Designing a Band Pass Filter with WIPL-D Filter Designer

This application note presents an application of **WIPL-D Filter Designer** tool together with other modules from WIPL-D program suite to design a band pass filter of *Hairpin-Line* type in microstrip technology. The power of the filter design tool will be described along with the demonstration of judicious method of filter circuit optimization including a circuit simulator and electromagnetic (EM) solver. The outline of the method is demonstrated first for the optimization at the schematic level where a microstrip filter circuit is optimized in just one or two simulations in **Microwave Pro** circuit simulator. The real power of the method is however demonstrated in optimizing EM model of a filter circuit in **WIPL-D CAD** environment.

The note also addresses the practical side of filter design by investigated the realizability of the filter with respect to limitations of a standard circuit fabrication technology.

Ideal Transmission Line Filter

Design procedure for a microstrip filter will be demonstrated on the example of a 5th order *Chebishev* filter with central frequency of 3.7 GHz and bandwidth of 400 MHz with passband ripple of 0.1 dB (corresponding to return loss of 16.4 dB). The *Hairpin-Line* topology has been selected due to its compactness. In WIPL-D program suite, the tool named **Filter Designer** has been introduced as an add-on to **WIPL-D Microwave Pro** circuit solver to ease the filter design process. The first window of the **Filter Designer** wizard, where specification for the particular filter described in this note are entered, is presented in Fig. 1.
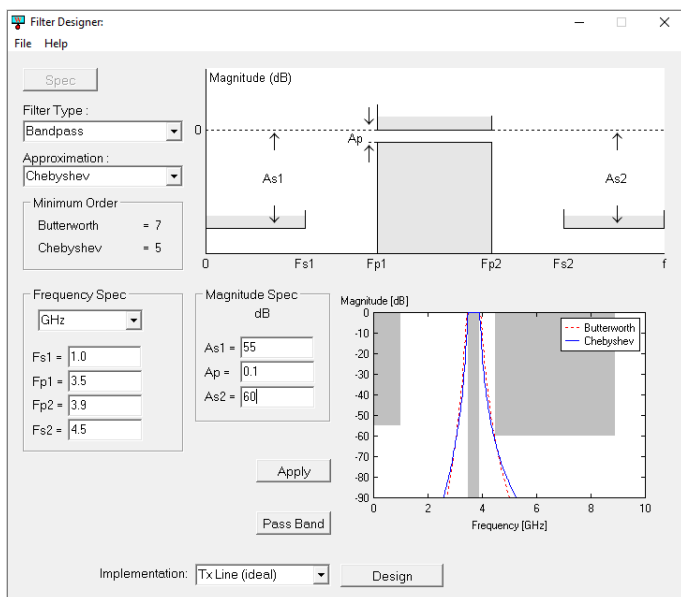

Figure 1. Filter Designer specification window for 5th order Chebishev band pass filter.

After the specifications have been entered, the user can choose the desired implementation, *TxLine* (ideal) in our case, and proceed to the second window where a particular bandpass filter type is chosen and related details entered. A part of the second window with the details relevant for the *Hairpin-Line* filters is shown in Fig. 2. After user is happy with the data entered, he/she can choose to export the synthetized filter to a schematic or to proceed to the third window where a filter circuit is converted from ideal to microstrip lines. For more details reader is advised to consult the **Filter Designer** User Manual.
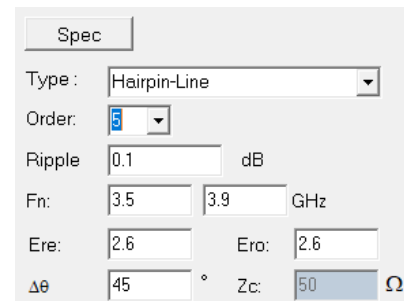

Figure 2. 5th order Hairpin-Line synthesis parameters in TxLine Ideal window – TEM lines.

In this particular case we choose to export the ideal circuit to a **WIPL-D Microwave** schematic. The exported schematic is presented in Fig. 3.
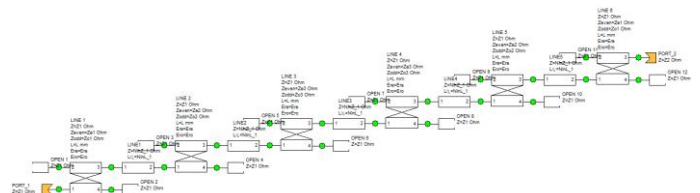

Figure 3. 5th order Hairpin-Line filter with ideal TxLines as exported to WIPL-D Microwave Pro schematic.
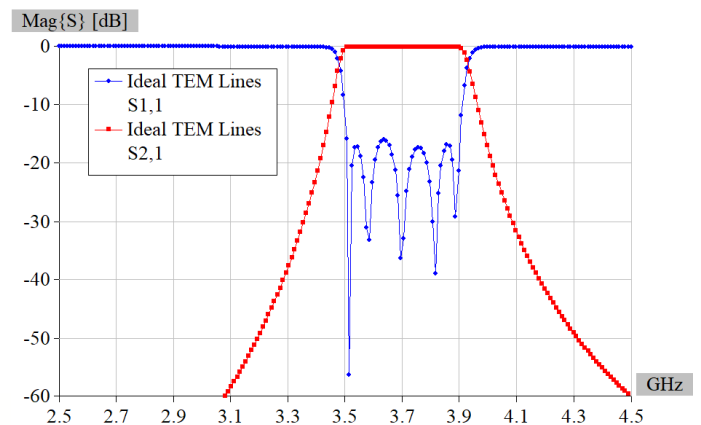

Figure 4. Frequency response of 5th order Hairpin-Line filter with ideal TEM lines.

