Transmission Line Characterization through the Enhanced Root Impulse Energy Loss

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Abstract

In today's PCB industry, the challenges are no longer just on how to control and improve the manufacturing processes, but also to ensure the fabricated product is compliant to the industry standards and leads to high quality. Due to the requests for more detailed information about the products, numerous techniques for PCB characterization were developed. In this paper, we proposed the Enhanced Root Impulse Energy (e–RIE) loss method. The original RIE was presented in the papers and presentations of IPC meetings. Different from previous work, instead of directly differentiating the time–domain TDR waveform and using it as the impulse response $h(t)$, the e–RIE method implements the time–domain Thru–Reflect–Line (t–TRL) calibration technique on the time–domain TDR/TDT measurements. The t–TRL is a complete calibration technique and it removes the discontinuities due to the transition from SMA connectors to the stripline launches and improves the accuracy of impulse response measurement and the RIE loss calculation. Excellent agreement is achieved for the RIE losses obtained from the t–TRL and the VNA measurements. Also in the paper, the relationship of the RIE loss and loss tangent is studied. Based on the theoretical derivation, the RIE loss is calculated as a function of $\tan\delta$ for a given pair of test and calibration lines. The sensitivity of RIE loss vs. different test and calibration pairs is studied. Overall, the longest test line (>10 inches) and the shortest calibration line (<1 inch) give the best RIE loss sensitivity. The e–RIE extended the applications of the original RIE method and it provides a simple and practical test method for the transmission line loss characterization in high–volume PCB manufacturing.

I. Introduction

As the demand for higher bandwidth increases it is pushing the modern telecom and datacom systems to increase their speed and data rate continuously to multi Gb/s per link. The channel density and the complexity of the systems are also increasing. Thus the need in characterizing these high-speed channels beyond the 10 GHz range is urgent. In the past few years, numerous techniques were developed for characterization of transmission lines. For example, VNA is widely used for measuring the S–parameters of the on–board structures and the complex permittivity can be extracted from the TRL de–embedded data [1]. However, using the VNA technique in manufacturing environment is difficult due to the associated cost and knowledge required for the operators. Furthermore, it is complicated and cumbersome to specify the transmission line loss by using the large set of frequency–dependent S parameters, especially in high–volume PCB manufacturing. It becomes obvious that the need in the simple, cost-effective methods developed within IPC characterization techniques.

In this paper, we present the Enhanced Root Impulse Energy (e–RIE) loss method derived from the time–domain TDR/TDT measurements for characterizing the transmission lines on PCBs. Different from the previous works [2–4], we applied the time–domain Thru–Reflect–Line (t–TRL) calibration technique on the time–domain measurements and the obtained RIE losses are comparable to the results obtained by using VNA. The RIE loss is especially useful in high–volume PCB manufacturing. By identifying the transmission line RIE loss, the products can be quickly checked to see if they yield the customers' expected loss performance.

II. The Theoretical Formulation of Root Impulse Energy Loss

The Root Impulse Energy (RIE) loss was originally presented in the papers and presentations of IPC [2–4]. When a signal propagates along the transmission line on PCB, not all its energy is delivered due to the limited conductivity, shunt capacitance and mismatches etc. The transmission line energy loss can be characterized by the RIE loss and it is defined as the ratio of the square roots of the impulse energy of the test line and the impulse energy of the calibration line [2]:

$$RIE_{loss} = \frac{\sqrt{IE_{test}}}{\sqrt{IE_{cal}}} \qquad (1)$$

This definition shows that the RIE loss is not measured directly, but a calculated single–valued entity from the impulse response measurement. The impulse response measurement can be performed in time–domain or frequency–domain.

In time–domain, the impulse responses of the test line and calibration line are $h_{test}(t)$ and $h_{cal}(t)$ respectively and the RIE loss in dB is:

$$RIE_{loss\_dB} = -10\log_{10}\left(\frac{\sqrt{\int_{t_0}^{t_1}(h_{test})^2 dt}}{\sqrt{\int_{t_0}^{t_1}(h_{cal})^2 dt}}\right) \quad (2)$$

In frequency–domain, the assumption is that the impedances are matched and there are no reflections at the both ports ($S_{11} = S_{22} = 0$). The RIE loss can be calculated from the transfer responses of the test line and calibration line, $S_{21\_test}(f)$ and $S_{21\_cal}(f)$:

$$RIE_{loss\_dB} = -10\log_{10}\left(\frac{\sqrt{\int_{f_0}^{f_1}\left|S_{21\_test}\right|^2 df}}{\sqrt{\int_{f_0}^{f_1}\left|S_{21\_cal}\right|^2 df}}\right) \quad (3)$$

The S_{21} parameter of a section of the transmission line of the length l can be written as [5]:

$$S_{21} = e^{-\gamma\cdot l} = e^{-\alpha\cdot l}e^{-j\beta\cdot l} \quad (4)$$

where $\gamma = \alpha + j\beta$ is the complex propagation constant, α is the loss parameter and β is the phase constant. The magnitude of S_{21} is:

$$\left|S_{21}\right| = e^{-\alpha\cdot l} \quad (5)$$

And α can be decomposed into conductor loss α_c and dielectric loss α_d :

$$\alpha = \alpha_c + \alpha_d \quad (6)$$

For the TEM mode propagation, the dielectric loss is calculated as:

$$\alpha_d = \xi \cdot f \tan\delta \quad (7)$$

where

$$\xi = \frac{\pi\sqrt{\varepsilon_r^{'}}}{c} \quad (8)$$

The stripline cross–section parameters are defined in Figure 1 and the characteristic impedance of the line is Z_c .

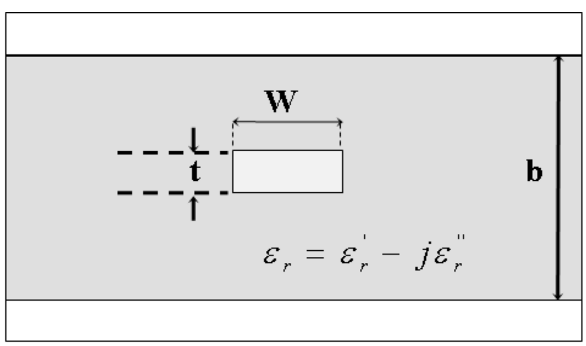

Figure 1 - Stripline cross–section geometry

The conductor loss α_c can be estimated as [5]:

$$\alpha_c = \zeta \cdot \sqrt{f} \quad (9)$$

where

$$\zeta = \frac{2.7\times10^{-3}\cdot\varepsilon_r^{'}\cdot Z_c}{30\pi(b-t)}\cdot A\cdot\sqrt{\frac{\pi\mu}{\sigma}} \quad (10)$$

with

$$A = 1 + \frac{2W}{b-t} + \frac{b+t}{\pi(b-t)} \cdot \ln\left(\frac{2b-t}{t}\right) \tag{11}$$

Plug (5–11) into (3) and the integral in (3) can be represented as:

$$\int_{f_0}^{f_1} |S_{21}|^2 df = \mathrm{X}(f_1, l) - \mathrm{X}(f_0, l) \tag{12}$$

where the $\mathrm{X}(f,l)$ as in [6] is:

$$\mathrm{X}(f,l) = -\left[\frac{\zeta \cdot e^{\frac{\zeta^2 \cdot l}{2\cdot\xi\cdot\tan\delta}} \cdot \sqrt{\frac{\pi}{2}} \cdot erf\left(\frac{\sqrt{l}\cdot\left(2\cdot\xi\cdot\tan\delta\cdot\sqrt{f}+\zeta\right)}{\sqrt{2\cdot\xi\cdot\tan\delta}}\right)}{2\cdot(\xi\cdot\tan\delta)^{\frac{3}{2}}\cdot\sqrt{l}}\right] - \left[\frac{e^{\left(-2\cdot f\cdot l\cdot\xi\cdot\tan\delta - 2\cdot l\cdot\zeta\cdot\sqrt{f}\right)}}{2\cdot l\cdot\xi\cdot\tan\delta}\right] \tag{13}$$

