Behavior of Materials in the Manufacturing Environment

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Abstract

This study was conducted to understand seven materials reliability, behavior of Dielectric constant and Dissipation factor over medium to high frequencies. A modified version of HDPUG design was used for evaluation. This test board contains IST, CAF, Thermal Cycling and Impedance (both Micro Strip and Strip line) coupons. In addition to these we added HATS coupons. Materials were chosen from FR4 family and selection was made based upon our present and future needs. Dielectric constants of these materials ranged from Dk 3.6 to Dk 4.2, as published, at 10GHz. This document shows the effect of Dk and Df values from 10GHz to 20GHz and also shows their performance for lead free assembly process when tested using IST and HATS test methods. In addition CAF testing was done on five of the seven materials.

Introduction:

As signal speeds are getting higher, a better understanding of material performance is required. Materials which were good at low frequencies may not be good for higher frequencies. The goal of this study was to:

1. Compare Material reliability using HATS and IST test methods.
2. CAF analysis of these materials.
3. Study insertion losses for materials chosen and do a comparison of these materials for frequencies between 1GHz – 20 GHz.

A modified HDPUG design, shown below (Fig 2) was adopted as a test vehicle. To keep the testing manageable, thermal cycling and Water absorption coupons were not tested. However, HATS coupons were added to the panel design. The stack up used is shown below in Fig 1..
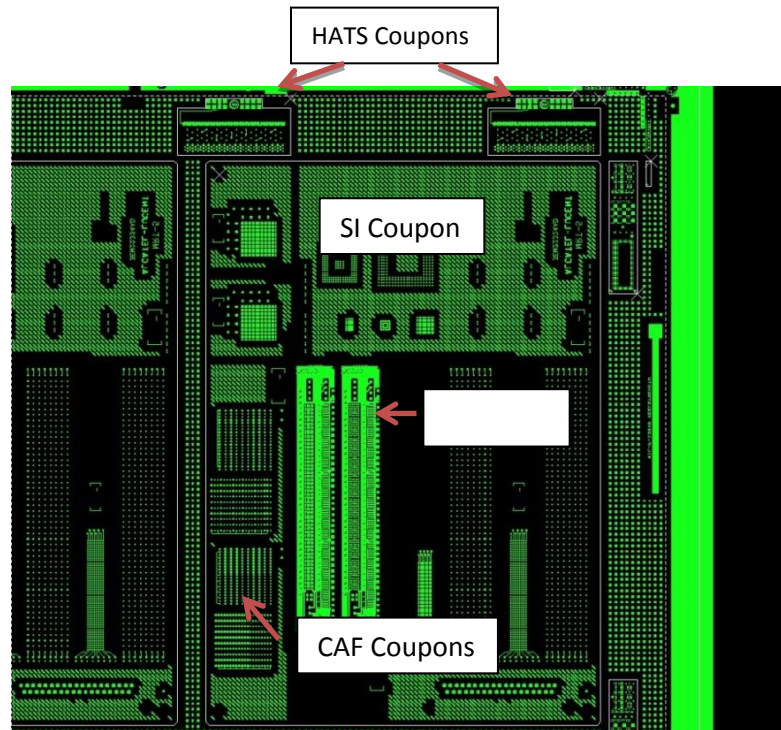

Fig. 1

Board Design

Fig. 2

Material for test was supplied free of cost by each material supplier. Materials were given a code name for the study. Each material supplier will have cross reference to their material only. Table 1, below, gives the detail of the material properties as published on technical data sheets. All material tested are rated by their manufacturers as lead free assembly compatible material. Materials ranged from a Dk of 3.7 to 4.7 and were in Tg range of $170^0 - 210^0$C.

Table 1

MATERIAL	TG – ^{0}C	Dk	Df	CTE 'z' PPM / ^{0}C
A	170	4.0	0.010	34
B	171	4.4	0.010	33
C	170	4.7	0.018	50
D	200	3.7	0.008	40
E	180	4.0	0.012	50
RA	200	3.7	0.009	55
RB	210	3.7	0.009	65

R& D NEW MATERIAL TESTS

All samples were produced using the same equipment and within a close time frame window. No process abnormalities were seen during processing period.

Test parameters selected are given below:

HATS Preconditioning and Test Parameters:
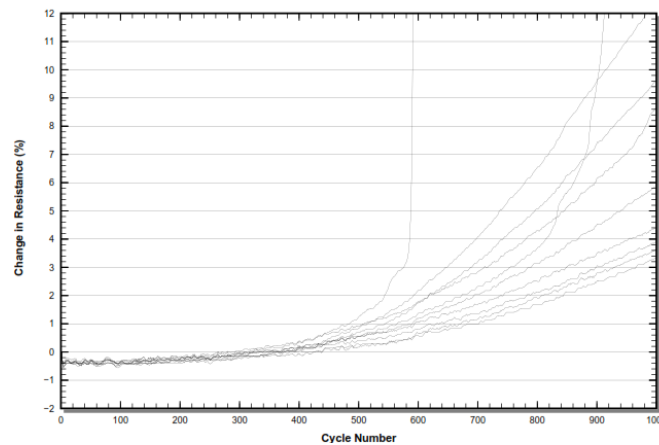
Test Conditions:

- 6 coupons for each material type to be cycled through 6X @ 260°C assy. simulation.
- Test temperatures for cycling to be (-) 40°C temperature to (+)145°C, 15 minutes @ temperature and transition time is 30 seconds.
- Test cycles to be 1,000. Cycles or a change of 10% in resistance, whichever comes first.
- Testing done by Integrated Reliability Test Systems, Inc. (IRTS)

HATS Test Analysis;

All coupons showed no signs of delamination after preconditioning. During hats testing all materials met the set criteria of 1,000 cycles without the exception of Material 'RA' which had an average of 941 cycles for net 2 and 900 cycles for net 4. Material 'B' had an anomaly where there were spikes of 6% change in resistance between 600 and 800 cycles and after that the coupon went back to less than 0.2% change. Below are the charts for Material 'A' (Fig. 3) (showing change in resistance for a typical good coupon), Material 'RA' (Fig.4) and Material 'B' (Fig.5).
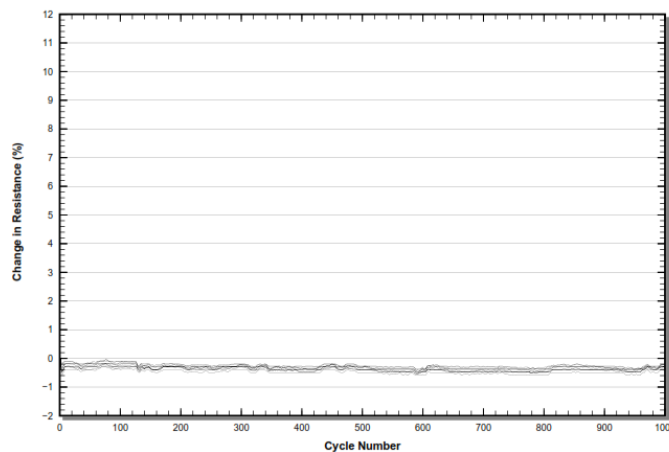
Fig. 3

Fig. 4
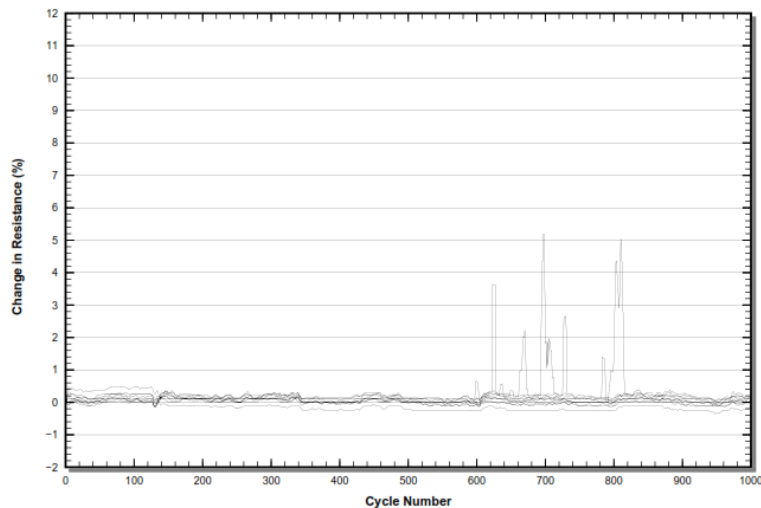
Fig. 5

IST Testing:

Preconditioning& Test Conditions

- 6 coupons for each material type will be cycled through 6X @ 260°C assy.
- Test the coupons for failure, any failure to be recorded.
- Capacitance readings will be taken before preconditioning, after preconditioning and at the end of cycling.
- Any change in capacitance > (-)6.5% will be considered a failure.
- Test temperatures cycling will be room temperature to (+) 1500°C in 3 minutes +/- 5 seconds and cooling in approximately 2 minutes.
- Test cycles will be 1,000. Cycles or a change of 10% in resistance, whichever comes first.
- Testing done at PWB Interconnect.

Test Results:

Capacitance Analysis:

Six sections for each of the seven materials tested showed various degree of % change in capacitance value. Material 'A'&'B' showed excellent results with a maximum of (-) 4.13% and (-) 3.46% change in capacitance. Results for material 'C' and 'D' had a maximum of (-) 5.40% and (-) 5.05% change, which is still considered acceptable below the maximum allowable percentage change of (-) 6.5%. Material 'RA' showed signs that material degradation had started but percentage change was still below the maximum allowable range. However, Material 'E' and 'RB' were at (-) 7.02% and (-) 8.59%. In both of these cases material damage was observed. See Table 2 for typical capacitance results for 0.8mm (0.032") test coupon.

