Hybrid S-Parameters Behavior of Weak and Strong Edge-Coupled Differential Lines on PCBs

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Abstract
Imbalanced weakly and strongly edge-coupled differential pairs on printed circuit boards (PCBs), both microstrip (MS) and stripline (SL), are studied under different conditions using mixed-mode S-parameters. The rate of coupling between the lines influences both signal integrity (SI) and electromagnetic compatibility (EMC) of the PCB design. Weakly coupled lines are preferable for SI, but this is not always the case for EMI. Common-mode and mode conversion that negatively affect EMC are typically higher in the weakly coupled cases than in the corresponding strongly-coupled. This is due to technological factors such as the difference in lengths of lines in a differential pair; trapezoid cross-section of signal traces; copper foil roughness; solder mask over microstrip lines; and presence of an epoxy-resin pocket between the stripline traces. In this work, results of 3D full-wave numerical electromagnetic modeling, taking into account these various technological features, are compared with the measured results on the designed test fixtures.

Introduction
Differential signaling plays an important part in high-speed digital design due to high immunity, low cross-talk, and potentially reduced EMI problems. Currently, high-speed serial link interfaces, *e.g.*, USB, Ethernet, InfiniBand, PCI Express, Serial Attached SCSI, operate in the differential signal mode at data rates ranging from a few to tens gigabit-per-second.

Important information for both signal integrity (SI) and electromagnetic compatibility (EMC) **[1], [2]** can be extracted from the hybrid, or mixed-mode S-parameters (S_{dd}, S_{cc}, S_{cd}, and S_{dc}) of differential nets on printed circuit boards (PCBs). Loss and frequency dispersion on a line depend on the electromagnetic properties of PCB materials - substrate dielectric and copper foil. Lines in a differential pair can be strongly (tightly) coupled or weakly (loosely) coupled. The rate of coupling depends on a ratio of the separation distance between the lines to the substrate height, *s/h*.

The differential mode (DM) quality determines SI and is associated with the frequency dispersion and loss of the line. The common mode (CM) is always present on a differential pair and may become a source of unwanted electromagnetic interference (EMI). This is especially true at multigigabit per second data rates in the I/O connector areas, where the transmission lines experience discontinuities and lack of shielding. Imbalanced differential microstrip lines on the top (or bottom) layers of a PCB may be the direct source of EMI. Imbalanced differential striplines on the inner layers of a PCB may also cause unwanted radiation, if the lines come with a certain distance to an edge of the board. In addition to DM and CM, the imbalanced differential pairs produce mode conversion from CM to DM that affects SI, and conversion from DM to CM that may contribute to EMC/EMI problems. The higher the imbalance, the more mode conversion takes place. For this reason, there are restrictions on known sources of imbalance, such as line length differences in a differential pair in high-speed digital designs.

The imbalances in edge-coupled microstrip lines with a bend-type discontinuity, *i.e.*, length difference, were studied numerically and experimentally in **[3]**. There were two types of coupling between lines: strong (tight) coupling ($h>s$) and weak (loose) coupling ($h<s$), where h is the thickness of the substrate, and s is the edge-to-edge separation of the traces. The differential impedance in both cases was 100Ω over the frequency range below 10 GHz. In **[3]**, it was shown that the weak coupling is preferable from both SI and EMI points of view.

Indeed, weakly coupled differential pairs are widely used in high-speed PCB designs **[4]**. However, strong coupling of signal traces may be desirable for space saving purposes. Then the question arises: how close can the lines be pushed together without compromising SI and EMC requirements? It is known that placing differential lines closer to each other reduces the widths of traces, and this always increases losses, especially at the higher frequencies.

Another issue is how various technological features, *e.g.*, frequency dispersive nature of laminate dielectric, conductor surface roughness, trapezoid shape of cross-sections of traces, possible “epoxy pockets” (EP) between the lines, etc., affect the DM, CM, and mode conversion on the loosely and tightly coupled lines, if there are significant imbalances and mismatches on the transmission path? In this work, MS and SL differential pairs, weakly and strongly coupled, with imbalanced line lengths are studied numerically using finite integral technique (FIT) **[5]**, and various technological effects are taken into account up to 40 GHz.

None of these technological factors were considered in **[3]**. However, they were implemented in **[6]**, where edge-coupled microstrip differential pairs, straight and bent, with different length imbalances were modeled numerically, but only as weakly-coupled cases. In **[7]**, both weak- and strong-coupled cases (microstrip and stripline), taking into account some technological factors, were studied numerically, but not experimentally. It was demonstrated numerically that weakly and strongly coupled imbalanced differential pairs behave differently over the wide frequency range. It was shown that though the weakly coupled lines are preferable for SI, due to some technological factors, *e.g.*, conductor surface roughness, trapezoid traces, and epoxy pockets between the traces, CM and mode conversion may be higher in the weakly-coupled cases than in the corresponding strongly-coupled, resulting in EMI problems. In this work, some experimental justification of the results observed in the numerical modeling is given.

Description of Electromagnetic Models

All the numerical electromagnetic simulations are run usingFIT solver **[5]**. The model outline for a differential pair, either microstrip or stripline, is shown in **Figure 1.** The structures in the general case are asymmetrically placed on a PCB ($h_{t1} \neq h_{t2}$) and have line length imbalance ($L_1 \neq L_2$). Ports 1 and 3 are on one side of the board, and Ports 2 and 4 are on the other.

The cross-sectional views of microstrip and stripline structures are shown in **Figure 2.** Copper foil roughness is modeled as effective roughness dielectric (ERD) **[8]**, **[9]**. In some stripline cases, an epoxy-resin pocket (EP) between the traces is modeled, as is shown in **Figure 2(b)**. The dielectric properties of this pocket are different from the homogenized parameters of the dielectric matrix where these traces are embedded. This provides different conditions for propagating CM and DM, since the DM fields are concentrated between the traces, while the CM fields are mainly between the traces as a whole and the ground planes.

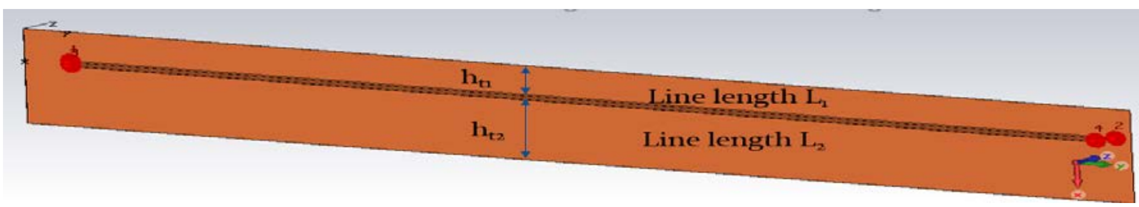


Figure 1– Schematically Shown Modeled PCB Structures

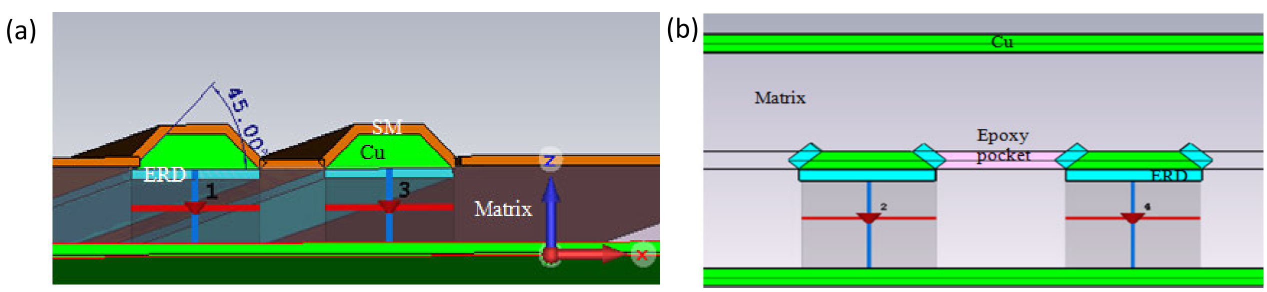


Figure 2 - Cross-sections of Modeled Microstrip (a) and Stripline (b)Differential Pairs

The cross-sections of all the modeled structures, both weak- and strong-coupled, provide the 100-Ω differential impedance. The signal traces are either rectangular (90^0), or trapezoid with the base angle of 60^0 or $45^0$with respect to the horizontal planes of the trace.

In all the cases, the dielectric matrix was modeled as the dispersive PPO Blend with the parameters as in **[8], [9]**. The frequency characteristics of its dielectric constant (DK) and dissipation factor (DF) are presented in **Figure 3**. These dielectric data were refined from copper roughness effects using the improved differential extrapolation roughness measurement (DERM) technique **[10]** and conductor roughness profile quantification using SEM pictures **[11]**.

An equivalent ERD layer corresponding to the standard (STD) foil is placed under the traces. STD foil is smooth on the "oxide" (drum) side, and is rough on the "foil" (matte) side. Since roughness on the "oxide" side of STD is significantly lower than that on the "foil" side, the ERD layer is modeled on the "foil" side only. The parameters of the ERD corresponding to STD foil are taken according to the design curves in **[8], [9]**. The average peak-to-valley roughness amplitude of the STD foil is A_r=6.2 µm; the ERD layer thickness in the model is $T_r=2A_r$=12.4 µm. Its dielectric parameters are independent of frequency: $\varepsilon_{rough}'=12$ and $\tan\delta_{rough}=0.17$. The ground planes (GPs) in all the models have the same thickness, t_{gp}=0.0175 mm. The surface roughness on the GPs is not modeled due to much lower current density on them, as compared to the signal traces. The peculiarities of models for microstrip and stripline differential pairs are given below.

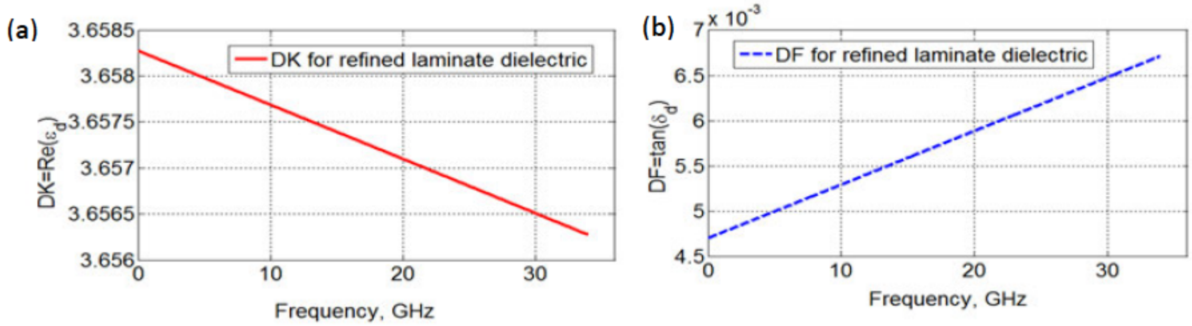


Figure 3–DK (a) and DF (b) of PCB Substrate (PPO Blend) Dielectric.

A. Microstrip Model

The thickness of copper on the microstrip line is t_{ms}=0.0462 mm, and the dielectric substrate height is d=0.1 mm. In the weak-coupled lines, the width of each signal trace is w_t= 0.203 mm, and separation distance is s_t=0.18 mm. The ratio s_t/d=1.8>1 in the weak-coupled case. In the strong-coupled case, the trace width is w_t=0.1735 mm, the trace spacing is s_t=0.0889 mm, and the ratio s_t/d=0. 889<1.The typical solder mask (SM) thickness is t_{sm}=0.5mil=0.0127 mm, and the constant dielectric parameters over the frequency range of interest are taken as ε'_{sm}=4.5 and tanδ_{sm}=0.05 as in **[6]**.

B. Stripline Model

The modeled striplines have the total distance between the ground planes of $d_s=d_1+d_2$=0.22 mm with $d_1=d_2$. Copper thickness on the traces and on the ground planes is $t_{sl}=t_{gp}$=0.0175 mm. In the weak-coupled lines, the width of each trace is w_t=0.087 mm and the trace spacing is s_t=0.275 mm. In the strong-coupled case, w_t=0.104 mm, and is s_t=0.1 mm. In some cases, the epoxy pocket region between the traces is modeled as shown in **Figure2(b)**. It is assumed to be pure non-dispersive epoxy resin, with ε'_{epoxy}=3.0 and tanδ_{epoxy}=0.07 at 10 GHz; these parameters are different from those of the ambient dielectric matrix. ERD layers placed on the sides of the traces may also affect mixed-mode S-parameters.

Results of Numerical Modelling

Time-domain simulations using finite integral technique (FIT) solver were used to model the microstrip and stripline differential structures. Herein, we provide the data for the mixed-mode S-parameters for differential pairs with 80-mm/80.127-mm imbalanced lines, *i.e.*, length imbalance is 5 mil (0.127 mm), which is typical for the PCB technology. In the given numerical examples, the lines are equidistant with respect to the edges of the PCB in the model: the distances between the edge of each trace to the nearest PCB edge are $h_{t1}=h_{t2}$=2 mm.

The results are given for trapezoid and rectangular traces and for weak/strong coupling. The slopes of the linearized frequency dependencies (in dB/GHz) are calculated to show how fast mixed-mode parameters change with frequencydue to various technological factors. Though this data is given for the lengths 80 mm and 80.127 mm of two lines in a differential pair, it can be normalized by the length and recalculated for the other lengths of the lines.

A. Microstrip Differential Lines

The modeled magnitudes of mixed-mode S-parameters $|S_{cc21}|$, $|S_{dd21}|$, and $|S_{cd21}|$ as functions of frequency for the cases of weak and strong coupling and rectangular cross-section of the traces are given in **Figures 4-6**.

From **Figure 4**, it is seen that insertion loss (IL) for CM becomes slightly larger for the strong-coupled case at the higher frequencies (>30 GHz) than for the weak-coupled lines, but below ~30 GHz the difference is insignificant. Comparing **Figures 5** and **4**, one can see that DM and CM have similar trends, and strong coupling at the higher frequencies results in the higher loss for DM than weak coupling. Overall, IL for DM is slightly smaller than for CM in both weak- and strong-coupled cases. In all the modeled cases (with/without solder mask and with/without copper roughness), IL for both CM and DM is higher when SM and ERD are taken into account, and the influence of ERD on damping dominates over the influence of SM.

Mode conversion parameter, herein $|S_{cd21}|$, is plotted in **Figure 6** for the case of the rectangular traces. In general, for comparatively small length imbalances in differential pairs, mode conversion does not depend much on whether there is weak or strong coupling. However, for the frequencies below 10 GHz, foil roughness (ERD) may cause slight enhancement of mode conversion when coupling is strong. This is because the rougher surface is beneath the traces, and at the strong coupling the microwave field is more concentrated between the traces, where DM mode propagates, rather than between the traces and the ground, where CM propagates. As the CM fields are less strongly coupled, a subtle effect of foil roughness becomes more significant, causing the bigger difference in the mode conversion. The mode conversion enhancement will be stronger as length imbalance increases.

The computed data for two frequencies, 10 GHz and 40 GHz, as well as slopes of the linearized frequency characteristics are shown in **Figures 4-6** and summarized in **Table 1**.

The frequency dependences analogous to those in **Figures 4-6** are also obtained for the cases of the trapezoid traces. The results for the 60^0 traces are plotted in **Figures 7-9** and summarized in **Table 2**; for the 45^0 traces, the results are presented in **Figures 10-12** and in **Table 3**.From these results, it follows that that both solder mask and conductor roughness modeled as ERD result in an increased insertion loss for both DM and CM. The influence of ERD on the insertion loss is stronger than that of the solder mask, which is seen when comparing the slopes for $|S_{dd21}|$ and $|S_{cc21}|$ as the functions of frequency. Both weak and strong coupling show similar trends for all types of trace cross-sections - rectangular and trapezoid.

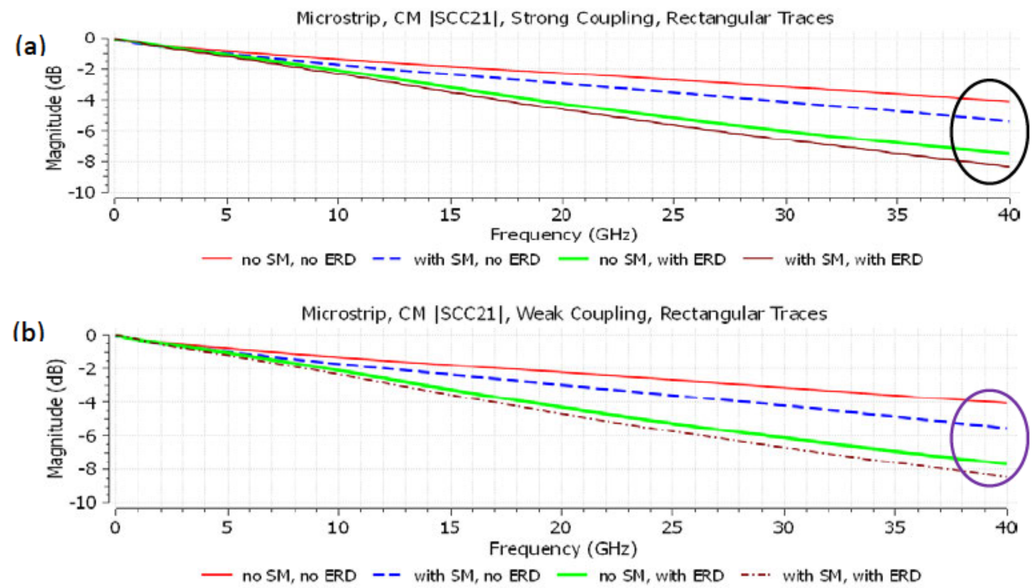


Figure 4– Insertion Loss for Common Mode in an Imbalanced (5 mil) Microstrip Pair with Rectangular Traces at Strong (a) and Weak (b) Coupling

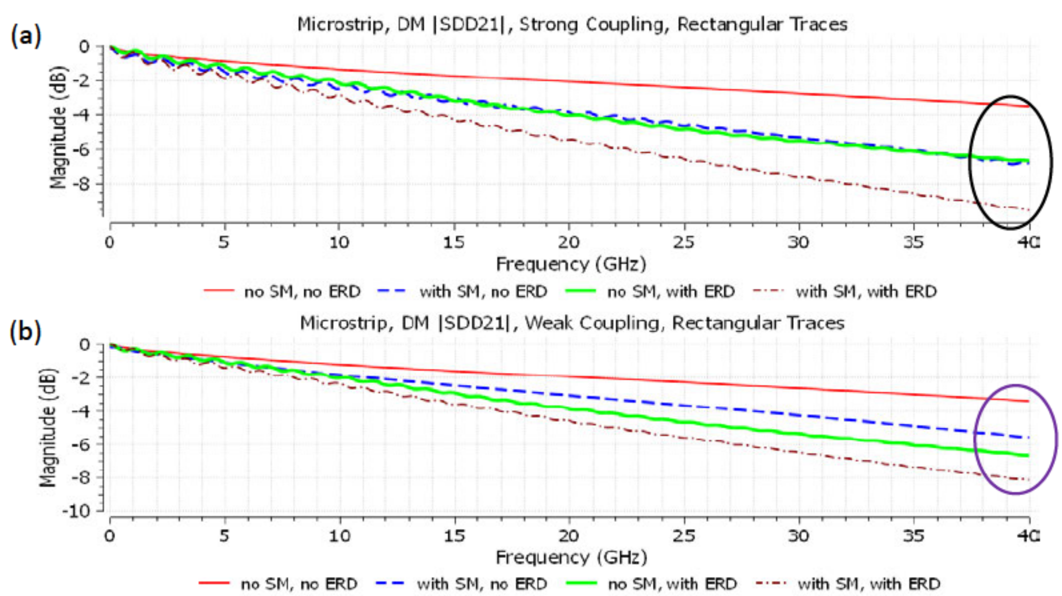


Figure 5– Insertion Loss for Differential Mode in an Imbalanced (5 mil) Microstrip Pair with Rectangular Traces at Strong (a) and Weak (b) Coupling

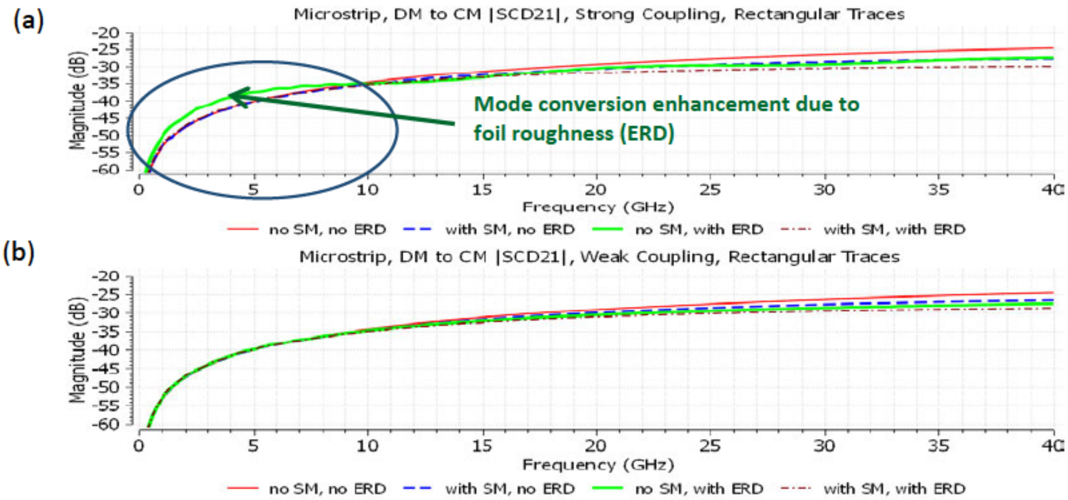


Figure 6– Insertion Loss for Mode Conversion in an Imbalanced (5 mil) Microstrip Pair with Rectangular Traces at Strong (a) and Weak (b) Coupling

Table 1- Mixed-mode S-parameters for Imbalanced (5 mil) Microstrip Differential Pair with Rectangular Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled	Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, rect. traces	|Scc21|	-1.378	-4.096	-0.0906	No SM, no ERD	Weak coupling, rect. traces	|Scc21|	-1.330	-4.075	-0.0915	No SM, no ERD
		-1.759	-5.389	-0.1210	With SM, no ERD			-1.732	-5.556	-0.1247	With SM, no ERD
		-2.092	-7.504	-0.1804	No SM, with ERD			-2.130	-7.695	-0.1843	No SM, with ERD
		-2.316	-8.307	-0.1997	With SM & ERD			-2.357	-8.473	-0.2033	With SM & ERD
	|Sdd21|	-1.342	-3.466	-0.0708	No SM, no ERD		|Sdd21|	-1.230	-3.397	-0.0722	No SM, no ERD
		-2.221	-6.739	-0.1386	With SM, no ERD			-1.842	-5.580	-0.1246	With SM, no ERD
		-2.148	-6.639	-0.1497	No SM, with ERD			-2.031	-6.661	-0.1543	No SM, with ERD
		-2.856	-9.528	-0.2224	With SM & ERD			-2.391	-8.158	-0.1922	With SM & ERD
	|Scd21|	-34.67	-24.75	+0.3307	No SM, no ERD		|Scd21|	-34.44	-24.56	+0.3293	No SM, no ERD
		-34.70	-27.47	+0.2410	With SM, no ERD			-34.43	-26.48	+0.2650	With SM, no ERD
		-34.70	-27.46	+0.2413	No SM, with ERD			-34.50	-27.45	+0.2350	No SM, with ERD
		-35.29	-29.98	+0.1770	With SM & ERD			-34.94	-28.73	+0.2070	With SM & ERD

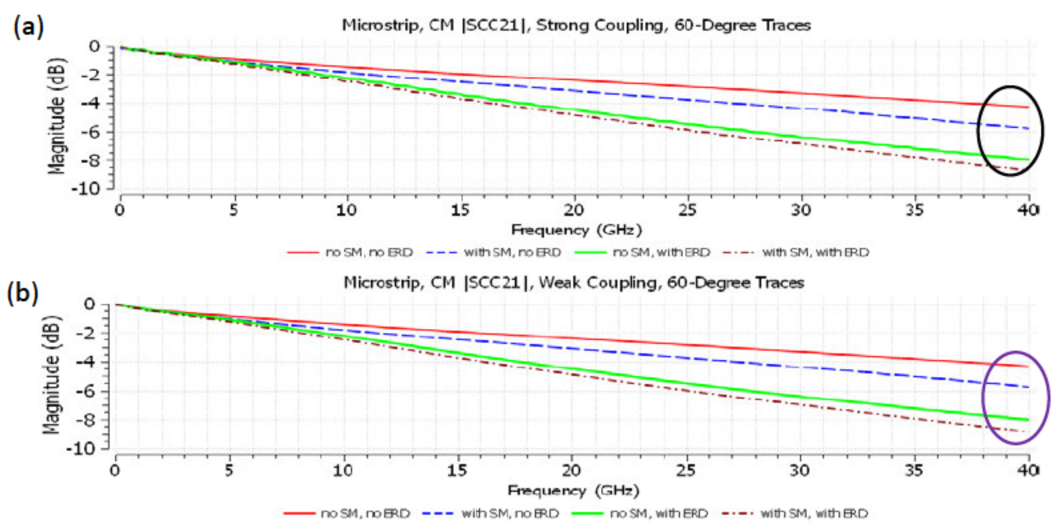


Figure 7– Insertion Loss for Common Mode in an Imbalanced (5 mil) Microstrip Pair with 60^0 Traces at Strong and Weak Coupling

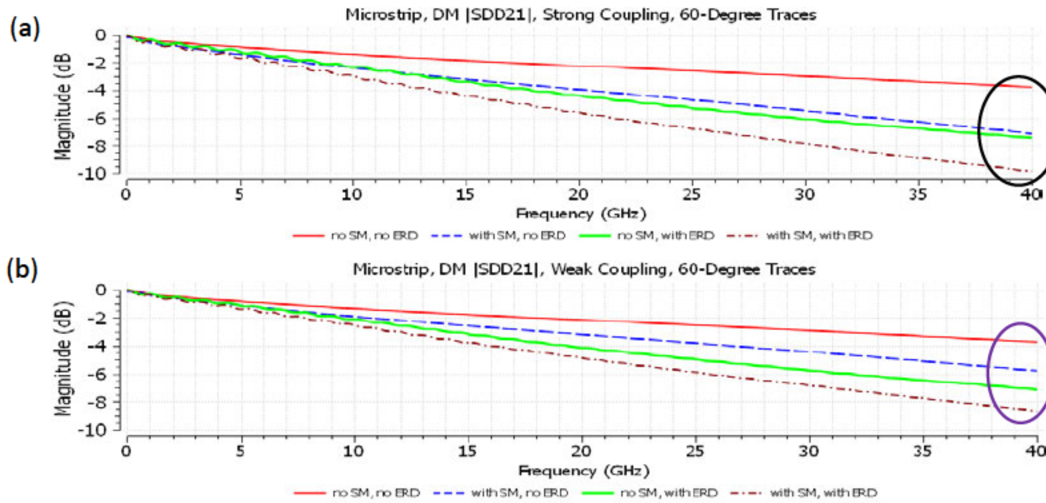


Figure 8– Insertion Loss for Differential Mode in an Imbalanced (5 mil) Microstrip Pair with 60^0 Traces at Strong (a) and Weak (b) Coupling

