DesignCon 2011

Characterization of Flexible Circuit Dielectrics for High Speed Applications

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Abstract

Designing flexible circuits for maximum signal integrity is often challenging since data for polyimide-based dielectrics are not as well characterized at high frequencies as well as better known low-loss materials. Data is presented and characterized for commonly used flexible circuit polyimide-based dielectrics and low-loss rigid dielectrics. Both in-plane (x-y) and out-of-plane (z) components of relative permittivity (dielectric constant) and loss tangent are measured using separate test fixtures and methods. Data is collected between 2 GHz and 25 GHz. By using different methods on the same samples, isotropy differences of dielectric constant and loss tangent can be determined for both polyimide-based flexible materials and glass reinforced low loss rigid laminates.

Author Biography

Glenn Oliver is a Senior Engineer with DuPont Electronics and Communications. He received his B.S. in Physics and his Masters in Engineering from North Carolina State University. His work background includes 8 years in Photonics research and development followed by 7 years in RF/Microwave development and applications. He is currently the principal engineer responsible for characterization of electrical properties of materials for high frequency applications. His other areas of focus are high speed flexible circuitry interconnect and high density interconnection applications support.

Introduction and Problem Statement

Designers and fabricators rely on valid and accurate measurements of dielectric constant (ε_r) and loss tangent (tan δ) to characterize materials and predict electrical performance. This is especially critical for applications at fast data rates or high frequencies. There is a rich history of data in the 10 GHz range on glass reinforced rigid laminates. Thin unreinforced laminates used in flexible circuits are not well characterized at high frequencies since historically their mechanical properties were more important than ε_r and tan δ. The traditional method [1, 2] for measuring ε_r and tan δ for rigid materials requires a stripline fixture utilizing specimens that are 1.6 mm thick. Most flexible dielectrics are less than 0.1 mm and often consist of a polyimide core that can not be laminated without adhesives that have significantly different properties. Stacking dozens of layers and maintaining intimate contact of resonator copper is both challenging and not representative of flex circuit applications.

A method utilizing a waveguide cavity [3] is an alternative that enables testing of thin (<0.1 mm) dielectrics. Since the electric field is oriented orthogonally to the stripline orientation, the ε_r and tan δ values reflect the “in plane” component of ε_r. These values are often different than those using the “normal” component of ε_r measured in the stripline method.

The work presented here is aimed at better characterizing thin unreinforced flexible dielectrics using different methods. Modifications had to be made to the stripline fixture to maintain intimate contact of dielectric stacks. Control samples of thick and thin glass reinforced laminates were measured for comparison and for purposes of “mapping” results between the two methods. Two types of fluoropolymer film were used to reference the values of ε_r and tan δ since Teflon® is the most well characterized material used in high frequency electronics.

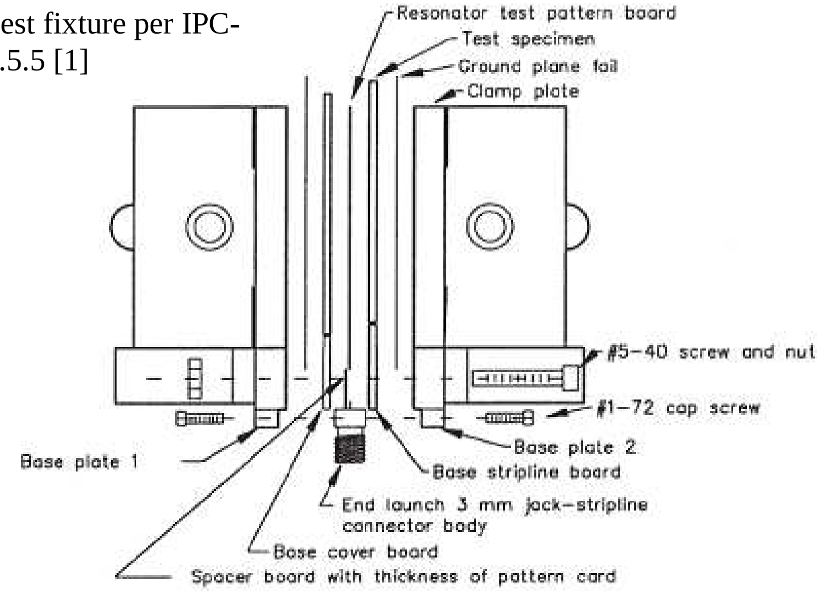
Stripline - Method and Test Fixture Modifications

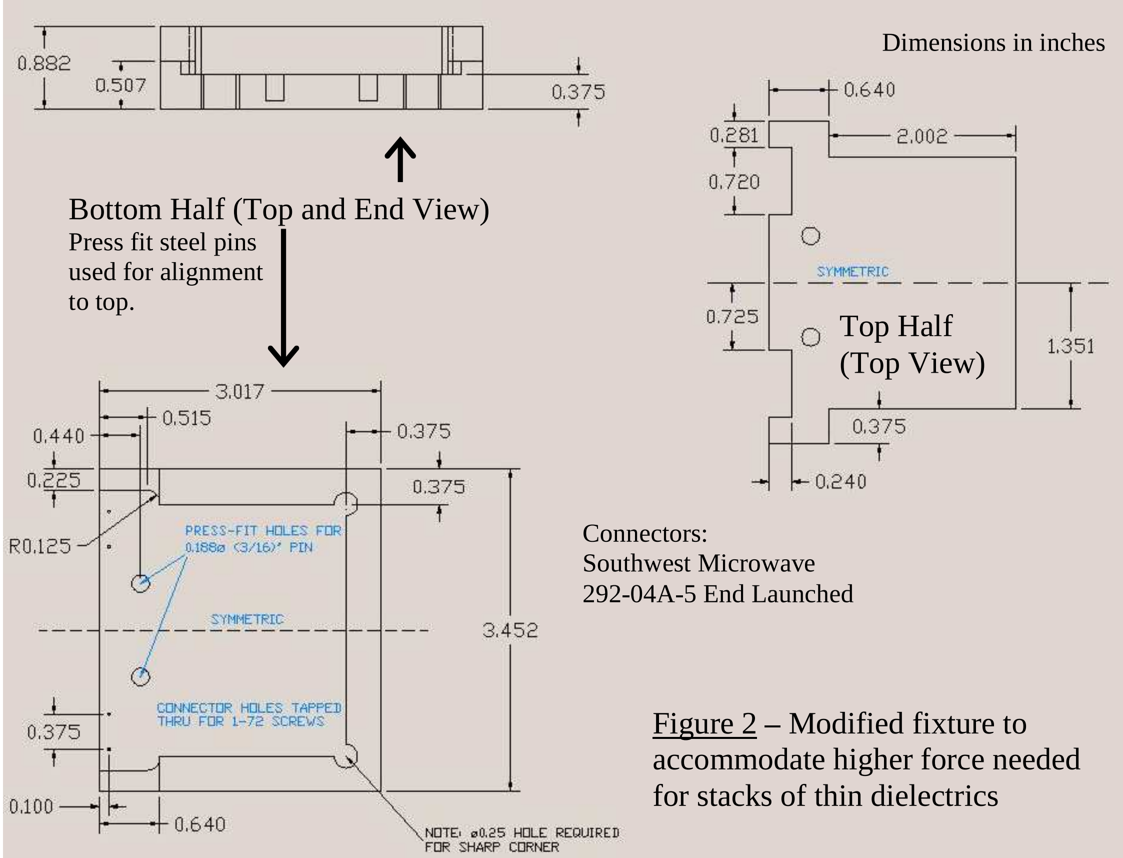
The most commonly used method for evaluating ε_r and tan δ of dielectrics at 10 GHz is IPC-TM-650-2.5.5.5. [1] This method is equivalent to ASTM-D-3380. [2] The original intent of this work was to use the same test fixture to evaluate both rigid glass reinforced and thin unreinforced dielectrics side-by-side. A fixture was made per the specifications of the test method stated above. A representation from IPC-TM-650-2.5.5.5 is shown in Figure 1.

Two stacks of twenty two 0.075 mm thick layers of unreinforced flexible dielectric were loaded in the fixture to obtain the required 1.59 mm overall thickness of the samples. Copper foil was used to provide a good ground connection for the stripline. Many attempts were made to obtain repeatable data from this structure at the pressure specified in the test method (1000 lbs). Only when the force was increased above 5000 lbs were the results repeatable enough to yield somewhat consistent data. Unfortunately, the fixture design in the test method is not capable of withstanding this level of force. After about

10 measurements done at 5000 lbs, the fixture broke at the ball (highest force point) where the internal water connection met the thinnest metal area.

