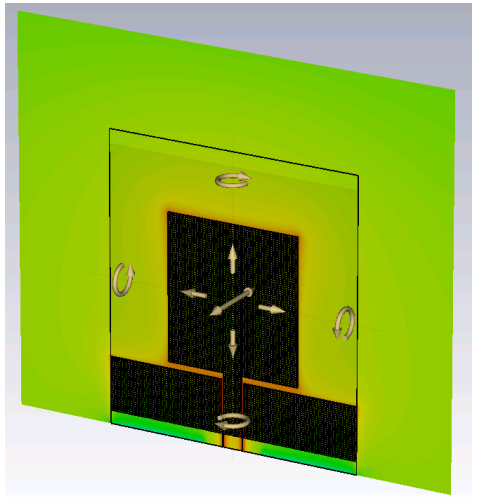
Metal Mesh vs Solid Copper Antenna Design

Metal mesh antennas can perform almost identically to solid Copper





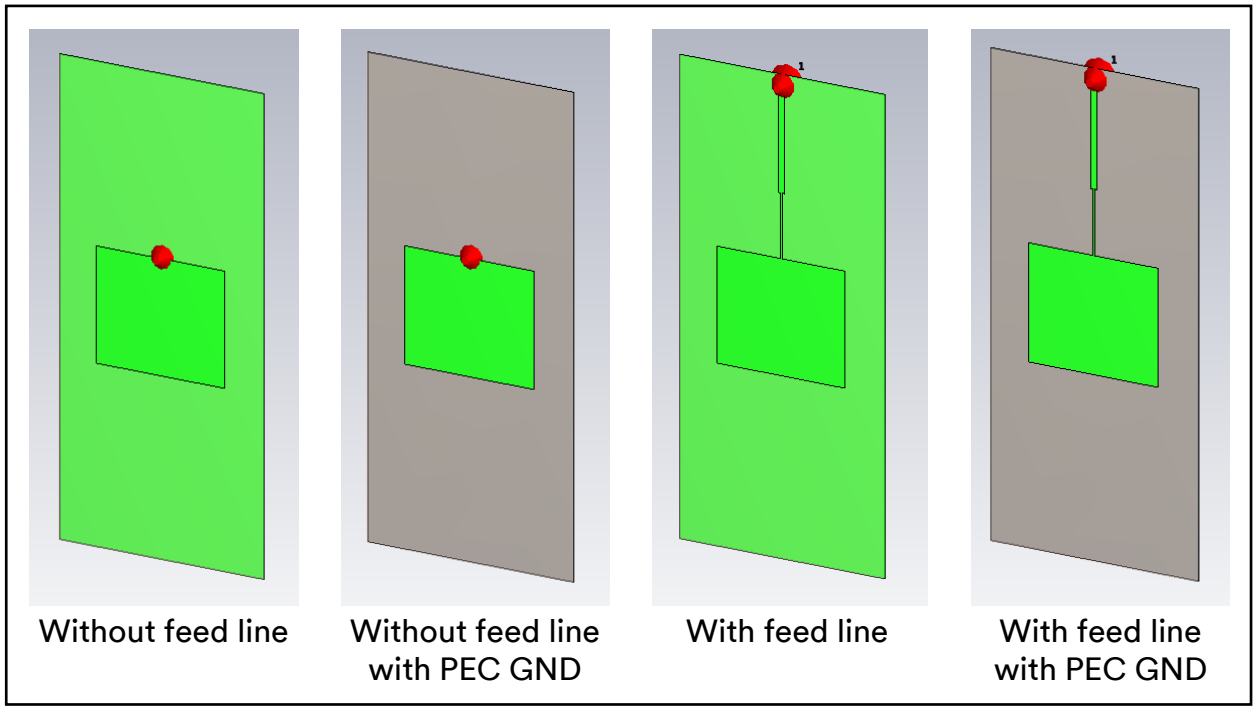




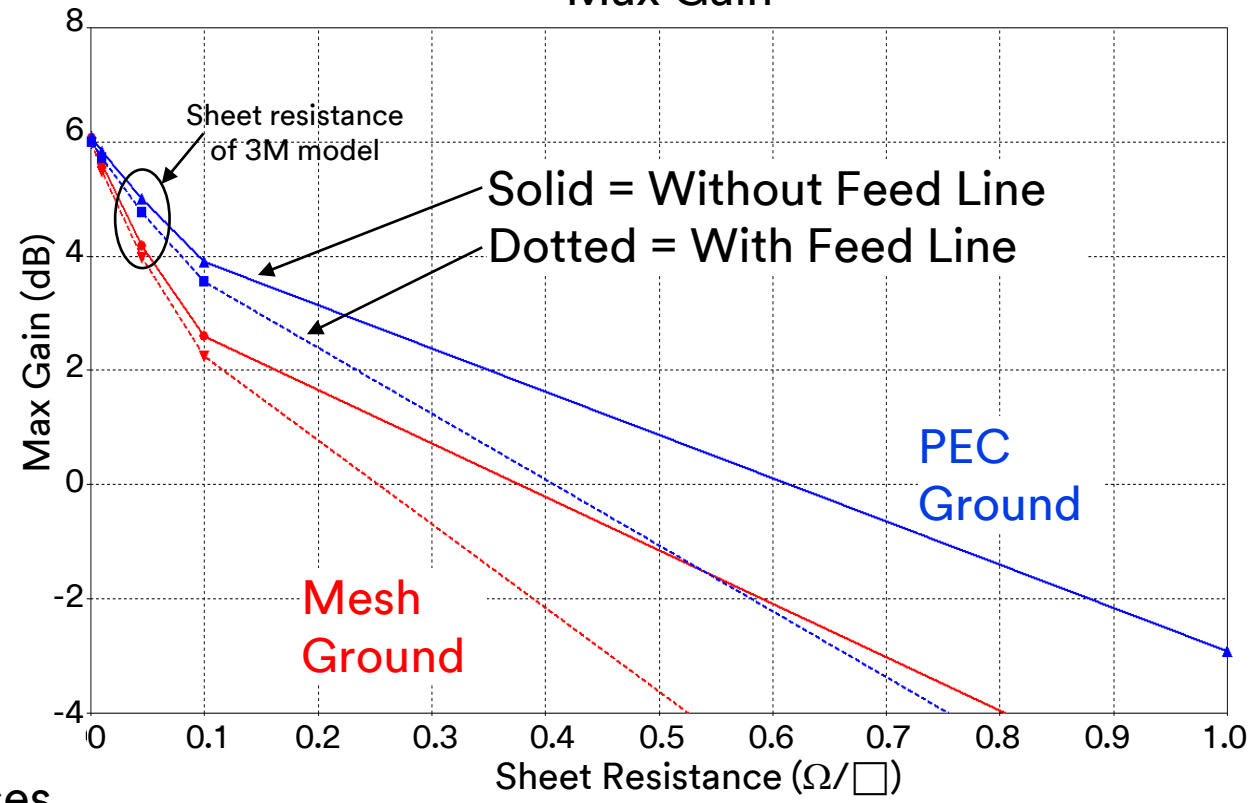
Effect of Feed Line Length/Resistivity

Antenna gain modeling results with sheet resistance sweep from 0.001 to 1 Ω/□

3M Reference Patch Antenna Models



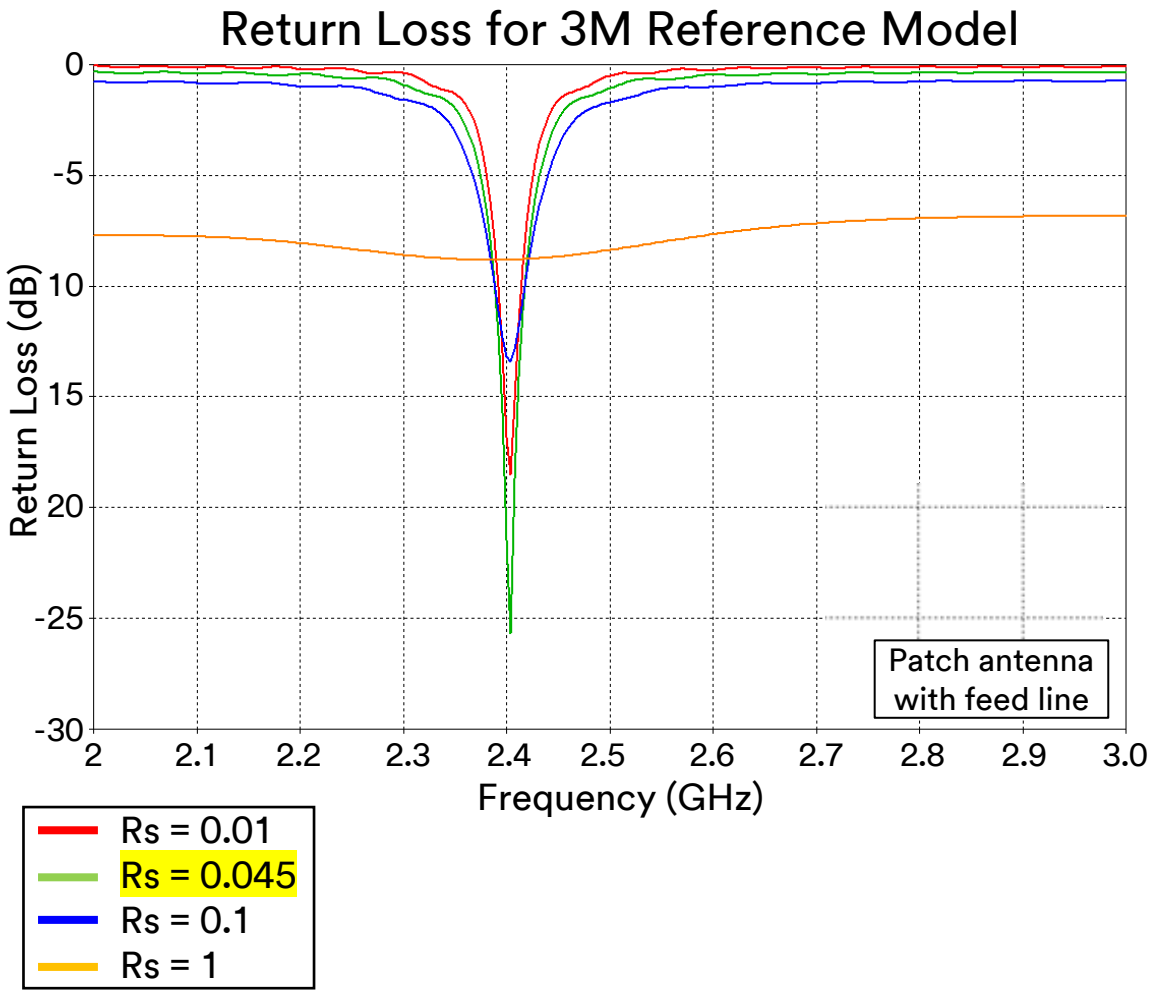
Max Gain

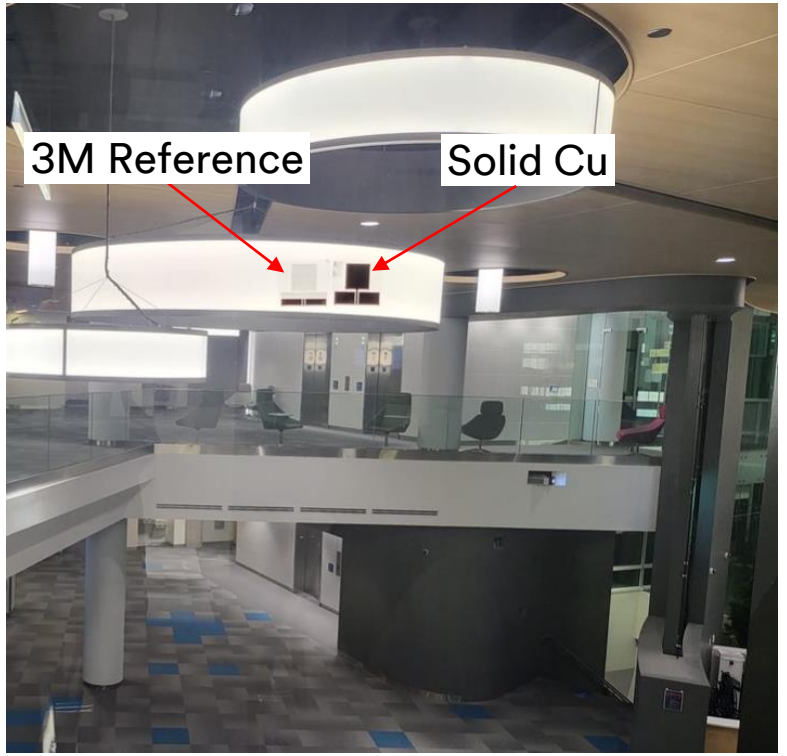


- Gain is reduced dramatically as sheet resistance increases
- Antennas have been created with up to 13dBi gain with this material

