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Jianmin Zhang

David Pommerenke
Missouri University of Science and Technology, davidjp@mst.edu

James L. Drewniak
Missouri University of Science and Technology, drewniak@mst.edu

Richard E. DuBroff
Missouri University of Science and Technology, red@mst.edu

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/ele_comeng_facwork/1366

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A Hybrid Approach To Decrease Port Influence In Transmission Line Charaterization

Jianmin Zhang, David J. Pommerenke,
James L. Drewniak, Richard E. DuBroff
Electromagnetic Compatibility Laboratory
Department of Electrical and Computer Engineering
University of Missouri - Rolla
Rolla, MO 65409
Email: jzp4f@umr.edu

Zhiping Yang, Wheling Cheng,
John Fisher, Sergio Camerlo
CISCO Systems, Inc.
170 West Tasman Dr
San Jose, CA 95134
Email: zhiping@cisco.com

***Abstract*—Characterization and models for multi-gigabit signaling is an important issue in modern digital system. A good physical based model relies on a precise characterization of the test board. Typically, the characterization of the test board is associated with scattering matrix parameter measurement, which can be done with a VNA (Vector Network Analyzer) in the frequency-domain or a TDR (Time Domain Reflectometer) in the time-domain. The commonly used launch techniques on PCBs (Printed Circuit Boards) associated with the VNA or TDR measurement in the microwave frequency range use SMA or 3.5 mm connectors, in edge-launch or vertical-launch fashions. The transition between the launch port and the DUT (Device Under Test) introduces errors in the measurement. Embedding/de-embedding techniques are used to remove the port influences in the measurement generally. For example, TRL (Through, Reflect, and Line) calibration is the typical method used in measurement to eliminate port influences. However, extra test kits are needed for TRL calibration, and furthermore the TRL calibration is sometimes difficult to implement, such as in coupled differential lines. In this paper, an effective hybrid approach for transmission line characterization is proposed, which includes choosing a suitable port launch technique for the test board, port parasitic parameters estimation, and building up a proper circuit model for evaluation with genetic algorithms (GA).**

Keywords-signal integrity; parasitic parameter estimation;TDR measurement; VNA measurement; lossy transmission line characterization; port launch technique; genetic algorithm

I. INTRODUCTION

In modern digital systems, on board data rates even in the Gigabits/s range is becoming common. An accurate model to simulate high-frequency effects, which include dielectric dispersion, skin-effect loss, and cross talk, is a critical issue for signal integrity. In order to take into account those high-frequency effects, traces on the PCBs must be treated as lossy transmission lines. Obtaining precise RLGC parameters to represent the transmission line in a full link path model is vital for multi-gigabit signaling. Usually, the RLGC parameters are extracted from measurements [1], which means that the well-controlled signals have to be launched onto the transmission line on a PCB, and their propagation parameters need to be measured. In most cases, this is done using specially designed test boards. These test boards are then characterized using, either a VNA or a TDR. Further processing is done by different time domain or frequency domain error corrections. Examples are SOLT (Short, Open, Load, and Through) or TRL calibration for VNAs, or deconvolution of time domain reflectometer data for TDRs [2] [3]. However, there are limitations to error corrections. Error corrections might even introduce artifacts or additional uncertainty, as the uncertainty of the calibration or the uncertainty of assumptions is "convolved" into the measured data. For that reason it is advisable to start from the best possible test setup, such that only a weak, not a strong correction of data is needed. Since today's PCB manufacture technologies are well developed, transmission lines (microstrip or stripline) can be controlled very well within the substrate (controlled to the same level that is possible during production) including control of the characteristic impedance and dimensions. Therefore, the significant errors introduced into the measurement come from the discontinuity between the launch port and the transmission line, and not from the line itself.

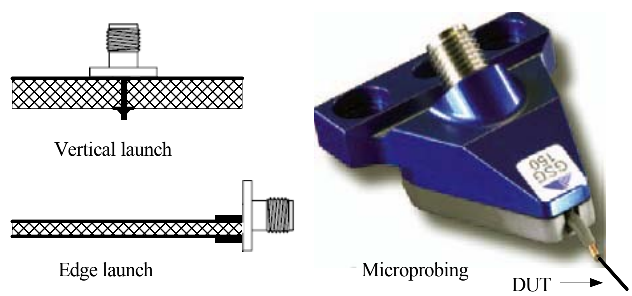


Figure 1. Three main wave-launch methods.

