New Thermoset PCB Materials Improve Millimeter Wave Performance and Reliability at Reduced Cost

Outline

- Printed Circuit Board (PCB) Requirements for Operation in mmWave Frequency Band
- Requirements for Automotive Safety Systems
- Available Materials
- Case Study: Automotive RADAR
- Summary

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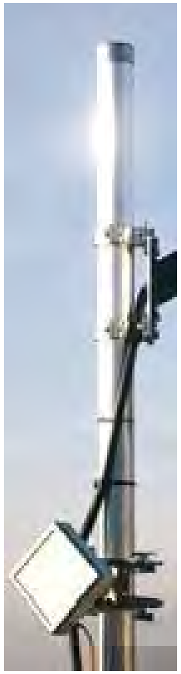
Active mmWave Applications

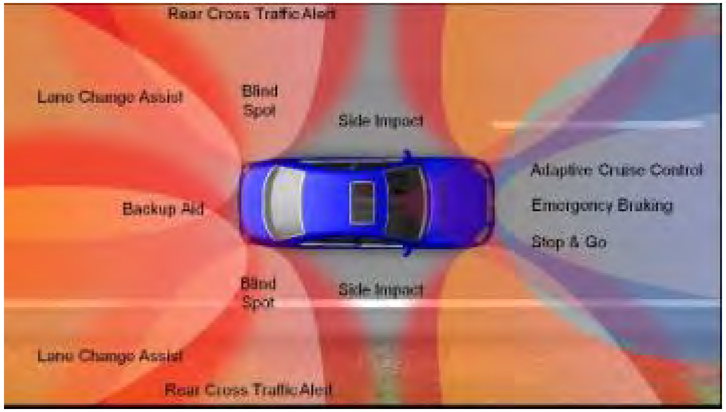
60 GHz Unlicensed Band

Applications
- Small cells
- Carrier Wi-Fi/WiGig
- Backhaul

Companies
- Qualcomm – Wilocity
- Google -- Alpental
- Samsung
- Many others…



Automotive Safety Systems



Advanced Automotive Safety Systems

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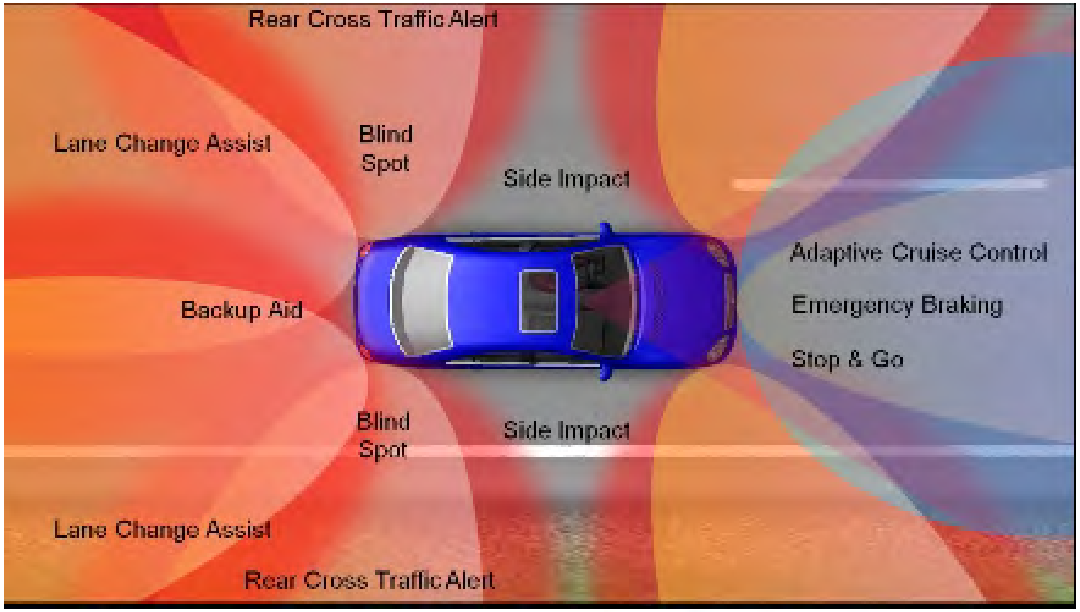
Active Safety Systems



RADAR sensor portfolio

- 25 GHz Ultra-wide Band RADARs
- 24 GHz Narrow Band RADARs
- 77 GHz Multi-mode RADARs

Supporting

- Blind Spot Detection
- Rear Cross-traffic Alert
- Lane Change Assist
- Forward Collision Warning
- Autonomous Emergency Braking
- Adaptive Cruise Control

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Vehicle RADAR Classification

- **Long Range RADAR (LRR)**
  - Range up to 250m
  - Vehicle velocity above 30 km/h to 250 km/h
  - Narrow beams to control driving path in front of the car to determine distance of vehicle driving ahead for maintaining minimum safety distance
  - Bandwidth below 1 GHz and typical spatial resolution 0.5m
- **Short Range RADAR (SRR)**
  - Range up to 30m
  - Speed range from 5 km/h to 150 km/h
  - Wide field of view
  - Bandwidth below 5 GHz and typical spatial resolution 0.1m

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RADAR Resolution Requirements

- **Scenarios Requiring High Resolution (wide bandwidth)**
  - Side Impact
  - Cross Traffic Alert
  - Narrow Pass Assistant
  - Evasion Maneuver
  - Pedestrian Protection
  - Front Collision Warning
  - Proximity Warning and Parking Assistant
- **Scenarios Needing Lower Resolution (narrow bandwidth)**
  - Adaptive Cruise Control – long range
  - Lane Change Assist – 24 GHz

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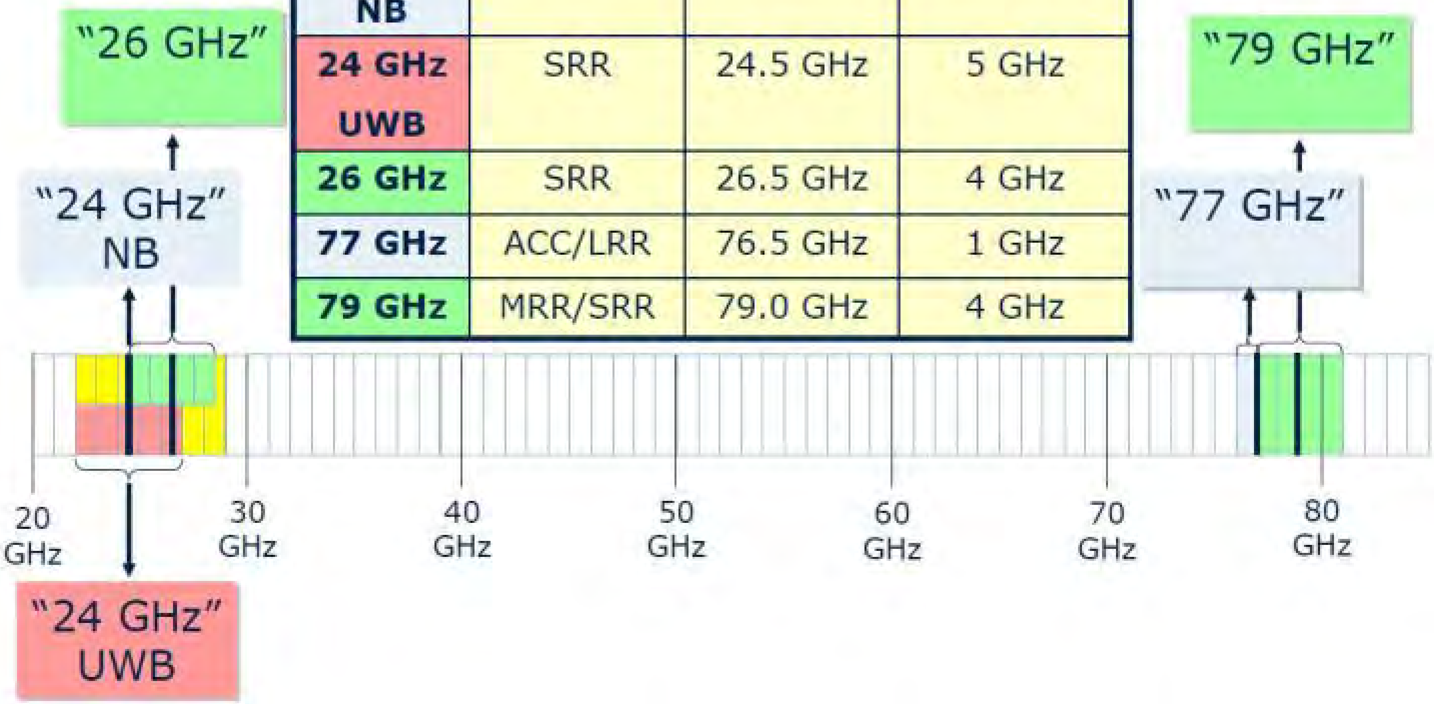
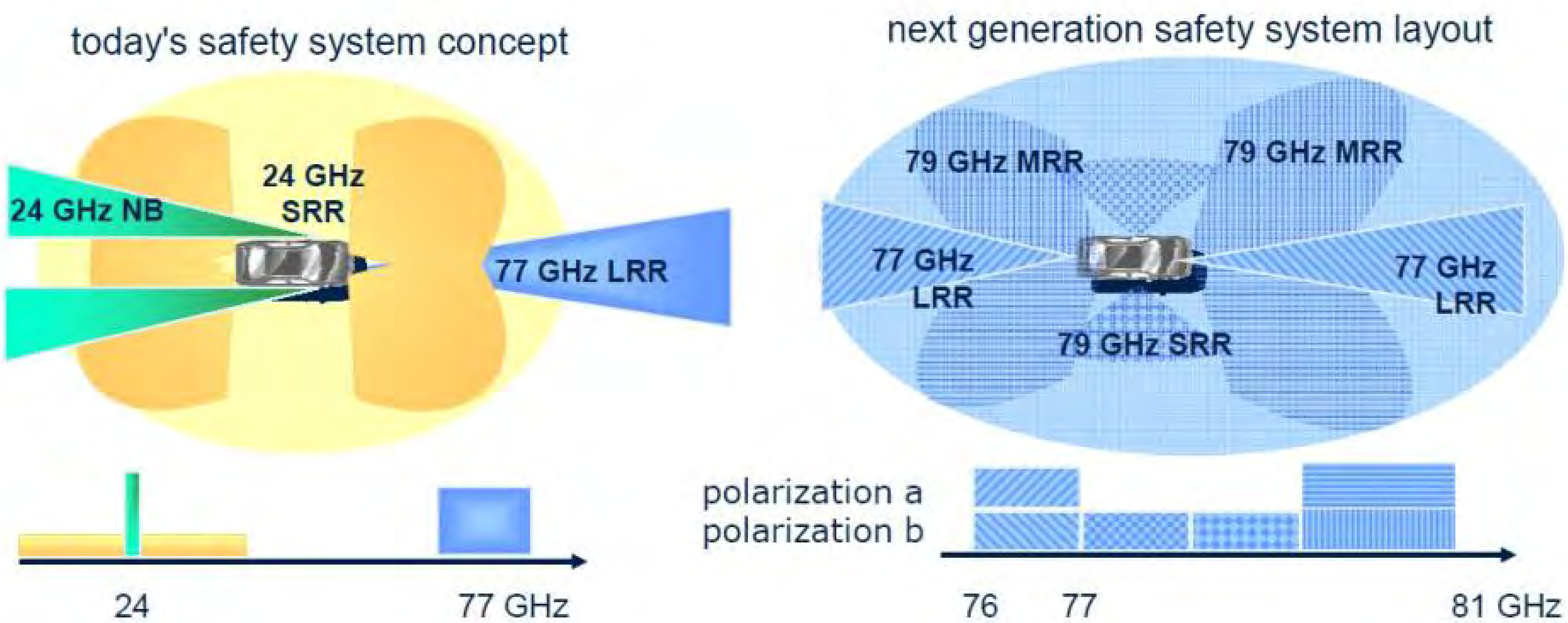
Frequency Bands for Automotive RADAR

