Signal Integrity Analysis Techniques Used to Characterize PCB Substrates

Sean Mirshafiei
Isola

Dan Enos
Northrop Grumman, Springfield, MO

Abstract

The electrical properties of PCB substrates are one of the primary factors used in designing high-frequency printed circuit boards. The loss tangent is the electrical property used by material suppliers to characterize the signal integrity of the PCB substrate. OEMs will perform additional electrical tests to characterize the performance of a PCB substrate before deciding to approve it for use in a design. This paper will discuss one technique used to characterize signal integrity by an OEM. Additionally, this test will be compared to values provided by material suppliers to determine the degree of correlation.

Introduction

The loss tangent is an intrinsic material property that represents the ratio of the power loss in a dielectric to the power stored in the dielectric. In high-speed designs, the loss tangent contributes significantly to the dielectric loss that, in turn, impacts the total loss of the system. The system loss is often represented as degradation in the signal rise time, the collapse of the eye pattern, or an increase in the attenuation of the transmitted signal.

Since the loss tangent greatly impacts the performance of high-speed designs, material suppliers have developed lower dielectric loss materials by modifying the resin system. Measurement techniques used to characterize the electrical properties of these resin systems are not only helpful in developing new resins, but also in providing PCB fabricators and signal integrity engineers information to assist them in predicting impedance and addressing signal integrity concerns.

There are several techniques that material suppliers have adopted in order to characterize materials. These techniques include the X-Band Stripline Resonator Method, the Clip Method, the Two Fluid Cell Method, and the Bereskin Stripline Method.

Functional tests performed by OEMs and some PCB fabricators to characterize finished printed circuit boards may include eye pattern analysis, S-Parameter characterization, and rise-time degradation.

This paper will correlate the results obtained from the Bereskin Method with the attenuation obtained from a Multi-Port Network Analyzer, using four different material types.

Bereskin Stripline Test Method[1,2]

The Bereskin Stripline Test Method was developed by A. Bereskin and is capable of characterizing the permittivity and loss tangent of materials as a function of frequency. The apparatus used for this test is shown in Figure 1, below.

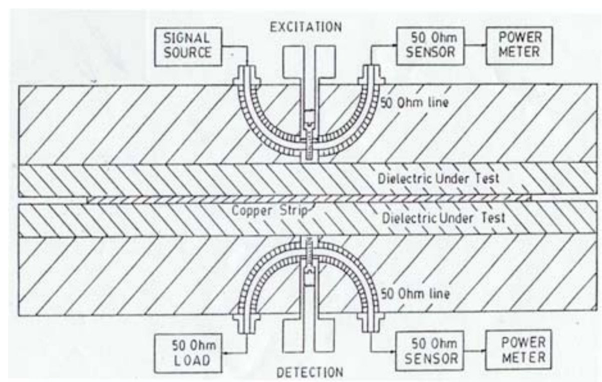

Figure 1. Bereskin diagram.[1,2]

This technique utilizes a stripline configuration, with probes contacting conductor planes. These planes sandwich the dielectric under test and copper strip. The probes, equally spaced from the center of the fixture, are used to excite and detect oscillations on the stripline.

The system is impedance matched to 50Ω so as to mitigate signal reflections, at both the excitation and detection positions.

After the sample has been placed into the fixture, the signal generator frequency is varied until the fundamental resonance is determined. The two probes (excitation and detection), are then retracted in unison until there is a 40 dB difference between their readings, at peak frequency.

Upon completion of the setup, the power meter is maintained at its present value and the frequency is varied in order to obtain the –3dB frequencies for each side of resonance. These two –3dB frequencies (F_{low} and F_{high}) are used to determine the resonant frequency and the loss of the system.

This process of determining the loss of the system is repeated for each harmonic frequency of interest. The equation used to determine the loss tangent is given by:

$$D = 1/Q - 1/(Q_{mo}\sqrt{f_o}) \qquad \text{[eq.1]}$$

where,

- D is the loss tangent of the material
- Q is the Quality Factor = 2π Energy stored/Energy lost in one cycle
- Q_{mo} is the metallic system Q at 1GHz, also referred to as the calibration of the test module
- f_0 is the resonant frequency

The Bereskin Method does not utilize the stripline to transmit a signal from the excitation to detection probes; rather it detects the oscillations in the stripline when a signal is applied to the fixture. The contribution to the total system loss, in this case, is only the dielectric loss and the conductor loss. The conductor loss is determined during the calibration of the unit and only varies as a function of strip geometry and sample thickness.

