Low Transmission Loss Multilayer PWB Materials for High-Speed and High-Frequency Applications

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Advanced Performance Materials Operational Headquaters
Outline

- Introduction
- Evaluation technologies of high-frequency performance by Hitachi Chemical
  - Properties of new mid-loss PWB material
  - Innovative ultra-low loss PWB material
    / Target & Technical concept
    / Features & Advantages
- Conclusions
Introduction

- Evaluation technologies of high-frequency performance by Hitachi Chemical
- Properties of new mid-loss PWB material
- Innovative ultra-low loss PWB material / Target & Technical concept / Features & Advantages

Conclusions
Background; Trend of transmission rate

Higher performance of communication on network platform

Throughput of equipment ≈ Double / 2 years (Predicted from telecommunication traffic)

Throughput rate of PWBs / Link ≈ Double / 3 years

Signal speed on PWBs is increasing year by year to meet the needs of large-volume data transmission.
Transmission rate vs. trace length on PWBs

Next generation transmission technology (25 Gbps / link)
⇒ Electrical ? or Optical ? or Both

Need of the lower loss PWB material is increasing for the next generation electrical transmission.
Requirement for High-frequency PWB material

Transmission loss ($\alpha$) $\div$ Dielectric loss ($\alpha_d$) + Conductor loss ($\alpha_c$)

$$\alpha_d \propto 27.3 \times \frac{f}{c} \times \sqrt{Dk} \times Df$$

$$\alpha_c \propto Rs \left( f, \rho, \cdots \right) \times \sqrt{Dk} \times (t, w, b, \cdots) \cdots$$

$Dk$: dielectric constant, $Df$: Dissipation factor
$f$: Frequency, $c$: Light velocity
$Rs$: Surface resistance of conductor
$\rho$: Resistivity of conductor, $b$: Dielectric thickness
$w$: Conductor width, $t$: Conductor thickness

< Solution to lowering transmission loss >

- Reduction of $\alpha_d$ $\Rightarrow$ Low Dk & Df Resin technology
- Reduction of $\alpha_c$ $\Rightarrow$ High adhesion technology between resin and conductor with very low surface roughness
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- Conclusions
Evaluation technologies of high-frequency PWBs

Hitachi Chemical can satisfy various evaluation requirements of high-frequency performance of materials & PWBs (e.g. Frequency bands, Form of specimen, Environmental test, etc.)

(1) Dielectric properties of materials (without conductor)
- Parallel plate capacitance
- Cavity resonator perturbation
- Split post dielectric resonator (SPDR)
- Whispering-gallery mode (WG)
- Under planning

(2) Practical electrical properties of PWBs (containing conductor)
- Strip-line resonator (JPCA-TM001)
- Short pulse propagation (SPP)
- Strip line (SL)
- Micro strip-line (MSL)

Transmission loss

Dk & Df
Evaluation of PWB (SL & MSL)

**Strip-line (SL) structure**
- SMA connector type (up to 20 GHz)
- Probe type (up to 40 GHz)
- Test board (SL)

**Micro strip-line (MSL) structure**
- V-NA & Probe station
- Test board (MSL)

**Measurement system**

Various high-frequency properties of PWBs can be evaluated.

**Connector available**
- e.g.) High Tg material for PKG substrate

**Probe available**
- PTFE material
- Low Df material (FX-2)

**Graphs**
- S21 (dB/cm)
- S11 (dB)
- Frequency (GHz)
Simulation technologies

**Simulator**

- **3D EM field solver (HFSS)**
- **Circuit simulator (ADS)**

HFSS : High-Frequency Structure Simulator  
ADS : Advanced Design System

- Guessing of electrical performance, combination of structures, and the suitable materials
- Designing of PWB structure (e.g. measurement terminals, etc.) for evaluation of transmission properties to W-band, 100 GHz
- Verification of the measured Df value by fitting calculated transmission loss, S21, to measured loss S21
- Guessing of dielectric drift properties, $\Delta$Dk, by fitting calculated resonance properties, S11, to measured S11, etc.