Figure 1 – Test fixture per IPC-TM-650-2.5.5.5 [1]





Connectors:
Southwest Microwave
292-04A-5 End Launched

Figure 2 – Modified fixture to accommodate higher force needed for stacks of thin dielectrics

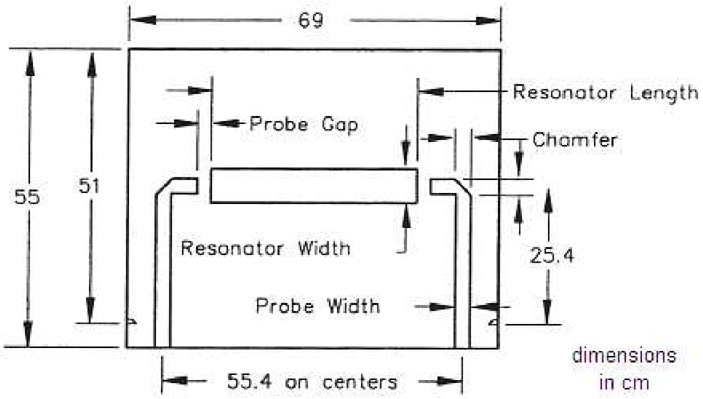
Since the laboratory used to perform the testing was maintained at relatively constant temperature and humidity (21 C at 50%RH), the fixture was re-designed to withstand higher force by eliminating the water connections and distributing force over a larger area. Elimination of the water connection allowed the design to be simplified by reducing the number of metal parts to two. The modified fixture design is shown in Figure 2 with dimensions shown in inches. The same circuit boards for both the launch and the resonators were utilized for modified design.

Stripline - Fixture and Sample Preparation

For organic materials, most low-loss materials based on Teflon® have ε_r values of between 2 and 3. Polyimide materials have dielectric constant values between 3 and 3.5. For this reason, resonator card structures were chosen from the IPC-TM-650-2.5.5.5 standard between 2.20 and 3.50. Commercially available glass-reinforced rigid materials were chosen. A list of these materials and their corresponding properties (according to manufacturer data sheets) is given in Table 1.

	Datasheet (10 GHz)		Res W (cm)		Res L (cm)		Probe G (cm)		Probe W (cm)	
Material Name	ε_r	tan δ	Spec	Actual	Spec	Actual	Spec	Actual	Spec	Actual
Arlon DiClad Series® 880	2.20	9E-04	6.35	6.32	38.1	38.1	2.54	2.58	2.74	2.73
Arlon DiClad Series® 870	2.33	0.001	6.35	6.34	38.1	38.3	2.54	2.50	2.67	2.67
Arlon AD Series® 250	2.50	0.002	6.35	6.33	38.1	38.1	2.54	2.59	2.49	2.46
Arlon CLTE-AT	3.00	0.001	5.08	5.24	31.8	37.9	2.54	2.51	2.13	2.14
Arlon AD Series® 350	3.50	0.003	5.08	5.17	31.8	37.9	2.54	2.52	1.85	1.86

Table 1 – Properties of the stripline resonators used for testing. [4]



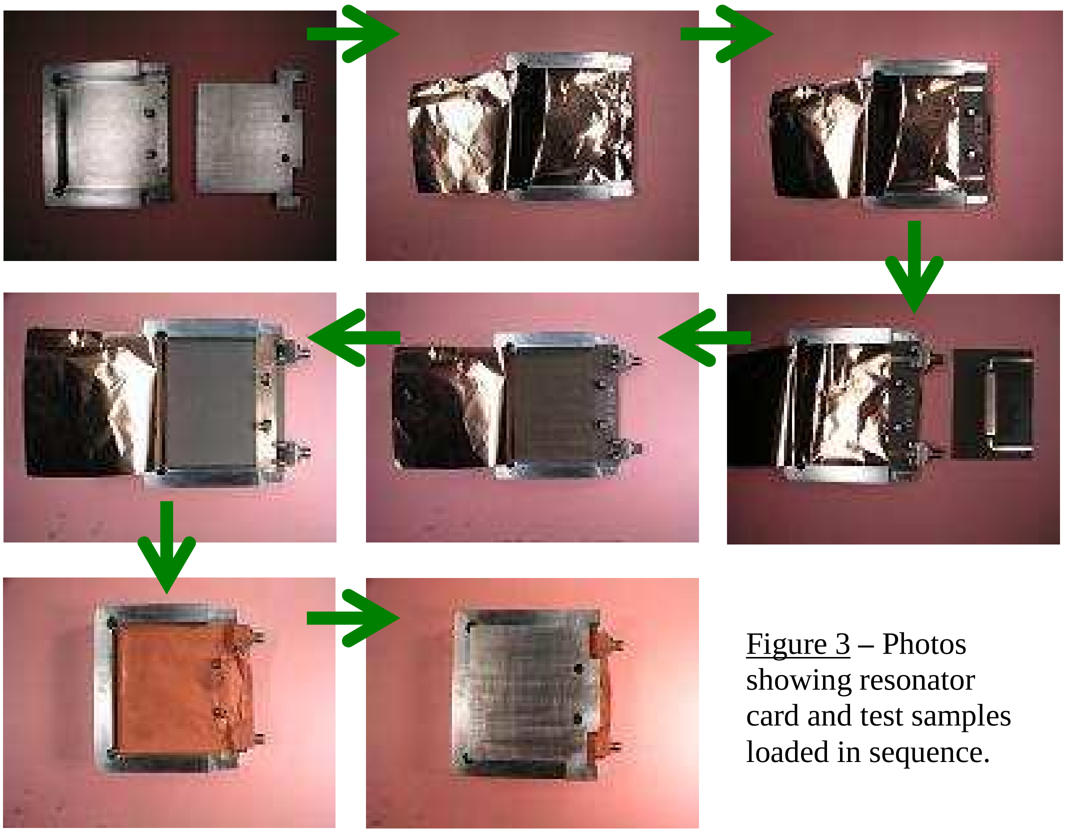


Figure 3 – Photos showing resonator card and test samples loaded in sequence.

The resonator card was placed between two sets of samples. In the case of thin dielectrics, the samples had to be stacked to make a total thickness of 1.59 mm on both the top and bottom of the resonator card. Figure 3 shows a progression of how samples were loaded. Figure 4 shows the individual layers prior to stacking. One key factor of note is that the same copper sheet was used for all samples and all fixtures. This minimizes the impact that the copper has on the loss tangent measurements of higher order modes.

Control samples of each fixture material (see Table 1) were prepared by etching copper off of both sides of the copper clad laminate. The same 1.59 mm thick dielectric used to make the fixture were used to make the control samples. The samples that were tested for comparison were two types of Teflon®, two types of Teflon® / Kapton® composites and two types of Kapton® based polyimide dielectrics.

Figure 4 – Close-up of fixture showing individual layers prior to stacking.

Specific descriptions of each dielectric are given below. To simplify, the six samples will be identified by the names in **bold**.

PFA Teflon® = 75 µm thick Teflon® film made from PFA 350 resin – stacked 21 layers high
FEP Teflon®= 75 µm thick Teflon® film made from FEP 100 resin – stacked 22 layers high
TK 75 = 75 µm thick Teflon®/Kapton® composite (T:K ratio 2:1) – stacked 22 layers high
TK 100 = 100 µm thick Teflon®/Kapton® composite (T:K ratio 1:1) – stacked 17 layers high
Pyralux® AP = 150 µm thick All Polyimide – stacked 12 layers high
H Kapton® = 50 µm thick commodity grade polyimide – stacked 33 layers high

Stripline – Measurement of Resonances

A vector network analyzer (VNA) was used to measure all resonances. The same settings were used for consistency. A scan bandwidth of 400 MHz with 1601 points yielded a frequency resolution of 250 kHz separating each point. The fundamental (n=1) resonance was located and measured. The higher order resonances (n=2 through 9) were located by assuming that the dielectric constant does not change substantially between adjacent resonances and higher order resonant frequencies will be multiples of the fundamental.

Early on in the testing, it became clear that higher press force yielded more consistent resonances, especially for high-order modes. Figure 5 shows examples of resonances in which the highest press force results in the resonance being most symmetrical. Also one can see that the 1000 lb force was not enough to maintain intimate contact. It also appears that the air trapped between the layers is less prevalent with increased pressure. In some cases, “clean” modes could not be obtained due to extraneous resonances and interfering modes. Figure 6 shows examples where clean resonances could not obtained. When clean resonances could not be obtained, the resonance is not used to determine ε_r or tan δ.

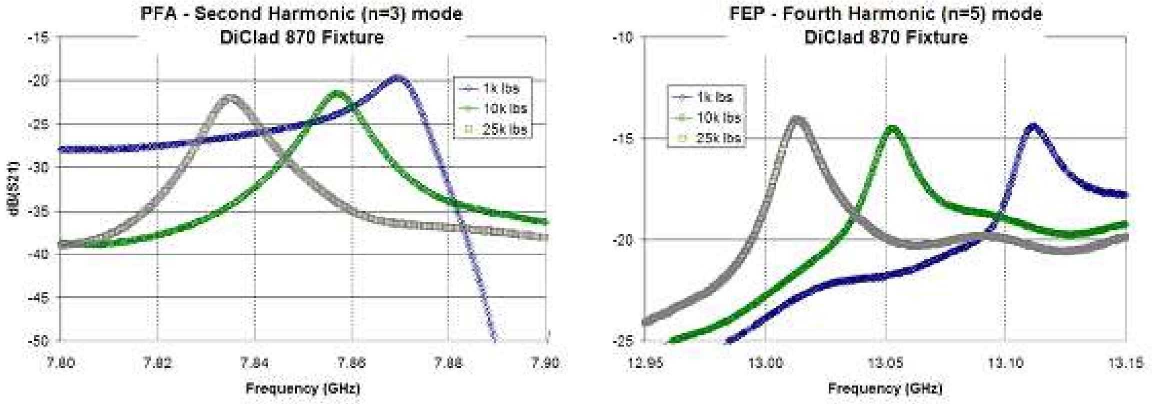


Figure 5 – Highest press force typically results in symmetric “clean” resonances.