The *Hairpin-Line* filter includes six coupled line filter elements. According to Fig. 2 second window in the **Filter Designer** wizard

has two fields to enter the effective dielectric constants for the even and odd mode propagating on coupled lines, *Ere* and *Ero* respectively. In the case *pure TEM* lines, like stripline, the dielectric constants are equal, so the input *Ere*=2.60 and *Ero*=2.60 corresponds to the *pure TEM* coupled line case. The filter response for that case is shown in Fig. 4.

In coupled *quasi TEM* lines, like microstrip, effective dielectric constants of even and odd modes are different. Unlike some other filter design tools, the effects of different effective dielectric constants of the modes on filter performance can be explored with **WIPL-D Filter Designer**. For example, for the particular filter values of *Ere*=2.80 and *Ero*=2.40, as shown in Fig. 5, are entered to explore the effects of the difference. The arithmetic mean of these values is taken to calculate the length of the lines, so the lengths of the corresponding lines in both filters are equal. The resulting filter response is shown in Fig. 6. The S_{11} curve is distorted compared to the one with ideal transmission lines form Fig. 4. Therefore, we can conclude at this point that for *Hairpin-Line* filters unequal effective dielectric constants of the modes can be the cause for a distorted passband response. The differences regarding the first spurious passband are not relevant for this demonstration.
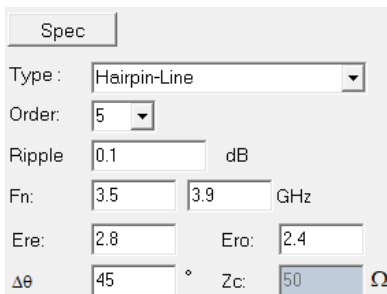

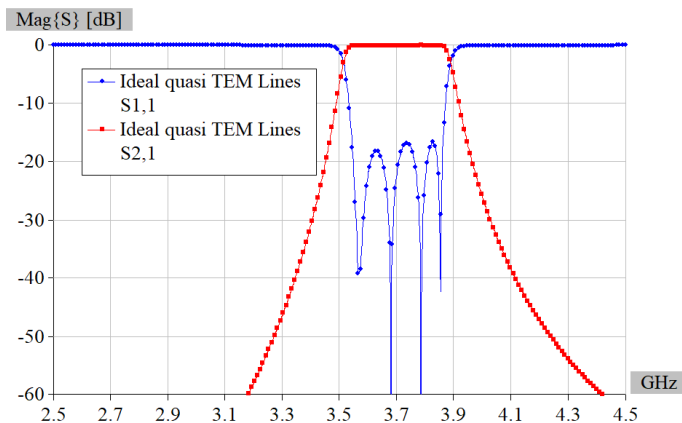**Figure 5. 5th order Hairpin-Line synthesis parameters in TxLine Ideal window – non-TEM lines.**

Figure 6. Frequency response of 5th order Hairpin-Line filter with ideal non-TEM lines.

Microstrip Filter

While in the second window, instead of choosing *Export to Schematic*, the user can choose *Convert to Microstrip*. If this is the

case, the program opens the third window. The details of the third window for the particular filter are presented in Fig. 7.
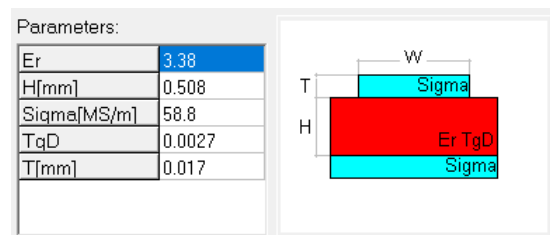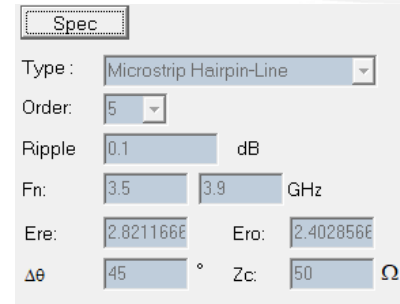

Figure 7. 5th order Hairpin-Line microstrip filter specifications and microstrip substrate parameters.

