Differential Filter Design and Optimization

Various differential components have recently gained significant attention from microwave system designers in many areas of wireless communication. The main reason for this interest is related to the ability of differential components to improve system immunity to spurious signals (sometimes also called *noise*) compared to the case where single ended devices are used. This is especially important in highly integrated systems where different circuits within the system can produce spurious signals which can interfere with the other circuits and produce deleterious effects. For an example, a classical, single ended amplifier has a single input and single output terminal appropriately referenced to the ground. A sum of useful input signal and noise coming from various external sources, such as oscillators, phased locked loops etc., is present at the input terminal of the amplifier and both of the signals are amplified by the device. The output signal from the amplifier therefore contains unwanted signals which affect the operation of the system parts connected to the amplifier output.

A differential amplifier, on the other hand, is constructed to amplify the difference between the signals present at two input electrodes i.e. the input signal is not referenced to the ground. Similarly, the amplified signal appears as a difference between the signals present at two output electrodes. This mode of operation describes the differential mode of the amplifier. The common part of the input signals present at the electrodes is usually significantly attenuated in well-designed differential amplifiers. As two input electrodes are usually located in close proximity, any spurious signal coming from external sources approximately comes with the same amplitude and phase to the electrodes. Therefore, it can be regarded as predominantly common mode signal which it is not amplified by the amplifier. In that sense, differential components in general make a system resilient to noise.

A typical modern wireless system frontend consists of several components, namely antennas, amplifiers, filters, couplers, mixers etc. that are integrated together in a closed proximity. To increase immunity to spurious signals, it is important to design all of these components as differential. This note describes one particular case of such a component – a differential microstrip filter using WIPL-D Microwave Pro design environment.

Differential Filter using Ideal Transmission Lines

Many examples of differential filters can be found in the literature. A schematic of one of the filters suitable to explain general guidelines associated with an analysis of a differential component using WIPL-D design environment is presented in Fig. 1. The underlying theory explaining the operation of the filter will not be presented here. The schematic from Fig. 1 uses ideal transmission line elements, adequate for the initial design.

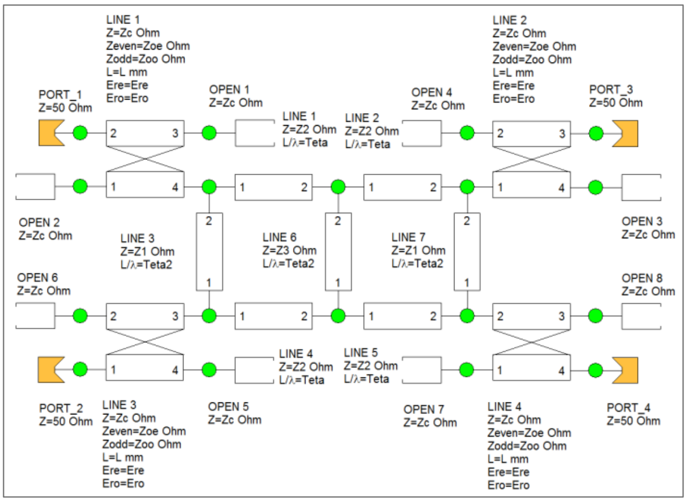

Figure 1. Schematic of single-ended terminated differential filter in WIPL-D Microwave.

The central frequency of the filter is 7 GHz, and the bandwidth is 4 GHz. Terminations applied to the filter from Fig 1. are all 50 Ω as required for the single-ended case. Ports 1 and 2 correspond to the input while ports 3 and 4 correspond to the output. When simulating such a structure, the immediate results obtained are single-ended S parameters. Several S parameter graphs are presented in Fig. 2. Generally speaking, simulated single ended S parameters can be used subsequently for differential and common mode S parameters by using conversion formulas available in the literature. However, this method of calculation is not supported in WIPL-D MW Pro.