	Application	Center Frequency	Band Width
24 GHz NB	ACC	~24.2 GHz	0.2 GHz
24 GHz UWB	SRR	24.5 GHz	5 GHz
26 GHz	SRR	26.5 GHz	4 GHz
77 GHz	ACC/LRR	76.5 GHz	1 GHz
79 GHz	MRR/SRR	79.0 GHz	4 GHz



Source: Infineon

Active Safety System Development



Source: Infineon

- **Systems are migrating to higher frequencies**
  - Change in frequency allocation
  - Improved Performance
  - Reduced size and improved affordability

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Active Safety System Trends

- **Shift to higher frequencies**
  - 76 GHz to 81 GHz
  - Development ongoing at 140 GHz
- **Integration of multiple system functions in one chipset**
  - RADAR front end
  - Microcontroller
- **Reduction in system size**
  - Smaller size offers more options for integration into vehicle front and rear fascia
- **Single PCB combining RF and high speed digital processing vs. more common two-board configurations**
- **Increasing demand for system cost reductions for a widening target market**

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PCB Requirements

Desirable PCB Electrical Properties

- **Low dissipation factor, Df = tanδ**
  - Maximize power delivered to antenna
  - Achieve desired effective isotropic radiated power (EIRP) with lower input power, P_{in}
  - Better s_{11} characteristics at resonance
- **Relatively low dielectric constant, Dk**
  - Allows rapid signal propagation
  - Provides high radiation efficiency
- **Consistent Df, Dk over RADAR operating bandwidth**
  - Provides consistent transmission line impedance
  - Prevents phase distortion of waveform (due to frequency dependence on phase velocity)
- **Consistent Df, Dk over temperature of operation (-40°C to 85°C) and varying humidity**
  - Provides consistent transmission line impedance and
  - Maintains antenna impedance and gain

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Additional PCB Attributes

- **Material must have consistent physical properties**
  - Uniform electrical properties
  - Consistent physical properties – thickness, Dk, Df
  - Physical uniformity batch-to-batch and within batch
- **Ease of processing**
  - Minimum amount of special material treatment for PCB fabrication
  - Single cure cycle with parameters consistent with mature products, well established at board shops
- **Compatibility with Hybrid Processing**
  - Systems are moving towards single board solution
  - Single board will have RF and High Speed Digital channels
- **As low cost as possible**
  - Choose material process-compatible with hybrid PCB construction
  - Select material that meets performance requirements and produces highest yields

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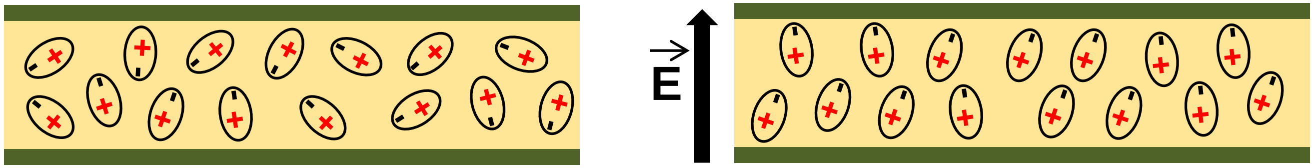
Sources of Loss in PCB

- **Dielectric Loss**
- **Conduction Loss**

PCB Material Dielectric Loss

- Dielectric materials have polarized molecules that move when subjected to the electric field of a digital signal



- This motion produces heat loss
- Loss results in signal attenuation that increases in direct proportion to signal frequency

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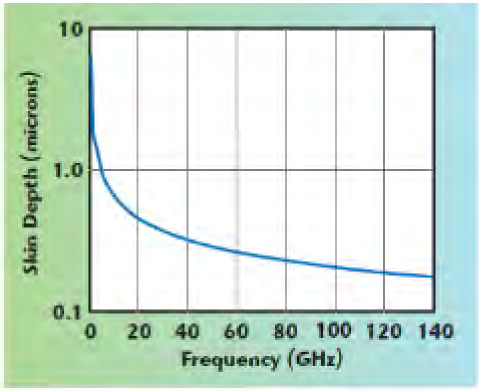
PCB Material Conduction Loss

- **The copper contributes to overall loss through the metal's resistive losses**
- **At high signal frequencies, the current in PCB copper is concentrated within a small depth near its surface (skin effect)**

Frequency	Skin Depth (Copper)
50 Hz	9.3 mm
10 MHz	21 µm
100 MHz	6.6 µm
1 GHz	2.1 µm
10 GHz	0.66 µm



- **Reduction in effective cross-sectional area increases the effective resistance**

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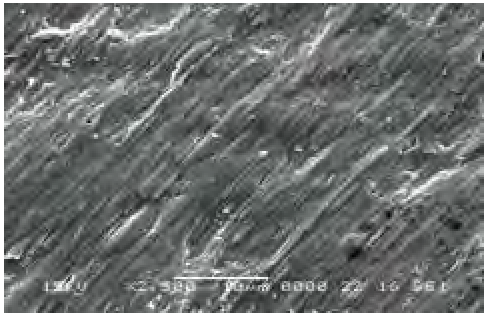
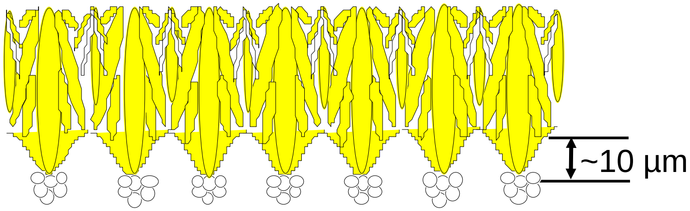
Conductor Surface Roughness

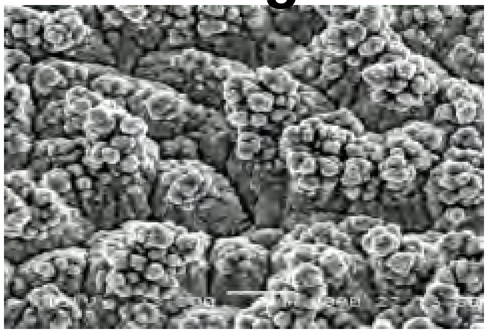
Resist side



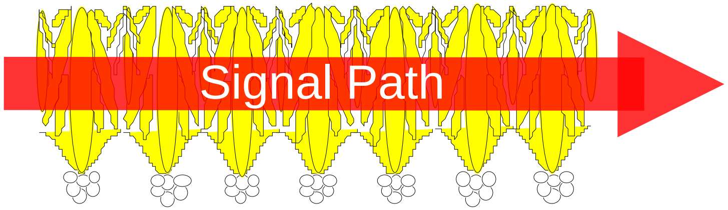
Standard foil



Bonding side

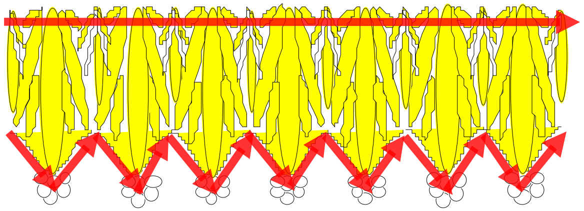


Frequency	Skin Depth
10 MHz	21 µm



The current is able to tunnel below the surface profile and through the bulk of the conductor