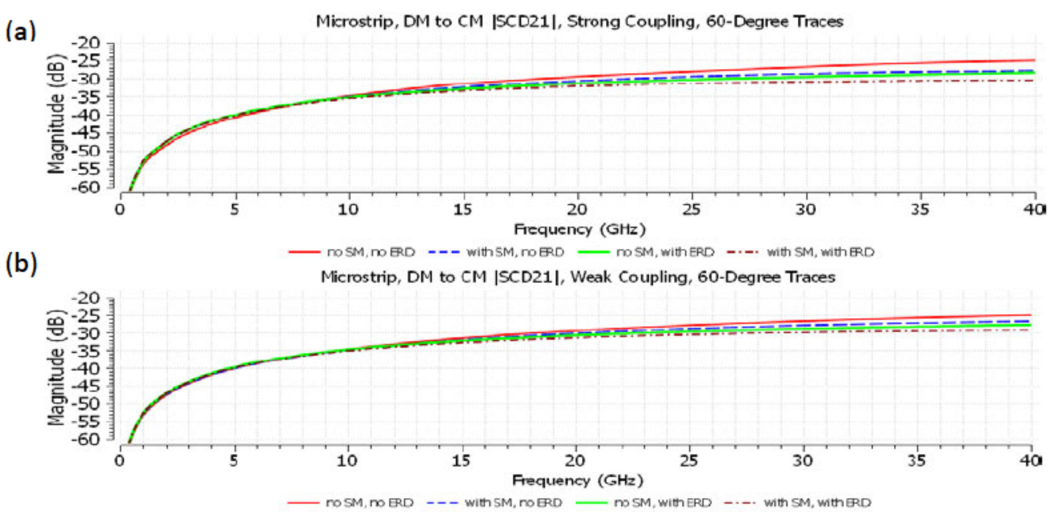


Figure 9– Insertion Loss for Mode Conversion in an Imbalanced (5 mil) Microstrip Pair with 60^0 Traces at Strong (a) and Weak (b) Coupling

Table 2- Mixed-mode S-parameters for Imbalanced (5 mil) Microstrip Differential Pair with 60^0 Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled	Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, 60° traces	|Scc21|	-1.499	-4.293	-0.0931	No SM, no ERD	Weak coupling, 60° traces	|Scc21|	-1.448	-4.329	-0.0960	No SM, no ERD
		-1.874	-5.804	-0.1310	With SM, no ERD			-1.448	-5.758	-0.1437	With SM, no ERD
		-2.311	-7.974	-0.1888	No SM, with ERD			-2.243	-8.013	-0.1923	No SM, with ERD
		-2.515	-8.732	-0.2072	With SM & ERD			-2.496	-8.849	-0.2177	With SM & ERD
	|Sdd21|	-1.432	-3.779	-0.0782	No SM, no ERD		|Sdd21|	-1.359	-3.730	-0.0790	No SM, no ERD
		-2.381	-7.155	-0.1591	With SM, no ERD			-1.917	-5.784	-0.1289	With SM, no ERD
		-2.381	-7.447	-0.1689	No SM, with ERD			-2.114	-7.150	-0.1679	No SM, with ERD
		-2.971	-9.869	-0.2300	With SM & ERD			-2.554	-8.648	-0.2031	With SM & ERD
	|Scd21|	-34.86	-25.01	+0.3283	No SM, no ERD		|Scd21|	-34.61	-24.94	+0.3223	No SM, no ERD
		-35.13	-27.81	+0.2440	With SM, no ERD			-34.71	-26.71	+0.2667	With SM, no ERD
		-35.34	-28.37	+0.2323	No SM, with ERD			-34.90	-27.73	+0.2390	No SM, with ERD
		-35.53	-30.44	+0.1697	With SM & ERD			-35.09	-29.19	+0.1967	With SM& ERD

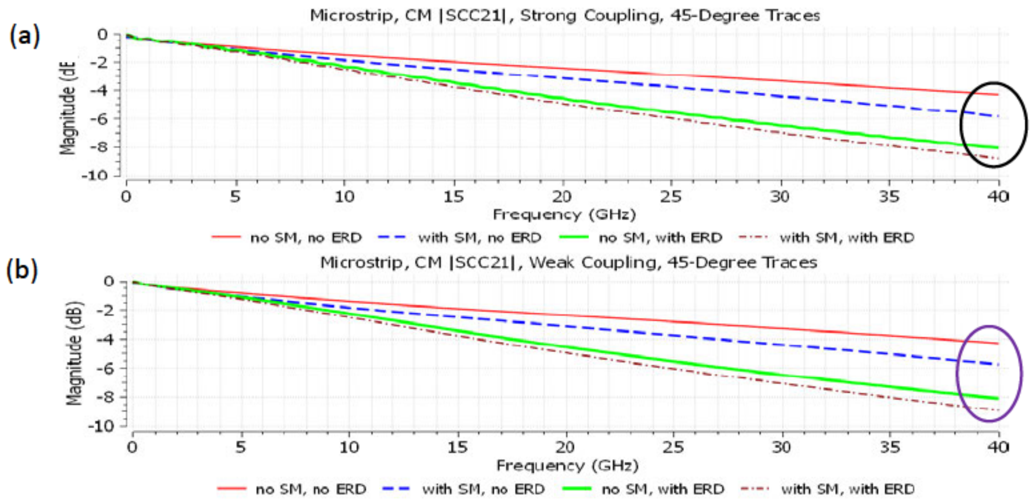


Figure 10– Insertion Loss for Common Mode in an Imbalanced (5 mil) Microstrip Pair with 45^0 Traces at Strong (a) and Weak (b) Coupling

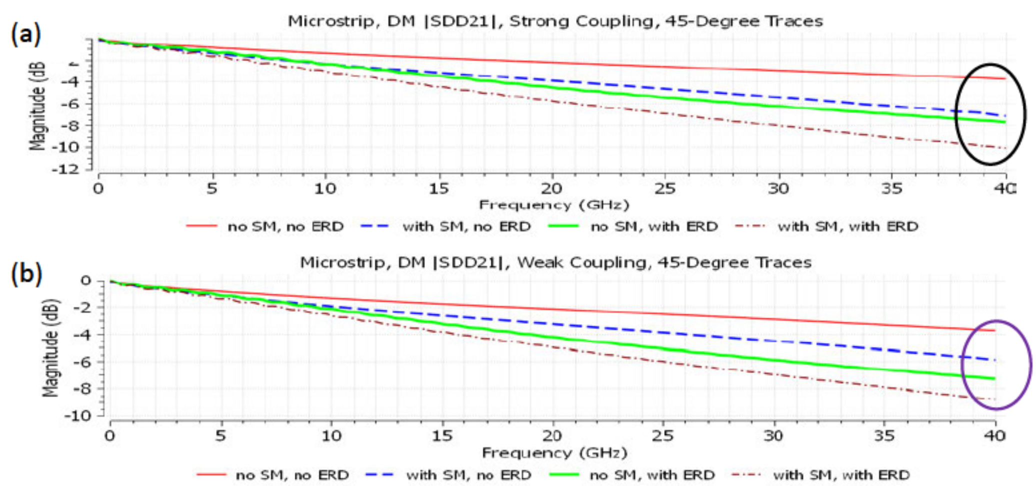


Figure 11– Insertion Loss for Differential Mode in an Imbalanced (5 mil) Microstrip Pair with 45^0 Traces at Strong (a) and Weak (b) Coupling

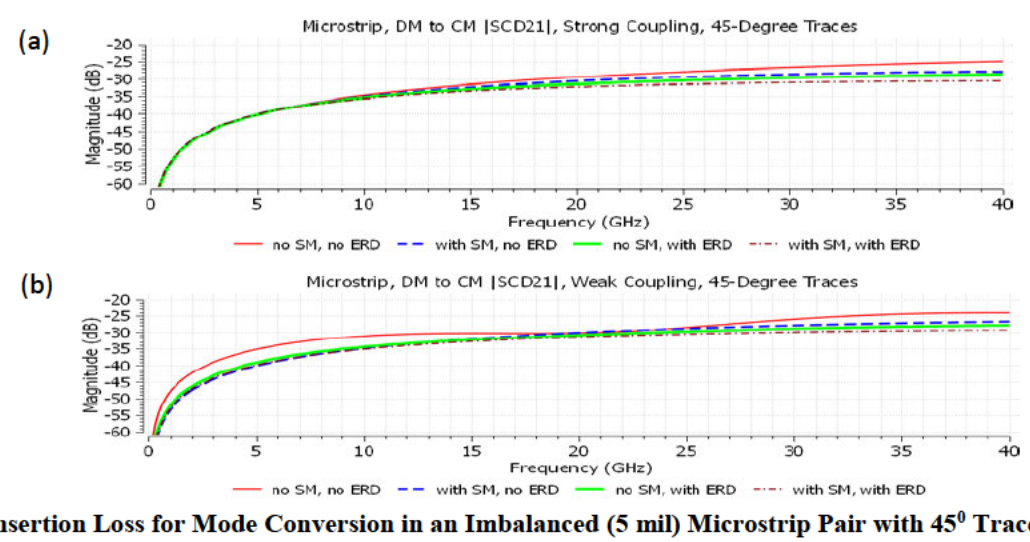


Figure 12– Insertion Loss for Mode Conversion in an Imbalanced (5 mil) Microstrip Pair with 45^0 Traces at Strong (a) and Weak (b) Coupling

Table 3- Mixed-mode S-parameters for Imbalanced (5 mil) Microstrip Differential Pair with 45^0 Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled	Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, 45° traces	|Scc21|	-1.514	-4.315	-0.0934	No SM, no ERD	Weak coupling, 45° traces	|Scc21|	-1.417	-4.295	-0.0959	No SM, no ERD
		-1.878	-5.846	-0.1323	With SM, no ERD			-1.842	-5.771	-0.1310	With SM, no ERD
		-2.347	-8.066	-0.1906	No SM, with ERD			-2.261	-8.096	-0.1945	No SM, with ERD
		-2.542	-8.795	-0.2084	With SM & ERD			-2.522	-8.948	-0.2142	With SM & ERD
	|Sdd21|	-1.408	-3.770	-0.0787	No SM, no ERD		|Sdd21|	-1.352	-3.709	-0.0786	No SM, no ERD
		-2.393	-7.142	-0.1583	With SM, no ERD			-1.938	-5.874	-0.1312	With SM, no ERD
		-2.393	-7.672	-0.1760	No SM, with ERD			-2.129	-7.300	-0.1724	No SM, with ERD
		-3.047	-10.101	-0.2351	With SM & ERD			-2.615	-8.800	-0.2062	With SM & ERD
	|Scd21|	-34.65	-24.960	+0.3230	No SM, no ERD		|Scd21|	-31.180	-24.150	+0.2343	No SM, no ERD
		-35.051	-27.851	+0.2400	With SM, no ERD			-34.431	-26.761	+0.2557	With SM, no ERD
		-35.052	-28.582	+0.2157	No SM, with ERD			-34.432	-27.852	+0.2193	No SM, with ERD
		-35.560	-30.622	+0.1647	With SM & ERD			-35.121	-29.31	+0.1937	With SM & ERD

As the trapezoid base angle becomes sharper, insertion losses for both DM and CM increase, especially when ERD and SM are taken into account. However, the increase of IL is only about 0.2-0.3 dB as compared to the rectangular traces at 40 GHz for the given lengths of the traces. As traces become longer, this difference may be substantial.

As for comparing the insertion loss on CM and DM, it is seen that for all cross-sections of the traces, the insertion loss for DM is slightly smaller than that for CM in both weak- and strong-coupled cases.

Mode conversion for trapezoid traces appears to be slightly larger in the weak-coupled case than for the strong-coupled. This is because of the more inhomogeneous field between the trapezoid traces as compared to the rectangular ones. The 60^0 traces give intermediate results between the 90^0 and 45^0 cases (see **Tables 1-3**); however, the difference is insignificant (fraction of a dB). Both ERD and SM damp mode conversion in the cases with trapezoid traces.

B. Stripline Differential Lines

The modeling results for edge-coupled stripline differential pairs are shown in **Figures 13-18**, and are also summarized in **Tables 4-6**.

The insertion loss for the common mode is presented in **Figure 13**. In this case, conductor surface roughness is taken into account, but epoxy pocket is not modeled; instead, the homogeneous dielectric matrix is between the traces. From **Figure 13**, it is seen that CM damping is higher with weak coupling than with strong coupling. In the weak coupled case, the sharper the base angle of the trapezoid cross-section, the higher IL for the CM. But in the strong-coupled case, the 60^0 traces show the lowest IL for CM as compared to $45^0$and 90^0 traces. This is related to the optimal redistribution of the fields between the CM and DM when ERD is present at 60^0 angle of the trapezoid trace. In **Figure 14**, ERD is not taken into account, and even though the epoxy pocket is modeled, there is less CM component insertion loss for the rectangular traces than for the trapezoid ones. However, the curves for 45^0 and 60^0 almost coincide for both strong and weak coupling.

Figures 15and **16** demonstrate that the DM is more damped at the strong coupling than at the weak one. With ERD modeled, one can see that the 60^0 case in the least lossy as compared to 90^0 and 45^0 cases; the sharpest 45^0 case causes the highest loss for the DM. However, if the ERD is not taken into account, the cases for 60^0 and 45^0 are almost identical in both the strong and weak-coupled cases. Since the DM is mainly concentrated between the traces, where the epoxy pocket can be, the effect of the epoxy pocket is more significant as the lines are stronger coupled.

Figures 17 and **18** show, respectively, the mode conversion (DM to CM) in the cases, when ERD is present and not present. When ERD is modeled, there is significant mode conversion enhancement (~10-15 dB) in the weak-coupled case for 45^0traces, and just a slight increase (<2 dB) for the 60^0 as compared to the rectangular traces. However, when ERD is not modeled, even if there is an epoxy resin pocket between the traces, there is no such mode conversion enhancement. The cases for 60^0 and 45^0 almost overlap, while the rectangular traces result in the slightly higher mode conversion for the weakly coupled case.

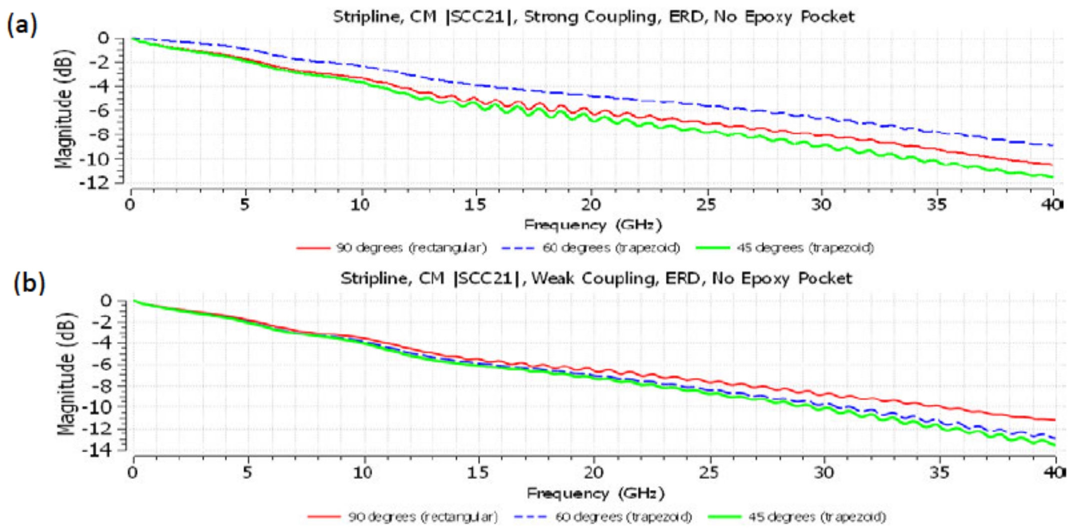


Figure 13– Insertion Loss for Common mode in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

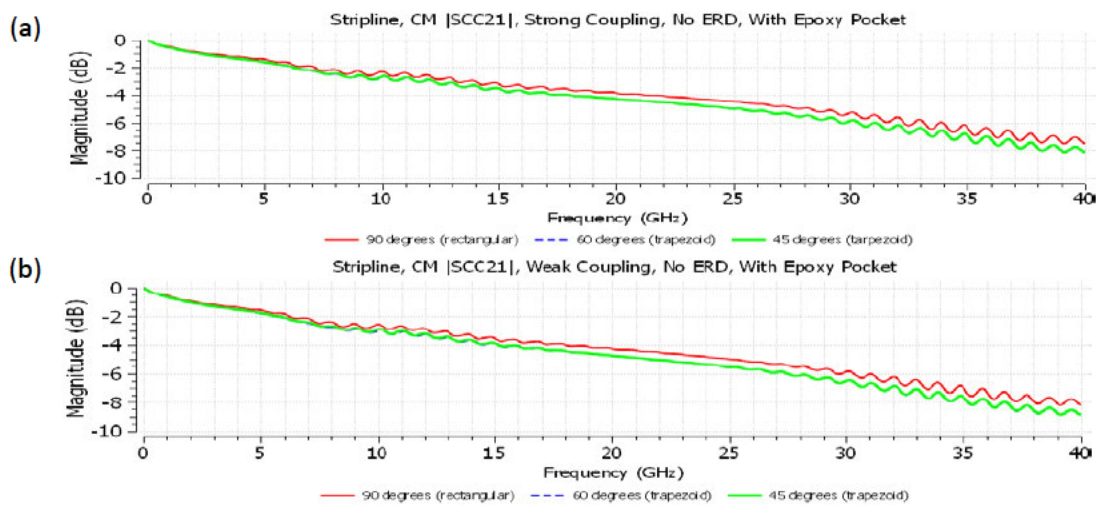


Figure 14– Insertion Loss for Common mode in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

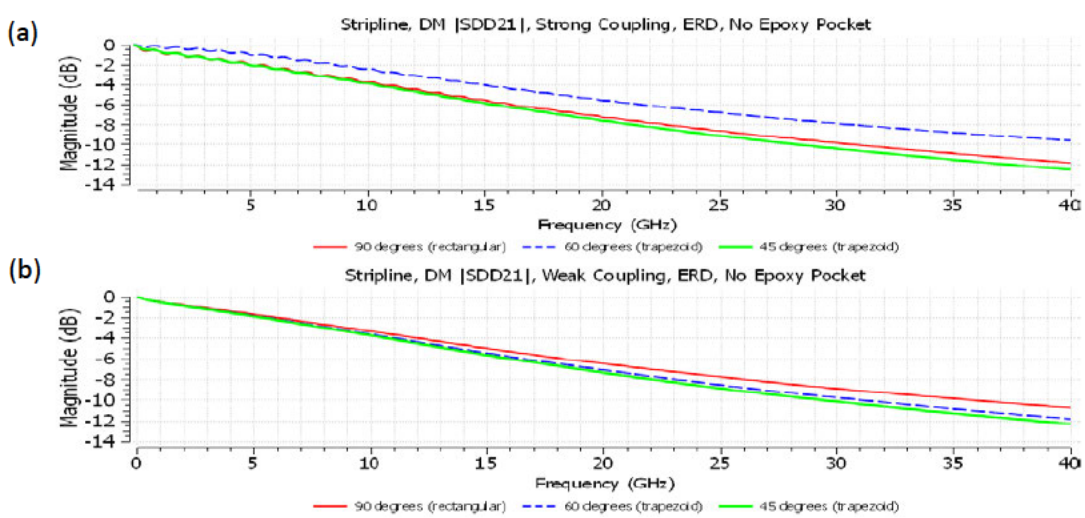


Figure 15– Insertion Loss for Differential mode in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

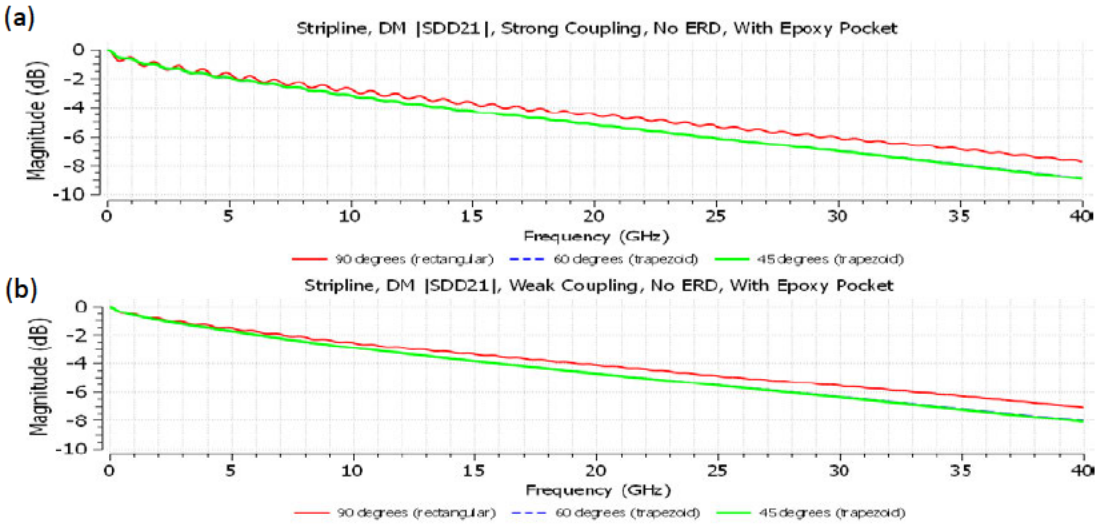


Figure 16– Insertion Loss for Differential mode in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

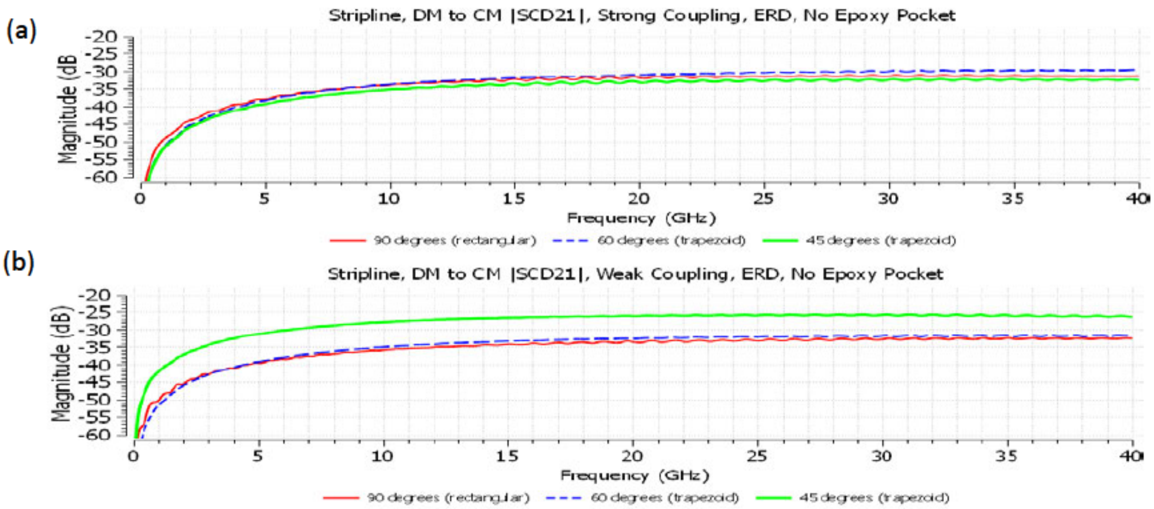


Figure 17– Insertion Loss for Mode Conversion in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

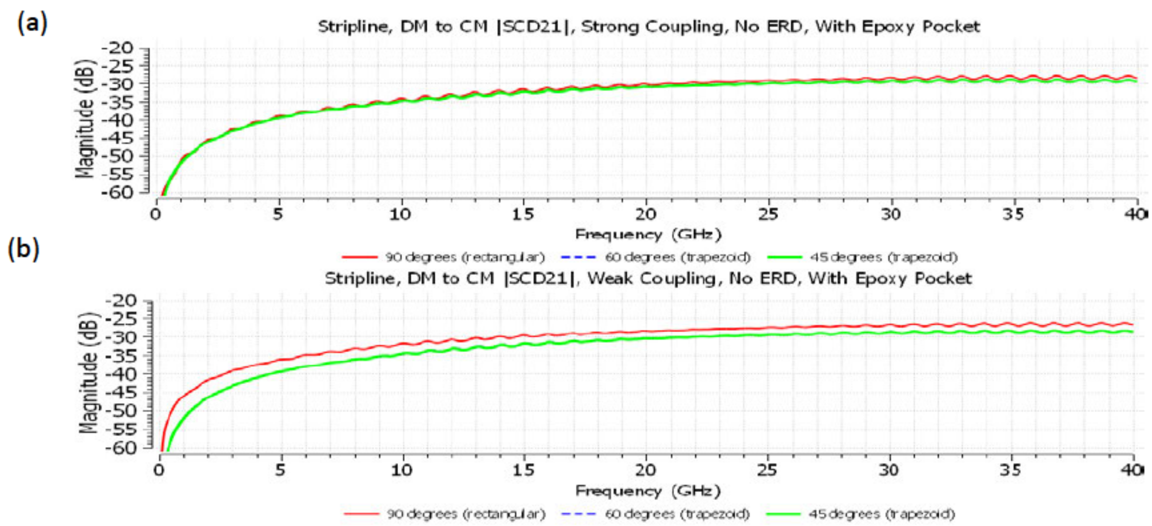


Figure 18– Insertion Loss for Mode Conversion in an Imbalanced (5 mil) Stripline Pair with 90^0, 60^0, and 45^0 Traces at Strong (a) and Weak (b) Coupling.