This is a simplified case where the dielectric parameters $\varepsilon_r^{'}$ and $\tan\delta$ are frequency–independent. The definition of the error function is:

$$erf(z) = \frac{2}{\sqrt{\pi}} \sum_{n=0}^{\infty} \left(\frac{(-1)^n z^{2n+1}}{n!(2n+1)!}\right) \tag{14}$$

Then the final formula for the RIE loss value is:

$$RIE_{loss\_dB} = -5\log_{10}\left(\frac{\mathrm{X}(f_1, l_{test}) - \mathrm{X}(f_0, l_{test})}{\mathrm{X}(f_1, l_{cal}) - \mathrm{X}(f_0, l_{cal})}\right) \tag{15}$$

III. The Sensitivity of RIE Loss with Test and Calibration Lines

Based on the above derivation, in this section the RIE loss of a stripline design is calculated. Table 1 is the parameters of the design.

Table 1 - The characteristics of the design

Test Line (mm)		Calibration Line (mm)		W (mm)	t (mm)	b (mm)	$\varepsilon_r^{'}$
Test 1	254	Cal 1	22.15	0.36	0.01	0.65	4.0
Test 2	127	Cal 2	55.26				

The integration interval in (12) is from 50 MHz to 25 GHz and the $\tan\delta$ value in equation (13) is varied from 0.015 to 0.025 which represents in reality the range of loss tangent of the base materials. Substituting the parameters into equation (15), the RIE loss is calculated for each given $\tan\delta$ value.

In Figure 2, the RIE loss is plotted vs. $\tan\delta$ and the four traces are corresponding to each test and calibration lines combination.

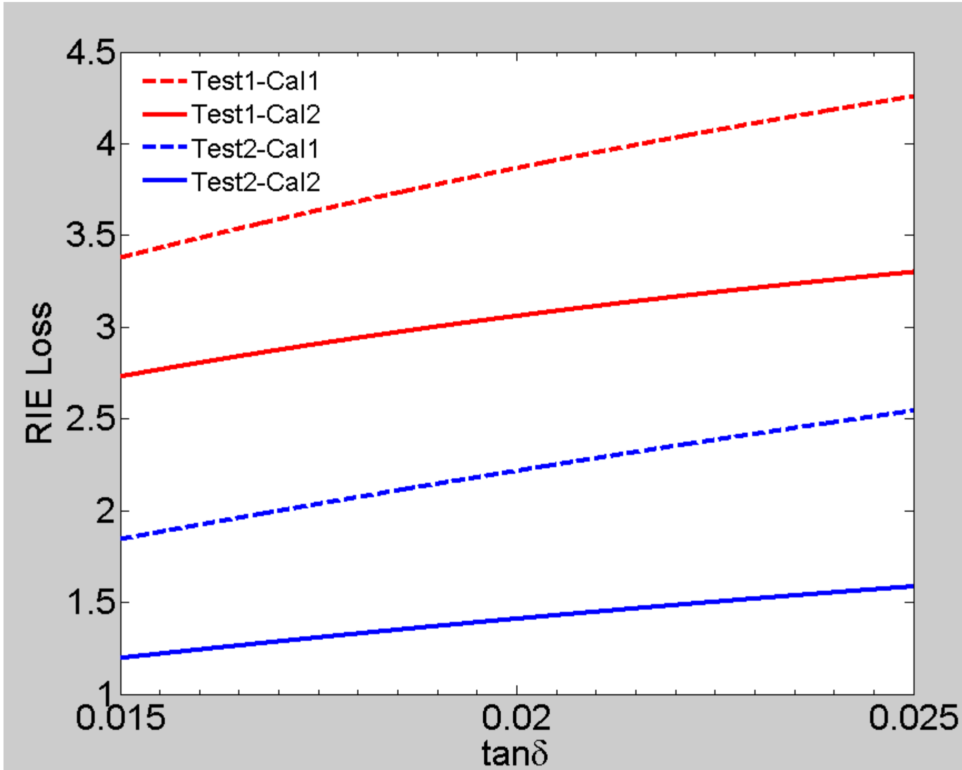

Figure 2 - RIE loss vs. $\tan\delta$

From the above figure the RIE loss sensitivity can be defined as: the steeper the curve is, the faster the RIE loss varies with the loss tangent and the more sensitive the RIE loss is. In Figure 2 the steepest trace (Test1-Cal1) which represents the best RIE loss sensitivity was calculated using the longest test line (10 inch) and the shortest calibration line (0.87 inch). The RIE loss sensitivity is very helpful when differentiating test boards manufactured with different base materials and in Section V we will show the application of the RIE loss sensitivity.

IV. The Time–Domain Impulse Response Measurement for the RIE Loss Calculation

Besides the theoretical calculation shown in Section III, the RIE loss can also be obtained from the time–domain impulse response measurement. The most commonly used measurement method is to apply a step pulse and take the derivative of the output. The differentiated output is the impulse response $h(t)$ and the RIE loss is calculated as a ratio of the roots of the areas under the differentiated TDR or TDT waveforms [2–4]. Figure 3 is an example of the TDR waveforms of the test and calibration lines. Figure 4 is the differentiated TDR waveforms. The circles in Figure 3 are the capacitance dips due to the transition from SMA connectors to the stripline launches. The discontinuities in Figure 3 are mapped one–to–one to those in Figure 4. When integrating over the curves in Figure 4, the discontinuities will add the extra area and introduce error in the RIE loss calculation.

Thus, a calibration technique is required to remove the effect of discontinuities. However, today's available TDR oscilloscopes in the market only support the vertical module normalization which can calibrate the gains and offsets of the data acquisition channels. Also, some instruments offer an option to do a "Load–Short–Thru" calibration for TDR/TDT measurements to compensate for the delay and the losses associated with the cables and the reflections to improve the pulse edge and its flatness [8]. The TDR instrument "Load–Short–Thru" calibration is similar to the Short–Open–Load–Thru (SOLT) calibration used in the VNA and it is not the complete calibration technique since the imperfections can not be removed by calibration. In our previous paper [7] the complete time–domain calibration technique, t–TRL, was developed for the time–domain TDR/TDT measurements. The excellent agreement is achieved up to 25 GHz and the discontinuities are de-embedded.

