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Common Mode Filtering with Metamaterial-Inspired Structures

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I. Introduction

High-speed digital communication links typically employ differential signaling as an alternative to single ended signaling. This is done in order to reduce electromagnetic noise generated by the cables as well as to decrease the effect of external noise on the cables. As just one example, PCI express is a high-speed bus standard, which also uses differential signaling that is used in computers for many kinds of expansion cards.   The design challenge using these differential lines are that perfect symmetry in the signals sent and in the physical communication line must be maintained to prevent some of the differential mode signal's energy to be converted to a common-mode signal. This is illustrated in Fig. 1.

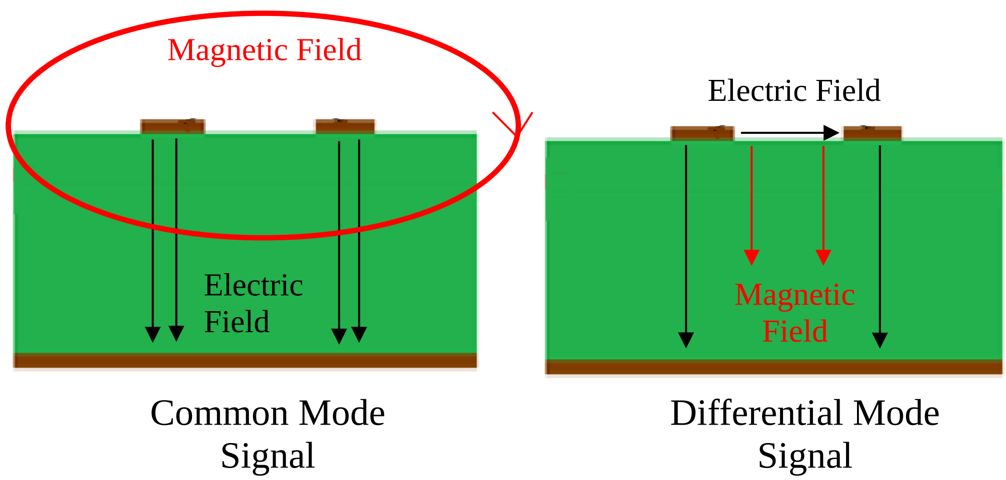

Figure 1. Common Mode vs Differential Mode Signals showing the fields in a microstrip

The common-mode signal creates a magnetic field that is generated outside of the cables, while for a differential mode signal, the fields are largely between the pair, particularly as we move away from the lines. The main objective of a common-mode filter is to filter out this common-mode noise while leaving the differential signal intact. Our strategy in this project was to look into past work on common mode filtering, to develop some accurate models for simulations, and to develop some new structures that also filter out the common mode noise.

II. Previous Work

Previous work shows that Complementary Split-Ring Resonators (CSRRs) are very effective in filtering out the common-mode signal at a target frequency and at the odd harmonics. Much of the previous work assumed two-layer boards however. In a multi-layer PCB environment, the filtering effect of the CSRR structures in previous work diminished. Our group found that this effect can be largely recovered through the use of VIA fences, which effectively cage each CSRR to prevent leakage of electromagnetic energy. These structures have been shown effective in simulations using CST Microwave Studio, as shown in Fig. 2. These same boards, when fabricated and measured in the laboratory, showed poor agreement due to breakdown of the differential mode signal at a much lower frequency than shown in simulation, as shown in Fig. 3.