The analysis of **Table 4** shows that for the lines with rectangular traces, weak and strong coupling produce very close results, with just slightly higher IL for the weak coupling case, when ERD is taken into account. Epoxy pocket results in additional insertion loss for DM in the stronger coupled case, but does not affect CM.

However, for the trapezoid cases, there is a significant difference between weak and strong coupling, especially for the 45^0 traces, see **Tables 5** and **6**. This is due to the stronger inhomogeneity of the fields around the trapezoid traces, so that the rate of coupling affects CM and DM differently. Weak coupling for the 45^0 case shows the largest mode conversion, while the mode conversion in the strong-coupled 60^0 case is the lowest.

The weak and strong coupled striplines of different lengths (50 mm, 80 mm, and 100-mm) imbalanced by 0.127 mm (5 mils) were also compared. The results are presented in **Table 7**, and are also shown in **Figure 18** for the weak-coupled lines with rectangular cross-section only. ERD was modeled in all these cases.

From **Figure 19** and **Table 7**, it is seen that the longer lines accumulate more IL for both DM and CM. The mode conversion also increases with the length of the line, though the relative imbalance reduces. This is most noticeable at lower frequencies. At higher frequencies (>30 GHz), there is a slight reduction of mode conversion level due to the increased losses (dielectric, conductor skin effect, and foil roughness) which tend to damp mode conversion as lines become longer.

Table 4- Mixed-mode S-parameters for Imbalanced (5 mil) Stripline Differential Pair with Rectangular Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, rect. traces	|Scc21|	-3.359	-10.462	-0.2368	With ERD, no EP
		-2.307	-7.547	-0.1746	No ERD, with EP
		-3.415	-10.633	-0.2406	With ERD, with EP
	|Sdd21|	-3.767	-11.873	-0.2702	With ERD, no EP
		-2.764	-7.768	-0.1668	No ERD, with EP
		-4.275	-13.681	-0.3135	With ERD, with EP
	|Scd21|	-33.980	-31.258	+0.0907	With ERD, no EP
		-34.081	-28.472	+0.1869	No ERD, with EP
		-31.546	-30.474	+0.0357	With ERD, with EP
Weak coupling, rect. traces	|Scc21|	-3.631	-11.227	-0.2531	With ERD, no EP
		-2.567	-8.207	-0.1879	No ERD, with EP
		-3.781	-11.765	-0.2661	With ERD, with EP
	|Sdd21|	-3.374	-10.758	-0.2461	With ERD, no EP
		-2.548	-7.097	-0.1516	No ERD, with EP
		-3.730	-12.120	-0.277	With ERD, with EP
	|Scd21|	-35.894	-32.600	+0.1098	With ERD, no EP
		-31.859	-26.714	+0.1715	No ERD, with EP
		-31.121	-28.407	+0.0904	With ERD, with EP

Table 5- Mixed-mode S-parameters for Imbalanced (5 mil) Stripline Differential Pair with 60^0 Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, 60-degree traces	|Scc21|	-2.319	-8.924	-0.2202	With ERD, no EP
		-2.694	-8.184	-0.1830	No ERD, with EP
		-3.732	-11.760	-0.2676	With ERD, with EP
	|Sdd21|	-2.430	-9.635	-0.2401	With ERD, no EP
		-3.216	-8.905	-0.1896	No ERD, with EP
		-4.484	-14.642	-0.3385	With ERD, with EP
	|Scd21|	-33.831	-29.608	+0.1407	With ERD, no EP
		-34.789	-29.438	+0.1783	No ERD, with EP
		-39.747	-36.157	+0.1196	With ERD, with EP
Weak coupling, 60-degree traces	|Scc21|	-3.9292	-12.971	-0.3014	With ERD, no EP
		-3.0153	-8.926	-0.1970	No ERD, with EP
		-4.1203	-13.605	-0.3161	With ERD, with EP
	|Sdd21|	-3.650	-11.830	-0.2727	With ERD, no EP
		-2.919	-8.057	-0.1712	No ERD, with EP
		-4.071	-13.355	-0.3095	With ERD, with EP
	|Scd21|	-35.098	-31.950	0.1049	With ERD, no EP
		-34.609	-28.562	0.2016	No ERD, with EP
		-34.915	-33.119	0.0598	With ERD, with EP

Table 6- Mixed-mode S-parameters for Imbalanced (5 mil) Stripline Differential Pair with 45^0 Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, 45-degree traces	|Scc21|	-3.684	-11.553	-0.2622	With ERD, no EP
		-2.653	-8.161	-0.1836	No ERD, with EP
		-3.776	-11.869	-0.2698	With ERD, with EP
	|Sdd21|	-3.908	-12.542	-0.2878	With ERD, no EP
		-3.197	-8.9561	-0.1920	No ERD, with EP
		-4.487	-14.642	-0.3384	With ERD, with EP
	|Scd21|	-35.239	-32.587	+0.0884	With ERD, no EP
		-34.736	-29.462	+0.1756	No ERD, with EP
		-35.685	-34.571	+0.0371	With ERD, with EP
Weak coupling, 45-degree traces	|Scc21|	-4.095	-13.586	-0.3164	With ERD, no EP
		-2.913	-8.897	-0.1995	No ERD, with EP
		-4.311	-14.288	-0.3325	With ERD, with EP
	|Sdd21|	-3.782	-12.295	-0.2838	With ERD, no EP
		-2.912	-8.125	-0.1738	No ERD, with EP
		-4.210	-13.874	-0.3222	With ERD, with EP
	|Scd21|	-27.868	-26.424	+0.0482	With ERD, no EP
		-34.506	-28.613	+0.1964	No ERD, with EP
		-28.233	-27.759	+0.0158	With ERD, with EP

Table 7- Line Length Effect for Imbalanced (5 mil) Stripline Differential Pair with Rectangular Traces

Case	Parameter, dB	10 GHz	40 GHz	Slope, dB/GHz	Technological effects modeled
Strong coupling, rect. traces, L=50 mm	|Scc21|	-1.890	-5.677	-0.1262	No ERD, with EP
		-2.141	-7.290	-0.1716	With ERD, with EP
	|Sdd21|	-1.923	-4.981	-0.1019	No ERD, with EP
		-2.801	-8.716	-0.1971	With ERD, with EP
	|Scd21|	-34.283	-25.903	+0.2793	No ERD, with EP
		-36.679	-30.268	+0.2137	With ERD, with EP
Strong coupling, rect. traces, L=80 mm	|Scc21|	-2.3073	-7.547	-0.1746	No ERD, with EP
		-3.415	-10.633	-0.2405	With ERD, with EP
	|Sdd21|	-2.764	-7.768	-0.1668	No ERD, with EP
		-4.275	-13.681	-0.3135	With ERD, with EP
	|Scd21|	-34.081	-28.472	+0.1870	No ERD, with EP
		-31.545	-30.474	+0.0357	With ERD, with EP
Strong coupling, rect. traces, L=100 mm	|Scc21|	-3.086	-9.461	-0.2125	No ERD, with EP
		-4.360	-13.845	-0.3161	With ERD, with EP
	|Sdd21|	-3.566	-9.750	-0.2061	No ERD, with EP
		-5.339	-16.953	-0.3871	With ERD, with EP
	|Scd21|	-35.565	-30.305	+0.1753	No ERD, with EP
		-35.202	-36.056	-0.0284	With ERD, with EP
Weak coupling, rect. traces, L=50 mm	|Scc21|	-2.059	-6.029	-0.1323	No ERD, with EP
		-2.364	-8.216	-0.1950	With ERD, with EP
	|Sdd21|	-1.639	-4.430	-0.0930	No ERD, with EP
		-2.349	-7.581	-0.1744	With ERD, with EP
	|Scd21|	-32.767	-24.758	+0.2669	No ERD, with EP
		-34.876	-29.014	+0.1953	With ERD, with EP
Weak coupling, rect. traces, L=80 mm	|Scc21|	-2.567	-8.207	-0.1879	No ERD, with EP
		-3.781	-11.765	-0.2661	With ERD, with EP
	|Sdd21|	-2.548	-7.097	-0.1516	No ERD, with EP
		-3.730	-12.12	-0.2797	With ERD, with EP
	|Scd21|	-31.859	-26.714	+0.1715	No ERD, with EP
		-31.121	-28.407	+0.0904	With ERD, with EP
Weak coupling, rect. traces, L=100 mm	|Scc21|	-3.579	-10.288	-0.2236	No ERD, with EP
		-4.859	-15.674	-0.3605	With ERD, with EP
	|Sdd21|	-3.174	-8.734	-0.1853	No ERD, with EP
		-4.639	-15.163	-0.3508	With ERD, with EP
	|Scd21|	-32.709	-28.180	+0.1509	No ERD, with EP
		-29.694	-28.919	+0.0258	With ERD, with EP

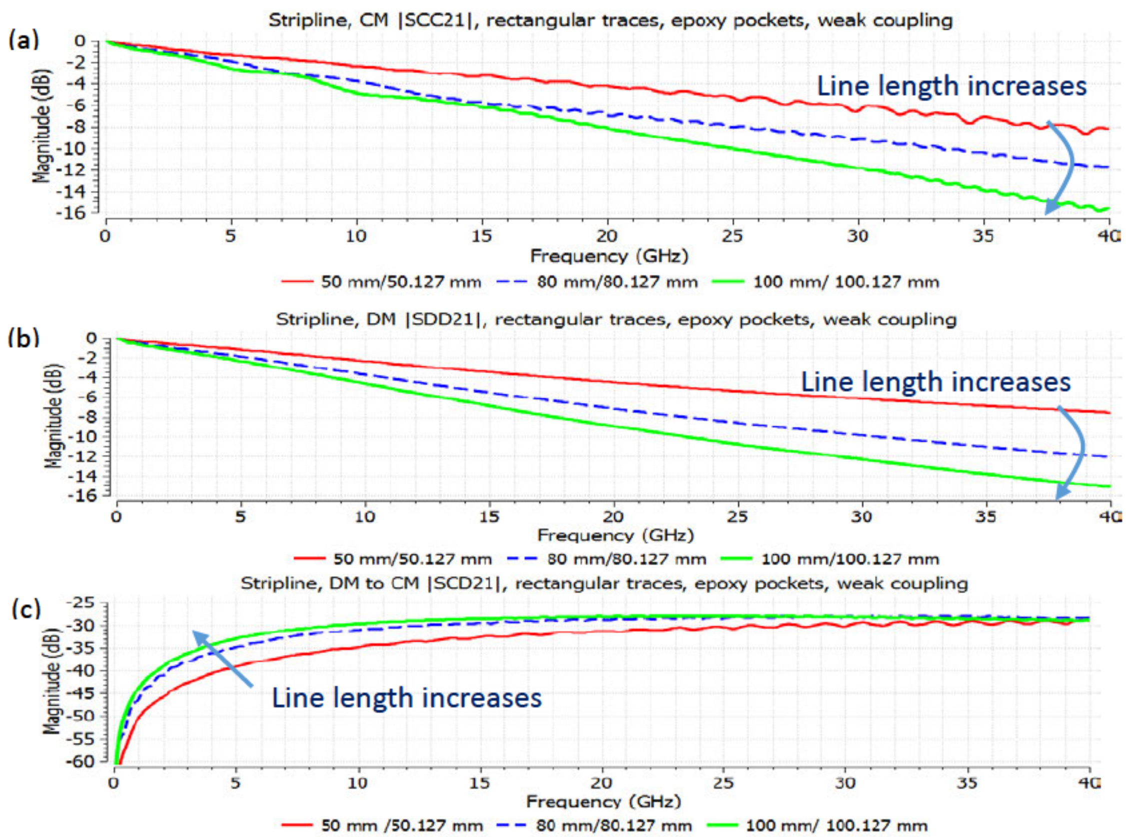


Figure 19– Insertion Loss for CM (a), DM (b), and Mode Conversion(c) in an Imbalanced (5 mil) Stripline Pair with Rectangular Traces at Weak Coupling. ERD and Epoxy pocket are Modeled.

Experimental Validation of Modeled Results

The fabricated PCB with strong- and weak-coupled microstrip and stripline differential pairs was designed based on PPO Blend dielectric and standard (STD) foil. Press-fit 2.92-mm connectors were mounted on the board. A two-port vector network analyzer took the measurements over the 40 MHz-25 GHz frequency range.

The fabricated PCB has a dielectric substrate thickness between the microstrip traces and the return plane (the ground) is d=0.130 mm (5.118 mil). In the weakly coupled case, traces are of w_t=0.2032 mm (8 mil) width, and the corresponding edge-to-edge separation distance is s_t=0.18 mm (7.09 mil). In the strongly coupled case, the trace width is w_t=0.1737 mm (6.84 mil), and the separation distance is s_t=0.0889 mm (3.5 mil). In the both cases, the differential impedance is 100Ω+/-10%. For the stripline test fixtures, the total thickness of the dielectric substrate is $d=d_1+d_2$=0.130+0.1138=0.2438 mm. The lines have the trace widths w_t=0.0869 mm (3.42 mil) and the separation distance s_t=0.275 mm (10.83 mil) for the weakly coupled case, and the trace width w_t=0.1036 mm (4.08 mil) and the separation distance s_t=0.1 mm (3.937 mil) for the strong coupling. Thickness The top (microstrip) copper layer is 0.5 oz + plating (total 50.8 µm); the stripline copper is 0.5 oz (17.5 µm), and the return planes are 1 oz copper (35 µm). The base length of the traces in the design is 80.4 mm (3165 mil), and the length imbalance is ±0.127 mm (±5 mil). These data slightly differ from the data in the previous numerical modeling presented in **Figures 4-19** and **Tables 1-7**; therefore, to compare with the measurements, the model input parameters were modified accordingly. The characteristics of the PPO Blend material, ERD, SM, and epoxy pocket are the same as in the previous models.

The comparison of the measured and modeled mixed-mode S-parameters for microstrip differential pairs are shown in **Figure 20** for the strong coupling, and in **Figure 21** for weak coupling case. It is seen from these two figures that the agreement between the measured and modeled results for $|S_{cc21}|$ and $|S_{dd21}|$ is within +/-0.2 dB over the entire frequency range of study. Mode conversion $|S_{cd21}|$ results agree within is +/-5 dB; but note that the overall level of mixed-mode conversion less than -25 dB; therefore, this agreement is considered to be good.

Comparison between the measured and modeling results in the cases of stripline differential structures are shown in **Figures 22** and **23**. The measured results show an artifact – a dip at the frequency about 12 GHz; it is related to the via stub resonance (the stripline traces are on the 7th layer of the PCB), and can be ignored. Otherwise, the agreement is reasonable for both weak- and strong-coupled cases. This agreement justifies the conclusions made of the modeling results.

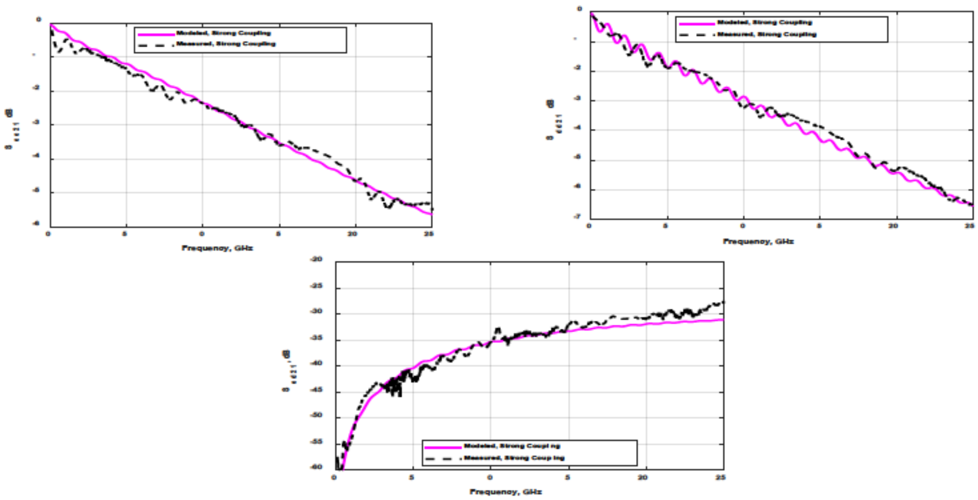


Figure 20– Measured and Modeled Insertion Loss for CM, DM, and Mode Conversion in an Imbalanced (5 mil) Microstrip Pair with 45^0 Traces at Strong Coupling (ERD and SM Modeled).

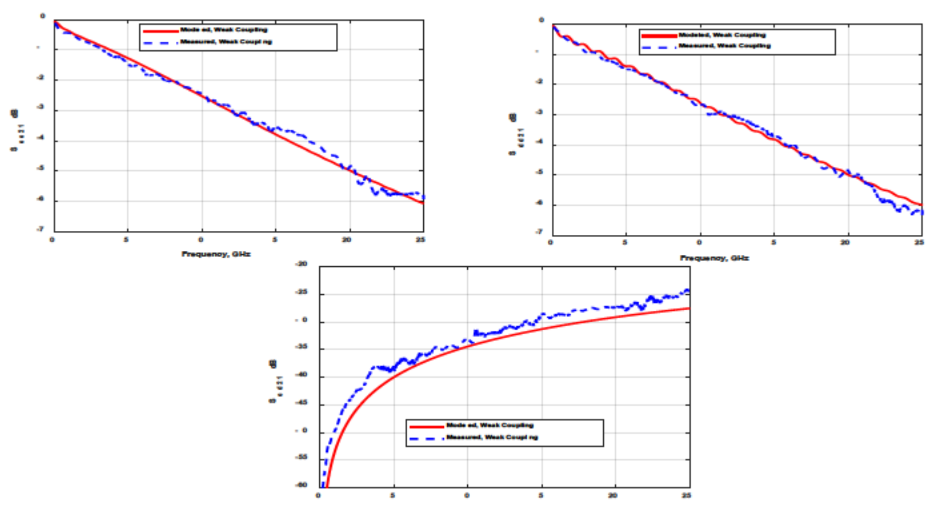


Figure 21– Measured and Modeled Insertion Loss for CM, DM, and Mode Conversion in an Imbalanced (5 mil) Microstrip Pair with 45^0 Traces at Weak Coupling (ERD and SM Modeled).

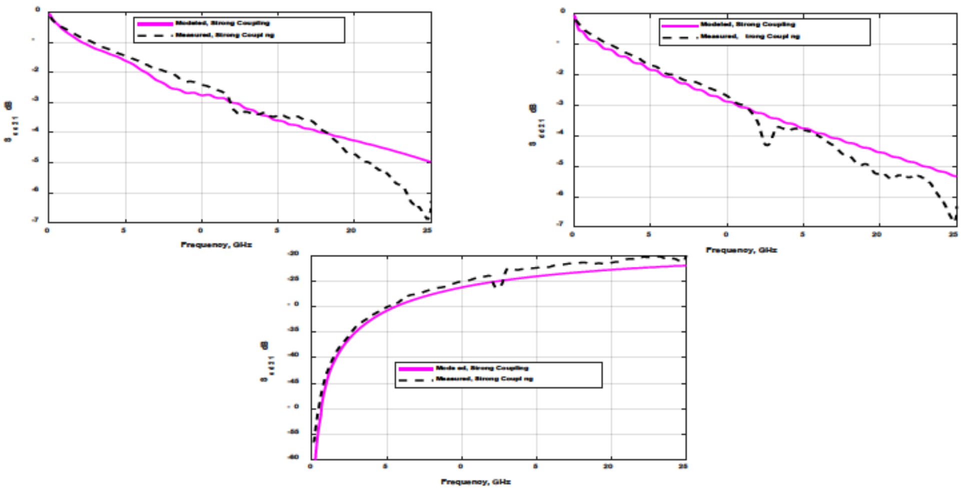


Figure 22– Measured and Modeled Insertion Loss for CM, DM, and Mode Conversion in an Imbalanced (5 mil) Stripline Pair with 60^0 Traces at Strong Coupling (ERD and SM Modeled).

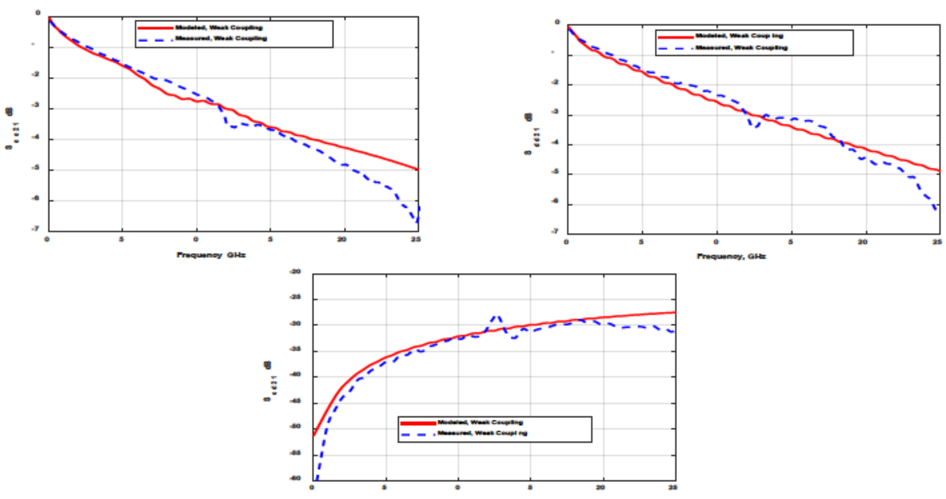


Figure 23– Measured and Modeled Insertion Loss for CM, DM, and Mode Conversion in an Imbalanced (5 mil) Stripline Pair with 60^0 Traces at Weak Coupling (ERD and SM Modeled).

Conclusions

Rate of coupling (strong versus weak) in edge-coupled imbalanced differential pairs, both microstrip and stripline, result in different behavior of mixed-mode S-parameters. For SI, weak coupling is preferable. However, this is not always the case for EMC. Mode conversion may be larger in the weak-coupled than in the strong-coupled cases, especially if the traces are trapezoid and other technological factors are considered. Copper foil roughness may enhance the mode conversion, and the latter may contribute to EMI. The most critical case for mode conversion enhancement in stripline case is when there is weak coupling, 45^0 trapezoid traces, and significant roughness, especially at lower frequencies. Strong coupling usually results in the mode conversion damping; therefore, it may be beneficial from the EMC point of view. However, in the strong-coupled case with the microstrip rectangular traces, the mode conversion enhancement at the lower frequencies due to the ERD may take place. Though the differences in slopes for the considered cases (80-mm lines, 5-mil imbalance) are just fractions of dB/GHz, as the line lengths of the differential pairs and frequencies increase, these differences may become significant.

References

[1] B. Archambeault, J. C. Diepenbrock, and S. Connor, "EMI emissions from mismatches in high speed differential signal traces and cables", *IEEE Symp. EMC*, July 9-13, 2007, Honolulu, pp. 1-6.

[2] P. Huray, *The Foundations of Signal Integrity*. Hoboken, NJ, USA: Wiley, 2010, pp. 216-277.

[3] Y. Kayano, M. Ohkoshi, and H. Inoue, "Weak-coupled cross-sectional differential-paired lines with bend discontinuities for SI and EMI performances", *EMC'14/Tokyo*, Japan, 2014, 13P1-B3, pp. 133-136.

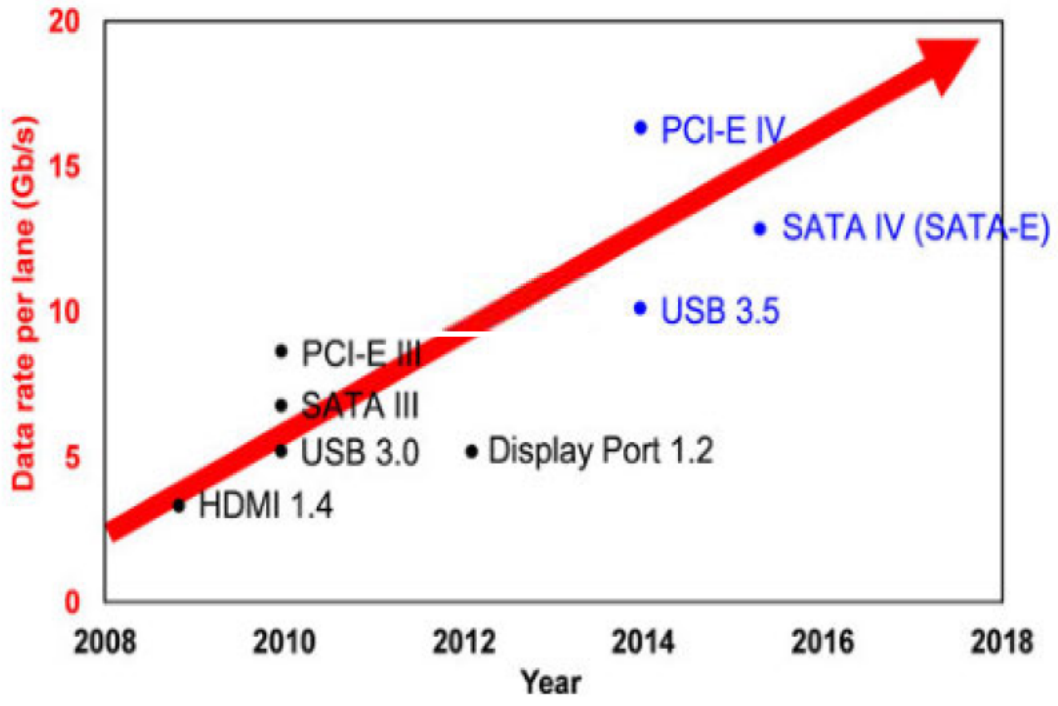
[4] H. Johnson, *High Speed Signal Propagation: Advanced Black Magic*, Prentice Hall, 2003, pp. 389-396.
[5] CST STUDIO SUITE2017,Dassault Systems Simulia, www.cst.com.
[6] M. Koledintseva, T. Vincent, and S. Radu, “Full-wave simulation of an imbalanced differential microstrip line with conductor surface roughness”, *Proc. IEEE Symp. EMC&SI 2015*, Santa Clara, CA, 2015, pp. 34-39.
[7] M.Y. Koledintseva and T.Vincent, “Comparison of mixed-mode S-parameters in weak and strong coupled differential pairs”, *Proc. IEEE Symp. EMC*, July 25-30, 2016, Ottawa, Canada, pp. 610-615.
[8] M. Koledintseva, T. Vincent, A. Ciccomancini, and S. Hinaga, “Method of effective roughness dielectric in a PCB: measurement and full-wave simulation verification”, *IEEE Trans. Electromag. Compat.*, vol. 57, no. 4, pp. 807-814, 2015.
[9]T. Vincent, M. Koledintseva, A. Ciccomancini, and S. Hinaga, “Effective roughness dielectric in a PCB: measurement and full-wave simulation verification”, *IEEE Symp. Electromag. Compat., Signal Integrity and Power Integrity* (*2014 IEEE EMC-SIPI*) Raleigh, NC, Aug. 3-8, 2014, pp. 798-802.
[10] M.Y. Koledintseva, A.V. Rakov, A.I. Koledintsev, J.L. Drewniak, and S. Hinaga, “Improved experiment-based technique to characterize dielectric properties of printed circuit boards”, *IEEE Trans. Electromag. Compat.*, vol. 56, no. 6, Dec. 2014, pp. 1559-1556.
[11] A.V. Rakov, S. De, M.Y. Koledintseva, S. Hinaga, J.L. Drewniak, and R.J. Stanley, “Quantification of conductor surface roughness profiles in printed circuit boards”, *IEEE Trans. Electromag. Compat.*, vol.57, no. 2, Apr. 2015, pp. 264-273.