In this window the filter specifications can not be changed, only the parameters of the microstrip substrate. The default substrate with parameters as presented in Fig. 7 will be used at this stage to continue with the filter design example. Any change of substrate parameters *Er* and *H* automatically restarts microstrip circuit synthesis and results in update of a microstrip filter circuit. For each pair of ideal coupled lines, the automatic wizard calculates the line widths *w* and the spacing between the coupled lines *s*. Also, the effective dielectric constants of the modes are calculated for each of the coupled line pairs and the average is used to compute the length of the lines. The average values of the effective dielectric constants of the modes are displayed in grayed fields. As can be seen from Fig. 7, the calculated values for the default substate are approximately equal to the values from Fig. 5 which explains the choice made there – the response of the microstrip filter can be meaningfully compared with the response of the filter with Ideal *quasi TEM* lines. By pressing *Export to Schematics*, the synthetized circuit is exported to **WIPL-D Microwave Pro** schematic.
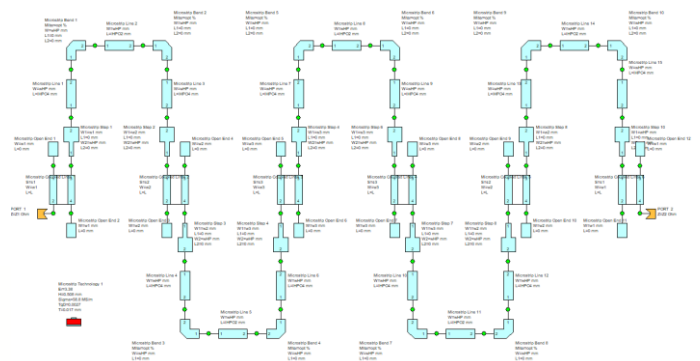

Figure 8. 5th order Hairpin-Line filter with microstrip lines as exported to WIPL-D Microwave Pro schematic.
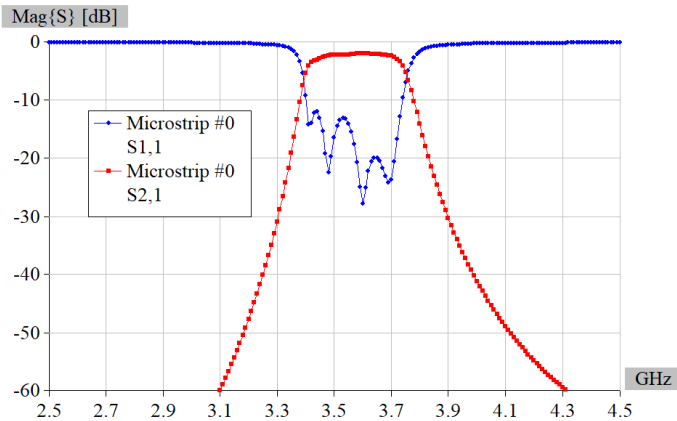
Figure 9. Frequency response of 5ᵗʰ order Hairpin-Line filter with microstrip lines.

The exported circuit is presented in Fig. 8, and the simulated *S* parameters of this initial design, namely **Iteration #0**, are displayed in Fig. 9. It is obvious that the filter performance is not according to the specifications. If we concentrate on the central frequency and bandwidth, we can conclude that the response is shifted downwards in frequency and that the filter is narrower than required. The more precise characterization of the discrepancy is presented in Fig. 10 where the marker readings provide exact values of the center frequency and passband edges.
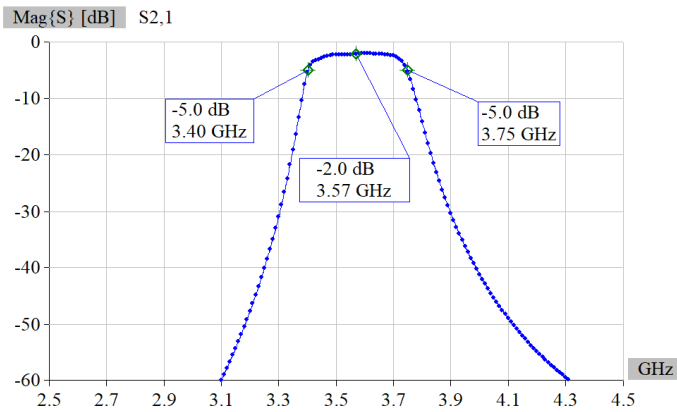

Figure 10. Central frequency and passband edges of 5ᵗʰ order Hairpin-Line filter with microstrip lines (Iteration #0).

The simulation results presented in Fig. 10 are summarized in *Table 1*. By comparison with specifications, one can conclude that the central frequency *Fmd* of the filter from **Iteration #0** is 120 MHz lower than the specified *Fm* (- 3.2%) and that the filter bandwidth *BW* is 50 MHz narrower than desired *BWd* (- 12.5%). The difference mainly comes from the effect of discontinuities introduced when synthesis wizard converts the circuit with ideal transmission lines to microstrip circuit. A judicious method to address the discrepancy is to repeat the same design steps with modified specifications – with higher central frequency and wider bandwidth to compensate for the effects of discontinuities.

Basically it means to modify the specifications to new center frequency *Fm1* = (1.000+0.032)*Fm and new bandwidth *BW1* = (1.000+0.125)*BW. This method of optimization can be considered as a simplified case of so-called *Space Mapping* optimization technique described in the literature.