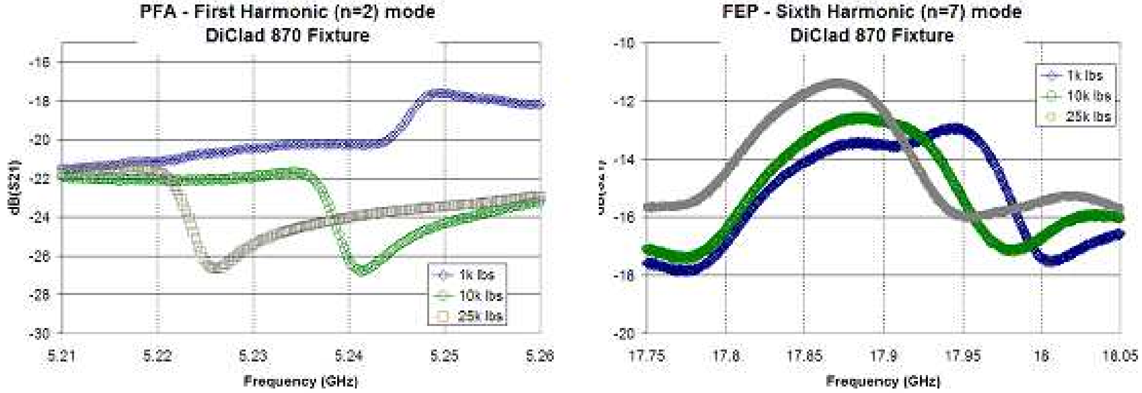


Figure 6 – Examples of modes where “clean” resonances could not be obtained.

The resonances were evaluated at 10 dB, 3 dB and 1 dB points. Only resonances that clearly represent the mode in question and are clearly symmetric were reported. To provide the most data availability, the resonance measurements at the 1 dB points were used for analysis. These data are reported in Table 2 through Table 5. Testing using the AD Series® 350 fixture material will be done in future work due to time constraints.

DiClad Series® 880	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.550	0.0023	-49.1
	2	5.103	0.0058	-43.3
	3	7.641	0.0093	-37.2
	4	10.196	0.0080	-45.8
	5	12.732	0.0128	-43.1
	6	15.271	0.0145	-39.4
	7	17.799	0.0215	-38.8
	8	20.361	0.0308	-31.3
	9	22.872	0.0410	-32.8

PFA Teflon®	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.637	0.0023	-31.2
	2	5.285	0.0037	-24.1
	3	7.901	0.0053	-25.1
	4	10.530	0.0068	-23.9
	5			
	6	15.793	0.0127	-17.0
	7	18.380	0.0150	-17.7
	8			
	9	23.617	0.0207	-18.6

FEP Teflon®	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.624	0.0025	-29.4
	2	5.248	0.0045	-24.2
	3	7.901	0.0060	-23.8
	4	10.459	0.0075	-23.6
	5	13.099	0.0102	-16.5
	6	15.670	0.0137	-13.4
	7	18.306	0.0190	-20.0
	8	20.819	0.0230	-15.1
	9	23.432	0.0300	-17.5

TK 75	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.481	0.0045	-35.0
	2	4.961	0.0097	-29.5
	3			
	4	9.894	0.0183	-26.9
	5	12.390	0.0225	-24.3
	6	14.827	0.0317	-21.3
	7			
	8	19.728	0.0548	-22.3
	9	22.398	0.0712	-30.6

TK 100	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.385	0.0050	-33.8
	2	4.772	0.0110	-26.8
	3	7.214	0.0165	-29.2
	4	9.563	0.0228	-26.9
	5	11.928	0.0232	-26.6
	6			
	7	16.706	0.0542	-23.1
	8			
	9			

Pyralux® AP	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.142	0.0048	-43.4
	2	4.250	0.0100	-53.7
	3	6.383	0.0180	-30.1
	4	8.508	0.0185	-25.5
	5	10.628	0.0263	-26.6
	6	12.736	0.0323	-23.1
	7	14.769	0.0520	-23.5
	8	16.967	0.0568	-16.4
	9			

H Kapton®	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.119	0.0113	-50.5
	2	4.255	0.0273	-43.4

Table 2 – Measurements using the resonator made from DiClad Series® 880

DiClad Series® 870	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.486	0.0028	-32.5
	2	4.993	0.0055	-29.1
	3	7.450	0.0077	-24.2
	4	9.932	0.0107	-22.9
	5	12.418	0.0148	-20.4
	6	14.889	0.0192	-17.9
	7			
	8			
	9	22.319	0.0308	-20.2

PFA Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.614	0.0020	-29.2
	2			
	3	7.857	0.0047	-21.5
	4	10.470	0.0060	-20.5
	5	13.043	0.0085	-17.2
	6	15.643	0.0120	-13.7
	7			
	8			
	9	23.362	0.0210	-16.7

FEP Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.617	0.0020	-29.2
	2	5.212	0.0040	-24.2
	3	7.818	0.0055	-20.8
	4	10.417	0.0070	-20.9
	5	13.014	0.0107	-14.1
	6	15.607	0.0137	-14.2
	7			
	8			
	9	23.304	0.0200	-16.7

TK 75	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.441	0.0035	-45.1
	2	4.921	0.0080	-35.3
	3	7.390	0.0135	-26.8
	4	9.834	0.0180	-25.1
	5	12.177	0.0205	-23.4
	6	14.738	0.0270	-20.4
	7	17.005	0.0437	-16.1
	8	19.591	0.0542	-14.6
	9	22.090	0.0392	-34.3

TK 100	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.380	0.0042	-43.1
	2	4.745	0.0097	-36.9
	3			
	4	9.495	0.0198	-30.5
	5	11.847	0.0257	-23.6
	6	14.230	0.0358	-21.3
	7	16.563	0.0430	-17.7
	8	18.884	0.0535	-20.2
	9	21.202	0.0658	-21.4

Pyralux® AP	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.113	0.0045	-36.4
	2	4.231	0.0097	-43.5
	3			
	4	8.445	0.0238	-29.6
	5	10.567	0.0273	-24.6
	6	12.669	0.0400	-21.5
	7	14.744	0.0543	-18.8
	8			
	9			

H Kapton®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.109	0.0113	-48.8
	2	4.232	0.0210	-40.0
	3	6.370	0.0352	-23.3
	4	8.494	0.0397	-40.1

Table 3 – Measurements using the resonator made from DiClad Series® 870

AD Series® 250	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.390	0.0030	-32.6
	2	4.782	0.0062	-28.3
	3	7.178	0.0095	-26.8
	4	9.568	0.0115	-24.5
	5	11.951	0.0168	-21.5
	6	14.330	0.0222	-16.2
	7	16.666	0.0305	-22.4
	8			
	9	21.358	0.0485	-16.0

PFA Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.606	0.0023	-30.5
	2	5.217	0.0042	-31.4
	3	7.820	0.0062	-23.8
	4	10.423	0.0075	-21.1
	5	13.026	0.0097	-21.9
	6			
	7			
	8	20.793	0.0192	-34.0
	9	23.314	0.0208	-21.0

FEP Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.598	0.0023	-30.0
	2	5.192	0.0045	-28.0
	3	7.788	0.0065	-26.0
	4	10.393	0.0080	-21.2
	5			
	6			
	7			
	8			
	9	23.254	0.0240	-19.9

TK 75	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.457	0.0042	-35.4
	2	4.913	0.0090	-30.3
	3	7.373	0.0142	-29.3
	4	9.823	0.0178	-25.6
	5	12.300	0.0260	-21.3
	6	14.724	0.0335	-18.7
	7			
	8			
	9	22.007	0.0660	-19.7

TK 100	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.369	0.0045	-45.1
	2	4.745	0.0110	-43.9
	3	7.119	0.0157	-34.6
	4	9.476	0.0240	-34.6
	5	11.849	0.0228	-30.9
	6	14.216	0.0415	-19.3
	7	16.579	0.0338	-23.4
	8			
	9	21.180	0.0685	-23.3

Pyralux® AP	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.119	0.0040	-40.7
	2	4.245	0.0098	-37.5
	3	6.373	0.0155	-31.9
	4	8.500	0.0192	-28.8
	5	10.612	0.0243	-26.2
	6	12.714	0.0323	-21.9
	7			
	8	16.920	0.0478	-20.6
	9	19.026	0.0412	-34.1

H Kapton®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.120	0.0107	-45.7
	2	4.244	0.0195	-39.6
	3	6.368	0.0368	-26.3
	4	8.487	0.0392	-37.0