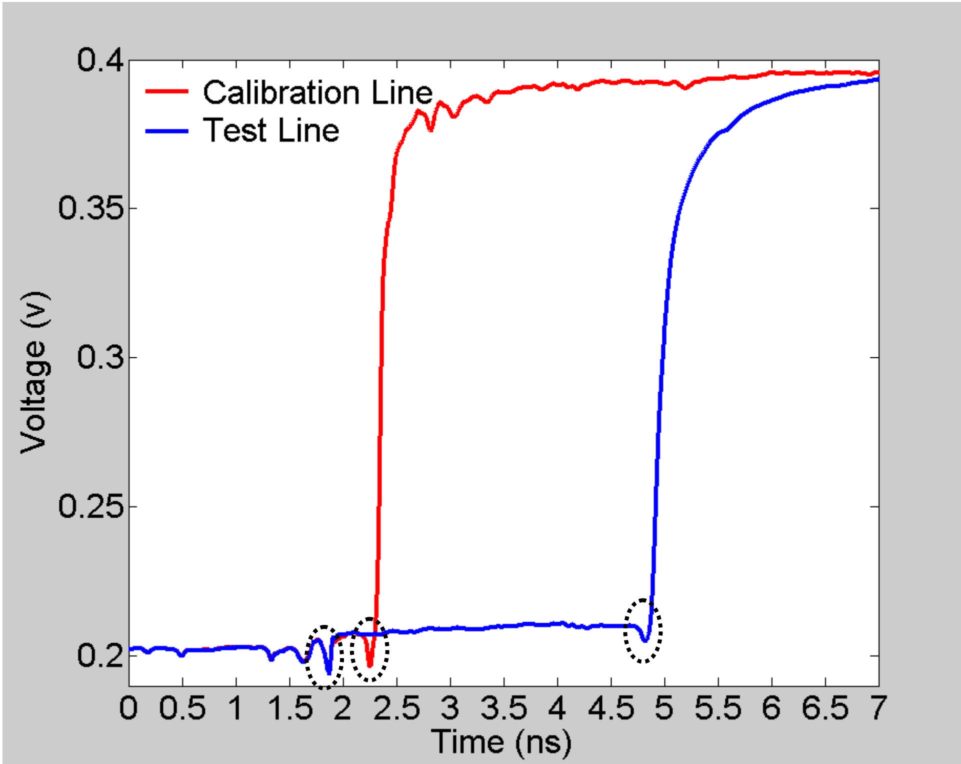

Figure 3 - The TDR waveforms of the transmission lines with the connectors

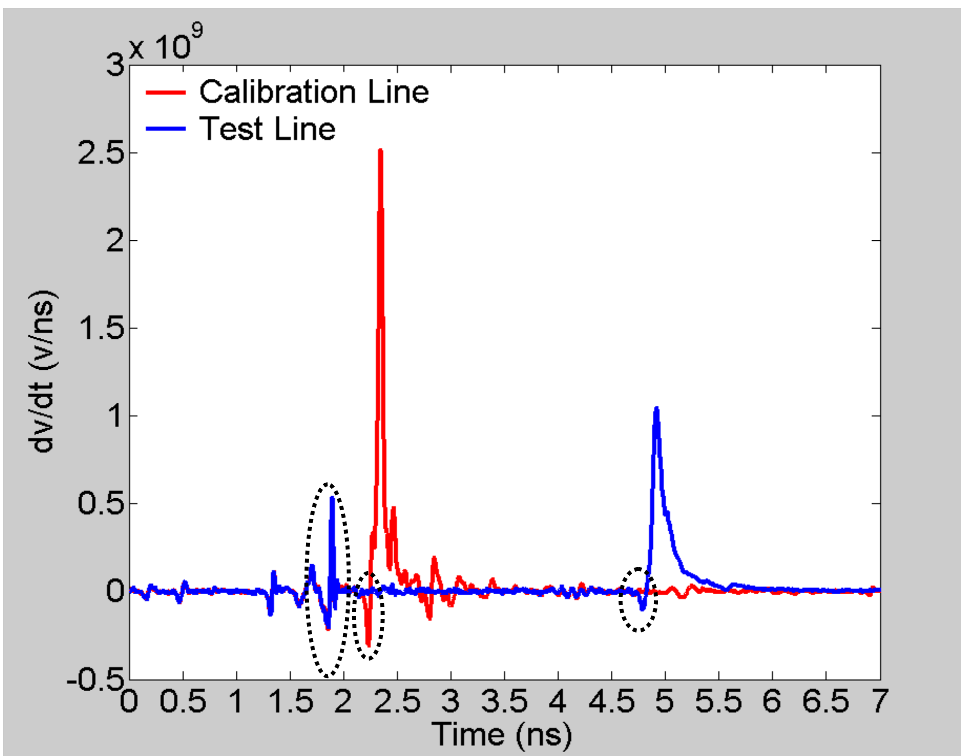

Figure 4 - The differentiated TDR waveforms

The rise–time of the TDR instrument used in this paper is 11 ps. Following the measurement set–up and procedure detailed in [7] the t–TRL calibration technique was applied to the recorded TDR/TDT data. The actual frequency response S_{21} of the transmission lines can be obtained. The RIE loss calculation is then straightforward by simply plugging the calibrated S_{21} responses of test and calibration lines into equation (3).

V. The RIE Loss Results

Two test vehicles (TV1 and TV2) were manufactured with the same design parameters as shown in Table 1. However, the resin contents of the base material of the two boards are slightly different. Both test boards have the TRL calibration pattern on it and the design guidelines for the TRL pattern are detailed in [7].

Figure 5 is the RIE loss of TV1 and TV2 calculated using the method in [2–4] by differentiating the TDT waveforms. The four groups of data in Figure 5 correspond to the four test–calibration pairs and the two columns in each group are the RIE losses of TV1 and TV2 respectively.

Although the resin contents of the two test vehicles are not the same, it is not able to tell the differences from their RIE losses calculated using the calibration line, Cal 2 (2.18 inch). Even for the shorter calibration line, Cal 1 (0.87 inch), the RIE loss differences between the two test vehicles are not very obvious which could be caused by the error introduced from the measurement.

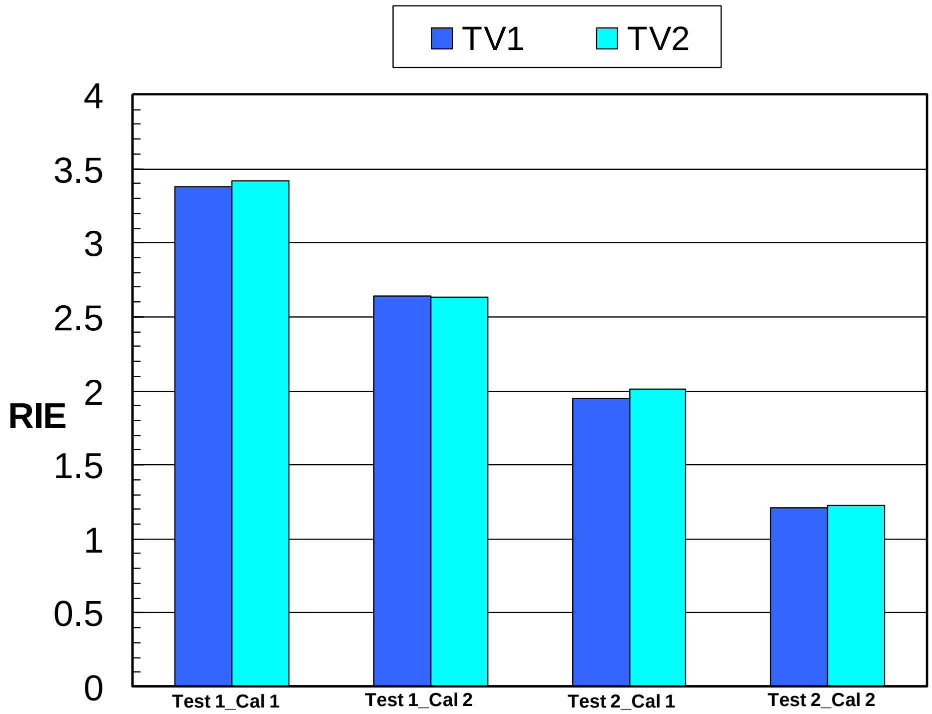

Figure 5 - The RIE loss calculated from differentiate the TDT waveform

Figure 6 is the RIE losses calculated from the calibrated frequency responses S_{21} obtained by applying the t–TRL calibration to the time–domain TDR/TDT measurements. The t–TRL calibration removes the discontinuities in Figure 3 and improves the accuracy of the RIE loss calculation. We can tell the differences between TV1 and TV2 from all the groups of data and the TV2 shows higher RIE loss than TV1, which means the base material of TV2 has relatively low resin content and higher loss. Also, as discussed in Section III, the longest test line (>10 inches) and the shortest calibration line (<1 inch) give the best RIE loss sensitivity which increases the distinctions between the test vehicles.

