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Novel Transmission Line for 40 GHz PCB Applications

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Abstract

In this paper, we discuss an electromagnetics based approach to transmission line design, and then explore a novel printed transmission line, Periodic Micro Transmission Line (PMTL™, Patents Pending), with improved signal integrity to 40 GHz. PMTL lines are constructed using traditional printed circuit manufacturing technologies and materials, and display the TEM propagation characteristics of a well-behaved coaxial line. We examine a 50 Ohm PMTL design in FR4 material, in lengths to 36", and compare its performance with a traditional stripline, providing simulated and measured data. Initial studies show a 36" PMTL has the same loss as a 24" stripline along with higher velocity of propagation, lower effective dielectric constant, and similar crosstalk.

Authors Biographies

Jamal S. Izadian, Ph.D. is the cofounder and president of RFCONNEXT, Inc. As a member of a development team, he has been instrumental in designing and promoting a new high speed interconnect ecosystem using new TEM transmission line technologies. He is the innovator of the patent pending PMTL™, VMTL™, and SMTL™ transmission line technologies which are designed to mitigate the shortcomings of the modern interconnects systems to 50GHz and beyond. Prior to RFCONNEXT, Inc., Dr. Izadian was cofounder and CTO, and Later CEO of ANTENNEM COMMUNICATION, LLC, In this capacity, Dr. Izadian helped establish the company as a leading antenna development and engineering services company in the wireless industry. He has seven issued patents, and six pending. He is the author of numerous technical articles and conference presentations, including the book "Microwave Transition Design" published by Artech House. He obtained his BSEE from University of KY, MSEE form Ohio State University, and Ph.D. in EE with emphasis in Electromagnetic/Antennas, and Radio Communication, from Ohio State University. He finished a year of MBA programs at Santa Clara University's Leavey School of Business.

Julian Ferry earned a BSEE with an emphasis in RF and microwave engineering from Penn State University, University Park, PA. He has more than twenty years experience in the high speed interconnect industry focusing on product design and development, test and simulation, and team management. Julian has authored more than twenty articles and papers and has been granted thirteen U.S. and numerous international patents covering products and processes for improved Signal Integrity and EMC performance.

Justin McAllister graduated from Penn State University with a BSEE. He has worked at Samtec for over four years as a member of the Signal Integrity Group assisting customers with electrical modeling request and technical support for their high speed applications.

Introduction

One challenge meeting multi-terabit data flow requirements in advanced routers and servers is squeezing more bandwidth out of traditional methods and materials. The integrity of the signal path is only as good as its narrowest bandwidth components, whether a connector, a trace, or SMT pads acting as 'speed bumps' in the signal path. Each must be resolved using a systematic and consistent design approach. Furthermore, as the demand for speed and bandwidth increases, the size and complexity of the PCBs (Printed Circuit Boards) often increase.

Novel innovative approaches and design techniques are paramount to meet these and many other challenges. In this paper we discuss a method for using 3D Electromagnetic Field Solvers in the design of advanced transmission line structures.

We then describe a printed 'coaxial-like' transmission line, known as Periodic Micro Transmission Line (PMTL), which is manufactured with traditional printed circuit technologies and materials. We present the study of 6", 12", 24", and 36" lengths of PMTL, and its equivalent stripline transmission lines, all designed for 50 ohms.

Theoretical studies have shown that up to 40GHz, a properly designed PMTL line will have at least a 33% improvement in signal loss versus a similar stripline design. For example, a 36" PMTL line will have about the same loss as an equivalent 24" stripline. Other advantages include higher velocity of propagation, lower dielectric constant, and better isolation performance. This is made possible by the fact that the structure exhibits a true TEM mode of propagation to 40 GHz. This will allow for extending the bandwidth of traditional low cost materials (such as FR4) by at least 2x with an even greater increase with premium materials (such as Nelco N4000-X).

We explore and discuss manufacturing issues and their subsequent integration into the development of high speed interconnect ecosystems. Finally, we present predicted and measured data for stripline and PMTL constructions.

Periodic Nature of Transmission Lines

A detailed discussion of transmission line theory is beyond the scope of this paper. However, because of its importance in the design approach discussion that follows, it is important to provide a brief overview of basic transmission line theory in order to demonstrate the nature of periodicity.

Microstrip, stripline, and coplanar waveguide are traditionally used in high speed PCB designs, while coaxial and twisted or parallel pair cables are often used for transmission lines for external interconnection between PCBs.

Theoretically, it is possible to consider a very short length of any of these transmission lines as a unit cell. A unit cell is comprised of a series resistance (R), a series inductance (L), a shunt conductance (G), and a shunt capacitance (C). It is common to express the unit cell as R, L, G, and C values per a unit length.

For meaningful mathematical analysis, the length of the unit cell must be much smaller than a wavelength of the highest nominal frequency of interest. A value of 1/10 to 1/20 of the shortest significant wave length is an often used rule of thumb.

In a PCB, these lumped components are directly related to the electrical parameters of the board materials, such as resistivity and permeability of the trace and conductivity and permittivity of the dielectric. For uniform transmission lines, it is usually sufficient to design a unit cell with the appropriate R, L, G, and C, values and then cascade the required number of these unit cells. With an appropriate fabrication process, i.e., a photolithographic process in a PCB, we can obtain a periodic transmission line of desirable length.

Under certain conditions, such a line can be treated in electrical analysis as infinitely long, with the electrical characteristics predictable from the properties of the original unit cell. Generally, the electromagnetic wave propagating along this transmission line must encounter no significant deviation from the ideal geometries and material properties of the cascaded unit cells. In such cases, signal degradation will be limited to phase retardation (delay) and attenuation along the path.

This theory can be applied to energy transmission at various frequencies. Ideal transmission lines are all-pass. That is, they allow all frequencies to pass through the line with similar distortion effects.   However, any deviation from the ideal will result in inconsistent frequency behavior. This will result in low pass, high pass, or band pass characteristics.

For example, a typical PCB microstrip or stripline has low pass characteristics. That is, lower frequencies are passed with less loss than higher frequencies. A typical waveguide, on the other hand, has high pass characteristics in that a signal will not propagate effectively until a certain moding frequency. Optical fibers typically have band pass characteristics, and thus their use is limited to certain frequency bands.

The art of good transmission line design is to optimize the various parameters of the unit cell to minimize or eliminate signal distortion in the signal bands of interest while avoiding potentially costly over design and specification.

Periodic Micro Transmission Lines (PMTL) introduced here utilize this basic approach to develop optimized transmission lines for PCBs and flex circuitry that use existing PCB design and layout processes for development and manufacturing.

Electromagnetic Engineered High Speed Transmission Lines

For many recent applications, PCB designs using microstrip traces on the outer layers and stripline transmission lines on internal layers are adequate. Geometries can be determined analytically in many cases or a 2D field solver can be used when greater accuracy is required. But as the signal edge rate and clock frequency is increased, the traditional look up tables based on trace and space are proving to be inadequate.

In addition to these design challenges, the size of PCBs is often increasing to provide more functional capabilities and scalability. Thus speed and bandwidth become highly desired commodities, ones that are directly impacted by the important aspects of signal integrity such as skew, delay, transmission loss, crosstalk (FEXT and NEXT), jitter, and dispersion. These elements combine to determine if a final system eye diagram meets the minimum pass/fail threshold.

These factors require a shift from traditional circuit based PCB design approaches to one based on electromagnetic design principles. In traditional PCB layout design, we relied on Ampere’s and Faraday's laws to reduce the electromagnetic field quantities H and E to circuit bound I and V. This allowed us to deal with local phenomenon related only to voltage and current. Thus we could design driver and termination models which yielded well defined and accurate prediction of transients for timing diagrams.