Frequency	Skin Depth
100 MHz	6.6 µm

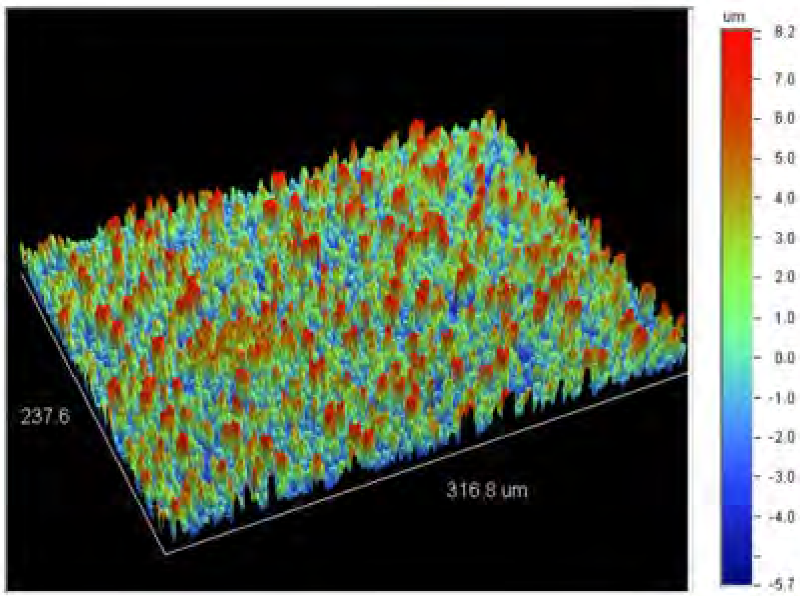


The current is forced to follow every peak and trough of the surface profile increasing path length and resistance

RTF and VLP Copper Profiles

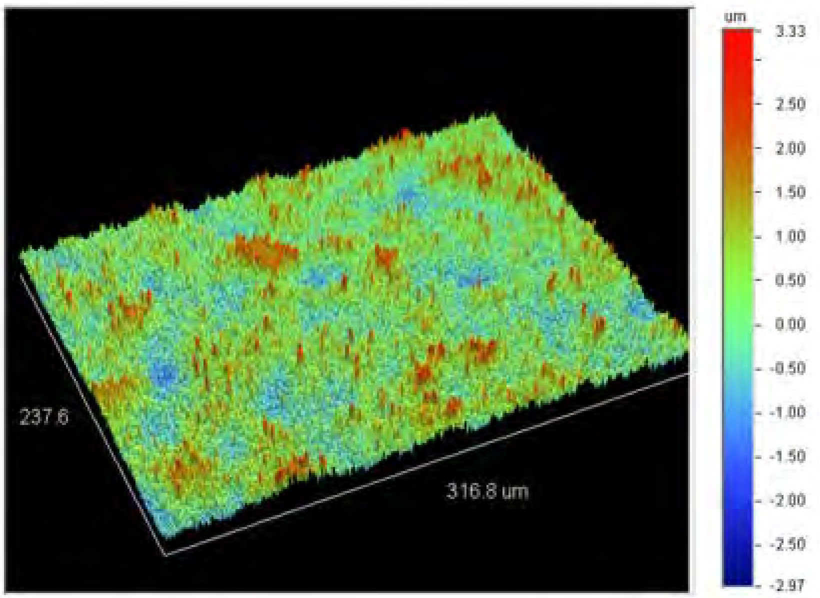
RTF

Rq=2.6 um, RF=1.85



VLP

Rq=0.68 um, RF=1.3



- Roughness parameters measured with profilometer

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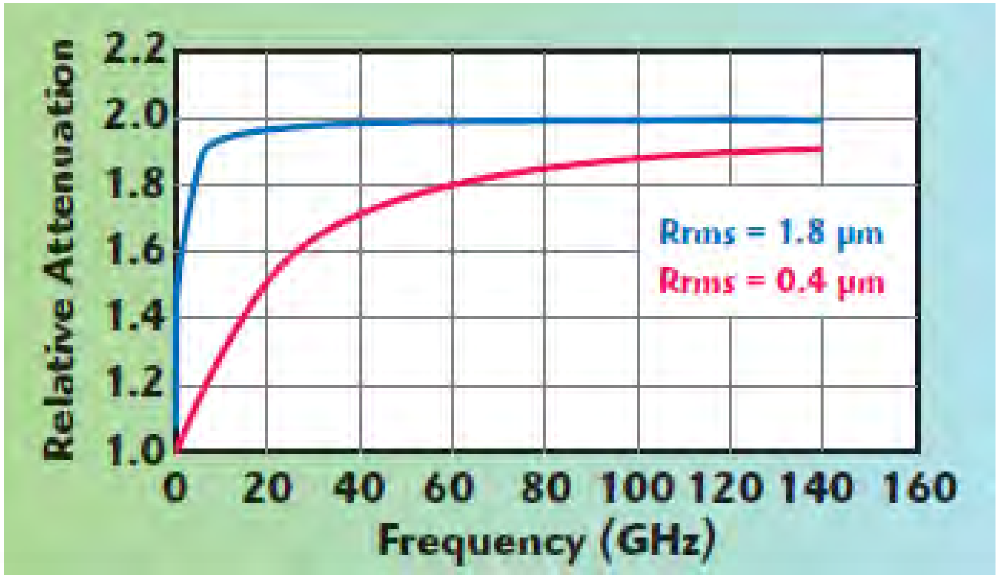
Effects of Surface Roughness

- **Increase in capacitance due singular electric fields on surface spikes**
- **Increase in signal group delay over perfectly smooth**
- **“Apparent” increase in Dk to match group delay vs frequency characteristics**

Relative Attenuation vs F (GHz)



$$\alpha_c' = \alpha_c \left\{ 1 + \frac{2}{\pi} \tan^{-1} \left[1.4 \left(\frac{\Delta}{\delta_s} \right)^2 \right] \right\}$$

where Δ = root mean square surface height

δ_s = skin depth

α_c = conductor loss

(Hammerstad- Bekkadel)

Available materials

- **PTFE**
- **Highly Filled Hydrocarbon Based Resins**
- **New Class of Thermoset Materials**

PTFE

PTFE Dielectric Properties

- PTFE based materials are in used in RF applications because of low Dk and Df
- Their material properties have been found to be stable through mmwave frequencies
- Common belief that material properties are very stable with temperature is somewhat of a misconception, however

PTFE Temperature Dependence

- **PTFE has a crystalline structure after polymerization**
- **The degree of crystallinity is affected by changes in temperature and processing steps, such as sintering above its melting point**
- **Changes in crystallinity result in changes in effective density, which result in changes in Dk**

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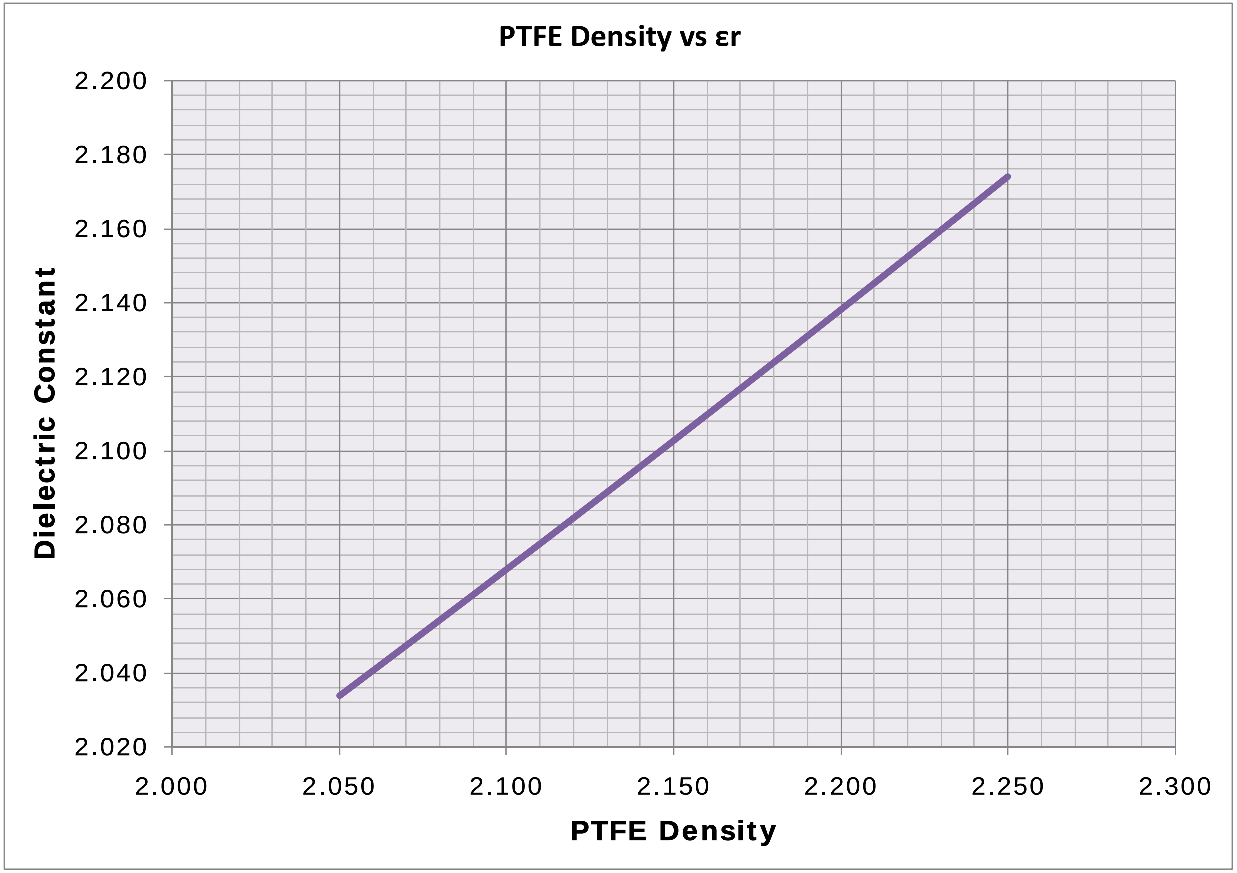
PTFE Dk Dependence on Density