Effect of Feed Line Length/Resistivity

Return loss modeling results with sheet resistance sweep from 0.001 to 1 Ω/□





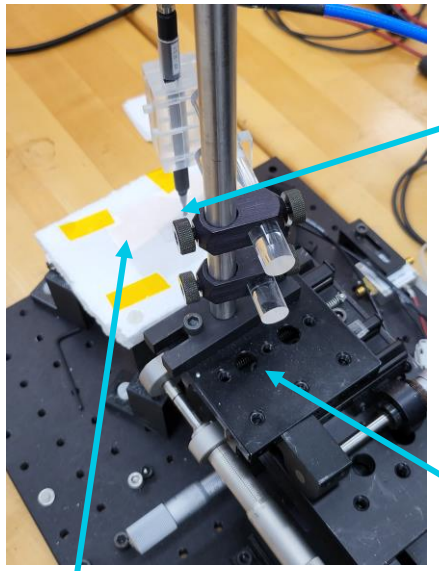
3M Reference antenna tuned for 2.4GHz

- Impact of feed line is mitigated by low sheet resistance
- Feed line length should be minimized when possible
- High conductivity required for antenna applications

3M PIM and Antenna Design Analysis

Highest IM3 PIM at hottest area (highest current density)

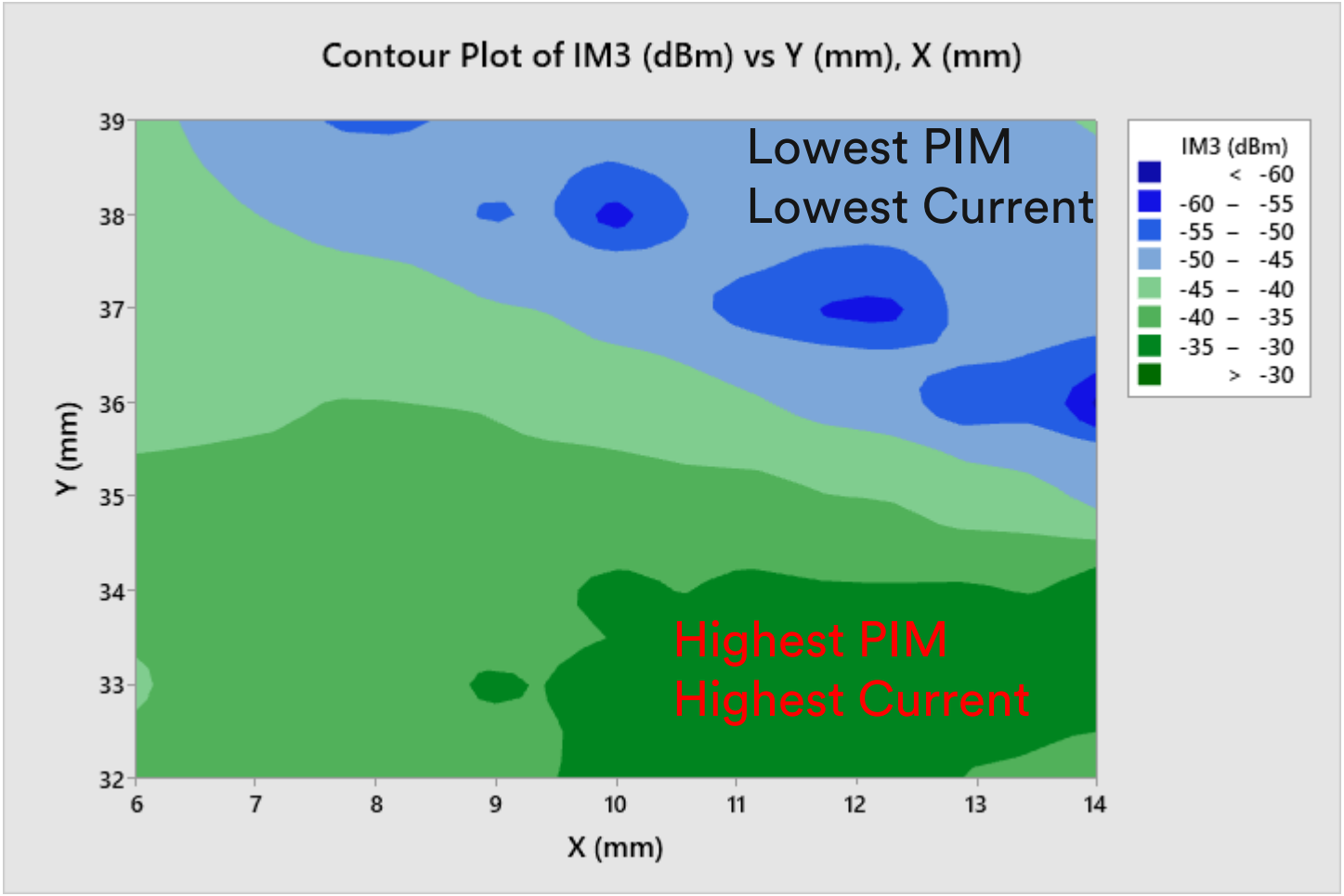
IR Camera



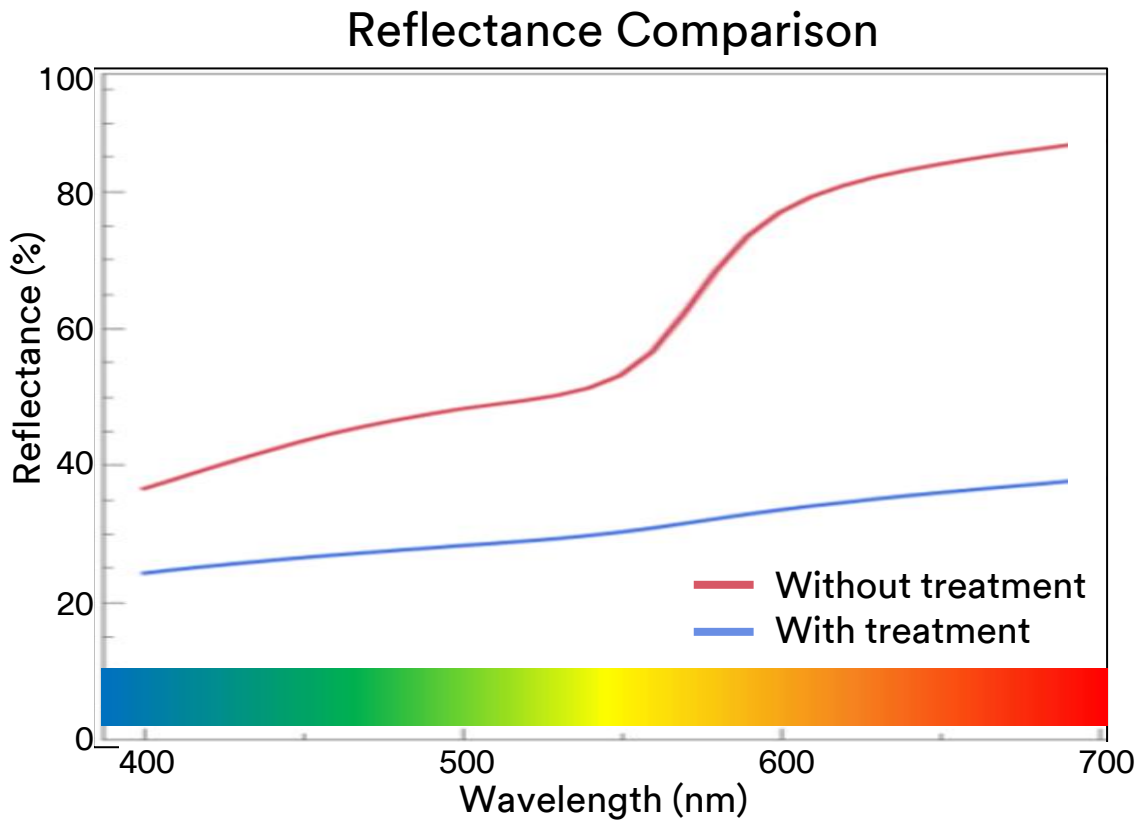
Field probe connected to spectrum analyzer optimized at IM3 Frequency

