PCB Material Selection for RF, Microwave and Millimeter-wave Design
Outline

- Printed Circuit Board (PCB) attributes for RF, microwave, millimeter-wave systems
- Application example – Advanced Automotive Safety System
- PCB material product solutions
- Summary
RF/Microwave/mm-Wave Trends

- Aerospace and defense applications are the foundation for RF/microwave/millimeter-wave PCBs
- Recent surge in RF/microwave/millimeter-wave commercial applications
  - Result is wider range of PCB product offerings meeting a wider range of needs
- Choosing the appropriate PCB material requires consideration of technical performance attributes and cost
Considerations for PCB Material Selection

- **System Requirements**
  - Frequency of operation, bandwidth and power
  - Electrical size of board and critical features
  - System loss requirements
  - Temperature range of system operation and cycle profile
  - Number of layers of PCB

- **PCB Material**
  - Electromagnetic loss, mechanical strength, thermal properties
  - Stability over varying environmental conditions – temperature, humidity, etc.
  - RF-power handling capability
  - Processability and compatibility with hybrid constructions
  - Cost
RF/Microwave/millimeter-Wave vs HSD

- RF/microwave/millimeter-wave PCBs traditionally have only a few layers, in some cases just 1 or 2
- PCBs for high-speed digital applications often have 20+ layers with hundreds of traces
- RF/microwave/millimeter wave systems require very low loss
  - Process low-level signals
  - Enable high-power applications
- HSD applications can be more tolerant of losses
- RF/microwave/millimeter-wave system applications generally require very precise control of critical dimensions on the PCB
- Boards with RF/microwave/millimeter-wave and HSD functionality present unique challenges but are becoming more common
PCB Laminate Material Considerations

- PCB laminates considered here consist of one or more plies of resin-impregnated glass cloth sandwiched between two copper foils.

- The RF/microwave/millimeter wave performance of the laminate & resulting PCB depends primarily on:
  - The resin and glass characteristics, dielectric constant and loss factors
  - The quality of the copper foil – surface roughness, purity
Desirable PCB Electrical Properties

- **Low dissipation factor, Df = tanδ**
  - Maximize power delivered
  - Enable high-power applications

- **Low dielectric constant, Dk**
  - Allows rapid signal propagation

- **Consistent Df, Dk over operating bandwidth of intended application**
  - Provides consistent transmission line impedance
  - Prevents phase distortion

- **Consistent Df, Dk with changes in temperature**
Electrical Loss Effects

Electrical Losses in the PCB result in performance degradation in antennas and transmission lines and components

- **Antenna**
  - Lower radiated power
  - Reduction in gain
  - Broadening of return loss resonance
  - Thermal effects at high power levels

- **Transmission Lines**
  - Lower delivered power
  - Thermal issues in high power applications
Microstrip line is dominate transmission line in RF/microwave/mm-wave with performance limited by:

- Dielectric Loss
- Conduction Loss
- Mismatch 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.
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)

- Reduction in effective cross-sectional area increases the effective resistance
Conductor Surface Roughness

- Conductors on PCBs do not have perfectly smooth surfaces
- Rough copper improves peel strength of laminate
- Maximum peak-peak tooth size varies ≈2-10 microns
- Surface roughness increases bulk copper resistance 10 to 50%
- Electrical impact of conductor roughness increases with increasing frequency

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Skin Depth (Copper)</th>
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<tbody>
<tr>
<td>50 Hz</td>
<td>9.3 mm</td>
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<td>10 MHz</td>
<td>21 μm</td>
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<tr>
<td>100 MHz</td>
<td>6.6 μm</td>
</tr>
<tr>
<td>1 GHz</td>
<td>2.1 μm</td>
</tr>
<tr>
<td>10 GHz</td>
<td>0.66 μm</td>
</tr>
</tbody>
</table>
Foil is fabricated by plating copper on a drum.