- Fabricated PTFE has crystallinity ranging from 50% to 75%, depending on rate of cooling
- Relative density of PTFE has been found to vary from 2.3 for 100% crystallinity to 2.0 for 0% (amorphous)
- The Clausius-Mossotti relation can be used to show the relationship between the density of PTFE and Dk

PTFE Dk Dependence on Density



- Dk is shown to be a function of PTFE density
- PTFE density can change with circuit board processing

PTFE Dimensional Instability

- **PTFE exhibits high degree of permanent plastic deformation due to**
  - Low glass transition temperature
  - Low yield strength
- **Deformation is on the order of a magnitude higher than FR-4 products**
- **This results in low yields and processing difficulties, particularly in hybrid constructions**

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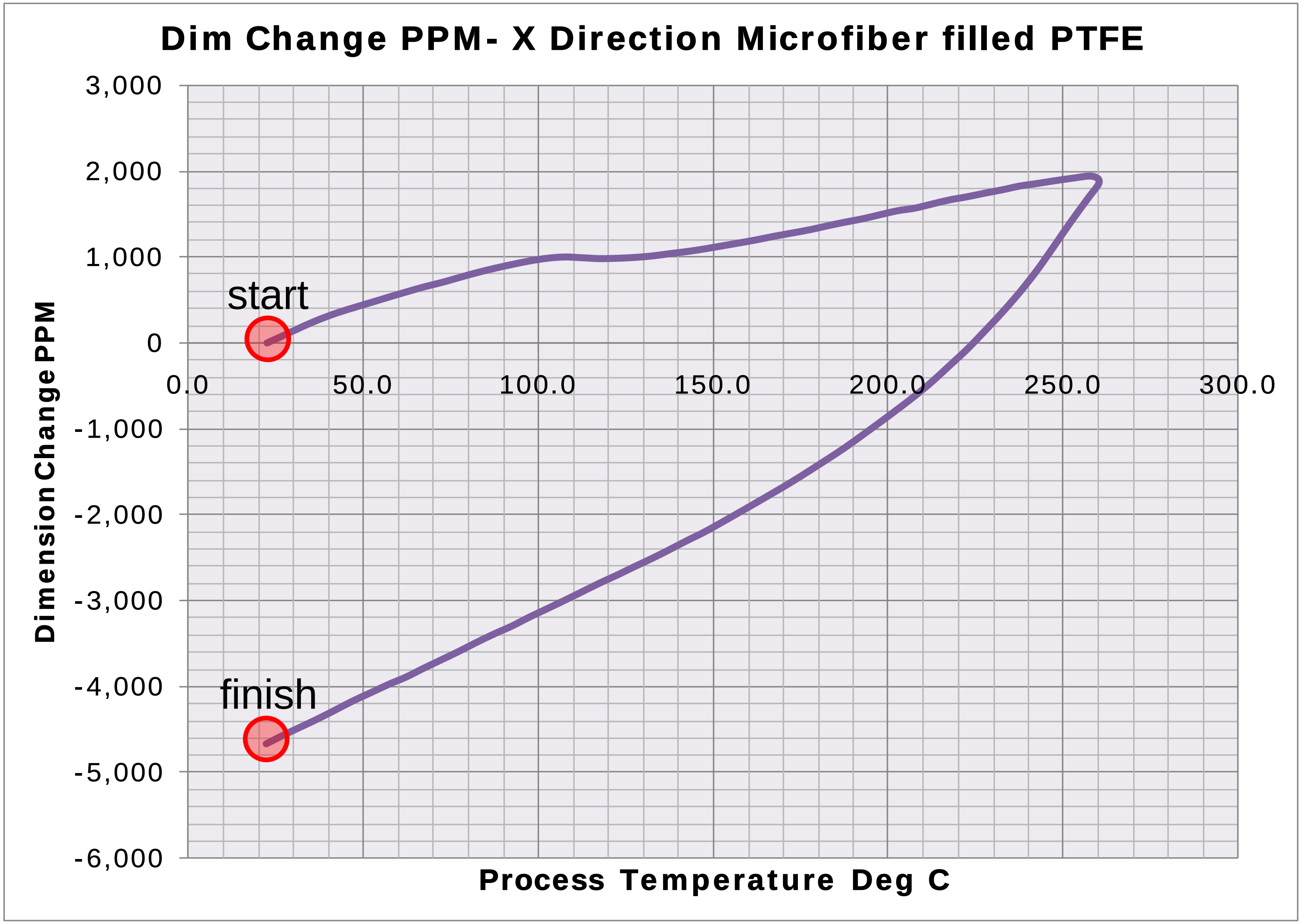
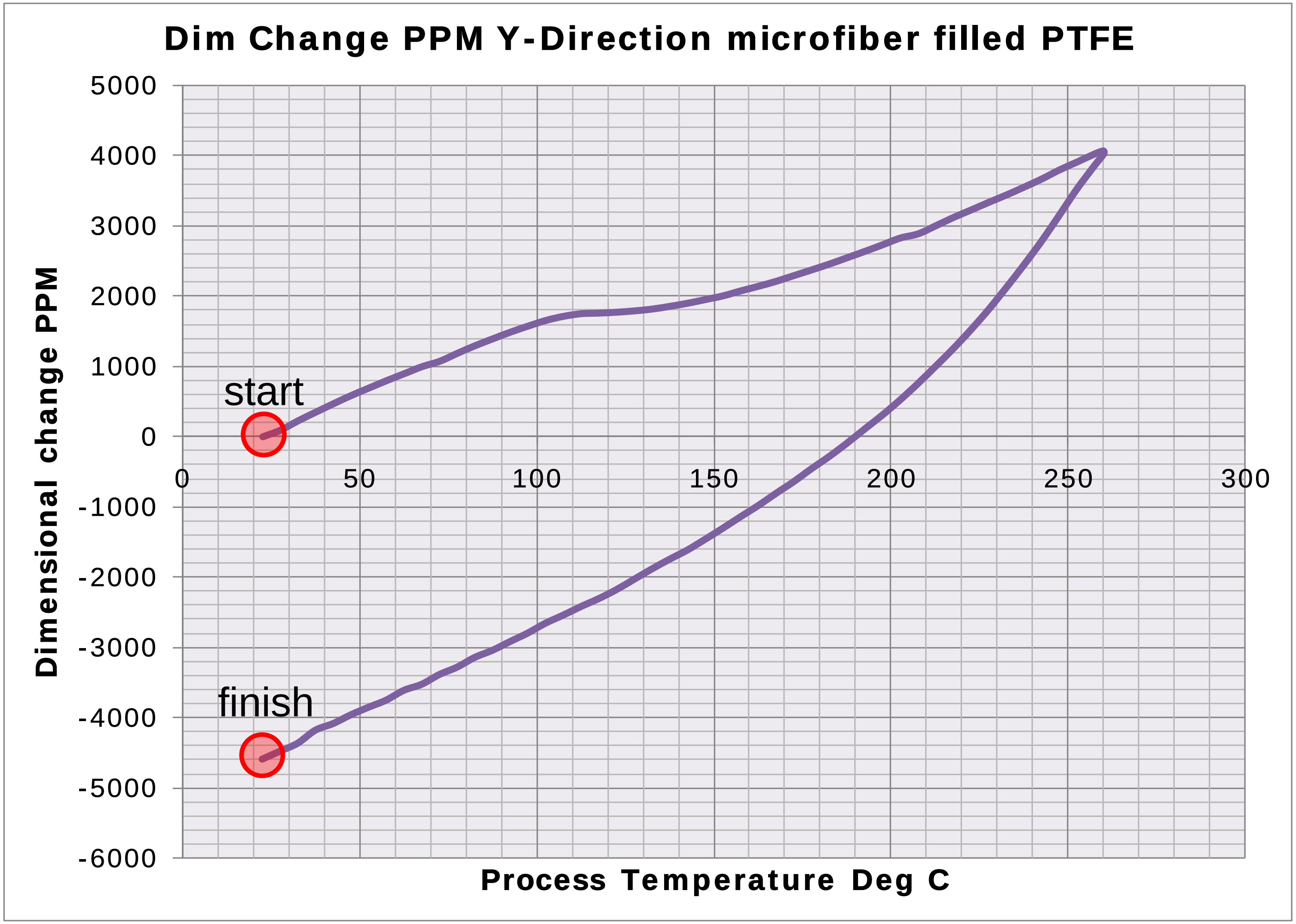
PTFE Dimensional Change