Verification of the measured properties, Dk & Df by using simulation, and feedback of them to the material design.
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  / Features & Advantages

- Conclusions
Mid-loss material, HE-679G(S), and ultra-low loss material, LW-900G / 910G have been newly developed.
### Laminate properties of new mid-loss material

<table>
<thead>
<tr>
<th>Item</th>
<th>New mid-loss HE-679G(S)</th>
<th>Current HE-679G</th>
<th>High-Tg FR-4</th>
<th>Conventional FR-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass type</td>
<td>E</td>
<td>E</td>
<td>E</td>
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<tr>
<td>Source of flame retardant</td>
<td>Halogen free</td>
<td>Halogen free</td>
<td>Halogen</td>
<td>Halogen</td>
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<tr>
<td>Dk (JPCA-TM001)</td>
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</tr>
<tr>
<td>1 GHz</td>
<td>3.70-3.80</td>
<td>4.00</td>
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<tr>
<td>10 GHz</td>
<td>3.65-3.75</td>
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<td>3.98</td>
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<td>Df (JPCA-TM001)</td>
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<tr>
<td>1 GHz</td>
<td>0.0065-0.0070</td>
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<td>10 GHz</td>
<td>0.0085-0.0090</td>
<td>0.0120</td>
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<td>Copper peel strength</td>
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<td>(kN/m, 1/2 oz)</td>
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<td>RTF</td>
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<td>Tg (°C)</td>
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<td>TMA</td>
<td>185</td>
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<td>CTE(±ppm/°C)</td>
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<td>Solder heat resistance</td>
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<td>288 °C</td>
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<td>&gt; 300 s</td>
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<td>T-300</td>
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<td>TMA</td>
<td>&gt; 60 min</td>
<td>30 min</td>
<td>&lt;10 min</td>
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<td>&lt;5 min</td>
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<td>Flammability</td>
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<td></td>
<td>UL-94</td>
<td>V-0</td>
<td>V-0</td>
<td>V-0</td>
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<tr>
<td>Reliability (CAF, IST, etc.)</td>
<td></td>
<td>Good</td>
<td>Good</td>
<td>Low</td>
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</table>

Dk & Df of the newly developed mid-loss material, HE-679G(S), have been enhanced by maintaining the other properties as HE-679G.
Transmission loss of new mid-loss material

< Measurement conditions >
/ Evaluation structure : Strip-line
/ Temperature & Humidity: 25 ℃/60 %RH
/ Characteristic impedance: ca. 50 Ω
/ Interlayer surface treatment: Black-reduction
/ Proofreading method: TRL

/ Dimension parameters

<table>
<thead>
<tr>
<th>P/P</th>
<th>w</th>
<th>t</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- Trace width (w): 0.11-0.12 mm
- Dielectric thickness (b): 0.22-0.23 mm
- Trace thickness (t): 18 μm

Transmission loss of HE-679G(S) has been improved, comparing with the current HE-679G.
Reliability of new mid-loss material

Heat resistance

< Evaluation conditions >
/ Test board: t2.47 mm / 20 layer PWB
/ Diameter: Φ0.25 mm (TH-TH pitch: 0.8 mm)
/ Pre-condition: 85 ℃/85 %RH/120 h
   + Reflow max.260 ℃ × 10 times

CAF Test

< Evaluation conditions >
/ Test board: t1.4 mm / 2 layer PWB
/ TH-TH spacing: 0.5 mm / 2000 holes
/ Pre-condition: 30 ℃/60 %RH / 168 h
   + Reflow max.260 ℃ × 6 times
/ Measurement condition: 85 ℃/85 %RH, DC 100 V
   (Measurement of insulation resistance in chamber)

⇒ Passed (No defect)

Excellent reliability as that of the current HE-679G
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Target properties of new ultra-low loss material

HF-Performance vs. Reliability (Heat-resistance, CAF, IST, ...)
Concept & target applications of new ultra-low loss material

Development concept

High-frequency performance

Reliability & Process-ability

Halogen free

Target applications & requirement

High-speed Digital / High-layer (Servers, Routers, HPC, etc.)
- High frequency performance
- High heat resistance
- High reliability (Low-CTE, CAF, etc)

RF / Wireless (Antenna, RF-modules, etc.)
- High frequency performance
- Dk & Df drift stability
  (Temperature, Humidity)

High-speed PKG (MMIC-PKG, OEIC-PKG, etc.)
- High frequency performance
- High heat resistance
- High reliability (Low-CTE, CAF, etc)
- Halogen free
Technical composition of novel resin system designed for new ultra-low loss material

**Rigid thermosetting resin**
- Low Df
- High Tg
- Low CTE
- High elastic modulus
- High heat resistance
- High flame retardancy

**Reactive low polar polymer**
- Low Dk & low Df
- High Tg
- Low water absorption
- High toughness
- High adhesion

**Polymer-blend modification technology with co-crosslinking reaction**

**Composing technology (Organic / Inorganic)**
by controlling interface between resin and filler

**Inorganic filler**
- Low CTE
- Low Df
- High heat resistance
- Low water absorption

New material has been designed by using both the resin-modification technology & filler-composition technology.
The control of interface between resin and filler is important to enhance various properties.