Table 1. Original filter specifications, results obtained in Iteration #0, and modified filter specifications for Iteration #1

Specs:	3.5 - 3.9 GHz	*Fm*=3.7 GHz	*BW*=0.4 GHz
Iteration #0:	3.40 - 3.75 GHz	*Fmd*=3.58 GHz	*BW*d=0.35 GHz
Absolute diff.		- 0.12 GHz	- 0.05 GHz
Relative diff.		-3.2 %	-12.5 %
Old Target		*Fm*=3.7 GHz	*BW*=0.4 GHz
New Target		*Fm1*=3.81 GHz	*BW1*=0.45 GHz
Modified Specs Iteration #1:		3.585 - 4.035 GHz	

The first step of Iteration #1 is to enter the modified specifications in the **Filter Designer** specification window. When progressing to the second window, the specifications for **Iteration #0** presented in Fig. 5 should be modified according to Fig. 11. Then, after choosing *Convert to Microstrip*, the wizard progresses to the third window and modified microstrip circuit of the filter is generated automatically.
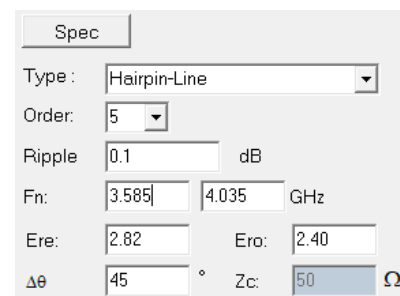

Figure 11. Modified central frequency and bandwidth of 5ᵗʰ order Hairpin-Line filter with microstrip lines.

The newly synthetized microstrip circuit is then exported in schematic in a usual manner and simulated. The response of the filter with modified specifications is presented in Fig. 12. The response is now much closer to the desired, but to completely match the original specifications, another iteration of the method is required. The details of the setup for the second iterations are presented in *Table 2*.
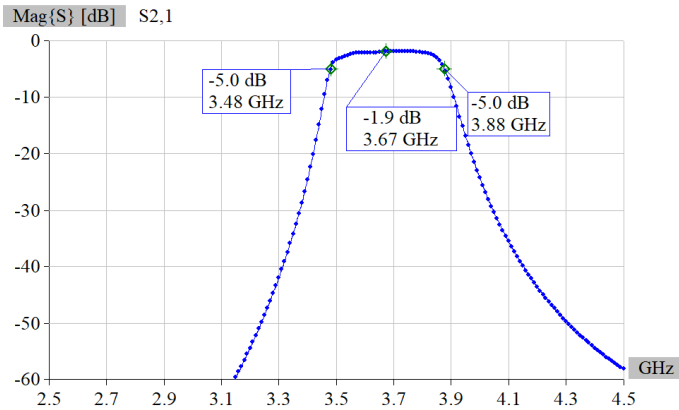
Figure 12. Central frequency and passband edges of 5th order Hairpin-Line filter with microstrip lines (Iteration #1).
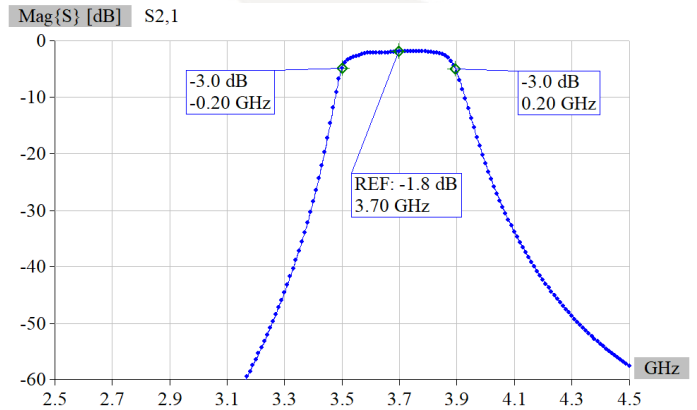

Figure 13. Central frequency and passband edges of 5th order Hairpin-Line filter with microstrip lines (Iteration #2).

Table 2. Original filter specifications, results obtained in Iteration #1, and modified filter specifications for Iteration #2

Specs:	3.5 - 3.9 GHz	Fm=3.7 GHz	BW=0.4 GHz
Iteration #1:	3.48 - 3.88 GHz	Fmd=3.68 GHz	BWd=0.4 GHz
Absolute diff.		- 0.02 GHz	0.0 GHz
Relative diff.		-0.5 %	0 %
Old Target		$Fm1$=3.81 GHz	$BW1$=0.45 GHz
New Target		$Fm2$=3.83 GHz	$BW2$=0.45 GHz
Modified Specs Iteration #2:		3.605 - 4.055 GHz	

The procedure in the **Iteration #2** is similar to the **Iteration #1**. The new design targets for **Iteration #2** are obtained by modifying the specifications for **Iteration #1** according to the differences between the results from **Iteration #1** and specifications ($Fm2$ = (1.000+0.005)*$Fm1$, $BW2$ = $BW1$). The results of the **Iteration #2** are presented in Fig. 13 where the markers indicate that the center frequency and bandwidth are according to the specification. The *S* parameters of the optimized filter are presented in Fig. 14.

Figure 14. S parameters of the optimized filter.

Considering an Alternative Substrate

As pointed earlier, the default microstrip substrate have been chosen to demonstrate the optimization process of the filter. Sometimes a choice of the substrate could be restricted e. g. by system integration requirements, technology limitations, cost, etc., but in other cases a filter designer can make his own choice and select the substrate himself. The demonstrated filter optimization process is very fast and can be executed quickly for any other substrate, so a set of designs can be examined in no time. In line with that idea, as additional examples, the filters with same specifications have been designed on *Teflon fiberglass* and *Alumina* substrates.