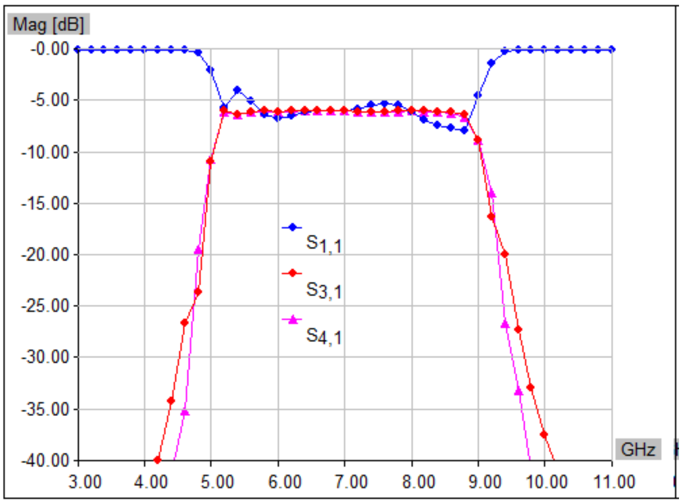

Figure 2. Single-ended S parameters of differential filter from Fig. 1.

In WIPL-D design environment differential and common mode S parameters can be obtained directly by applying minor modifications to schematic from Fig. 1. Modifications include introduction of a pair of trasformers at both, the input and the output, single-ended ports. Each pair consists of one transformer with a central tap and one simple transformer. The former is used to trasform single-ended signals into diffrential signal while the later is used to extract the common mode from single-ended signals. Details on how to make connections between the transformers and the filter circuit are illustrated in Fig. 3. Please note that the diffrential mode termination impedance is 100 Ω and common mode termination impedance is 25 Ω. Results of the simulation of the circuit from Fig. 3 are presented in Fig. 4 and Fig. 5 as transmission and reflection S parameters for differential and common mode.

Analyzing the results from Fig. 4 and Fig. 5 one can conclude that differential filter has excellent performance. Differential insertion loss shows high selectivity within the operating frequency band and differential return loss has acceptable values. The attenuation of common mode is very high. Comparing Fig. 2 and Fig. 4-5, it becomes apparent that there is no intuitive way to deduce differential/common mode performance by simply looking at the single-ended S parameters.

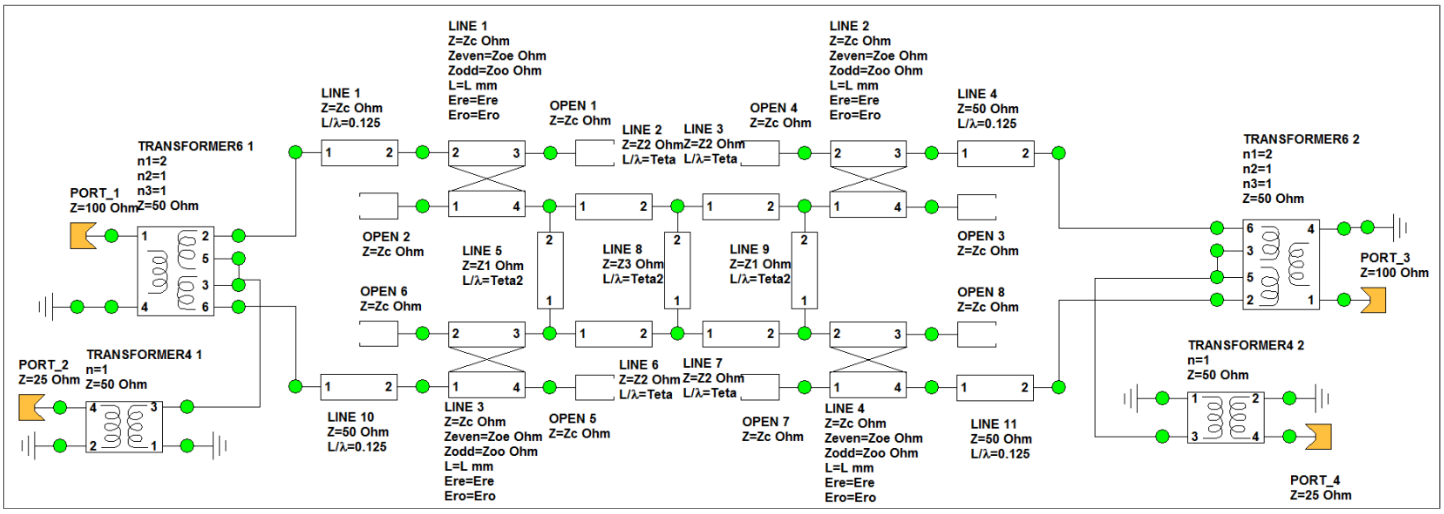

Figure 3. Schematic of differential filter from Fig. 1 with differential/common mode terminations.