RTF ≠ a foil roughness designator.
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
Conductor Surface Roughness

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

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

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<th>Frequency</th>
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Standard foil ~10 µm
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
- Multiple spikes are about 10 µm from top to bottom
- Electric field is singular on the spikes (similar to strip edges)
- Consistent for 2 line types
  - About 5% increase for MSL with one RTF surface
  - >10% increase for strip line with two RTF surfaces
- Consistent increase in group delay and decrease in characteristic impedance over very wide frequency band

With the adjusted Dk of 3.15 the group delay matches that of Dk = 3.0 case with RTF copper surface profile
Microstrip Transmission Line

Transmission Line Effects

\[ \alpha_d = 27.3 \frac{\varepsilon_r (\varepsilon_{\text{eff}} - 1) \tan \delta}{\varepsilon_{\text{eff}}^{1/2} (\varepsilon_r - 1) \lambda_0} \] (dB/m) \[1\]

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{(1 + 12h/w)^{1/2}} \]

(static effective permittivity)

\[ \varepsilon_{\text{eff}}(f) = \frac{\varepsilon_r - \varepsilon_{\text{eff}}}{1 + G f^2 / f_p^2} \]

, \[ f_p = \frac{Z_c}{2 \mu_0 h} \]

, \[ G = 0.6 + 0.009 \frac{Z_c}{\text{ohm}} \]

Getsinger effective permittivity

Attenuation constant is linear with respect to loss tangent and can be significant contributor when \( \tan \delta \sim 0.005 \, \text{to} \, 0.01 \)
Transmission Line Effects

Microstrip Conductor Loss

\[ \alpha_c = 8.68 \frac{R_s}{Z_ch} \alpha'_c \quad \text{(dB/m)} \quad \text{with} \quad \alpha'_c = f(w_{eq}, h, t) \] [1]

\[ w_{eq} = w + \frac{t}{\pi}(\ln a + 1), \quad a = 4\pi w/t, \quad w/h < 1/2\pi \]

\[ w_{eq} = w + \frac{t}{\pi}(\ln b + 1), \quad b = 4h/t, \quad w/h > 1/2\pi \]

\[ R_s = \left( \frac{\omega \mu}{2\sigma} \right)^{1/2} \]

To take surface roughness into account replace \( R_s \) with the following

\[ R_s(\Delta) = R_s \left( 1 + \left( \frac{2}{\pi} \right) \tan^{-1}\left( 1.4(\Delta/\delta)^2 \right) \right) \] [2]

\[ \Delta = \text{root mean square surface roughness,} \quad \delta = \text{skin depth} \]

[1] Noyan Kinayman, Modern Microwave Circuits, Norwood, MA, Artech House, 2005
Microwave circuit elements commonly have $\lambda/4$ critical dimensions
Several are typically cascaded requiring propagation distances on order of $\lambda$’s
System signal loss due to dielectric and conductor losses can be significant
Microstrip Characteristic Impedance

\[ Z_c = \frac{120 \pi (\varepsilon_{\text{eff}})^{1/2} [ w/h + 1.393 + 0.667 \ln (w/h + 1.444) ]}{(\varepsilon_{\text{eff}})^{1/2}[ w/h + 1.393 + 0.667 \ln (w/h + 1.444) ]} \]

for \( w/h > 1 \)

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{(1 + 12h/w)^{1/2}} \]  

(static effective permittivity)

\[ \varepsilon_{\text{eff}}(f) = \frac{\varepsilon_r - \varepsilon_{\text{eff}}}{1 + Gf^2/f_p^2}, \quad f_p = \frac{Z_c}{2\mu_0 h}, \quad G = 0.6 + 0.009 \frac{Z_c}{\text{ohm}} \]  

(Getzinger effective permittivity)