Table 4 – Measurements using the resonator made from AD Series® 250

CLTE-AT	n	f_r (GHz)	1dB BW (GHz)	S21 at f_r (dB)
	1	2.229	0.0020	-36.0
	2	4.463	0.0040	-30.3
	3	6.873	0.0062	-33.1
	4	8.870	0.0083	-22.8
	5	11.083	0.0105	-23.3
	6	13.299	0.0130	-23.7
	7	15.472	0.0170	-20.8
	8	17.665	0.0262	-16.0
	9	19.923	0.0335	-24.1

PFA Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.658	0.0022	-31.6
	2	5.306	0.0042	-35.5
	3	7.955	0.0046	-20.8
	4	10.592	0.0072	-19.4
	5	13.263	0.0090	-31.0
	6	15.867	0.0122	-22.8
	7			
	8	21.107	0.0260	-20.5
	9	23.823	0.0297	-24.9

FEP Teflon®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.645	0.0023	-30.1
	2	5.289	0.0050	-24.8
	3	7.851	0.0055	-24.5
	4	10.555	0.0083	-19.7
	5	13.183	0.0143	-29.2
	6	15.831	0.0165	-16.0
	7	18.311	0.0130	-15.0
	8	20.961	0.0330	-18.2
	9	23.745	0.0258	-25.2

TK 75	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.490	0.0042	-40.5
	2			
	3	7.474	0.0127	-29.0
	4	9.949	0.0172	-29.3
	5	12.442	0.0208	-24.0
	6	14.908	0.0282	-24.3
	7	17.401	0.0322	-20.2
	8			
	9			

TK 100	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.404	0.0043	-42.6
	2	4.804	0.0095	-41.7
	3	7.235	0.0135	-32.0
	4	9.620	0.0192	-32.7
	5			
	6	14.369	0.0333	-26.9
	7			
	8			
	9	21.488	0.0550	-22.3

Pyralux® AP	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.146	0.0042	-30.6
	2	4.297	0.0088	-29.9
	3	6.458	0.0147	-27.0
	4	8.582	0.0188	-31.0
	5	10.706	0.0205	-30.8
	6	12.864	0.0447	-21.4
	7	14.965	0.0360	-21.3
	8	17.005	0.0428	-16.8
	9	19.030	0.0755	-17.3

H Kapton®	n	fr (GHz)	1dB BW (GHz)	S21 at fr (dB)
	1	2.173	0.0115	-47.0
	2	4.357	0.0233	-43.3
	3	6.493	0.0390	-35.9

Table 5 – Measurements using the resonator made from CLTE-AT

Stripline – ε_r Analysis of Resonances

To determine permittivity, equation 1 from section 7.1 of the IPC method was used. [1]

$$\varepsilon_r = [n\, C / (2\, f_r\, (L + \Delta L))]^2$$

Where n is the mode number, C is the speed of light, f_r is the measured resonant frequency, L is the measured length of the resonator and ΔL is a correction factor to capture the difference in physical length and electrical length. Since Teflon® is one of the most well characterized electronic materials; PFA and FEP were chosen as the references to determine the correction factor (ΔL) for all fixtures. The value for ΔL was determined empirically as the value needed to obtain the known values of the PFA and FEP resins used. The known value for ε_r of PFA 350 resin is 2.03 and the known value for ε_r of FEP 100 resin is 2.06. [5] Figure 7 through Figure 10 show the values of ε_r determined form the resonant measurements. The value of ΔL is shown in each plot. The lines shown on the plots are linear trend lines.

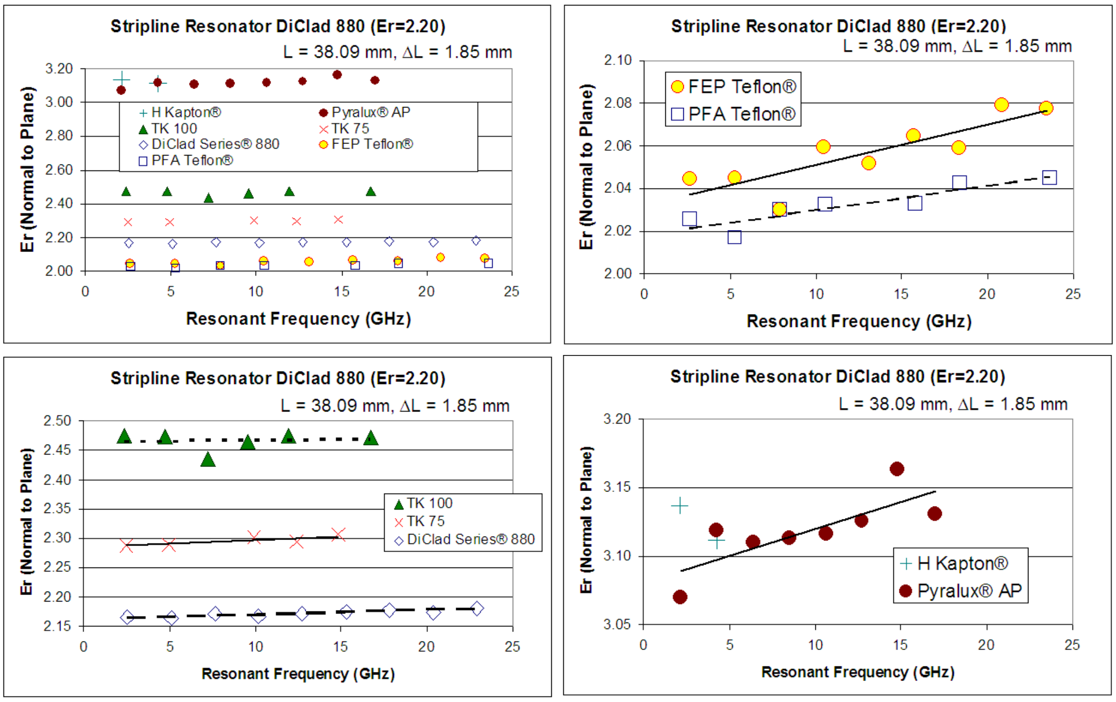


Figure 7 – Permittivity (ε_r) measurements from test fixture made from DiClad 880.

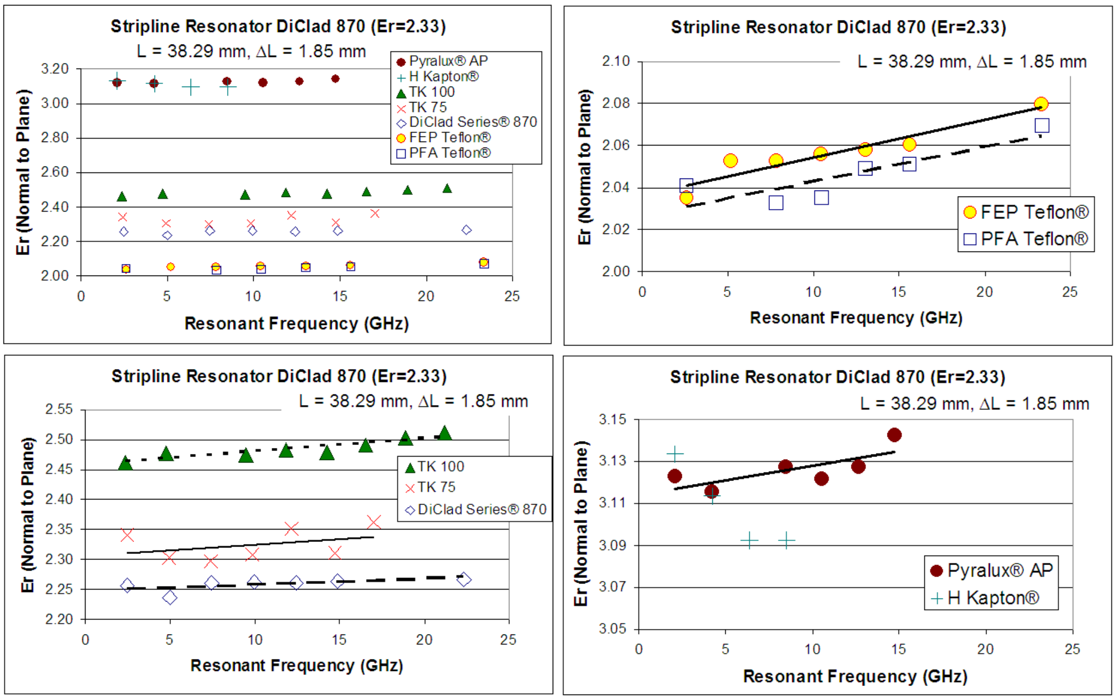


Figure 8 – Permittivity (ε_r) measurements from test fixture made from DiClad 870.