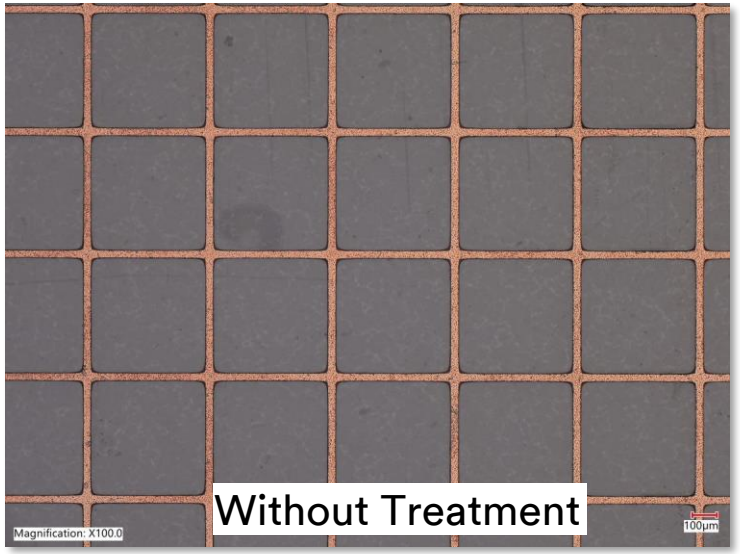
X, Y, Z positioners

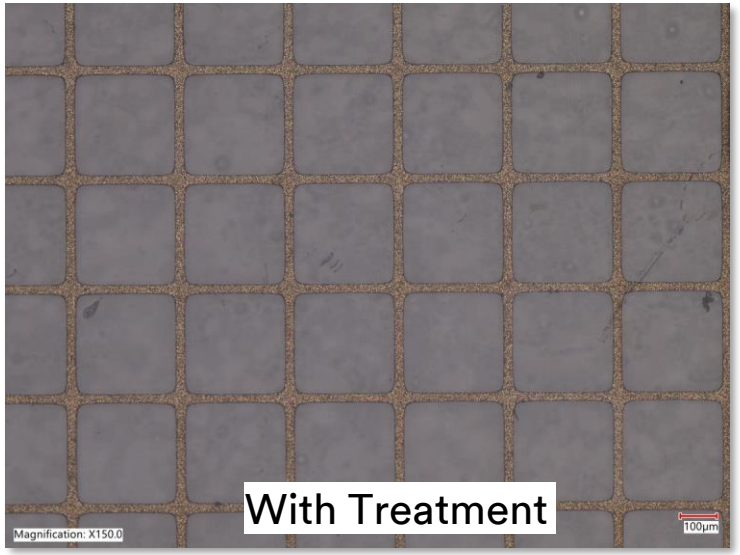
DUT



Surface Treatment

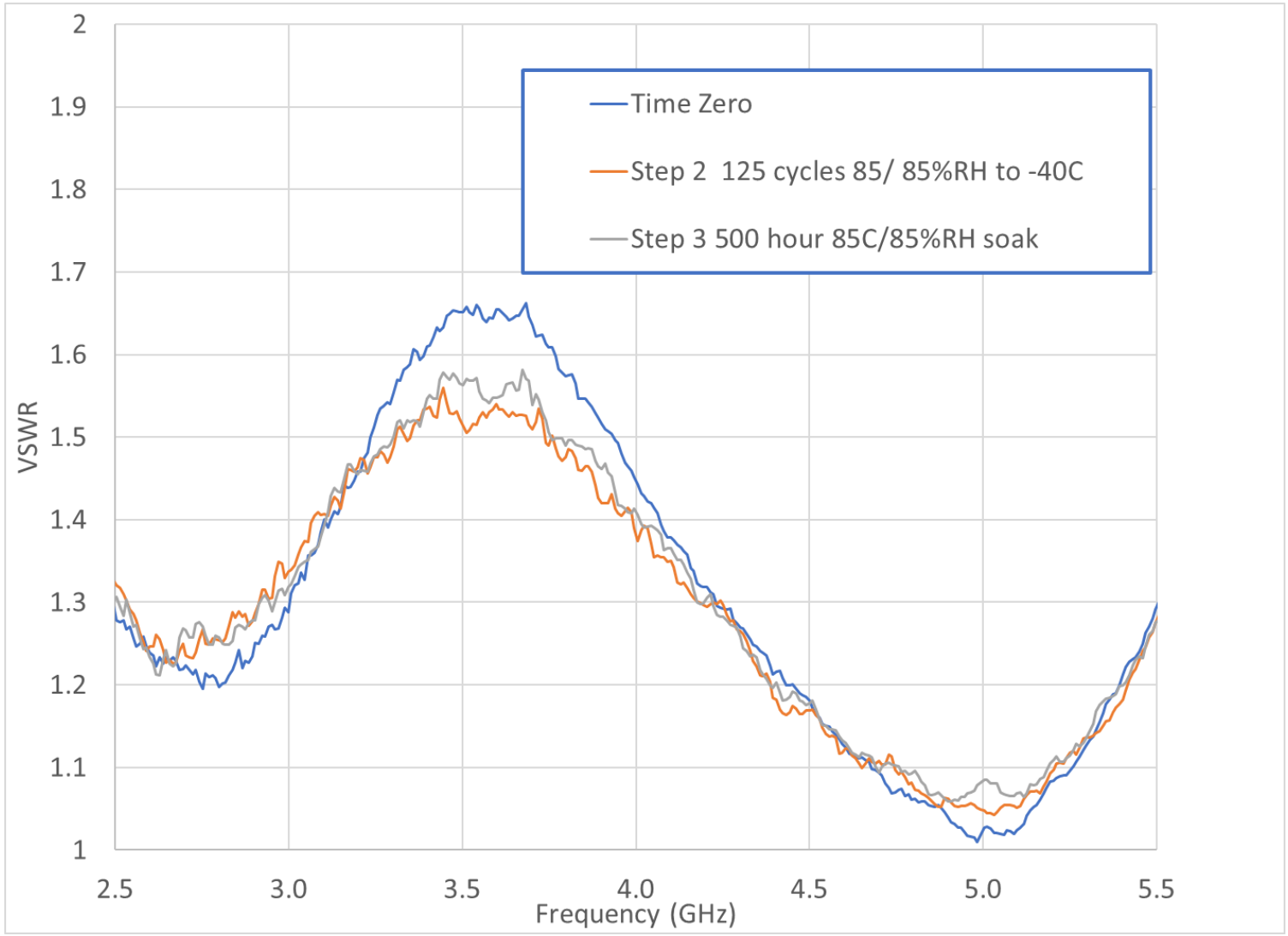






- Reference metal mesh configuration results in 80% “open area”
- However, some light is reflected, and Copper color can be apparent
- Treatment inhibits oxidation and enhances environmental robustness

Accelerated Aging – Stable Transparent Conductor Film



Test points

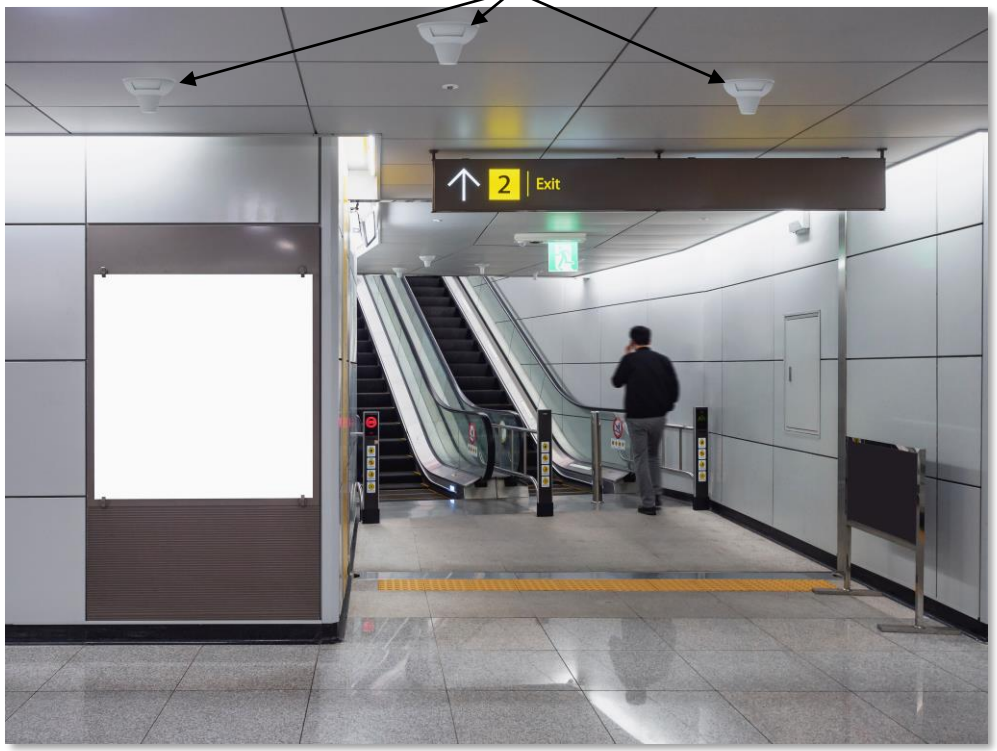
- **Step 1** - Time Zero
- **Step 2** - After 125 thermal cycles -40C/dry to 85C/85%RH soak for one hour at endpoints.
- **Step 3** - Then after 500 hours 85C/85%RH soak.