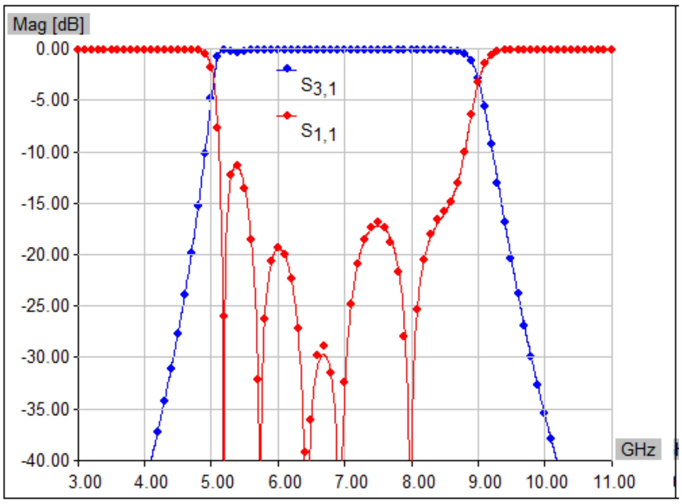

Figure 4. Differential mode S parameters of filter from Fig. 3.

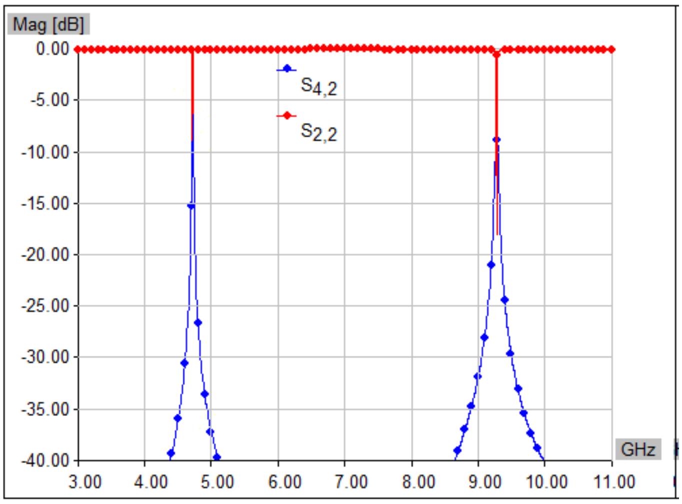

Figure 5. Common mode S parameters of filter from Fig. 3.

Microstrip Differential Filter

The next step in a filter design typically include the simulation of some kind of a physical realization of the ideal filter from Fig. 1 by using appropriate analytical models. The technology chosen for the particular design was microstrip technology. Consequently, all of the ideal transmission lines from Fig. 1 have been converted to microstrip lines. Models of realistic microstrip junctions, i. e. discontinuities, were added to the circuit. Complete microstrip schematic is presented in Fig. 6. The results of the simulations are presented in Fig. 7-8. The performance of the microstrip filter is not good as differential return loss has high values in a lower part of the operating frequency band.

The logical step would be to proceed to some kind of optimization to improve the performance level. However, modeling microstrip circuit with analytical models or electromagnetic (EM) models for individual transmission lines and discontinuities, as implemented in schematic from Fig. 6, has been found to be inaccurate for this particular case. The reason for this lies in the fact that the schematic in Fig. 6 does not strictly describe all of the effects occurring in the physical microstrip circuit of the filter. The discrepancies will be explained in more details in the following section.

Under the circumstances, it is not appropriate to perform optimization of microstrip elements in the schematic presented in Fig. 6. The efficient optimization taking into account all of the effects which affect the performance of the filter should be applied to the full 3D EM model.