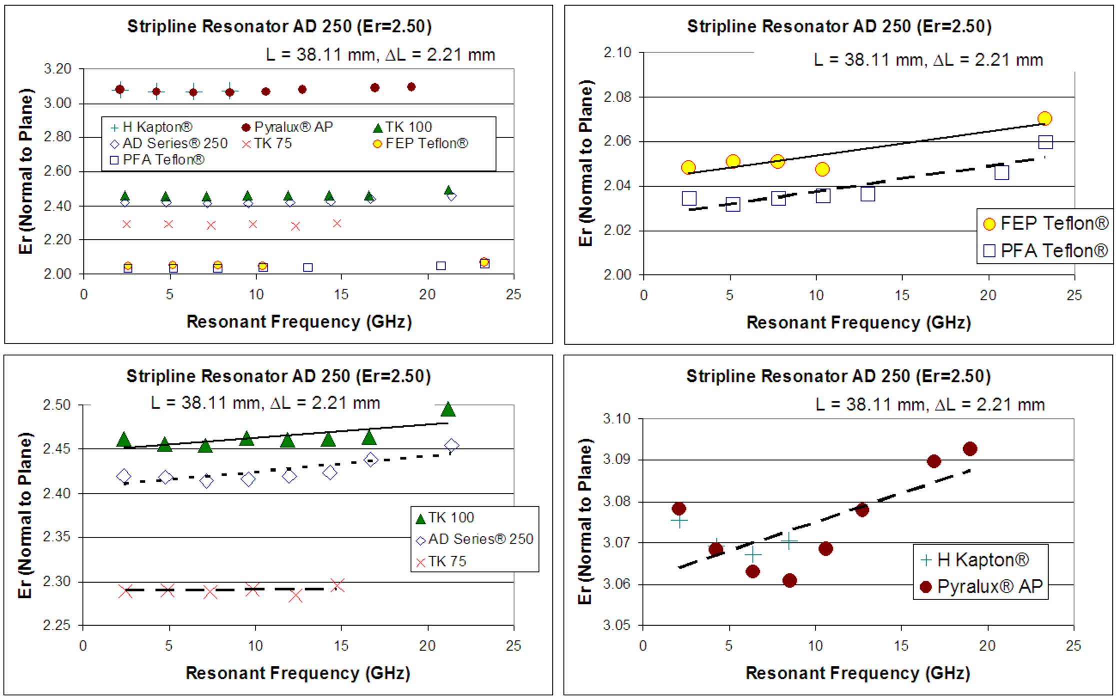


Figure 9 – Permittivity (ε_r) measurements from test fixture made from AD 250.

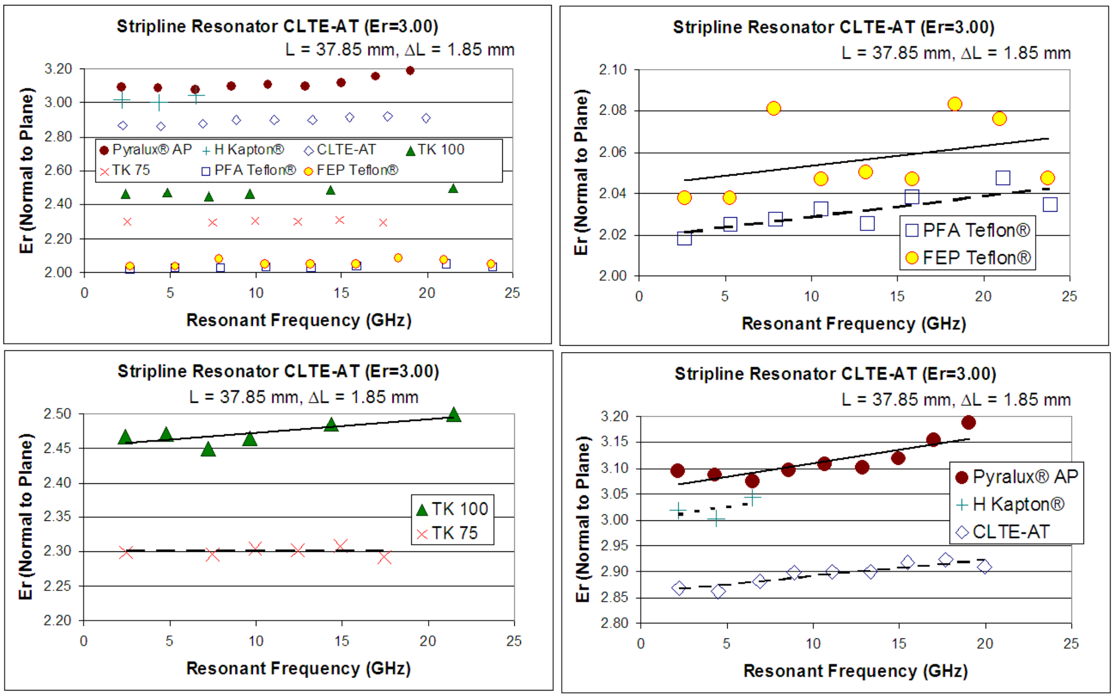


Figure 10 – Permittivity (ε_r) measurements from test fixture made from CLTE-AT.

Note the H Kapton® values in Figure 7 through Figure 10 reflected no measurements above 10 GHz. This is due to the fact that modes above n=4 were not strong enough to be resolved over the noise. This commercial grade of Kapton® has the highest dielectric loss of any of the samples measured.

Stripline – tan δ Analysis of Resonances

Since the magnitude of the resonances varied significantly between lower order and higher order modes, the measurements were normalized to reflect the unloaded Q in all cases. The resonances were measured based on the 1 dB criterion to determine the bandwidth. The calculations are detailed in section 7.2 in the IPC method. [1]

It was necessary to add an additional correction factor to make the results self consistent. This bias was determined empirically to be the value needed to make the loss tangent of PFA greater than zero. This correction factor was included as a constant bias of all loss tangent values. This correction factor is referred to as 1/Qcorr and its value is shown on the summary plots shown in Figure 11 through Figure 14.

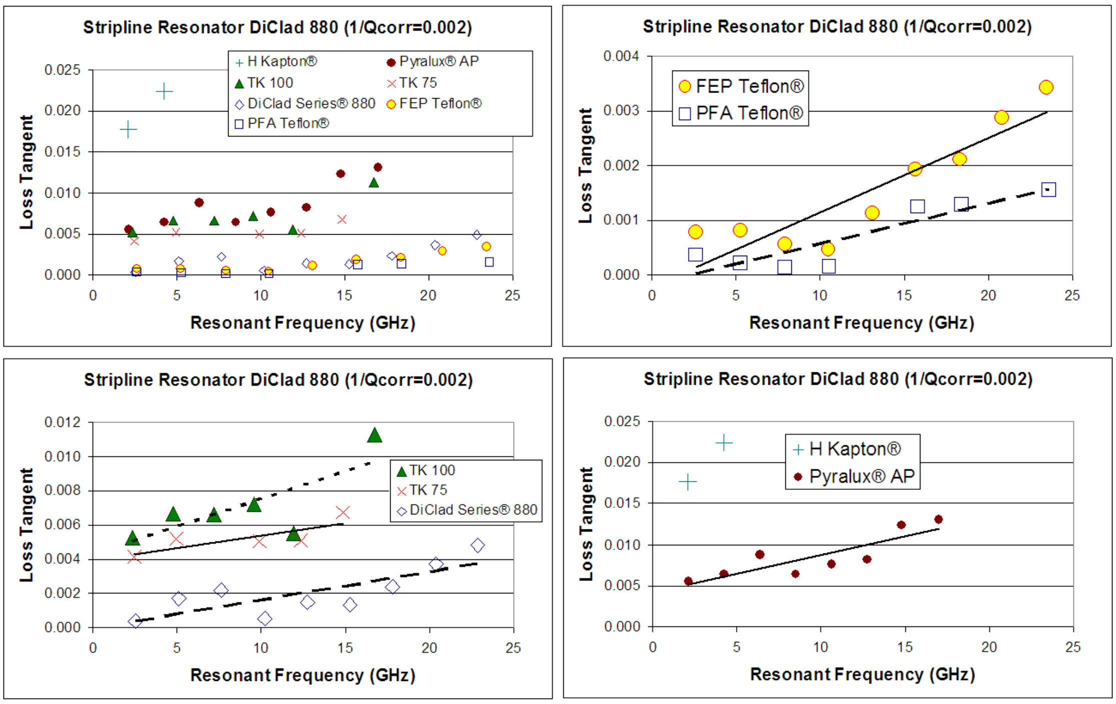


Figure 11 – Loss Tangent measurements from test fixture made from DiClad 880.