Table 2

% Capacitance Change in Picofarads - Group A .032" / 0.8mm after 6x260°C						
Layer	A	B	C	D	E	RA	RB
2/4	-4.13%	-2.84%	-5.40%	-5.05%	-7.02%	-6.26%	-6.59%
4/6	-2.67%	-2.59%	-4.08%	-3.89%	-7.02%	-5.50%	-7.13%
6/7	-1.61%	-1.60%	-2.98%	-3.13%	-6.70%	-4.15%	-6.10%
7/8	-1.69%	-1.92%	-2.84%	-3.14%	-5.71%	-4.52%	-8.59%
8/9	-1.57%	-1.64%	-2.92%	-3.18%	-6.67%	-4.20%	-6.04%
9/11	-2.78%	-2.66%	-4.11%	-3.60%	-7.05%	-5.57%	-7.08%
11/13	-3.98%	-3.46%	-4.95%	-4.00%	-6.74%	-5.82%	-5.99%

Table 3

% Capacitance Change in Picofarads - Group A -1.0mm (0.040") after 6x260^{0}C							
Layer	A	B	C	D	E	RA	RB
2/4	-5.02%	-4.56%	-6.01%	-1.89%	-7.33%	-6.48%	-3.62%
4/6	-3.24%	-3.90%	-4.46%	-2.51%	-6.77%	-6.20%	-3.68%
6/7	-1.98%	-1.96%	-3.17%	-2.46%	-5.46%	-4.81%	-3.62%
7/8	-1.96%	-2.49%	-3.07%	-2.86%	-5.66%	-5.26%	-3.59%
8/9	-1.82%	-1.95%	-3.12%	-2.71%	-5.43%	-4.83%	-3.49%
9/11	-3.20%	-3.64%	-4.47%	-2.50%	-6.79%	-6.06%	-3.67%
11/13	-4.85%	-4.62%	-5.73%	-1.51%	-7.00%	-5.93%	-3.69%

It was observed that if test coupons have retained moisture then we will see an improvement in capacitance value for the outer layers as the test progresses. This was particularly evident in case of Material 'E' which showed an improvement in capacitance value between 6x260°C and at the end of test measurements. Since all materials were stored under the same conditions, it leads us to believe that material is more hydroscopic. Also, 0.8mm pitch showed early capacitance failure for material 'RA' indicating that either the material bond was compromised during drilling or that the material bond strength was not the best.

IST Test Analysis;

A summary of test results is shown below in Table 4. The data shown is cycles to failure for 6 coupons of each material type. Any failure that was process related has been taken out.

Table 4

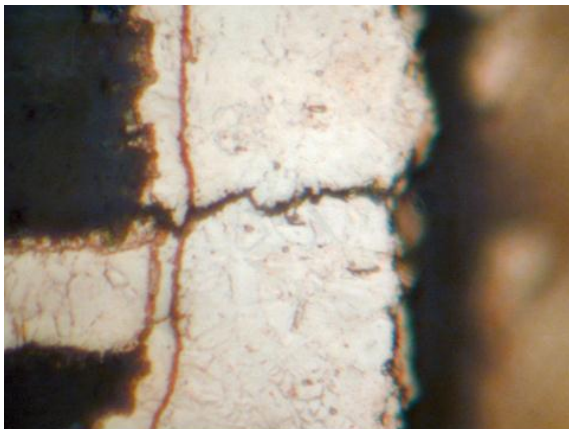| .032" / 0.8mm Via to Via Spacing							
Type	A	B	C	D	E	RA	RB
1	3000	3000	1162	1587	1847	232	1108
2	3000	3000	1738	839	2847	355	981
3	3000	3000	1329	1074	731	149	1313
4	3000	3000	487	1042	1573	160	482
5	3000	3000	1437	792	2557	151	804
6	3000	3000	1793	1078		241	
Mean	3000	3000	1324	1069	1911	215	892
Std Dev	0	0	476	282	837	80	315
Min	3000	3000	487	792	731	149	482
Max	3000	3000	1793	1587	2847	355	1313

Fig. 6

Fig. 7
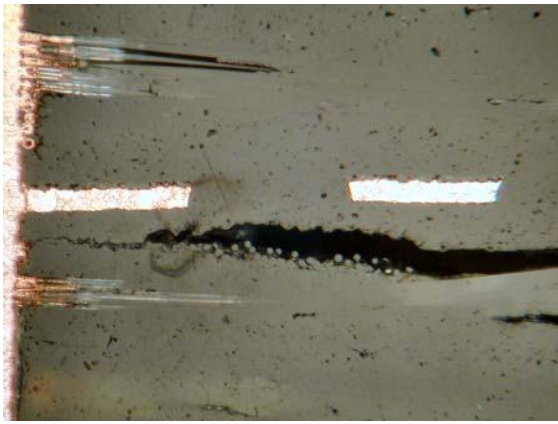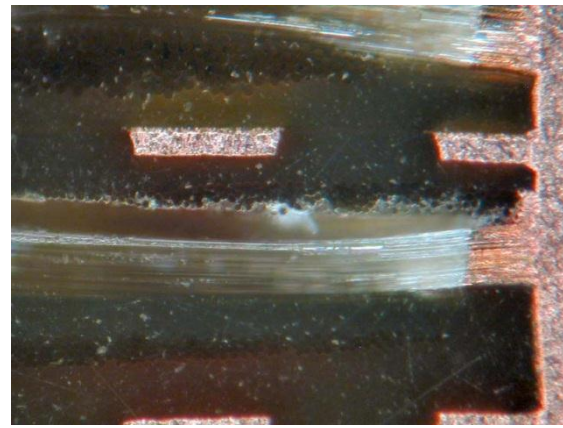
| Fig. 8 | Fig. 9 |

In our IST results Material 'RB' showed good cycles to failure but when sectioned we saw the extent of damage to the material. The degree of delamination seen in Fig.10 below agrees with the results seen in capacitance measurements of these coupons. The material had degraded to a stage where further cycling would not have had any further degradation.
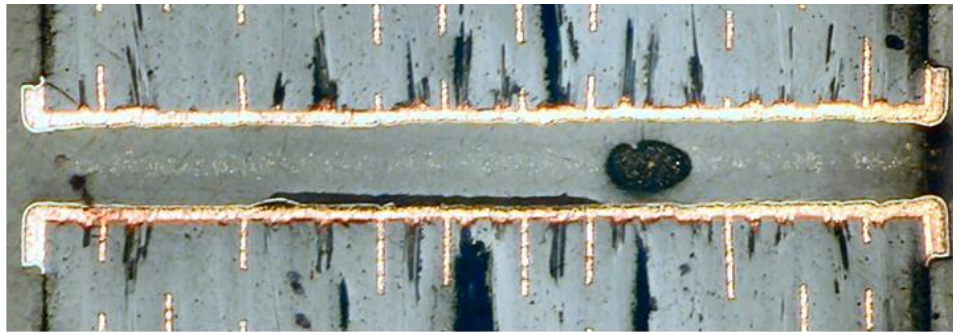
Fig.10

CAF Preconditioning and Test Parameters

Test Methods

1. Testing was carried out in accordance with IPC-TM-650 Method 2.6.25, Conductive Anodic Filament (CAF) Test.
2. 100 Volts DC bias was applied to each circuit through a 1 mega-ohm series resistor. Voltage drop across the resistor was measured daily in each sample with a high-impedance voltmeter, without removing or altering the applied bias.
3. The test method allows for two humidity levels. The more aggressive environmental condition option of 85°C (+/-2°C) and 87% (+3/-2%) relative humidity was chosen for this test.

In all, 30 coupons were tested. No coupons were tested for Material 'A' and 'D'. For Materials 'B', 'C', 'E', 'RA' and 'RB' 3 coupons each for grid size 40mm (16mil) and 50mm (20) were tested in accordance with IPC-TM-650, method 2.3.25. Below is a summary of the results for the 30 coupons tested.

Table 5

Material	Hole wall to Hole wall 20mil				Hole wall to Hole Wall 16mil			
	Coupons tested	Coupons failed	Min. Hrs.	Max. Hrs	Coupons tested	Coupons failed	Min. Hrs.	Max. Hrs
B	3	1*	120	>500	3	1**	24	>500
C	3	2**	24	>500	3	2	24	>500
E	3	0	>500	>500	3	2	24	>500
RA	3	3	24	48	3	3	24	24
RB	3	3	24	24	3	3	24	48

* - Failure due to surface contamination, see Fig. 11

** - Failure mode could not be found for one 'B' and one 'C' material.

Fig.11

Fig. 12 and Fig. 13, below, show the Typical CAF failures seen on failed coupons.
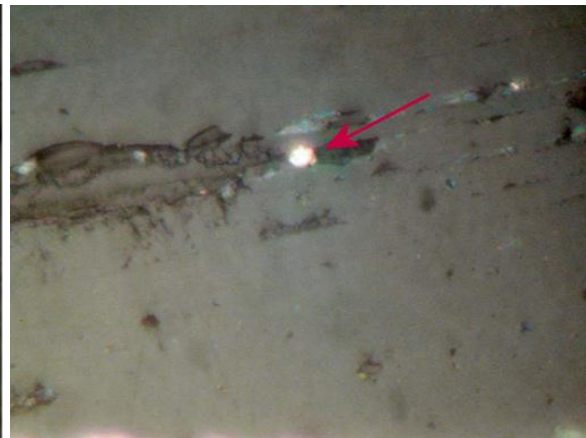