The dielectric properties of the substrates are presented in Fig. 15, while the optimized responses of filters on *Teflon fiberglass* and *Alumina* substrates are presented in Fig. 16 and Fig. 17 respectively.
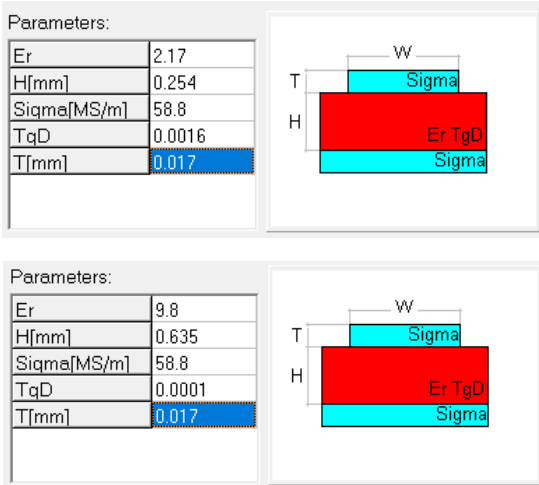
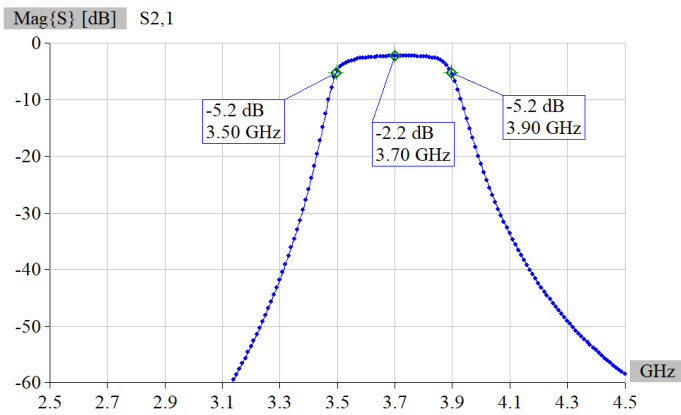Figure 15. Details of Teflon Fiberglas and Alumina microstrip substrate properties.

Figure 16. Central frequency and passband edges of 5th order Hairpin-Line filter with microstrip lines on Teflon fiberglass substrate
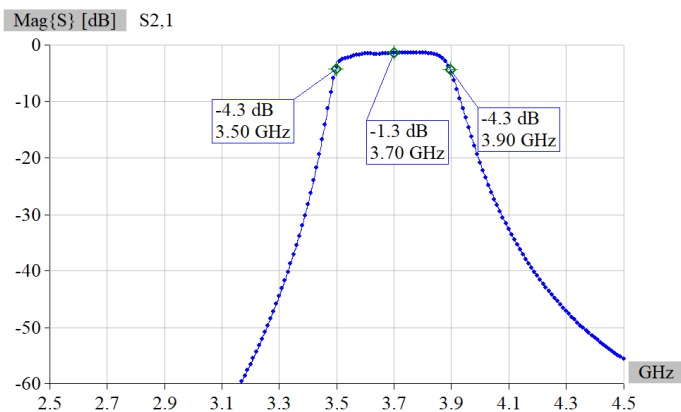

Figure 17. Central frequency and passband edges of 5th order Hairpin-Line filter with microstrip lines on Alumina substrate.
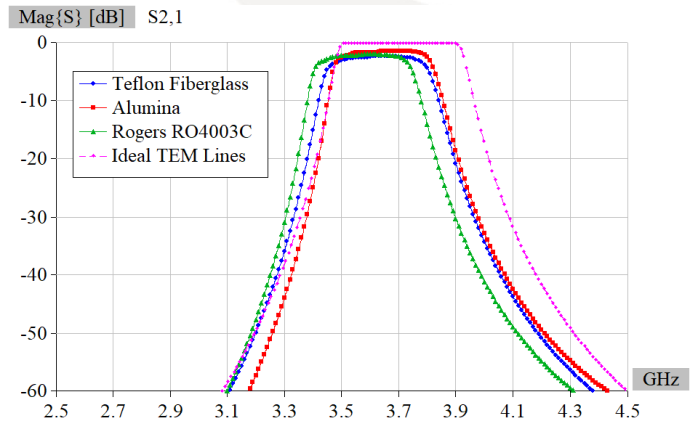

Figure 18. Comparison of responses of Iteration #0 for three microstrip substrates and ideal TEM line filter.

For the choice of the two substrates, only one iteration was sufficient to achieve the required specifications. The reason for this can be seen on Fig. 18 where the results obtained in **Iteration #0** for all three substrates have been presented and compared. It is clear that the initial results of the filter on default substrate are with largest downwards shift and the most shrunk bandwidth compared to the referent results of the filter with ideal *quasi TEM* lines from Fig. 6.

Addressing Fabrication Technology

At the end of the design process, the filter should be fabricated, tested and ultimately used in a particular application. Each fabrication technology has its limitations, and any circuit design should address these limitations early in the design process. The fabrication limits are typically concerning minimum conductor width w_{min}, minimum spaces between the conductors, s_{min} and the tolerances for the two. A standard, classic and therefore lowest price fabrication processes which is preferable to use in most of the cases, typically has w_{min}=100μm and s_{min}=100μm, both with ±10μm tolerances. Next, we will check the three filter designs against the properties of such a standard fabrication technology. The most critical in the particular design are the dimensions of the first (and, due to the filter symmetry, the last) coupled lines section. The dimensions of the first coupled line section for the three filters designed in the previous text are summarized in Fig. 19 where screenshots from **WIPL-D Microwave Pro** symbol list are shown.

