

Design Flow for Microstrip Bandpass Filter

A filter is an indispensable component of almost every microwave system. When used along with a receiver chain, an input filter will predominantly define the bandwidth of the receiver. Therefore, filter minimizes the interference with unwanted signals and noise power entering succeeding components, typically low noise amplifier, both leading to more susceptible and sensitive receiver chains. On the transmitter side, an output filter can be used to stop parasitic harmonic signals to enter the antenna and to be radiated potentially causing problems to neighboring systems.

Since the massive utilization of the printing circuit technologies has extended to microwave frequencies, microstrip filters have gained significant attention as they can be easily manufactured and effectively integrated with many other circuits leading to compact and cost-efficient systems.

This application note describes how WIPL-D design environment can be efficiently used for microstrip bandpass filter design, from synthesis to optimization and further expanded to study more complex topics like parasitic bandwidths and various effects occurring in realistic operating environment.

Using Filter Designer Tool from WIPL-D Microwave for Filter Synthesis

WIPL-D Microwave has a built-in tool call Filter Designer that automates filter design. An interface to the filter synthesis module is user friendly and operates on wizard-like bases. The wizard comprises a sequence of two windows. In the first window main filter specifications are entered. This includes filter type, approximation function, frequency specification, magnitude specification and technology implementation. For this illustrative example of a bandpass filter, the targeted filter has a passband extending from 1.2 GHz to 2.2 GHz (i.e. center operating frequency of $f_0=1.7$ GHz and a bandwidth of $BW=1$ GHz). Within the operating bandwidth the ripple is specified to be 0.5 dB, and filter attenuation of 20 dB is required at 1 GHz. Chebyshev approximation function has been chosen and the technology for the filter realization selected was microstrip. After the selection has completed, the first window looks like the one presented in Fig. 1. By pressing Design button, the user is transferred to the second window (Fig. 2).

Based on specifications, the program calculates the required filter order n ($n=4$ for our example). To complete the synthesis, some other details related to filter implementation should be filled in. These include a microstrip substrate selection (relative dielectric constant $\epsilon_r=3.38$ and height $h=0.254$ mm), filter type (double shunt short-circuited stubs as single shunt stubs would have required narrow microstrip lines beyond the fabrication capability) and terminal impedances ($Z_1=Z_2=50 \Omega$). By pressing Export to Schematic the wizard finishes and microstrip filter

schematic window with microstrip circuit opens, as shown in Fig. 3.

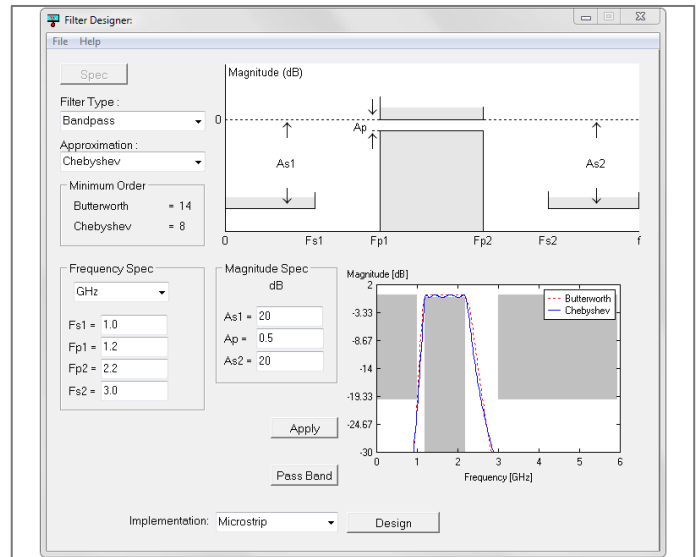


Figure 1. Specification window of Filter Designer tool available directly from WIPL-D Microwave

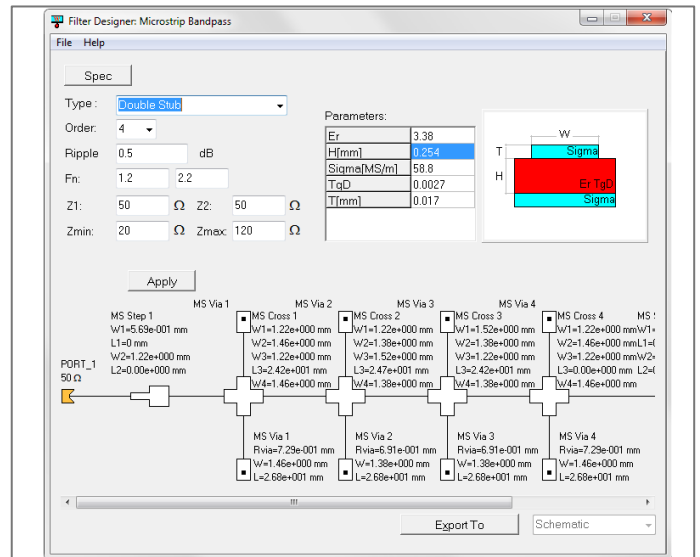


Figure 2. Technology window of Filter Designer tool available directly from WIPL-D Microwave.