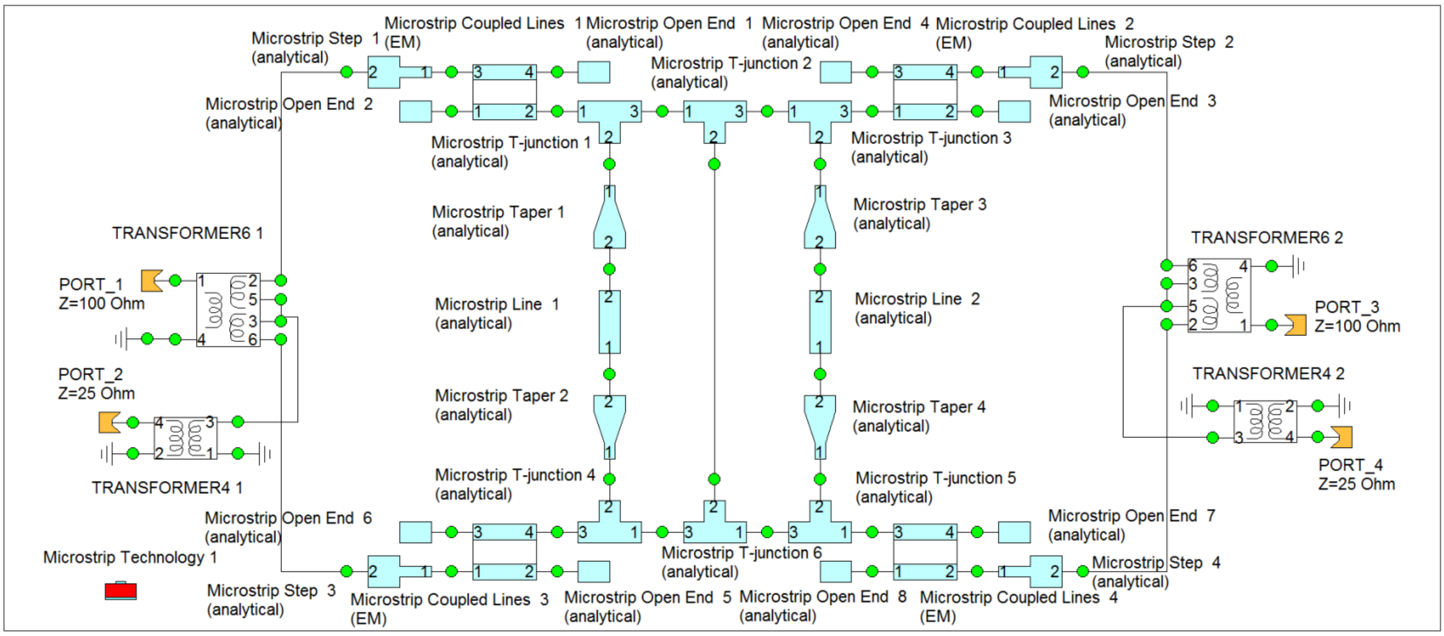

Figure 6. Microstrip schematic of differential filter from Fig. 1 with differential/common mode terminations.

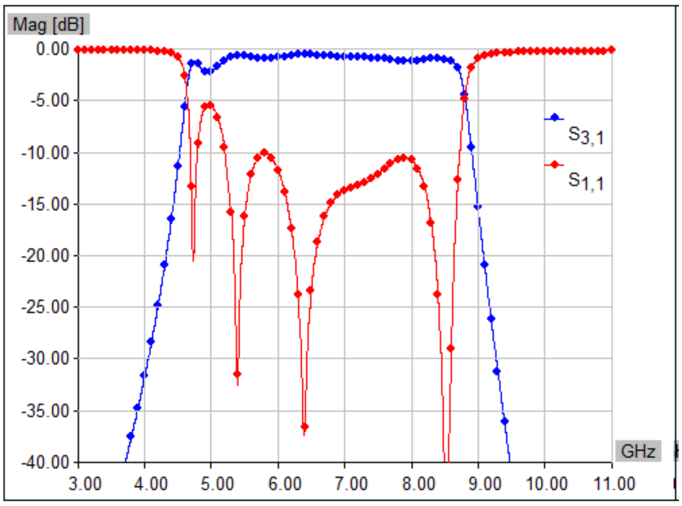

Figure 7. Differential mode S parameters of microstrip filter from Fig. 6.