In this regime, path lengths are small compared to the wavelength of nominal signal edge rate, so most parameters of the circuit could be safely modeled using lumped elements. But as the signal edge rate and the clock frequencies increase, signal reconstruction requires consideration of many more of the Fourier harmonics components to reconstruct the signal without significant distortion.

Therefore, the PCB designer is forced to employ distributed models. This requires a design approach based not on simply current and voltage, but rather one which fully considers the electric and magnetic fields, E and H. Thus, the designer must now work with Maxwell's equations solved in the space of the signal propagation path. We might therefore describe the new designs as electromagnetic engineered transmission lines.

We must follow the high speed signal along its path from source to sink, analyze, and possibly remove the speed bumps along the way. Such analysis requires that we define the problem space with EM boundary conditions that ensure the validity of Maxwell's Equations.

Thus high speed interconnect and PCB designers must now think in a distributed way, but design with a cellular vision using the theory of periodicity and the ability to cascade basic unit cells to allow us to make high speed board design a viable process.

Heaviside Optimal Condition

Electromagnetically engineered interconnects are essential to meet the bandwidths requirements of 40 GHz PCBs. An understanding of basic requirements for optimal transmission line design can help reduce the scale of the design to a more manageable size.

To help the designer better understand the new design paradigm, we will discuss the phenomenon of physical periodicity and continuous (distributed) resonance.

In the current/voltage regime (I, V), the incremental model of short unit cell transmission line shown in Figure1 provides a basic understanding of the behavior of the optimal transmission line. As the structure represents a self resonant unit, we can cascade a finite number of these cells in a periodic manner, and we will have distortionless signal transmission from matched input source to the matched output load.

Oliver Heaviside developed a theory to optimize such transmission which showed that we must keep R/L = G/C. We can examine the telegrapher's equation which relate time varying voltage V and current I to the unit cell. For simplicity, we’ll consider the lossless case.

The telegrapher’s equation states that the time varying voltage and current on a transmission line are forever coupled, and time variation in one generates spatial variations in the other, and vice versa. This coupling is described by the constitutive parameters inductance L and capacitance C which are directly related to the physical construction (geometries and materials) of the transmission line.

One can think of this as a continuous self resonant structure of resonant frequency of fo=1/sqrt (LC). As long as one can cascade these cells efficiently and physically, one will have an optimal distortionless signal transmission line.

It is important to remember also that Zo=sqrt(L/C). If we terminate this periodic transmission line to Zo on both ends, we have no reflections and therefore the transmission line would appear infinite in both directions. The Heaviside condition of R/L=G/C was derived from this fact, and this provides a clue as how to fix less than perfect transmission lines.

Another simplified way to consider this phenomenon is that optimum signal transmission through the transmission line is the result of continuous resonance of signal energy, exchanged in the direction of propagation, from L to C, then from C to L, then from L to C, then from C to L, and on and on, from one periodic cell to the next.

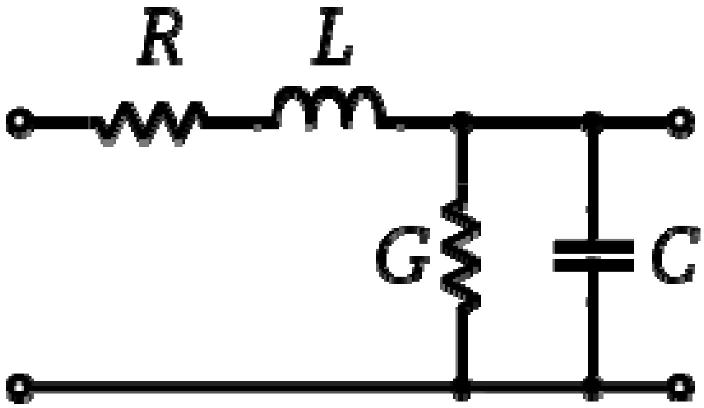


Figure 1: Equivalent Circuit of a unit cell of a Transmission line, as represented by lumped elements R, L, G, and C, that constitutes the basis of a periodic, self resonant transmission line.

The following formulas present the lossless version of telegrapher’s equations as related to the unit cell of Figure 1.

$$\frac{\partial}{\partial x}V(x,t) = -L\frac{\partial}{\partial t}I(x,t)$$
$$\frac{\partial}{\partial x}I(x,t) = -C\frac{\partial}{\partial t}V(x,t)$$

The equation below shows the Heaviside conditions for distortionless transmission which is derived from a variation of the telegrapher's equations.

$$\frac{G}{C} = \frac{R}{L}.$$

Now consider Maxwell's equations shown below (in the lossless, free space condition to keep the discussion simple).

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}.$$

These equations relate the nature of time varying electric field E and magnetic field H, (B=uH), as they vary with time and space. They are key to understanding the ripple propagation nature of waves.

We can simply state that time changes of B, the magnetic flux density give rise to spatial variations of the electric field E, and vice versa. The two equations are coupled via the medium in which the signal is propagating. In PCBs, the coupling factor is represented by Mu and Epsilon, the latter of which is defined by the familiar DK value.

The parallelism between Maxwell’s and the telegrapher’s equations centers on the equivalence of L and u, and C and e, and V and E (Faraday's Law), and H and I (Ampere' Law). The bottom line is that the telegrapher’s equations relate the E and H to a V and I with sufficiently localized considerations, which is why we can safely use L and C unit cells for low frequencies.

As structures become larger relative to wavelength, the electromagnetic fields become less constrained, and we must consider their interactions within a larger environment. For example, in a PCB, we now need to consider the effects of ground planes, power planes, vias, other traces in proximity, etc. Therefore, we must abandon the more simplified telegrapher’s equations, and instead, work with the all encompassing Maxwell’s equations and the EM boundary conditions.

Modern ectromagnetic field solver software allows us to solve Maxwell's equations in a straightforward manner. Unfortunately, the problem size of most currently available 3D field solver software is limited by runtime and convergence considerations. Because of the feature size of a typical PMTL design for PCB, we are practically constrained to solving design optimization problems to a volume of a few square inches. But as long as we are careful in the selection of our problem space, the cascadeable nature of periodic transmission lines allows us to work around this issue. So to design an optimal transmission lines, all we have to do is find the correct representative unit cell to solve [1,2].

Development of Advanced Transmission Lines

One example of the electromagnetically engineered transmission line is the evolution and acceptance of the hybrid stripline [3]. It is now customary to design high speed PCBs utilizing a combination of various materials. For example, it is now common for the top and bottom layers of a multilayer board to use a premium material with lower DK and DF or to embed high speed layers within traditional FR4 material [3].

Periodic Micro Transmission Line (PMTL) represents a more advanced EM Engineered transmission line designed to be used in increasingly larger PCBs. Other advanced transmission lines which can mitigate many of SI and PI (SIPI) challenges can be developed using this same design philosophy.

An outline of several steps required to make good transitional interfaces from various transmission lines is provided in reference [4]. Here it is stated that to get a good impedance match, first one must provide a good field match. But it is important to keep in mind that impedance match alone is in many cases no longer good enough.

The process used in designing PMTL achieves the field match objectives by first developing an accurate representation of the unit cell, and then ensuring field match to achieve the byproduct of impedance match. Optimization is centered around material properties and geometries in a manner consistent with available manufacturing processes. One of the most important requirements for practical application of any new PCB transmission line design is to maintain compatibility with existing design, development, and manufacturing processes and equipment.