Fig. 12   **Fig. 13**

CAF data above shows that the CAF failures increase as the pitch reduces. Coupons at 16 mil pitch had 16% higher failures as compared to 20 mil pitch. The failure rate is influenced by both the material and the drilling process. Since this exercise was to compare different materials under the same manufacturing conditions, we evaluated the degree of failures for each material. It is also important to see that materials 'E', 'RA' and 'RB' had 100% failures. These results are in line with IST and Capacitance results. Those materials which had poor performance for IST and Capacitance also showed poor results for CAF.
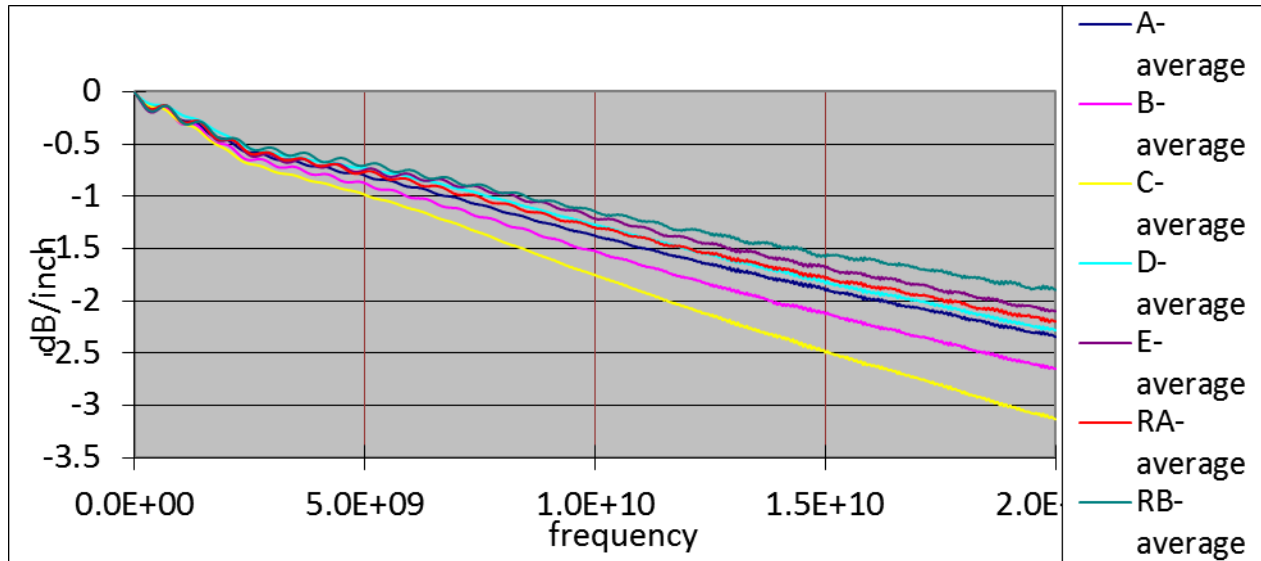
Signal Integrity (Overall Insertion loss)

Test Conditions;
- Conductor Length: 5 inches
- Impedance: 50 ohms
- Materials: RA, RB, A, B, C, D and E
- Equipment Used: Agilent VNA N5230
- Testing done at ITEQ labs

Test Results:

Insertion Losses for Micro Strip Line

Fig. 14

Figure 14 shows that a clear separation is seen between materials as the frequency increases from 10GHz to 20GHz. Material 'RB' still has the lowest Df value at (-) 1.894dB/inch at 20GHz. Percentage change for Material 'RB' was the lowest at 66%. Material 'C' had the highest percentage change at 79%.

The same was true for the Strip Line. Material 'RB' had the lowest Df value at (-) 1.939dB/inch and Material 'C' had the highest Dk loss at (-) 3.376dB/inch. Materials 'A' and 'RB' had the lowest percentage change at 87%. Materials 'E' and 'RA' had the highest percentage change at 94%.
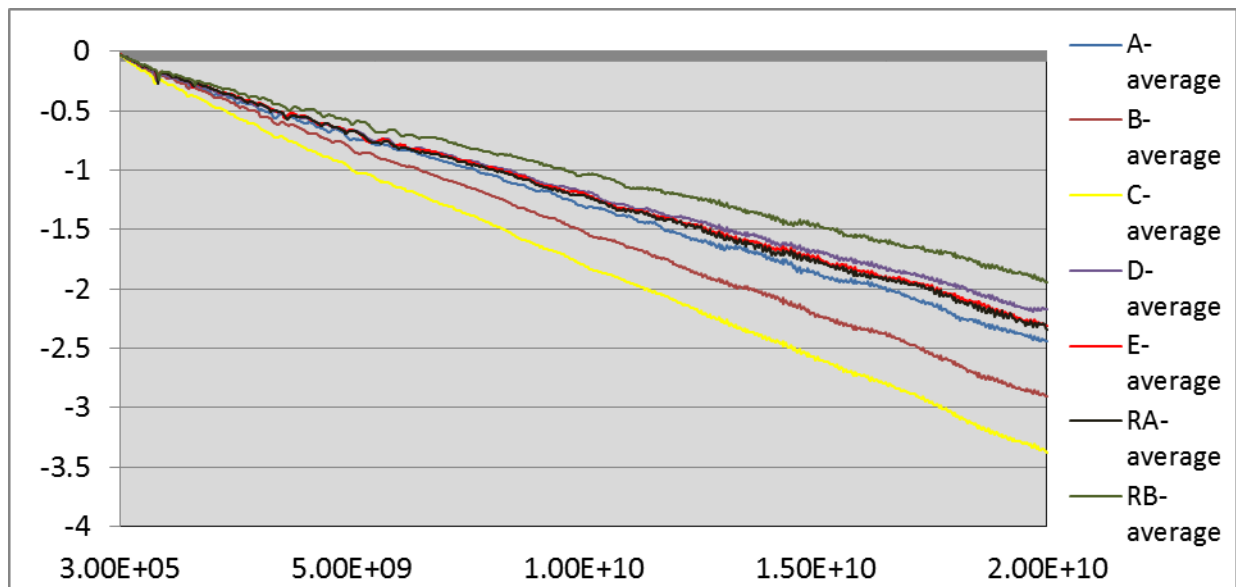
Insertion Losses for Strip Line

Fig. 15

Table 6

Materials	Delay time @ 10GHz (ps)	
	Micro-strip line	Strip-line
A	706	878
B	700	858
C	707	855
D	673	801
E	671	813
RA	672	810
RB	658	797

Observations based on SI Data :

1. Published and actual Df and Dk values were found to be very close.
2. Insertion losses for both Strip and micro – strip line of materials tested are in a small band width below 10GHz. However, the gap widens as we move towards 20GHz.
3. Percentage change in Df value ranged from 7.3% for material 'C' to 17.9% for material 'RA" as the frequency increases from 10GHz to 20GHz.
4. Percentage change in Dk values for materials is below 1.5% as the frequency increases from 10GHz to 20 GHz
5. There is a direct relationship between Dk and delay time. Material 'RB' with a Dk value of 3.7 has the lowest delay time.

SI results Conclusion

1. By the insertion loss measurement, material 'RB' has the best signal integrity. We can classify these materials as below:

    -- signal integrity (overall insertion loss):

    RB (the best) > RA~E~D > A > B >C

2. Evaluation based upon delay time and Dk and Df extraction, the material (in order of Dk and Df value) are;

Dk -- RB (the lowest) < RA~E~D < A~B~C

Df -- RB (the lowest) < D < RA~E < A < B< C

Project Summary:

Below Table 6 gives a summary of all the test result. It should be noted that some of the values are averaged for ease of data review. However, this is still representative of actual test results. Based on the test data available the a suitable material can be selected to fit individual needs.

Table 6

Material	HATS Cycles	% Change in Capacitance	IST Cycles	CAF Cycles		Dk @20GHz	Df @ 20GHz
				0.5mm	0.4mm		
A	1,000	(-)2.25	3,000	Data Not Available		4.24	0.0155
B	1,000	(-)2.38	3,000	500	1 out of 3 below 500	4.09	0.0207
C	1,000	(-)3.89	1,324	1 out of 3 below 500	2 out of 3 below 500	4.04	0.025
D	1,000	(-)3.71	1,069	Data Not Available		3.57	0.0130
E	1,000	(-)6.70	1,911	500	2 out of 3 below 500	3.68	0.0145
RA	960	(-)5.15	215	24	24	3.62	0.0151
RB	1,000	(-)6.79	892	24	24	3.53	0.0109

Data has shown that, among the materials tested, materials that had least insertion losses performed poorly for reliability. The materials selection process should take all aspects of material performances into account when selecting a material. With that in mind, material 'D' would be the best performing material in Dk range of 3.57, @ 20GHz, followed closely by material 'B' with Dk of 4.09 and material 'A' at 4.24 Dk. However if a variation of 0.52in Dk value, @ 20GHz, can be compensated by design, then material 'B' becomes the best overall choice.

Similar studies are planned for Polyimide, RF and thermally conductive materials.

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Project Goal

- To test materials for Performance and Reliability as they relate to our manufacturing environment.

- To understand the reliability of the materials, their Dielectric constant and their Dissipation factor behaviour over a range of frequencies.

- To be able to recommend suitable material/s to meet customer's electrical and reliability needs.

Project Outline

- A modified version of HDPUG design was used for evaluation.

- Materials chosen were from FR4 family and selection was made based upon our present and future needs for these type of materials.

- Published Dielectric Constants (Dk) ranged between 3.6-4.2 @ 10GHz.

- Published Dissipation Factors (Df) ranged from 0.009-0.018.

- Materials were tested for Cycles to failure (IST, HATS), CAF, Capacitance and SI parameters.

Material Parameters

Table 1

Properties of Materials Tested					
Material	**Tg ^{0} C**	**Dk**	**Df**	CTE 'Z' ppm / ^{0} C	Moisture %
A	170	4.0	0.010	34	0.08
B	171	4.4	0.010	33	0.26
C	170	4.7	0.018	50	0.18
D	200	3.7	0.008	40	0.11
E	180	4.0	0.012	50	0.04
RA	200	3.7	0.009	55	0.06
RB	210	3.7	0.009	65	0.10

Test Vehicle – Stack up

- Number of Layers – 14
- All cores are 127μm (5 mil).
- Dielectric between 3/4,5/6,7/8,9/10 and 11/12 is 140μm (5.5 mil) and between Layers 1/2 and 13/14 is 100μm (4 mil).
- Microvias are between layer 1 and 2.
- All layers have ½ oz starting copper.
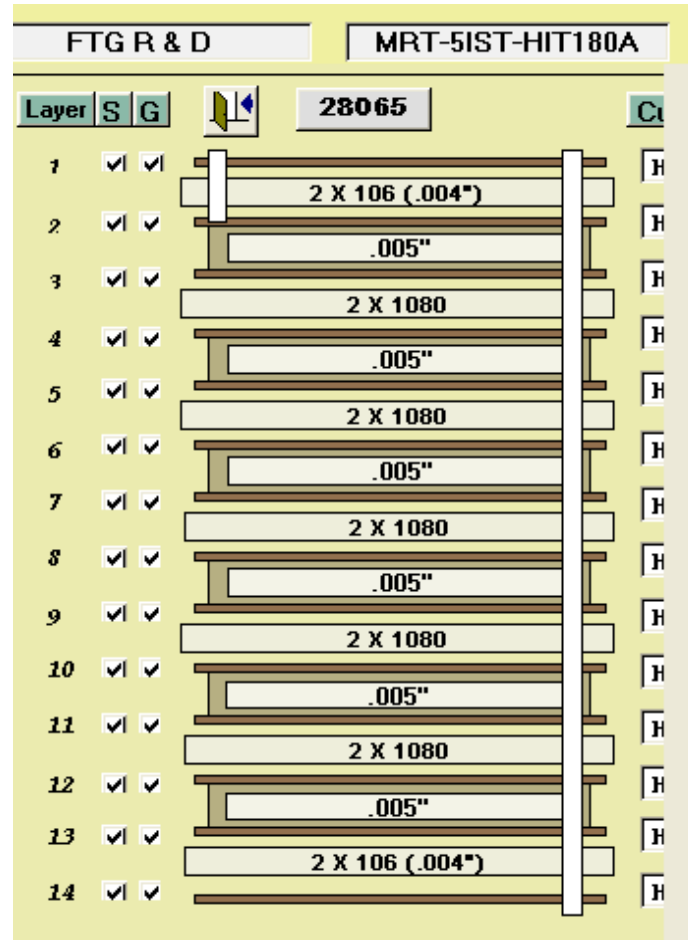
Fig. 1