Filler / Resin - composing technology

Filler interface control system (FICS)

Optimization of interface (Filler / Resin)
⇒ Excellent adhesion & dispersion
/ Low water absorption
/ High peel strength
/ Excellent heat resistance
/ Excellent CAF restraining property

Example of importance of FICS

Matrix resin
Inorganic Filler

Conventional
Aggregation

Exfoliation mode on Cu-peeling test
None
→ Exfoliation between filler & resin
Optimum (FICS)
→ Cohesive failure of resin

Optimum

Water absorption (% after 85°C / 85%RH /500h)

0.5
0.4
0.3
0.2
0.1
0

None ref-1 ref-2 ref-3 ref-4 ref-5 Optimum

Treatment type on filler surface

Copper peel strength (kN/m)

0.8
0.6
0.4
0.2
0

The control of interface between resin and filler is important to enhance various properties.
# Laminate properties of new ultra-low loss material

<table>
<thead>
<tr>
<th>Item</th>
<th><strong>New ultra-low loss</strong></th>
<th>Current low loss</th>
<th>HE-679G</th>
<th>Standard PTFE laminate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>LW-900G</strong></td>
<td><strong>LW-910G</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resin system</td>
<td>Thermosetting</td>
<td>Thermosetting</td>
<td>Thermosetting</td>
<td>Thermoplastic</td>
</tr>
<tr>
<td>Glass type</td>
<td>E</td>
<td><strong>Low Dk</strong></td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Source of flame retardant</td>
<td><strong>Halogen free</strong></td>
<td>Halogen</td>
<td><strong>Halogen free</strong></td>
<td>-</td>
</tr>
<tr>
<td>Dk (JPCA-TM001)</td>
<td>10 GHz</td>
<td>3.57</td>
<td>3.32</td>
<td>3.45</td>
</tr>
<tr>
<td>Df (JPCA-TM001)</td>
<td>10 GHz</td>
<td><strong>0.0048</strong></td>
<td><strong>0.0038</strong></td>
<td><strong>0.0034</strong></td>
</tr>
<tr>
<td>Copper peel strength (kN/m, 1/2 oz)</td>
<td>RTF</td>
<td>0.75</td>
<td>0.75</td>
<td>0.60</td>
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<tr>
<td></td>
<td>HVLP</td>
<td>0.63</td>
<td>0.63</td>
<td>-</td>
</tr>
<tr>
<td>Tg (℃)</td>
<td>TMA</td>
<td>198</td>
<td>198</td>
<td>185</td>
</tr>
<tr>
<td>CTE(ppm/℃)</td>
<td>XY</td>
<td>13</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Z(α1)</td>
<td>40</td>
<td>40</td>
<td>47</td>
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<tr>
<td></td>
<td>Z(α2)</td>
<td>250</td>
<td>250</td>
<td>110</td>
</tr>
<tr>
<td>Solder heat resistance</td>
<td>288 ℃</td>
<td>&gt; 300 s</td>
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<tr>
<td>T-300</td>
<td>TMA</td>
<td>&gt; 60 min</td>
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<tr>
<td>Flammability</td>
<td>UL-94</td>
<td>(V-0)</td>
<td>(V-0)</td>
<td>V-0</td>
</tr>
<tr>
<td>Reliability(CAF, IST, etc.)</td>
<td>On internal evaluation</td>
<td>On internal evaluation</td>
<td>On evaluation by PWB maker</td>
<td>Good</td>
</tr>
</tbody>
</table>

*1) Practical value calculated by the condition of strip-line structure with Cu-foil(RTF, Rz≒3 μm)

*2) Practical value calculated by the condition of strip-line structure with Cu-foil(HVLP, Rz≒1.5 μm)
Excellent stability of Dk in wide frequency range

Df of standard type is lower than the current low loss material (FX-2). Df of low-Dk type with HVLP is better than that of PTFE laminate.
Dk & Df vs. Temperature

< Measurement conditions >
/ Method: Strip-line resonator (JPCA-TM001)
/ Temperature: -25~100 ℃
/ Dielectric thickness: 1.6 mm (Ground - Ground), Copper foil: 18 μm

Excellent stability against temperature change
Dk & Df vs. Moisture absorption

< Measurement conditions >
/ Method : Strip-line resonator (JPCA-TM001)
/ Moisture absorption treatment : 85 °C/85 %RH/—1000 h
/ Dielectric thickness : 1.6 mm(Ground - Ground), Copper foil : 18 μm