For instance, much work has been demonstrated in optical and other wave guide backplane transmission lines. While such designs can offer wider signal bandwidths than stripline, they require unusual or exotic materials and manufacturing techniques. In addition, such approaches also require additional electrical to optical circuitry or other up-converting schemes. In addition, neither approach allows transmission of lower frequency signals which can be important in both signal and power delivery.

Furthermore, we must design new PCB transmission lines with an eye toward backward compatibility with the existing PCB transmission lines such as coplanar waveguide, microstrip, and stripline. Any new transmission line must allow efficient transitions to and from various types of common existing line designs and connector interfaces, and to external cabling and connectors as needed.

The figure below illustrates one possible cross section of one PMTL PCB transmission line design. It should be noted that this particular design is described in a Patent Application of RFConnext, with further expansions and applications described in follow up patents filings. However, the principles it illustrates can be useful in understanding many EM engineered transmission line designs.

The red trace in the center can be thought of as the center conductor of a typical coaxial transmission line with outer metal layers and vias functioning as an effective "shield".

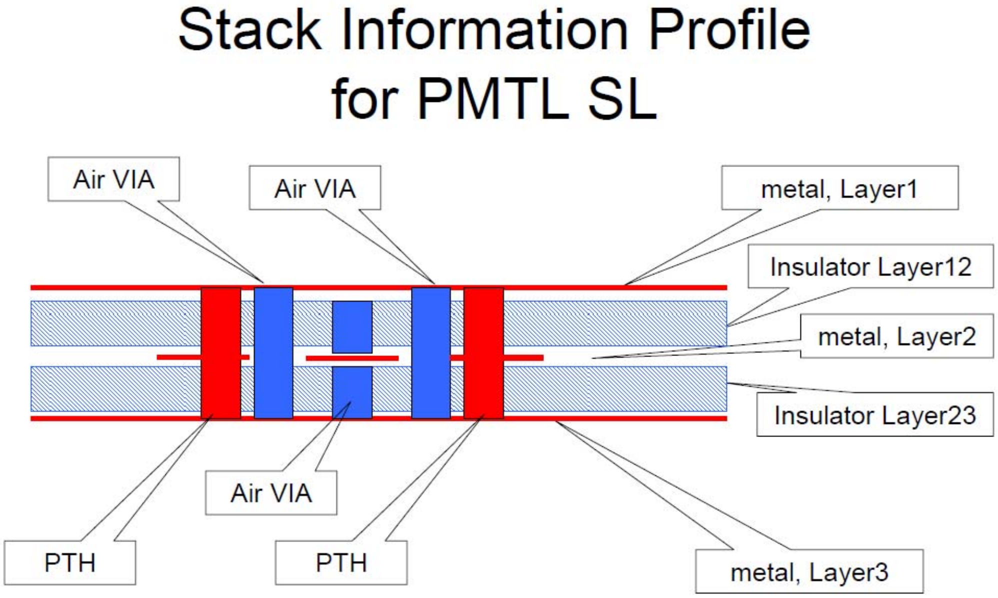
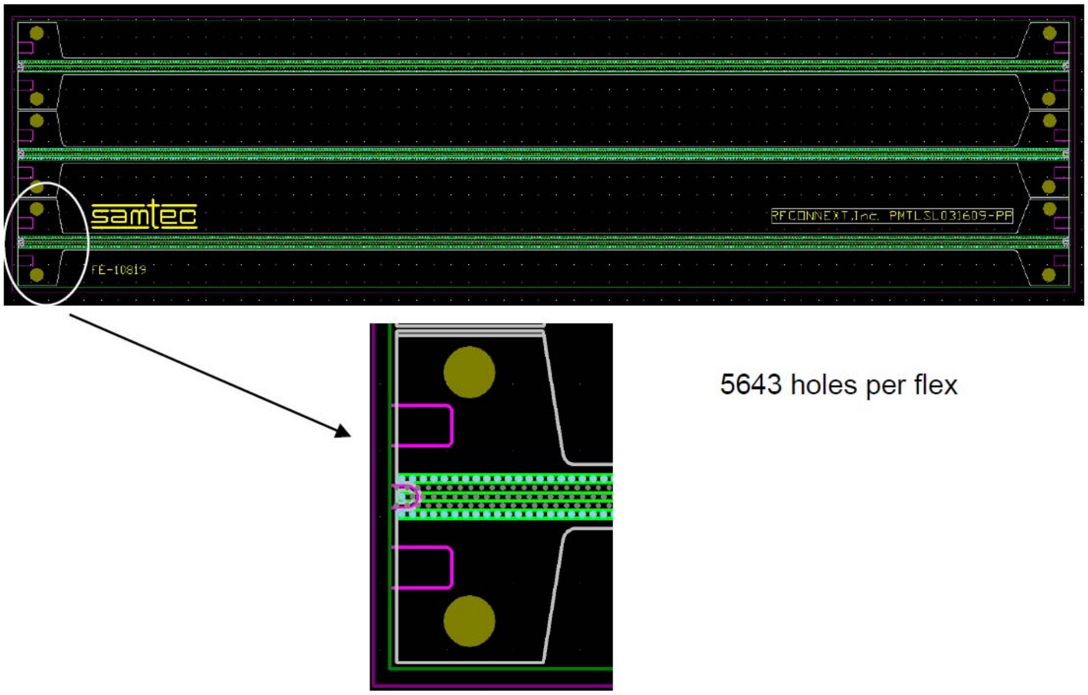


Figure 2: Cross section view of one type of PMTL stack up

A top view of this design is presented below. The periodicity of the transmission line design is evident.


PMTL Design

5643 holes per flex

Figure 3: Top view of flex based PMTL design with blow up of SMA connector transition area.

This design provides a good illustration of some of the variables at play that can lead to computational challenges and the need for a 3D full wave solver for analysis and optimization. We can also design complex PMTL type lines for 2, 3, 4 or greater , including various forms of differential pairs, twisted pairs etc. Several such designs are described in other RF Connext Patent Applications.

Most importantly, we are now in the realm of 3D design optimization as a 2D field solver is no longer sufficient in optimizing transmission line design. Not only will variation of the metal and air vias effect signal propagation, but their number, diameter, location, and spacing are important as well.

Measured Data and Validation of PMTL Technology

In this section, we provide predicted and measured data from actual fabricated PMTL transmission lines to illustrate how the concept can be used as a basis of a high speed interconnect ecosystem.

Because of unexpected manufacturing delays, the rigid PCB specifically designed for this study was only available one day before the deadline for publishing this paper. Therefore, we are only able to present a limited data set at this time. Full results of the study will be included in the live presentation. To fill this void, we will present data for a flex based assembly constructed with a PMTL design. This design is illustrated in Figure 3 above and in the photograph below.