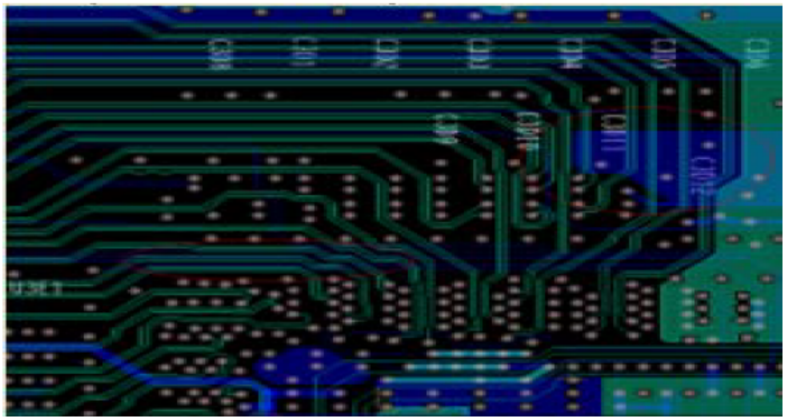
Hybrid S-Parameters Behavior of Weak and Strong Edge-Coupled Differential Lines on PCBs

Marina Koledintseva, Joe Nuebel, Sergiu Radu, and Karl Sauter (Oracle, USA) and Tracey Vincent (CST of America)

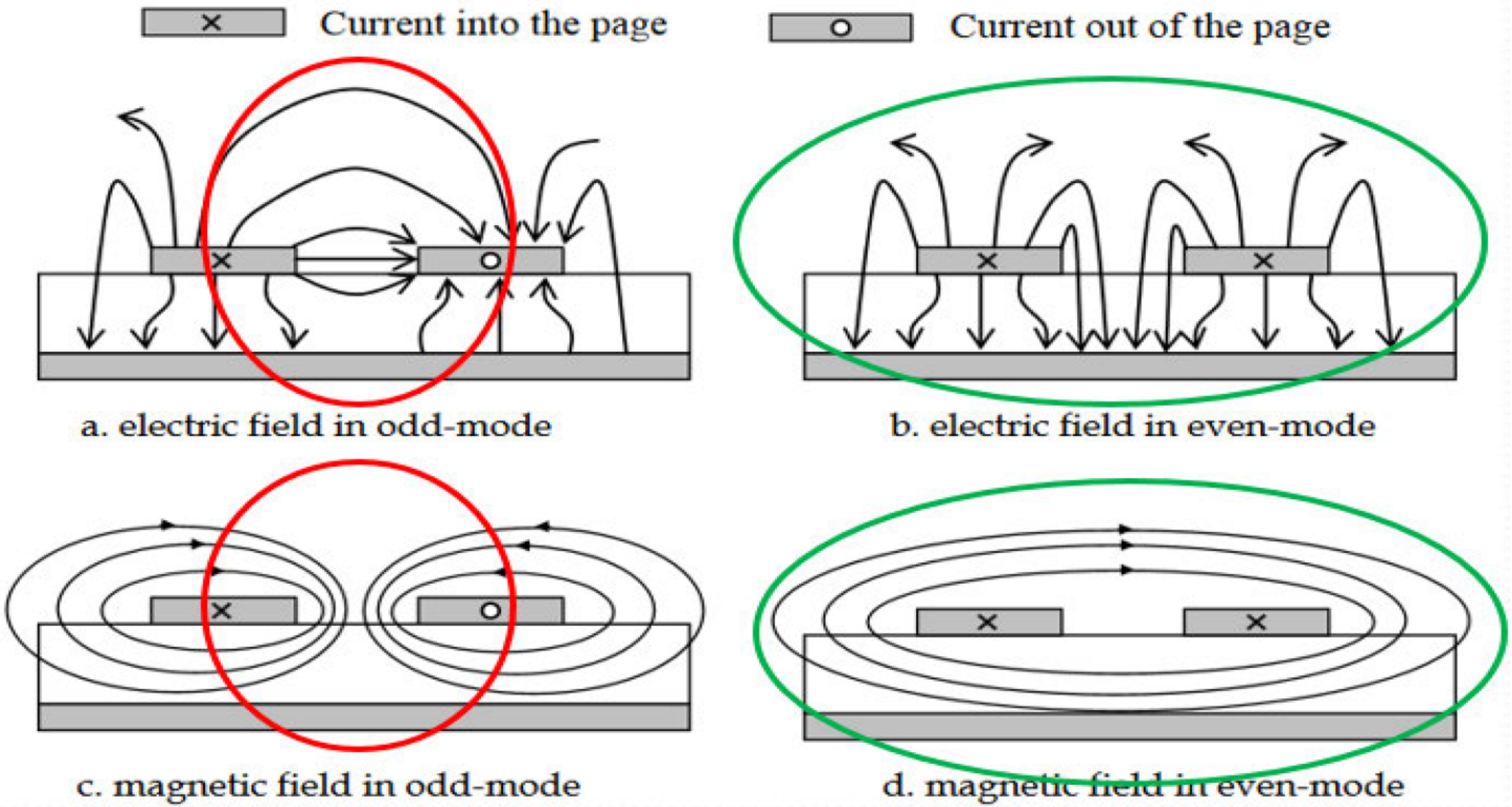
Introduction and Motivation for Study

- Differential signaling in high-speed digital design is widely used due to high immunity, low cross-talk, and potentially reduced EMI problems.
- In this work, imbalanced weakly and strongly edge-coupled differential pairs, both microstrip (MS) and stripline (SL), are studied under different conditions using hybrid (mixed-mode) S-parameters.
- Results of 3D numerical electromagnetic modeling, taking into account various technological features, are validated by measurements.



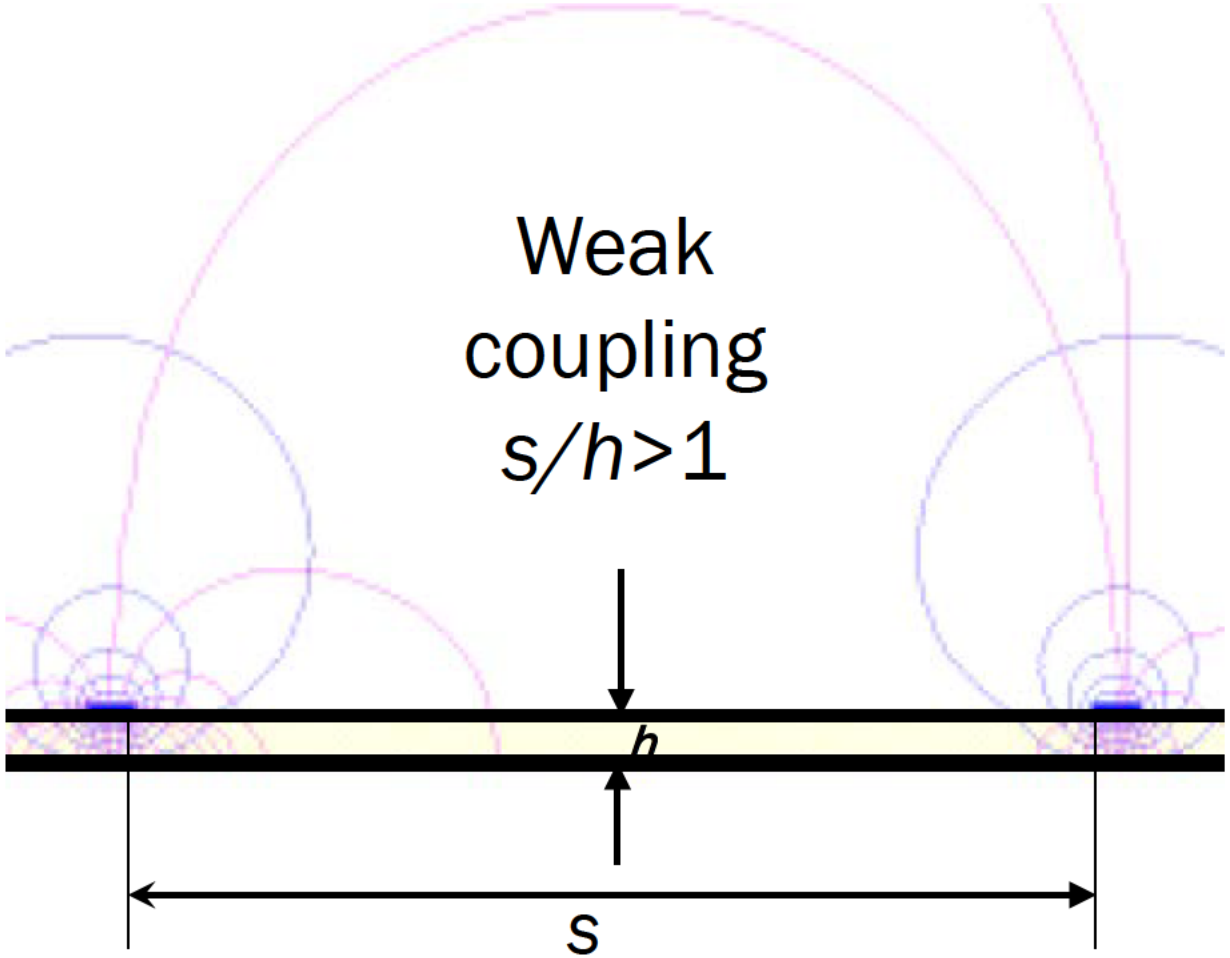


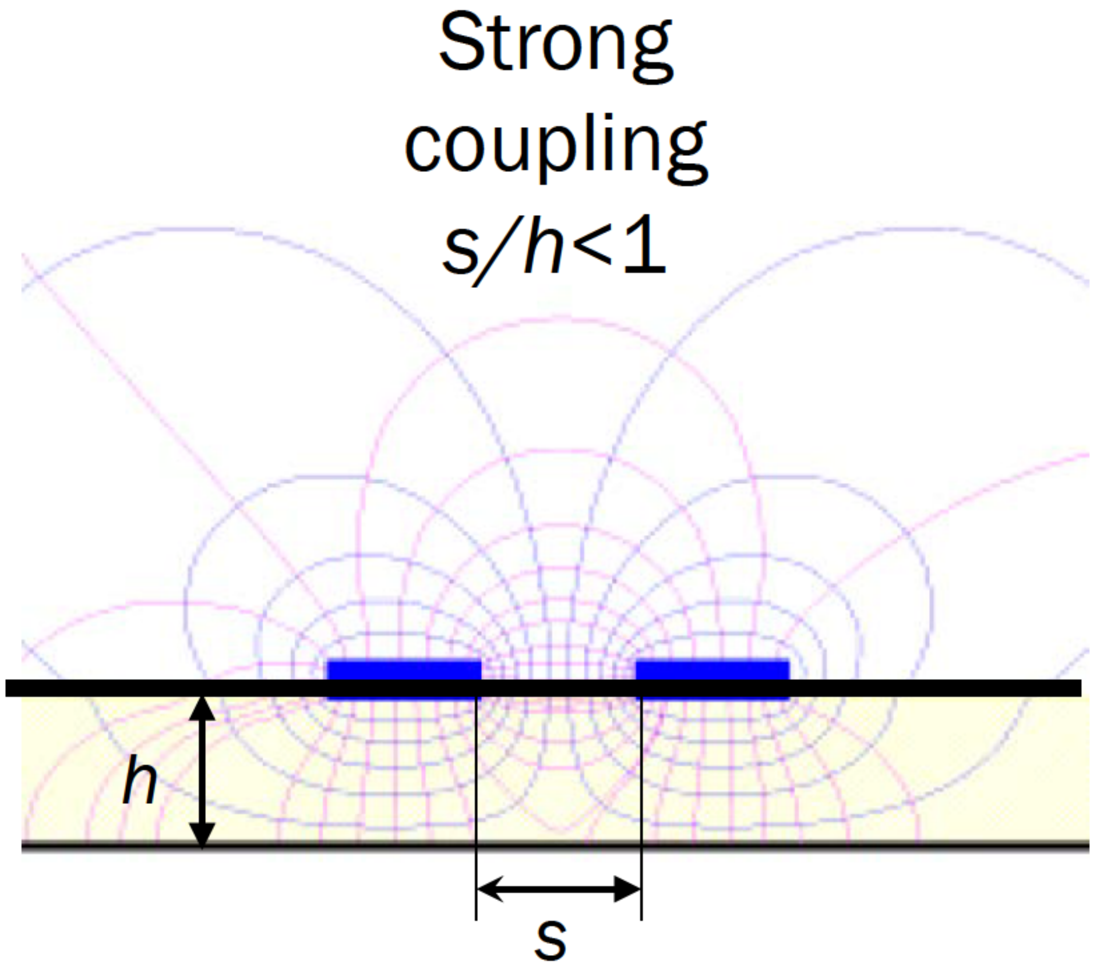
EM Field Structure in Edge-coupled Differential Lines



Differential / Odd Mode **Common/ Even Mode**

Weak vs. Strong Coupling





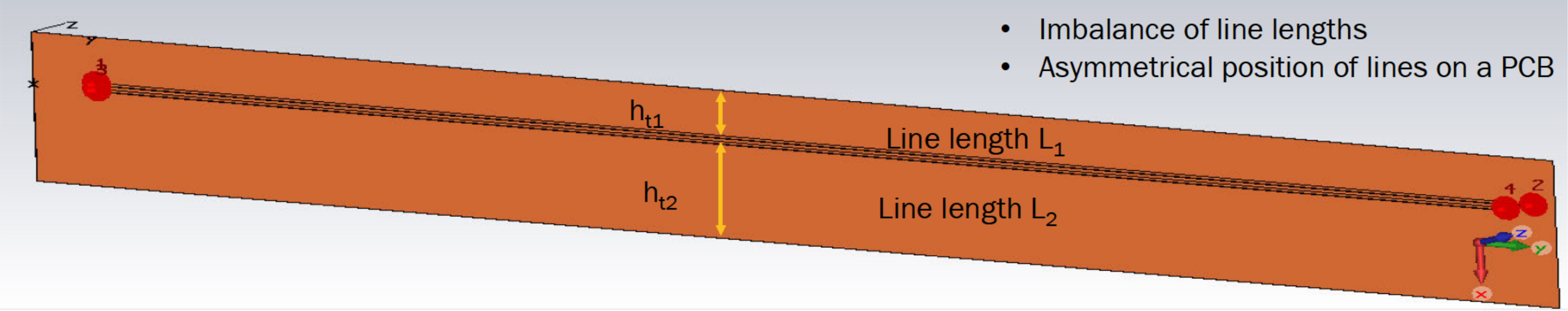
Background Publications

- Y. Kayano, M. Ohkoshi, and H. Inoue, “Weak-coupled cross-sectional differential-paired lines with bend discontinuities for SI and EMI preformances”, *EMC’14/Tokyo*, Japan, 2014, 13P1-B3, pp. 133-136.
    - only microstrip studied numerically and experimentally, no technological effects modeled, concluded that weak coupling is preferable for both SI and EMI
- M. Koledintseva, T. Vincent, and S. Radu, “Full-wave simulation of an imbalanced differential microstrip line with conductor surface roughness”, *Proc. IEEE Symp. EMC&SI 2015*, Santa Clara, CA, 2015.
    - only microstrip studied numerically, some technological features modeled, only weak coupling studied
- M. Koledintseva, T. Vincent “Comparison of mixed-mode S-parameters in weak and strong coupled differential pairs”, Proc. IEEE Symp on EMC/SIPI, Ottawa, Canada, 2016.
    - microstrip and stripline studied numerically, some technological features modeled, concluded that weak is good for SI, but not always for EMI; no experimental validation.
- In this work, in addition to numerical modeling, experimental validation is provided.

Setups of 3D Numerical Models

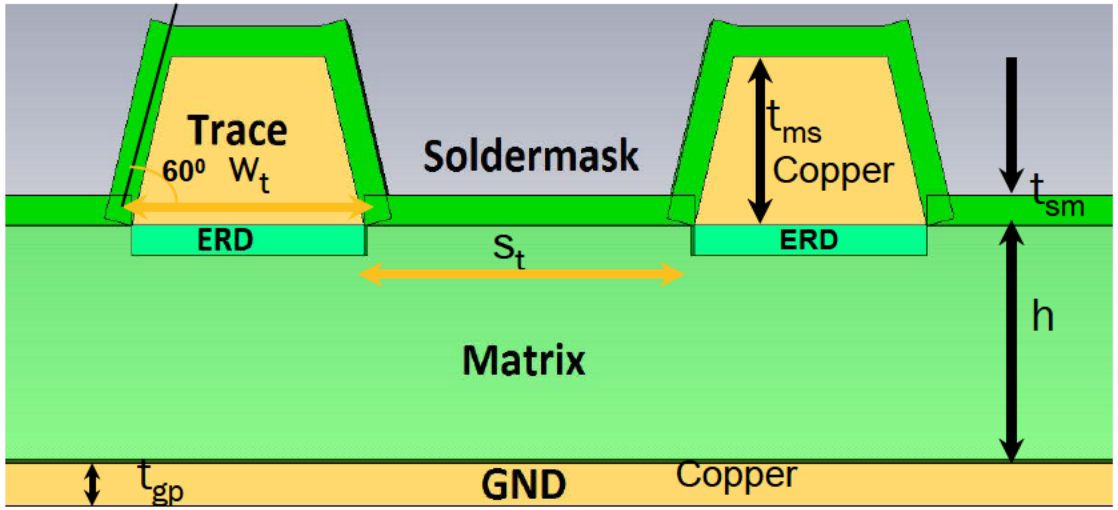
Time-domain FIT Solver is used

- Imbalance of line lengths
- Asymmetrical position of lines on a PCB

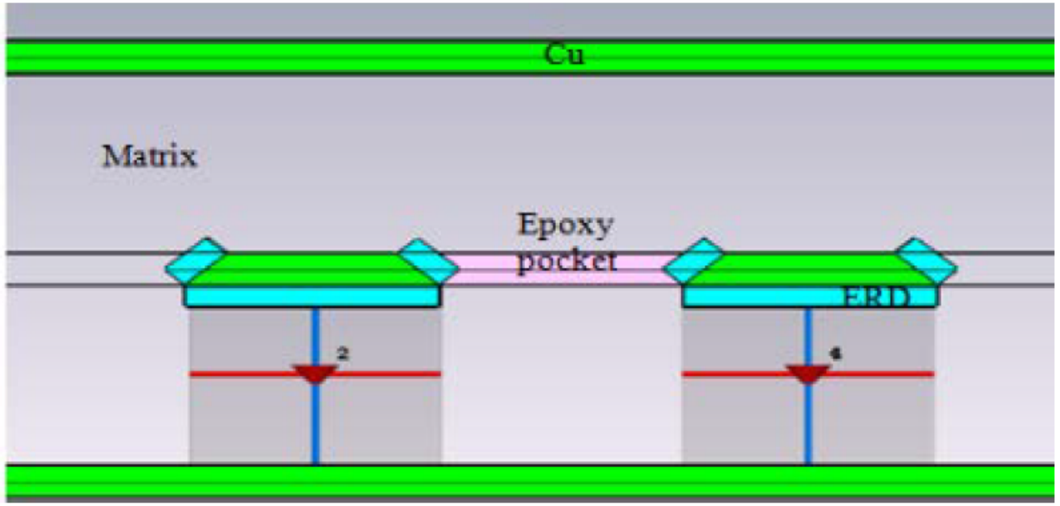


Technological features modeled

MS

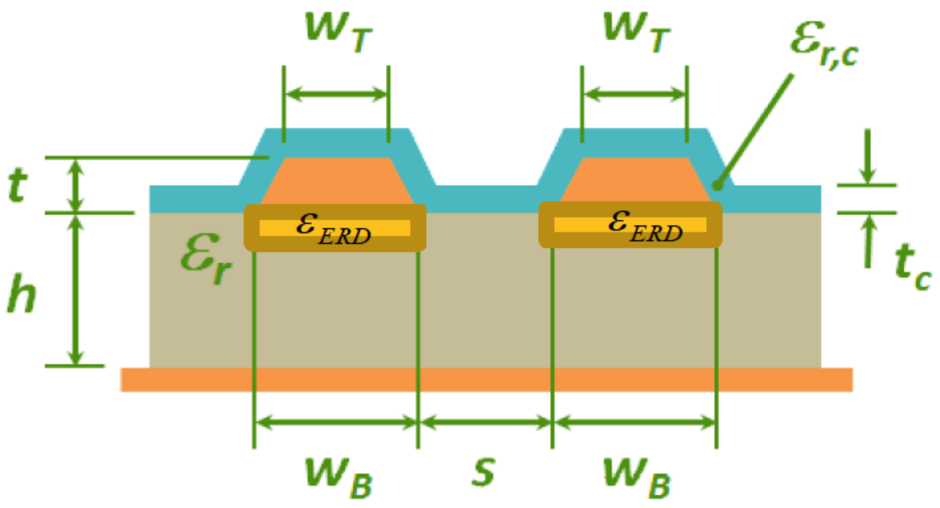


SL

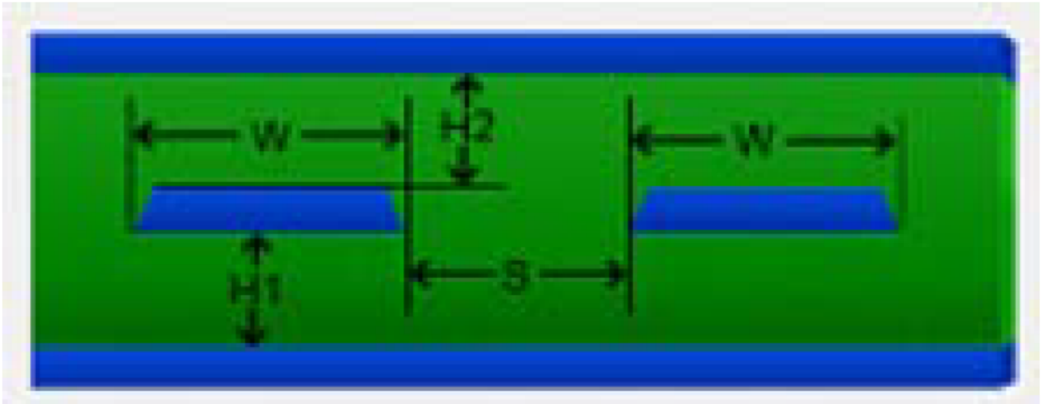


Peculiarities of Numerical Models

MS edge-coupled pair:
- weak vs. strong coupling
- rectangular vs. trapezoid traces
- with or without copper foil roughness*
- with or without solder mask

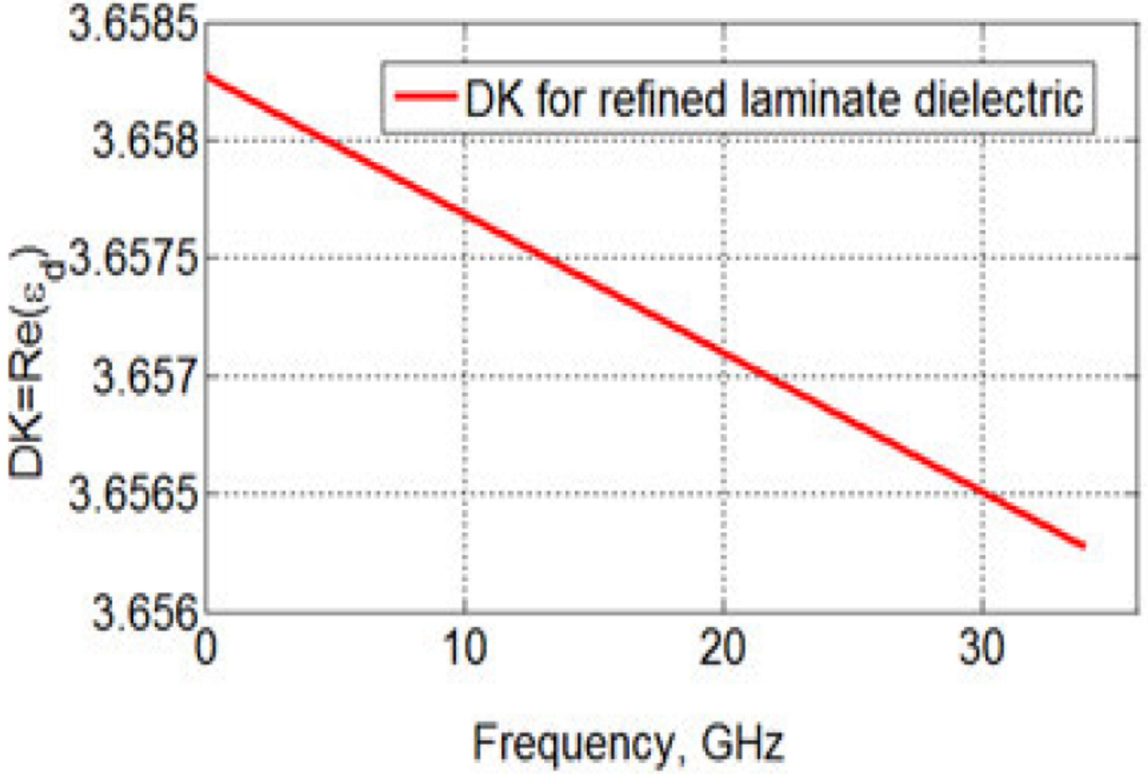


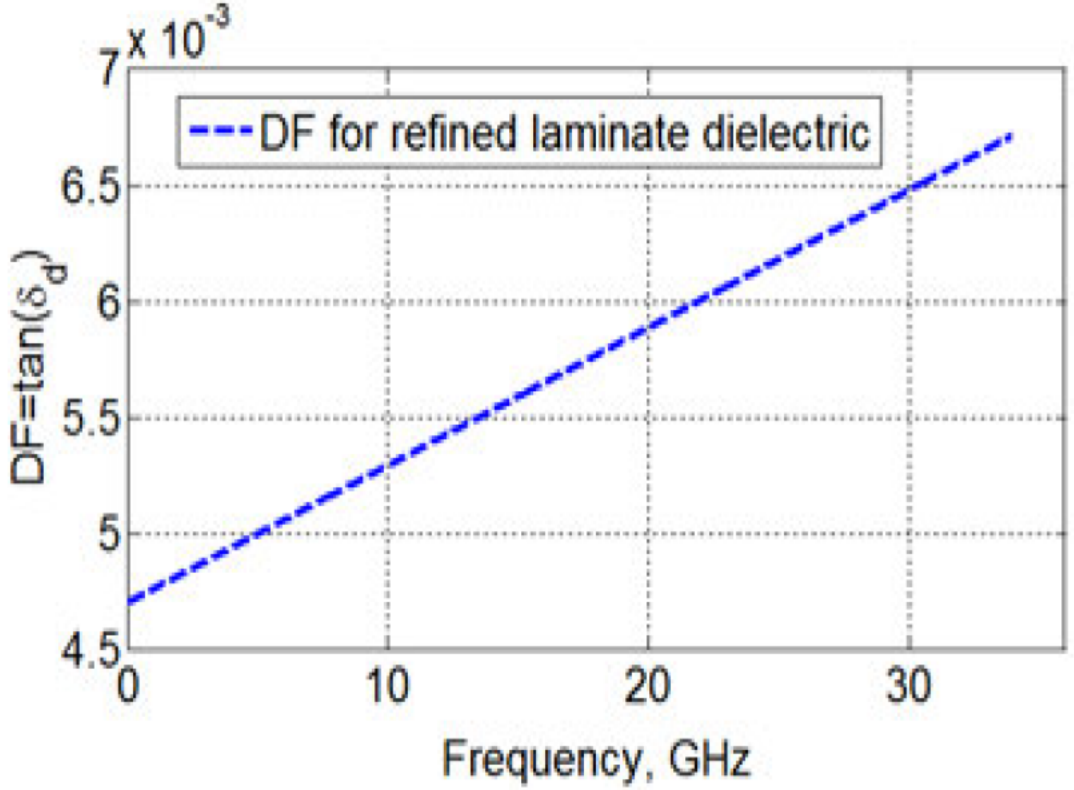
SL edge-coupled pair:
- weak vs. strong coupling
- rectangular vs. trapezoid traces
- with or without copper foil roughness*
- With or without epoxy-resin pocket



*PCB foil roughness is modeled as layers of effective roughness dielectric (ERD):
M. Koledintseva, T. Vincent, A. Ciccomancini, and S. Hinaga, "Method of effective roughness dielectric in a PCB: measurement and full-wave simulation verification", IEEE Trans. Electromag. Compat., vol. 57, no. 4, pp. 807-814, 2015.