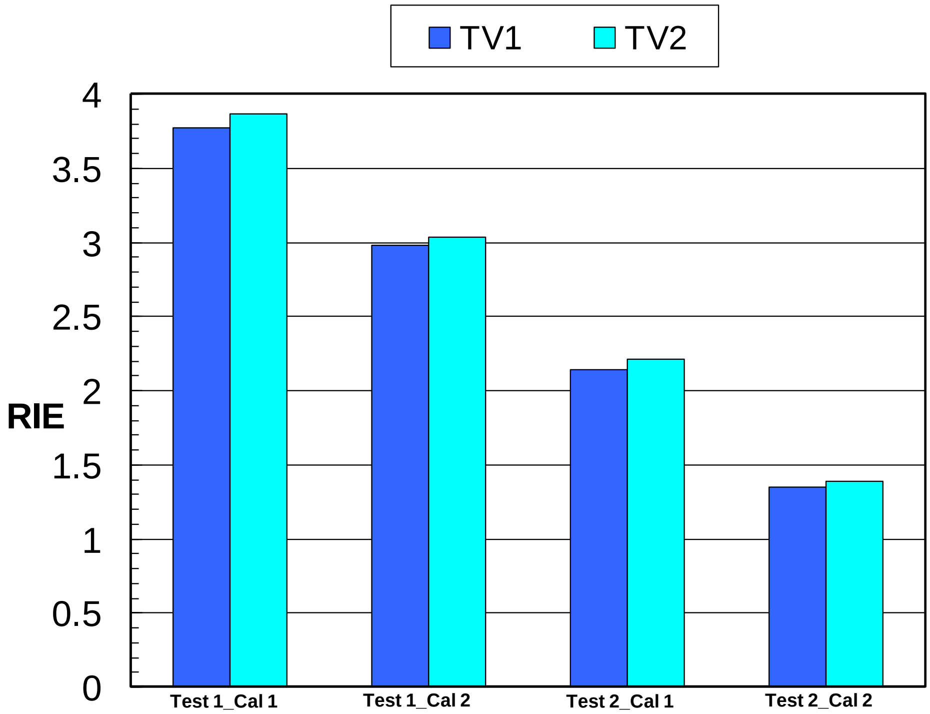

Figure 6 - The RIE loss calculated from t-TRL calibration

In order to validate the RIE losses calculated from the t–TRL calibration, we also performed the VNA TRL calibration on the same test vehicles. The RIE losses obtained from the two methods are compared in Table 2 and they agreed very well.

Table 2 - The RIE loss of TDR vs. the RIE loss of VNA

	Test Line/Cal Line	RIE Loss from TDR	RIE Loss from VNA
TV1	Test 1_Cal 1	3.773	3.773
	Test 1_Cal 2	2.980	2.981
	Test 2_ Cal 1	2.143	2.137
	Test 2_Cal 2	1.350	1.345
TV2	Test 1_Cal 1	3.867	3.820
	Test 1_Cal 2	3.039	3.007
	Test 2_ Cal 1	2.213	2.179
	Test 2_Cal 2	1.385	1.367

VI. Conclusion and Discussion

In this paper, at beginning we showed how to theoretically derive the RIE loss for the impedance matched system. In Section III the RIE loss is calculated for a stripline design and for the first time the concept of RIE loss sensitivity is proposed and defined as the sensitivity of the RIE loss changing with $\tan\delta$ for a given pair of test and calibration lines. Overall, the longest test line (>10 inches) and the shortest calibration line (<1 inch) give the best RIE loss sensitivity. In Section IV it explained how to improve the time–domain impulse response measurement using the t–TRL calibration technique. And at the end we showed the excellent agreement for the RIE losses obtained from the t–TRL calibration and the VNA measurement. Also, in this section we explained the application the RIE loss sensitivity on differentiating the test boards manufactured with different base material. The idea of e–RIE provided a simple and practical test method for the transmission line loss characterization and test board screening in high–volume PCB manufacturing.

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Introduction

•The bandwidth and channel density of telecom and datacom systems keep increasing. The need for characterizing the high-speed channel beyond 10 GHz range is urgent.

•The RIE loss was originally presented in the papers and presentations of IPC meeting. In this paper, we proposed the enhanced RIE loss.

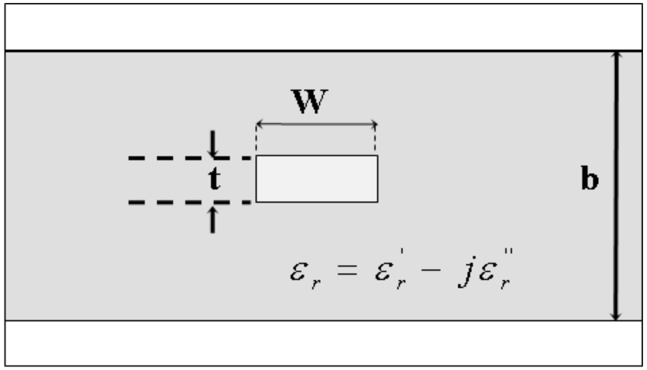
•Different from previous work, the impulse response is obtained from t-TRL calibration for the TDR and TDT measurements.

•And for the first time the concept of RIE loss sensitivity is brought up and it can be used for test board screening in high-volume PCB manufacturing.

The Theoretical Formulation of Root Impulse Energy Loss

$$RIE_{loss\_dB} = -10\log_{10}\left(\frac{\sqrt{\int_{t_0}^{t_1}(h_{test})^2 dt}}{\sqrt{\int_{t_0}^{t_1}(h_{cal})^2 dt}}\right)$$

$$RIE_{loss\_dB} = -10\log_{10}\left(\frac{\sqrt{\int_{f_0}^{f_1}\left|S_{21\_test}\right|^2 df}}{\sqrt{\int_{f_0}^{f_1}\left|S_{21\_cal}\right|^2 df}}\right)$$