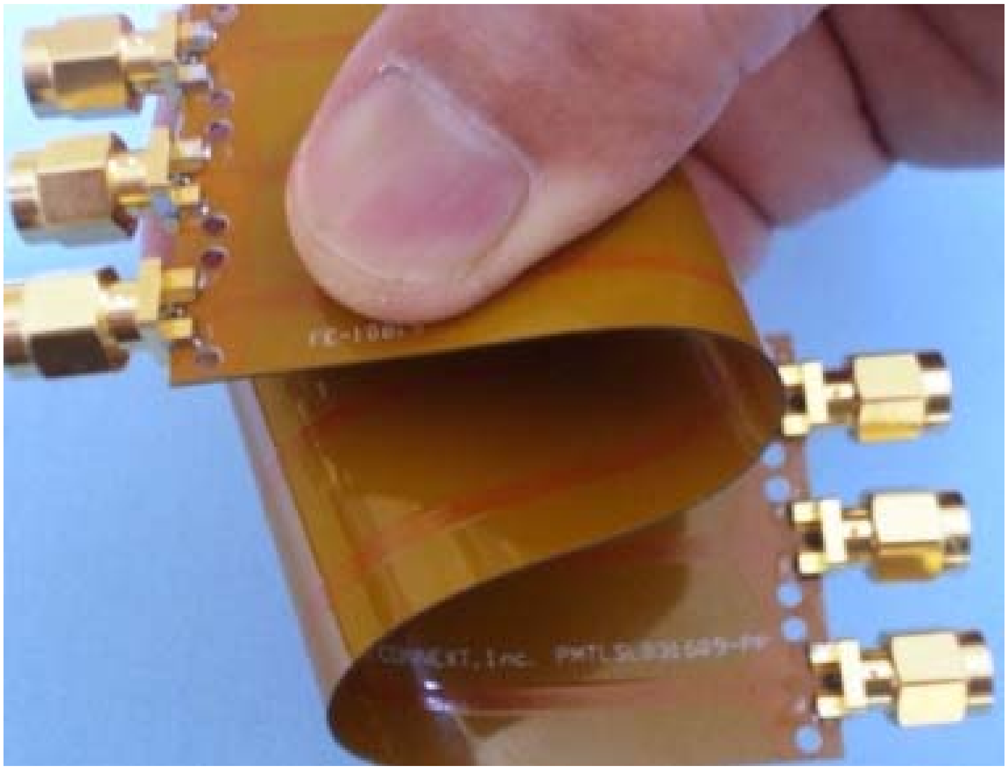


Figure 4: Photograph of triple PMTL Flex of 6" length designed and fabricated using Kapton(PyraluxAP), and existing flex manufacturing processes.

This assembly was designed as a higher bandwidth replacement for an existing RF flex assembly. That product was originally designed as a replacement for 3 SMA micro-coaxial cable assemblies. The original design was constructed using a custom SMA that is optimized for use with flex circuitry. It was constructed using standard microstrip technology and was designed for use in applications up to 10 GHz.

Simulations suggested that we could effectively double the bandwidth of this assembly by switching to an optimized PMTL transmission line in place of the microstrip.

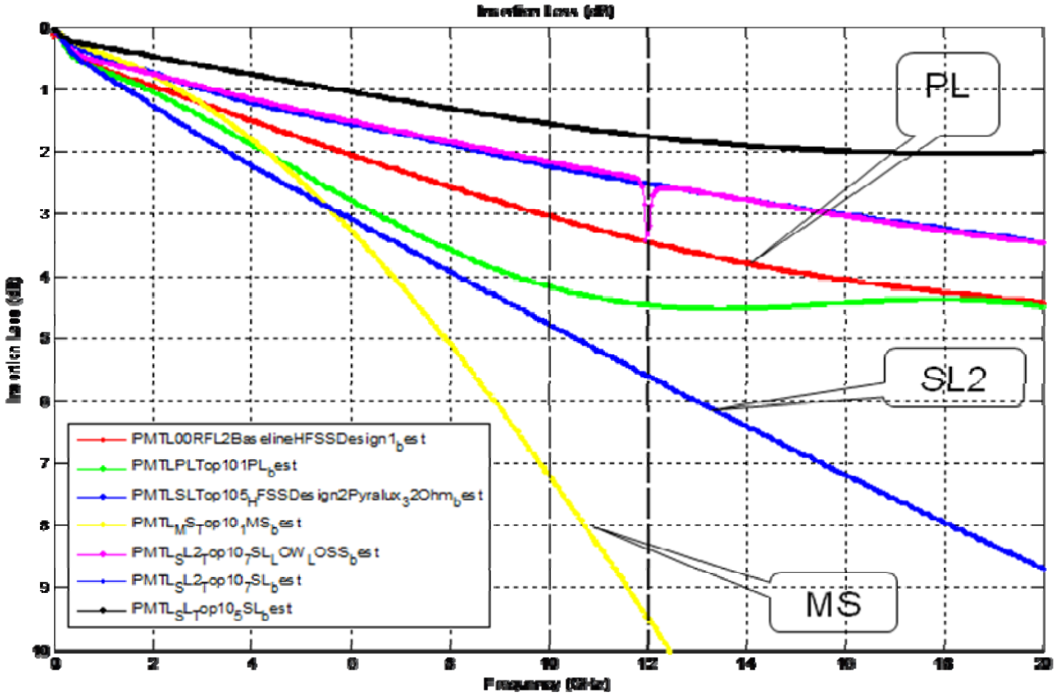


Figure 5: Predicted loss of various transmission line designs.

The data above was derived by optimizing a small unit cell with a 3D solver, and then cascading multiple cells to obtain predicted loss for a 6” total transmission line length. The red trace (labeled “PL”) is the prediction for the optimized PMTL design. The blue trace (labeled “SL2”) is simulated data for a similar stack up based on a strip line design. The yellow trace (labeled “MS”) is simulated data for the existing design.

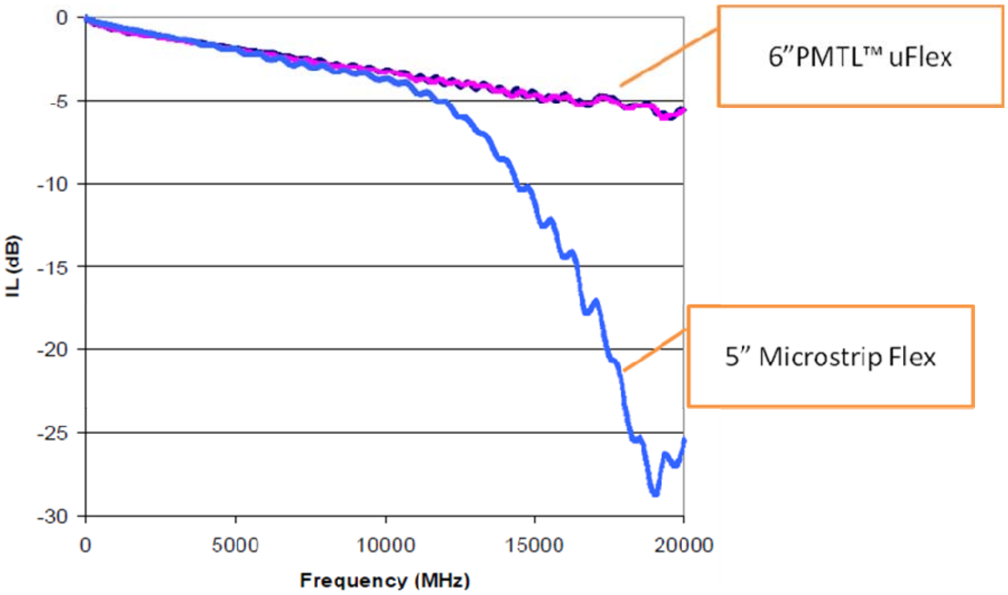


Figure 6: Measured Loss of stripline and PMTL assemblies.

Above is a plot of measured insertion loss data for both the original microstrip design and the equivalent improved PMTL design. It should be noted that the predicted loss presented earlier did not include connector or launch effects. However, the accuracy of the predicted data is quite acceptable with the microstrip predicted at about 4.6 dB at 10 GHz, and measured at about 4.5 dB. The PMTL loss was predicted to be about 3.1 dB at 10 GHz, and 4.5 dB at 20 GHz. This compares well with the 3.2 dB and 5.2 dB values measured, especially considering that connector and launch effects were not included in the predicted losses.