PCB Laminate Dielectric Properties





DK and DF of PPO Blend Dielectric extracted using DERM technique

M.Y. Koledintseva, A.V. Rakov, A.I. Koledintsev, J.L. Drewniak, and S. Hinaga, "Improved experiment-based technique to characterize dielectric properties of printed circuit boards", IEEE Trans. Electromag. Compat., vol. 56, no. 6, 2014, pp. 1559-1566.

Effective Roughness Dielectric and Solder Mask Properties

ERD for Standard Foil:

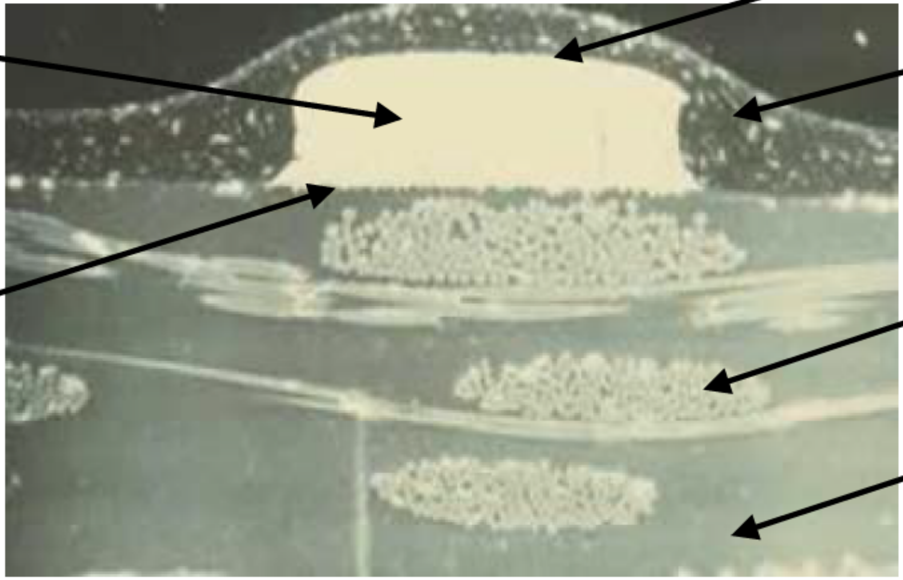
ERD on matte (“foil”) side of STD foil:

- ε_{rough}'=12 and $\tan\delta_{rough}$=0.17
- thickness ERD STD=T_r=12.4 μm.

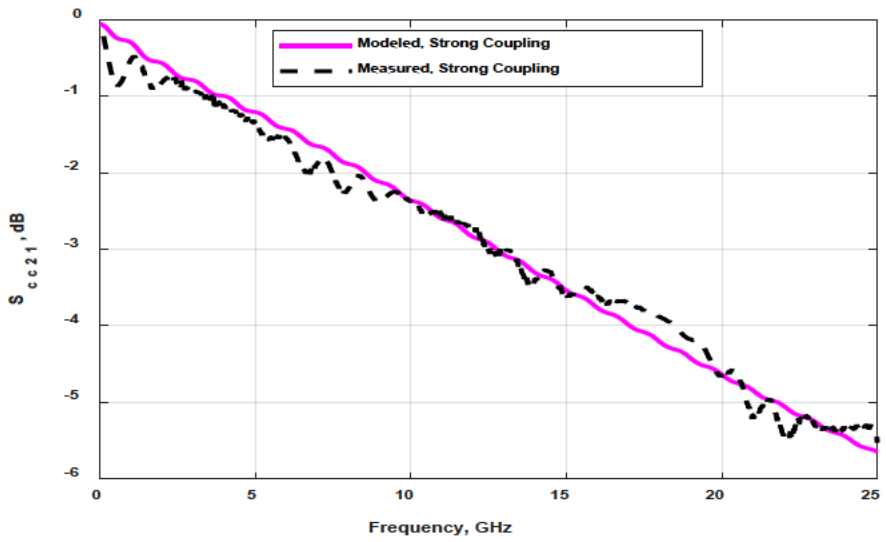
ERD on smooth drum (“oxide”) side on top of the traces and on ground planes is not modeled.

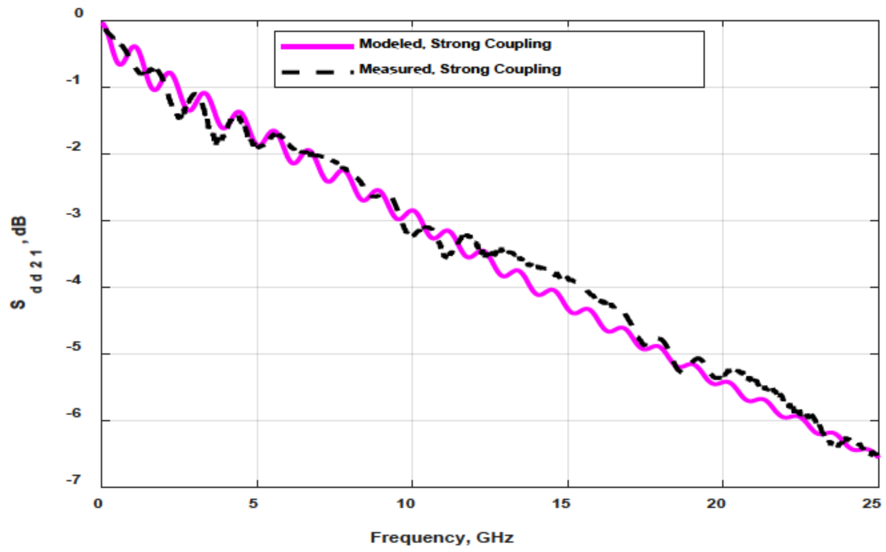
Solder mask (SM) in MS Lines:

ε'_{sm}=3.55 μm
$\tan\delta_{sm}$=0.0205
thickness t_{SM}=15 μm.

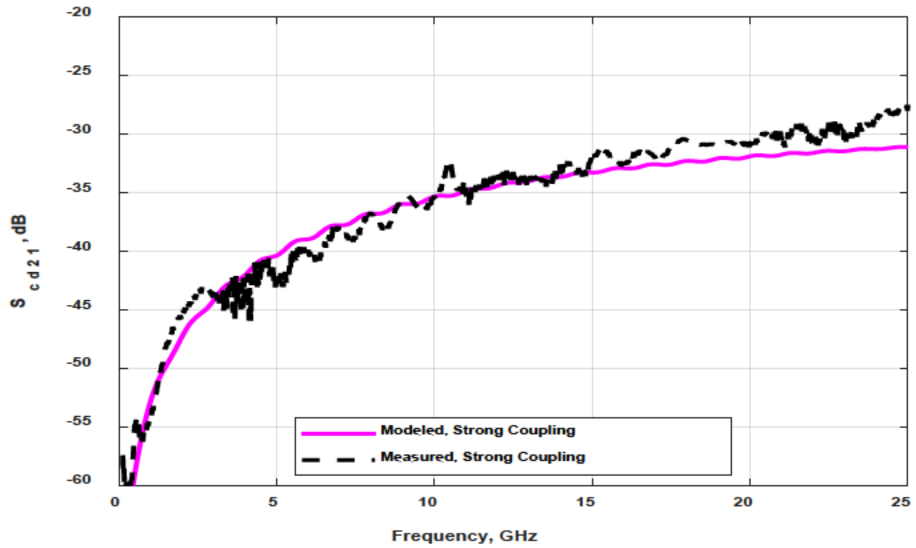


Experimental vs. Modeled Results: MS Case, Strong Coupling



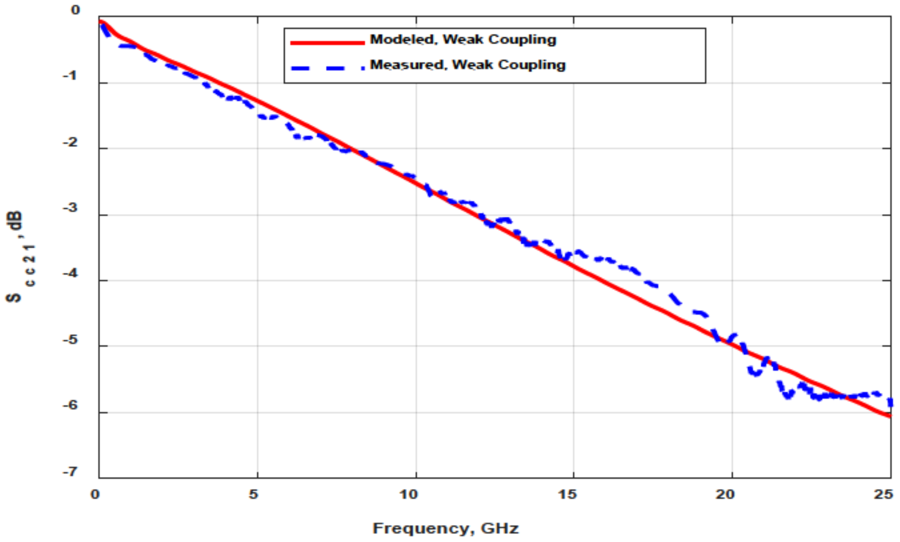


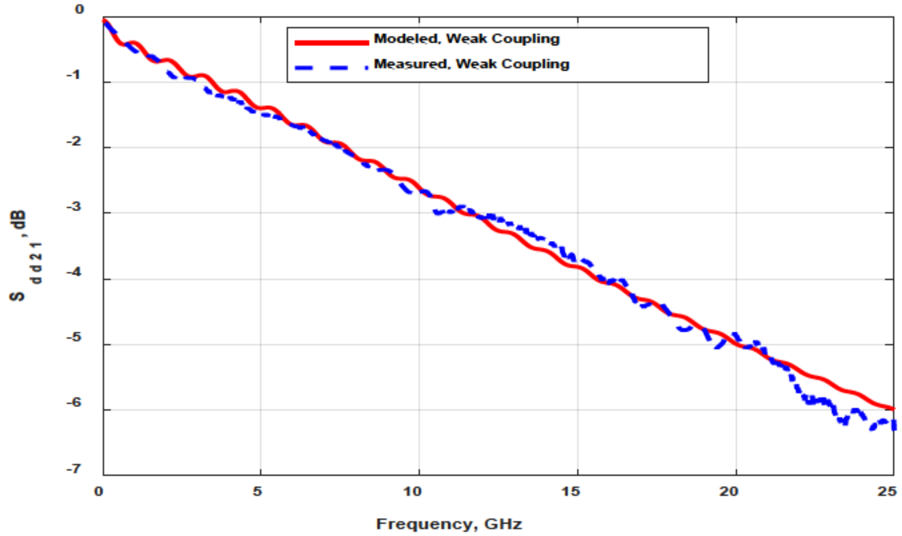
Modeled technological effects: dispersive PPO Blend, ERD, 45^0 trapezoid traces, solder mask

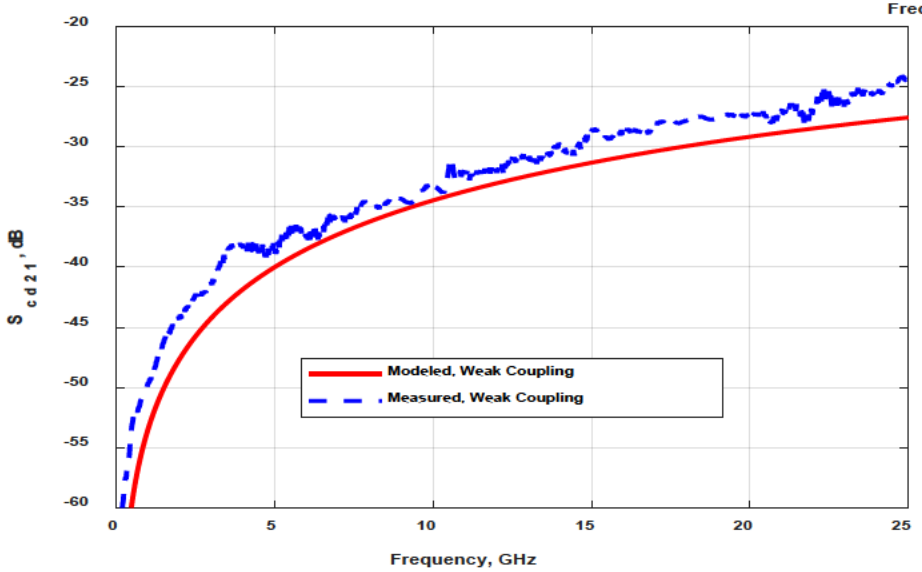


Line lengths are 80 mm and 80.127 mm (5 mil length imbalance)

Experimental vs. Modeled Results: MS Case, Weak Coupling



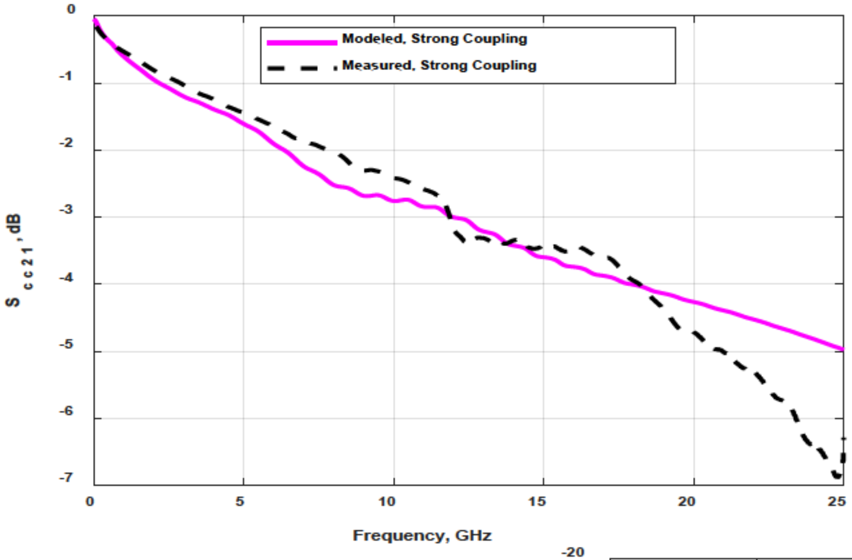


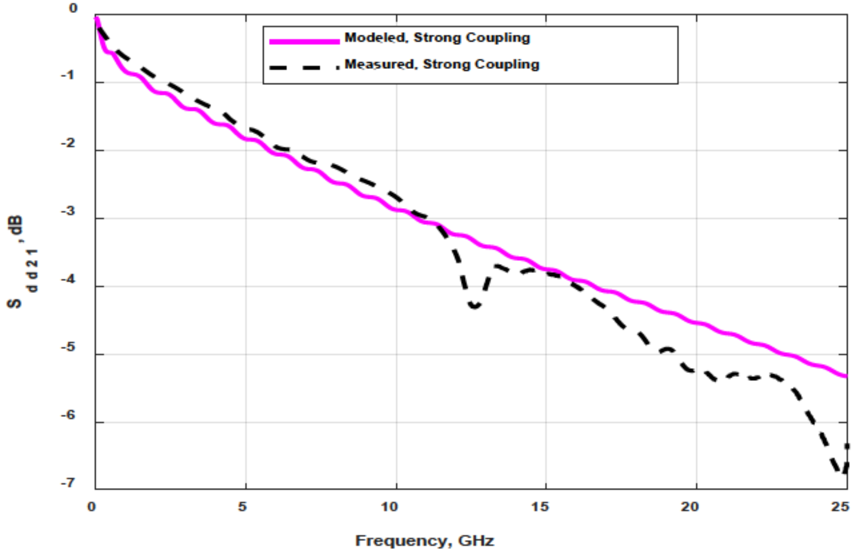


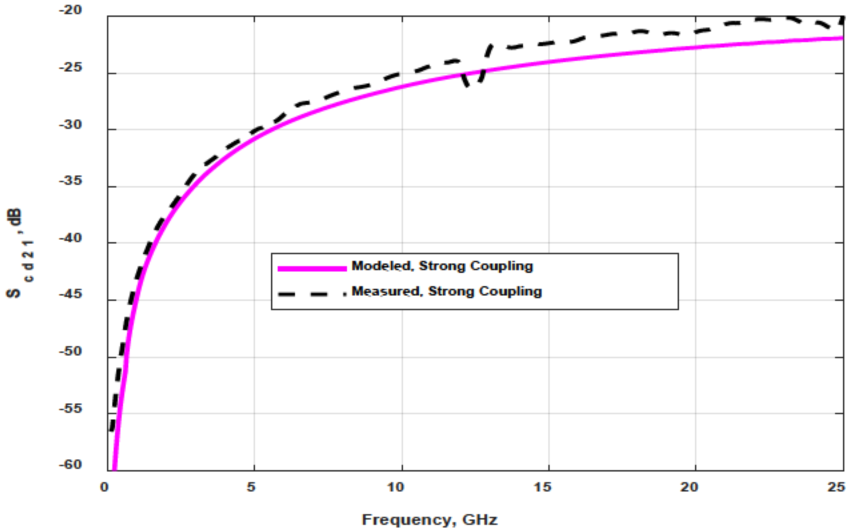
Modeled technological effects: dispersive PPO Blend, ERD, SM, 45^0 trapezoid traces

Line lengths are 80 mm and 80.127 mm (5 mil length imbalance)

Experimental vs. Modeled Results: SL Case, Strong Coupling



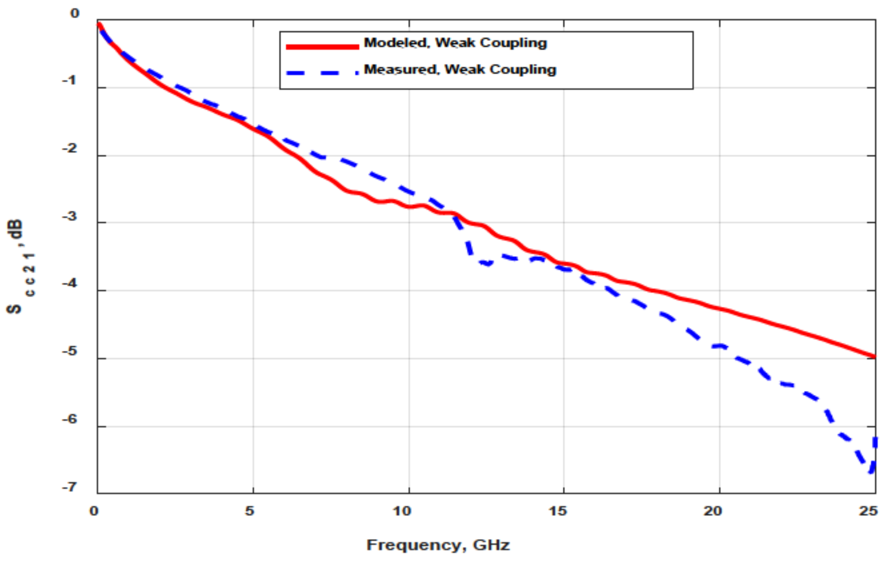


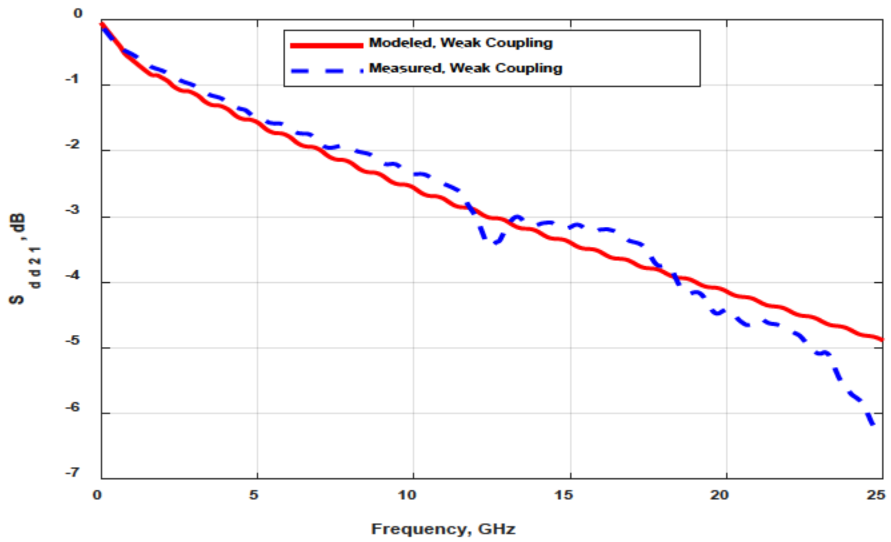


Modeled technological effects: dispersive PPO Blend, ERD, epoxy resin pocket, 60^0 trapezoid traces

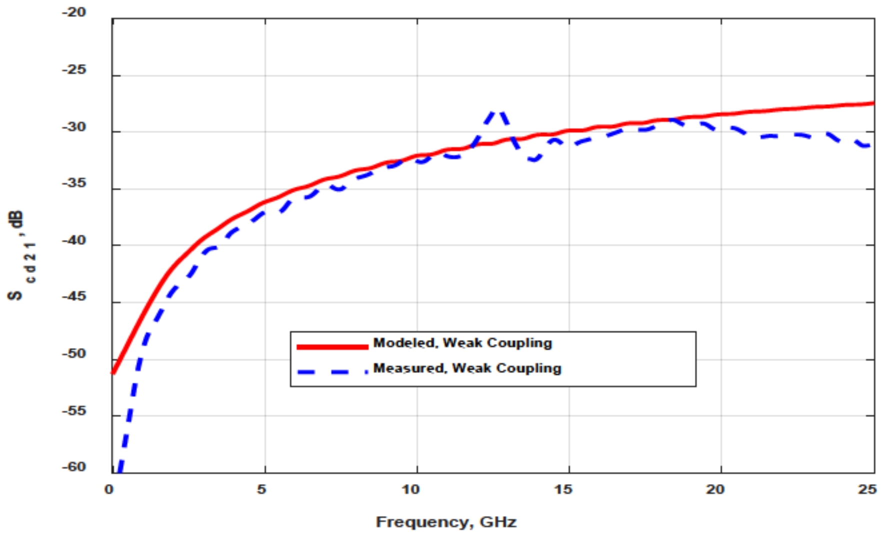
Line lengths are 80 mm and 80.254 mm (10 mil length imbalance)