Filter schematic automatically generated by the wizard contains all necessary model elements to perform simulations and optimization. The user can make the choice whether to work with ideal elements, closed form microstrip models or EM microstrip models of microstrip transmission lines and discontinuities (crosses and vias). An additional example on using Filter Designer tool can be found in an application note “Lowpass Filter Design by Circuit-EM Co-simulation” available for download at WIPL-D web site.

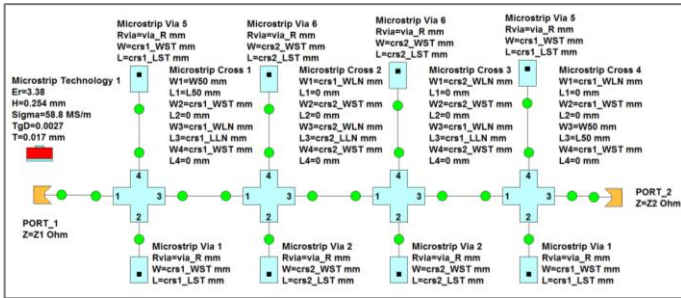


Figure 3. Synthesized microstrip schematic of band-pass filter according to specifications selected in Fig. 1 and Fig 2.

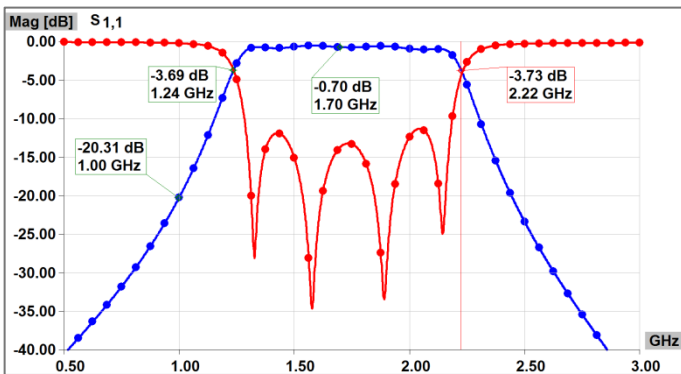


Figure 4. Optimized S parameters of filter from Fig. 3.

The filter comprises four pairs of transmission line resonators and transmission lines connecting the resonators. Within a pair, end of one resonator is connected to end of another resonator, while the remaining two ends are short circuited. The resonators are quarter wavelength long at the operating frequency of the filter. Two adjacent resonator pairs are connected with a transmission line section that is also quarter wavelength long at the operating frequency. The filter performance is determined by the widths and the lengths of the microstrip lines comprising a filter. For the filter to have desired frequency response these dimensions must all be set to appropriate values. For that reason, circuit optimization is usually performed immediately after synthesis as synthesis routines do not account for the influence of discontinuities.

S parameters of the filter, after schematic from Fig. 3 using microstrip analytical models for all elements have been optimized, are presented in Fig. 4. It can be concluded that the specification selected through the wizard have been mostly achieved. The small degree of the discrepancy is not important at this stage as in the final design step more accurate modeling is required and the filter circuit should be submitted to electromagnetic (EM) simulations and optimization.

EM Analysis/Optimization with WIPL-D Pro

Transfer from microstrip element modeling to EM modeling of the complete filter circuit is very easy within WIPL-D design suite. Microstrip schematic from WIPL-D Microwave can be seamlessly exported to WIPL-D Pro by a single mouse click. The EM model resulting from direct export is presented in Fig. 5.

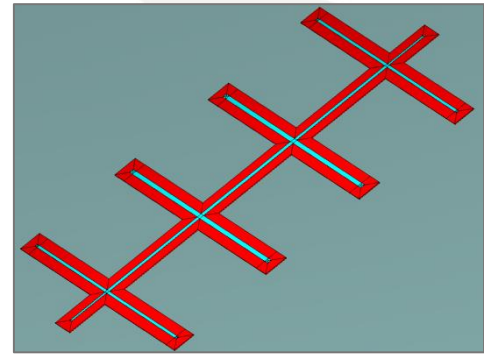


Figure 5. Microstrip layout of the filter automatically generated from schematic from Fig. 2.