In any case, the predicted performance improvement of the PMTL line is clearly evident with the new design indeed showing a doubling in useable bandwidth with linear, well behaved loss characteristics to at least 20 GHz.

Below, we present measured values of other parameters of interest.

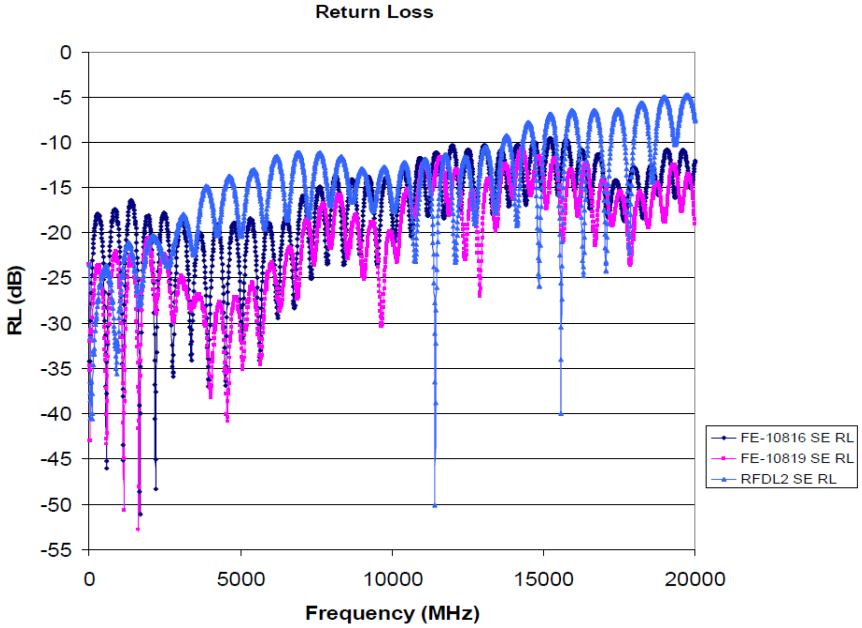


Figure 7: Measured return loss of stripline and PMTL assemblies.

The FE-10819 sample was constructed with the optimized PMTL design, and it demonstrates improved impedance match at higher frequencies compared to the original design. The FE-10816 sample was constructed with non-optimal via sizes to examine the effects of via size variation. The TDR Impedance profile below illustrates these differences.

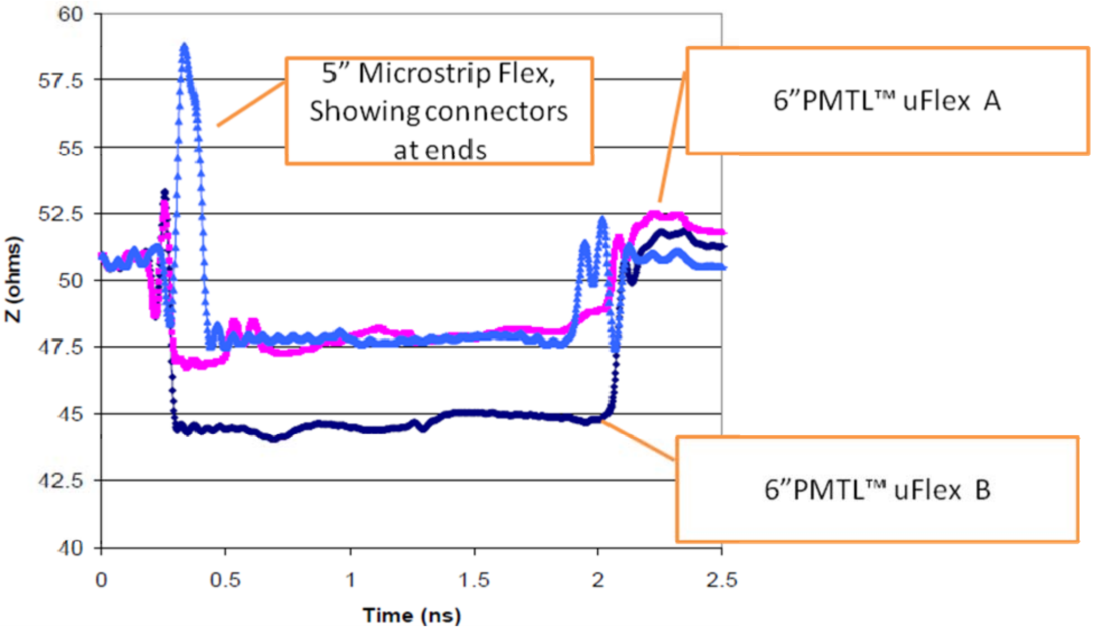


Figure 8: Measured TDR(Tr 36ps) of PMTL Flex compared to an equivalent microstrip flex.

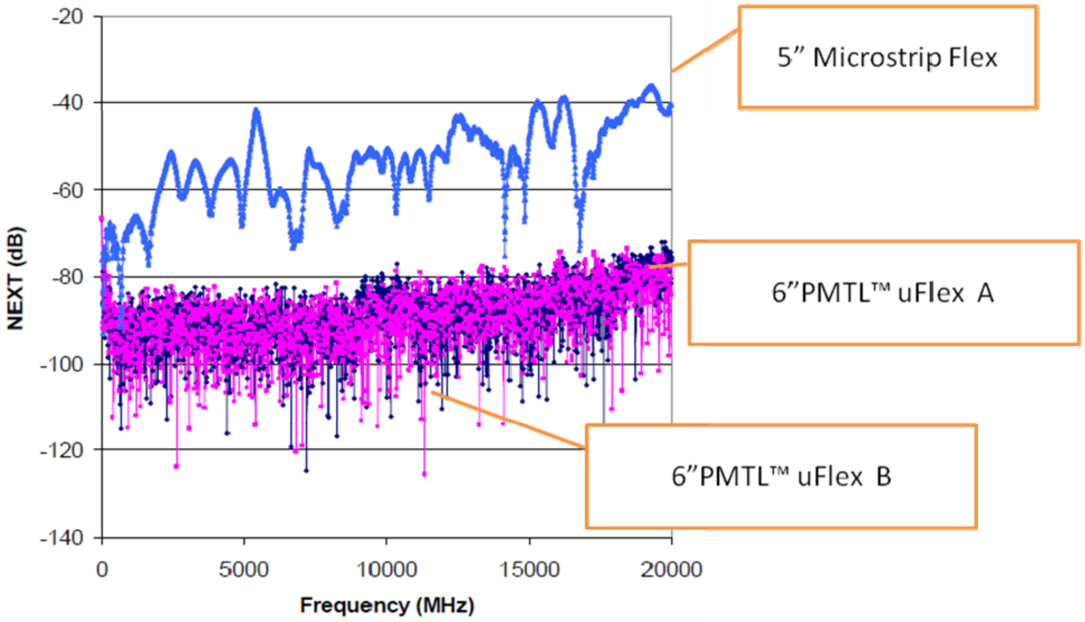


Figure 9: Measured Near End Crosstalk of PMTL flex compared to an equivalent microstrip flex.

The PMTL design demonstrates significantly improved near end crosstalk versus the microstrip design. The PMTL measurement is practically in the noise floor of the instrument, and it shows at least a 30 to 40 dB improvement across the entire frequency band.