Test Vehicle
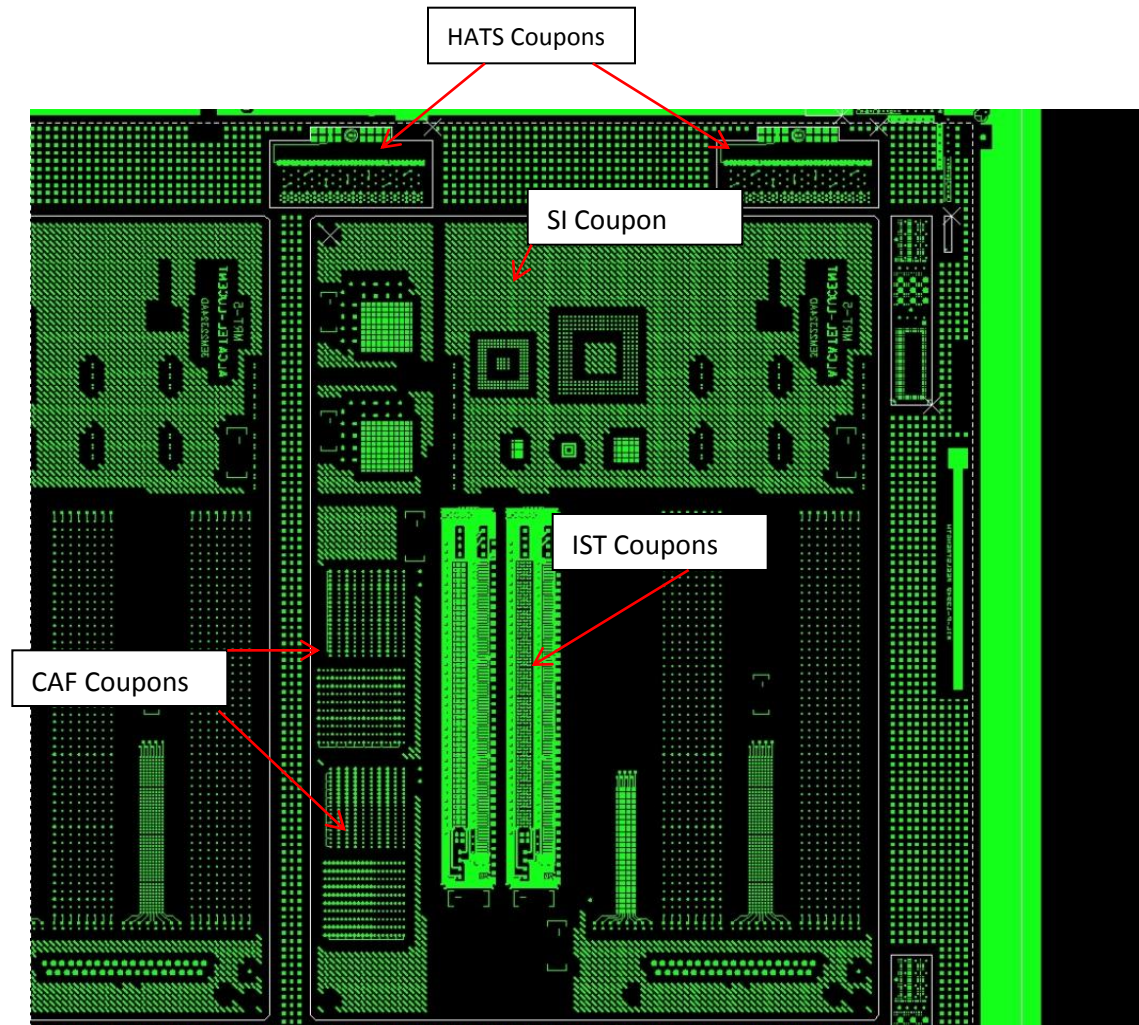
Fig. 2

HATS and IST

Test Parameters – HATS

- All coupons were preconditioned for 6X @ (+)260°C prior to thermal cycling.

- Cycling temperatures were from (-) 40°C to (+)145°C, 15 minutes at temperature. Transition time is 30 seconds.

- Test cycles to be 1,000 Cycles or a 10% change in resistance, whichever came first.

HATS – Test Results

Material	Reference Resistance at 145C (ohms)				Cycles to 10% Change				Percent Change at 1000 Cycles			
	Net 1	Net 2	Net 3	Net 4	Net 1	Net 2	Net 3	Net 4	Net 1	Net 2	Net 3	Net 4
A	1.112	0.754	0.971	0.786	>1000	>1000	>1000	>1000	−0.4	−0.6	-0.2	0.3
B	1.228	0.823	1.048	0.847	>1000	>1000	>1000	>1000	-0.4	-0.6	-0.3	-0.2
C	1.097	0.752	1.049	0.837	>1000	>1000	>1000	>1000	-0.4	-0.5	-0.2	-0.1
D	1.059	.0.685	1.017	0.821	>1000	>1000	>1000	>1000	-0.1	0.4	-0.1	0.1
E	1.104	0.929	1.021	0.838	>1000	>1000	>1000	>1000	-0.4	-0.5	-0.3	-0.3
RA	1.262	0.758	1.035	0.839	>1000	941	>1000	900	-0.2	12.5	0.2	-0.6
RB	1.147	0.828	1.03	0.84	>1000	>1000	>1000	>1000	-0.4	3.2	0.3	0.1

Table 2

Numbers shown are an average of 6 coupons for each of the materials.

HATS - Results
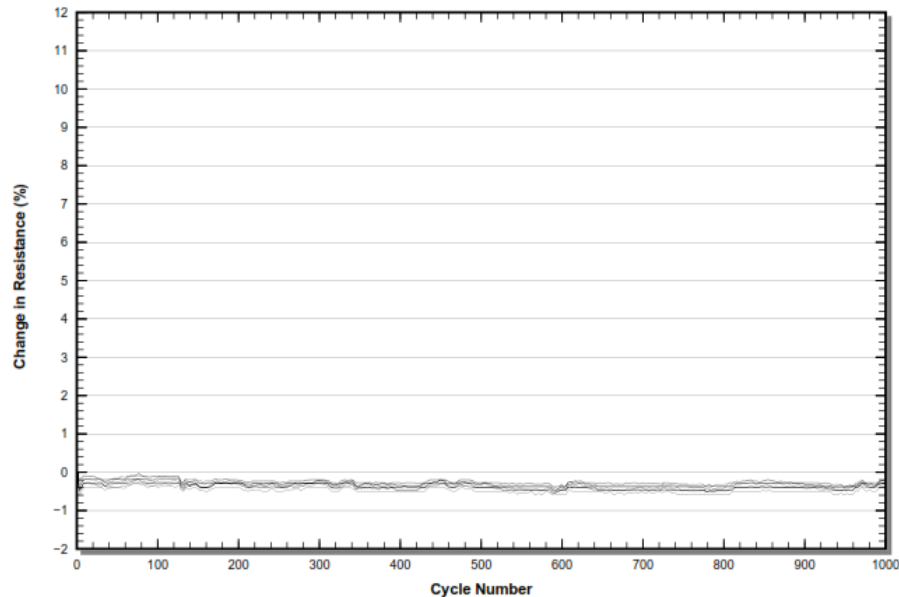
Fig. 3

Fig. 4

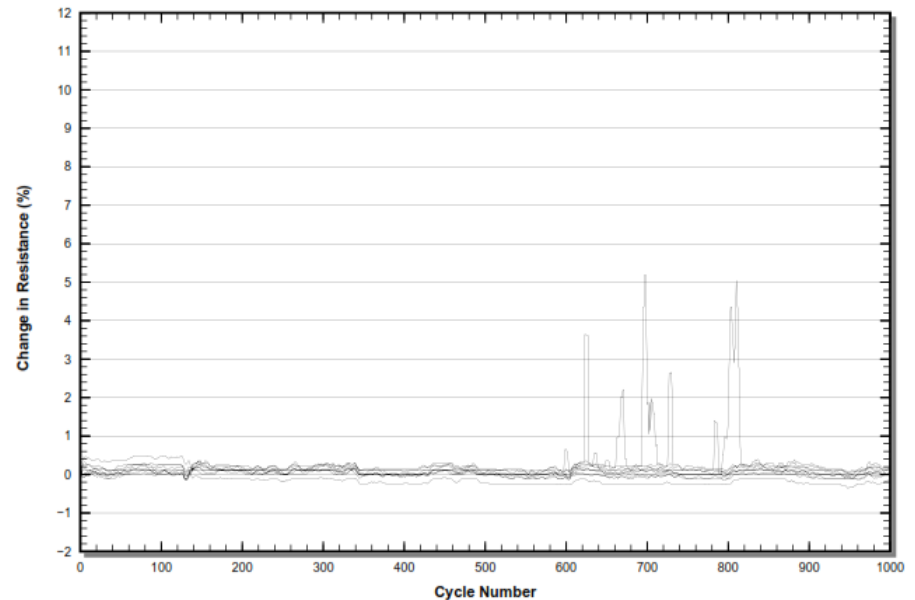Material 'A', 'B', 'C', 'D' and 'E'
– Showed similar results