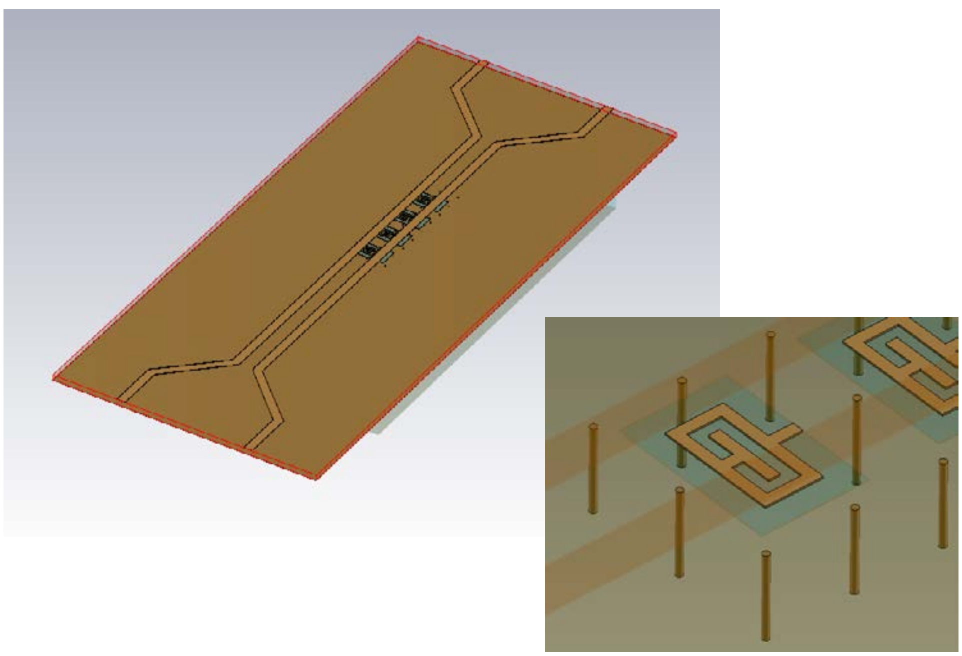

Figure 2. CST Model of CSRR CM filter with VIAs

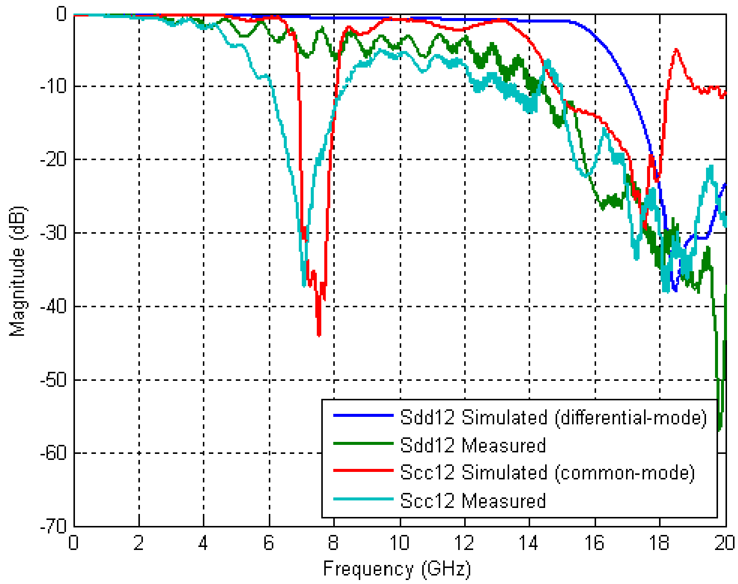

Figure 3. Simulation vs Measurement Results from previous work

III. Attaining Accurate Simulation Results

In order to investigate the source of the poor agreement between simulation and measurement, I followed several lines of inquiry. First, the simulation was rerun with a lower tolerance as well as a higher accuracy and multiple small parameter sweeps were conducted in order to account for the imperfect nature of fabricated models. These changes had little effect in the simulation results. Next, the SMA edge-launch connector was included in the simulation to investigate the possibility that connector imperfections might be the cause of the imperfect signal launches. The results from this investigation can be seen in Fig. 4. The CST model including the connector can be seen in Fig. 5.

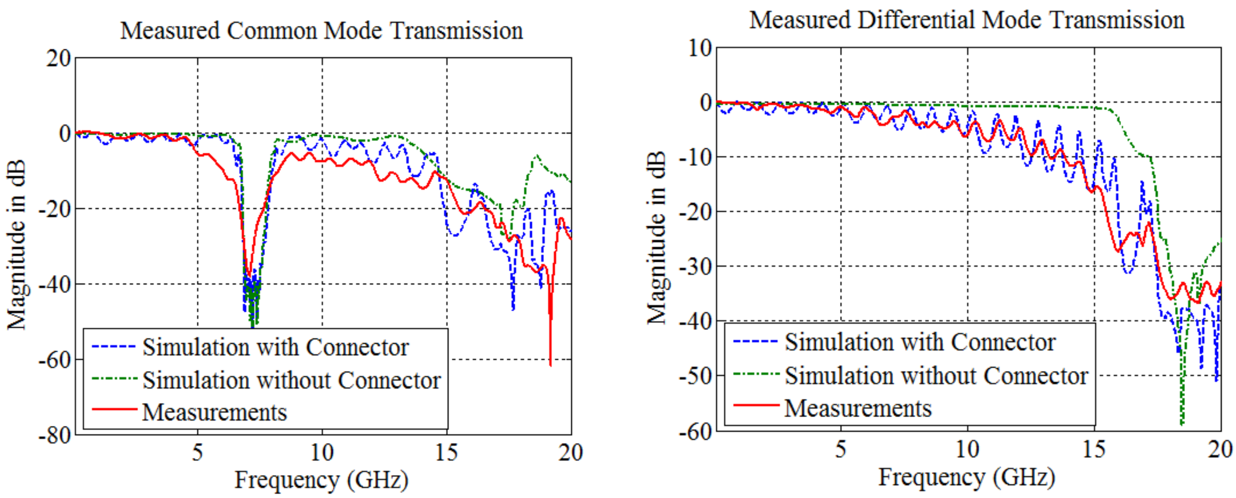

Figure 4. Measured vs Simulation showing the more accurate model when the connector model is included.

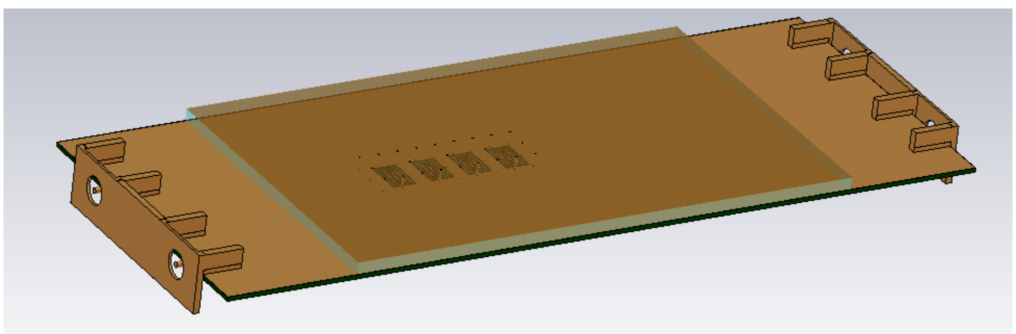

Figure 5. Simulated Model including SMA edge launch structure

The connector model can be shown to significantly improve the correlation between simulation and measurements. The source of the early breakdown in the measured results were ultimately attributed to a 0.5mm air gap in the connectors that causes an impedance mismatch at approximately 12GHz, as shown in Fig. 6.