PTFE Dimensional Change



PTFE Mechanical Properties and Creep

- **PTFE has a low elastic modulus of approximately 0.5 GPa**
- **The coefficient of thermal expansion (CTE) of PTFE is also highly variable and demonstrates high expansion**
- **At elevated temperatures, permanent deformation can occur over time at a stress level below it's yield strength**
- **PTFE is highly prone to this deformation known as creep**

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Creep in PTFE

- Creep occurs at low stress levels and at temperatures above $0.5T_m$, the absolute melting point (27°C for PTFE)
- Creep is measured by loading at a constant stress level and measuring the deformation versus time
- In PTFE, the creep rate can be shown to double with a 20°C change in temperature
- The creep rate of PTFE materials raises doubt about their suitability for applications with demanding environments such as automotive applications

PTFE Process Challenges

- **Technology is shifting to higher layer-count boards combining RF and digital functions**
- **PTFE based materials are less desirable for these boards due to higher cost, high CTE, and other processing concerns**
  - High temperature and pressure required
  - Lack of bonding sheets available and absence of flow and fill for encapsulation
  - Limited compatibility with hybrids
  - Increased drilling cost due to presence of abrasive fillers added in attempt to lower CTE

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Effects of High CTE

- **High CTE can lead to a number of issues including**
  - Dimensional deformation
  - Inter-laminar shear stress and residual stress in the PCB
- **High CTE in Z-direction affects plated through hole reliability**
  - Copper has a low coefficient of expansion
  - Mismatch causes stress and results in fatigue failure

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Highly-filled, Hydrocarbon-based Resins

Highly-filled, Hydrocarbon-based Resins

- **These materials are cross-linked with other polymers in an attempt to increase the Tg, yet when measured the Tg is low**
- **The materials don’t have the low loss properties of PTFE or the adhesion required for use of low profile copper**
- **Their dielectric properties have been known to shift due to oxidation under operation at moderate temperatures**
- **Materials offered as “oxidation resistant” exhibit discoloration upon exposure to elevated temperatures**
- **There are a number of issues using these in hybrid constructions**

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Hybrid Construction

- **CTE mismatch with other materials in desirable hybrid construction presents many issues**
  - CTE in Z direction is very low due to highly filled nature of the materials
  - There is no Tg Above 60°C
  - CTEs in X and Y show no inflection, expanding at uniform rates vs FR-4 materials which exhibit rapidly increasing Z expansion and significant drop in X, Y
  - When bonded together, the hybrid board experiences strain, leading to high thermal stress and potential for delamination

Factors Limiting Utility

- **There are many attributes that limit their utility for higher layer-count boards**
  - Inability to produce robust hybrid boards
  - Higher dielectric loss and inability to effectively use low-profile copper
  - Lack of suitable bonding sheets
  - Low dielectric stability under elevated temperature
  - Oxidation risks and associated change in dielectric properties

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New Class of Thermoset Polymers

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Attributes

- Behavior like FR-4 materials for hybrid processing, while delivering excellent electrical and mechanical performance
- High peel strength while using the lowest profile copper available for minimum conduction losses and PIM
- Stable dielectric properties from 1GHz through 100 GHz
- Low sensitivity to prolonged exposure to high temperature
- Availability of full compliment of laminates and prepregs meeting requirements for high-speed digital, RF, and mmwave designs

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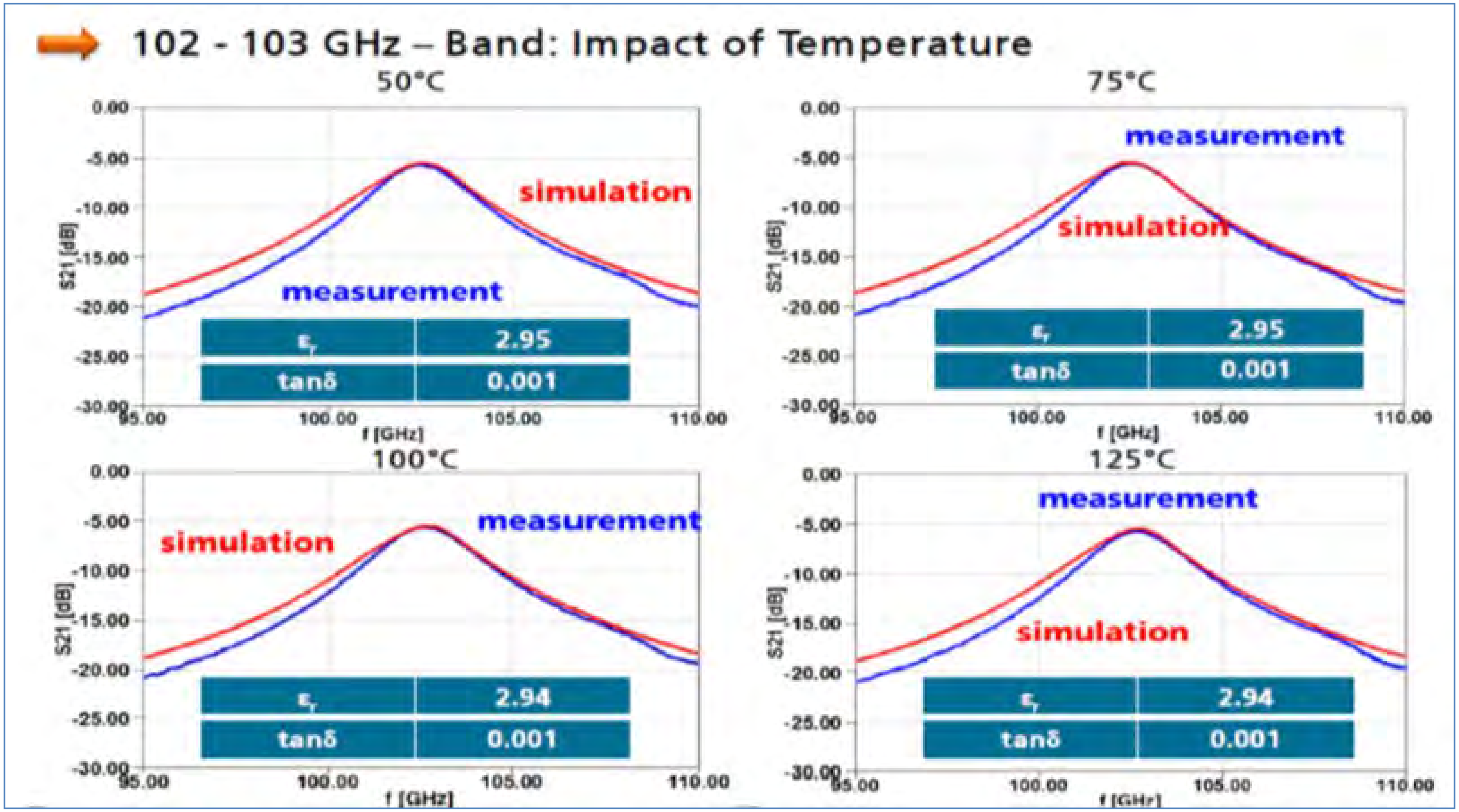
Dk Stability vs. T

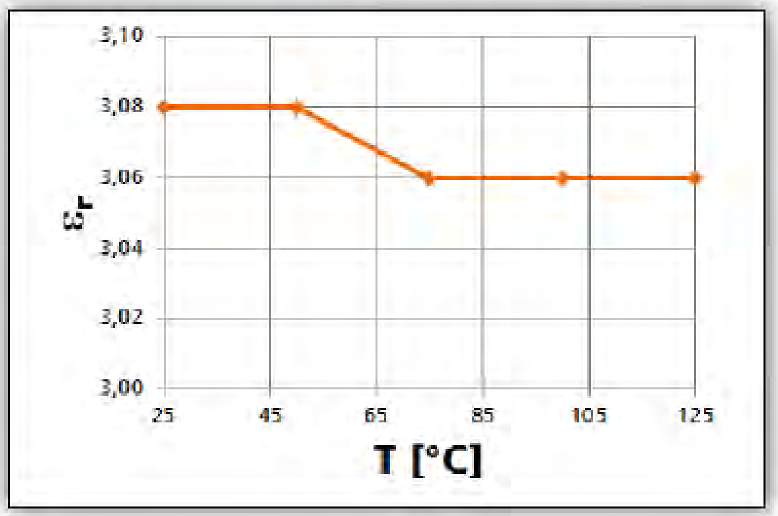


Data generated at IZM Fraunhofer shows stability versus temperature

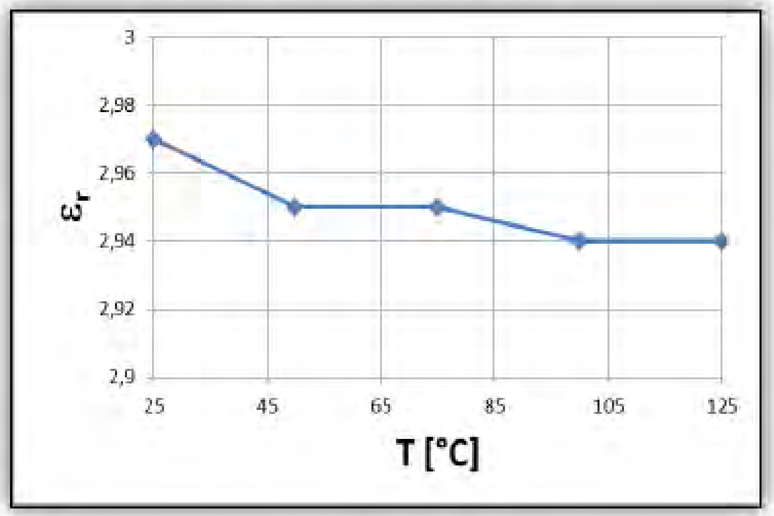
Permittivity vs Temperature

Permittivity Vs Temperature at Frequency Bands of Interest

76 GHz – Band



102 - 103 GHz – Band



Astra® MT 77 and 100 GHz Testing

Extraction of the Dielectric Material Properties – 7/7

➡ Typical Uncertainty

Extracted Values (25°C, 100GHz)