Variations in \( \varepsilon_r \) result in impedance mismatches

- Variations in dielectric thickness and dielectric properties
  - Manufacturing tolerances
  - Temperature and frequency dependent dielectric constant and loss factor
- Variations in conductor geometry
Advanced Automotive Safety Systems
Active Safety Systems

Radar sensor portfolio
• 25 GHz ultra-wide band RADARs
• 24 GHz narrow-band RADARs
• 77 GHz multimode RADARs

Supporting
• Blind spot detection
• Rear cross-traffic alert
• Lane change assist
• Forward collision warning
• Autonomous emergency braking
• Adaptive cruise control
### RADAR Resolution Requirements

**Scenarios Requiring High Resolution**
- Side impact
- Cross-traffic alert
- Narrow pass assistant
- Evasion maneuver
- Pedestrian protection
- Front collision warning
- Proximity warning and parking assistant

**Scenarios Needing Lower Resolution**
- Adaptive cruise control – long range
- Lane change assist – 24 GHz

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<th>Bandwidth</th>
<th>Resolution</th>
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<td>24 – 24.25 GHz</td>
<td>250 MHz</td>
<td>0.6m</td>
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<tr>
<td>21 – 26 GHz</td>
<td>5 GHz</td>
<td>0.03m</td>
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<tr>
<td>76 – 77 GHz</td>
<td>1 GHz</td>
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<tr>
<td>77 – 81 GHz</td>
<td>4 GHz</td>
<td>0.0375m</td>
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</table>
Active Safety System Development

Systems are migrating to higher frequencies

- Change in frequency allocation
- Improved Performance
- Reduced size and improved affordability

Source: Infineon
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

- Increasing demand for system cost reductions for a widening target market
PCB Material Selection

- Frequency of operation requires high performance material
- Dk, Df as flat as possible over range of frequency for LRR and SRR
- Dk, Df temperature stable over operating range (-40°C to 85°C)
- Lowest cost as possible
  - Choose sufficient material to satisfy requirements
  - Hybrid construction
  - Process compatible with hybrid
This hybrid structure utilizes high performance material where necessary and standard process-compatible materials to reduce cost.
Isola Product Solutions
Isola Product Offering