$$S_{21} = e^{-\gamma\cdot l} = e^{-\alpha\cdot l}e^{-j\beta\cdot l}$$

$$\alpha = \alpha_c + \alpha_d$$

The RIE Loss Calculated for a Stripline Design

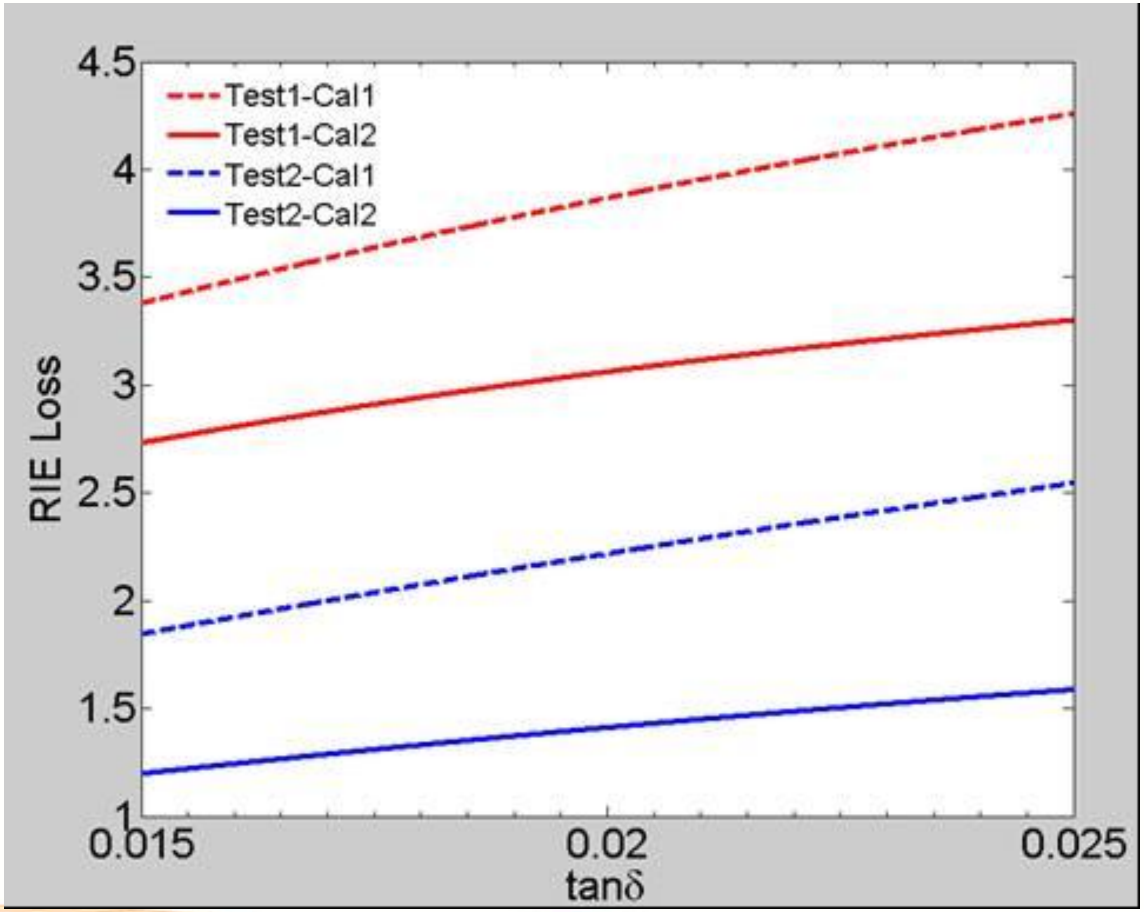
$$RIE_{loss\_dB} = -5\log_{10}\left(\frac{\mathrm{X}\left(f_1, l_{test}\right) - \mathrm{X}\left(f_0, l_{test}\right)}{\mathrm{X}\left(f_1, l_{cal}\right) - \mathrm{X}\left(f_0, l_{cal}\right)}\right)$$

$$\mathrm{X}(f,l) = -\left[\frac{\zeta \cdot e^{\frac{\zeta^2 \cdot l}{2\cdot\xi\cdot\tan\delta}} \cdot \sqrt{\frac{\pi}{2}} \cdot erf\left(\frac{\sqrt{l}\cdot\left(2\cdot\xi\cdot\tan\delta\cdot\sqrt{f}+\zeta\right)}{\sqrt{2\cdot\xi\cdot\tan\delta}}\right)}{2\cdot\left(\xi\cdot\tan\delta\right)^{\frac{3}{2}}\cdot\sqrt{l}}\right] - \left[\frac{e^{\left(-2\cdot f\cdot l\cdot\xi\cdot\tan\delta - 2\cdot l\cdot\zeta\cdot\sqrt{f}\right)}}{2\cdot l\cdot\xi\cdot\tan\delta}\right]$$

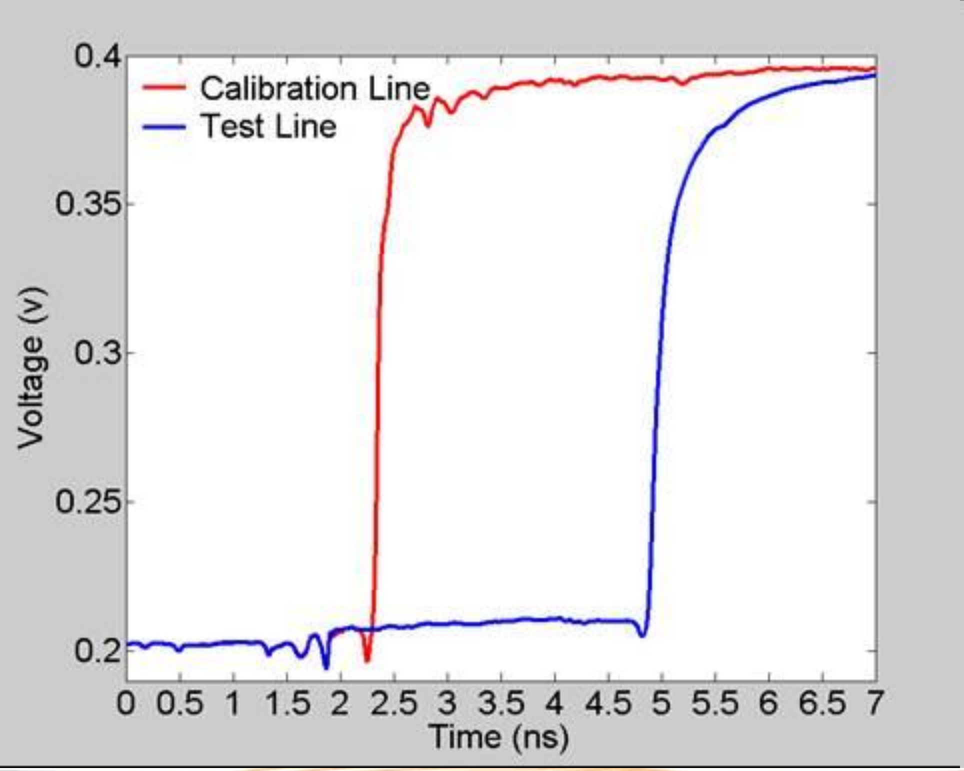
$$erf(z) = \frac{2}{\sqrt{\pi}}\sum_{n=0}^{\infty}\left(\frac{(-1)^n z^{2n+1}}{n!(2n+1)!}\right)$$

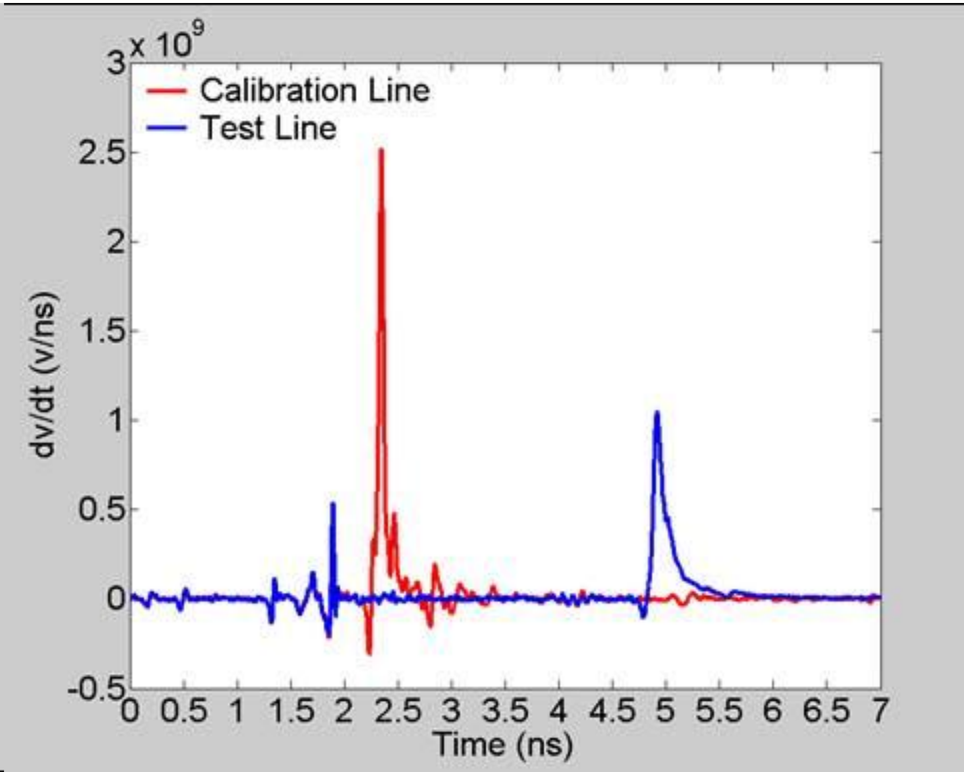
Test Line (mm)		Calibration Line (mm)		W (mm)	t (mm)	b (mm)	ε_r'
Test 1	**254**	**Cal 1**	**22.15**	**0.36**	**0.01**	**0.65**	**4.0**
Test 2	**127**	**Cal 2**	**55.26**				