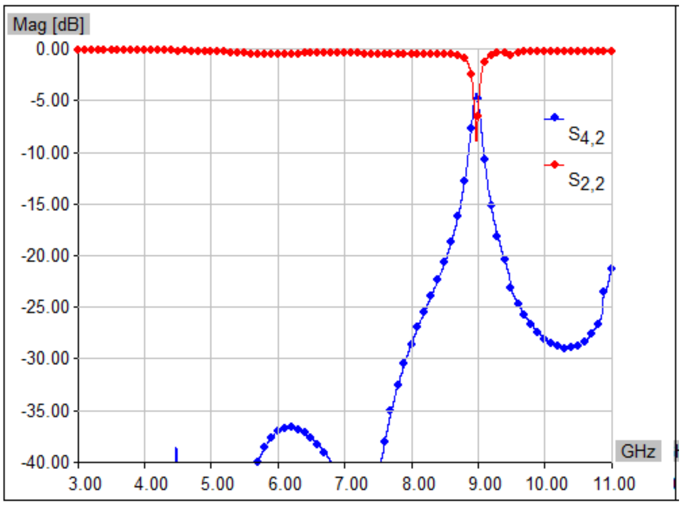

Figure 8. Common mode S parameters of microstrip filter from Fig. 6.

Differential Filter as EM Component

The final step in differential filter design presented in this note should include EM simulations of the whole filter circuit. This type of simulation represents the most accurate method as it can include all of the effects occurring in the real circuit. Calculated physical dimensions of the microstrip lines found in the previous design step have been used to create initial 3D EM model of the differential filter from Fig. 6 in WIPL-D Pro. The model is shown in Fig. 9.

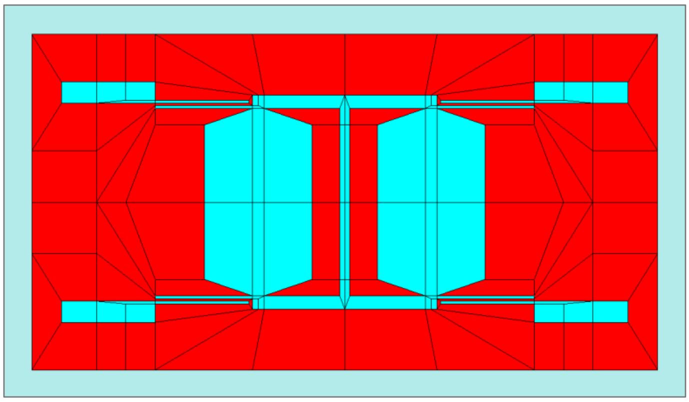

Figure 9. Top view of microstrip circuit of differential filter from Fig. 1 built as a 3D EM component in WIPL-D Pro.

Differential and common mode of the filter from Fig. 9 can be calculated if the filter is imported as EM component in WIPL-D Microwave Pro schematic. Then described method of converting single-ended S parameters to differential/common mode parameters can be applied. The schematic is presented in Fig. 10.

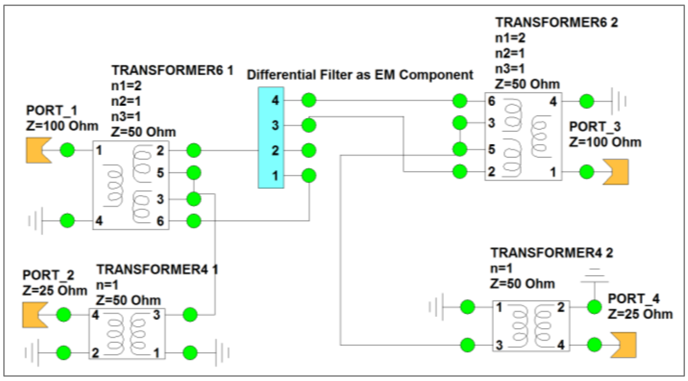

Figure 10. Schematic for simulation of differential/common mode S parameters of microstrip differential filter from Fig. 6 imported as EM component in WIPL-D Microwave.

Results of the simulations of the schematic from Fig. 10 are presented in Fig. 11-12. The figures suggest that the characteristics of the differential filter should be optimized. Optimization can be easily setup directly in the project, as the 3D EM model has been built as parametrized, i.e. dimensions have been defined using symbolic variables, so the optimization of the model can be applied in a straightforward manner. The criteria can immediately address the differential/common mode S parameters as they are available as simulation results without any postprocessing required. In this particular case, requiring the differential return loss, which corresponds to either S_{11} or S_{33}, to be better than 10 dB in the frequency range from 5 GHz to 9 GHz, was sufficient to significantly improve the filter characteristics after one simulation batch of 50 iterations.