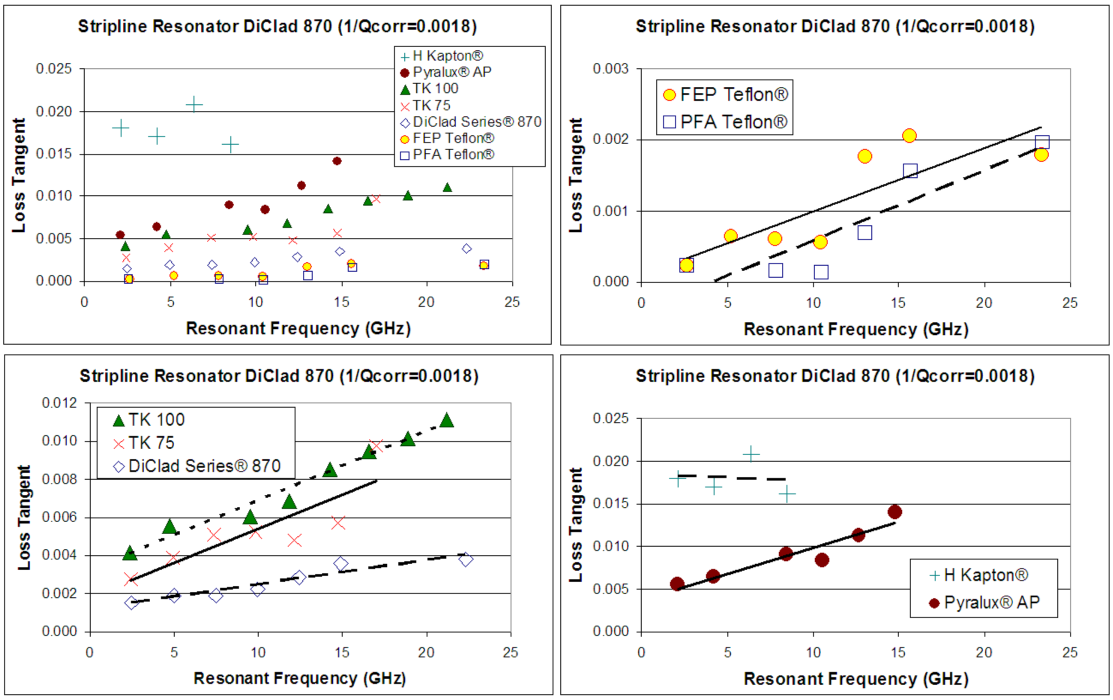


Figure 12 – Loss Tangent measurements from test fixture made from DiClad 870.

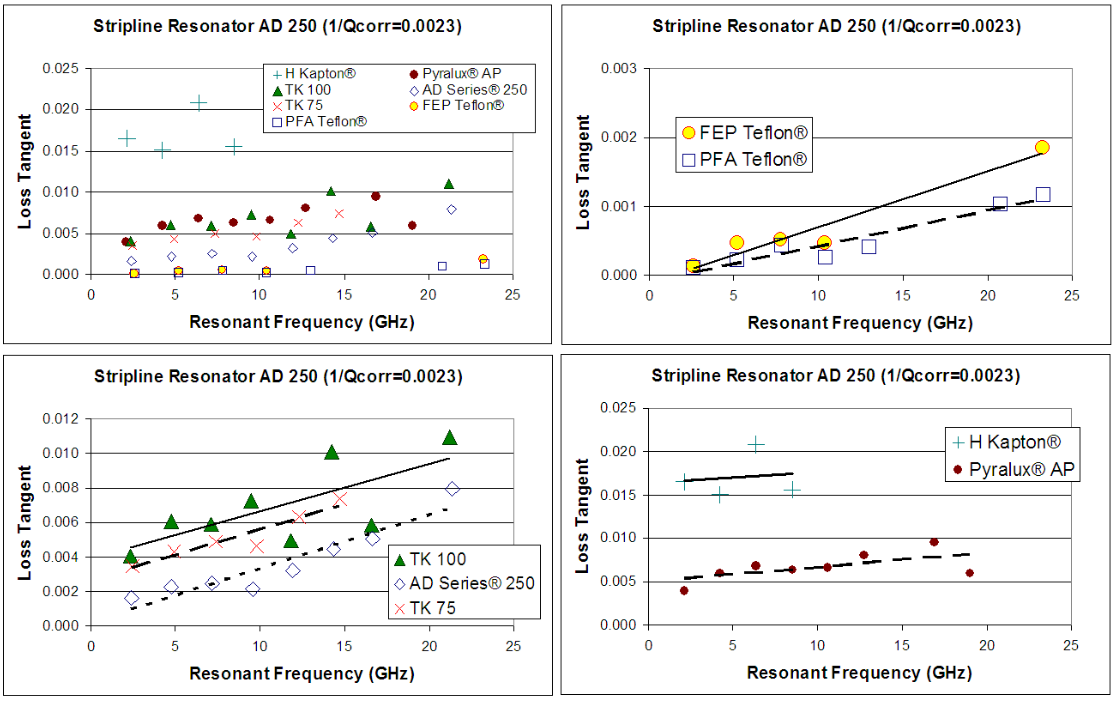


Figure 13 – Loss Tangent measurements from test fixture made from AD 250.

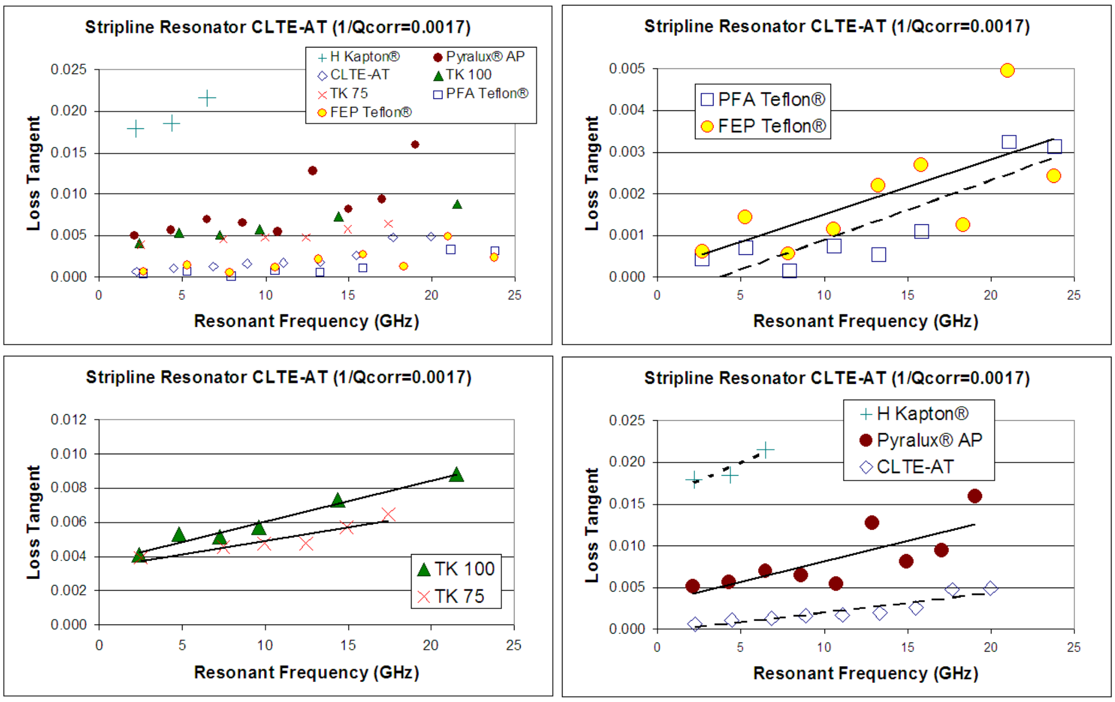


Figure 14 – Loss Tangent measurements from test fixture made from CLTE-AT.

Stripline – Comparison of Fixtures

Self consistency of results was a critical parameter in determining characterized values from raw measurements. It is assumed that measurements of the same samples using different fixtures will yield results that are consistent. The purpose of Figure 15 is to show the variation between the materials under test. Note that the variation is about 2%-3% of the value of ε_r.