Experimental vs. Modeled Results: SL Case, Weak Coupling



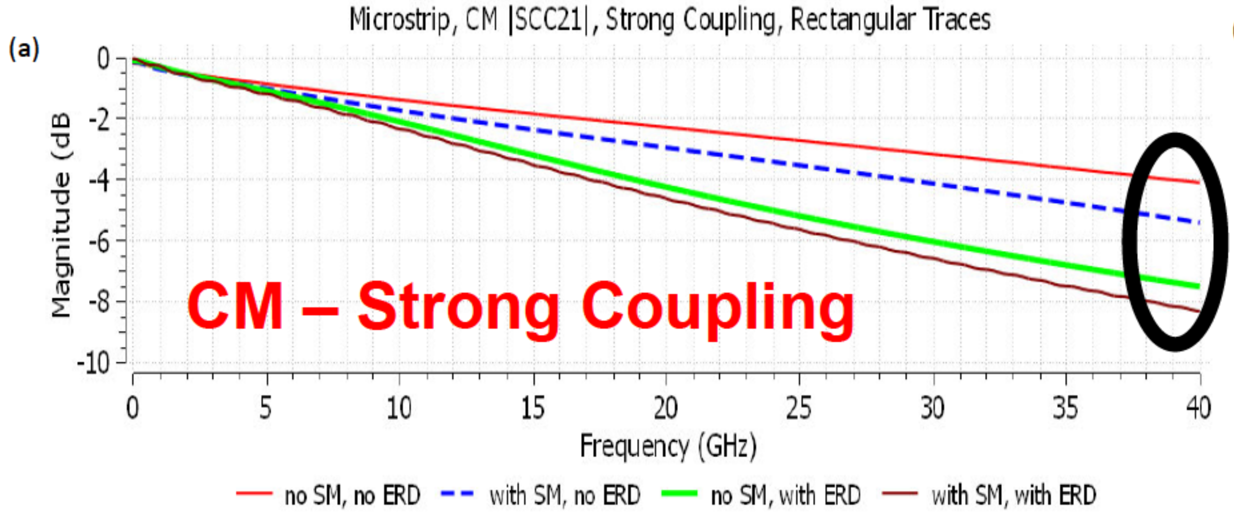


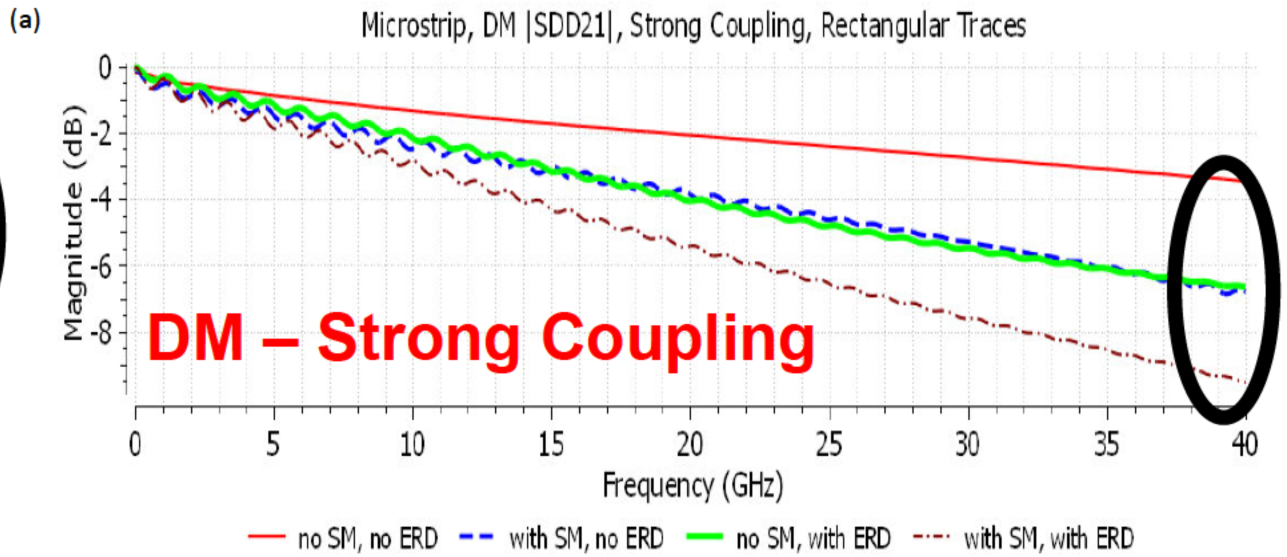
Modeled technological effects: dispersive PPO Blend, ERD, 60^0 trapezoid traces, Epoxy pocket

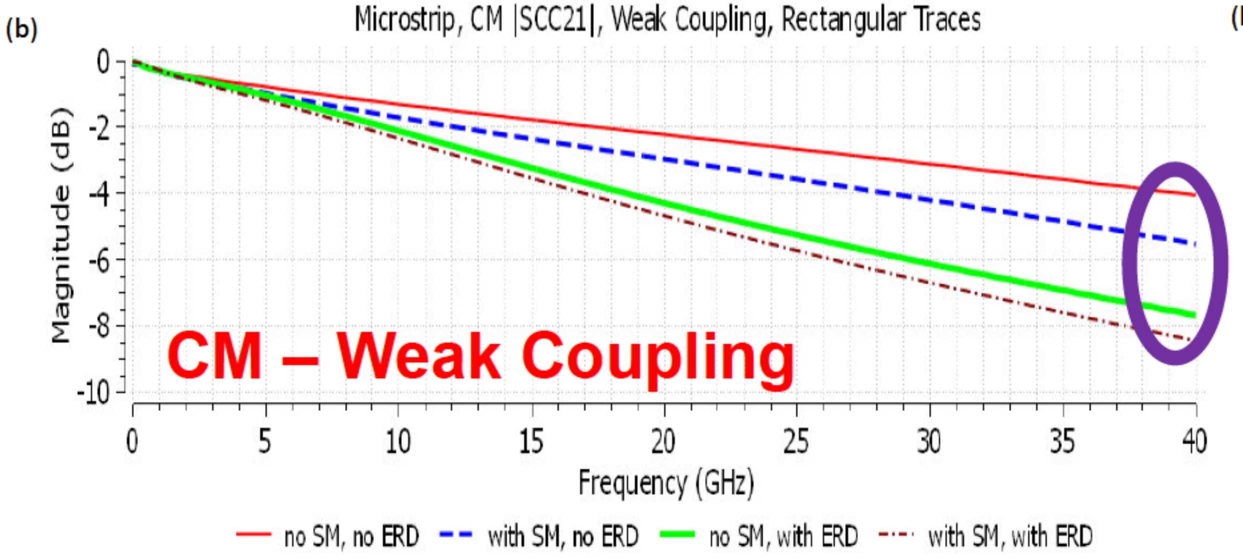


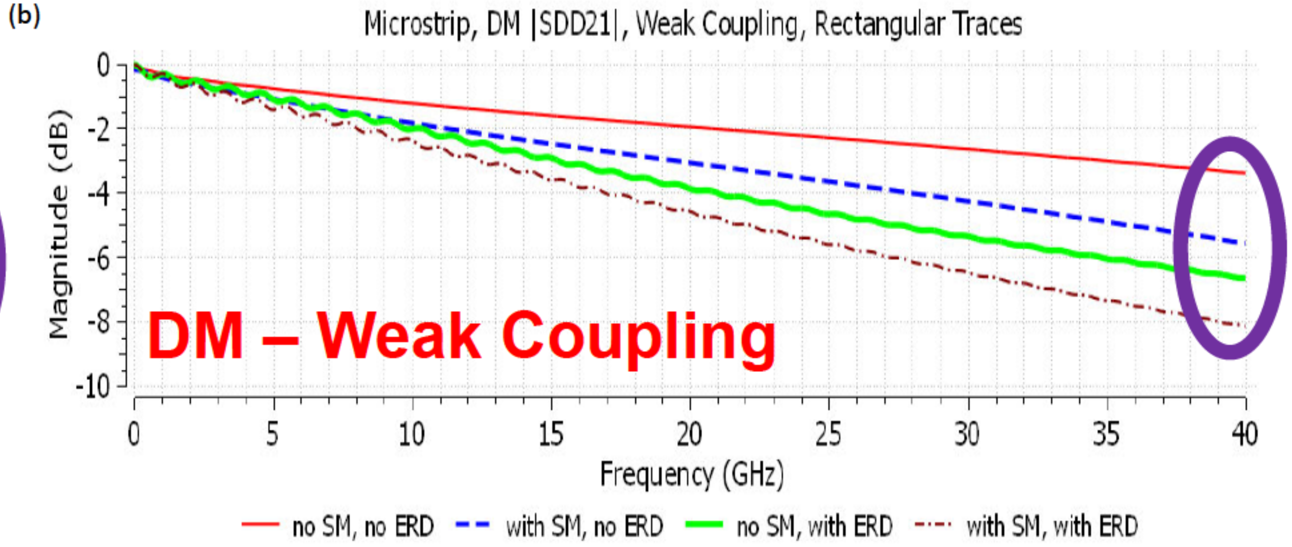
Line lengths are 80 mm and 80.127 mm (5 mil length imbalance)

Insertion Loss for Common & Differential Modes – MS 90^0 Traces



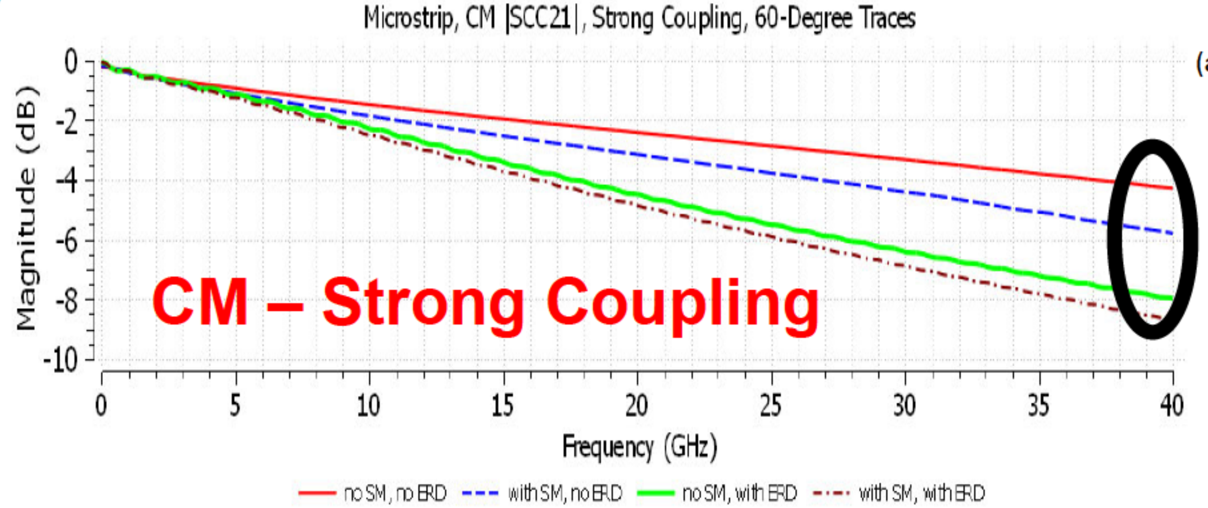




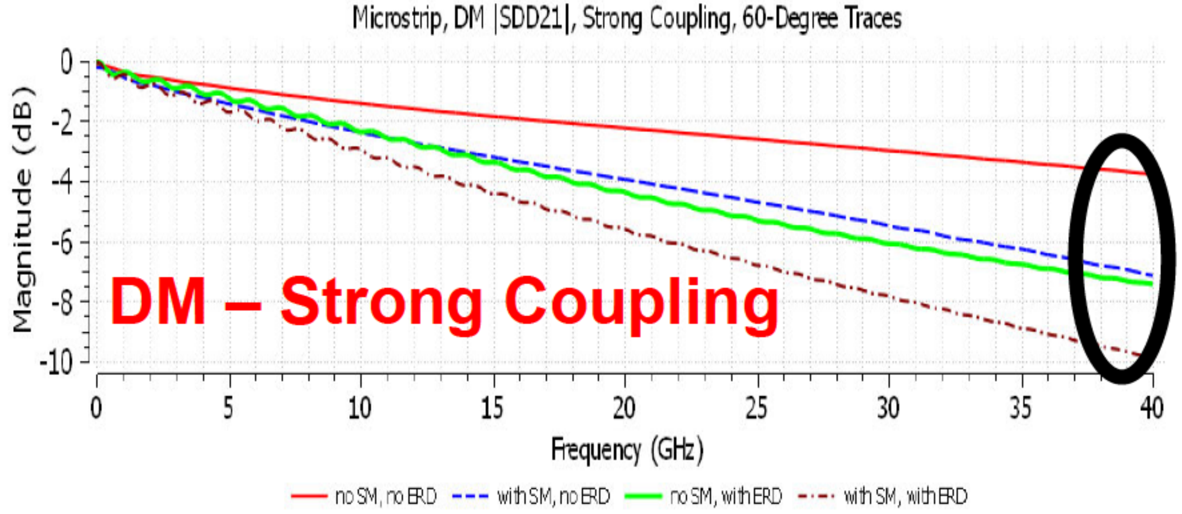


Insertion Loss for Common & Differential Modes – MS 60^0 Traces

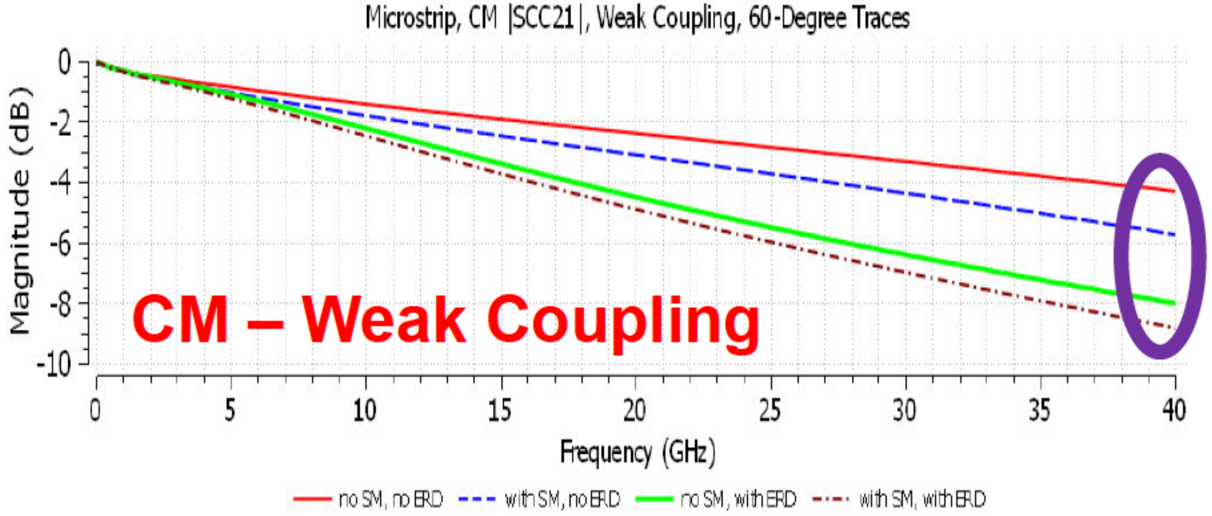
(a)



(a)



(b)



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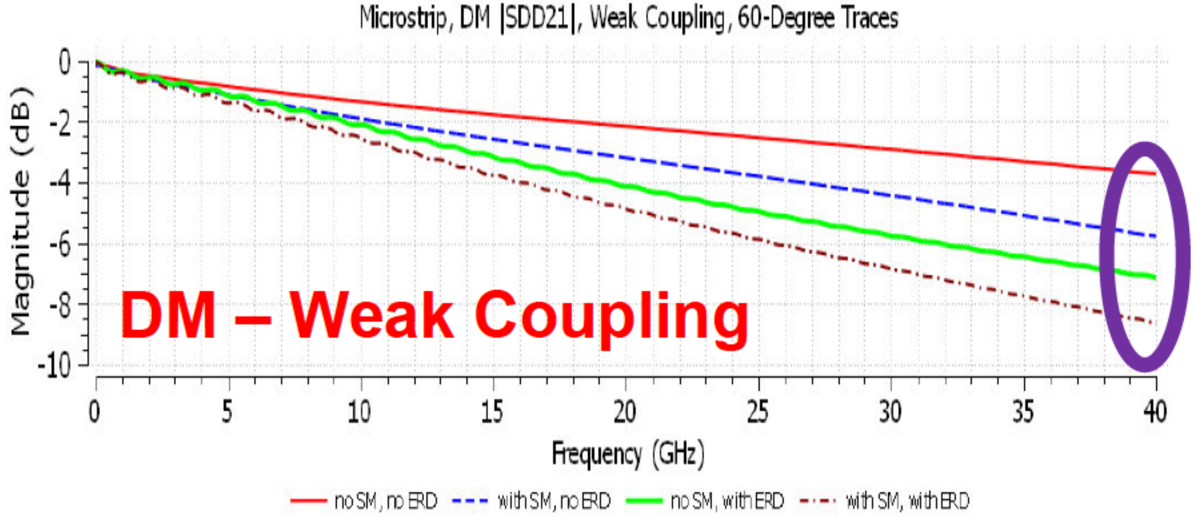
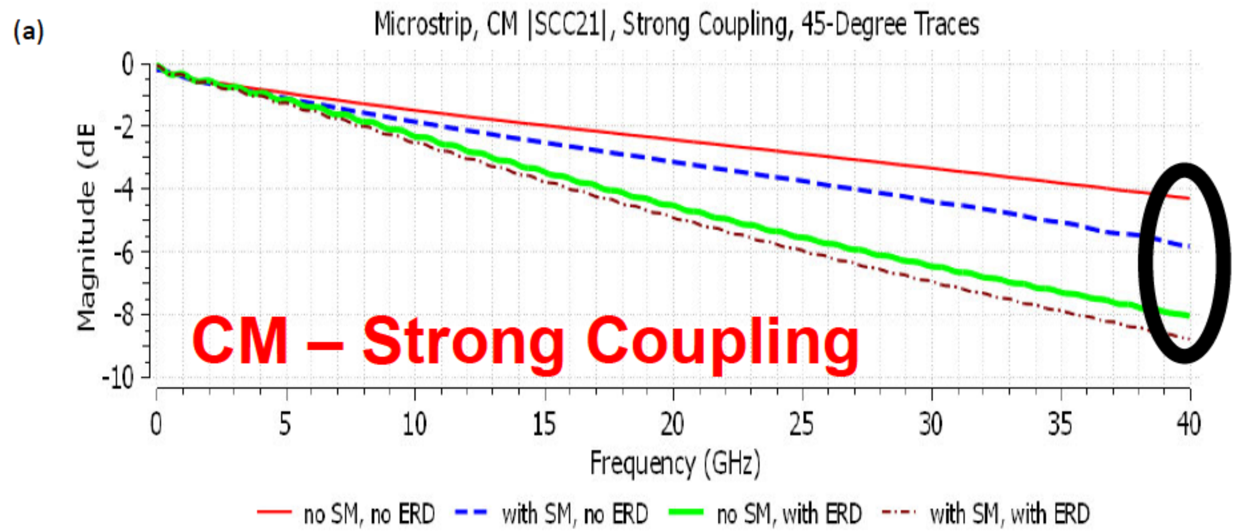
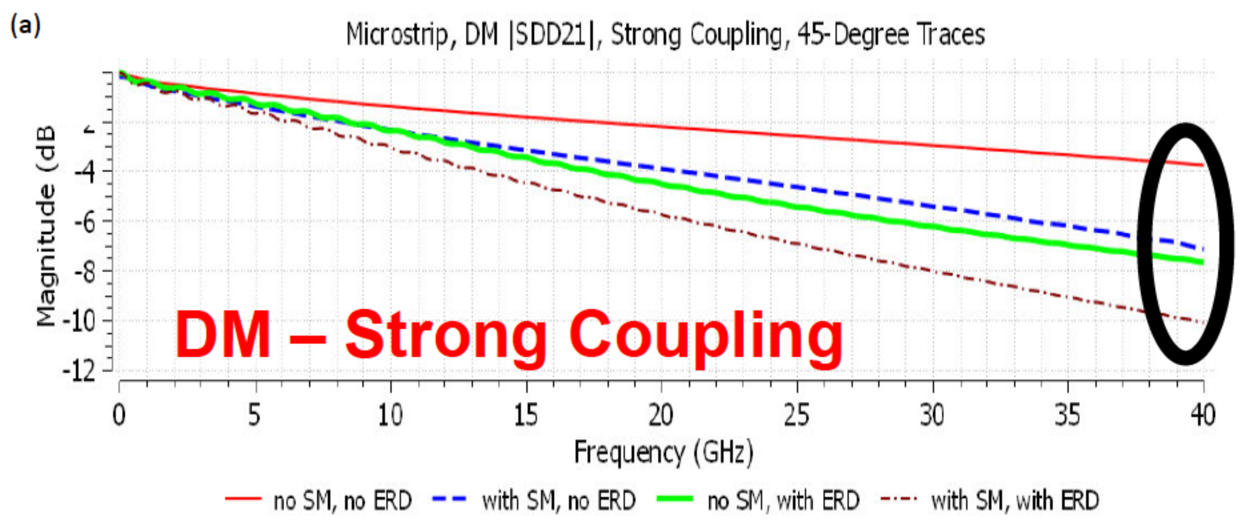
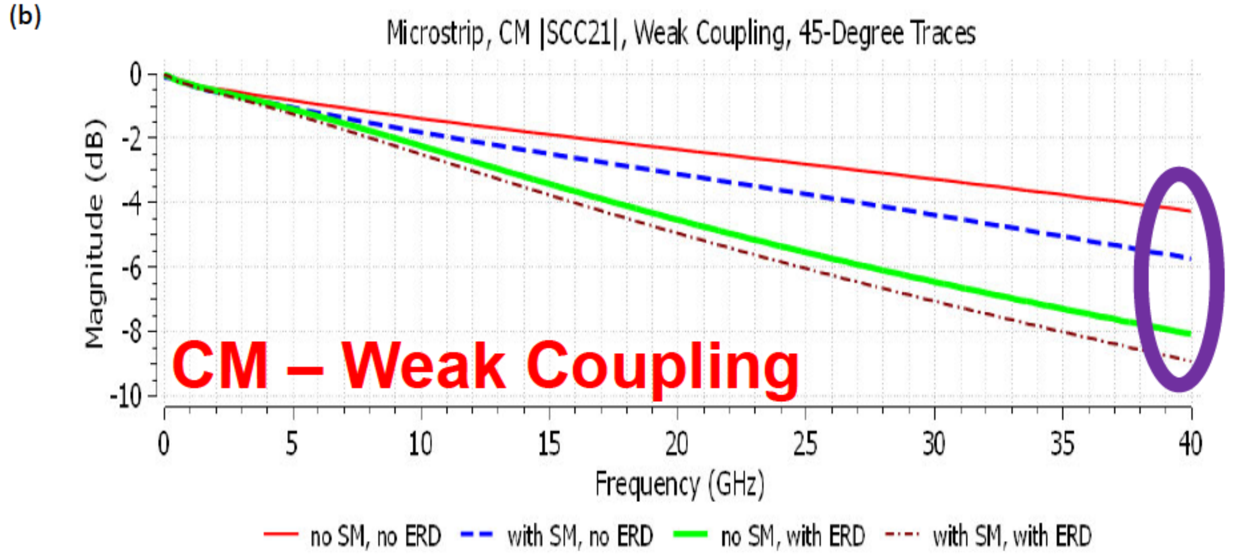
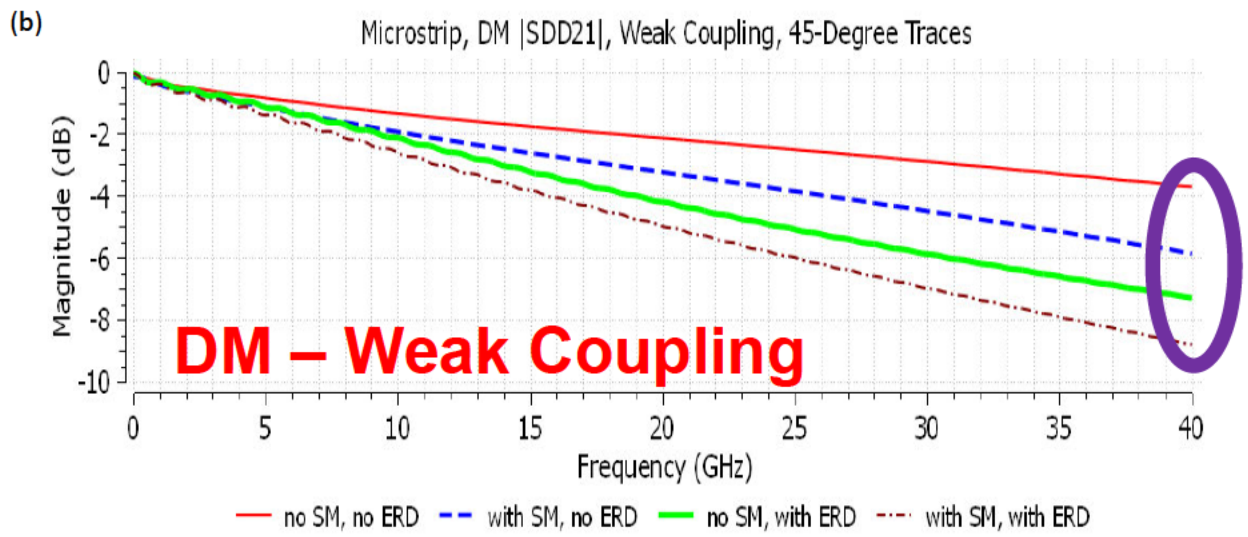