Methods used for launching waves onto PCBs, referring to Figure 1, include vertical launch (an SMA/3.5 mm connector mounted on PCBs vertically), edge launch (an SMA/3.5 mm connector mounted on the side of PCBs), and mircroprobing (the tip of a microprobe directly contacts to a DUT) [4] [5] [6]. The launch methods differ not only in their practicability but also in their electrical performance. Different edge and vertical launch techniques are discussed in part II, and the dominant parasitic parameter for each launch technique is estimated. The influence of different levels of error correction is detailed in part III describing transmission line characterization. However, microprobing or other launch methods based on slot lines are not discussed in the paper.

Further complications are encountered in characterizing differential transmission lines due to the limitation of implementing the TRL calibration in the measurement and the mounting issue of side launch on striplines. Furthermore, the TRL calibration method is not always available if the calibration kit is not designed for the measurement. Based on these considerations, an effective hybrid method with decreased port influence for characterizing transmission lines is proposed. It consists of VNA measurements (S-parameters), TDR (reflected wave) measurements, genetic algorithm, and parasitic parameter estimations.

II. Launch Techniques And Port Parasitic Parameters Estimation

A. *Measuring Transition for Different Launch Techniques*

A three-layer test board was used to investigate the transition at the port for different launch techniques. The top and the bottom layers of the test board are references, and the signal layer is in the middle. The substrate material is NELCO-4000 13SI. It has a low dielectric constant and low loss tangent at high frequencies, which results in much better electrical performance. A Tektronix 11801B TDR is used to measure reflected waveforms for three different port configurations, edge-launch 3.5 mm connector, vertical-launch SMA, and edge-launch 3.5 mm connector with port compensation. The measurement setup for an edge-launch configuration without port compensation is shown in Figure 2.

Figure 2. Measurement setup for edge-launch port without compensation.

The reflected waveform measured for the edge-launch 3.5 mm connector without compensation is shown in Figure 3, and the compensated one is shown in Figure 4. The reflected waveform measured for the vertical-launch SMA is given in Figure 5. The 3.5 mm edge-launch connector, made by SRI Connector Gage Co, is a precision connector designed for broadband microwave applications with good electrical performance from DC through 34.5 GHz, and measurement repeatability. The vertical launch SMA has good electrical performance up to 18 GHz. The edge-launch connector is directly soldered to the center conductor of a 50 Ω asymmetry stripline, 14 inches long, after part of the upper reference plane and the dielectric material above the center conductor have been removed. A small piece of copper tape was used to compensate for the missing upper reference planes in the vicinity of the port due to the edge-launch installation, referring to Figure 6.

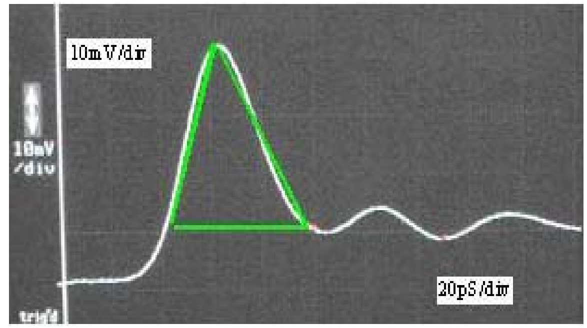


Figure 3. Reflected waveform for edge-launch port without port compensation.

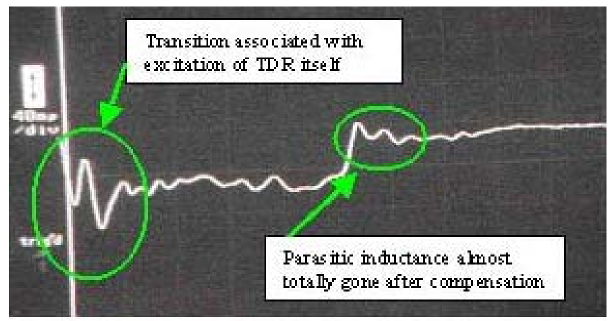


Figure 4. Reflected waveform for edge-launch port with port compensation.