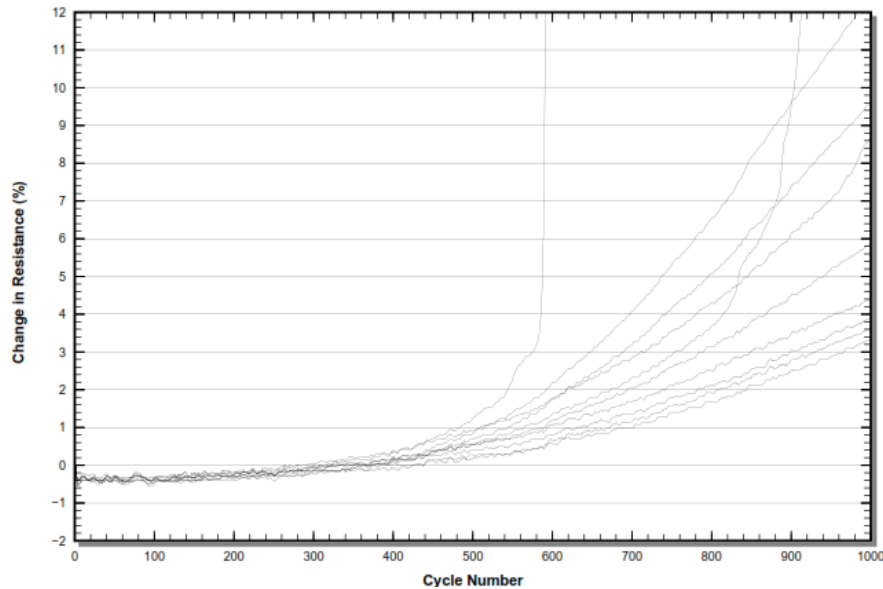One coupon of Net 4 of
Material 'B' showed Anomaly

HATS

Fig. 5
Material 'RA'
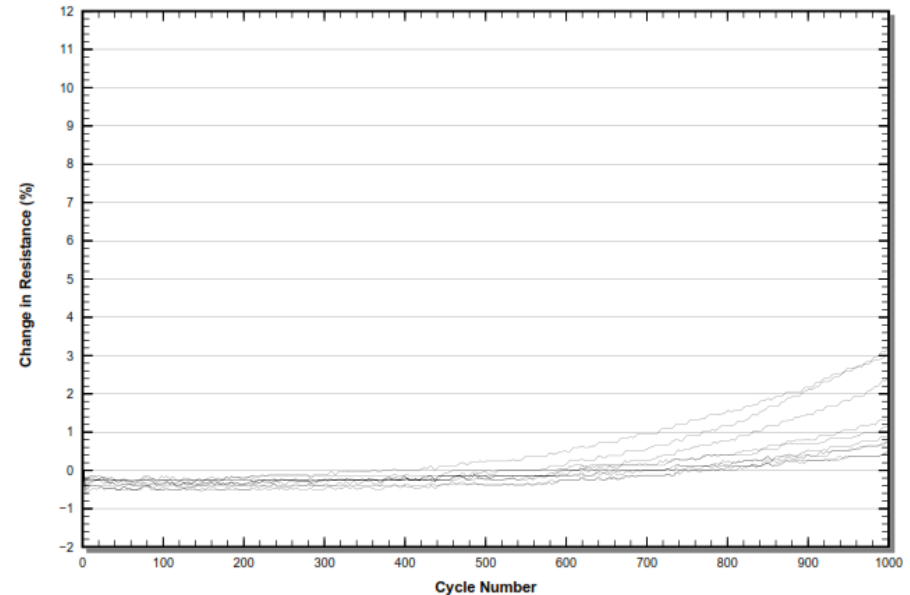

Fig. 6
Material 'RB'

Material 'RA' showed failure
as low as 591 cycles

Material 'RB' showed signs of
degradation after 600 cycles

HATS - Summary

- Material 'A', 'B', 'C', 'D', 'E' and 'RB' reached 1,000 cycles without any failure.

- All materials had > 500 cycles to failure.

- Overall average for Material 'RA' was 941 cycles. Net 2 had three coupons which did not reach 1,000 cycles. The lowest number of cycles to failure for 'RA' was 591.

- On one coupon (Net 4) of Material 'B', we saw unusual resistance change spikes between 600 - 800 cycles but then went back to lower resistance. This could be an indication of material degradation.

- None of the materials showed any visual delamination after pre-conditioning.

Test Parameters – IST

- All coupons were subjected to preconditioning of 6X @ 260ºC as part of testing.

Capacitance Test

- % Change in Capacitance Value – a % change of (-) 6.5% in capacitance was considered as a significant change and an indication of material degradation.

IST Cycles to Failure

- Test temperatures:
    - Ambient to (+)150ºC in 3 minutes (+/- 5 seconds)
    - Cooling in Approx. 2 minutes
- Test cycles to be 1,000 Cycles or a change in resistance of 10%, whichever came first.
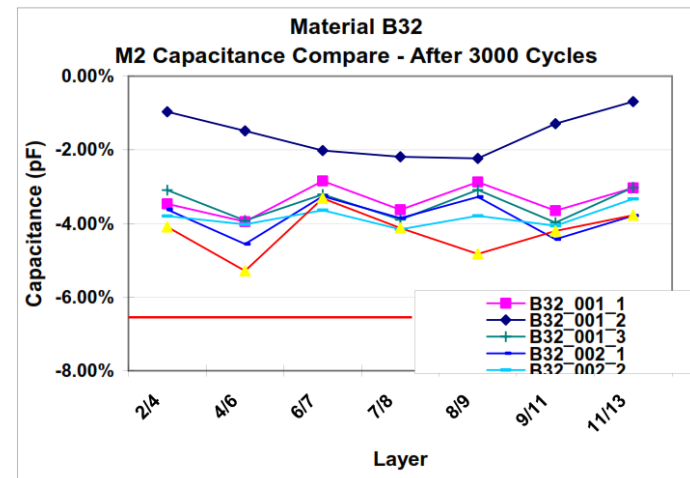
IST – Capacitance Analysis
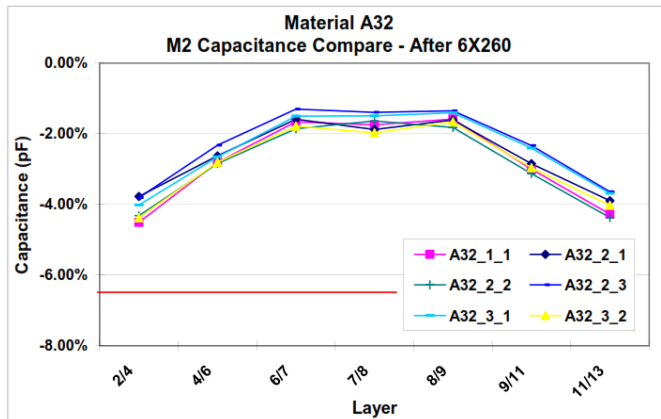
Fig. 7
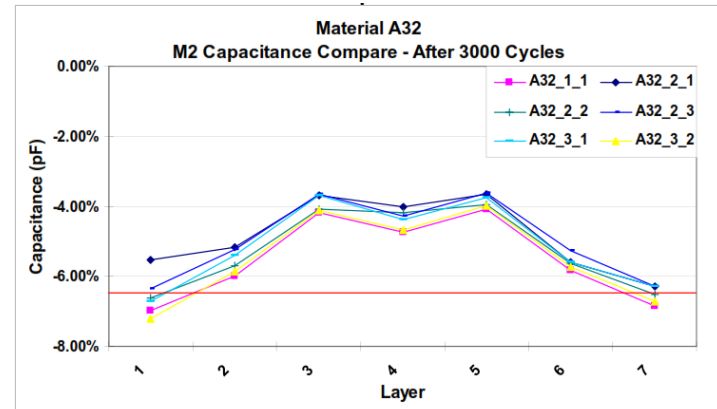
Fig. 8
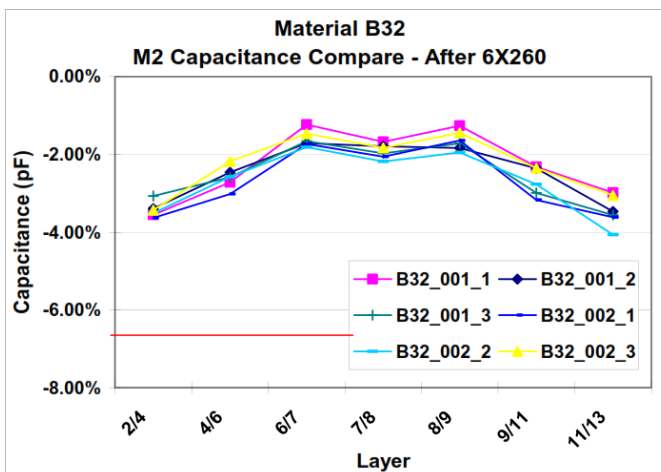
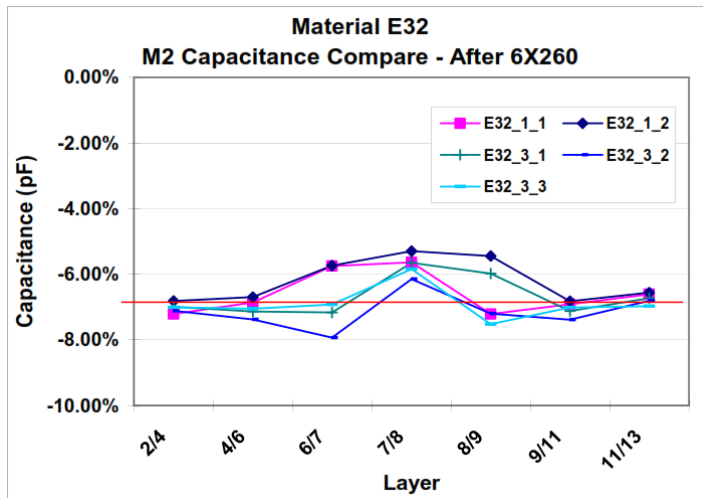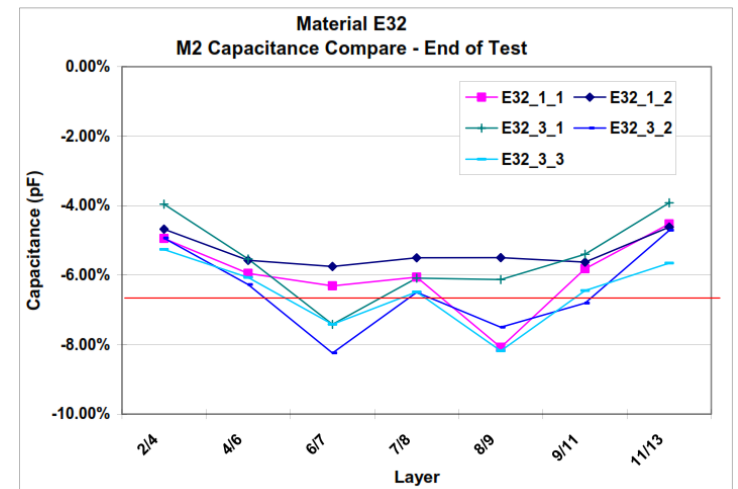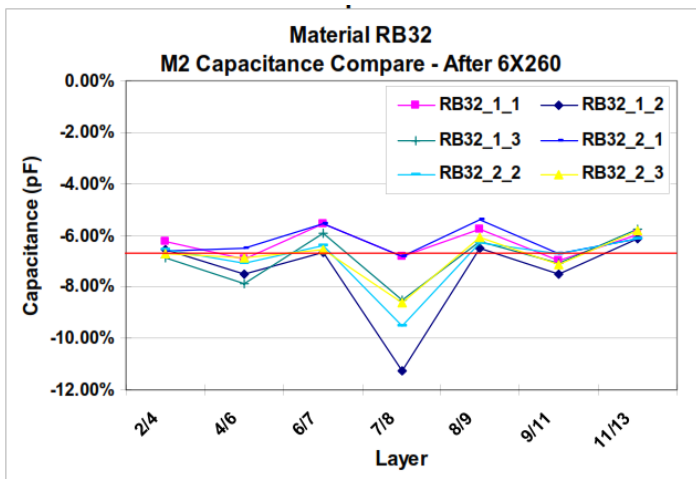Fig. 9