The samples used to generate the permittivity and loss tangent are resin moldings instead of laminates. The reason for this approach is that the Bereskin Method requires a minimum sample thickness that precludes measuring thin dielectrics. This method of characterizing the resin as a molding has been found to be more useful since once a resin has been characterized, a rule of mixtures may be applied to determine the composite electrical properties of laminates at any resin content.

The equipment list used to generate the Bereskin Stripline Test data is as follows:

- 1 – HP 8340A Synthesized Signal Generator
- 1 – HP8485A Power Sensor
- 1 – HP8485D Power Sensor
- 2 – HP437 Power Meters
- 1 – Pasternak SMA 50 Ohm Termination
- 1 – Test Module built by A. Bereskin
- 1 – Arbor Press Modified by A. Bereskin

The material types used in this evaluation are as follows:

- High T_G FR4 (T_G =170°C)
- High Thermal Reliability FR4 (T_G =180°C)
- Modified Epoxy Low Loss 1 (T_G =180°C)
- Modified Epoxy Low Loss 2 (T_G =205°C)

Table 1 and 2, shown below, summarize the permittivity and loss tangent for the four materials based on the retained resin content used in the finished printed circuit boards.

Table 1. Permittivity, Bereskin Method

Material Type	Dk, 2GHz	Dk, 5GHz	Dk, 10GHz
Hi-Tg FR4	3.88	3.85	3.85
Hi-Thermal FR4	3.83	3.76	3.76
Low Loss 1	3.65	3.64	3.63
Low Loss 2	3.69	3.68	3.70

Table 2. Loss Tangent, Bereskin Method

Material Type	Df, 2 GHz	Df, 5 GHz	Df, 10 GHz
Hi-Tg FR4	0.0187	0.0199	0.0199
Hi-Thermal FR4	0.0239	0.0252	0.0252
Low Loss 1	0.0117	0.0123	0.0122
Low Loss 2	0.009	0.0091	0.0091

Multi-Port Network Analyzer Method

Each material type, previously discussed, was used to fabricate a homogenous multi-layer PCB that contains multiple single-ended and differential impedance coupons. The general stackup for each board is shown in Figure 2, below.

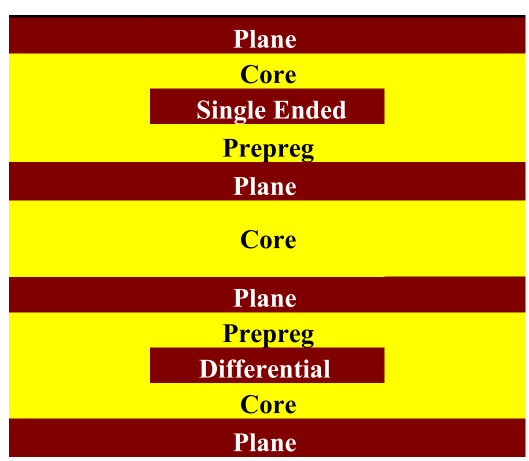

Figure 2. Device under test (DUT) Stackup

The attributes of the device under test (DUT) are as follows:

- Configuration: Stripline
- Trace length: 16”
- Trace width: 0.010” – 0.0115”
- Trace height: 0.0012”
- Board thickness: 0.110” – 0.115”
- Via Diameter: 0.012”

Each resin system has a unique range of permittivity values and those values vary as a function of the resin content. In order to avoid impedance mismatch, which may cause reflections in the transmitted signals, the line widths of each set of materials was slightly adjusted. The test conditions for this DUT was as follows:

- Frequency range: 500 MHz – 20GHz
- Frequency step: 100 MHz
- Initial calibration for connector and end cable loss

Surface mounted compression SMA connectors were used to launch and receive the signals on the DUT. Initially, thirty-two (32) PCBs were manufactured for each material type and the ten (10) PCBs closest to the target impedance were selected for further characterization.

The insertion loss (attenuation) was measured on ten DUT samples for each material type. The permittivity value for each material type was determined using a TDT, time-domain transmission instrument. A summary table, Table 3, shown below, compares the measured and predicted values for permittivity.