Applications in Communications Infrastructure

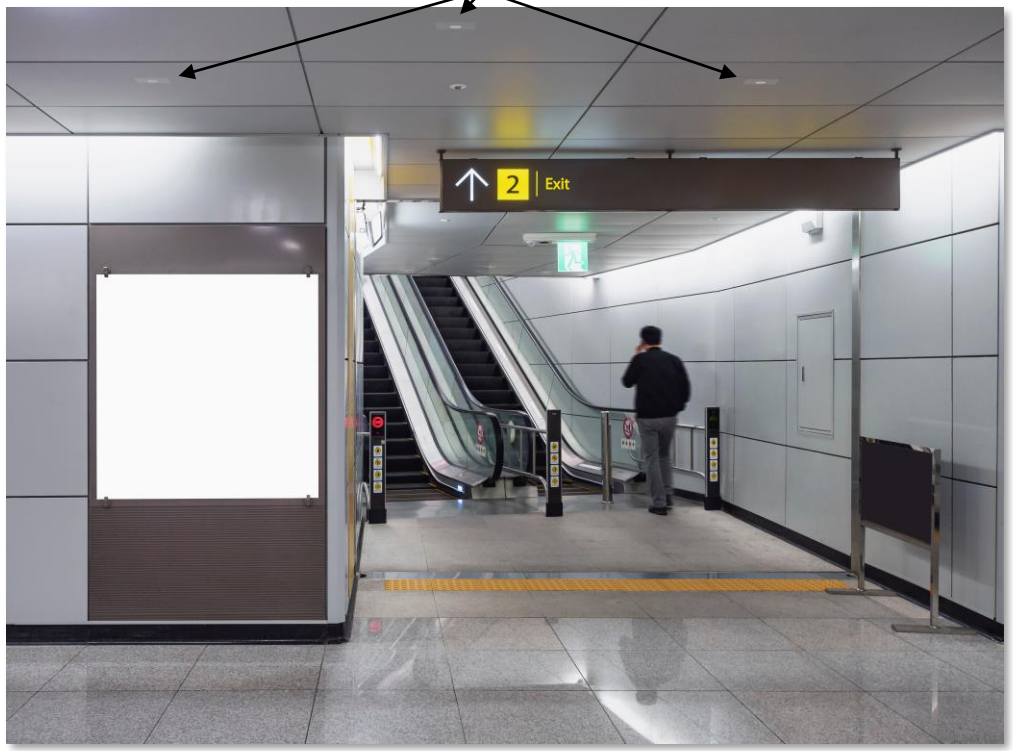
Many potential applications in Communications Infrastructure, supporting LTE, 5G, WiFi 6/6E

- Indoor
  >80% of mobile data traffic
- Private Networks
  Airport, campus, factory, etc.
- Outdoor DAS

Conventional antennas



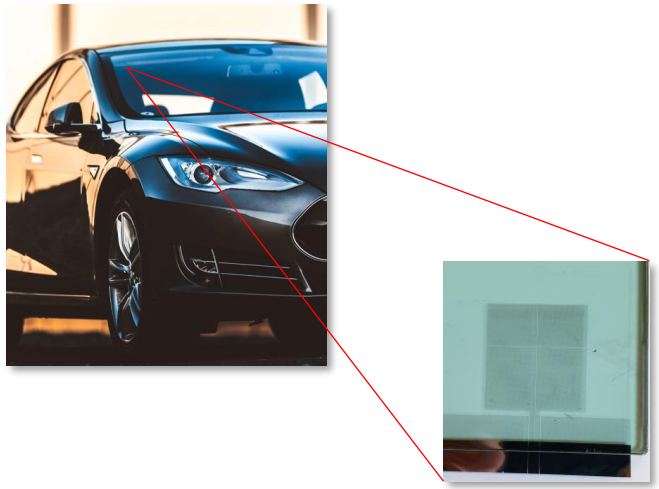
Transparent antennas



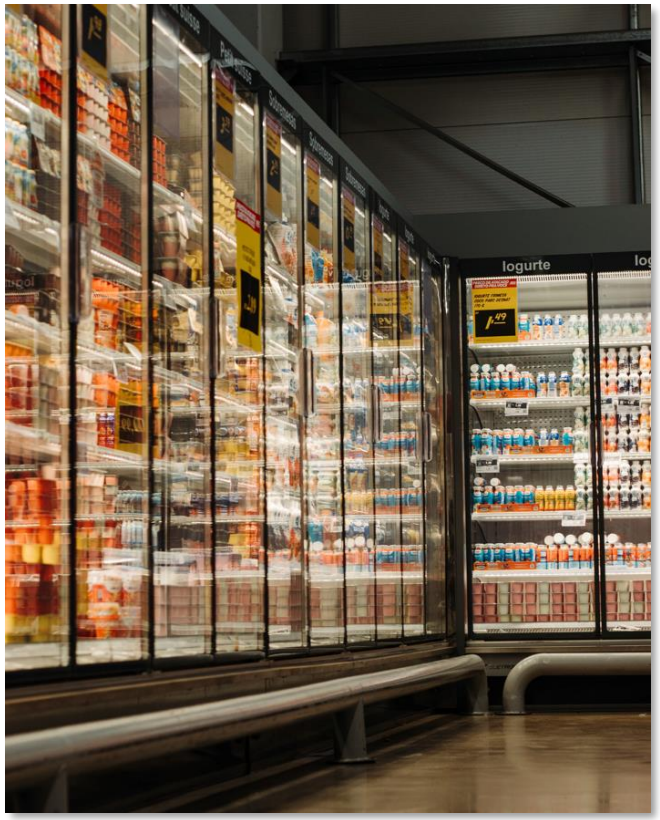
Potential Alternative Use Cases

Applications for transparent antennas are not limited to infrastructure…

Automotive



IoT Sensors

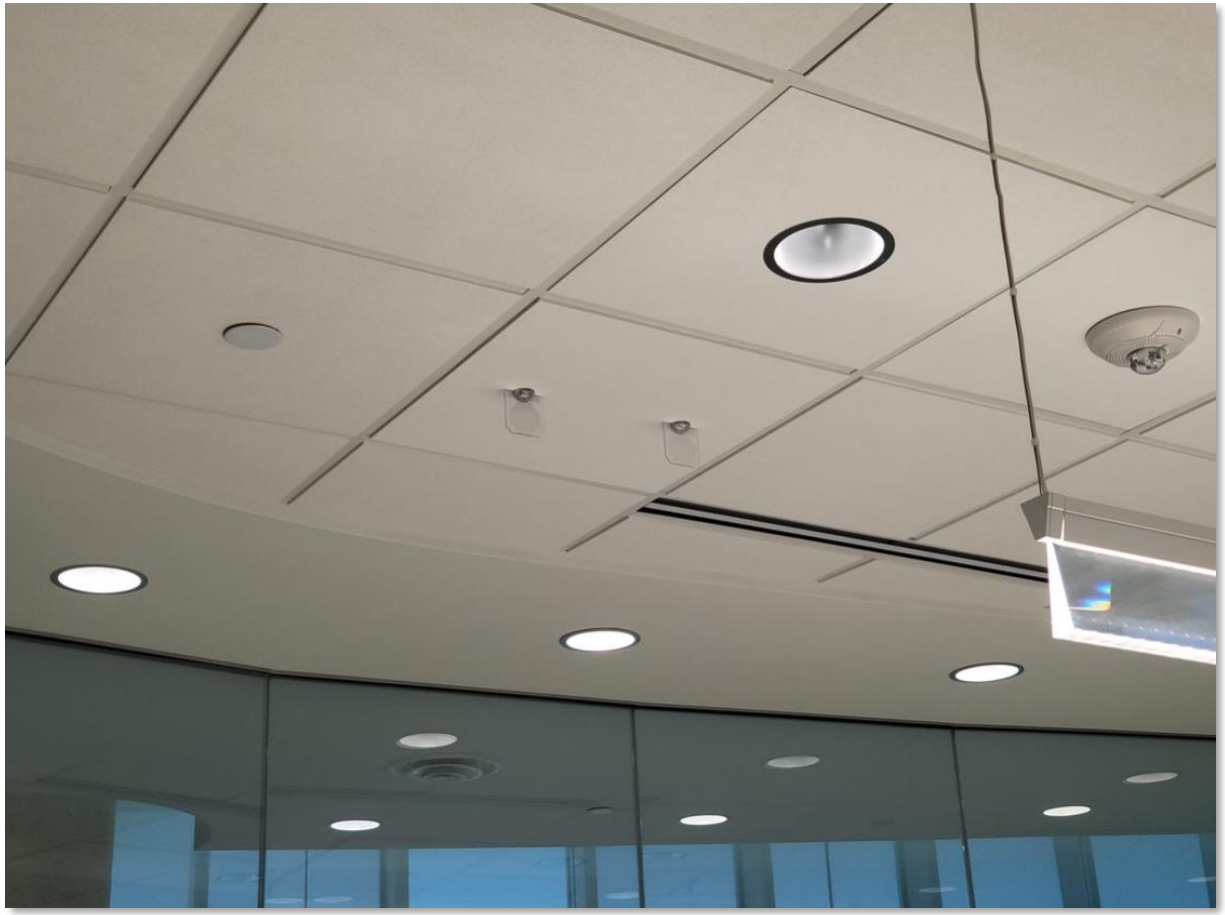


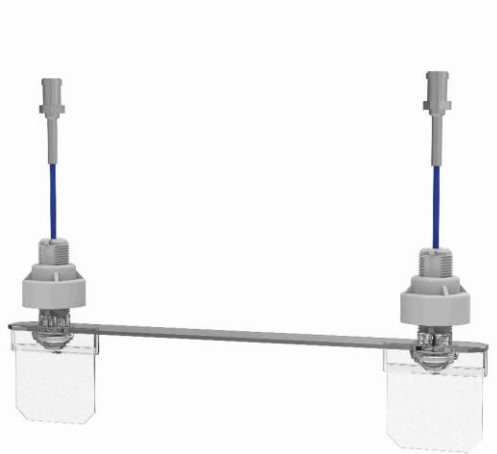
Emergency Services

Positioning, Navigation, and Timing (PNT)