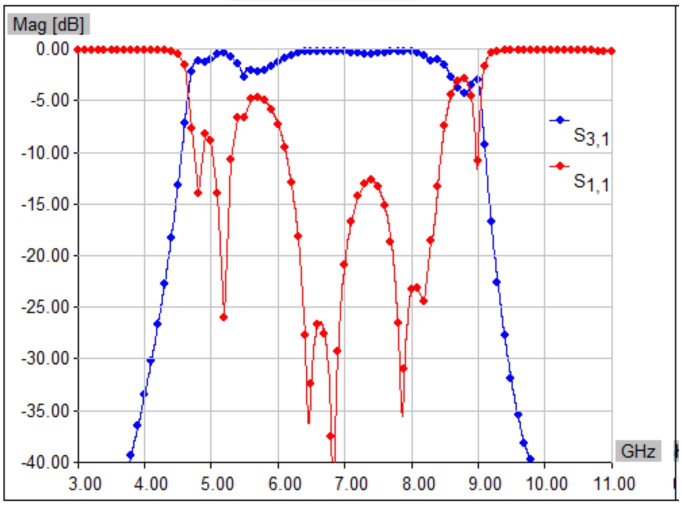

Figure 11. Differential mode S parameters of microstrip filter from Fig. 9.

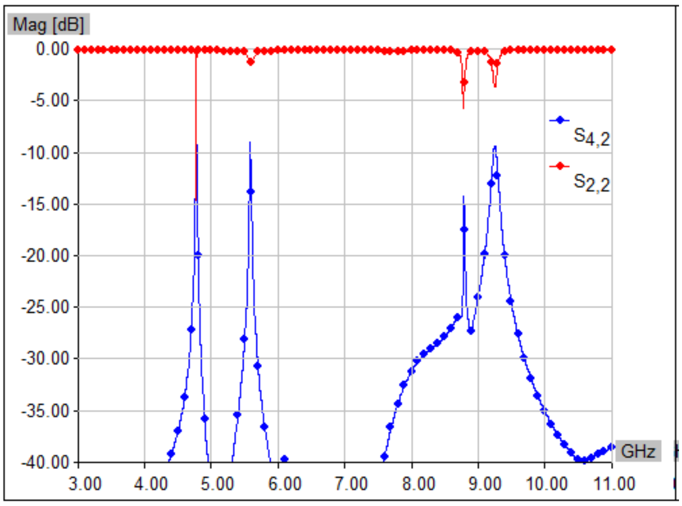

Figure 12. Common mode S parameters of microstrip filter from Fig. 9.

The results after the optimization are presented in Fig. 13-14. Although not fully recovered, the achieved level of performance can be regarded as acceptable. Taking further steps in the optimization does not bring any significant improvement. The basic reason for this lies in the specifics of the differential filter topology. Namely, shunt resonator sections at the input and output of the filter have very low characteristic impedance. When transferred to microstrip technology, very low transmission line impedance translates into very wide conductors. The presence of a wide conductor section has an implication that the ideal schematic from Fig. 1 does not describe adequately the microstrip schematic from Fig. 6 and the microstrip layout from Fig. 9.

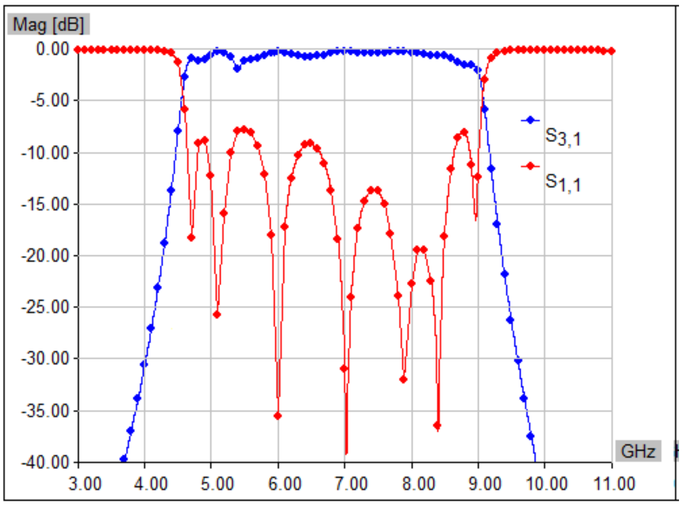

Figure 13. Differential mode S parameters of microstrip filter from Fig. 9 after optimization of schematic from Fig. 10.