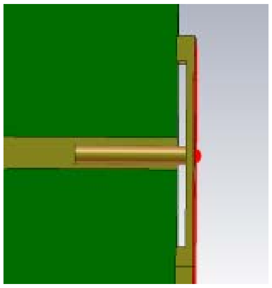

Figure 6. Top view of SMA connector model

In order to confirm that the problem presented by the SMA connectors, an additional CSRR common-mode filter was fabricated. This filter was made as a single layer filter as shown in Fig. 7, and results can be seen in Fig. 8.

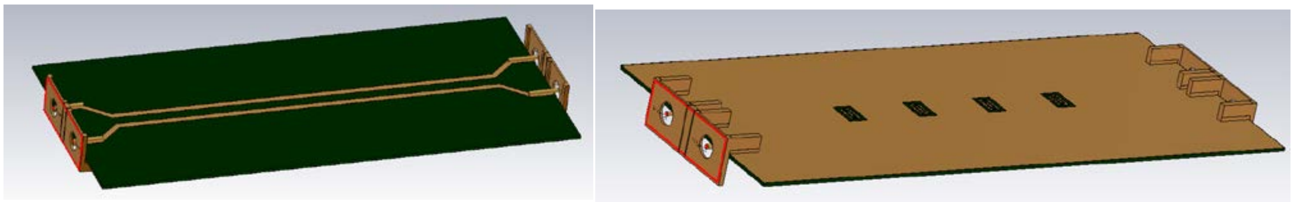

Figure 7. Top and Bottom View of Single Layer CSRR based CM Filter

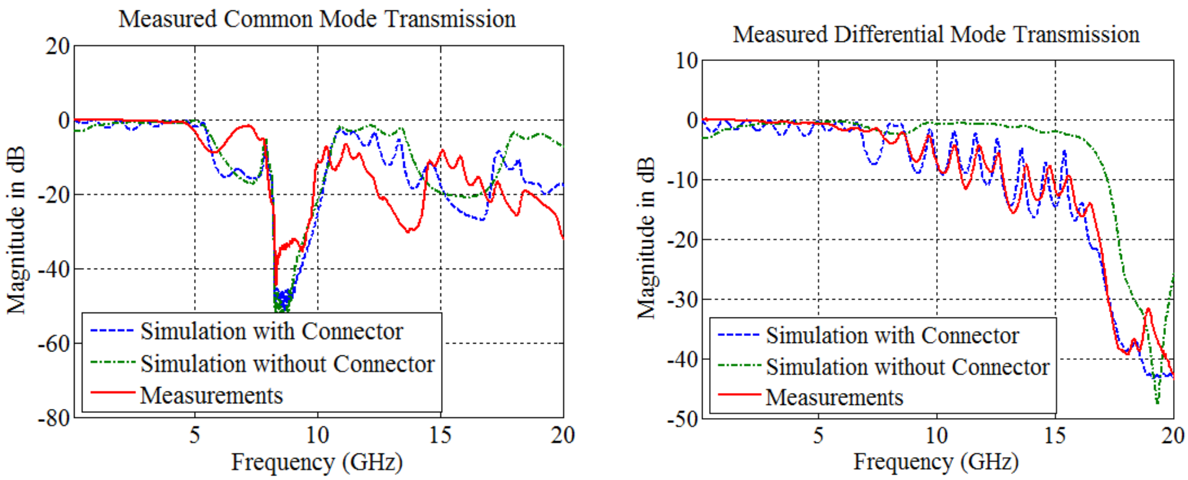

Figure 8. Measured vs Simulated Results for Single Layer CSRR CM Filter

These results show that it is indeed the SMA connectors causing the signal integrity problem at higher frequencies and that when this is modeled in CST, the measurements and simulations agree very reasonably.

IV. Developing New Common-Mode Filters

In this project, another method, based on transmission line theory, was discovered which proved effective in filtering out common-mode noise. Instead of adding a CSRR to the reference layer of a board, a transmission line was added in between the differential pair. This is because in a perfect differential mode signal in a microstrip, one cable can be said to have a +A voltage while the other cable can be said to have a –A voltage at any given point. The middle of the cables will have a 0V, meaning that adding a structure in the middle should have no effect on the differential mode signal. When a common-mode signal is input into the device, however, both cables will be at a +A voltage, meaning that some of the energy will be coupled to any structure in the middle. Due to this, the structure in the middle could potentially affect the common-mode signal without affecting the differential mode signal.