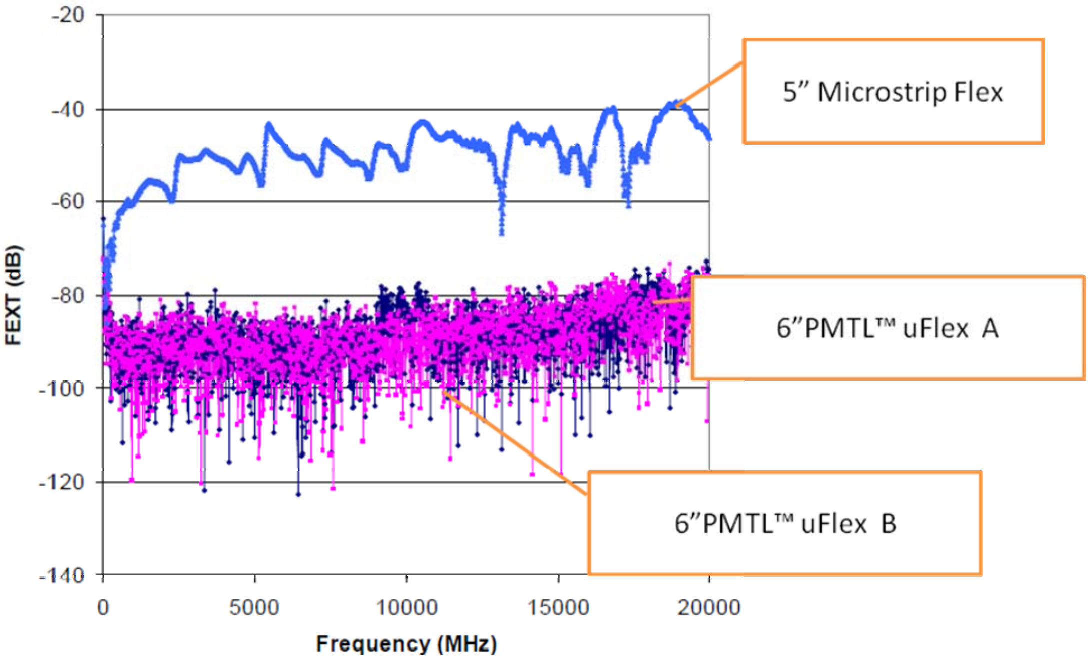
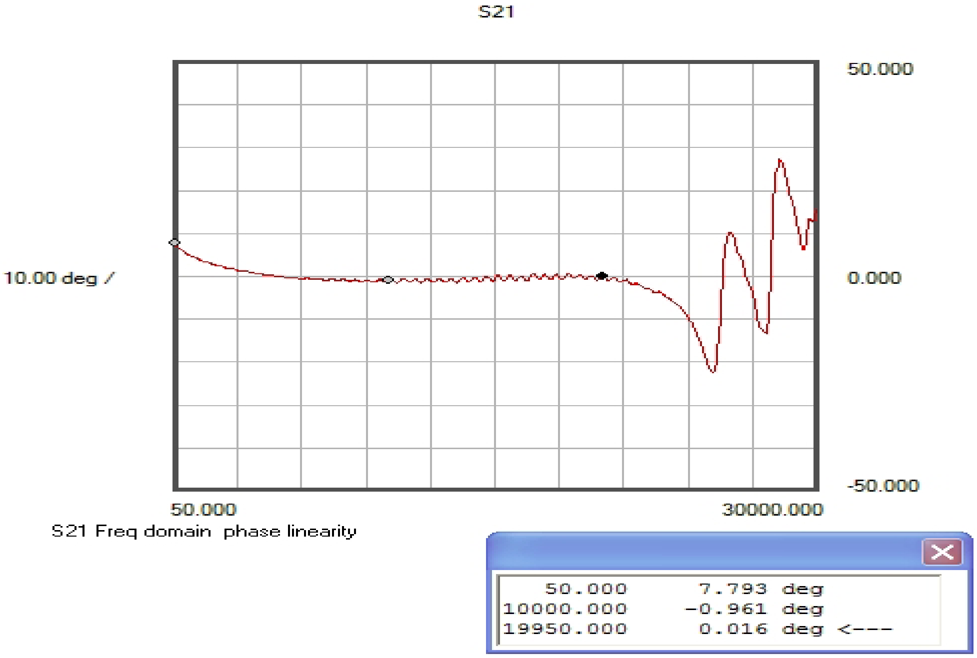


Figure 10: Measured Far End Crosstalk of PMTL Flex compared to equivalent microstrip flex.

The PMTL design shows an even greater improvement in far end crosstalk performance.



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    50.000       7.793 deg
10000.000      -0.961 deg
19950.000       0.016 deg <---
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Figure 11: Measured S21 phase linearity of PMTL Flex.

Rigid Board Stripline to PMTL Comparison

To investigate the performance potential of the PMTL approach in backplane type, long haul applications, we initiated a study into its performance in a long length (36 inch) rigid PCB construction. The use of low cost materials and standard PCB manufacturing technologies was a requirement.

Our desire was to compare PMTL side by side with a typical stripline design. Our initial approach was to compare 50 Ohm single-ended designs which would allow use in single-ended or 100 Ohm differential applications. We have also designed a 100 Ohm differential PMTL line which offers greater density than two 50 Ohm lines, but did not fabricate it for this study because of time constraints.

We began this experiment by designing optimal stripline and PMTL lines using a typical PCB stack up in low cost "FR-4" type material. We simulated loss lengths of 6, 12, 24, and 36 inches. Predicted performance is shown below.

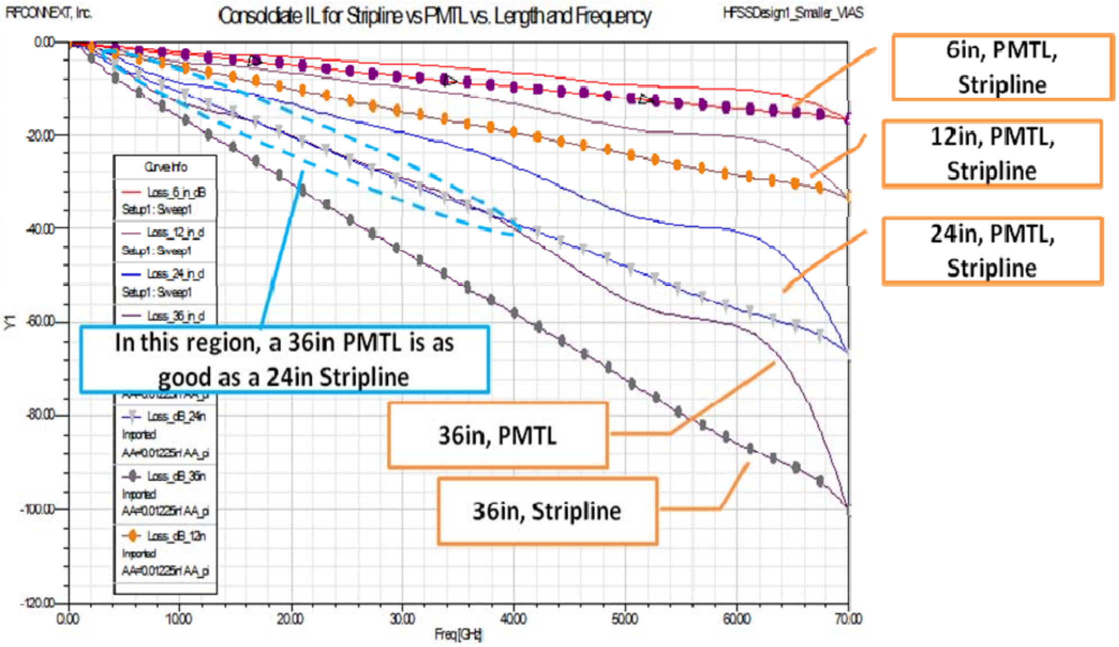

Figure 12: Simulated insertion loss for various lengths of PMTL compared to equivalent stripline.