Only the microstrip filter designed for *Alumina* substrate has the preferable separation between the coupled conductors i. e. conforms with the technology limitations regarding the minimum separation width between the conductors. Apart from that, it can be easily calculated that it requires the smallest substrate area, which can be an important advantage in some practical cases. According to the Fig. 13, Fig. 16 and Fig. 17 it has yet another important advantage of lowest insertion loss. However, it must be said that the *Alumina* is a very hard material and consequently hard to process mechanically which can be a disadvantage if the

filter is a part of more complex system integrated on the same piece of dielectric substrate. If this is the case, then fabrication of holes, such as vias or similar, possibly required by some other circuit from the system, may be difficult or expensive. Besides that, the price of *Alumina* is much higher compared to the other two substrates. Nevertheless, considering manufacturability and electrical performance of the filter as most important and disregarding any other aspect, we adopt *Alumina* as the final substrate choice.

Figure 19. Line widths w1 and spacing s1 for the first coupled line pair on Teflon fiberglass, Rogers RO4003C and Alumina substrates (top to down respectively).

EM Modeling and Optimization

The last design stage of the filter should include the EM modeling and simulation of the filter circuit. When working with **WIPL-D** program suite, it is convenient to build a parametrized model in **WIPL-D CAD** environment where a rich set of graphic primitives, editing command and manipulations is available to comfortably create even highly complex models. *Hairpin-Line* filter is a relatively simple circuit to build. The symmetry of the filter structure can be exploited to save drawing and subsequently the simulation effort. The half of the model of the filter with the *Symmetry* option activated is presented in Fig. 20.

The process of the design of the filter in the **WIPL-D CAD** environment starts again from synthesis of a *TxLine* filter according the specifications presented in Fig. 5. In the next step the filter is converted to microstrip circuit and exported to the schematic, the same way it was described for the case of microstrip schematic circuit filter. The dimensions of the microstrip circuit elements from the schematic are then directly transferred to the EM model. In other words, the relation between electrical parameters of ideal transmission lines from

Filter Designer tool and dimensions of EM model counterparts in **WIPL-D CAD** is established through the use of microstrip schematics from **WIPL-D Microwave**.

Once the dimensions in EM model are set as in the circuit schematic, the EM model becomes simulation ready. At this point we assume that standard procedures of establishing accuracy of the EM simulation when working with **WIPL-D** suite are known and they will not be described here.
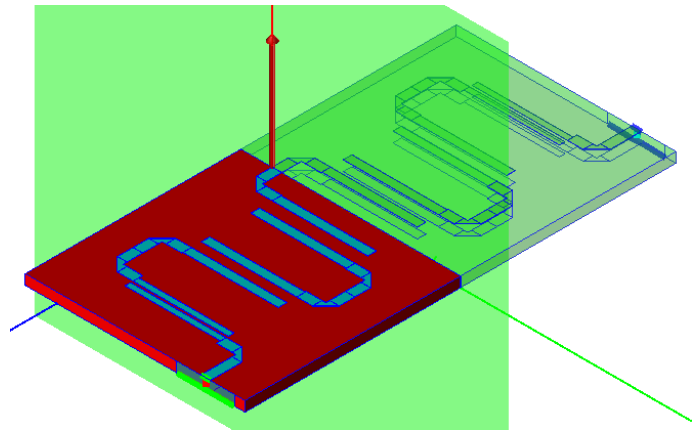

Figure 20. WIPL-D CAD model of 5th order Hairpin-Line microstrip filter

After the accuracy is ensured and EM simulation performed, the center frequency and band edges can be determined through maker readings as before. The iterative procedure then should proceed the same way it has been carried out for the case of microstrip circuit model - generating modified specification, synthesis of *TxLine* filter, conversion to microstrip, changing of the dimensions in EM model and so on.
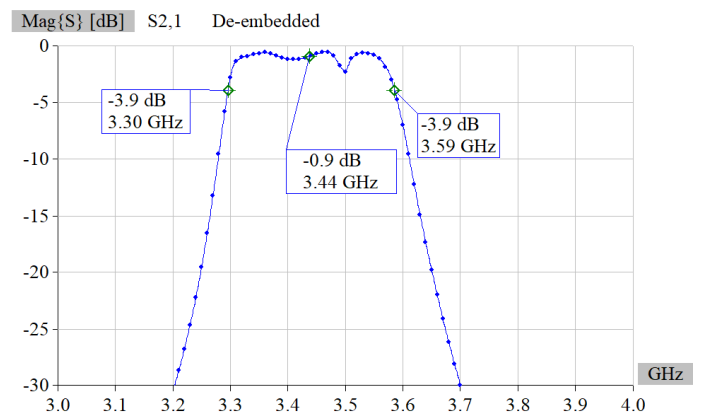

Figure 21. Central frequency and passband edges of 5th order Hairpin-Line filter EM model (Iteration EM #0).