Fig. 10
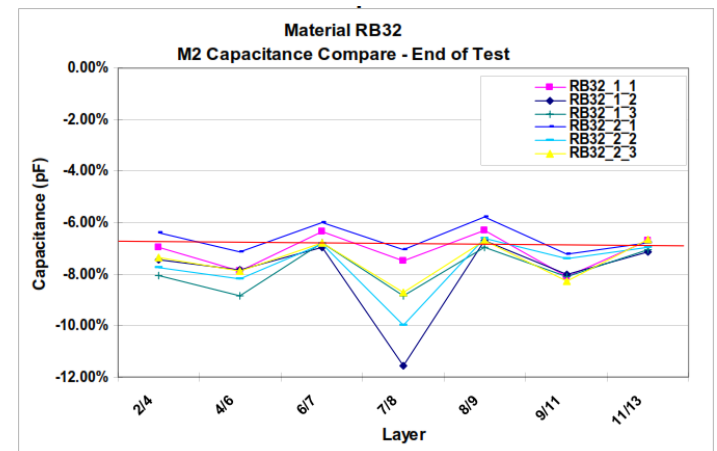
IST – Capacitance Analysis

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Capacitance Summary

% Capacitance Change in Picofarads - Group A .032" / 0.8mm after 6x260^{0}C							
Layer	A	B	C	D	E	RA	RB
2/4	-4.13%	-2.84%	-5.40%	-5.05%	-7.02%	-6.26%	-6.59%
4/6	-2.67%	-2.59%	-4.08%	-3.89%	-7.02%	-5.50%	-7.13%
6/7	-1.61%	-1.60%	-2.98%	-3.13%	-6.70%	-4.15%	-6.10%
7/8	-1.69%	-1.92%	-2.84%	-3.14%	-5.71%	-4.52%	-8.59%
8/9	-1.57%	-1.64%	-2.92%	-3.18%	-6.67%	-4.20%	-6.04%
9/11	-2.78%	-2.66%	-4.11%	-3.60%	-7.05%	-5.57%	-7.08%
11/13	-3.98%	-3.46%	-4.95%	-4.00%	-6.74%	-5.82%	-5.99%

Table 4

- Materials
  - Materials 'A' and 'B' showed excellent results
  - Materials 'C' and 'D' showed good results.
  - Material 'RA's results were acceptable.
  - Materials 'E' and 'RB' were unacceptable.
- Outer layers showed higher change in capacitance in comparison to Inner layers, leading to a possibility of entrapped moisture.
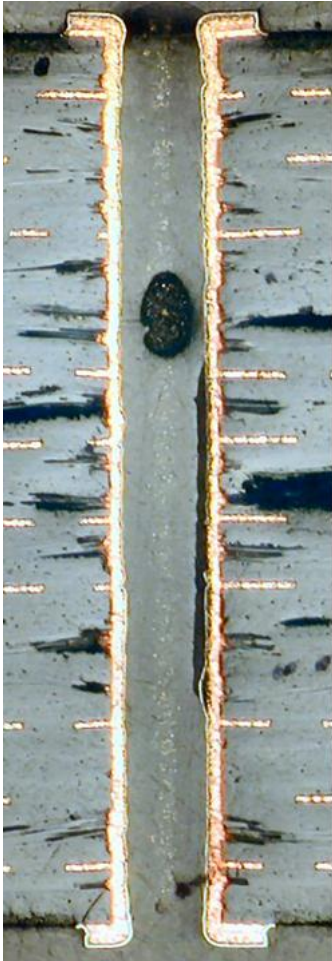
IST – Test Results

IST Cycles to Failure for .032"/ 0.8mm Grid

.032" / 0.8mm Via to Via Spacing							
Type	A	B	C	D	E	RA	RB
1	3000	3000	1162	1587	1847	232	1108
2	3000	3000	1738	839	2847	355	981
3	3000	3000	1329	1074	731	149	1313
4	3000	3000	487	1042	1573	160	482
5	3000	3000	1437	792	2557	151	804
6	3000	3000	1793	1078		241	
Mean	3000	3000	1324	1069	1911	215	892
Std Dev	0	0	476	282	837	80	315
Min	3000	3000	487	792	731	149	482
Max	3000	3000	1793	1587	2847	355	1313

Table 5

Failure Types

'D' 32 @ 1573 cycles

'RB' @ 804 cycles
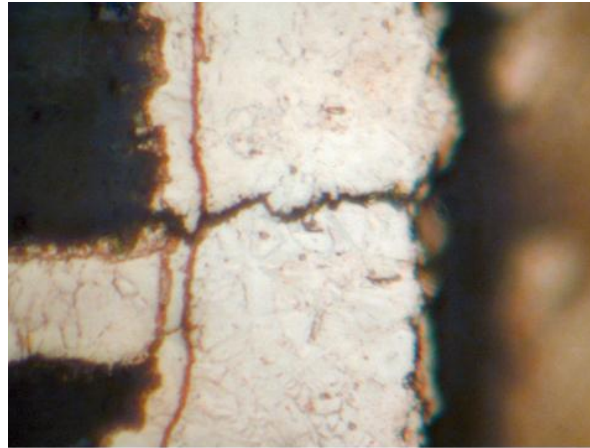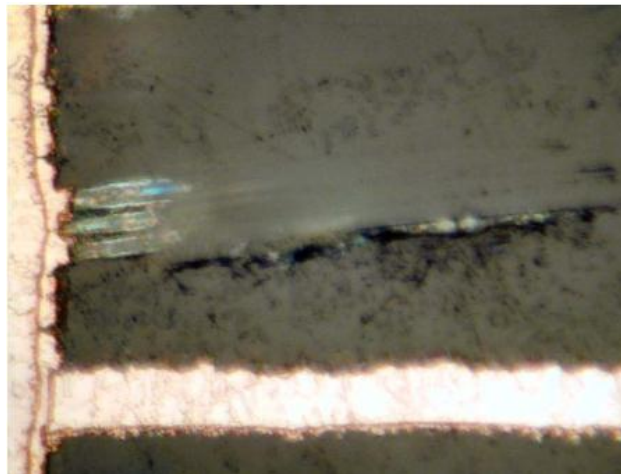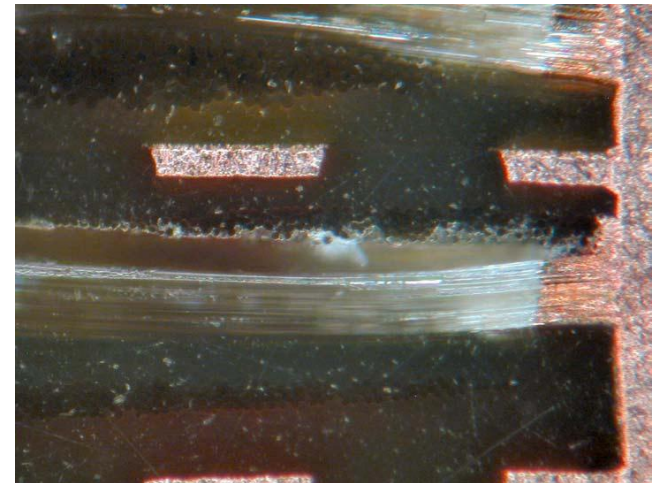
RB @ 804 cycles

'D' 32 @ 1573 cycles

'RB' @ 804 cycles

Fig. 15

IST – Test Results Summary

- The data suggests that Materials 'A' and 'B' are extremely robust, reaching 3,000 cycles without any material damage.

- Material 'C' and 'D' proved to be in good acceptable range, mean IST cycles at 1324 and1069 respectably.

- Material 'RA' has Mean IST @ 215 cycles, well below the acceptable range.

- Material 'E' and 'RB' had Mean IST results @ 1911 and 892 cycles respectably but had poor Capacitance results, indicating material damage. Delamination was seen during sectioning, as such they are considered unacceptable material.