Test Structure	ε_r	tanδ
Resonator 1	2.97	0.0010
Resonator 2	2.96	0.0015

ε_r	tanδ
3.0 ± 0.1	$0.0015 \pm 5 \times 10^{-4}$

Considering typical uncertainty

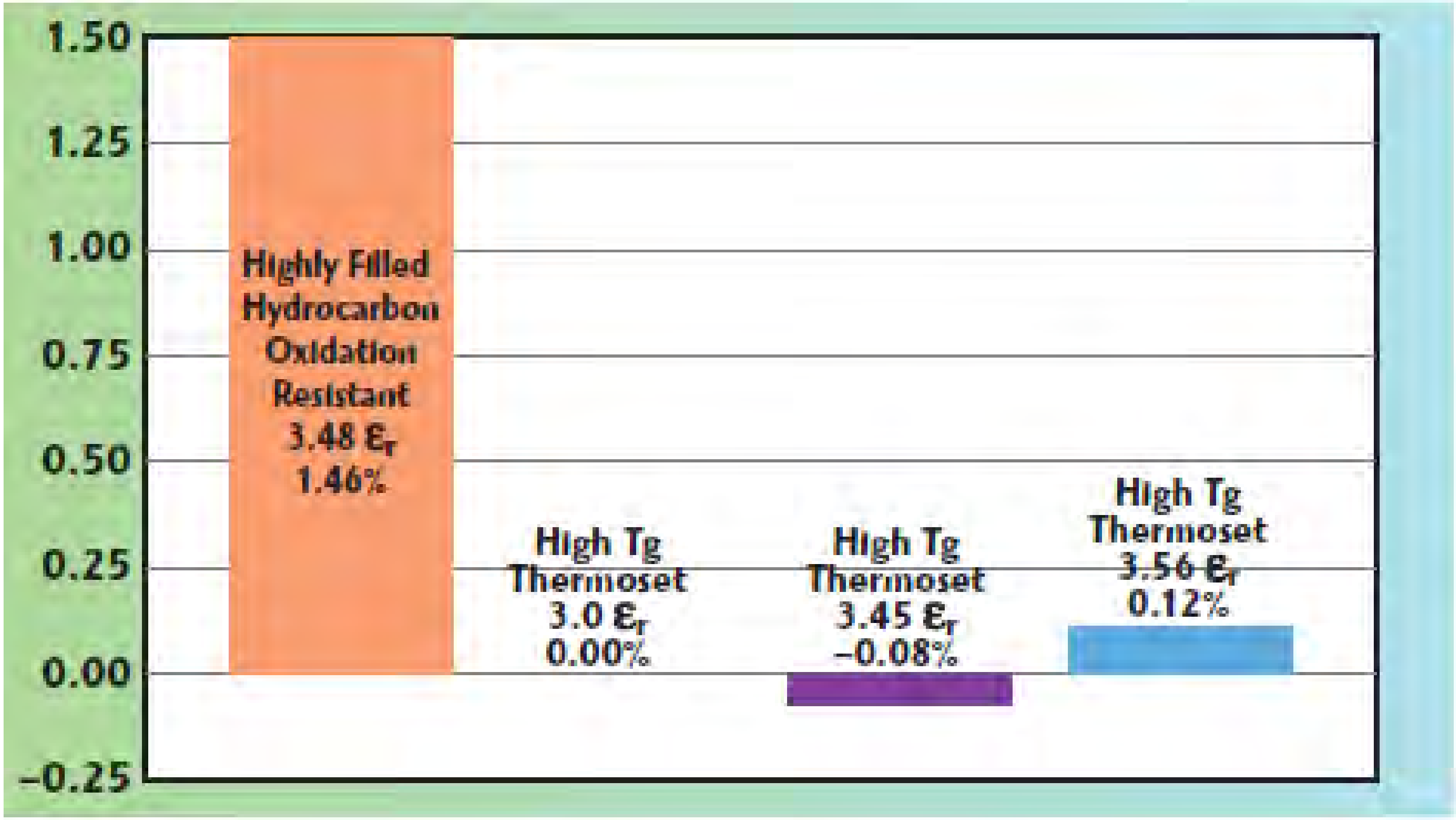
Dept.: System Design & Integration (Head: Dr. S. Guttowski)
RF & High-Speed System Design Group
Head of Group: Dr.-Ing. Ivan Ndip

Technische Universität Berlin
Forschungsschwerpunkt
Technologien der Mikroperipherik

Fraunhofer IZM

Beyreuther, Bierwirth, Curran, Duan
Fotheringham, Maaß,
Ndip, Öz, Thognon, Tschoban

Percent Change in Dk



Percent change in dielectric constant after 1000 hours aging at 125°C is shown to be low for high Tg thermosets

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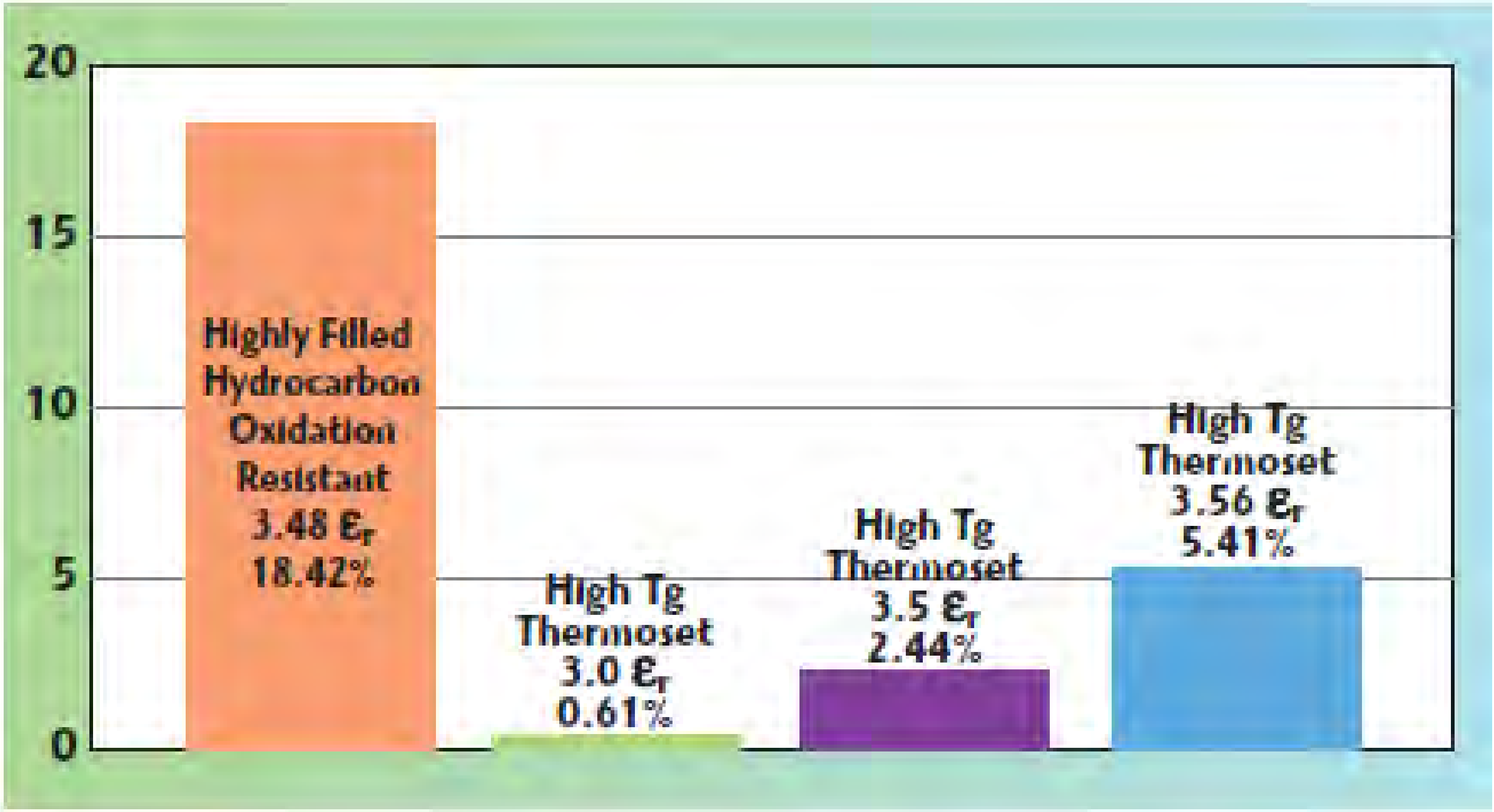
Percent Change in Df



- **Percent change in dielectric loss after 1000 hours aging at 125°C is shown to be low for high Tg thermosets**