The EM model of the filter of Iteration **EM #0** is presented in Fig. 20, and the calculated S_{21} parameter of the filter EM model is presented in Fig. 21. The remaining optimization process is similar to the one already described. Two iterations are required to meet the specifications for central frequency and passband edges. Corresponding S_{21} graphs are presented in Fig. 22 and Fig. 23.
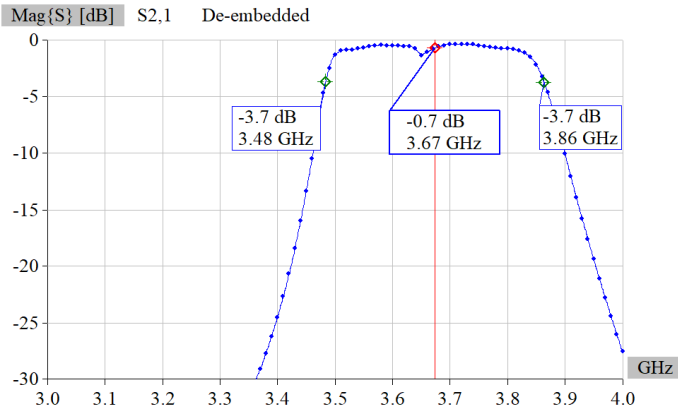
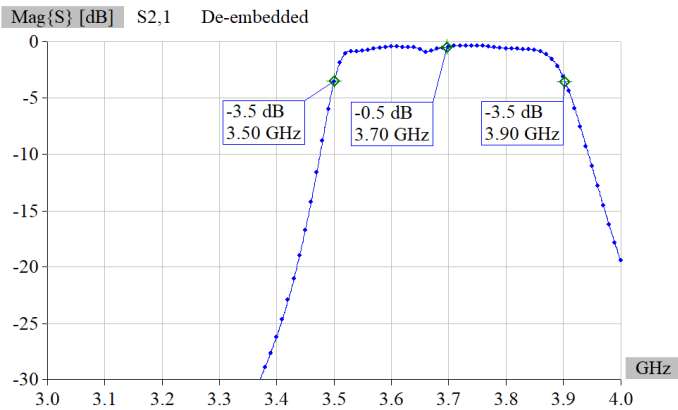**Figure 22. Central frequency and passband edges of 5th order Hairpin-Line filter EM model (Iteration EM #1).**

Figure 23. Central frequency and passband edges of 5th order Hairpin-Line filter EM model (Iteration EM #2).
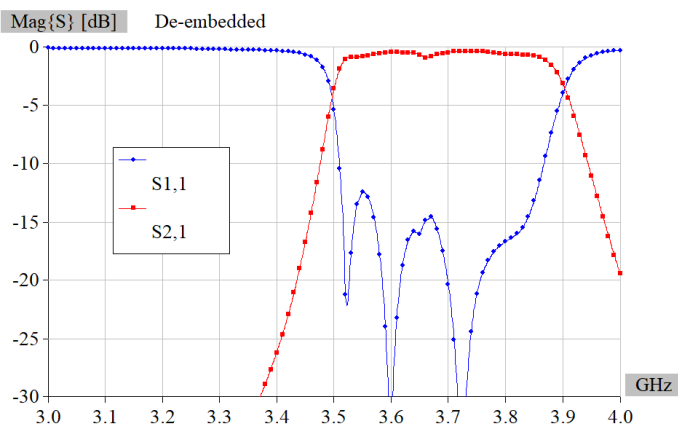

Figure 24. Frequency response of optimized order EM model 5th of Hairpin-Line filter with microstrip lines.

The S parameters of the filter obtained in Iteration **EM #2** are presented in Fig. 24. While S_{21} has the usual performance, the S_{11} does not have the shape common to *Chebishev* type of filters, mainly considering that there are three distinct dips instead of five, as presented for the case of ideal *pure TEM* transmission line presented earlier in Fig. 4. However, even for the ideal *quasi TEM* lines, presented in Fig. 6 and shown again in Fig. 25, one of the dips is not seen i. e. it has moved so that the two dips are joined together. The S_{11} shape is further distorted with microstrip circuit

model although there still are four distinct dips, and finally it moves so that only three dips become visible for the EM optimized model. The values of the maximum S_{11} in the passband is also deteriorating as the fidelity of the modeling increases from ideal *quasi TEM* lines to EM circuit model.
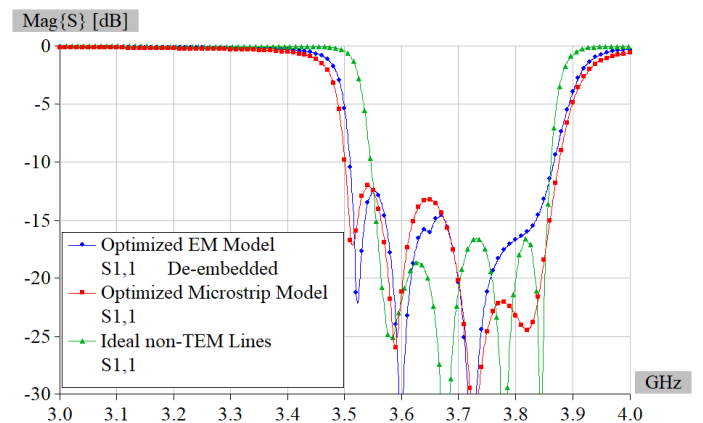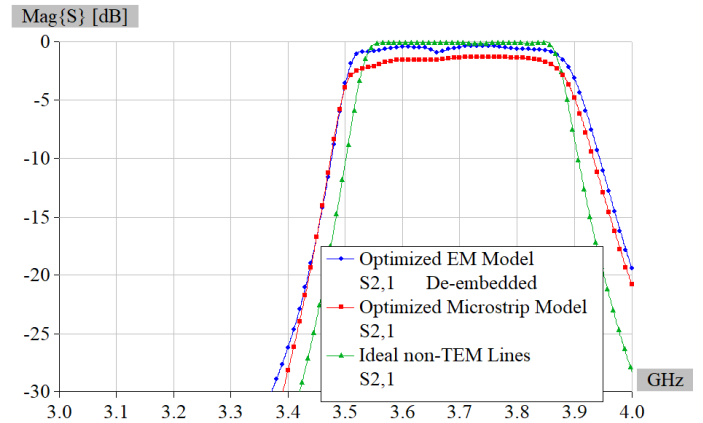