Better stability against moisture absorption treatment compared with high-Tg FR-4
Transmission loss of new ultra-low loss material

< Measurement conditions >
/ Evaluation structure: Strip-line
/ Temperature & Humidity: 25 ℃/60 %RH
/ Characteristic impedance: ca. 50 Ω
/ Interlayer surface treatment: Black-reduction
/ Proofreading method: TRL

/ Dimension parameters

P/P

Core

- Trace width (w): 0.120 mm
- Dielectric thickness (b): 0.23-0.25 mm
- Trace thickness (t): 18 μm

Dimension parameters

Improved by 8 dB/m (12.5 GHz) compared with current low loss material

-25 dB/m @ 12.5 GHz

-33 dB/m @ 12.5 GHz

Improved by 8 dB/m (12.5 GHz) compared with current low loss material
**Eye pattern diagrams**

< Measurement conditions >
- Evaluation PWB : Former S21 evaluation PWB(Strip-line)
- Bit rate : 12.5 Gbps (Trace length : 300 mm), 25 Gbps (Trace length : 100 & 300 mm)

<table>
<thead>
<tr>
<th>Item</th>
<th>HE-679G</th>
<th>FX-2</th>
<th>LW-900G(RTF)</th>
<th>LW-910G(HVLP)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>12.5 Gbps</strong></td>
<td><img src="image" alt="Graph" /></td>
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<td>L:300mm</td>
<td><img src="image" alt="Graph" /></td>
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<td><img src="image" alt="Graph" /></td>
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<tr>
<td><strong>25 Gbps</strong></td>
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<td>L:100mm</td>
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<td><strong>25 Gbps</strong></td>
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</tr>
</tbody>
</table>

Eye-opening of LW-900G is better than the others.
Construction of PWB (20 layers)

Layer Count: 20 layers
PCB Thickness: 2.9mm
The result of Heat Resistance

Test condition: 260°C Reflow x 6times

There is no delamination and pad-lifting.
The result of IST

<Test condition>
Pre-Condition: 260 °C Reflow x 6times
Cycles: 2000 (10 % resistance change)
Test Temperature: RT to 150 °C (Heated in 180 seconds)
Φ0.25 mm, pitch:0.8 mm

Figure. IST sample
The result of IST

<Test condition>
Pre-Condition: 260 °C Reflow x 6 times  Cycles: 2000 (10 % resistance change)

Test Temperature: RT to 150 °C(Heated for 180 s), Φ0.25 mm, pitch:0.8 mm
<Test condition>
Pre-Condition: 260 °C Reflow x 6times

Cycles: 1000 (10 % resistance change)

Test Temperature: -65°C (30 min) to 125 °C(30 min)

Test 1: Φ0.25 mm, pitch:0.8 mm,  Test 2: Φ0.25 mm, pitch:1.0 mm
Test 3: Φ0.65 mm, pitch:2.5 mm,  Test 4: Φ0.25 mm, pitch:0.8 mm

Figure. TCT sample
The result of TCT

<Test Condition>
Pre-Condition: 260 °C Reflow x 6 times
Cycles: 1000 (10 % resistance change)
Test temperature: -65°C (30 min) to 125 °C(30 min)
Insulation reliability (CAF evaluation) (1)

< Evaluation conditions >
/ Evaluation board: t0.8 mm (Cu: 18 μm) / 2 layer PWB
/ Diameter: Ø0.15 mm / TH-TH spacing: 0.2 mm
/ Pre-condition: 85 °C/85 %RH/120 h + Reflow max. 260 °C x 8 times
/ Measurement condition: HAST(130 °C/85 %RH), DC 5.5 V
(Continuous measurement of insulation resistance in chamber)

Excellent CAF restraining property & drilling process-ability

Crack (glass/resin) by drilling: <10 ~ 20 μm

Diameter: Ø0.15 mm

TH - TH spacing: 0.2 mm

Conventional FR-4

High-Tg FR-4

LW-900G

HE-679G
< Board spec. >
- Board thickness: 2.0 mm
- T/H pitch: 0.8 mm, Wall-Wall distance: 0.5 mm, 2,000 holes

< Test condition >
- Precondition: 255 °C reflow x 8 times
- CAF testing: 85 °C / 85 %RH, DC 100V
- Measurement of insulation resistance in chamber
Features & Current status of new ultra-low loss material (LW-900G)