We then designed an actual PCB test vehicle using these stripline and PMTL designs. We also designed an optimized launch from an edge mount SMA connector to the transmission lines.

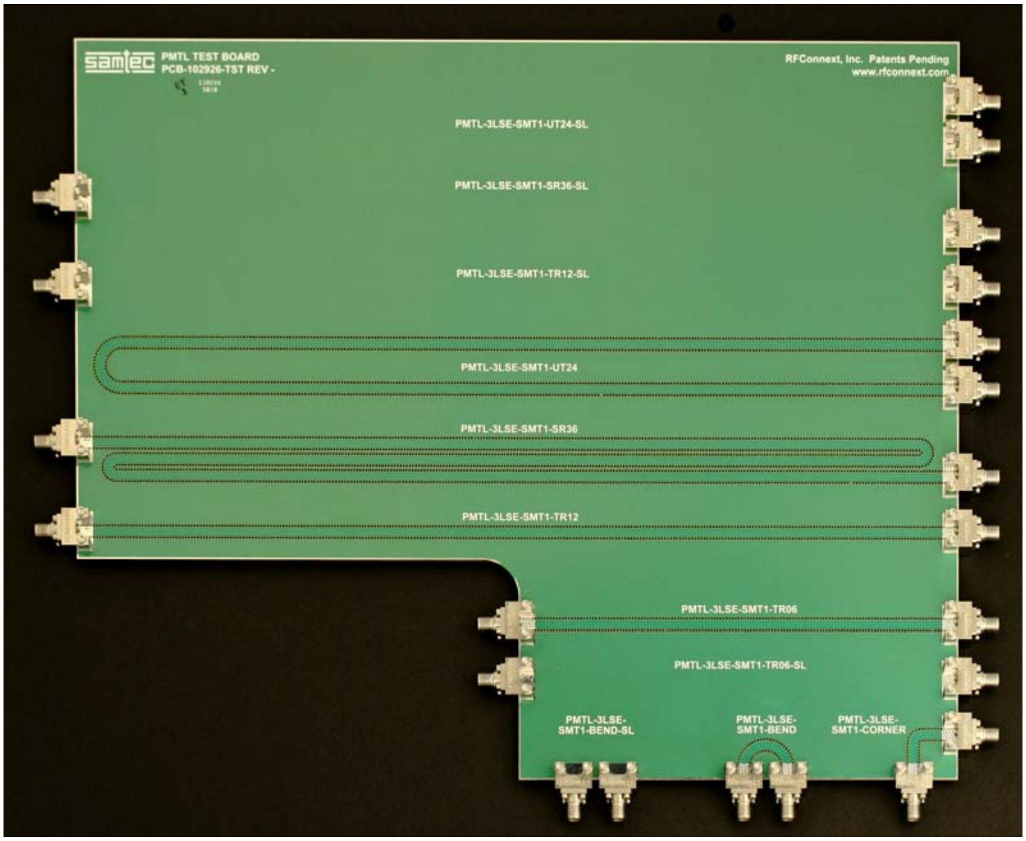

Figure 13: Photograph of PCB test structure.

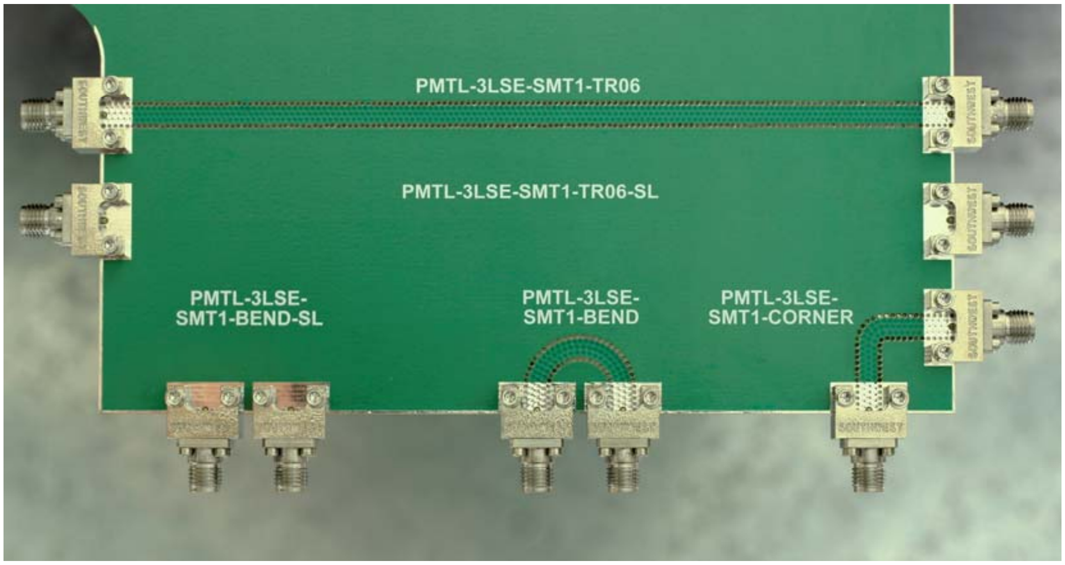

Figure 14: Close up of lower corner of PCB, showing stripline and PMTL structures side by side.

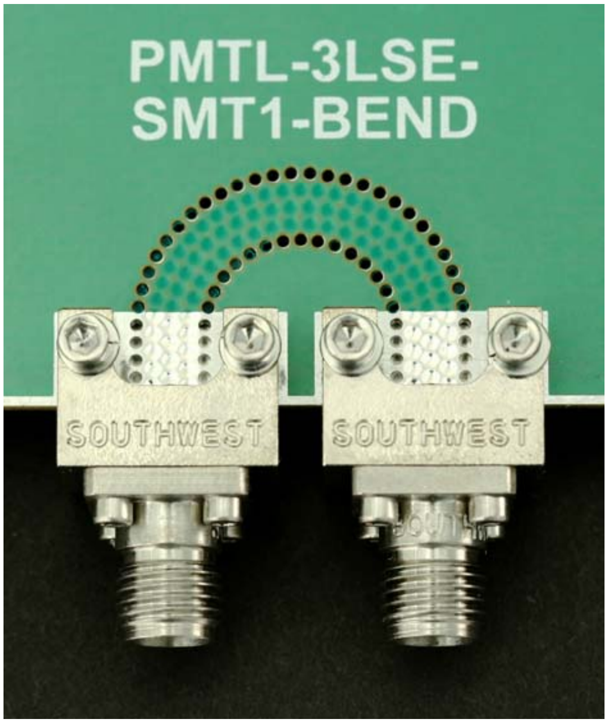

Figure 15: PMTL bend analysis structure.

Below is a plot of measured Insertion Loss for 12” PMTL and stripline traces from the test structure. The PMTL design shows about 4 dB less loss than the stripline, matching well with the predicted values (refer to Figure 12).