Insertion Loss for Common & Differential Modes – MS 45^0 Traces



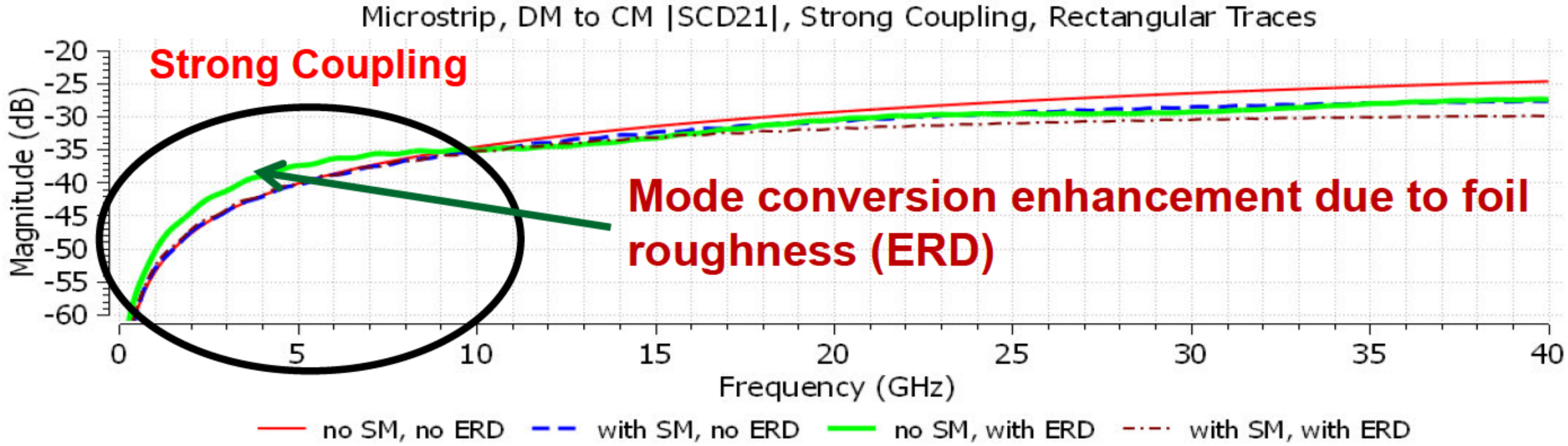




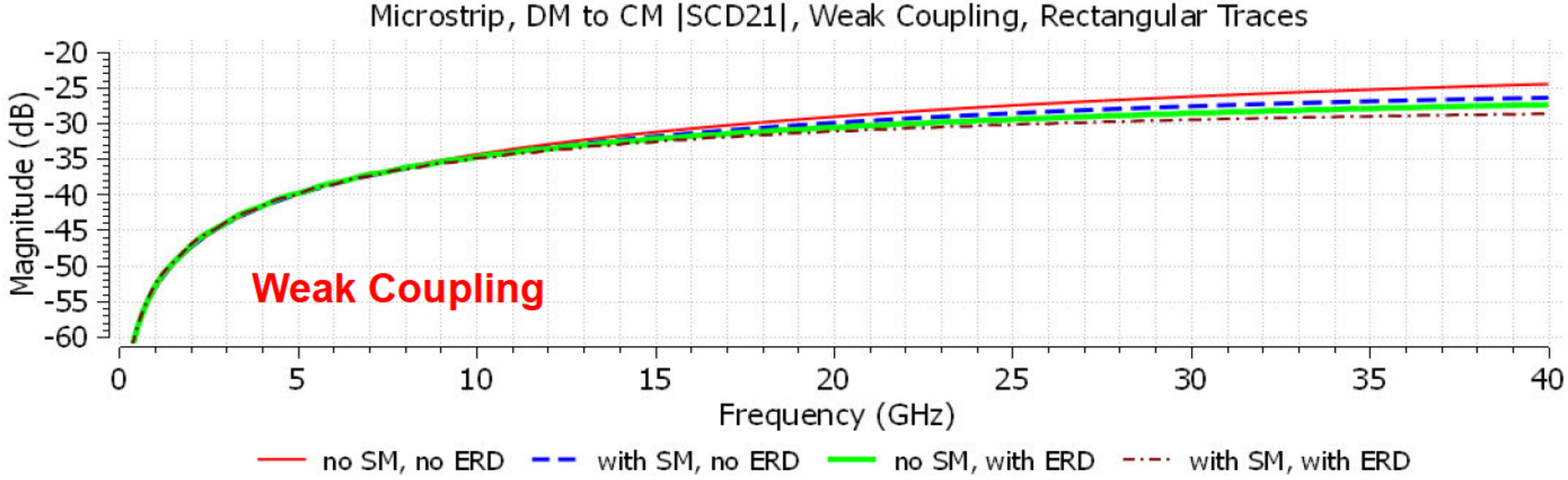


Mode Conversion for Different MS Cases

(a)



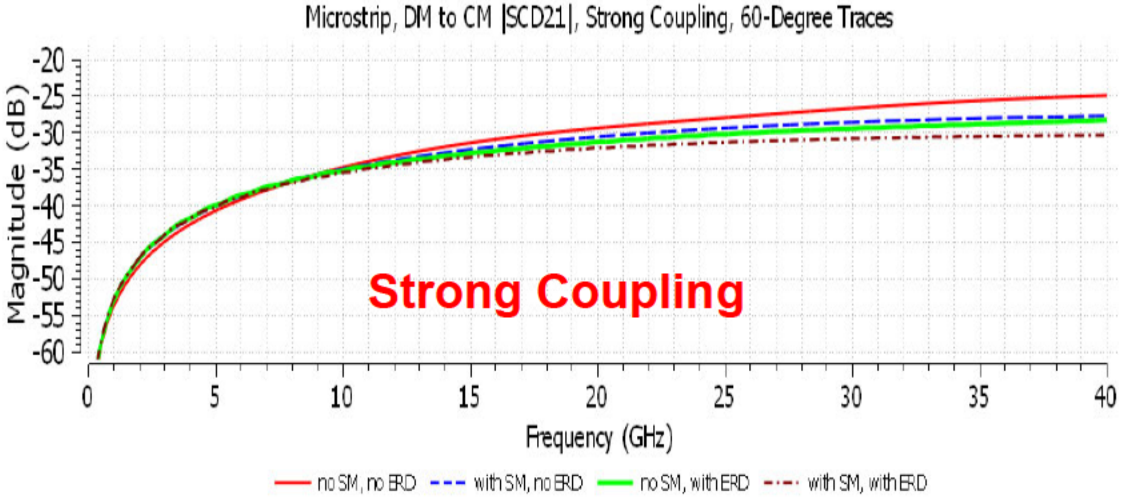
(b)



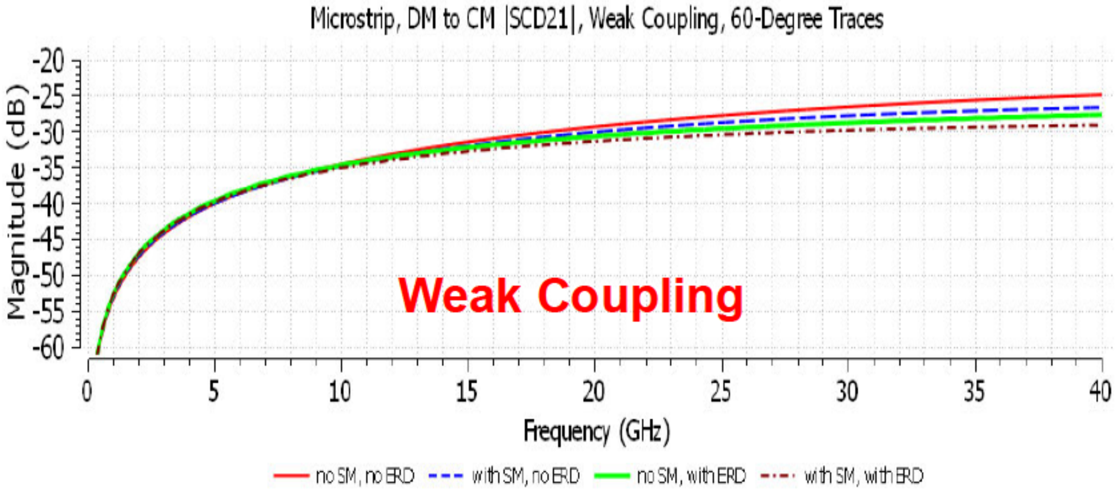
Mode Conversion in MS Cases with Trapezoid Traces

60^0 Traces

(a)

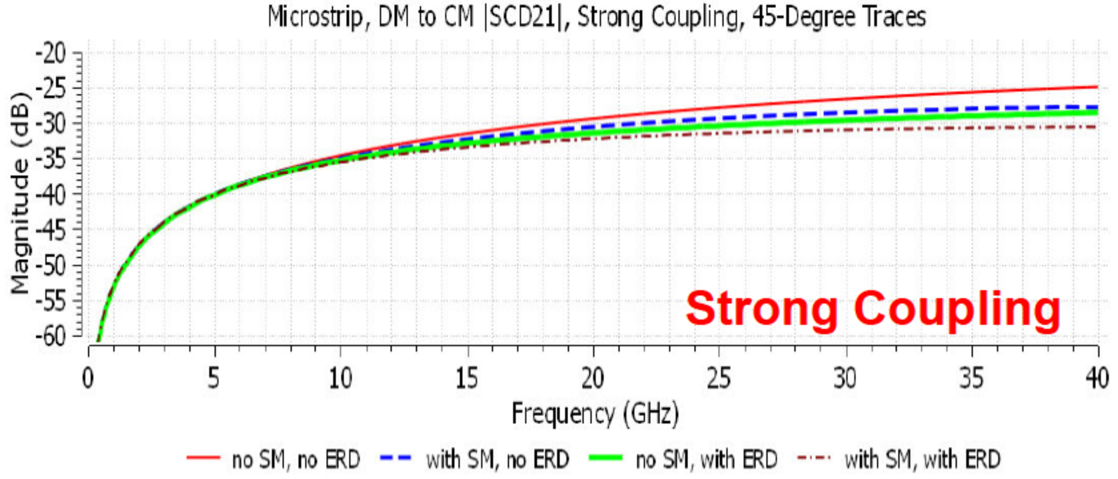


(b)



45^0 Traces

(a)



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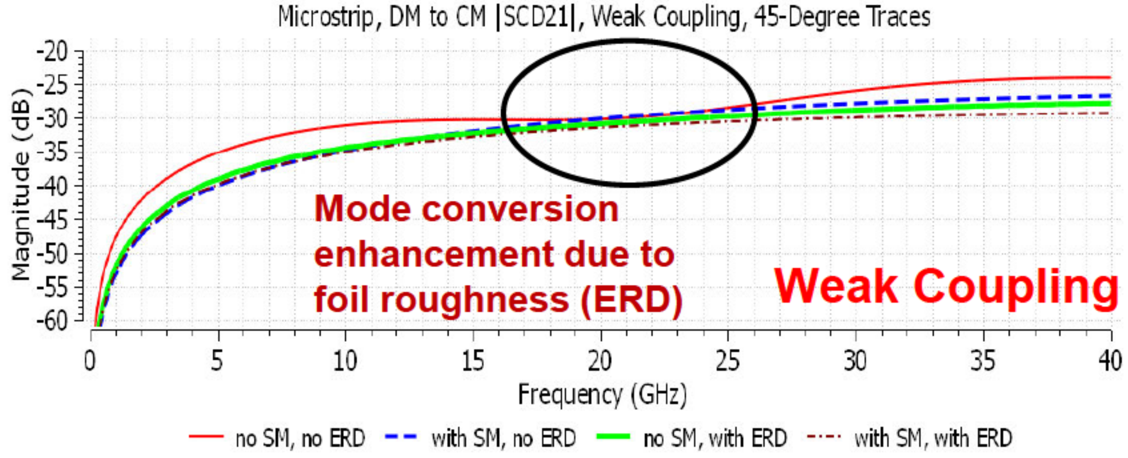
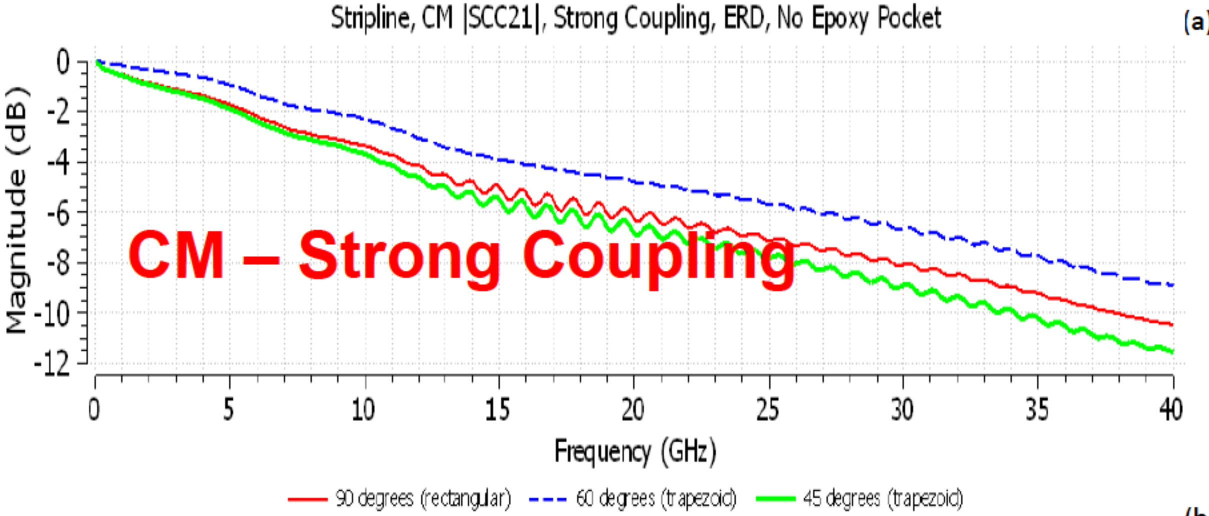


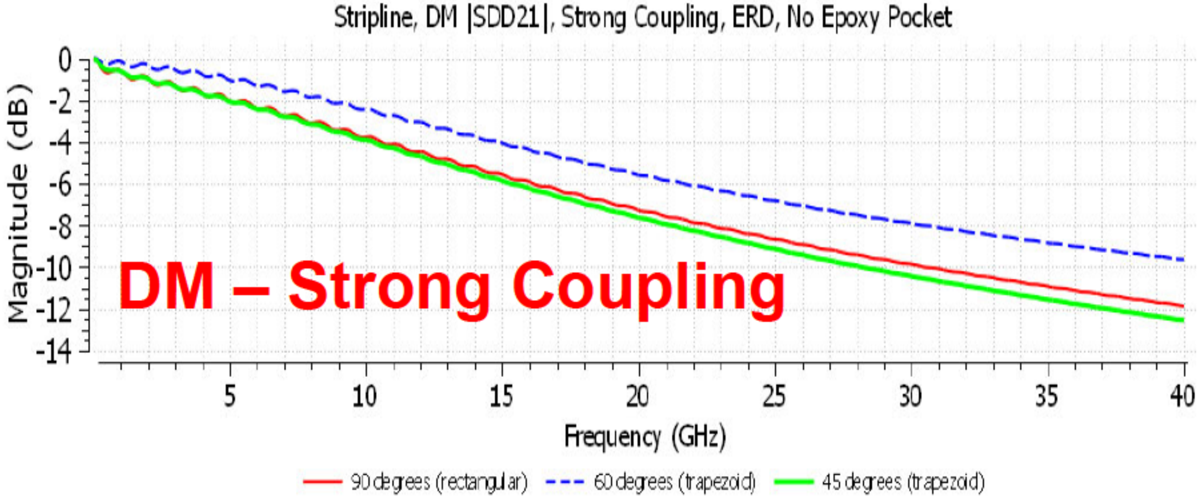
Insertion Loss for Common & Differential Modes in SL Cases

With ERD, but without Epoxy Pocket

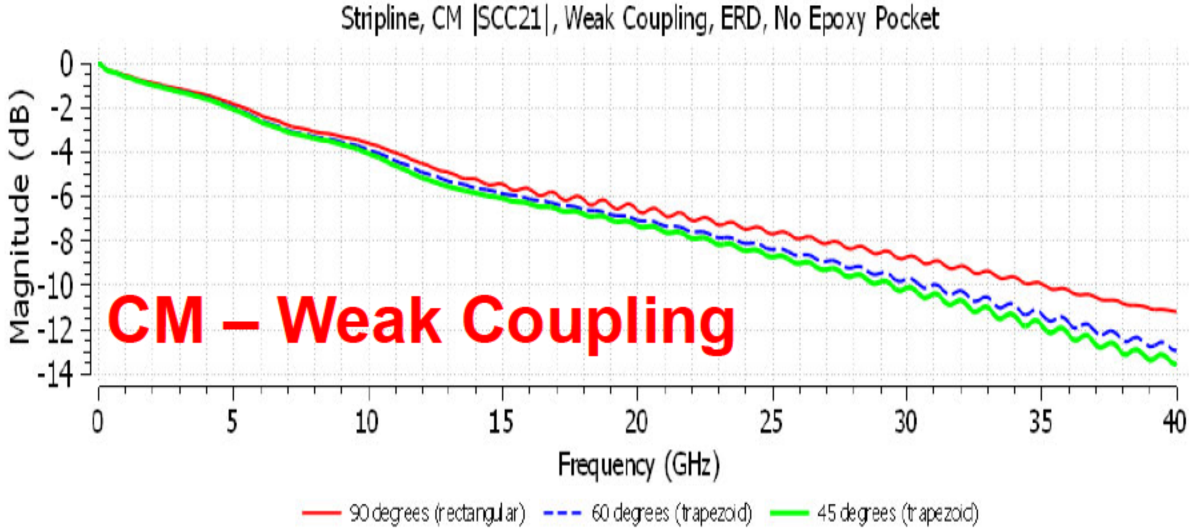
(a)



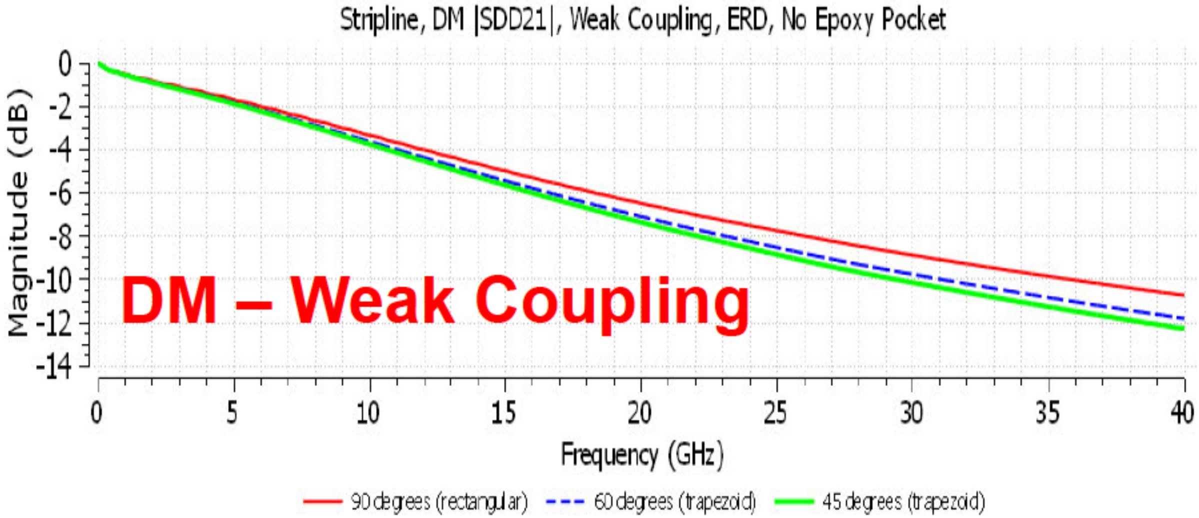
(a)



(b)



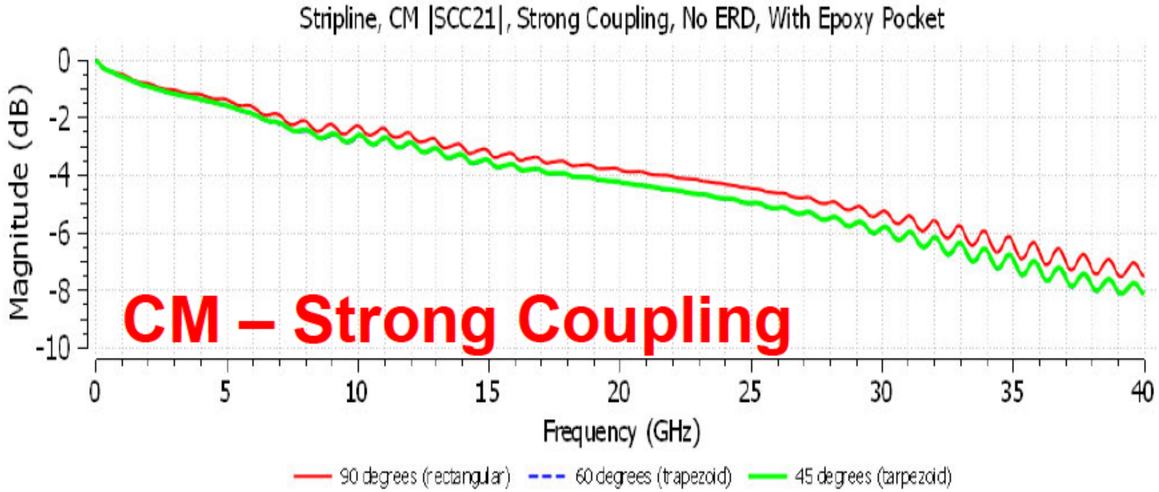
(b)



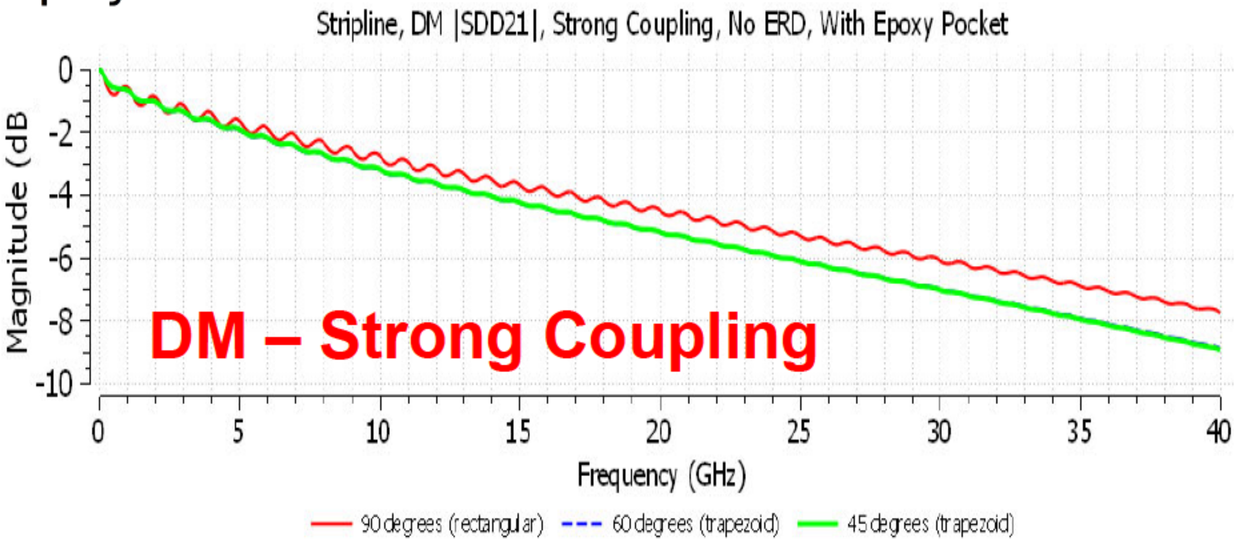
Insertion Loss for Common & Differential Modes in SL Cases

Without ERD, but with Epoxy Pocket

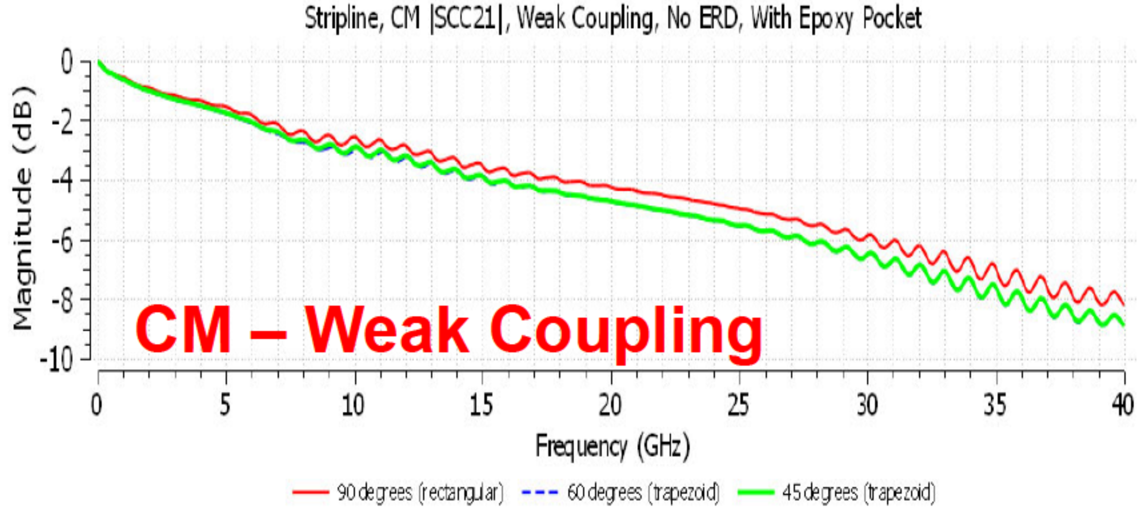
(a)



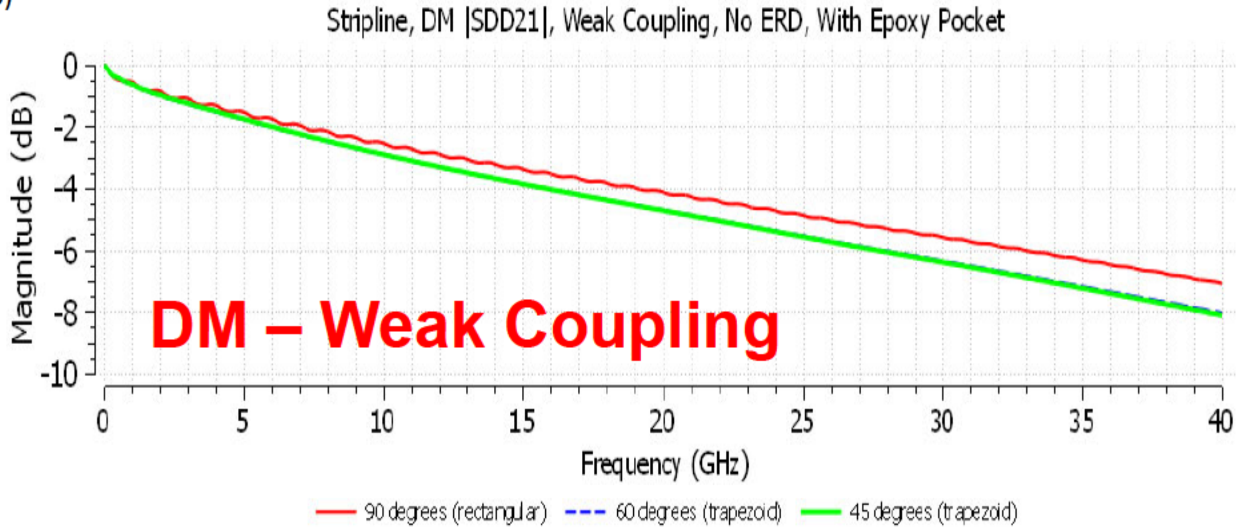
(a)



(b)