Performance

Green Speed®

IS415

High Tg 200
Lead Free, Mid Dk Df

FR408HRIS

Tg 200
FR408HR Low-Dk Glass

IS620i

Tg 225 Low Loss
0.007 @ 10 GHz Laminate

P96/P26

Tg 260
Polyimide Laminate V0/V1

P95/P25

Tg 260
Polyimide Laminate HB

GETEK®

Tg 180
Mid Dk Df

G200

BT/Epoxy Laminate

Ultra-EC®

Ultrathin 25 µm (1 mil)
Laminate Tg 170

FR406N

A11
Polyimide – P26N

Lo-Flo®/No Flow Prepreg

New Products

FR408HB

Tg 180
Low Dk Df, Low CTE

IS680-325

Dk 3.25 Df 0.0032

IS680-320

Dk 3.20 Df 0.0032

IS680-300

Dk 3.00 Df 0.0030

IS680-280

Dk 2.80 Df 0.0028

I-Speed®IS

I-Speed® on
Low-Dk Glass, Dk 3.28

I-Speed®

Tg 200 Low Loss
0.0066 @10 GHz, Dk 3.64

Tachyon®-100G

Dk 3.04, Ultra-low
Loss <0.0021 @ 10 GHz

I-Tera®MT

Tg 200, Dk 3.00, Ultra-low
Loss <0.0035 @ 10 GHz

TerraGreen®

Ultra-low Loss Df <0.0035
DK 3.44 Halogen Free

GigaSync®

Tg 180, Low Skew & Loss
0.0066 @10GHz, Dk 4.13

Astra® MT

Dk 3.00 Df 0.0017

IS680-345

Dk 3.45 Df 0.0036

IS680-340

Dk 3.38 Df 0.0034

IS680-338

Dk 3.38 Df 0.0034

IS680-305

Dk 3.00 Df 0.0030

IS680-280

Dk 2.80 Df 0.0028

IS680-260

Dk 2.60 Df 0.0026

IS680-250

Dk 2.50 Df 0.0025

IS680-240

Dk 2.40 Df 0.0024

IS680-220

Dk 2.20 Df 0.0022

IS680-200

Dk 2.00 Df 0.0020

IS680-180

Dk 1.80 Df 0.0018

IS680-160

Dk 1.60 Df 0.0016

IS680-140

Dk 1.40 Df 0.0014

IS680-120

Dk 1.20 Df 0.0012

IS680-100

Dk 1.00 Df 0.0010

IS680-80

Dk 0.80 Df 0.0008

IS680-60

Dk 0.60 Df 0.0006

IS680-40

Dk 0.40 Df 0.0004

IS680-20

Dk 0.20 Df 0.0002

IS680-10

Dk 0.10 Df 0.0001

IS680-0

Dk 0.00 Df 0.0000
Isola Product Positioning
RF/Microwave Products

**Improving Thermal Performance**
- **T260/Td/IST**

**Improving Electrical Performance**
- Lower Dk/Df – Higher Speed

**Multilayer, Hybrid & Double-sided Applications**

- **Astra® MT**
  - Very Low Df, Dk 3.00 Df 0.0017
  - 0.005”, 0.010”, 0.015”, 0.020”, 0.030” & 0.060” cores only

- **I-Tera® MT - Very Low Loss**
  - 0.002” to 0.018” core, full prepreg offering
  - Dk 3.15 to 3.45, Df – 0.0031 - 0.0037
  - I-Tera MT RF 0.020” & 0.030 3.38 and 3.45 Dk

**Double-sided Applications**

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<tr>
<th>Product Code</th>
<th>Dk</th>
<th>Df</th>
<th>Thickness</th>
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</thead>
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<td>3.45</td>
<td>0.0036</td>
<td>20, 30 &amp; 60 mil</td>
</tr>
<tr>
<td>IS680-333</td>
<td>3.33</td>
<td>0.0034</td>
<td>20, 30 &amp; 60 mil</td>
</tr>
<tr>
<td>IS680-338</td>
<td>3.38</td>
<td>0.0035</td>
<td>20, 30 &amp; 60 mil</td>
</tr>
<tr>
<td>IS680-320</td>
<td>3.20</td>
<td>0.0032</td>
<td>20, 30 &amp; 60 mil</td>
</tr>
<tr>
<td>IS680-300</td>
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<td>20, 30 &amp; 60 mil</td>
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<tr>
<td>IS680-280</td>
<td>2.80</td>
<td>0.0028</td>
<td>20, 30 &amp; 60 mil</td>
</tr>
</tbody>
</table>

**5 GHz** – **77 GHz**

**Improving Electrical Performance** — Lower Dk/Df — Higher Speed
RF/Microwave Product Offerings

- IS680
- I-Tera® MT
- Astra® MT
IS680
IS680 Product Strengths

- IS680 is available in 0.020”, 0.030” and 0.060” thicknesses

- Typical solder floats > 3000 seconds

- Superior drilling performance – IS680 does not contain a ceramic filler!

- IS680 has been granted a UL 94 V-0 Flammability Rating

- MOT 110°C
IS680 Electrical Properties

- Stable Df over Frequency 2 to 20 GHz
- Stable Df over temperature from -40°C to 125°C
- Stable Dk over frequency range of 2 to 20 GHz
- Stable Dk over temperature from -40°C to 125°C
- Customized Dk on thick cores for different applications (ie. 2.80, 3.00, 3.20, 3.33, 3.38, 3.45)
- The ability to customize Dk to match competitive products vs. advertised Dk values on certain thicknesses
- Excellent power handling ability
IS680 Product Positioning