Transparent Antenna Examples - Dengyo

Visible Light Transmittance Antenna



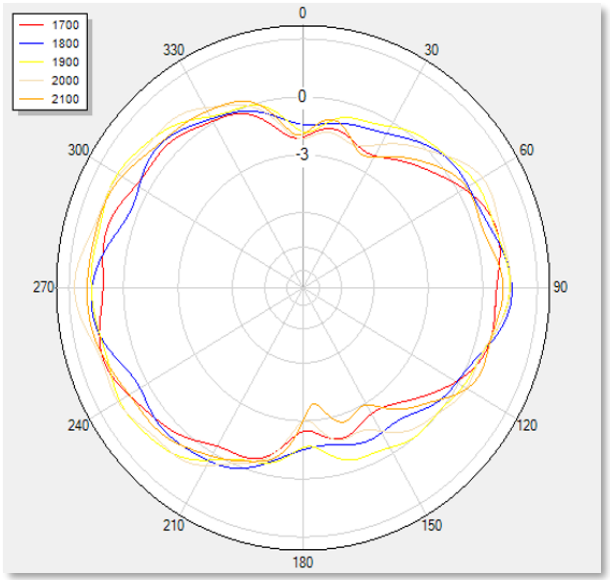


- Transparent
- Unobstructive ceiling mount
- Wide band 1710 MHz to 5 Ghz
- Dual Antenna for MIMO configurations
- Excellent PIM <-153 dBc
- Suitable for 2G/3G/4G/5G and Wi-Fi applications

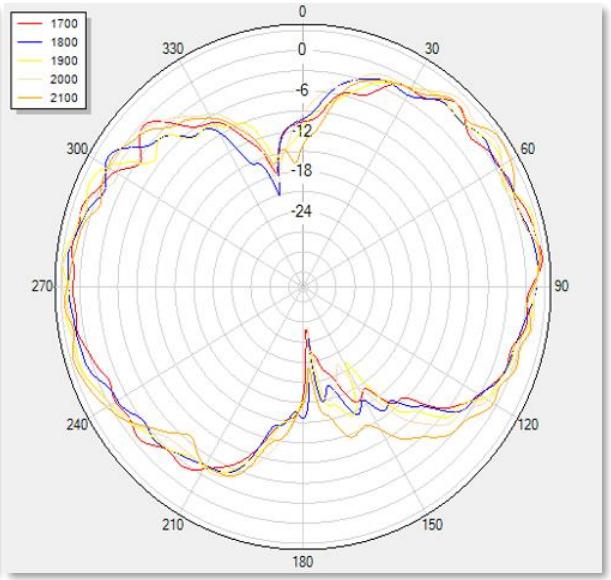
Images and data courtesy of Dengyo

Transparent Antenna Examples - Dengyo

Horizontal Plane



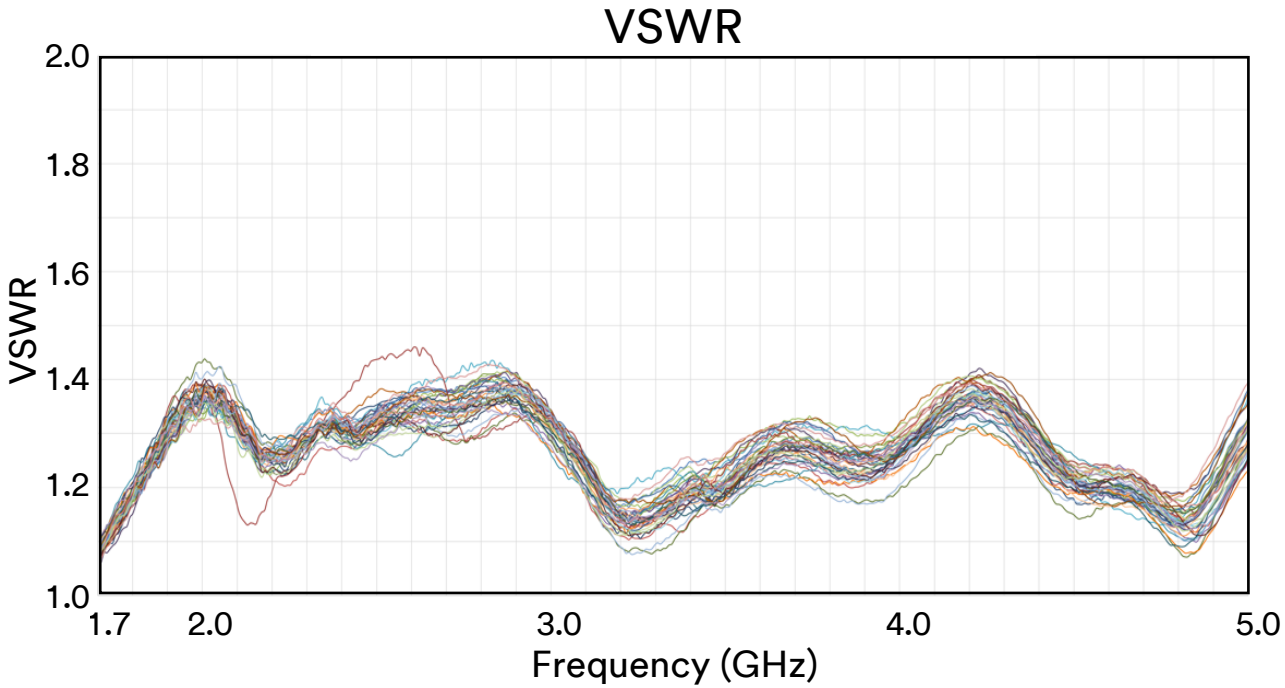
Vertical Plane



Electrical Specifications

Frequency (GHz)	1.71-1.85	1.85-2.0	2.0-2.2	2.2-2.4	2.4-2.7	3.3-4.2	4.2-5.0	5.0- 6.0 (Note 1)
Impedance	50Ω							
Polarization	Vertical ×2							
V.S.W.R	≦ 1.5							2.4
Gain (max.)	3.7	5.4	4.3	5	5.8	6.8	6.5	6.0
Gain (avg.)	3	4.4	3.7	4.1	4.4	6.1	5.4	5.0
Horizontal 3dB Beamwidth	360 degree - Omni							
Vertical 3dB Bandwidth	See Plots Below							
Isolation	>25dB							
Max. Power	50 Watts @ each port							
IM3	< -153dBc (2x 43 dBm)							

(Note 1: Specifications in this band provided as reference only.)



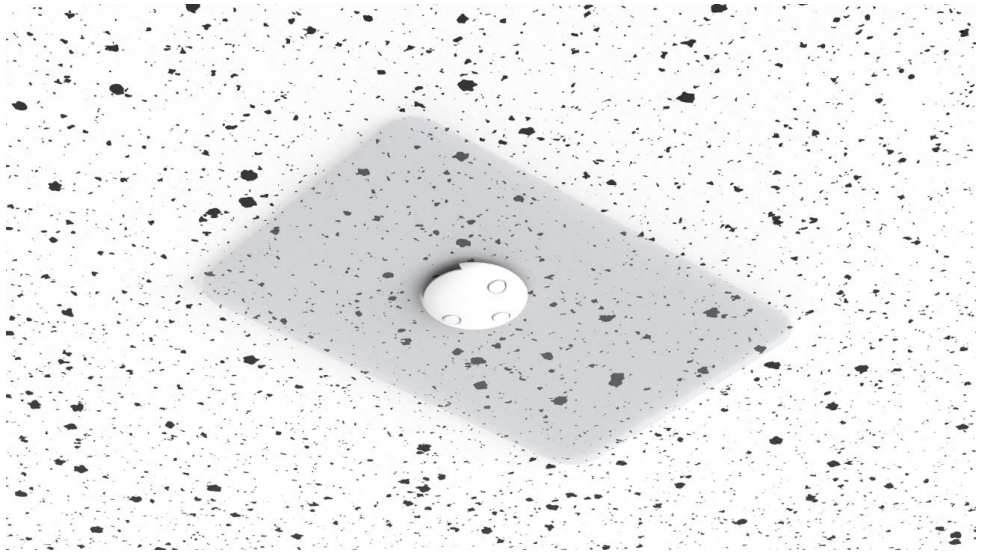
"Using high performance 3M Transparent Conductor Film allows Dengyo to build high performance Transparent Antennas."