This structure was modeled using Panasonic Megtron 6 dielectric, a very common laminated used in industry and the dielectric to be used in a test board to be fabricated in an on-going collaboration with IBM, the relative permittivity of Megtron 6 being 3.6. Dielectric layer thicknesses of 5 mils (127 μm) we used for the signal layers. Since this filtering structure required no patterns to be etched in the reference layer, we expected no coupling to other layers. This was checked by modeling the structures multi-layer environment to confirm that it functions as expected in a multi-layer environment. The connector model discussed in the previous section was not added to show the results only due to the Device Under Test (DUT). The CST model can be seen in Fig. 9.

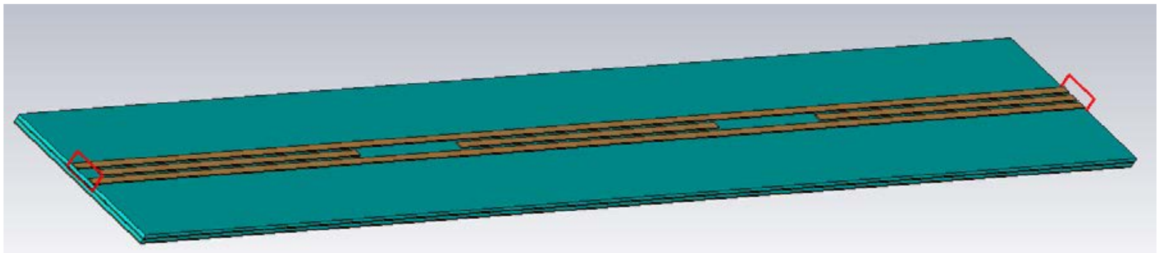

Figure 9. CST Model for Differential Pair with added Transmission Lines in between

The results from simulation are as shown in Fig. 10.

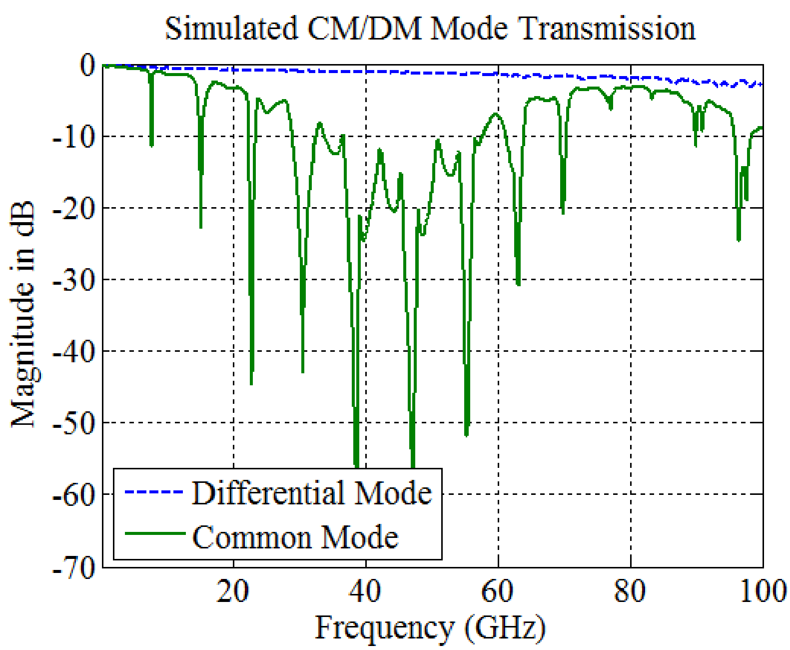

Figure 10. Common Mode vs Differential Mode Transmission

The results are very promising. Even when the simulation frequency was extended to 100GHz, there was no resonance or any behavior to adversely affect the differential mode signal, which resulted in the transmission attenuation being maintained at under 5dB. The common mode has shown to be very significantly attenuated at a harmonic interval. The first harmonic was noted to be the frequency at which the length of the filter transmission line is half a wavelength. This showed that there is a very strong correlation between the length of the filtering transmission line and the filtering frequencies. Following through on the idea of using a transmission line to filter out common-mode energy, a composite right/left-handed (CRLH) transmission line was put in between the differential pair. CRLH transmission lines can be used to allow phase progression to be in a direction opposite to that of energy flow. In the model, several strips were placed very close to each other, and each one had a VIA to ground in the middle. This effectively makes the circuit model of the filtering structure identical to that of a metamaterial line. The model used for simulation can be seen in Fig. 11, with results shown in Fig. 12.