Table 3. Permittivity Comparison by Test Method

Material Type	ε_r, Bereskin	ε_r, TDT	Δ
HiTg FR4	3.86	4.08	-0.22
Hi-Thermal FR4	3.78	4.05	-0.27
Low Loss 1	3.64	3.86	-0.22
Low Loss 2	3.69	3.70	-0.01

With the exception for the Low Loss 2 material, the permittivity comparison appears to indicate a 0.2 offset in values between two methods.

Table 4. Loss Tangent Comparison by Test Method

Material Type	Bereskin Df (Avg)	Network A. Df (Avg)	Δ
HiTg FR4	0.0195	0.0179	0.002
Hi-Thermal FR4	0.0248	0.0234	0.001
Low Loss 1	0.0121	0.0151	-0.003
Low Loss 2	0.0091	0.0111	-0.002

Northrop Grumman determined the loss tangent of a test material by applying a normalization method to a known material’s loss tangent and interpolating the new results. The results shown in table 4 indicate that the Network Analyzer Normalization Method yielded slightly lower values than those found using the Bereskin method. The greatest difference was noted on the Low Loss 1 material with a large difference in loss tangent at all three frequency levels. The average value of attenuation for each material type was calculated and plotted, shown in Figure 3.

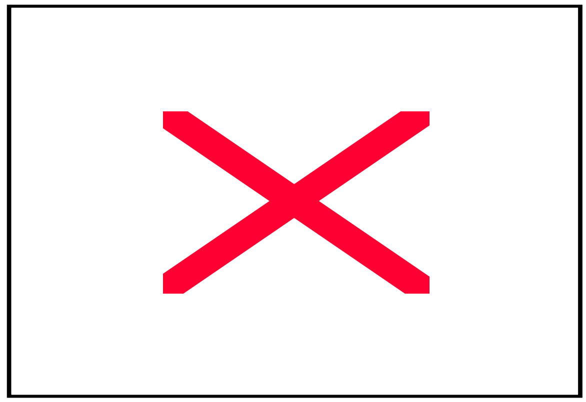

Figure 3. Insertion loss (attenuation)

Values were extracted from each curve, at specific frequency intervals, in order to correlate the results with those determined using the Bereskin Stripline Method. The values for attenuation, or α, used for the subsequent correlations are shown in Table 5.

Table 5. Attenuation Values from Network Analyzer

	α (Attenuation, dB)		
Material Type	2GHz	5GHz	10Ghz
Hi-T_G FR4	-4.19	-9.28	-16.2
Hi-Thermal FR4	-5.23	-12.1	-22.1
Low Loss 1	-3.38	-7.88	-14.2
Low Loss 2	-2.62	-5.79	-9.86

These total system loss values include all the factors that are typically ascribed to attenuation. These factors include dielectric loss, conductor loss, and via loss. At these high frequencies, it is believed that the dielectric loss accounts largely for the total system loss.

Table 6. Standard Deviation for Attenuation

Material Type	2 GHz	5GHz	10GHz
HiTg FR4	0.065	0.094	0.210
Hi-Thermal FR4	0.040	0.084	0.150
Low Loss 1	0.040	0.053	0.090
Low Loss 2	0.030	N.A.	0.210

The results from Table 6 suggest that the variation in attenuation is quite small, for each material type. Similarly, the standard deviation of ε_r and Df using the Bereskin method is minimal.

Evident from the data shown in Table 5, the material types with the lower permittivity, Dk, and lower loss tangent, Df, exhibit the least attenuation. However, this data also shows that regardless of the flatness of the material properties as a function of frequency, the attenuation continues to increase as the frequency increases. Since we know that the dielectric loss is the largest contributor to the system loss, the material properties, alone, do not dictate the dielectric loss.

Mathematical Models

In order to find an explanation for the increase in attenuation and to breakdown the individual loss components, several mathematical models were considered. One particular model, equation 2, given by Eric Bogatin, GigaTest Labs, is shown below.

$\alpha_{dielectric} = 2.3 \cdot f \cdot \tan(\delta) \cdot \sqrt{(\varepsilon_r)}$ (dB/in) [eq. 2][3]

where,

- $\alpha_{dielectric}$ is the dielectric loss
- f is the frequency (GHz)
- $\tan(\delta)$ is the material loss tangent
- ε_r is the relative permittivity

This equation defines the attenuation, or loss, due only to the dielectric. According to the reference material, this equation is a first-order approximation for a stripline configuration. This equation shows that the attenuation is directly related to both material properties and frequency.

Using this equation, we can calculate the dielectric loss based on the calculated permittivity, ε_r, and loss tangent, Df, from the Bereskin Test Method. The results from these calculations are shown in Table 7.