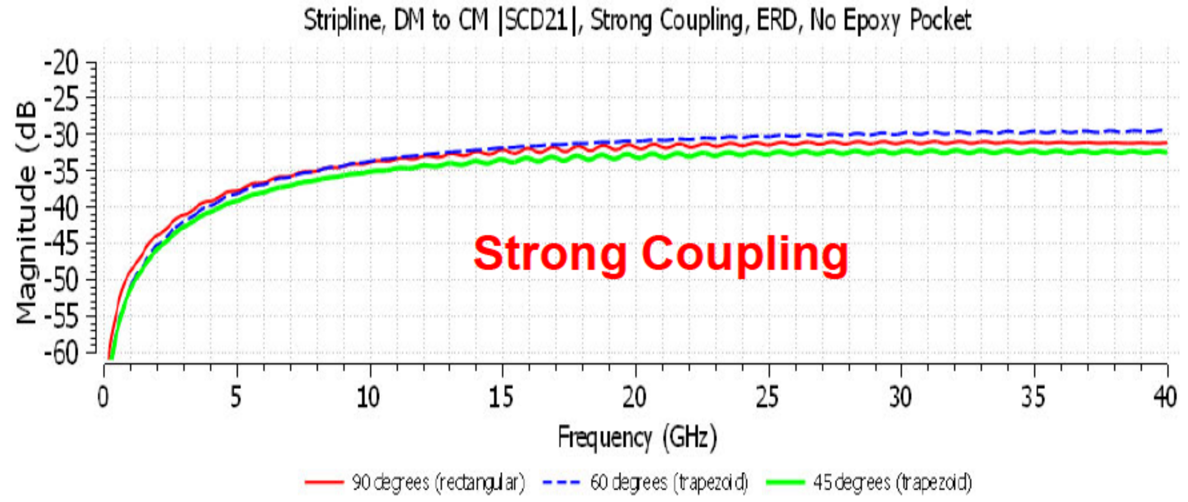
(b)



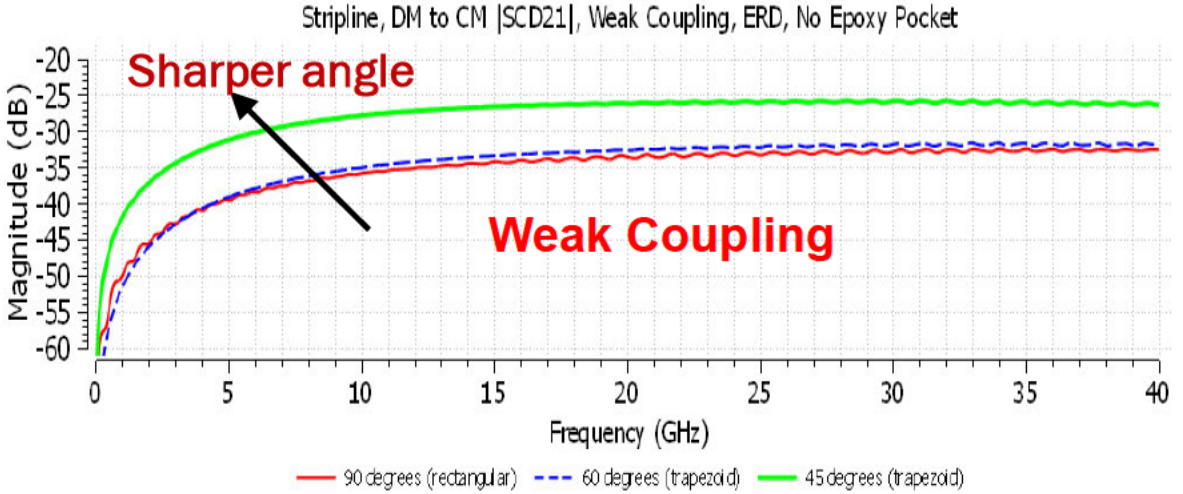
Mode Conversion for SL Cases

With ERD, but without Epoxy Pocket

(a)

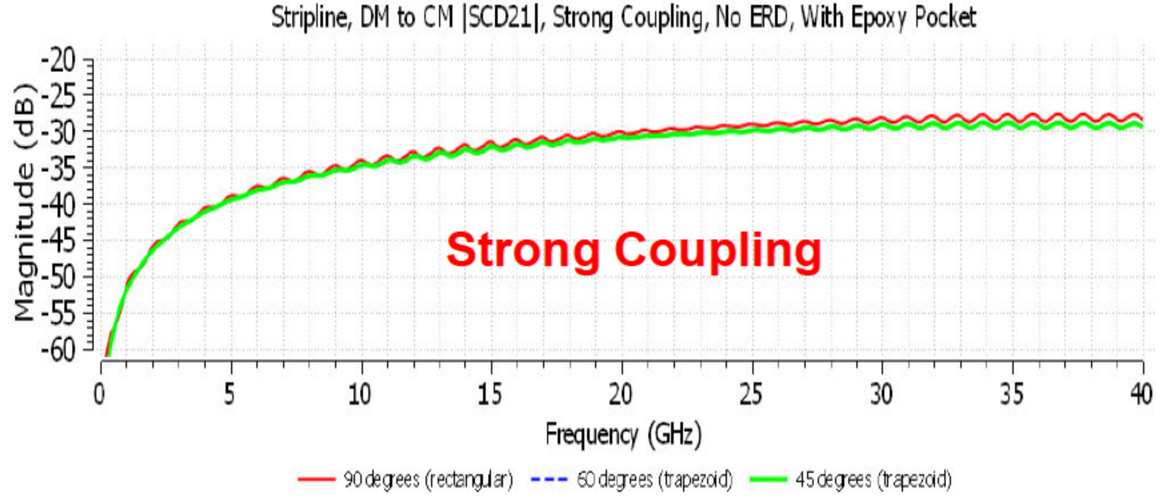


(b)

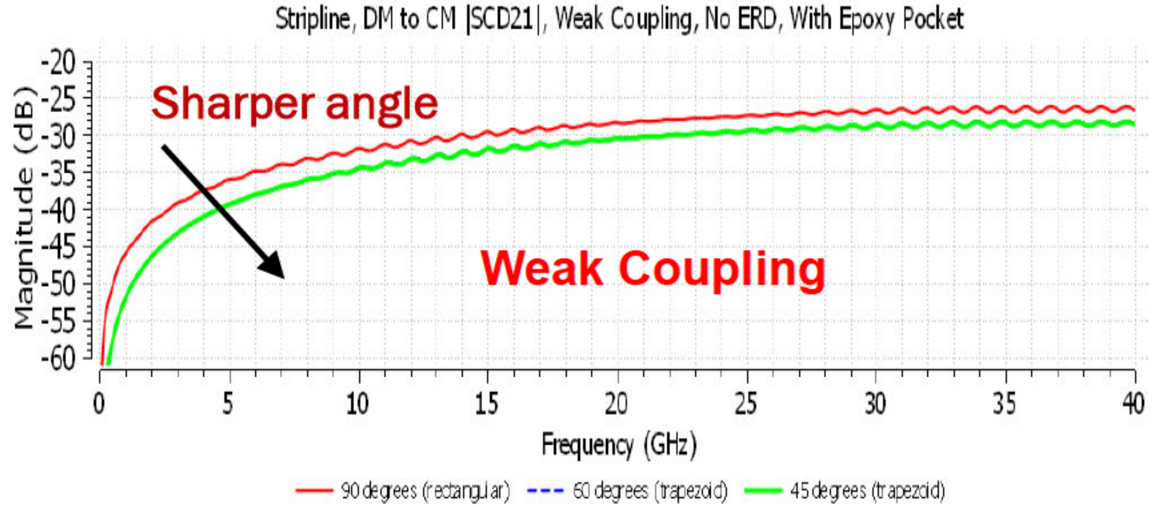


Without ERD, but with Epoxy Pocket

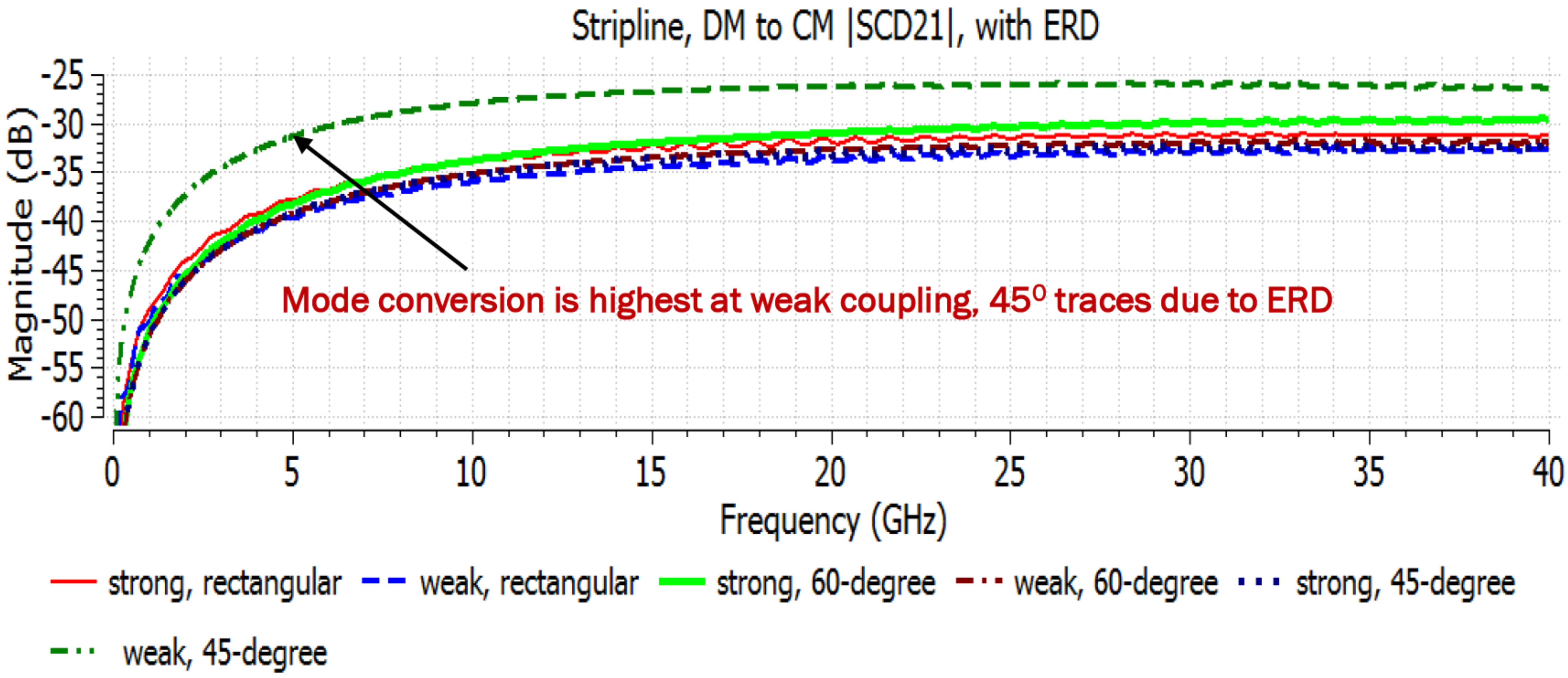
(a)



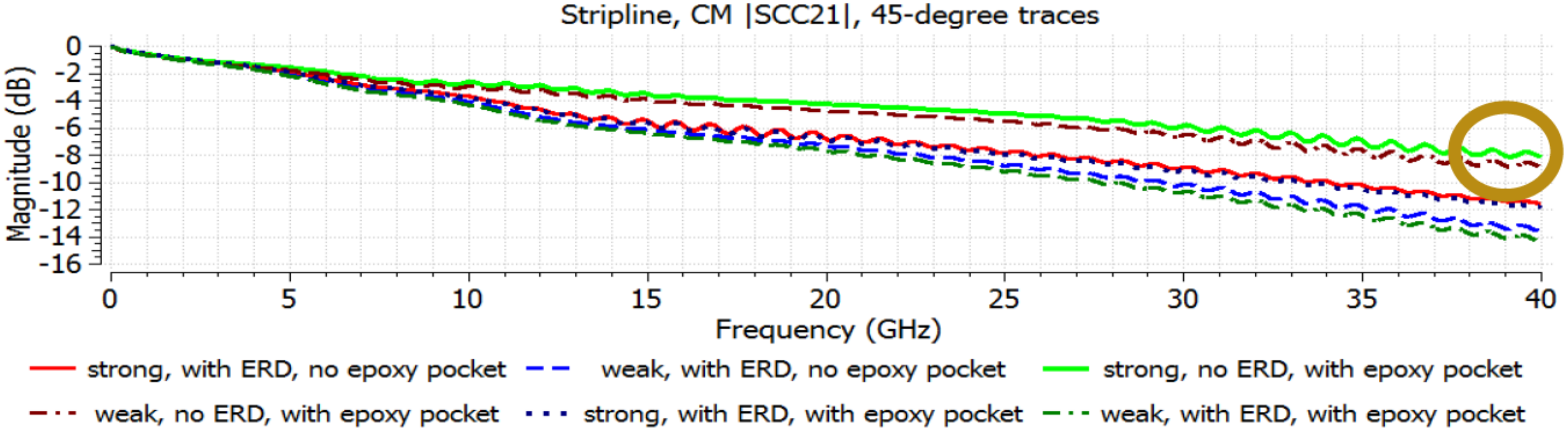
(b)



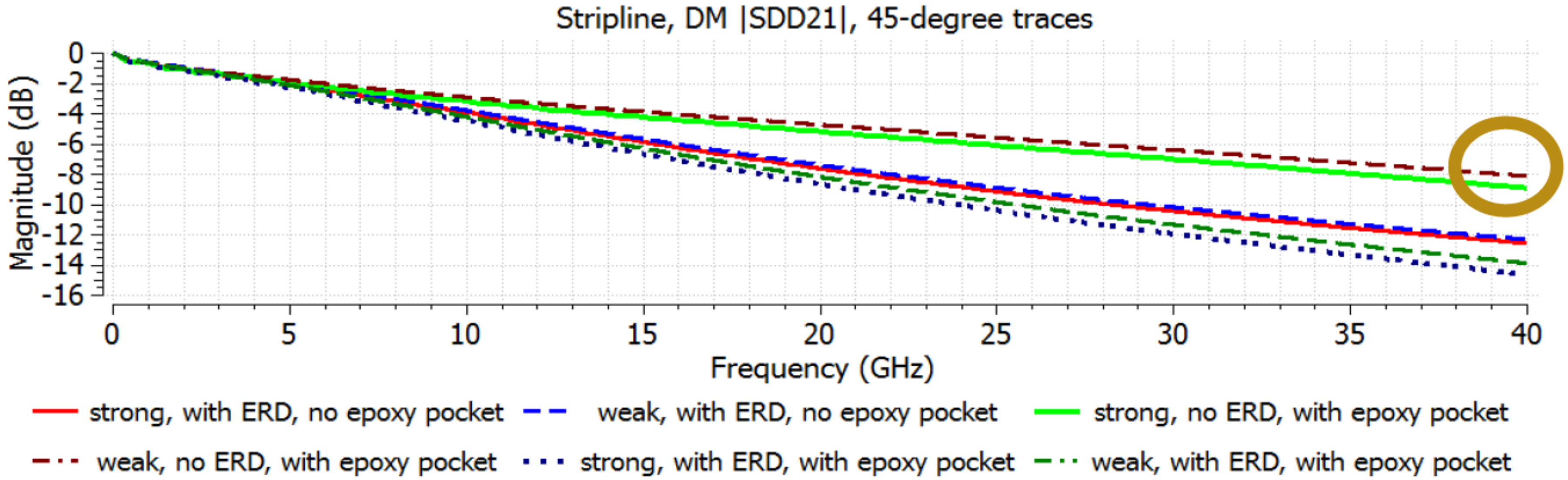
Comparison for Different SL Cases



Epoxy Pocket Effect on DM and CM in Differential SL Pair

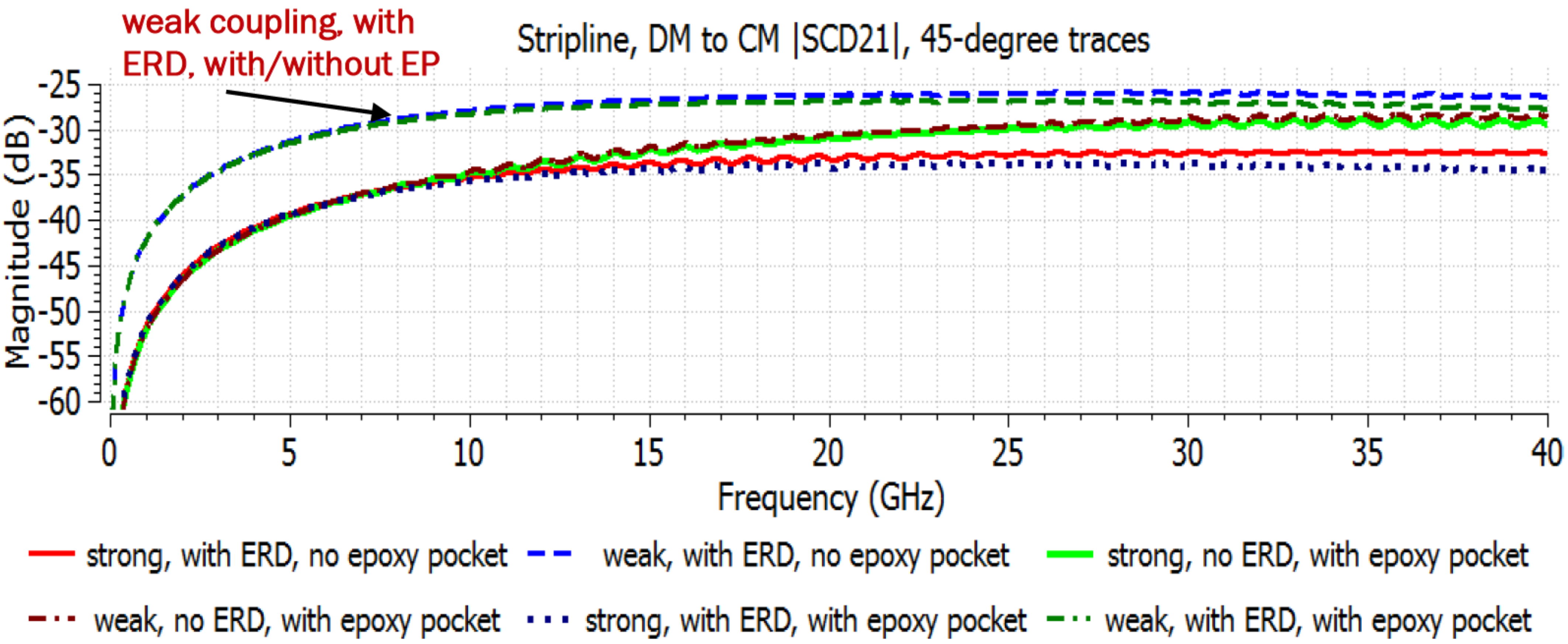


with Epoxy Pocket, strong and weak coupling



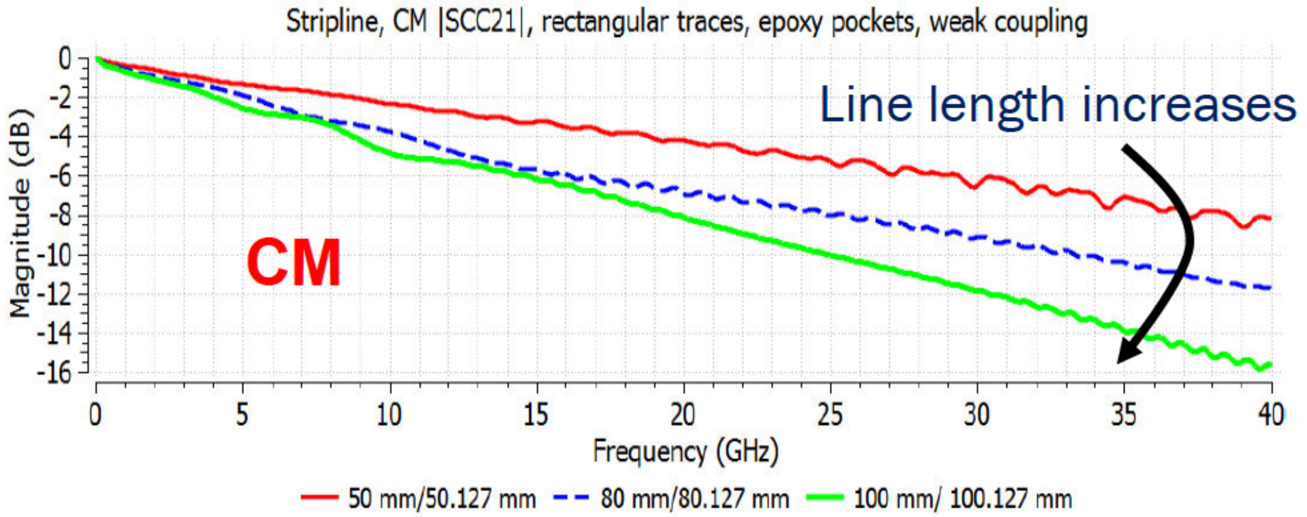
with Epoxy Pocket, strong and weak coupling

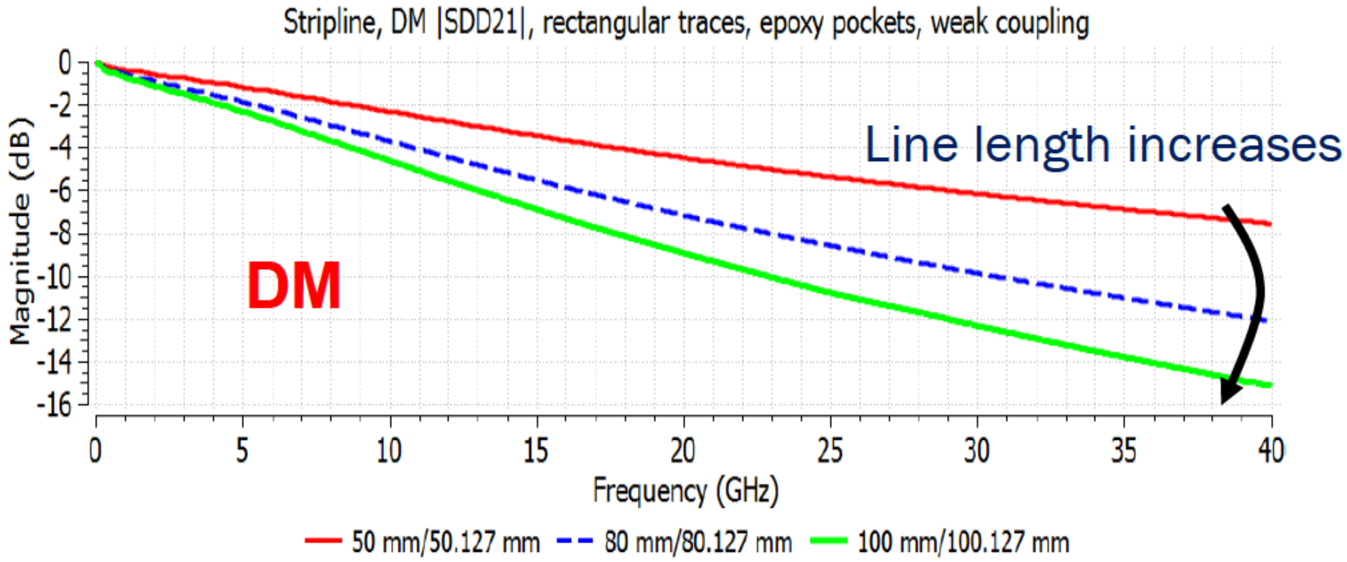
Epoxy Pocket Effect on Mode Conversion in SL Pair



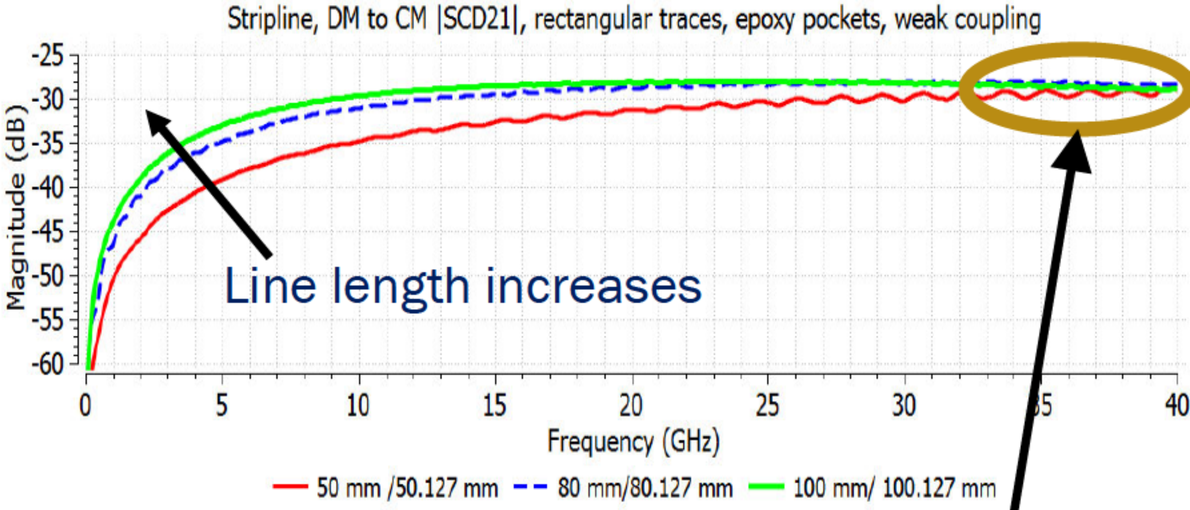
Effect of epoxy pocket is not as important for mode conversion as ERD and weak coupling

Effect of Different Line Lengths





Mode Conversion



Reduction of mode conversion for longer lines at higher frequencies

Conclusions

- Rate of coupling (strong vs. weak) in edge-coupled imbalanced differential pairs, both MS and SL, result in different behavior of mixed-mode S-parameters.
- For SI, weak coupling is preferable. However, this is not always the case for EMC.
- Mode conversion may be larger in the weak-coupled than in the strong-coupled cases, especially if the traces are trapezoid and other technological factors are considered.
- Copper foil roughness may enhance the mode conversion. The most critical case for mode conversion enhancement is when there is *weak coupling, 45^0 trapezoid traces, and significant roughness*, especially *at the lower frequencies*.
- Strong coupling usually results in the mode conversion damping, in both MS and SL cases, and may be beneficial from EMI point of view.

Thank you!

Questions?

marina.koledintseva@oracle.com