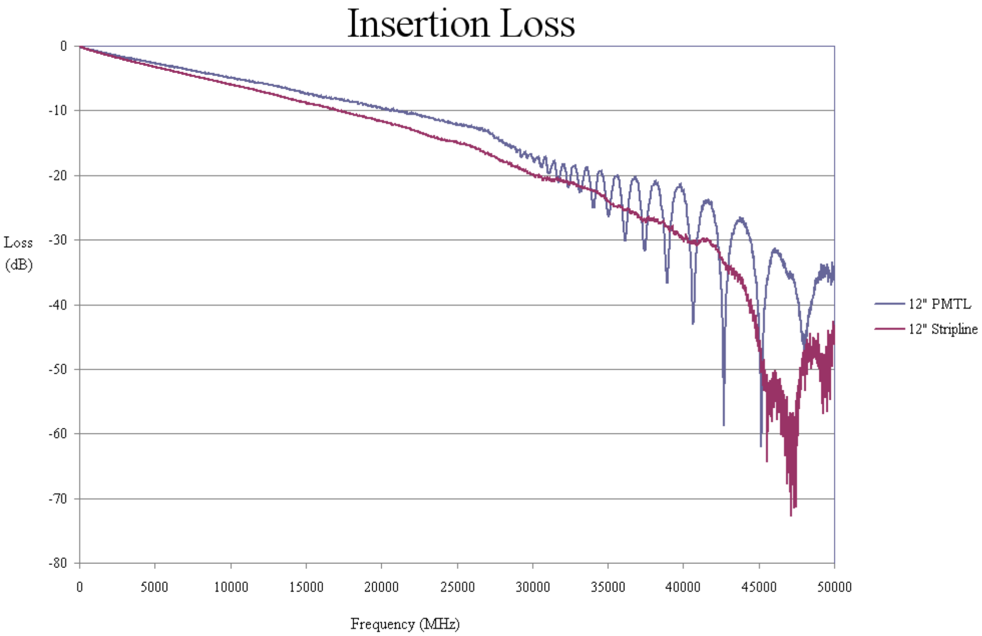

Figure 16: Measured loss of 36” PMTL and stripline traces.

Below is a plot of insertion loss of the 36” PMTL and stripline structures. The PMTL line shows about 6 dB less loss than the stripline at 25 GHz. The simulations (refer to figure 12) predicted a loss difference of about 9 dB, but it should again be noted that the simulation did not include loss effects of the connector and launch areas. The PMTL design also shows near linear loss performance past 40 GHz and shows increasing benefits for longer length runs.

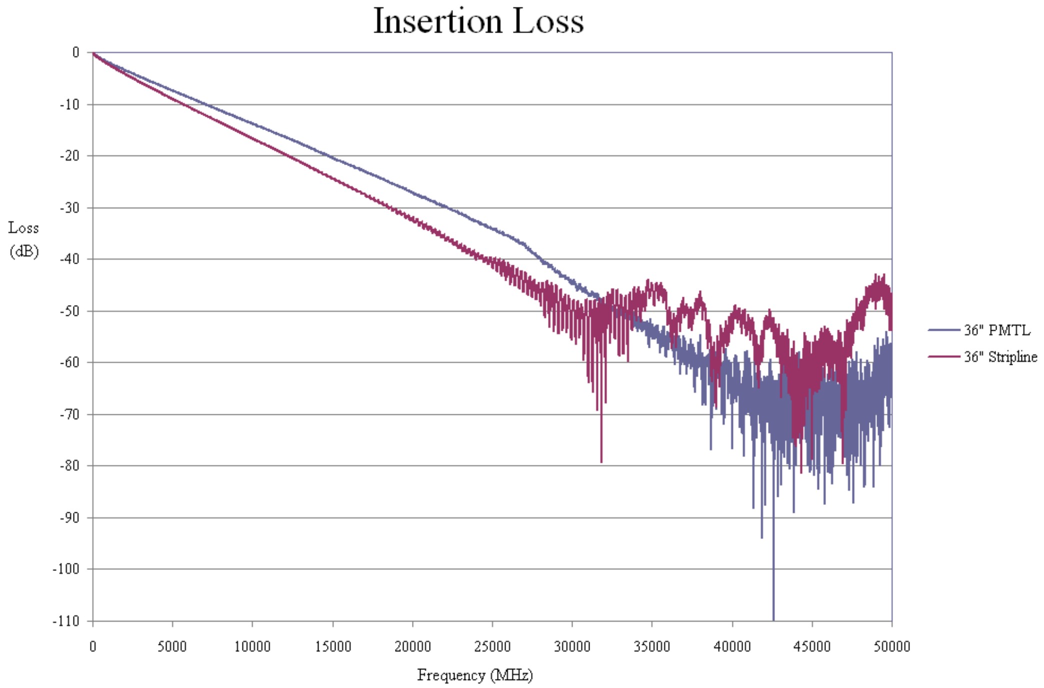

Figure 17: Measured loss of 36” PMTL and stripline traces.

Manufacturing Considerations of the PMTL Design

As with any emerging technology, manufacturing hurdles must be overcome to translate simulated performance to viable product. This is not a trivial process and continues to be one of the challenges with the PMTL approach. While materials and manufacturing methods are identical to standard stripline or microstrip approaches, processing time is greater. This however is being addressed with other variations of the PMTL design approach.

A first case examination of the PMTL approach was implemented in flex circuitry using standard mechanical drilling techniques for the air and metal vias. An initial goal was to benchmark this technology against an existing product. Because interconnect performance at shorter lengths is generally limited by the connector interface and related transition area, we chose a flex cable product with edge-mounted SMAs on the ends. We chose an upper frequency cut off of 20 GHz (single channel) as a reasonable tradeoff between manufacturing limitations and typical current system bandwidth requirements.

The SMA connectors used for edge-mount flex circuit applications are considered electrically insignificant in the measurement comparison between the two technologies (PMTL vs. microstrip).

The via drilling process was ultimately the most time consuming step in manufacturing. In an effort to reduce cost and processing time, we concentrated our efforts on finding ways to shrink the overall structure and minimize the number of drilling operations required.

For a second generation effort, we considered laser drilling. Lasers offer a much faster processing time and less tool wear concerns. Second generation prototypes incorporated these changes by reducing via diameters and eliminating rows of vias (from 5 rows in the first generation to 3 rows) at a small price of reduced inter-line isolation. In addition, we designed an optimized connector that allowed the trace to trace width to be greatly reduced. We expect that as laser drilling technology advances, the cost and processing time will decline. In addition, we continue to develop new PMTL designs which require significantly fewer vias.

After further analysis, we determined that we could also change the materials to a less expensive and more easily processed alternative with minimal impact on performance to 20 GHz.

At first glance, the number of vias required by such a PMTL design might appear to be a deal breaker in a typical PCB design environment. But when system bandwidth requirements are traded off against realistic manufacturing capabilities, the PMTL approach offers significant cost and implementation advantages over more exotic approaches such as optical or wave guide backplanes.

Conclusions

We have described an electromagnetics based design approach for high frequency transmission line structures with specific focus on PCB and flex circuitry applications. We have also presented a new, optimized transmission line structure called PMTL.

PMTL advantages over typical PCB transmission lines include:

- Loss linearity to higher frequencies, (no dispersion) due to TEM mode of propagation
- Phase linearity to higher frequencies, thus predictable well defined delay and skew
- Faster propagation
- Lower DK and DF, thus providing lower signal loss
- Less external interference and lower crosstalk
- More consistent impedance
- Improved overall SIPI

PMTL challenges compared to typical PCB transmission lines include:

- More complex design process
- Potentially longer drilling operations

Compared to optical or other wave guide printed circuit board approaches, the PMTL approach offers these advantages:

- 100% traditional PCB manufacturing processes
- 100% traditional PCB design and layout processes
- DC to 20-40-60-100 GHz bandwidth, as desired
- No need for electrical to optical transceivers or frequency up-converters
- Highly scalable and embeddable into various elements of a high speed interconnect ecosystem

REFERENCES

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