Table 7. Dielectric Loss, Bereskin Data

	α□□□□□□□□□□□ (dB) calc, Bereskin		
Material Type	2GHz	5GHz	10GHz
Hi-T_G FR4	-2.71	-7.18	-14.37
Hi-Thermal FR4	-3.44	-8.99	-17.98
Low Loss 1	-1.65	-4.32	-8.55
Low Loss 2	-1.27	-3.21	-6.44

By comparing the data shown in the table above to the values shown in Table 5, it is evident that a large fraction of the total attenuation is driven by the dielectric loss. In order to further refine the components for the total system loss, another mathematical model was obtained, modeling the conductor loss, which is shown in equation 3, below.

$\alpha_{conductor} = 21.6/Z_0 \cdot \sqrt{(f)}/w$ (dB/in) [eq. 3][3]

where,

- $\alpha_{conductor}$ is the conductor loss (dB/in)
- f is the frequency (GHz)
- Z_0 is the impedance (Ω)
- w is the trace width (mil)

This equation is also a first order approximation for a stripline configuration. The conductor loss results obtained for each material type is shown in Table 8.

Table 8. Conductor Loss, DUT characteristics

	$\alpha_{conductor}$ (dB) calc		
Material Type	2GHz	5GHz	10GHz
Hi-T_G FR4	-0.06	-0.09	-0.13
Hi-Thermal FR4	-0.06	-0.10	-0.14
Low Loss 1	-0.05	-0.09	-0.12
Low Loss 2	-0.06	-0.09	-0.13

The impedance values used to calculate the conductor loss for each material is based on measured impedances for each material type, rather than the targeted 50Ω value. Aside from the impedance variation, the trace width variation also contributed to the differences in the conductor loss values among the material types.

By combining the conductor loss and the dielectric loss, we will have accounted for all the individual contributors to the total system loss with the exception of via loss. Table 9, shows the combined conductor and dielectric loss values for each material type.

Table 9. Combined Dielectric and Conductor Loss

	$\alpha_{conductor+dielectric}$ (dB) calc		
Material Type	2GHz	5GHz	10GHz
Hi-T_G FR4	-3.63	-8.64	-16.43
Hi-Thermal FR4	-4.42	-10.53	-20.16
Low Loss 1	-2.51	-5.69	-10.50
Low Loss 2	-2.18	-4.65	-8.48

Figure 4, graphically illustrates the attenuation calculated from the two models using the Bereskin material properties.

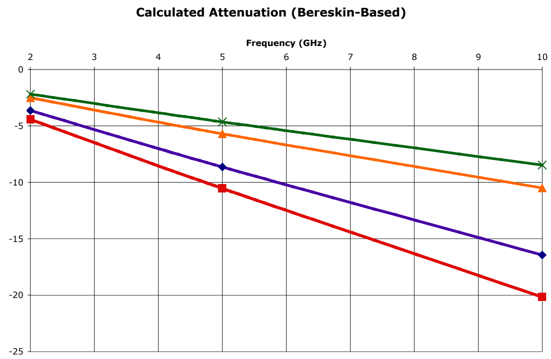

Figure 4. Attenuation (dielectric+conductor loss)

Similarly, the measured attenuation, at 2, 5 and 10 GHz, is shown in Figure 5.

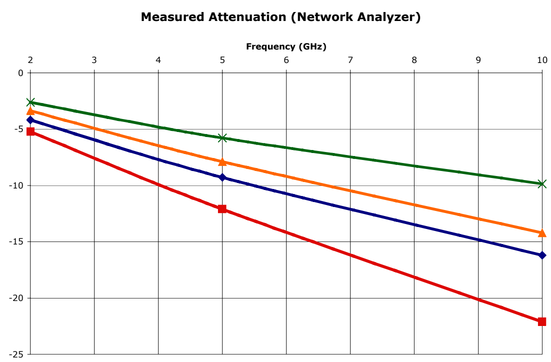

Figure 5. Attenuation (Network Analyzer@ 2, 5, 10 GHz)

Figure 6, shows the absolute value difference between the mathematical models and the measured attenuation.