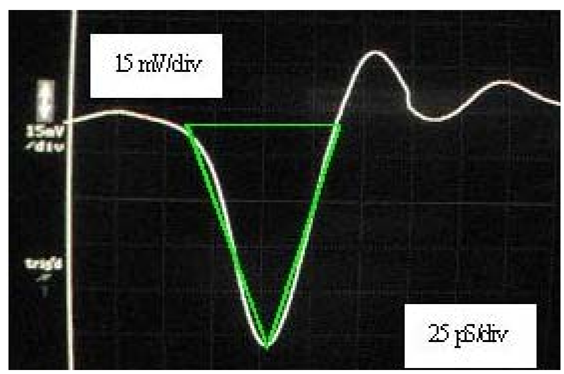


Figure 5. Reflected waveform for vertical-launch SMA.

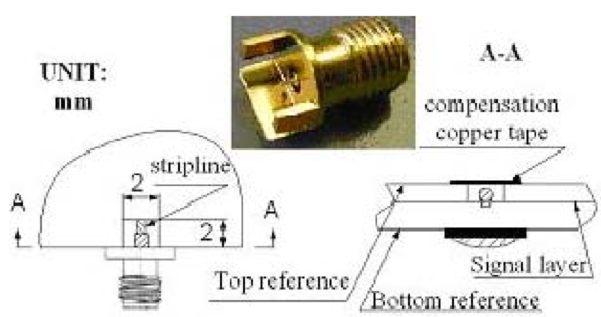
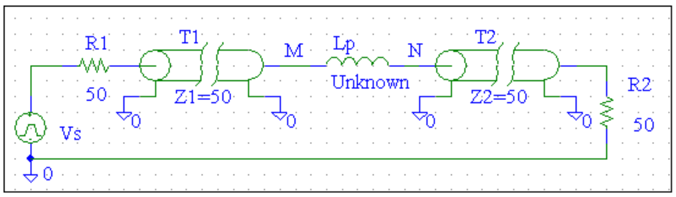


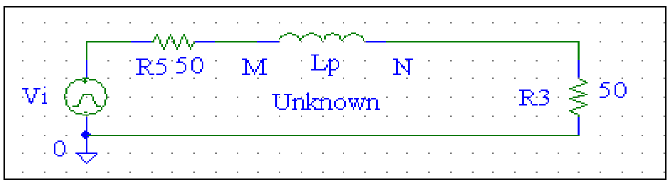
Figure 6. Schematic edge-launch structure and port compensation.

B. Port Parasitic Parameters Calculation

From the measured reflected waveform, the parasitic parameters can be estimated [7]. Looking at Figure 3, the parasitic inductance plays a role in the transition when waves launch from the port onto the on board transmission line. The measurement system is represented using the equivalent circuit given in Figure 7 (a) where the (b) is the simplified circuit for the purpose of analysis. In Figure 7 (b), V_i is the incident voltage, which is half of V_s, and V_s is the TDR initiated voltage with an amplitude of 0.5 volts.



(a)



(b)

Figure 7. Equivalent circuit for edge-launch transition measurement.

If a step pulse produced by the TDR propagates through the transmission line T1 to node M, referring to Figure 7 (a), the total voltage at node M can be expressed as

$$V_M = V_i\left(1 + e^{\frac{-t}{\tau}}\right) \quad (1)$$

and the total voltage at node N can be found using

$$V_N = V_i\left(1 - e^{\frac{-t}{\tau}}\right) \quad (2)$$

where

$$\tau = \frac{L_p}{R3 + R5} \; . \quad (3)$$

Since the reflected voltage can be calculated as

$$V_r = V_i e^{\frac{-t}{\tau}} \, , \quad (4)$$

then the reflected voltage can be normalized to the incident voltage as

$$R_{fn} = \left|\frac{V_r}{V_i}\right| = e^{\frac{-t}{\tau}} \; . \quad (5)$$

The integration of equation (5) is

$$\int_0^\infty R_{fn} dt = \int_0^\infty e^{\frac{-t}{\tau}} dt = \tau \; . \quad (6)$$