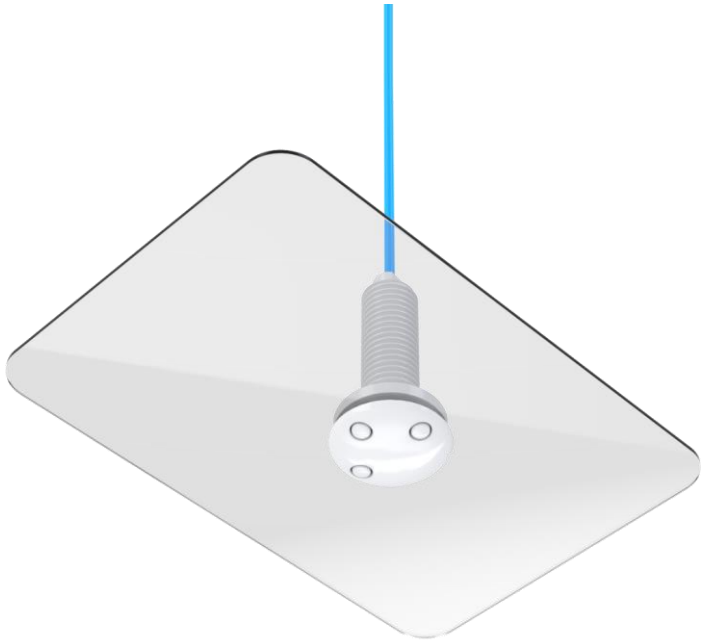
- John Conceicao, Director, Global PLM & SAE Dengyo

Images and data courtesy of Dengyo

Transparent Antenna Examples - VENTI

Ceiling Mount iDAS OMNI SISO Antenna





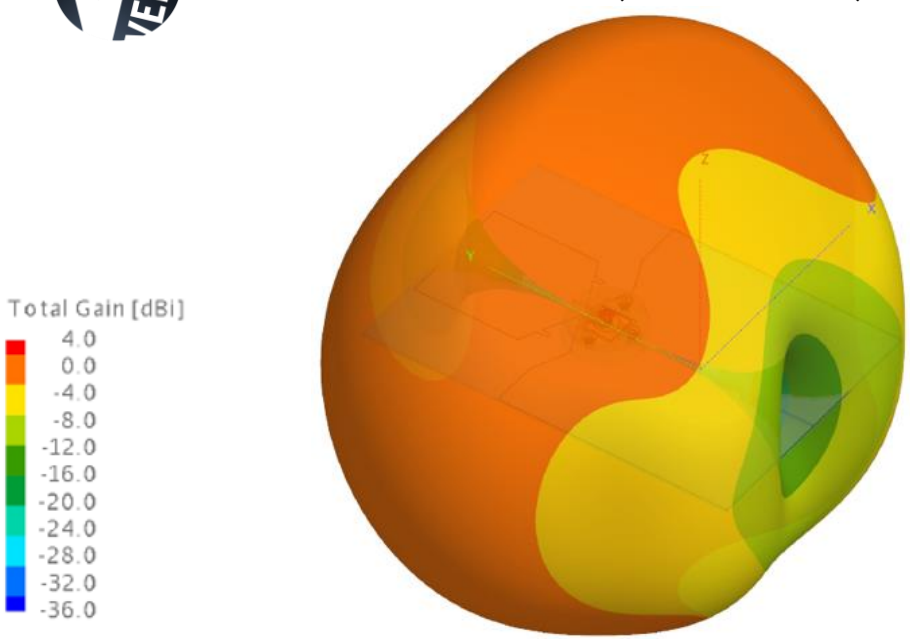
- Transparent
- Low-profile
- Broadband 617 MHz to 5.925 Ghz
- Indoor Carrier DAS antenna – NA, EU, Asia

"VENTI Group - The Leader in transparent DAS & IoT Antennas uses 3M Transparent Conductor Film for superior performance in their new Low Profile Stealth Antennas!"

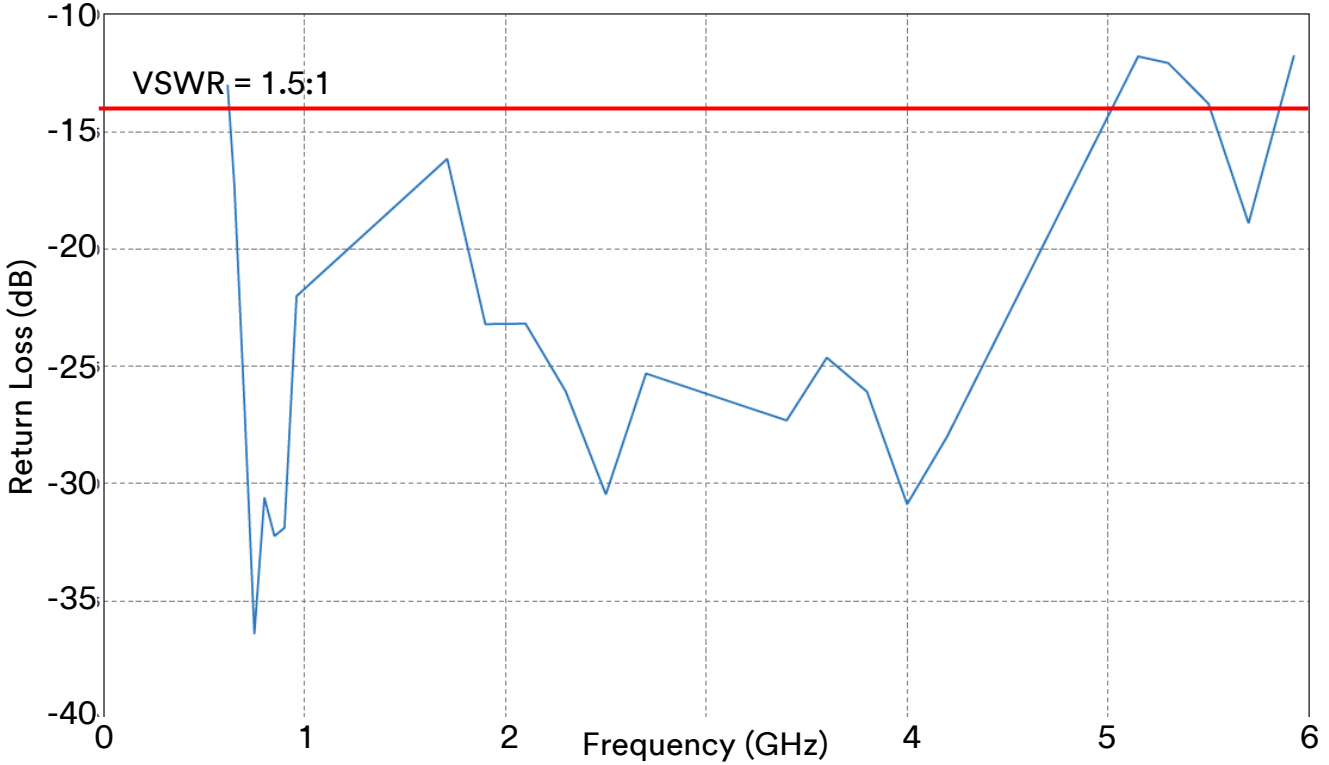
- Robert Mark, Vice President, Sales & Marketing
  VENTI Group

Transparent Antenna Examples - VENTI

Total Gain (1900 MHz)



Return Loss



Specifications

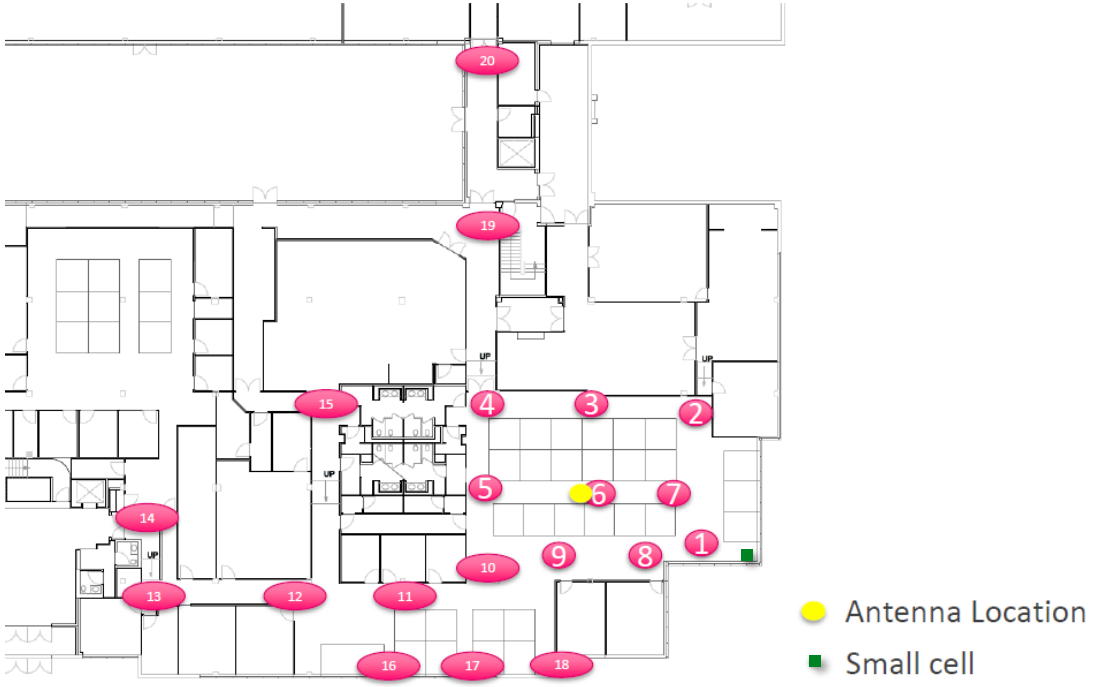
Frequency Range: 617-5925 MHz
PIM (2 x 20W) measured < -150dBc for 700, 850, 1900MHz bands
Connection: 12” pigtail with 4.3-10 (F)
Dimensions: 7.4 in x 5 in x 0.06 in

Frequency (MHz)	617-698	698-960	1695-2700	3300-4200	5150-5925
Return Loss - max (dB)	-12.5	-20	-20	-25	-12
Return Loss - min (dB)	-20	-35	-30	-30	-19
VSWR	1.6:1 – 1.2:1	1.2:1 – 1.1:1	1.2:1 – 1.1:1	1.1:1	1.7:1 – 1.3:1
Gain - max (dBi)	2.5	3.7	4.4	4.4	5.3
Gain - min (dBi)	2.4	2.5	2.7	3.4	3.8

LTE Field Trial with T-Mobile (Reston, VA)

Objective: Evaluate transparent antenna for indoor use case at T-Mobile offices in Reston, VA.