The RIE Loss Calculated for a Stripline Design

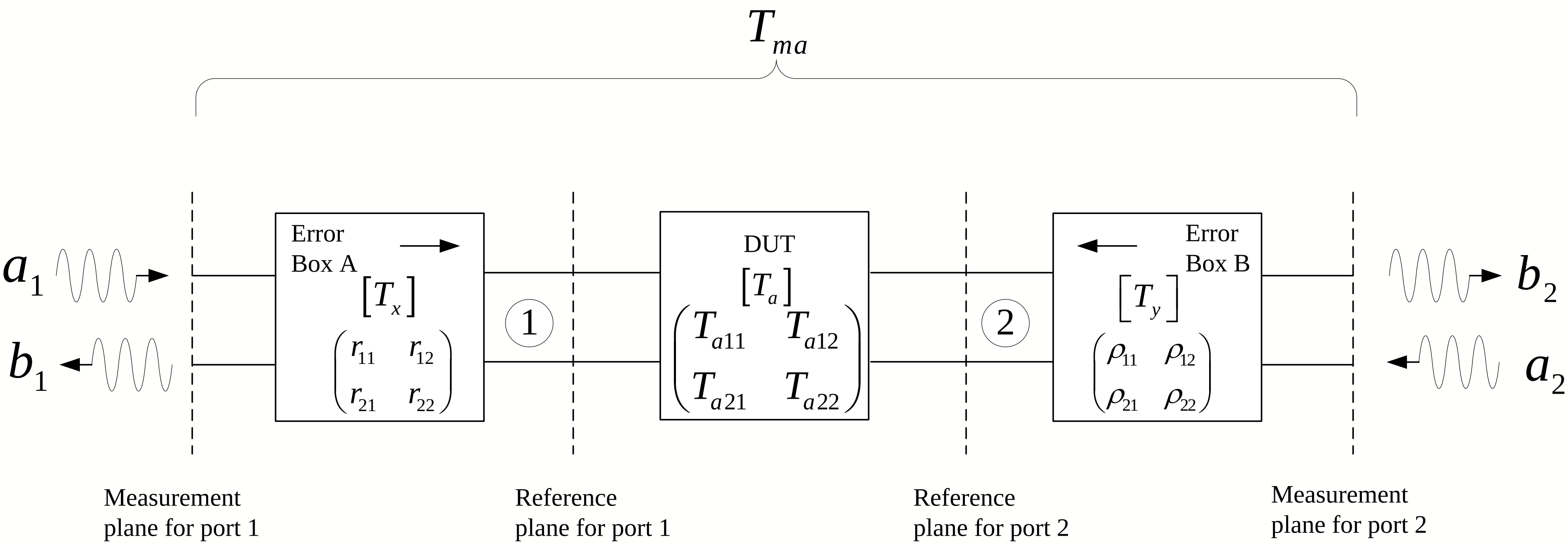


The Time-Domain Impulse Response Measurement for the RIE Loss Calculation

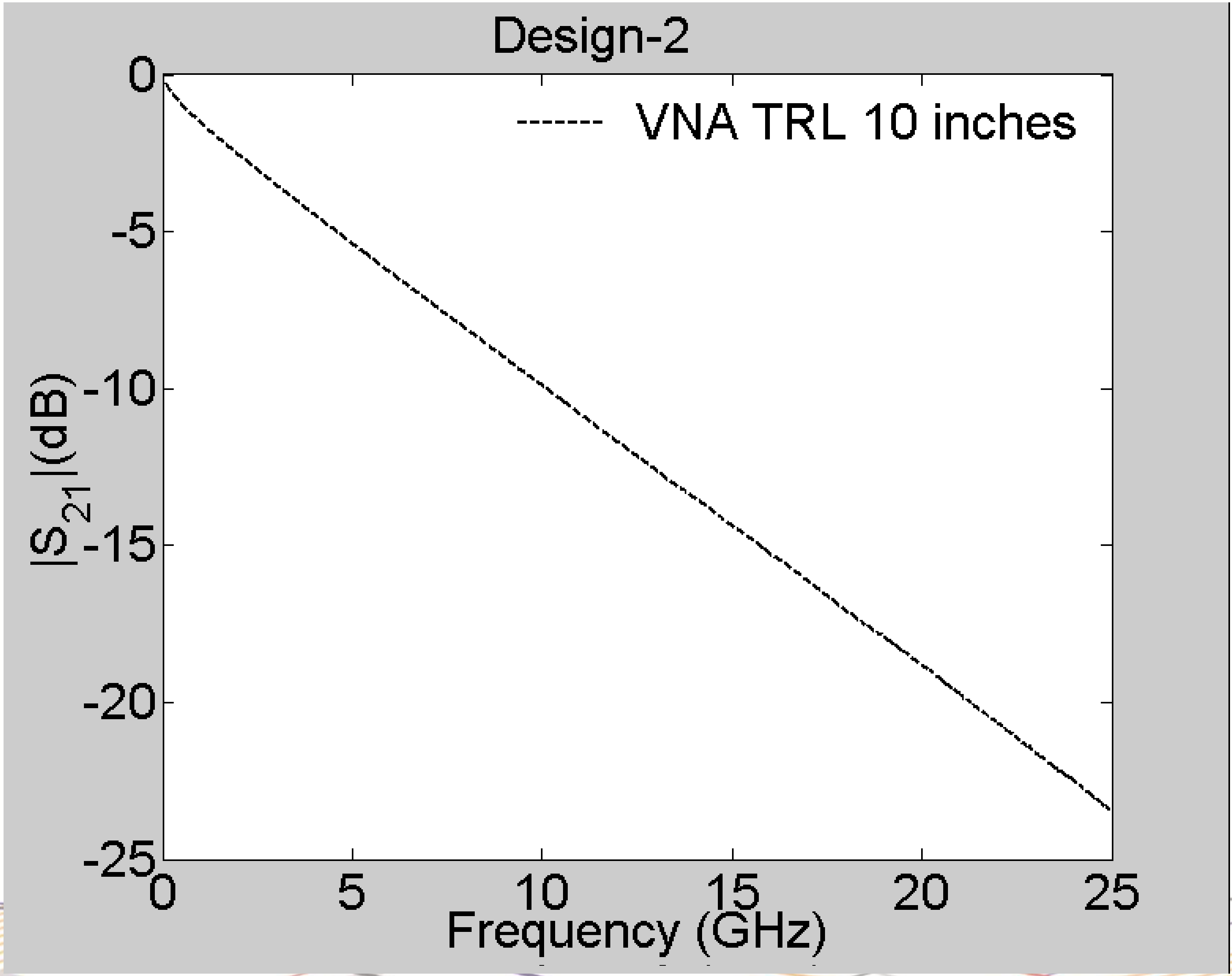




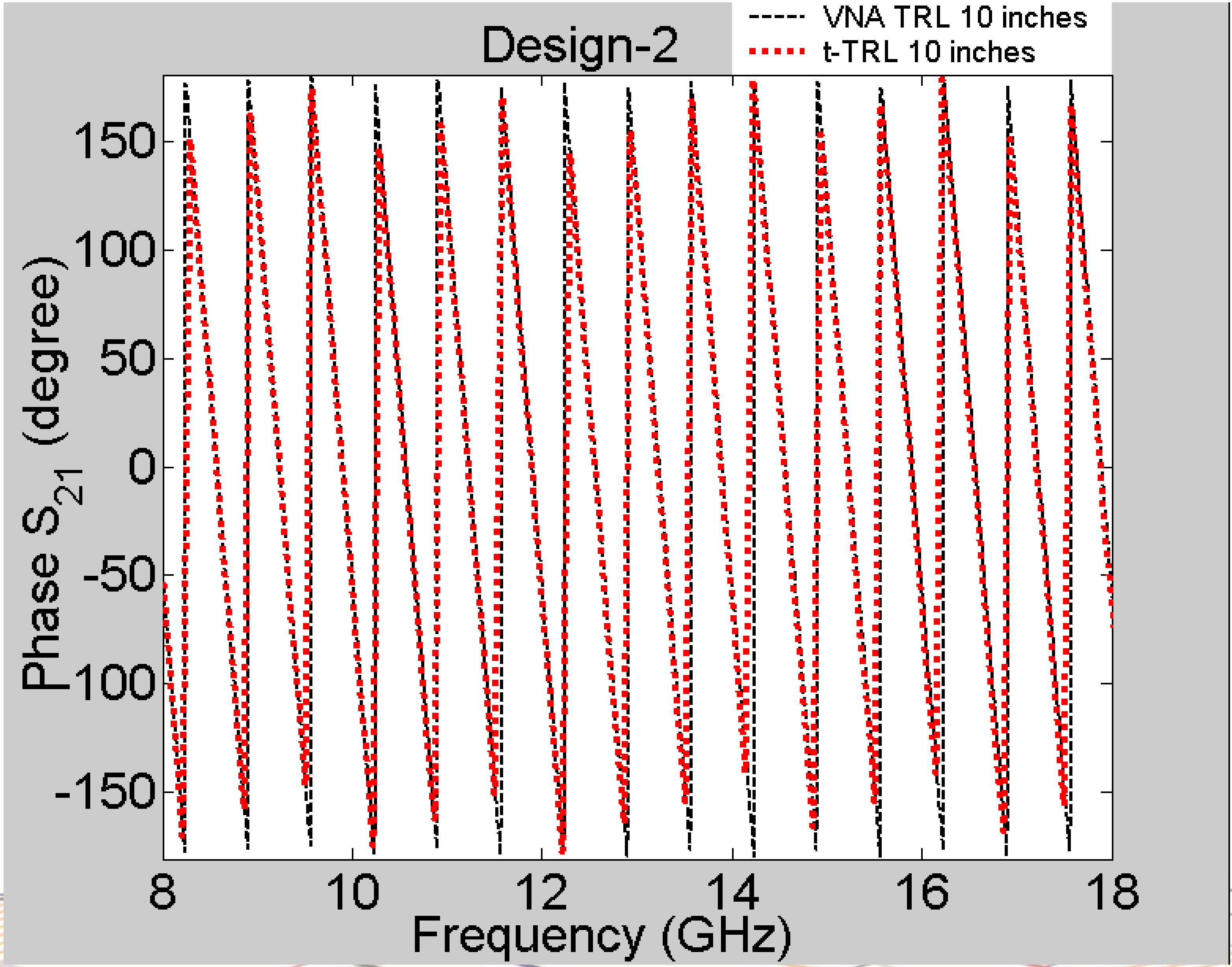
t-TRL Calculation