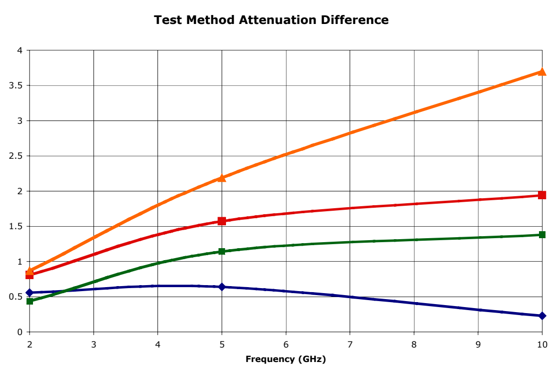

Figure 6. Test Method Attenuation difference

The test method difference ranges from less than 0.5 dB with the HiTg FR4 to as high as 3.7 dB on the Low Loss 1 material. Further investigation needs to be conducted to determine the root cause for the poor correlation with the Low Loss 1 material.

Table 10. Theoretical Via Loss

	α_{via} (dB)		
Material Type	2GHz	5GHz	10GHz
Hi-T_G FR4	-0.52	-1.17	-1.13
Hi-Thermal FR4	-0.83	-1.93	-2.29
Low Loss 1	-0.36	-1.05	-1.20
Low Loss 2	-0.08	-0.42	-0.32

The theoretical via loss calculations, shown above, were obtained by deducting the attenuation due to the dielectric and conductor (Table 9) from the total system loss (Table 5).

Table 11. Percentage of Total Loss

	% [illegible]		
Material Type	Dielectric	Conductor	Via
Hi-T_G FR4	80%	13%	7%
Hi-Thermal FR4	80%	10%	10%
Low Loss 1	78%	14%	8%
Low Loss 2	76%	21%	3%

The results shown in Table 11, at 10 GHz confirm that mathematically, the dielectric loss, regardless of material type represents nearly 80% of the total loss of the system. Although not shown, the percentage of loss ratios do not vary more than a few points at the lower frequency values.

Finite Element Analysis Model

As a third method of correlating data, Ansoft HFSS™ and Ansoft Designer™ were used to obtain FEA simulation results. The 3-D models were created using Ansoft HFSS™. These models were created using quarter-inch transmission lines. Using de-embedding tools, a model was generated that represented a 16-inch transmission line with vias on both ends, which matched the actual manufactured PCBs. This data was fed into Ansoft Designer™ to generate a full model. The S_{21} parameters that are shown in each of the following three figures illustrate the predicted results from a 16-inch transmission line. The Hi-Tg FR4 is modeled in Figure 7, the Hi-Thermal FR4 in Figure 8, the Low Loss 1 in Figure 9, and the Low Loss 2 in Figure 10. These models include proper vias and launching structures on each end.