Test Description: Transparent antenna performance was compared against a reference antenna with similar gain (4.4 dBi vs. 4.5 dBi) in Band 41 (2.5GHz). RSRP was measured over a wide range of distances and LOS/NLOS conditions at 20 locations.



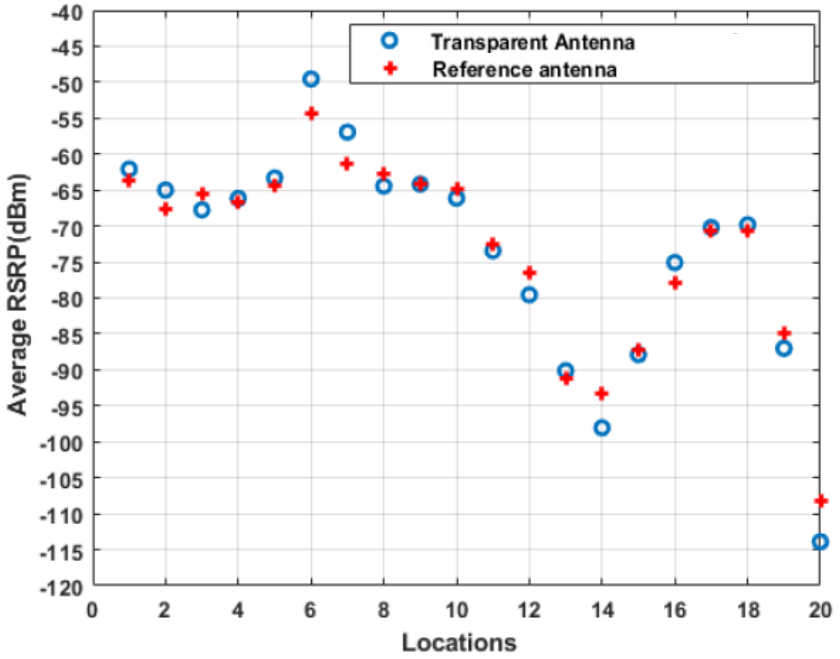
Transparent antenna designed by Dengyo using 3M Transparent Conductor Film

Images and data courtesy of T-Mobile

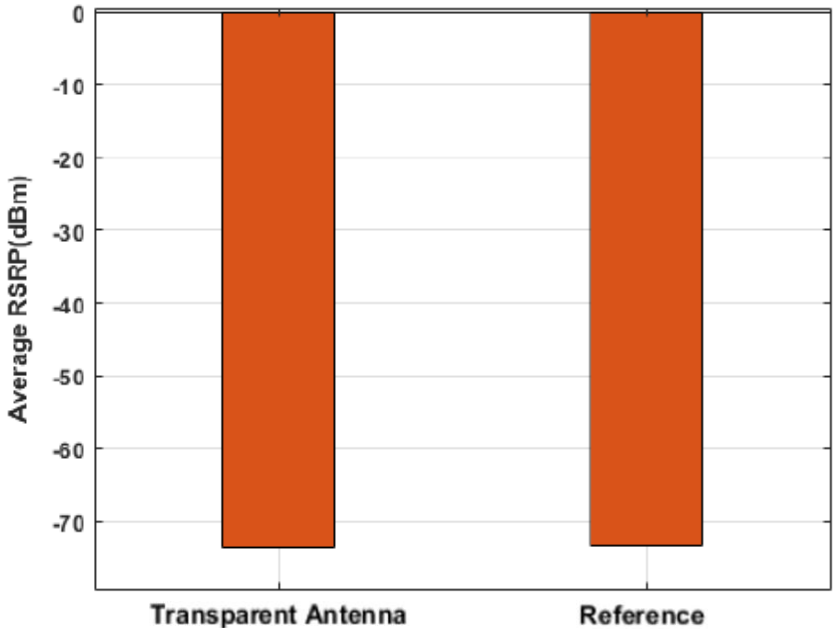
LTE Field Trial with T-Mobile (Reston, VA)

Performance Comparison

Average RSRP by Location



Average RSRP of all Locations



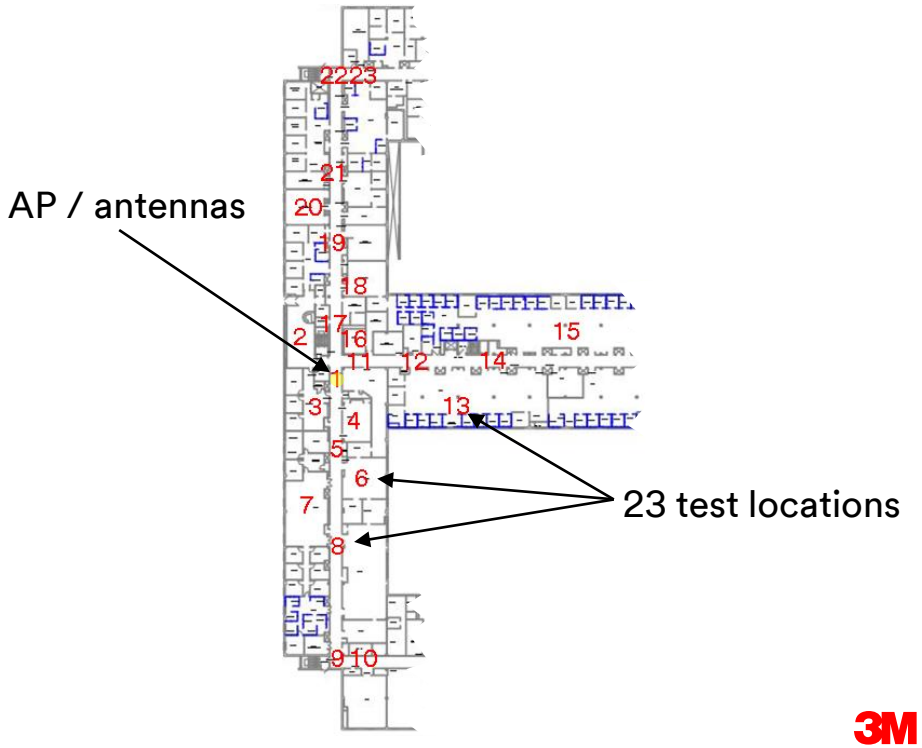
Results show coverage performance of the transparent antenna is comparable to reference antenna

Images and data courtesy of T-Mobile

WiFi 6 Field Trial (3M Center - St. Paul, MN)

Objective: Compare WiFi coverage of transparent antenna against reference antenna (same antenna used in LTE trial).

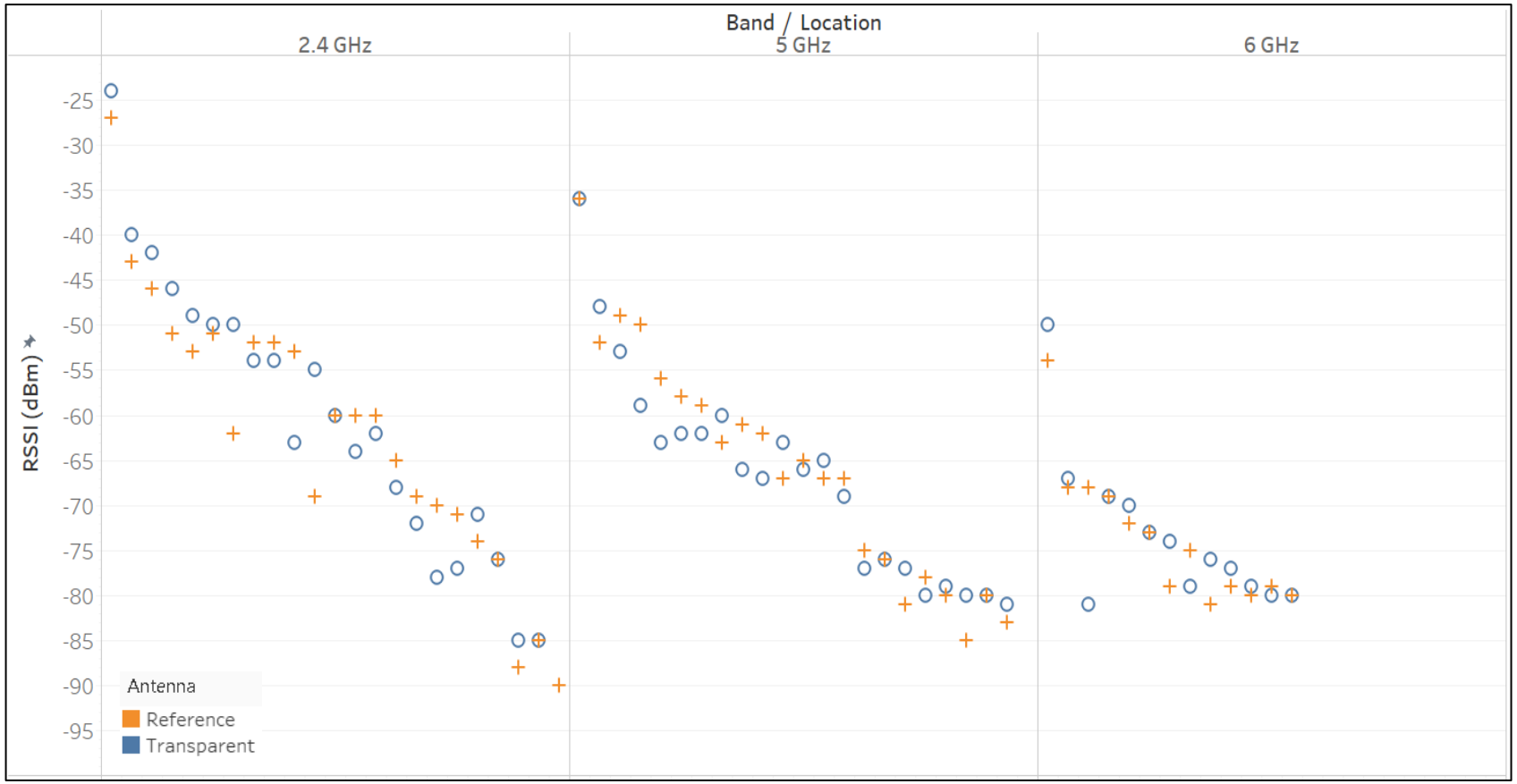
Test Description: Indoor WiFi coverage of each antenna was evaluated throughout a building for 2.4GHz/5GHz/6GHz frequency bands. RSSI was measured over a wide range of distances and LOS/NLOS conditions at 23 locations.