$$[T_{ma}] = [T_x][T_a][T_y]$$



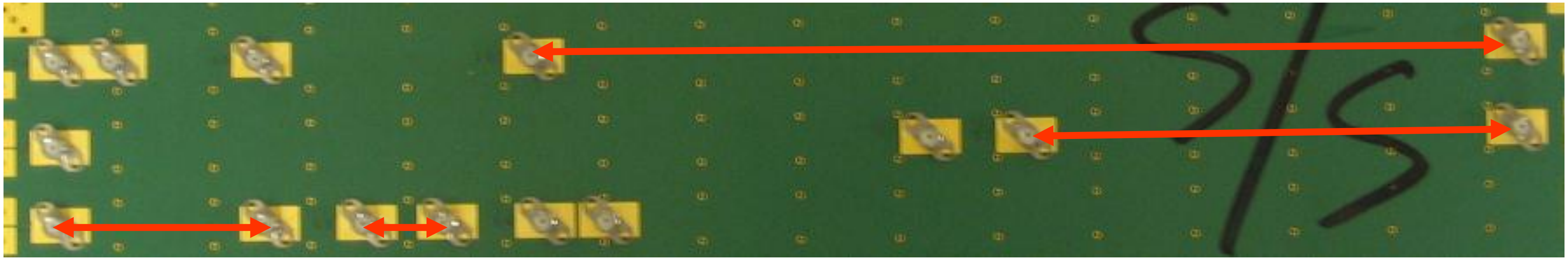
Design-2
VNA TRL 10 inches
0
-5
-10
-15
-20
-25
|S21|(dB)
0
5
10
15
20
25
Frequency (GHz)



Design-2
VNA TRL 10 inches
t-TRL 10 inches
Phase S_{21} (degree)
150
100
50
0
-50
-100
-150
8
10
12
14
16
18
Frequency (GHz)