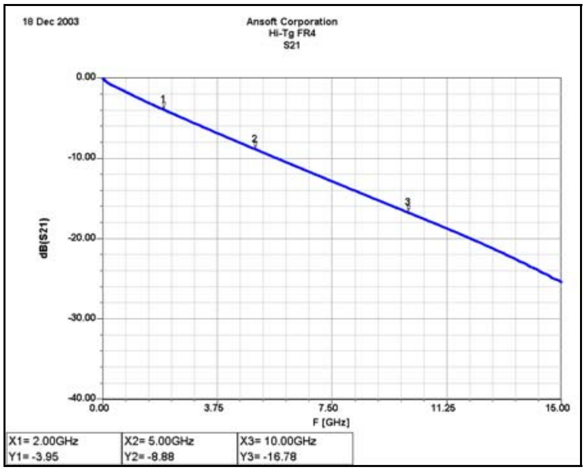

Figure 7. FEA transmission line 16" Hi-Tg FR4

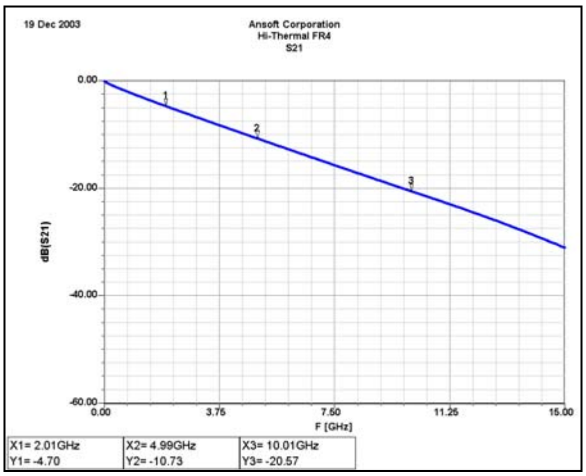

Figure 8. FEA transmission line 16" Hi-ThermalFR4

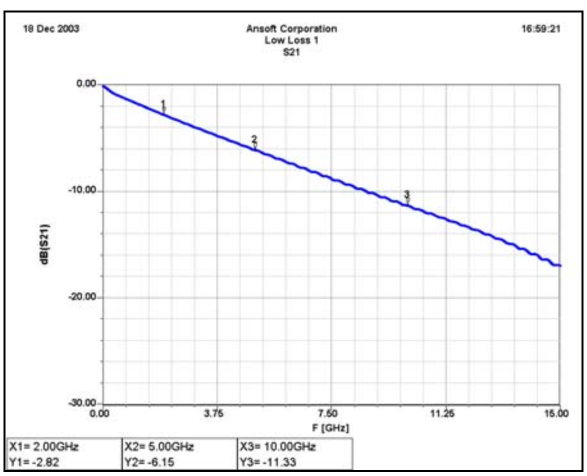

Figure 9. FEA transmission line 16" Low loss 1

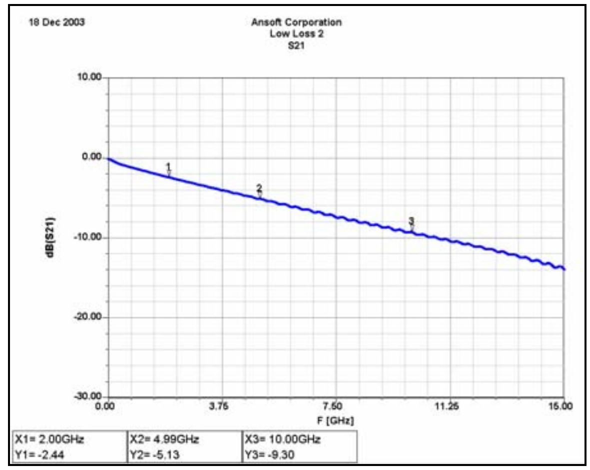

Figure 10. FEA transmission line 16" Low loss 2

As shown in the Table 12, the modeled attenuation for the four material types nearly matches the actual measured attenuation from the test boards. The FEA model uses the Bereskin-derived permittivity and loss tangent, along with the DUT transmission line characteristics.

Table 12. Measured and FEA modeled attenuation

	Actual α, dB			FEA α, dB		
Material Type	2GHz	5 GHz	10 GHz	2 GHz	5 GHz	10 GHz
Hi-Tg FR4	-4.19	-9.28	-16.2	-3.95	-8.88	-16.78
Hi-Thermal FR4	-5.23	-12.1	-22.1	-4.70	-10.73	-20.57
Low Loss 1	-3.38	-7.88	-14.2	-2.82	-6.15	-11.33
Low Loss 2	-2.62	-5.79	-9.86	-2.44	-5.13	-9.3

Conclusions

This paper has explored several methods used to characterize PCB substrate electrical performance.

These methods have been compared to one another to determine the degree of correlation between the results. This correlation work has involved using mathematical approximations and finite element analysis models. Through this exercise, we have shown that the mathematical models and finite element analysis tools not only correlate, but also closely match the actual board measurements. Although this may be true, few signal integrity engineers will abandon building test boards as there is no single criterion, such as a specific loss tangent threshold that will predicate whether a material is suitable for a given application. The value in exploring these techniques is that these approximations may be an initial screening method towards gauging the impact a material's electrical properties will have on the loss of the system.

We would recommend that the results from the testing conducted on the Low Loss 1 material be re-evaluated due to the lack of correlation found in the measurements.

Acknowledgments

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References

1. Bereskin, A. B. "*Microwave Dielectric Property Measurements.*" *Microwave Journal*, vol. 35, no.7, pp. 98 – 112.

2. Bereskin, A.B. "*Microwave Dielectric Property Measurements II*" (handout)

3. Bogatin, Eric. "*Lossy Transmission Lines: Plain and Simple*". Presented at PCB West, March 2002, www.GigaTest.com.

4. Bogatin, Eric. "*How do you spell S parameters?*" *Printed Circuit Design Magazine*, February 2003, www.GigaTest.com.

5. Araktingi, et al., "*New Developments in High Frequency Dielectric Measurements of PWB Materials Part II: Applications of the Bereskin Method to PWB Materials*." Presented at IPC Expo 1999, www.isola-usa.com