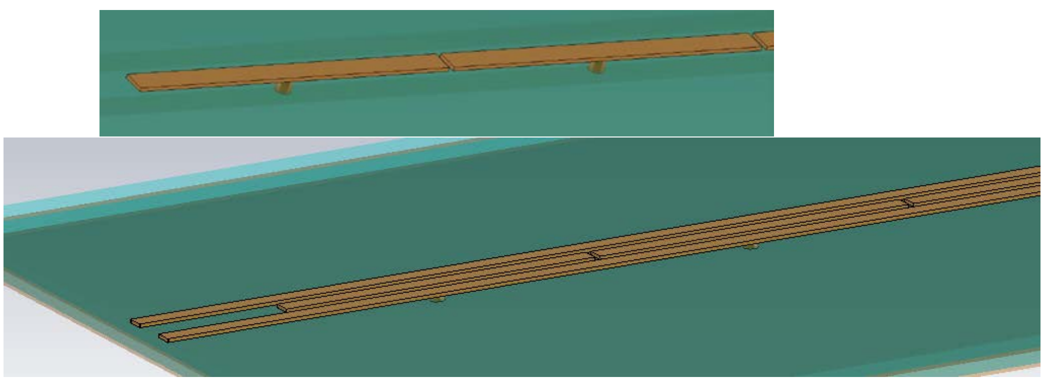

Figure 11. CST model of CRLH based CM Filter with a close-up of the CRLH line

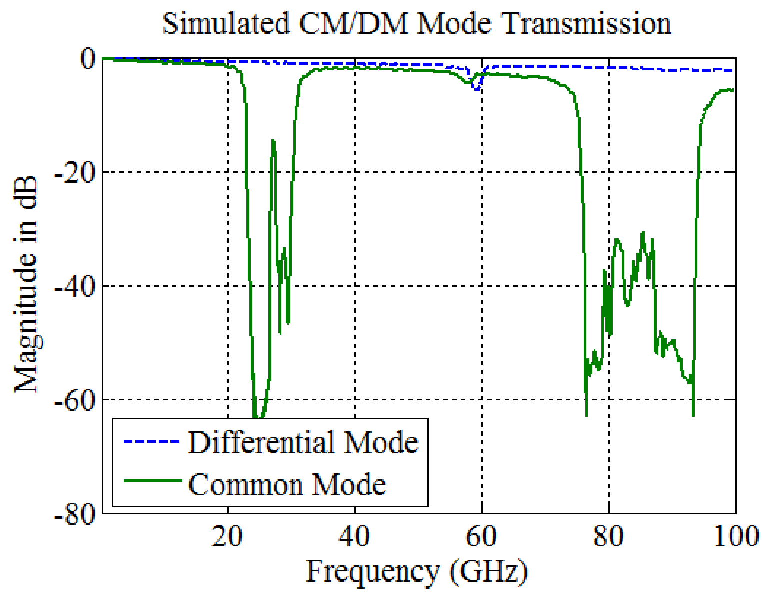

Figure 12. Common Mode vs Differential Mode Tranmission

These results were seen to be significantly different from when right-handed strips were added. The filtering behavior is very similar to an EBG such as the CSRR design, where a fundamental frequency is filtered out, along with a wider band third harmonic being filtered out. However, the differential mode experiences attenuation near the second harmonic of the filtering frequency. Other than that, the differential signal is shown to be very effective even through 100GHz.

Due to the success of the CRLH transmission line based CM filter, a broadband filter based on the CRLH line was designed. The lengths of strips have been varied by slowly incrementing them by 10% for each strip, with all other parameters remaining the same. The results from this can be seen in Fig. 13.

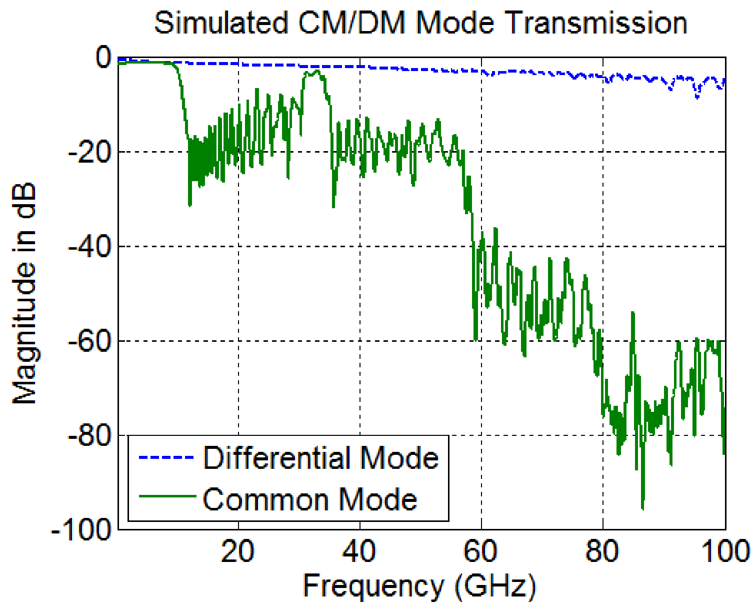

Figure 13. Common Mode vs Differential Mode Transmission

The results show very promising common-mode filtering effects, with it staying consistently under 10dB from 35GHz through 100GHz, as well as between 10GHz and 30GHz. The differential signal is attenuated less than 10dB over the entire range.

Due to the success of implementing a transmission line in between a differential pair, a similar approach was attempted on stripline pairs, which are essentially lines that do not rest on the top of a multilayer board but in any of the middle layers. When the simple transmission line was implemented, the differential mode had very promising results but the common mode transmission had not been attenuated at any filtering frequency. This difference was attributed to stripline signals being perfectly Transverse Electric and Magnetic (TEM) while microstrip lines are quasi-TEM, resulting in some structures behaving differently or not at all in different lines. After this, a CRLH line was input between the differential pair, where a via in the middle of the line connects the bottom reference to the top reference instead of simply from the bottom reference to the stripline layer. The structure can be seen in Fig. 14, and the results are shown in Fig. 15.