- Applicable for RF/microwave designs
  - LNB (satellite TV)
  - Antenna
  - Power amplifier
  - Traffic sensors
  - RFID
  - Collision warning
  - Base station
  - Base Station antenna
  - Sat telephone
  - WiMAX antenna

- Capable of meeting lead-free requirements
<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>IS680</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tg, (DSC)</td>
<td>C</td>
<td>200</td>
</tr>
<tr>
<td>Td, (TGA - ASTM)</td>
<td>C</td>
<td>360</td>
</tr>
<tr>
<td>CTE - z-axis (50-260°C)</td>
<td>%</td>
<td>2.80</td>
</tr>
<tr>
<td>T-260 (TMA)</td>
<td>minutes</td>
<td>60</td>
</tr>
<tr>
<td>T-288 (TMA)</td>
<td>minutes</td>
<td>&gt; 60</td>
</tr>
<tr>
<td>Dk - 2 GHz</td>
<td></td>
<td>2.80 - 3.45</td>
</tr>
<tr>
<td>Dk - 5 GHz</td>
<td></td>
<td>2.80 - 3.45</td>
</tr>
<tr>
<td>Dk - 10 GHz</td>
<td></td>
<td>2.80 - 3.45</td>
</tr>
<tr>
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<tr>
<td>Peels, 1 oz after thermal stress</td>
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<td>5</td>
</tr>
<tr>
<td>Moisture Absorption</td>
<td>%</td>
<td>0.01</td>
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<tr>
<td>Flammability</td>
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<tr>
<td>UL recognition</td>
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<td>non-Ansi</td>
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</table>
IS680 dB/inch Data

IS680 Comparison dB/INCH

Frequency in GHz

dB/INCH

IS680 vs Competitive Products

IS680 vs Competition

Frequency in GHz

dB/INCH

-0.900
-0.800
-0.700
-0.600
-0.500
-0.400
-0.300
-0.200
-0.100
0.000

RO4350B®
AR 25N
IS680-345
IS680-338
TCK Data
Temperature range
-40°C to +125°C at 10 GHz
Total delta on Dk of 0.005 – very stable over the temperature range
IS680 TCK Df -40°C to 125°C

Very stable Df (loss tangent) over the temperature range
I-Tera® MT
I-Tera® Product Strengths

- Standard thicknesses available (nominal ± 5% for 0.020” and above)
- Full thin core offering from 0.0020 (non-ZBC) to 0.018” for multilayer designs
- I-Tera MT RF 0.020” & 0.030” available for multilayer or hybrid-multilayer designs
- Square and MS-spread glass weaves used: 1035, 1067, 1086, 1078
- Very-low loss material for backplane, high data rate daughter cards, hybrid applications
- Superior drilling performance – I-Tera MT does not contain a ceramic filler
- Processing to date – plasma desmear not required
- No issues with ENIG in testing to date.
- Passed 1000 HATS cycles
- Passed 10x 700°F re-work simulation testing
- Compatible with Isola 185HR, 370HR and IS415 for hybrid constructions
- I-Tera MT prepreg can be stored at standard FR-4 conditions
- UL: 94 V- 0
- UL MOT: 130°C, I-Tera MT is the UL designation
<table>
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<tr>
<th>Property</th>
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<tr>
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<td>Dk - 10 GHz</td>
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<td>3.00 - 3.45</td>
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<td>Df - 2 GHz</td>
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I-Tera® MT Thermal Coefficient of Loss Tangent

![Graph showing the thermal coefficient of loss tangent for I-Tera® MT material over a range of temperatures.](image)
20-25% Improved performance over the competition!
Astra® MT
Astra® MT

- **RF/Microwave Applications**
  - Automotive RADARs and sensors - 77 Gigahertz
  - DAS antennas
  - CPE antennas
  - Feed networks
  - Point to point – microwave links
  - mm-wave applications
  - Aerospace applications
  - GPS satellite antennas