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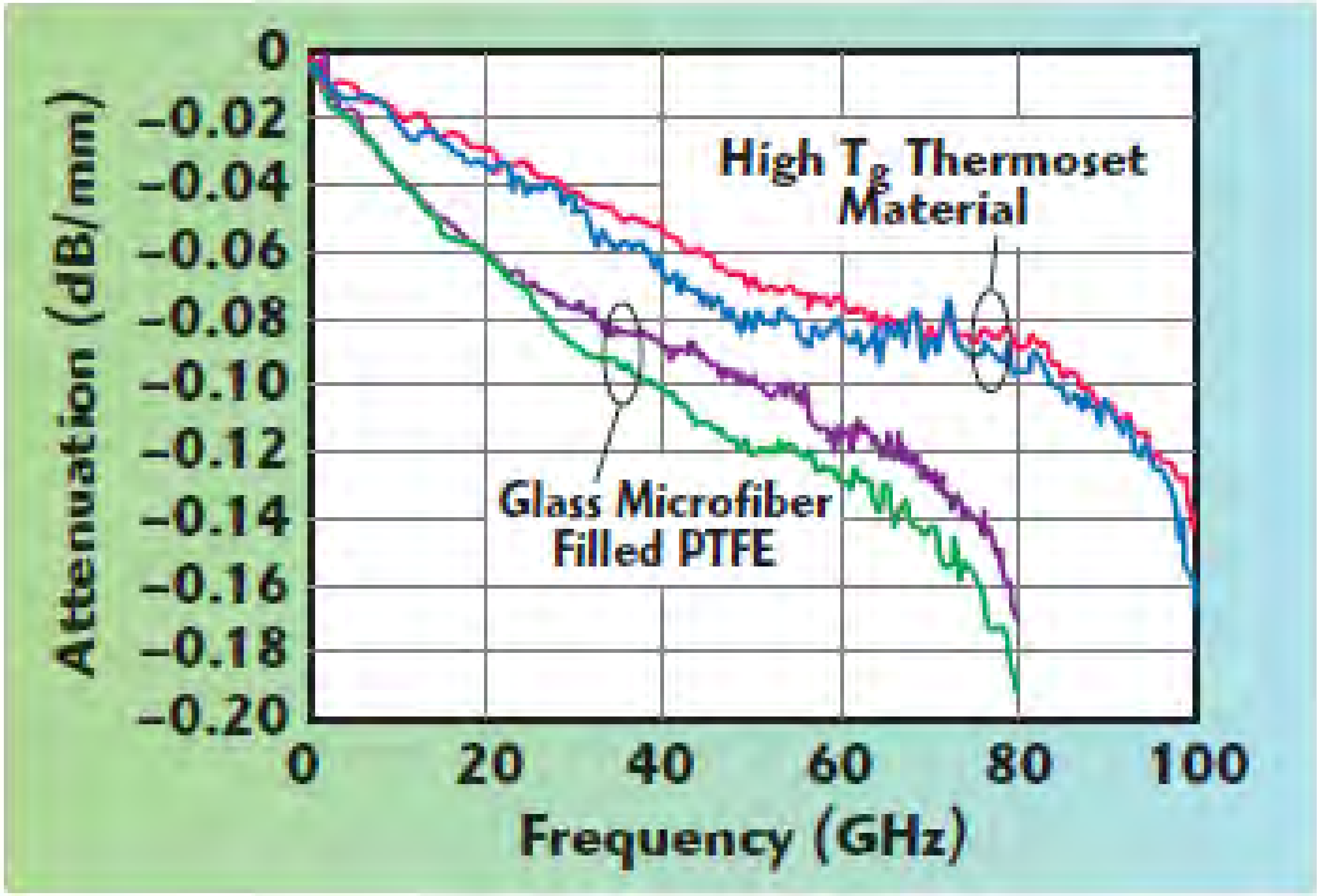
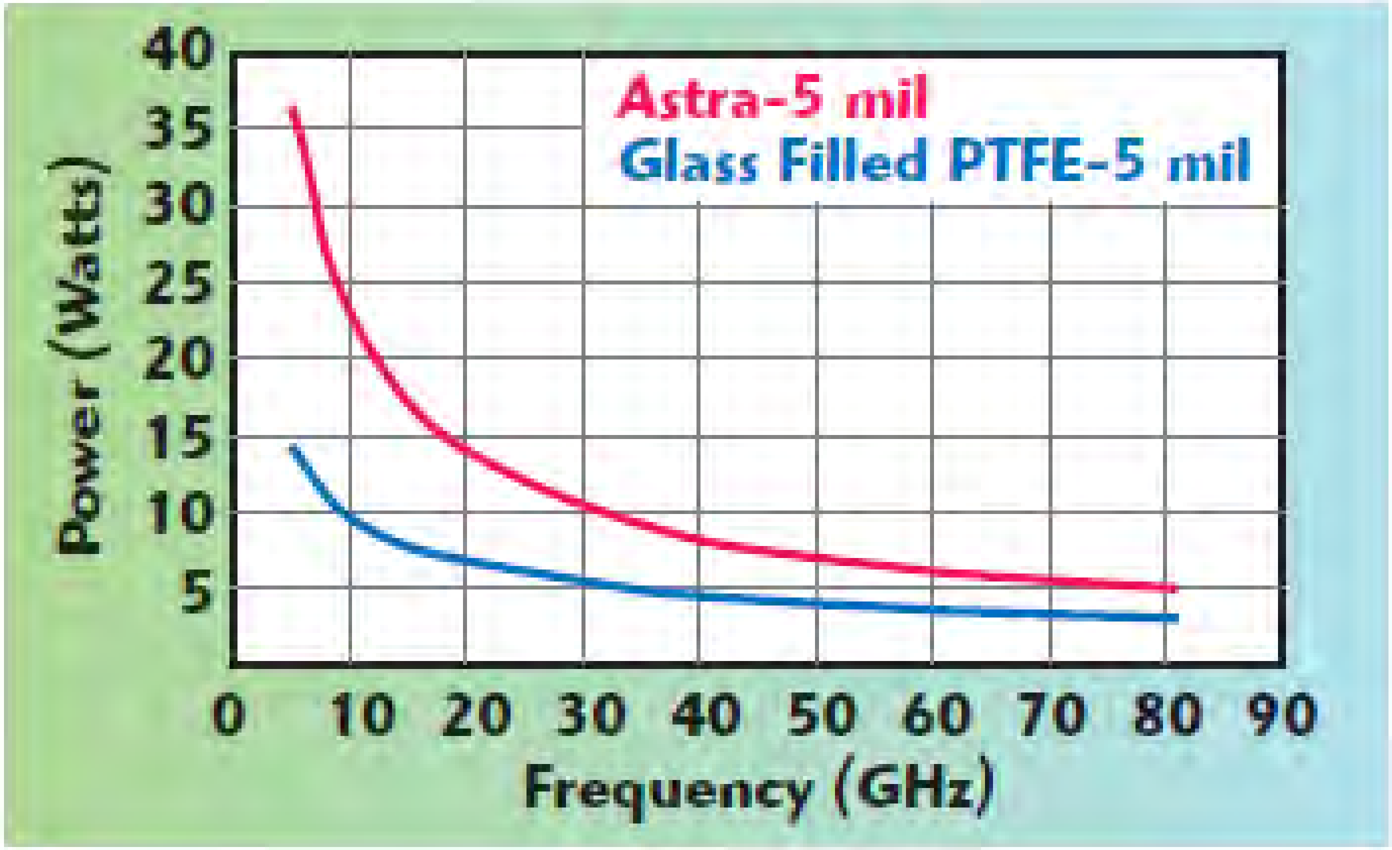
Attenuation vs Frequency



- **High-Tg thermoset shown to have lower loss than filled PTFE product**

Maximum Power Handling



- **Higher power handling in Astra is enabled by its high thermal conductivity and use of very smooth copper**

Cost of Ownership

- Ease of processing using FR-4 standards
- Availability of many choices of laminates and prepregs
- Superior dimensional stability resulting in higher yields
- Lower processing and drilling costs (no plasma de-smear needed, no ceramic fillers to shorten drill life)
- Fill and float properties offering compatibility with wider range of package options
- Absence of creep and aging issues of alternative materials

Many factors contribute to the low cost of ownership of new high Tg thermoset polymers

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Astra® MT

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Astra® MT

- Dk 3.00, Df 0.0017
- Core Thickness available – 0.005”, 0.010”, 0.015” 0.020”, 0.030” and 0.060” cores
- Copper VLP-2 (2 micron) copper foil
- Prepreg – 4 glass thicknesses, 0.0020”, 0.0025”, 0.0030” and 0.0035” after lamination

Astra® MT Core Offering

Core Thickness (in)	Core Thickness (mm)	Dk at 2.0 GHz	Dk at 5.0 GHz	Dk at 10.0 GHz	Dk at 15 GHz	Dk at 20 GHz
0.0050	0.1250	3.00	3.00	3.00	3.00	3.00
0.0100	0.2500	3.00	3.00	3.00	3.00	3.00
0.0150	0.3750	3.00	3.00	3.00	3.00	3.00
0.0200	0.5000	3.00	3.00	3.00	3.00	3.00
0.0300	0.7500	3.00	3.00	3.00	3.00	3.00
0.0600	1.5000	3.00	3.00	3.00	3.00	3.00

Core Thickness (in)	Core Thickness (mm)	Df at 2.0 GHz	Df at 5.0 GHz	Df at 10.0 GHz	Df at 15 GHz	Df at 20 GHz
0.0050	0.1250	0.0017	0.0017	0.0017	0.0017	0.0017
0.0100	0.2500	0.0017	0.0017	0.0017	0.0017	0.0017
0.0150	0.3750	0.0017	0.0017	0.0017	0.0017	0.0017
0.0200	0.5000	0.0017	0.0017	0.0017	0.0017	0.0017
0.0300	0.7500	0.0017	0.0017	0.0017	0.0017	0.0017
0.0600	1.5000	0.0017	0.0017	0.0017	0.0017	0.0017