Features of LW-900G & 910G

- **Df@10 GHz** ⇒ E-glass type: Lower than current low loss material (FX-2)
  - Low-Dk type: same or better compared with PTFE material
- **Thermal-mechanical properties (Tg, CTE, etc.)** ⇒ Better than FX-2
- **Heat resistance** ⇒ Excellent
- **Flame retardancy** ⇒ V-0 by Halogen-free resin system
- **Reliability of high-layer PWB (CAF, TCT, IST, etc.)** ⇒ Excellent
- **Drilling process-ability of high-layer PWB** ⇒ On evaluation

Ongoing study

- Optimization of mass production process
- **Reliability test (CAF, TCT & IST) of high-layer PWB using Hybrid structure**
- **Further improvement of dielectric properties**
  - for the next generation material (Df Target: < 0.002@10-20 GHz)
Road Map of HC's high-frequency Materials

<table>
<thead>
<tr>
<th>Applications</th>
<th>2010</th>
<th>2012</th>
<th>2014</th>
<th>2016</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission rate/link (Backplane) (Mobile)</td>
<td>3.2~6.4 Gbps</td>
<td>~12.5 Gbps</td>
<td>~25 Gbps</td>
<td>&gt;50 Gbps</td>
<td>&gt;25 Gbps</td>
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<tr>
<td>High-end digital (High-speed &amp; High-layer)</td>
<td>Dk&lt;3.7/Df&lt;0.003</td>
<td>Dk&lt;3.3/Df&lt;0.002</td>
<td>Dk&lt;3.0/Df&lt;0.001</td>
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<tr>
<td>Router</td>
<td>LZ-71G</td>
<td>FX-2</td>
<td>LW-900G(S)</td>
<td>New</td>
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<tr>
<td>Server</td>
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<td>Df&lt;0.001</td>
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<td>Storage</td>
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<td>Transport</td>
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<tr>
<td>HPC</td>
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<tr>
<td>Measurement equipment</td>
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<tr>
<td>IC-tester, etc.</td>
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<tr>
<td>Middle ~ Std. digital</td>
<td>Dk&lt;4.0/Df&lt;0.01</td>
<td>Dk&lt;3.8/Df&lt;0.007</td>
<td>Dk&lt;3.6/Df&lt;0.005</td>
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<tr>
<td>RF/Wireless (Analog high-Freq.)</td>
<td>FX-2/FX-3</td>
<td>LW-900G</td>
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<tr>
<td>Antenna</td>
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<tr>
<td>Sensor</td>
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<tr>
<td>RF-Module</td>
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<tr>
<td>Base station</td>
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<tr>
<td>Mobile devices</td>
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<tr>
<td>High-speed -PKG</td>
<td>Df&lt;0.01</td>
<td>Df&lt;0.005</td>
<td>Df&lt;0.002</td>
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<tr>
<td>PC/Server</td>
<td>LZ-71G</td>
<td>E-800G</td>
<td>LW-900G</td>
<td>New</td>
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<tr>
<td>Mobile devices</td>
<td>Dk:3.6/Df:0.006</td>
<td>Dk:4.0/Df:0.005</td>
<td>Df:0.002</td>
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<td>RF-Module</td>
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<td>MMIC-PKG</td>
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<td>Build-up material for PKG</td>
<td>Df&lt;0.02</td>
<td>Df&lt;0.015</td>
<td>Df&lt;0.005</td>
<td>Df&lt;0.002</td>
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<tr>
<td>PC/Server</td>
<td>AS-Z2</td>
<td>AS-Z3(K)</td>
<td>AS-Z5</td>
<td>New</td>
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<td>Mobile devices</td>
<td>Df:0.015</td>
<td>Df:0.013</td>
<td>Df:0.005</td>
<td>Df&lt;0.002</td>
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<td>RF-Module</td>
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<td>MMIC-PKG</td>
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Dk&Df: value of 1GHz
Outline

- Introduction
- Evaluation technologies of high-frequency performance by Hitachi Chemical
- Properties of new mid-loss PWB material
- Innovative ultra-low loss PWB material / Target & Technical concept / Features & Advantages
- Conclusions
Conclusions

■ We have lined up low transmission loss PWB materials for high-speed and high-frequency applications.

■ The new mid-loss material, HE-679G(S) has lower Dk and Df than current material, HE-679G, and has the excellent reliability as HE-679G.

■ Novel low loss and halogen free thermosetting resin system has been designed for the next generation high-speed applications.

■ Innovative ultra-low loss material, LW-900G&910G with the novel resin technology shows lower Df than standard PTFE laminate, and is characterized by high Tg, low CTE, high heat resistance, the excellent CAF property, and the process-ability almost similar to FR-4.

Note: The contents of this report are based on the results of experiments and do not represent a guarantee of the values for each property.
Thank you for your attention!