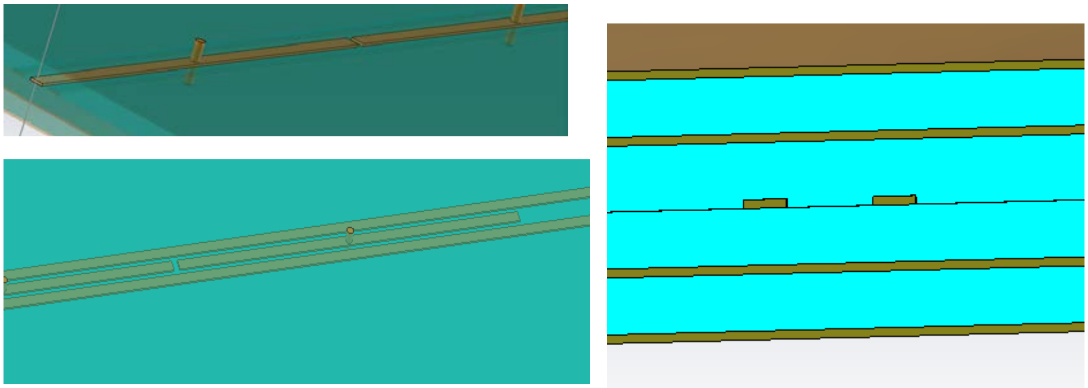

Figure 14. CST Model of Stripline Structure with CRLH based CM Filter

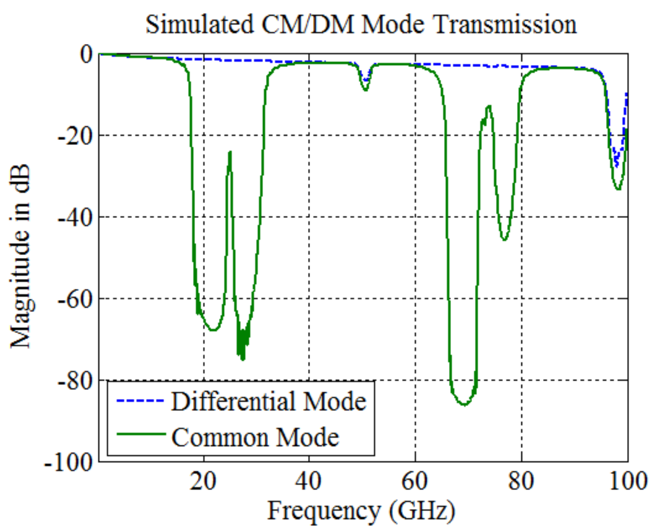

Figure 15. Common Mode vs Differential Mode Transmission

These results can be seen to be very similar to the previous results of the CRLH lines in a microstip format. The only noticeable difference is the lower frequency of attenuation, as well as a breakdown in the differential mode transmission near 100GHz. The lower filtering frequency is due to the same feature length corresponding to a lower wavelength in a stripline, since a stripline has an effective permittivity that is identical to the dielectric, while a microstrip has an effective permittivity slightly lower than that of the dielectric due to the effect of the air.

V. Radiation Testing

Although the newly developed CM filters are very effective, the radiation leakage had to be checked in order to guard against filtered common-mode energy being coupled into the board thereby presenting a signal integrity hazard. This was tested on the stripline filter. In order to measure the energy being coupled to the board, the voltage at every point on the same plane as the stripline on the board was measured. Afterwards, the points corresponding to the same coordinates as the differential pair and the filter itself were excluded, so that the effects can be more accurately measured. When the voltage was measured, it was analyzed in order to find an average and a peak voltage for the entire board over the entire time of simulation. This parallel-plate voltage can be seen in Fig. 16.

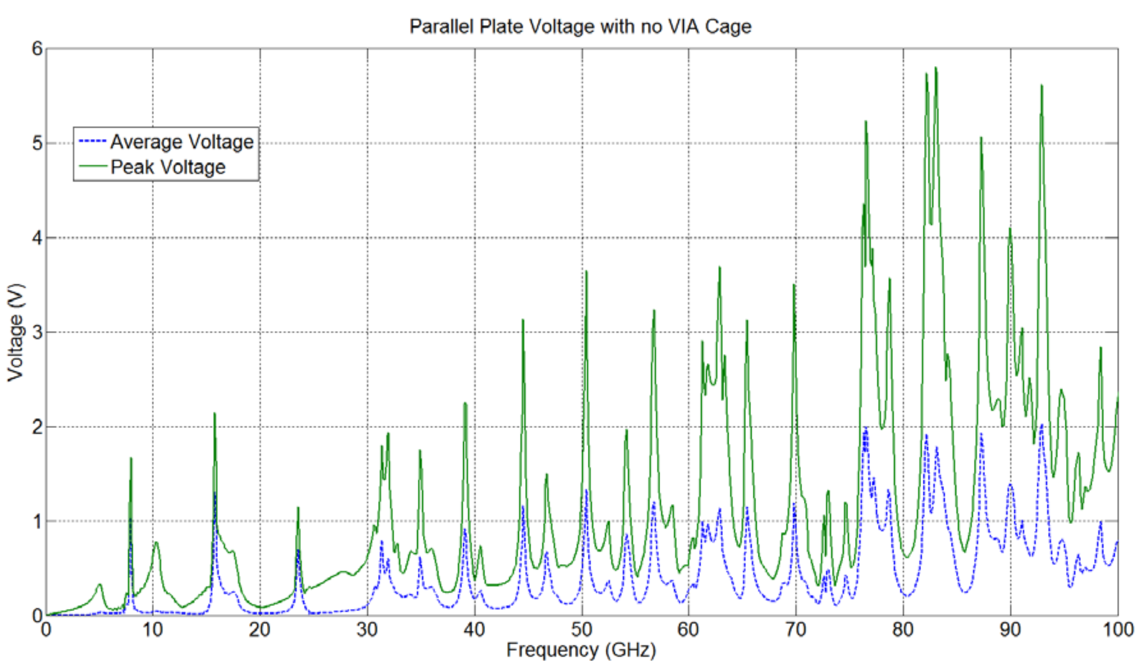

Figure 16. Parallel Plate Voltage for the Stripline CRLH Filter

The parallel plate voltage is seen to be very significant, especially in higher frequencies. This suggests that much of the energy from the common mode signal is radiated into the board.