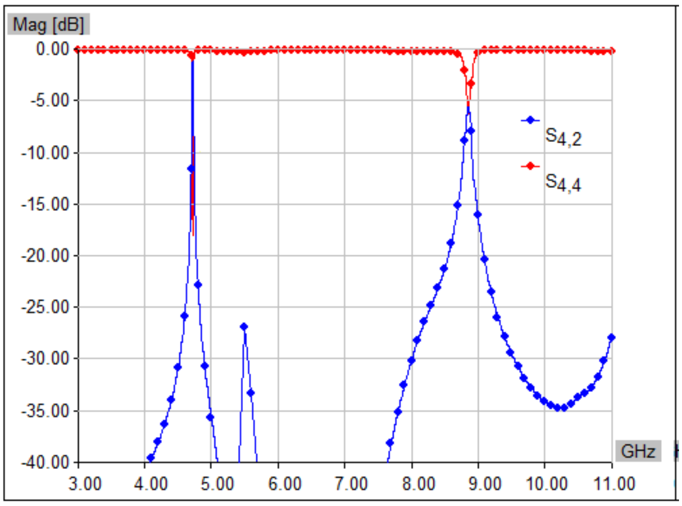

Figure 14. Common mode S parameters of microstrip filter from Fig. 9 after optimization of schematic from Fig. 10.

Looking into Fig. 6 and Fig. 9, the most obvious difference with respect to the circuit from Fig. 1 is related to the introduction of short tapers in places where a shunt section is connected to a series section at one end, and to a pair of coupled lines to the other. The tapers are necessary to reduce otherwise significant influence of T junction discontinuity when such an extremely wide line is a part of the junction. The taper is present in the microstrip schematic from Fig. 6. However, the influence of the taper is not fully taken into account as it introduces parasitic coupling between the shunt line and coupled lines on one side, and shunt line and series line on the other. In addition, the presence of very wide lines introduces parasitic coupling between the low impedance sections and a high impedance section located in the middle of the filter circuits. Both coupling effects are included in full 3D EM model only.

To sum up, the realistic, physical microstrip layout of the filter must be built with significant discrepancies with respect to the ideal filter circuit. The complete influence of the differences must be addressed by using full 3D EM simulations. Along with the preceding discussion, one should be aware that even when using EM simulations, the optimization procedure could possibly not be able to fully recover the performance seen in Fig. 4-5 as EM model from Fig. 9 include effects which have not been taken in the account in schematics from Fig. 1 and Fig. 6.

The most obvious difference between the results obtained for circuit with ideal transmission lines and full 3D EM model is that the return loss in Fig. 4 has five distinct dips, while the number of dips is increased to seven in Fig. 13.In the same time, there is no increase in filter order, as the selectivity of the filter didn't change. This suggests that the increased number of return loss dips occurs as two of the double poles of the filtering function from Fig. 4 got split due to the various effects introduced when a microstrip circuit is created. However, this effect seems to be beneficial to the overall filter performance as it helps optimizing return loss to acceptable levels. The pole splitting could not be seen in the results from Fig. 7 where microstrip analytical models have been used with the simulations.

Conclusion

This note explains how to analyze and optimize a general differential microwave circuit using WIPL-D design environment. Weather it is the circuit or EM component the differential/common mode analysis can be carried out within WIPL-D Microwave Pro by adequate connection of several transformer elements to convert single-mode S parameters to differential/common mode S Parameters.

The innovative differential filter, which has been taken from the literature, has been used to illustrate the analysis and optimization procedures. The filter has been analyzed as ideal transmission line circuit, as microstrip schematic and as 3D EM component. It has been explained that when converting ideal transmission line circuit into the realistic microstrip layout, several parasitic effects can occur, not included in the ideal model. Therefore, the optimization process should be applied to EM component as it is includes all of the parasitic effects in the simulations.

The modeling method similar to the one demonstrated here for the case of a differential filter can be applied to directly obtain differential/common mode S parameters when analyzing and optimizing other differential components, such as amplifiers, couplers, antenna matching networks, etc.