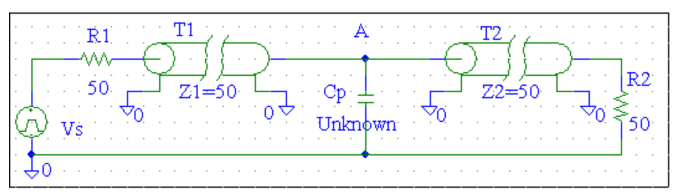
Substituting (3) into (6), the parasitic inductance can be calculated as

$$L_p = (R3 + R5)\int_0^\infty R_{fn} dt = 100 A_n \, , \quad (7)$$

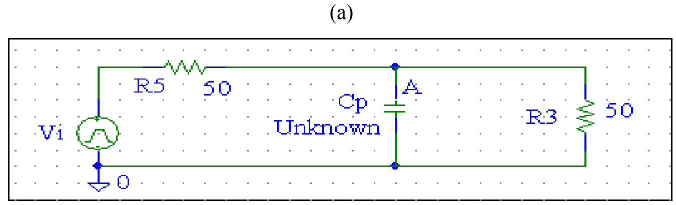
where A_n is the waveform area due to the parasitic inductance, and is normalized to a unit incident voltage. The normalized area for the waveform shown in Figure 3 is approximated to $3.72\text{x}10^{-12}$ by the triangular, and the parasitic inductance in the edge-launch configuration is then calculated as 0.372 nH.

Referring to Figure 4, it is observed that the parasitic inductance associated with an edge-launch 3.5 mm connector with port compensation is much smaller than that without port compensation. The transition caused by the port after compensation is even smaller than the TDR inner transition corresponding to the excitation. Therefore, to estimate the parasitic parameters in this case is meaningless. The measured S-parameters then can be directly used as objective data to characterize the transmission line. Port influences in this case are negligible.

Similar to the parasitic inductance calculation in Figure 3, the parasitic parameters associated with a vertical-launch SMA connector can be evaluated from the reflected waveform shown in Figure 5. Two possible parasitic parameters exist in this launch technique. Namely are shunt capacitance and series inductance. Observing the reflected waveform shown in Figure 5, the shunt capacitance is dominant in the vertical-launch transition. For simplicity, only the dominant parasitic parameter, shunt capacitance, is estimated here. The equivalent circuit of the vertical-launch SMA measurement system is shown in Figure 8 (a), and a simplified version is shown in Figure 8 (b) when equivalent source is viewed at T1. In Figure 8, V_s and V_i have the same value as given in the parasitic inductance calculation in Figure 3.



(a)



(b)

Figure 8. Equivalent circuit for vertical-launch transition measurement.

Assuming a step pulse generated by the TDR propagates through transmission line T1 to node A, referring to Figure 8 (a), the total voltage at node A can be calculated as

$$V_A = V_i\left(1 - e^{\frac{-t}{\tau}}\right) = V_i + V_r, \quad (8)$$

where V_i is the incident voltage and V_r is the reflected voltage, and τ is the time constant. For the circuit given in Figure 8 (b), the time constant can be evaluated as

$$\tau = \left(R_3 \parallel R_5\right)C_p. \quad (9)$$

Normalizing the reflected voltage to the incident voltage as previously done in the parasitic inductance calculation, the ratio is then

$$R_{fn} = \left|\frac{V_r}{V_i}\right| = e^{\frac{-t}{\tau}}. \quad (10)$$

Integrating both sides of (10), the following equation is obtained

$$\int_0^\infty R_{fn}dt = \int_0^\infty e^{\frac{-t}{\tau}}dt = \tau. \quad (11)$$

Solving equations (9) and (11), the parasitic capacitance is found as

$$C_p = \frac{A_n}{25}, \quad (12)$$

where A_n is the waveform area normalized to the unit incident voltage. In Figure 5, the normalized area is estimated as $12.5\text{x}10^{-12}$ by a triangular approximation, and the parasitic capacitance is then calculated as 0.5 pF in the vertical-launch SMA connector transition.

III. The Hybrid Approach and the Influence of Different Launch Techniques in Transmission Line Characterization

A. Parameter Sensitivity Analysis in Transmission Line Characterization

For the 50 Ω asymmetric transmission line used in the port transition measurement, the line has already been characterized using a genetic algorithm and measured S-parameters with TRL calibration before this study. The RLGC parameters are given in Table I where the R_s, G_d are detailed in [1]. The sensitivity of the RLGC parameters to the S-parameters is investigated by adding 50% of its initial value given in the Table I to see how the S-parameters are changed with the variation in the RLGC parameters as shown in Figure 9.