CAF – Test Parameters

Test Methods

1. Testing was carried out in accordance with IPC-TM-650 Method 2.6.25, Conductive Anodic Filament (CAF) Test.

2. 100 Volts DC bias was applied to each circuit through a 1 mega-ohm series resistor. Voltage drop across the resistor was measured daily in each sample with a high-impedance voltmeter, without removing or altering the applied bias.

3. The test method allows for two humidity levels. The more aggressive environmental condition option of 85ºC +/- 2ºC and 87%RH +3/-2 %RH was chosen for this test.

CAF Testing

Material	Hole wall to Hole wall 0.5mm (20mil)				Hole wall to Hole Wall 0.4mm (16mil)			
	Coupons tested	Coupons failed	Min. Hrs.	Max. Hrs	Coupons tested	Coupons failed	Min. Hrs.	Max. Hrs
B	3	1*	120	>500	3	1**	24	>500
C	3	2**	24	>500	3	2	24	>500
E	3	0	>500	>500	3	2	24	>500
RA	3	3	24	48	3	3	24	24
RB	3	3	24	24	3	3	24	48

Table 6

* Surface Contamination
** For 'B' and one coupon of 'C', Failure, mode not found
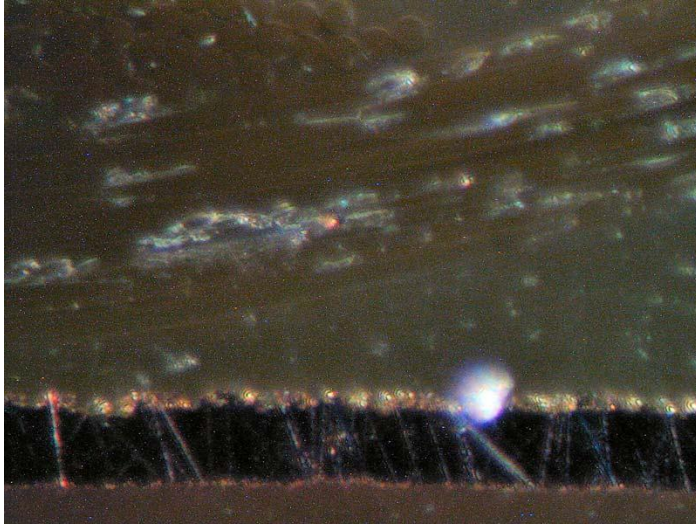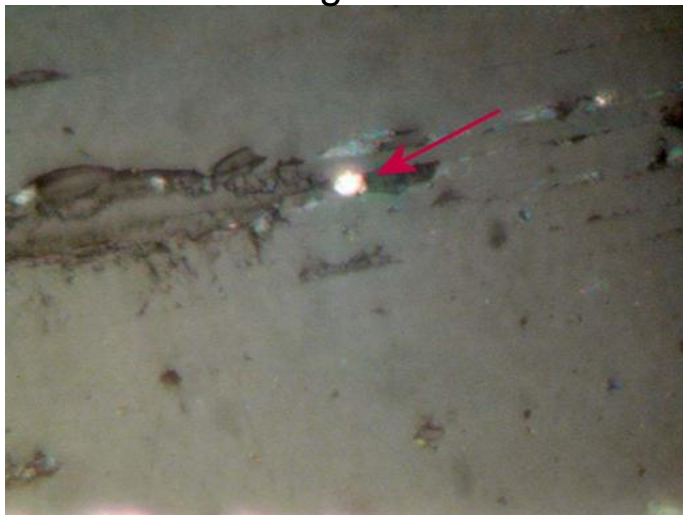
CAF – Typical Failures

Fig. 16

Fig. 17

Fig. 18

Fig. 19

CAF - Summary

- 0.4mm (0.016") pitch had 17% higher failures than 0.5mm (0.020") pitch.

- Material 'B' only had one failure for 0.5mm pitch at 24 cycles.

- Materials 'RA' and 'RB' had poor CAF performance. Material 'E' had low CAF cycles, only for 0.4mm pitch.

- There was a correlation between poor IST/HATS results and CAF failures.

Signal Integrity

SI - Testing

- Key elements evaluated between 10GHz – 20GHz were:

  – Insertion Loss for Strip and Micro-Strip lines over frequency range of 1 GHz – 20 GHz.

  – Dielectric Constant (Dk)

    • Change in Dk value over Frequency

    • Comparison of published Dk value against actual Dk value measured

  – Dissipation Factor (Df)

    • Change in Df value over frequency

SI – Test Conditions

- Test Vehicle: HDPUG SI Test Vehicle
- Conductor length: 5 inch
- Impedance : 50 ohm
- Material: 'A', 'B', C, 'D', 'E', 'RA', 'RB'
- Equipment : Agilent VNA N5230C

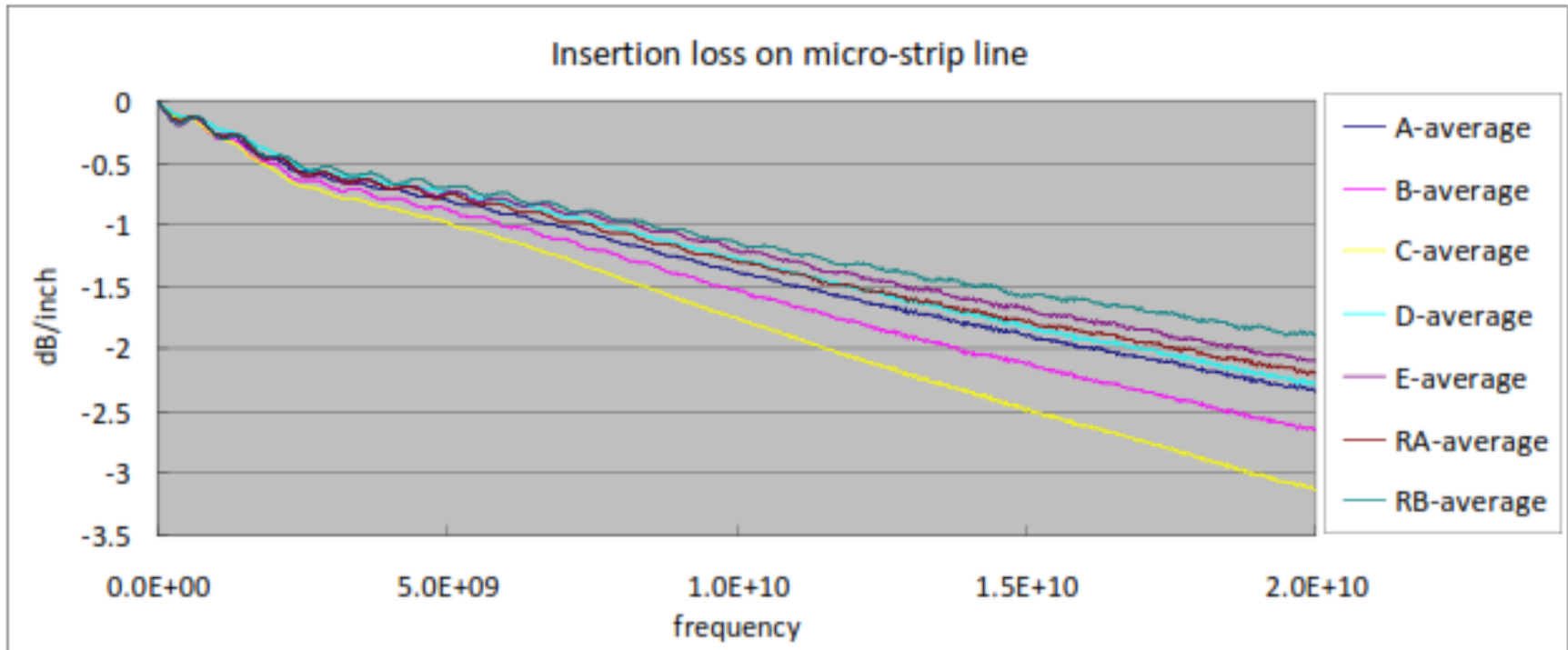SI testing done by ITEQ in collaboration with National University, Taiwan

SI – Strip Line

Insertion loss on strip-line
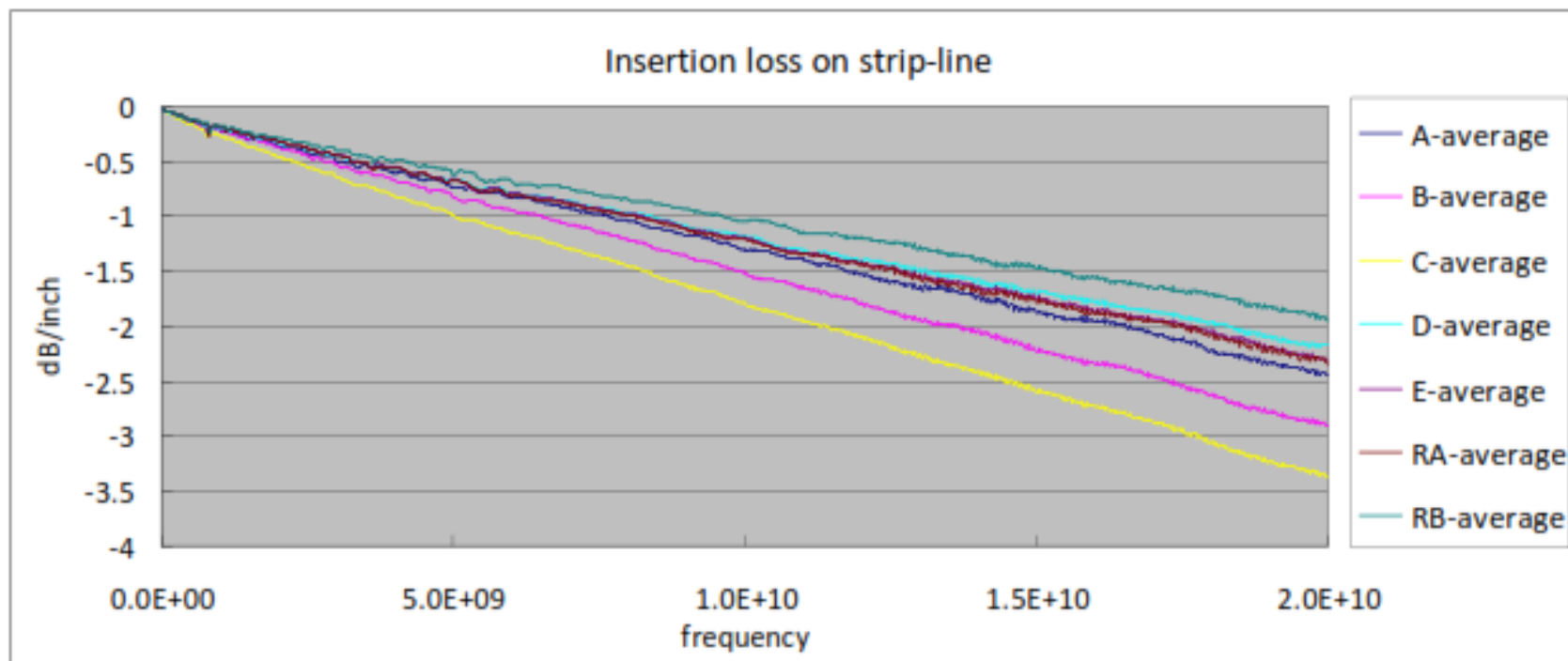
SL-fine line	A	B	C	D	E	RA	RB
10GHz	-1.306	-1.515	-1.798	-1.181	-1.193	-1.211	-1.042
20GHz	-2.442	-2.908	-3.376	-2.173	-2.311	-2.347	-1.939