Test Vehicle

Test 1: 10 inch

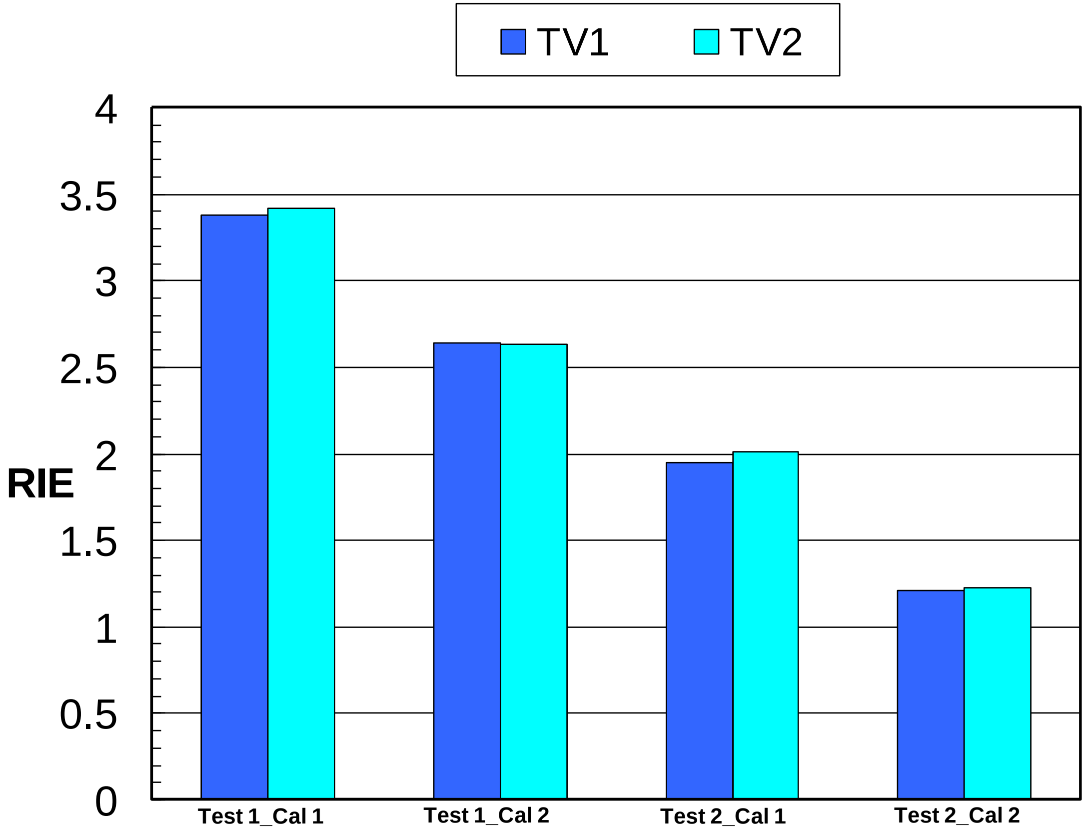


Cal-2: 2.18inch

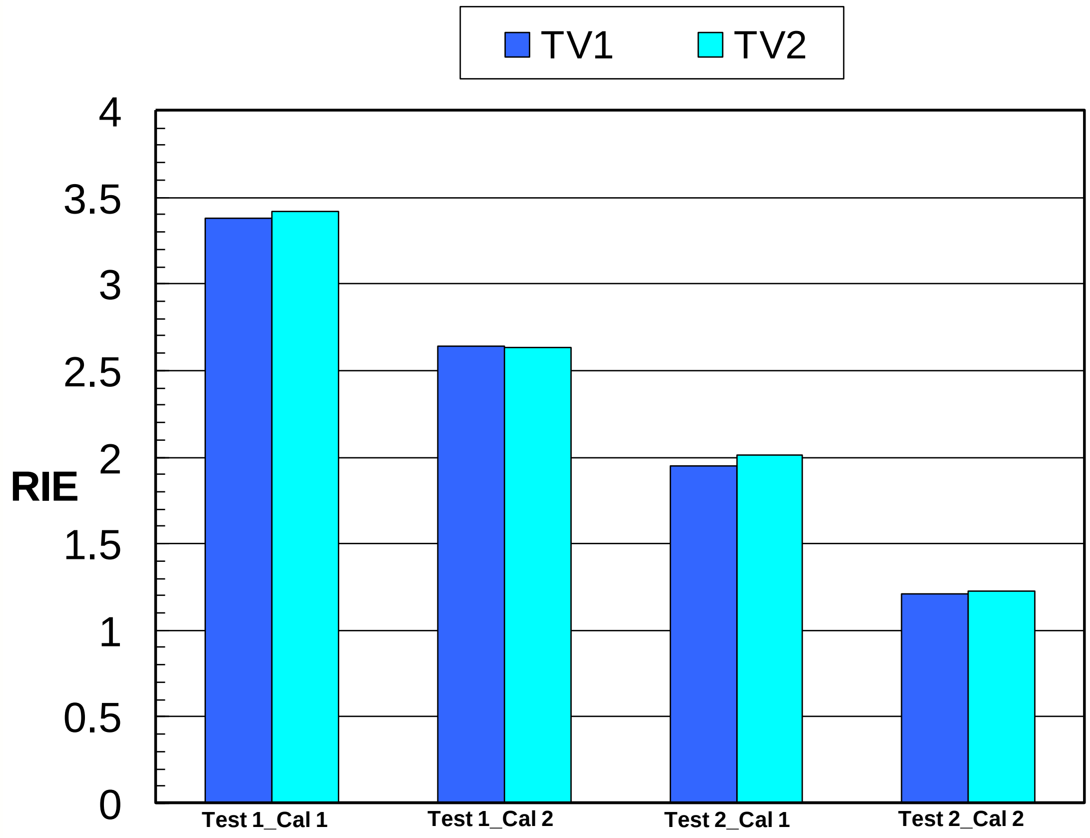
Cal-1: 0.87 inch

Test 2: 5 inch

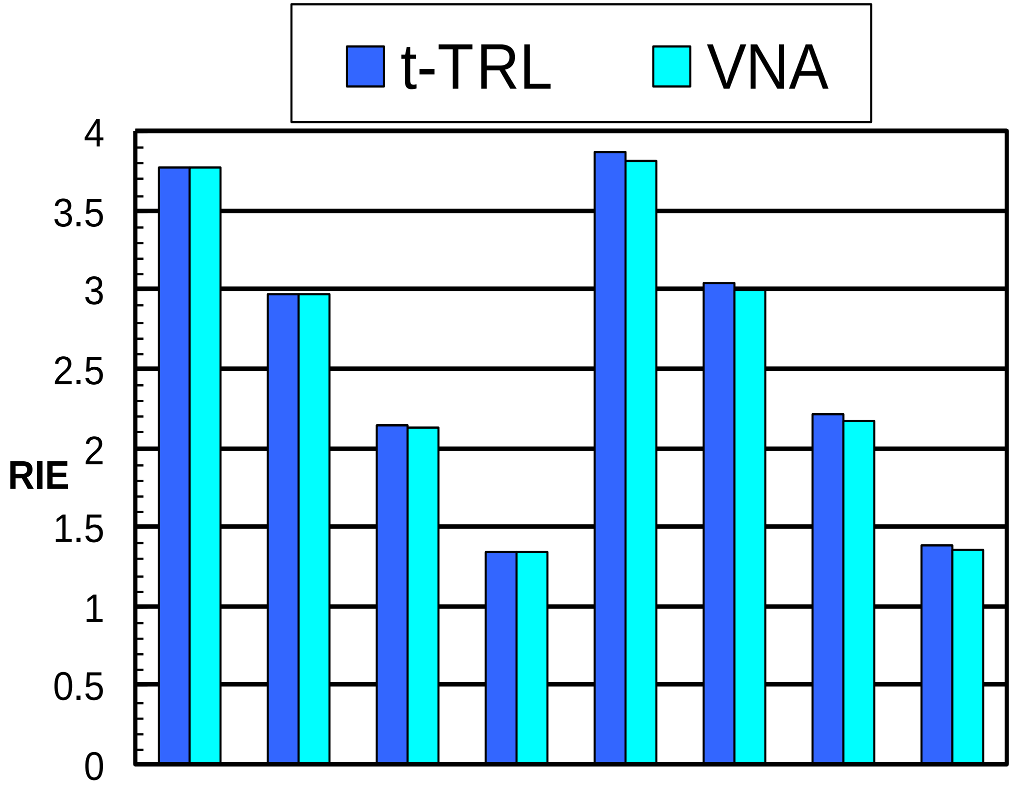
The RIE Loss Results from Differentiate the TDT waveform



The e-RIE Loss Results from t-TRL Calibration



The e-RIE Loss Results Vs. the RIE loss of VNA



Conclusion

- The RIE loss is theoretically derived for a stripline design and the RIE loss sensitivity is defined as the sensitivity of the RIE loss changing with loss tangent with a given pair of test and calibration lines.
- Overall, the longest test line (>10inch) and the shortest calibration line (<1 inch) give the best RIE loss sensitivity.
- The RIE loss sensitivity can be used when differentiating the test boards manufactured with different base material.
- The t-TRL calibration is used to improve the accuracy of impulse response measurement and RIE loss calculation accuracy.
- Excellent agreement for the RIE losses obtained from the t-TRL calibration and VNA measurement.