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Astra® MT Prepreg Dk Df

Prepreg	Resin Content	Thickness (in)	Thickness (mm)	Dk at 100 MHz	Dk at 500 MHz	Dk at 1 GHz	Dk at 2.0 GHz	Dk at 5.0 GHz	Dk at 10.0 GHz	Dk at 15 GHz	Dk at 20 GHz
1035	73	0.0023	0.0575	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
1067	77	0.0028	0.0700	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
1078	70	0.0033	0.0825	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01
1078	74	0.0036	0.0900	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95

Prepreg	Resin Content	Thickness (in)	Thickness (mm)	Df at 100 MHz	Df at 500 MHz	Df at 1 GHz	Df at 2.0 GHz	Df at 5.0 GHz	Df at 10.0 GHz	Df at 15 GHz	Df at 20 GHz
1035	73	0.0023	0.0575	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1067	76	0.0028	0.0700	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
1078	70	0.0033	0.0825	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1078	74	0.0036	0.0900	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019

- **Prepreg thicknesses are as pressed between two solid copper planes**
- **The rheology of Astra MT prepreg allows for good flow and fill during lamination**
- **Astra MT prepreg capable of multiple lamination cycles**
- **Astra MT prepreg - laser via formation can be done with CO_2 and YAG laser**

Astra® MT Properties

Property	Units	Astra MT
Tg, (DSC)	C	200
Td, (TGA)	C	360
CTE - z-axis (50-260 C)	%	2.80
T-260 (TMA)	minutes	60
T-288 (TMA)	minutes	> 60
Dk - 2 GHz		3.00
Dk - 5 GHz		3.00
Dk - 10 GHz		3.00
Df - 2 GHz		0.0017
Df - 5 GHz		0.0018
Df - 10 GHz		0.002
Peels, 1 oz after thermal stress		5
Moisture Absorption	%	0.01
Flammability	-	94 V-0
UL recognition		non Ansi

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Case Study:
Automotive RADAR

Freescale RADAR Starter Kit

- KITRADAR2001EVM is for demonstration and evaluation of Freescale mmwave RADAR chipsets and micro-controllers
- Modular design consists of RADAR process board, RF front end board, mechanical waveguide adapter, antenna board
- System operates at 76 to 77 GHz and has 4 transmit channels and 6 receive channels
- Antennas are designed for both long range and short range sensing

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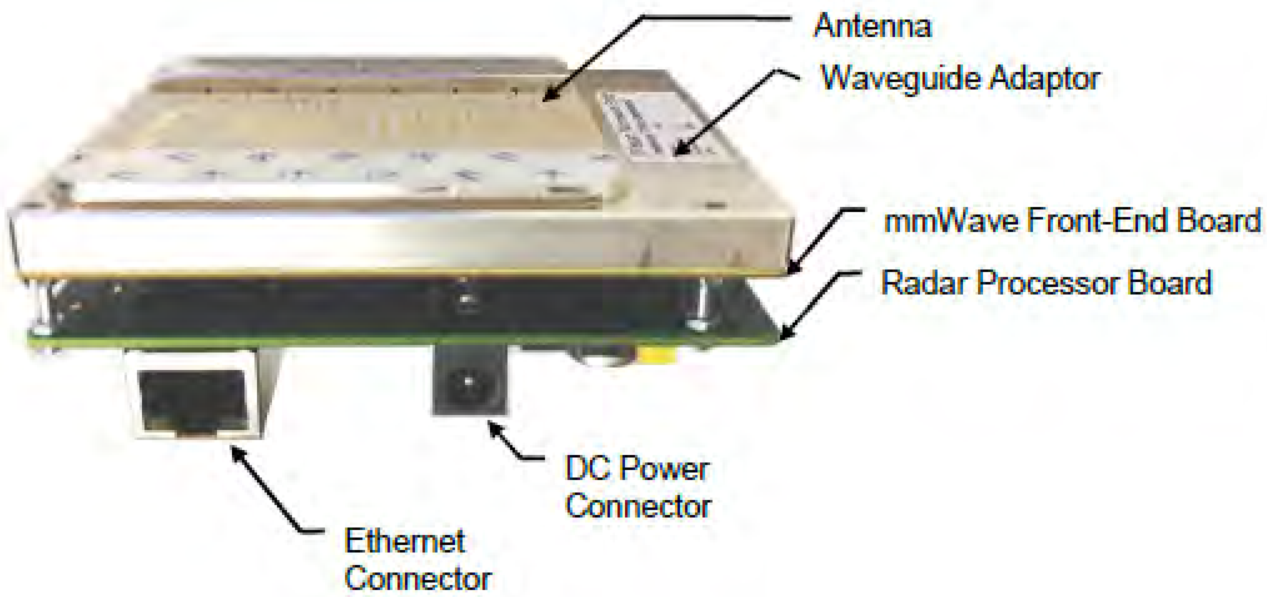
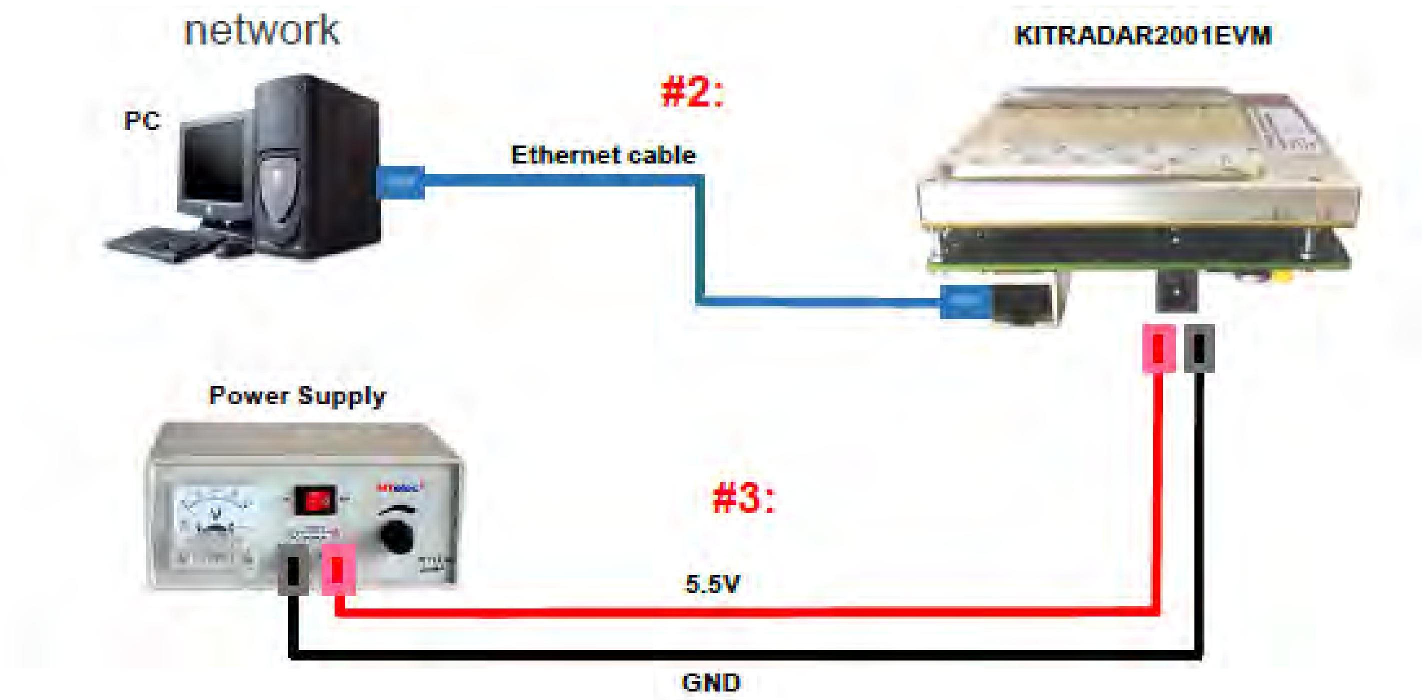
Freescale KITRADAR2001EVM



Modular design of KITRADAR2001EVM

Demonstration Hardware



- **Demonstration hardware consists of KITRADAR2001EVM, power supply, and PC for control**

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Astra MT vs. PTFE

- Astra MT was used for antenna/RF board replacing PTFE-based material
- Astra MT had superior mechanical properties, better registration and doesn’t experience the process challenges of PTFE
- Additionally, substantial material cost saving and fabrication cost savings are realized with use of Astra MT thermoset
- RF performance of Astra met or exceeded that of the PTFE product – antenna gain and EIRP

Conclusions

- Automotive safety systems present the designer with challenges in balancing performance and cost
- Further material constraints come from the challenging operating environment and thermal cycling necessary in the operational environment
- Designs by several OEMs are trending towards single board solutions combining RF and High Speed Digital functionality
- Current PTFE-based substrates are not suitable for hybrid technology required
- High Tg thermoset polymer systems presented here can be used effectively in a high layer-count hybrid and offer high reliability and lower cost

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Summary

- Printed Circuit Board (PCB) requirements for mm-wave frequency band
- Requirements for mm-wave Advanced Automotive Safety Systems
- PCB Material Availability in Industry
- Case study using Astra® MT on mmwave automotive RADAR application

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