Unit: dB/inch

Fig. 20

SI – Micro-Strip Line

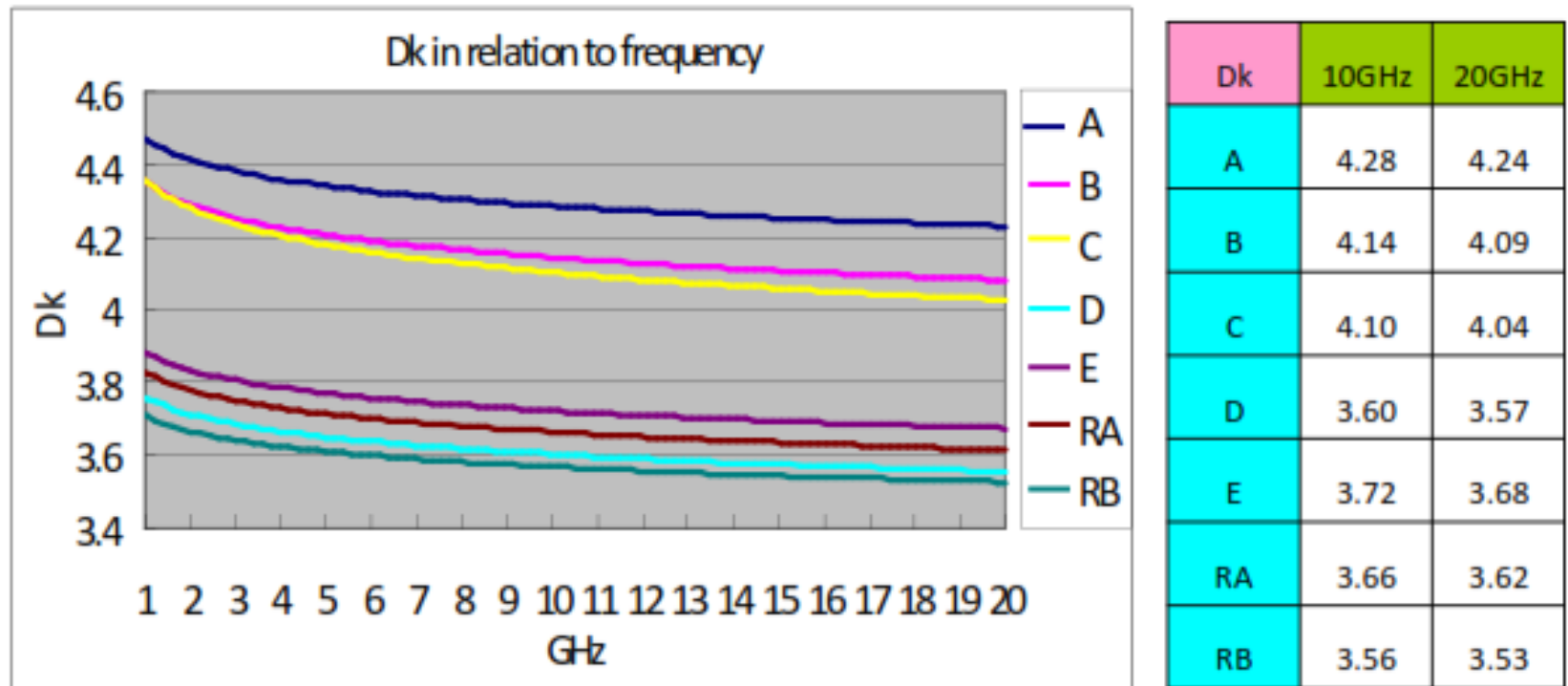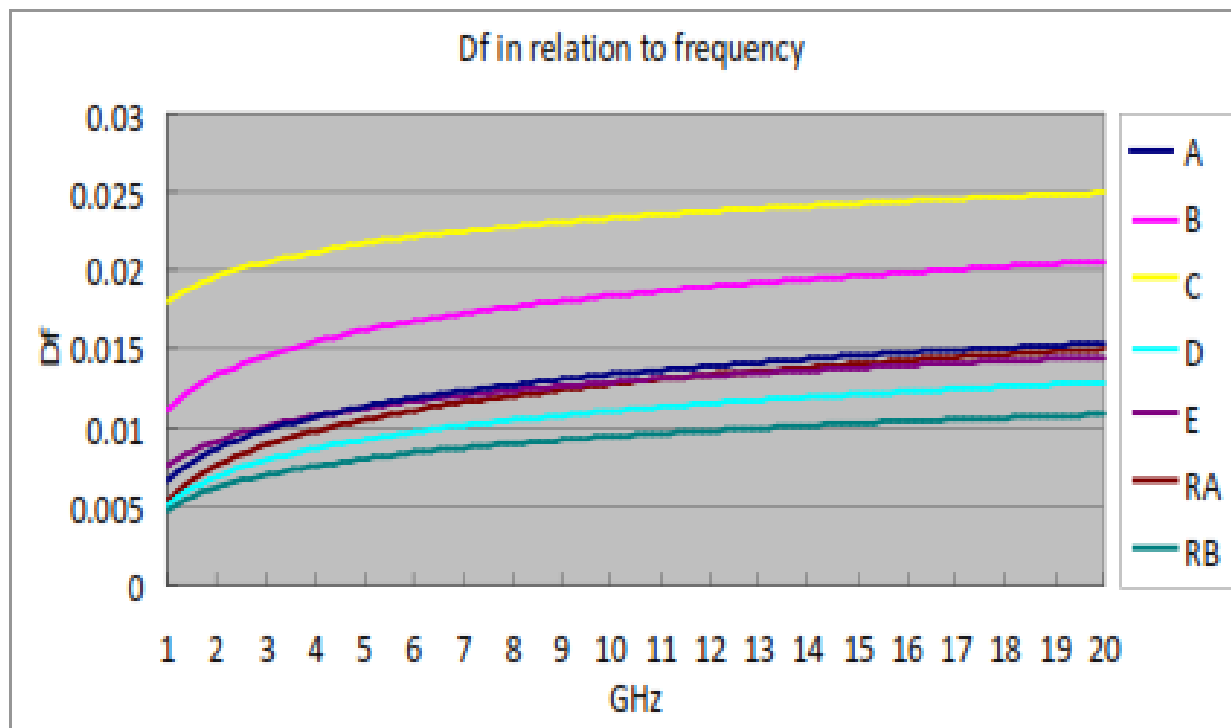| MS-fine line	A	B	C	D	E	RA	RB
10GHz	-1.376	-1.521	-1.752	-1.272	-1.213	-1.297	-1.143
20GHz	-2.345	-2.651	-3.133	-2.282	-2.098	-2.197	-1.894

Unit: dB/inch

Fig. 21

SI – Dk in Relation to Frequency

Fig. 22

- % change in Dk value from 1GHz to 20 GHz ranged from 0.83% - 1.46%.

SI – Df in relation to Frequency

Df in relation to frequency

Df	10GHz	20GHz
A	0.0134	0.0155
B	0.0184	0.0207
C	0.0233	0.0250
D	0.0112	0.0130
E	0.0129	0.0145
RA	0.0128	0.0151
RB	0.0094	0.0109

Fig. 23

- Percentage change in Df values ranged between 7.3% for Material 'C' and 17.97% for Material 'RA'

Delay Time Measurements

Materials	Delay time @ 10GHz (ps)	
	Micro-strip line	Strip-line
A	706	878
B	700	858
C	707	855
D	673	801
E	671	813
RA	672	810
RB	658	797

Table 7

In general, delay time relates to Dk values, except for Materials 'D' and 'RA'. Both of these materials should have delay time similar to 'RB'.

SI - Summary

- The spread for both Strip and Micro strip widens from 10GHz to 20GHz;
  - For Strip line
    - @ 10GHz is 0.699GHz dB/inch and @ 20GHz is 1.239GHZ dB/inch
  - For Micro Strip Line
    - @ 10GHz is 0.756 dB/inch and @ 20GHz is 1.437 dB/inch..
- From the insertion loss measurement, RB has the best signal integrity. All in order are:
  - 'RB' (the best) > 'RA'~'E'~'D' > 'A' > 'B' > 'C'
- From above delay time and Dk extraction, the Dk ranking is:
  - 'RB' (the lowest) < 'RA'~'E'~'D' < 'A'~'B'~'C'
- In turn of Df extraction data:
  - 'RB' (the lowest) < 'D' < 'RA'~'E' < 'A' < 'B' < 'C'

Project Summary

- Materials with similar published Values can perform differently.

- Material with best electrical performance might not be the most reliable material.

- Higher IST cycles for 'RB' could be because material had already degraded during preconditioning and did not have any additional stress during IST cycles.

- Published Dk / Df values are very close to tested values.

- Losses are higher for some materials as we go above 10GHz operating frequencies.

Thank you