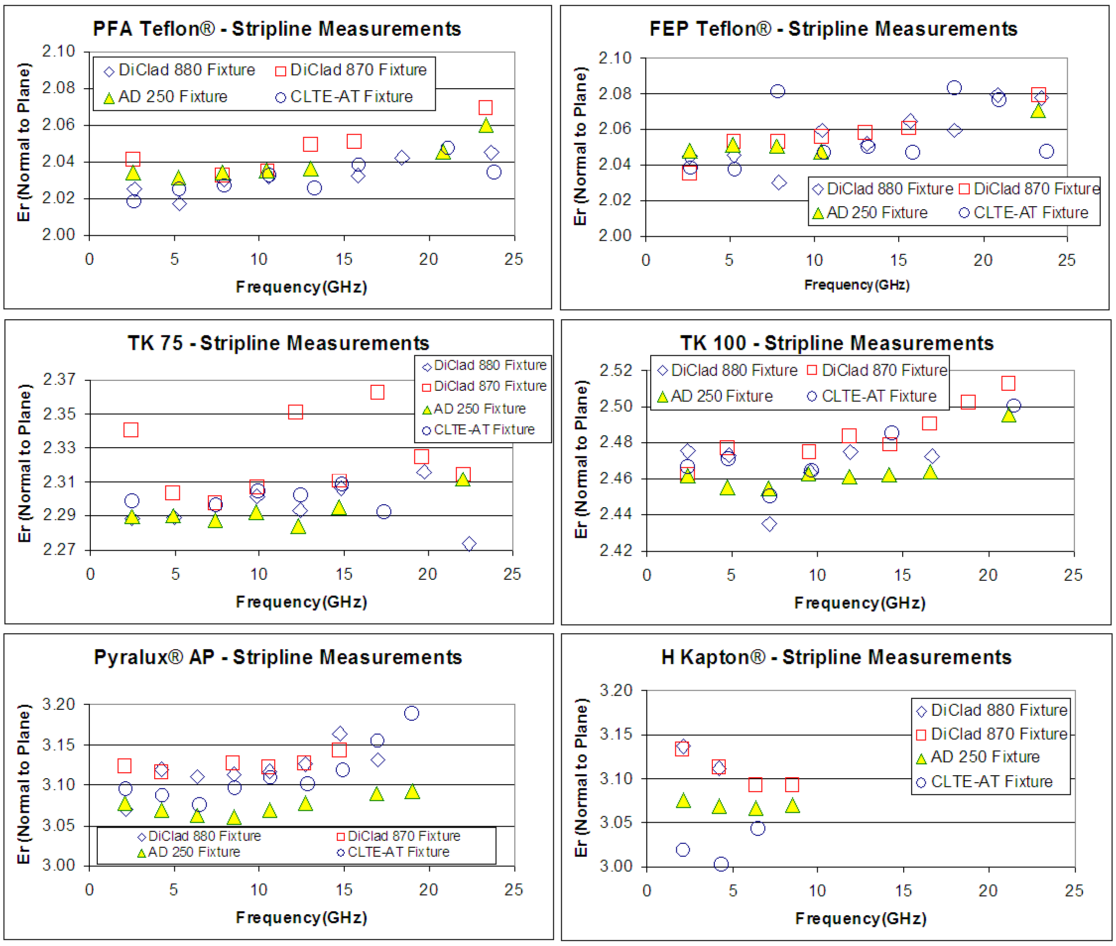


Figure 15 – Comparison of fixtures illustrating variation of ε_r values.

For loss tangent, one would expect a stronger dependence on frequency than for relative permittivity. Since PFA and FEP do not significantly increase in loss with frequency and these samples are used as references for loss tangent, the variation is less for Teflon® than any other materials evaluated. The variation between the test fixtures is illustrated in Figure 16. Loss tangent varies by about 0.001-0.002 at 2 GHz. Higher order modes (above 10 GHz) have larger variation of loss tangent of about 0.002-0.004.

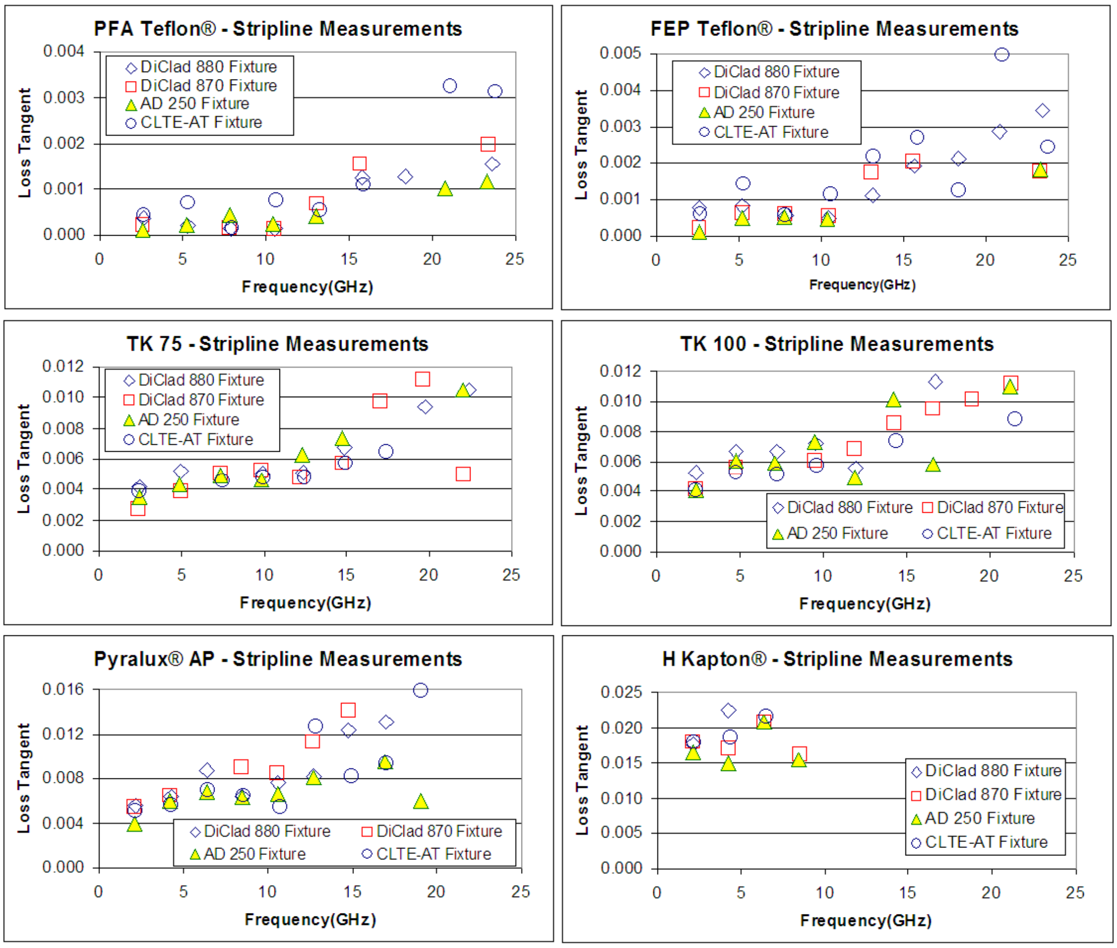


Figure 16 – Comparison of fixtures illustrating variation of loss tangent values.

Waveguide – Thin Sheet Fixture and Method

One advantage of the stripline method is that it produces values that are very self-consistent. A major disadvantage of the stripline method is that a relatively thick layer of dielectric is necessary to perform the test. For thin dielectrics typical of flexible circuits, this is especially difficult since dozens of layers need to be stacked and sample preparation in this case becomes a significant variable. An alternative method is described in previous work by this author [6] that utilizes a waveguide instead of a stripline fixture. The associated procedure developed with this fixture is based on ASTM D-2520 Method C. [3] The fixture was built and automated software was prepared by Damaskos Incorporated. [7] This fixture is designed to measure dielectrics with thickness values less than 0.5 mm. Typically this fixture is utilized to measure samples less than 0.1 mm thick.

One significant difference between the waveguide fixture and the stripline fixture is the orientation of the electric field during testing. In the stripline method, the electric field is oriented roughly normal to the plane of the dielectric under test. In the waveguide fixture, the electric field is oriented in the same plane as the dielectric. Since the waveguide is rectangular, the dielectric can be rotated 90 degrees to determine if there are differences between the “x” and “y” directions in the plane of the dielectric. Unless there are defects in manufacturing, most dielectric materials used in flexible circuits do not have significant differences between the in-plane “x” and “y” directions. Each sample is measured twice, once with the film oriented in the “x” direction and once with the film oriented in the “y” direction. These two measurements are averaged together and reported as “in plane” measurements.

Waveguide – Measurement Results

Since the sample thickness is much smaller for the in-plane direction, both individual layers of the material under test and stacks of material were evaluated. Thickness of each material was measured with a precision micrometer. All samples were measured at the same time using the same micrometer. For the materials used to make the stripline fixtures, copper was etched off of resonator cards (0.25 mm samples) and the fixture layer materials (1.59 mm samples). Figure 17 shows the measurement results of the fixture samples.

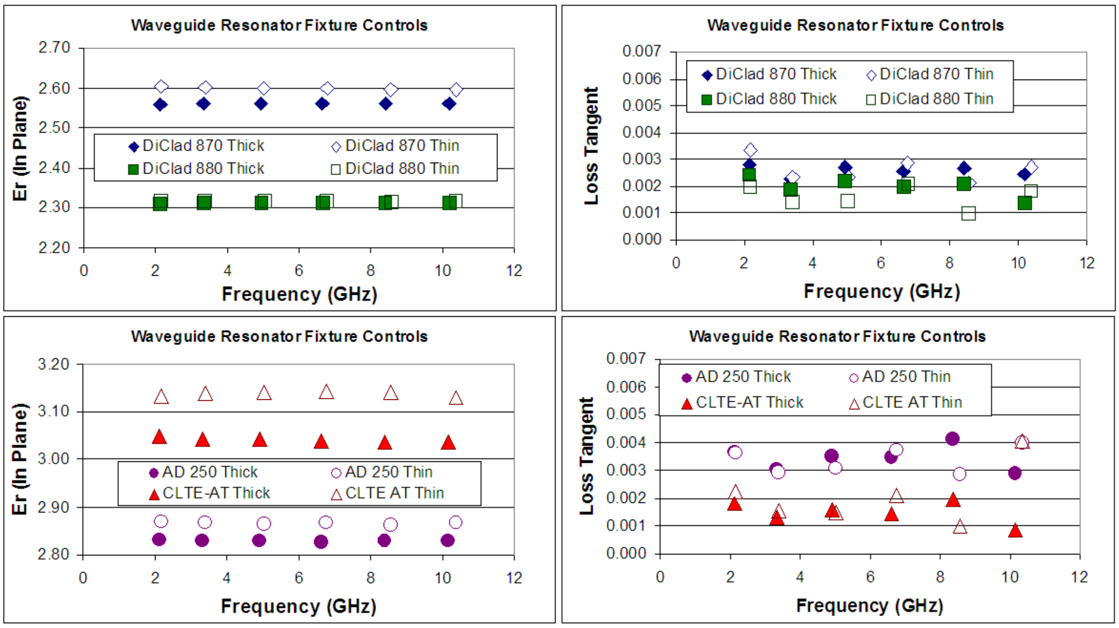


Figure 17 – Waveguide measurements of the materials used to make the stripline resonators.