TABLE I. Original RLGC Parameters Extracted From S-Parametrs Measurement With TRL Calibration

Ro	Lo	Go	Co	Rs	Gd
(Ω/m)	(nH/m)	(uS/m)	(pF/m)	(uΩ/m $\cdot\sqrt{Hz}$)	(pS/m)
0.8376	316.7	99.81	118.8	482	8.077

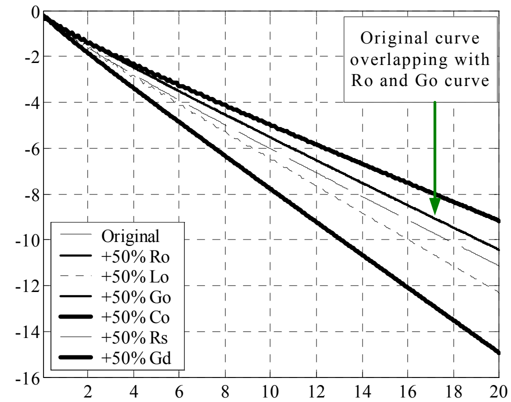


Figure 9. $|S_{21}|$ variation vs. frequency for a 50% increase in each parameter value.

It can be seen from Figure 9 that the $|S_{21}|$ are not sensitive to variation in Ro and Go since the +50% variation of Ro and Go results in almost no changes to $|S_{21}|$. This is also true for –50% variation of Ro and Go. Here Ro and Go are the per unit length dc resistance and shunt capacitance. However, the $|S_{21}|$ is sensitive to other parameter variations. This investigation shows that up to ±50% deviation of Ro and Go is allowable in the transmission line characterization for wide frequency range case, but a similar deviation of any other parameters is undesirable.

B. S-parameters Comparison for Different Launch Techniques

The data given in Table I are the extracted pure RLGC parameters for the transmission line using GA since the influences associated with the launch techniques are eliminated by TRL calibration in the measurement. The parasitic parameters calculated in part II are intentionally added to the both sides of the pure transmission line with a length of 0.248 m to observe the port influences. Then two HSPICE models are formulated including port parasitic parameters. The simulations are launched in HSPICE then, and the results are shown in Figures 10-11.

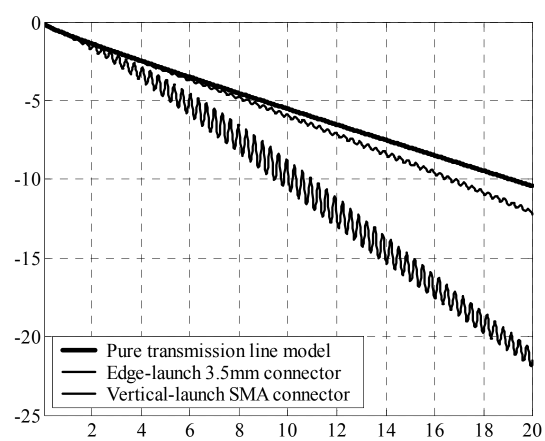


Figure 10. $|S_{21}|$ comparison for different launch techniques.

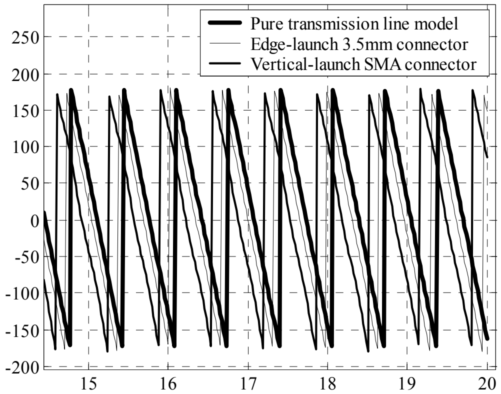


Figure 11. S_{21} phase comparison for different launch techniques.

It is observed from Figure 10 that the magnitude variation is about 1.5 dB in the edge-launch technique up to 20 GHz, but it is about 10 dB in vertical-launch technique. Therefore, errors introduced by the edge-launch technique are much smaller than the errors introduced by vertical-launch technique. In other words, if the measured S-parameters including port influences are used as objective data in characterizing transmission lines, the characterization results may be acceptable or may not, which depends on frequency range of interest and the launch techniques. For the three launch techniques discussed above, if the vertical-launch technique is used in a measurement without removing port parasitic capacitance, the characterization results may be totally useless in the GHz range. However, if an edge-launch port is used in the measurement though the influences from the parasitic inductance are still there, the characterization results may good up to 10 GHz since the error, 0.7 dB, is not significant when compared with other errors. If the edge-launch with port compensation technique is used in the measurement, the characterized results can be good enough up to 20 GHz. This is because the compensation makes the transition between the port and the line trivial. This investigation shows that the edge-launch with port compensation is the best launch technique if the compensation is easy to realize, and the edge-launch technique is always better than the vertical-launch technique in a co-axial line to planar transmission line transition. Therefore, in the board/transmission line characterization, the edge-launch technique should be considered in test boards when the TRL calibration is not allowed or desired in a measurement.