In order to counter the parallel plate radiation, VIA fences were implemented around the structure in two different ways. In the first method, a fence was made around the entire filtering structure (Fig. 17). In the second method, a fence was made around individual filters (Fig. 18). The results are shown in Fig. 19.

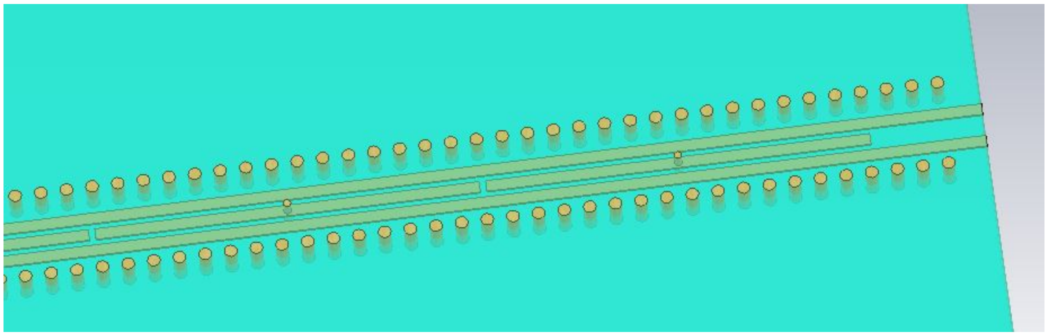

Figure 17. VIA fence implemented around entire filter

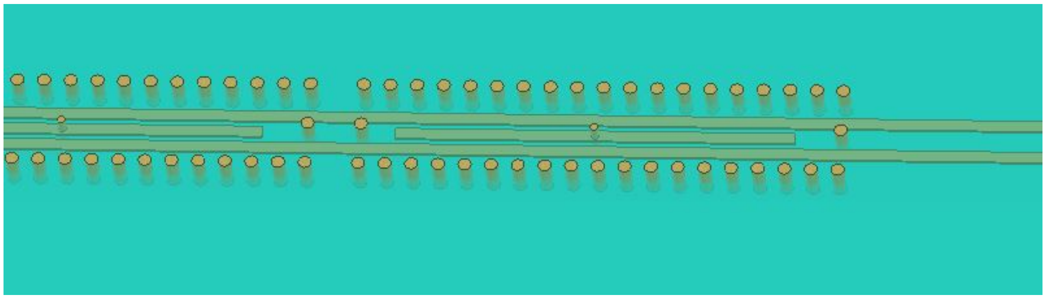

Figure 18. VIA fence implemented around individual filtering structures

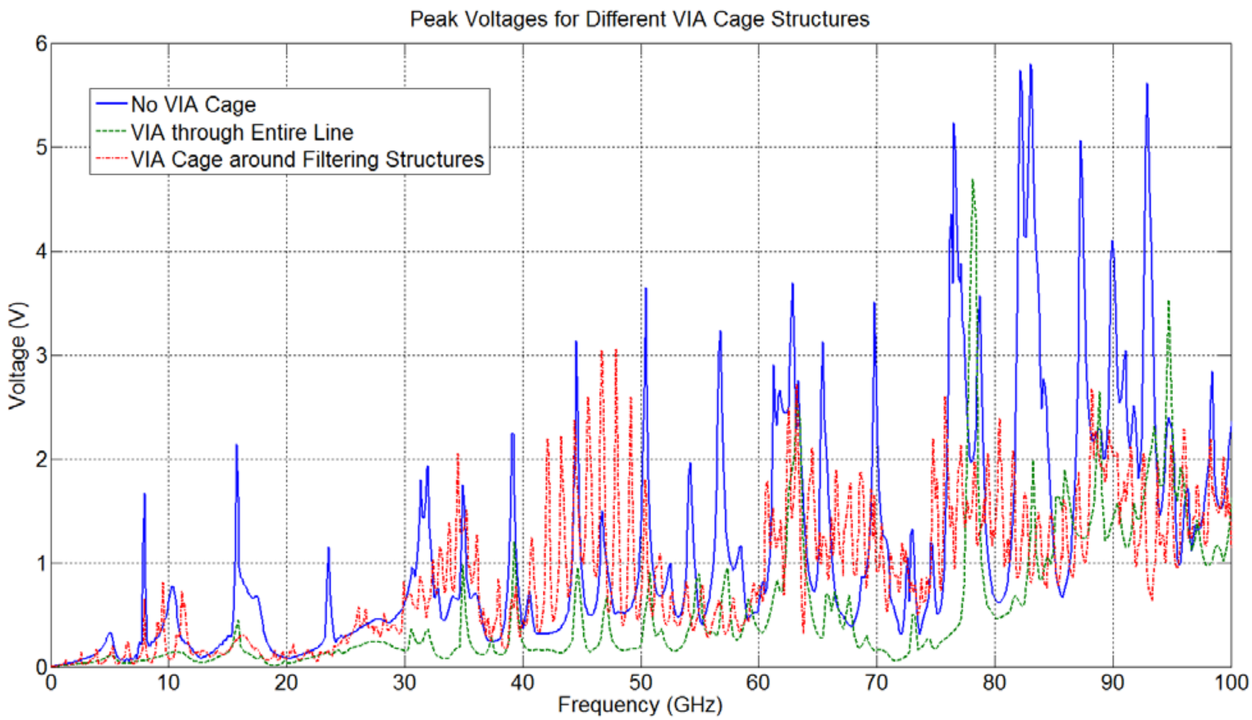

Figure 19. Parallel Plate Voltages for the different VIA cage options

Through this graph it can be seen that, depending on the frequency range to be focused on, different solutions must be used. If a lower frequency range is targeted, the VIA fence should be placed around the entire filter. If a higher frequency range is used, a VIA cage around each filtering structure ensures the peak voltages are sufficiently controlled.

VI. Conclusions

Although the newly developed CM filters are very effective, there were still several things to be worked on before the designs can be implemented. However, due to the promising nature of the completed work, it can be said with reasonable confidence that several of the structures developed in this research project will lead to better ways to filter out common-mode noise, as well as models being made so that these structures can more easily be tuned to specific target frequencies.

References

1. .M. Wojnowski, V.Issakov, G. sommer, R. Weigel, “Multimode TRL Calibration Technique for Characterization of Differential Devices” *IEEE Trans. Microw. Theory Techn.*, vol. 60, pp 2220-2246, July 2012.
2. Dick Anderson, Lee Smith, and Jeff Gruszynski. “S-Parameter Techniques for Faster, More Accurate Network Design.” *Hewlett Packard Test & Measurement Application Note 95-1*. 1997.
3. J. Naqui et al., “Common-Mode Suppression in Microstrip Differential Lines by Means of Complementary Split Ring Resonators: Theory and Applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 10, pp. 3023-3034, Oct. 2012.
4. P. Vélez et al., “Differential Bandpass Filter with Common-Mode Suppression Based on Open Split Ring Resonators and Open Complementary Split Ring Resonators,” *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 1, pp. 22-24, Jan. 2013.