Figure 25. Comparison of 5th of Hairpin-Line filter responses of optimized EM model, optimized model with microstrip lines and model with Ideal non-TEM Lines.

The Goals and Merits of Subsequent EM Optimization

The described method of optimization through modifications of filter specifications has reached its limits. It seems like some additional effort should be exercised to perfect the performance of the filter, especially to improve S_{11} values. In **WIPL-D** suite, there is a powerful **Optimizer** that can be used to fulfil this requirement. A 50 iterations of the *Simplex* optimization method to optimize w_i, s_i, $i=1,...,3$ is sufficient to obtain the acceptable performance shown in Fig. 26. There are again four dips of S_{11} and the maximum value within the passband is around -15 dB, which can be considered as very good. Namely, specification of 0.1 dB for the filter ripple corresponds to the S_{11} value of approximately -16.4 dB, so there is no room for significant improvement. As established earlier, even the filter using the ideal, *quasi TEM* transmission lines, with no discontinuities included, has a distorted response, so it seems like the filter design is finished.
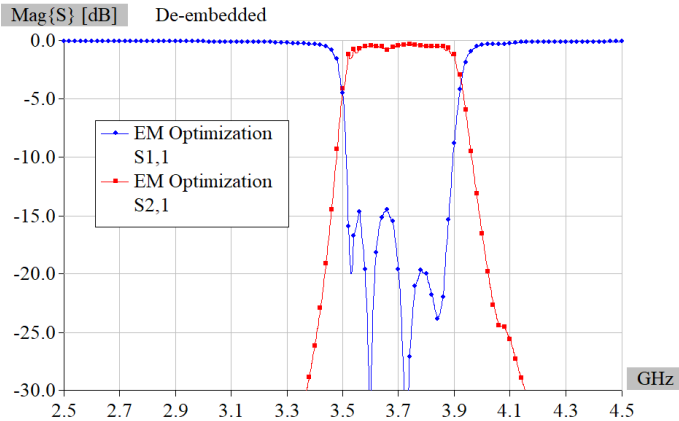
Mag{S} [dB]   De-embedded

Figure 26. Frequency response of optimized order EM model 5th of Hairpin-Line filter with microstrip lines.

However, a user may feel that the response does not look perfect, i. e. is not like the performance usually shown in textbooks on filters. So, one could be tempted to execute much more optimization steps to achieve such a response. Besides the doubtful success of such an effort, let's look into the practical side of things. Optimization variables and their values for *EM#0*, *EM#1*, *EM#2* and *EM Opt* are listed in *Table 3*. It is obvious that, as the optimization progresses, the difference between physical dimension of most of the filter variables becomes smaller, amounting only several µm between *EM#2* and *EM Opt*. Such a small difference is beyond the capabilities of the standard technology as defined previously in the text, meaning that such small differences will be indistinguishable in the practical fabrication of the filter. Therefore, there is a little merit of subsequent optimization of the filter.

Conclusion

A process of microstrip filter design has been described in this application note with a special focus on a technique of filter optimization, a simplified case of *Space Mapping* method. As a result of the design process a microstrip filter ready for sample fabrication is available with minimum human and numerical effort. The success of the design should be high as the limitations of a standard fabrication process are taken into account during the design. This includes the choice of the best suited substrate and the dimensional constrains.

The complete set of tools required for this process can be found in WIPL-D program suite. This includes **WIPL-D Microwave** with add-on tool **Filter Designer**, **Optimizer** and **WIPL-D CAD**. At current stage of the interoperability of the modules within the suite, the process of conversion of ideal *TxLine* and microstrip circuits to schematic runs automatically, while the conversion to **WIPL-D CAD** model must be performed manually. Although creation of an EM filter model from scratch is easy and straightforward owing to a rich set of drawing primitives and versatility of drawing commands and tools, the process will be automated in future software releases and the process of EM model generation from synthetized ideal *TxLine* circuit will be just two mouse clicks away.

Regarding computer resources used along this application note, there is no need to use any special piece of hardware as all of the simulations required can be performed with high numerical efficiency on a standard desktop machine.

Table 3. The changes in filter dimensions during optimization process

Symbolic variable	EM#0	EM#1	EM#2	EM Opt
S_1	0.156	0.136	0.131	0.131
W_1	0.352	0.323	0.315	0.320
S_2	0.617	0.514	0.487	0.482
W_2	0.532	0.518	0.514	0.511
S_3	0.796	0.679	0.648	0.635
W_3	0.545	0.537	0.535	0.517
L	5.975	5.6	5.554	/
L_{50}	3.929	3.673	3.641	/