C. Hybrid-GA Approach Comparing with the Transmission Line Characterization with TRL De-embedding Techniques

In section *B* part III, the possible influences in S-parameter measurements from the different launch-techniques are investigated. The results show that if an accurate characterization is desired for a transmission line, the parasitic port influences must be removed in the measurement. However, this is not always the case due to practical issues such as cost and board space. Especially, if the test board is already there, but no TRL calibration kits are designed with the board, it is impossible to remove all port influences. Although the parasitic parameters can be estimated using the method introduced in part II, the exact parasitic parameters can't be obtained using that method since the normalized area calculation is approximate. Therefore, a hybrid approach is proposed herein to characterize transmission lines precisely and effectively. This approach is based on S-parameter measurements, port parasitic parameter estimation, and a genetic algorithm where the parasitic lumped port parameters are taken into account in the GA (genetic algorithm) model.

In a simple GA extraction method, typically, the analytical GA model only considers the per unit length parameters of the transmission line such as $R_{(f)}LG_{(f)}C$ and port impedance. If the parasitic parameter influences in the measurement are removed using de-embedding techniques, such as TRL calibration, the simple GA method can extract precise per unit length parameters for the transmission line [1]. However, if port parasitic influences are included in the measurement, the simple GA method is inefficient. The hybrid method is needed. In the hybrid method, the analytical GA model is based on the transition measurement where the dominant parasitic parameter must be determined and evaluated. Then the GA model will include $R_{(f)}LG_{(f)}C$, port impedance, and lumped port parasitic inductor $L_{p,}$ capacitor $C_{p,}$ or even loss resistor. The evaluated L_p or C_p value is used to provide an initial range for the parasitic lumped parameter to be extracted in the GA extraction in a range from one-tenth to ten times the estimated value. In the hybrid-GA extraction, the roulette-wheel selection method is used though the convergence speed is slow in this selection approach, but it keeps good diversity, and no bias is introduced into the selection procedure. A generation dependent recombination factor in the range from 0.65 to 0.89 is used in the genetic algorithm to balance the convergence speed and diversity. Similar to the recombination factor, the mutation factor is also generation number dependent. The fitness function used in the hybrid-GA method is normalized so that no weighting factors are imposed to parameters to be extracted.

One single-ended stripline was investigated and characterized in the frequency range of 0.2 GHz to 20 GHz using both the TRL calibration de-embedding technique and the GA-hybrid de-embedding method. The stripline was built in a 8-layer test board. The total length of the stripline is 8976 mils, and it is 7976 mils long after subtracting the through length of the TRL calibration kit. Two SMA connectors (field replaceable jack receptacle manufactured by Molex) were connected to the both ends of the stripline. This type of SMA is totally different from the vertical launch SMAs discussed above. Minimum port transition can be achieved by this kind of SMAs. The S-parameters were measured in a 8720ES VNA. The characterized parameters are given in Table II.

TABLE II. CHARACTERIZATION COMPARISON BETWEEN TRL CALIBRATION METHOD AND HYBRID-GA

De-embedding Method	**Ro** (Ω/m)	**Lo** (nH/m)	**Co** (pF/m)	**Rs** (uΩ/m $\cdot\sqrt{Hz}$)	**Gd** (pS/m)
TRL	1.758	318.8	141	429.8	14.33
Hybrid-GA	1.98	311	124.8	411.1	13.7
Relative error	12.6%	2.5%	11.5%	4.4%	4.4%

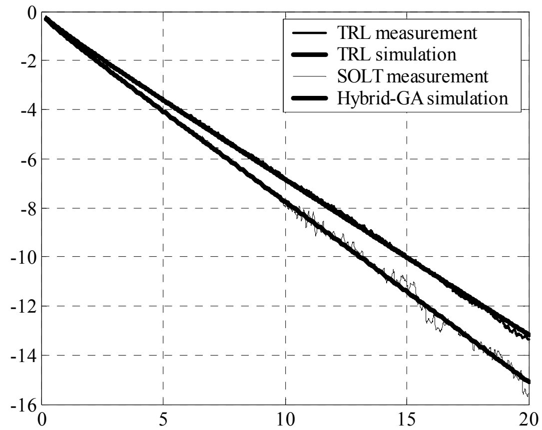


Figure 12. $|S_{21}|$ comparison between different characterization methods and their corresponding measurement.