5. J. D. Baena et al., “Equivalent-Circuit Models for Split-Ring Resonators and Complementary Split-Ring Resonators Coupled to Planar Tranmission Lines,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1451-1461, Apr. 2005.
6. S. N. Khan, X. G. Liu, L. X. Shao and Y. Wang, “Complementary Split Ring Resonators of Large Stop Bandwidth,” *Prog. In Electromagn. Research Letters*, vol. 14, pp. 127-132, 2010.
7. B. C. Tseng and L. K. Wu, “Design of miniaturized common-mode filter by multilayer low-temperature co-fired ceramic,” *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 4, pp. 571–579, Nov. 2004.
8. C.-H. Tsai and T.-L. Wu, “A broadband and miniaturized commonmode filter for gigahertz differential signals based on negative-permittivity metamaterials,” *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 1, pp. 195–202, Jan. 2010.
9. G. V. Eleftheriades, “Analysis of bandwidth and loss in negative-refractive-index transmission-line (NRI-TL) media using coupled resonators,” *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 6, pp. 412–414, Jun. 2007.
10. W. T. Liu, C.-H. Tsai, T.-W. Han, and T.-L. Wu, “An embedded common-mode suppression filter for GHz differential signals using periodic defected ground plane,” *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 4, pp. 248–250, Apr. 2008.
11. S.-J. Wu, C.-H. Tsai, T.-L. Wu, and T. Itoh, “A novel wideband common-mode suppression filter for gigahertz differential signals using coupled patterned ground structure,” *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 4, pp. 848–855, Apr. 2009.
12. G.-H. Shiue, C.-M. Hsu, C.-L. Yeh, C.-F. Hsu, “A Compresensive Investigation of a Common-Mode Filter for Gigahertz Differential Signals Using Quarter-Wavelength Resonators,” *IEEE Trans. Compon., Packaging, and Manuf. Techn.*, vol.4, pp. 134-144, Jan. 2014.
13. Suntives, A. Khajooeizadeh, R. Anhari, “Using Via Fences for Crosstalk Reduction in PCB Circuits,” *IEEE Int. Symposium on Electromagnetic Compatibility*, vol. 1, pp 34-37, Aug. 2006

14. M. Wojnowski, V.Issakov, G. sommer, R. Weigel, “Multimode TRL Calibration Technique for Characterization of Differential Devices” *IEEE Trans. Microw. Theory Techn.*, vol. 60, pp 2220-2246, July 2012.
15. E. Sawyer, C. Kodama, C. O’Daniel, J. Cook, and E. Wheeler, “Using Common-Mode Filtering Structures with Microstrip Differential Lines in a Multilayer Printed Circuit Board Environment,” *2014 European Microwave Conference*, October 5-10, Rome, Italy.