- **Competitive products**
  - Rogers RO3003™ high frequency circuit materials
  - Taconic ORCER RF-35
  - Arlon AD300C
Astra® MT Product Offering

- RF/microwave and mm wave applications
  - Dk: 3.00
  - Core thickness available: 0.005”, 0.010”, 0.015”, 0.020”, 0.030” and 0.060”
  - Copper: HVLP-2 (2 micron) copper foil
### Astra® MT Key Properties

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<td>3.00</td>
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<td>Dk - 10 GHz</td>
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Astra MT
Testing at 77 and 100 GHz
Astra® MT vs. Competition

Frequency in GHz

- dB/in

1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0 12.5 13.0 13.5 14.0 14.5 15.0 15.5 16.0 16.5 17.0 17.5 18.0 18.5 19.0 19.5 20.0

0.000

-0.100

-0.200

-0.300

-0.400

-0.500

-0.600

Astra 3.0

R03003

RF-35A2

™
Astra® MT TCk -40°C to 140°C

Astra offers very stable Dielectric Constant (Dk) over temperature due to its high Tg.
Astra® MT Testing at 77 & 100 GHz

IZM’s Approach for the Extraction of Material Parameters

- Measurement of the Geometrical Dimensions via Microsection
- Measurement of Surface Roughness

3D Full Wave Simulation

Layout

Fabrication

Test Structure

RF - Measurement

Extraction of $\varepsilon_r$ and $\tan \delta$

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

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Adaptation of 3D Simulation Models

Measurement of surface roughness using a Hommel Profilometer

Geometrical measurement of cross-section and optical measurement of the surface roughness parameters (microsection)

Impact of surface roughness and geometrical fluctuations during fabrication were considered in HFSS simulations. For the surface roughness, the Huray model was used.
Astra® MT Testing at 77 & 100 GHz

Extraction of the Dielectric Material Properties – 6/7

Permittivity Vs Temperature at Frequency Bands of Interest

76 GHz – Band

102 - 103 GHz – Band

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Technische Universität Berlin
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Beyreuther, Bierwirth, Curran, Duan,
Fotheringham, Maaß,
Ndip, Öz, Thognon, Tschoban

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Extraction of the Dielectric Material Properties – 7/7

Typical Uncertainty

Extracted Values (25°C, 100GHz)

<table>
<thead>
<tr>
<th>Test Structure</th>
<th>$\varepsilon_r$</th>
<th>$\tan\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonator 1</td>
<td>2.97</td>
<td>0.0010</td>
</tr>
<tr>
<td>Resonator 2</td>
<td>2.96</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

Considering typical uncertainty

<table>
<thead>
<tr>
<th>$\varepsilon_r$</th>
<th>$\tan\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 ± 0.1</td>
<td>0.0015 ± 5x10^{-4}</td>
</tr>
</tbody>
</table>
Astra® MT

- Astra MT has been used in automotive 77 GHz hybrid board designs with Isola 185HR & 370HR
- Astra MT was processed with the Isola 370HR processing parameters with very good results
- **Processing advantages:**
  - Predictable scaling (Competition does not use glass weave)
  - Microvia and drill processes used 370HR parameters and had standard hit counts vs reduced hit counts with the competitive products
  - Plasma desmear is not required
  - Astra MT does not need to be processed in a certain time period at microvia plating, electroless and soldermask processes.
    - Competitive products need to go through these process steps in a certain amount of time or will need to repeat the plasma process
  - Planarization of Astra MT is similar to FR-4
Selecting the Right Material

- Laminate material selection can not be condensed into a single-page chart for easy selection
- High-performance laminate material suppliers have a better understanding of material performance
- Cost-to-performance evaluations must still be done by the system design team to ensure the lowest cost material that will do the job is selected
Summary

- Printed Circuit Board (PCB) attributes for RF, microwave, millimeter-wave systems
- Application example – Advanced Automotive Safety System
- PCB material product solutions