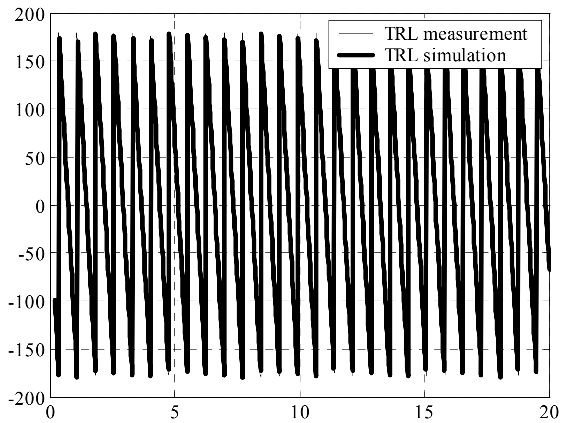


Figure 13. S_{21} phase comparison between simulation and measurement with TRL de-embedding.

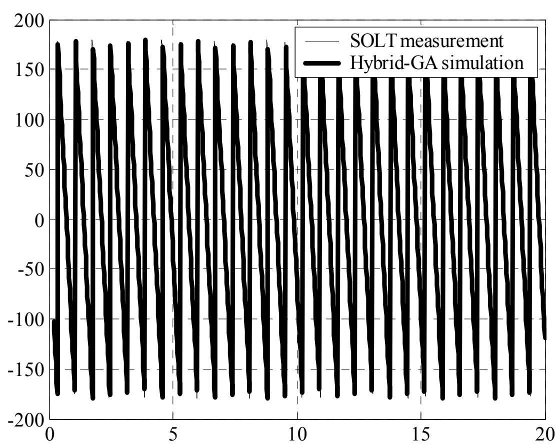


Figure 14. S_{21} phase comparison between simulation and measurement with hybrid-GA de-embedding.

The measured $|S_{21}|$ are shown in Figure 12 with thick solid line for TRL calibration, and the thin line for SOLT calibration. Port extinction was used in the measurement for SOLT calibration to remove the electric length of SMA port. Since the via stub is 15 mils long in the test board, which is relative small when compared with the total via length 106 mils. This leads to only a parasitic inductance is extracted in the hybrid-GA method with the value of 123 pH. The characterized parameters given in Table II are then used in HSPICE simulation. The simulated $|S_{21}|$ given in Figure 12 with the dot line uses the characterization parameters of the TRL de-embedding technique. The dash-dot line is the simulation result using characterization parameters from the hybrid-GA de-embedding method. The phase comparison between measurement and simulation is shown in Figure 13 for TRL de-embedding characterization method, and Figure 14 for hybrid-GA de-embedding characterization approach. It is observed that the magnitude difference between simulation and measurement in the TRL de-embedding method is less than 0.3 dB while the difference associated with the GA-hybrid method is less than 0.6 dB. The phase differences are hard to tell in both cases, since measurement overlaps the simulation.

IV. Conclusion

Prior literature has been shown that a careful TRL calibration will allow removal of the errors in the measurement due to parasitic port parameters. However, this method needs extremely well-designed calibration kits, in an additional cost, and requires more board space. Furthermore, this method is not even allowable in some special cases such as coupled differential pair measurement. In this paper, a hybrid approach for characterization of a transmission line is proposed. It is practical and efficient in transmission line characterization. With the help of TDR measurement and parasitic parameter estimation, even with the port parasitic parameters involved in the frequency domain data, good characterization results can still be obtained. The launch technique investigations show that edge-launch configuration can provide a coax-microstrip transition that does not need TRL calibration for a frequency range up to 10 GHz, and a novel side launch technique has been shown for stripline that allows the transition from coax to stripline in such a matter that no TRL calibration is needed.

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