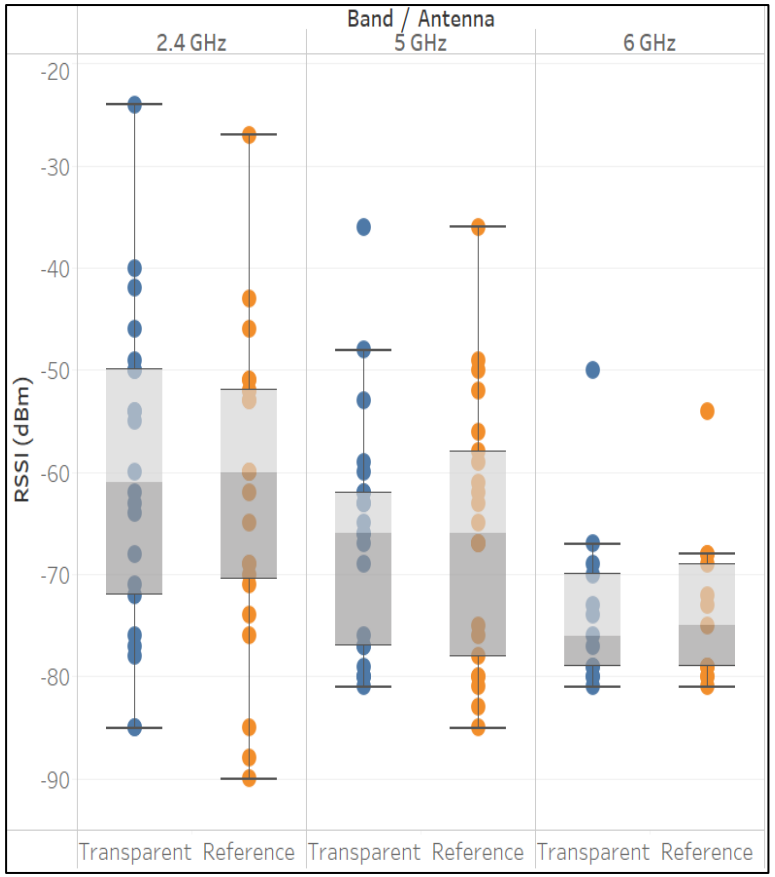


Transparent antenna designed by Dengyo using 3M Transparent Conductor Film

WiFi 6 Field Trial (3M Center - St. Paul, MN)

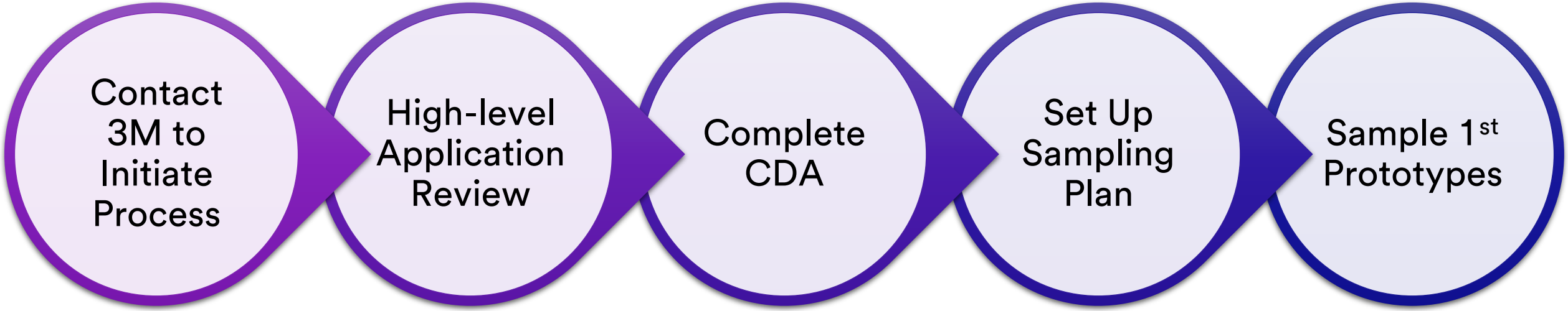
Performance Comparison





Results show coverage performance of the transparent antenna is comparable to reference antenna

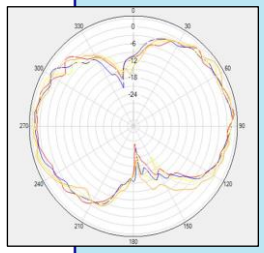
Design Process, Working with 3M



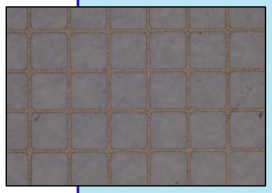
- Reach out to Jeff Tostenrude jtostenrude@mmm.com +1 512 647 9302 or Taesung (TS) Kim tskim@mmm.com +1 651 733 6626
- Review scope of application and requirements
- Typically required to support detailed discussions
- Draft sampling plan and exchange technical drawings
- 3M provides initial samples to customer for evaluation

Summary

The increasing demand for inconspicuous antenna technologies drives the need for transparent conductive film



Transparent antennas can meet the same performance requirements as conventional antennas, with much less visual impact



Antenna OEMs are capitalizing on this technology and launching new products this year

References

Chen, Yuanming et al. “Effect of Surface Finishing on Signal Transmission Loss of Microstrip Copper Lines for High-Speed PCB.” Journal of materials science. Materials in electronics 30.17 (2019): 16226–16233.

Coonrod, John. “Choosing Circuit Materials for Millimeter Wave Applications.” *High Frequency Electronics*, 2013, https://www.highfrequencyelectronics.com/Archives/Jul13/1307_HFE_CircuitMaterials.pdf.

Lee, Paul, et al. “Private 5G Networks: Enterprise Untethered.” *Deloitte Insights*, 2020, https://www2.deloitte.com/us/en/insights/industry/technology/technology-media-and-telecom-predictions/2020/private-5g-networks.html.

Lévy, David, and Erick Castellón. Transparent Conductive Materials : from Materials via Synthesis and Characterization to Applications. Weinheim, Germany: Wiley-VCH, 2018.

Marshall, Nick. “ABI Research Anticipates in-Building Mobile Data Traffic to Grow by More than 600% by 2020.” *ABI Research: The Tech Intelligence Experts*, 2016, https://www.abiresearch.com/press/abi-research-anticipates-building-mobile-data-traf/.

Patent Literature

US9823786
US10101868
US11165171
Other patents also apply

Country	Patent Applications	Granted Patents
China	14	7
Europe	11	6
India	2	0
Japan	20	13
Korea	21	13
Singapore	1	1
Taiwan	6	5
United States	35	21

Questions?

Technical Contact:
Jeff Tostenrude
jtostenrude@mmm.com
+1 512 647 9302

Business Contact:
Taesung (TS) Kim
tskim@mmm.com
+1 651 733 6626

IMPORTANT NOTICE

Regulatory: For regulatory information about these products, contact your 3M representative.

Technical Information: The technical information, recommendations and other statements contained in this document are based upon tests or experience that 3M believes are reliable, but the accuracy or completeness of such information is not guaranteed.

Product Use: Many factors beyond 3M's control and uniquely within user's knowledge and control can affect the use and performance of a 3M product in a particular application. Given the variety of factors that can affect the use and performance of a 3M product, user is solely responsible for evaluating the 3M product and determining whether it is fit for a particular purpose and suitable for user's method of application.

Warranty, Limited Remedy, and Disclaimer: Unless an additional warranty is specifically stated on the applicable 3M product packaging or product literature, 3M warrants that each 3M product meets the applicable 3M product specification at the time 3M ships the product. **3M MAKES NO OTHER WARRANTIES OR CONDITIONS, EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OR CONDITION OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OR ANY IMPLIED WARRANTY OR CONDITION ARISING OUT OF A COURSE OF DEALING, CUSTOM OR USAGE OF TRADE.** If the 3M product does not conform to this warranty, then the sole and exclusive remedy is, at 3M's option, replacement of the 3M product or refund of the purchase price.

Limitation of Liability: Except where prohibited by law, 3M will not be liable for any loss or damage arising from the 3M product, whether direct, indirect, special, incidental or consequential, regardless of the legal theory asserted, including warranty, contract, negligence or strict liability.

Electronics Materials Solutions Division
3M Center, Building 224-3N-11
St. Paul, MN 55144-1000
1-800-251-8634 phone
651-778-4244 fax
www.3M.com/electronics

Thank you