The same specimens used for testing in the stripline fixtures were evaluated using the waveguide resonator. Two or three stack thicknesses were measured in addition to single layers of each material. These data are summarized in Figure 18.

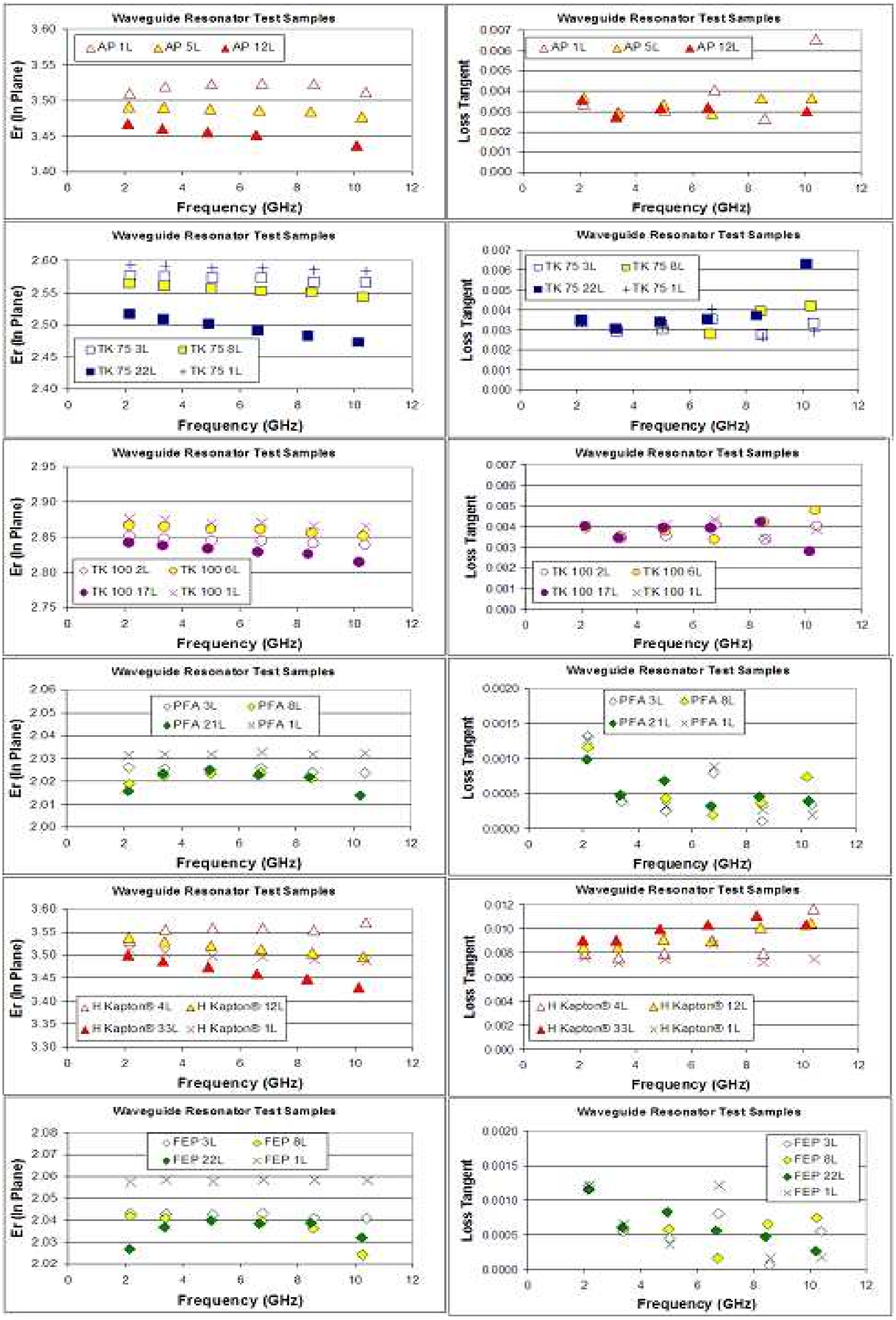


Figure 18 – Waveguide measurements of test specimens tested in the stripline fixture.

Comparison of Stripline to Waveguide Results

A summary of the results from both the fixture boards (rigid/glass reinforced) and the flexible (test samples) are shown in Table 6. For fixture materials, ε_r values measured with the waveguide method tend to be between 5%-15% higher than the values measured with the stripline method. A similar level of bias is also noted for the test samples that were not used as references (TK 75, TK 100, Pyralux® AP, and H Kapton®). Interestingly, this bias in ε_r is not noted with the reference samples (PFA and FEP).

Fixture Materials (Rigid/Glass Reinforced)

	Stripline		Waveguide (in-plane)				Values From	
	1.6 mm thick		1.6 mm thick		0.25 mm thick		Datasheet	
	ε_r	tan δ	ε_r	tan δ	ε_r	tan δ	ε_r	tan δ
DiClad Series® 880	2.17	0.0014	2.31	0.0014	2.32	0.0018	2.20	0.0009
DiClad Series® 870	2.26	0.0023	2.56	0.0025	2.60	0.0027	2.33	0.0013
AD Series® 250	2.42	0.0026	2.83	0.0029	2.87	0.0040	2.50	0.0018
CLTE-AT	2.90	0.0018	3.04	0.0009	3.13	0.0041	3.00	0.0013

Test Samples (Unreinforced Dielectrics)

	Stripline		Waveguide (in-plane)					
	1.6 mm thick		1.6 mm thick		Small Stack		Single Layer	
	ε_r	tan δ	ε_r	tan δ	ε_r	tan δ	ε_r	tan δ
PFA Teflon®	2.03	0.0003	2.01	0.0004	2.02	0.0003	2.03	0.0002
FEP Teflon®	2.05	0.0007	2.03	0.0003	2.04	0.0005	2.06	0.0002
TK 75	2.30	0.0049	2.47	0.0063	2.57	0.0033	2.58	0.0029
TK 100	2.47	0.0066	2.82	0.0028	2.84	0.0040	2.87	0.0039
Pyralux® AP	3.10	0.0070	3.44	0.0030	3.48	0.0037	3.51	0.0066
H Kapton®	3.08	0.0189	3.43	0.0103	3.57	0.0116	3.49	0.0075

Table 6 – Comparison of values measured using the stripline and waveguide methods

The difference between the methods in tan δ results is not as clear as it is for ε_r. If one observes the tan δ summary plots in Figure 18, one can note that the tan δ results at 10 GHz do not follow the linear trend versus frequency than the rest of the modes. It is not known if these data points reflect upward trends in tan δ or if they are outliers. Further, there are significant differences in tan δ values when the same materials are measured at different thicknesses. This is true for both stacked materials (test samples) and homogeneous fixture materials.

Discussion of Results and Future Work

There are clear differences in ε_r values between the stripline and waveguide methods for both rigid, glass reinforced and polyimide-based flexible dielectrics. In this study, both methods utilize Teflon® to determine reference values. There are two possible explanations for the bias in ε_r values between the two methods. The first possibility is that there is anisotropy in the ε_r between the "in-plane" and the "out-of-plane" directions. The second possibility is that the reference values of ε_r for Teflon® are not equal in both the "in-plane" and "out-of-plane" directions. Further study will be required to determine which (if either) explanation is valid.

Loss tangent results at higher frequencies are inconsistent, but in general the values for flexible circuit materials are lower than expected. While the H Kapton® clearly had the highest loss, the high frequency grade polyimide based materials (TK and AP) had reasonably low loss tangent values. The influence of the copper may contribute to some of the inconsistency in loss tangent. Although this experiment utilized the same copper sheets for all testing, the interfaces between the stacked dielectrics may have contributed to the inconsistent loss tangent results.

Other possibilities for future work include:

- Finishing measurement and analysis on all test boards (AD Series® 350 fixture not tested yet due to time constraints).
- Building microstrip or coplanar waveguide transmission lines and perform impedance testing to extract ε_r values.
- Round robin testing working in collaboration with rigid board suppliers.

Acknowledgements

Jim Parisi assisted with measurements reflected in this work. Ahmed Camacho prepared the CAD design for the redesigned fixture in addition to assisting with measurements. Larry Esbanshade performed tool design and fabricated test fixtures.

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