The exported EM model is simulation ready and EM analysis can be carried out immediately after the export. The result of such a simulation is shown in Fig. 6 where S21 is presented with a red trace. Comparison with the S parameters obtained from circuit simulations from Fig. 4 indicates that the circuit does not meet specification and requires additional optimization of the EM model. After a few optimization iterations the specification has been recovered as shown with a blue trace in the same figure.

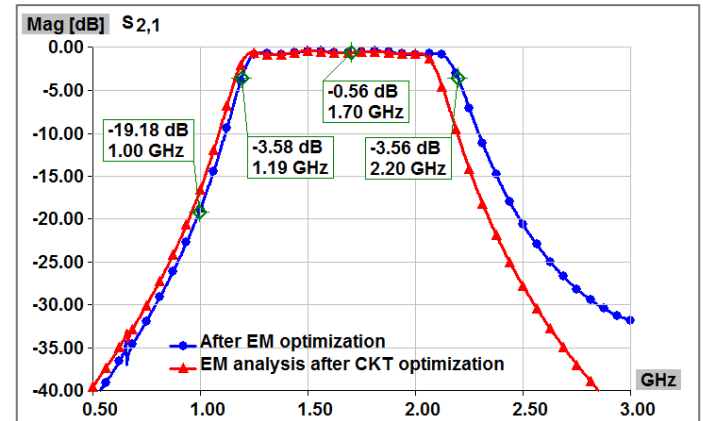


Figure 6. Comparison of S21 before and after EM optimization.

The EM analysis and accordingly an optimization iteration requires significantly more time to complete than a circuit level simulation, therefore bringing a design to meet the specification during circuit optimization is a must for an efficient design. If this approach has been exercised, a minimum number of EM simulations is required for adjustment of the dimensions of the microstrip elements comprising the filter to account for the minor differences occurring from limited accuracy in closed-form modeling of microstrip discontinuities.

A model presented in Fig. 5 may not seem realistic as the substrate has unusual shape resembling the shape of the microstrip conductors as it follows directly from circuit schematic. The relevance of the S parameters obtained for the simulation of the filter circuit on such partial substrate to the performance when the more common, full size rectangular substrate is utilized, should be justified. In order to explore the relevance of the simulations made with partial substrate, it can be very easily adjusted to take rectangular shape by defining a

few new nodes and adding corresponding plates. The adjusted filter circuit is shown in Fig. 7.

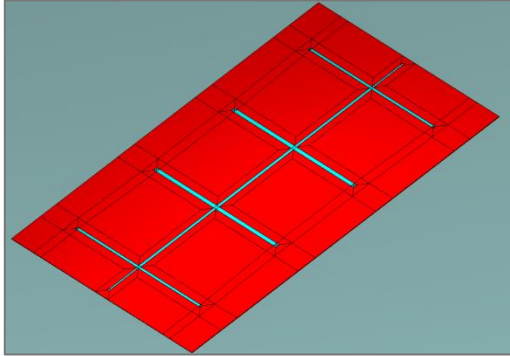


Figure 7. Microstrip layout of the filter from Fig. 4 with substrate manually adjusted to rectangular shape.

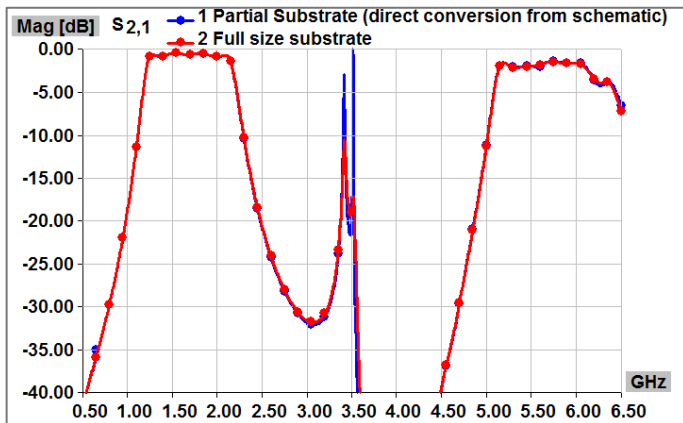


Figure 8. Comparison of S21 of the filters from Figs 5 and 7

The simulated S parameters of the filter on partial substrate as it comes directly from the schematic export and adjusted full size rectangular substrate are compared in Fig. 8 for the wide frequency range up to 6.5 GHz to include fundamental and first two harmonic parasitic pass bands. It can be concluded that the agreement between the two traces is excellent. Therefore, the results obtained for the partial substrate can be reliably used for filter simulation and optimization.

Parasitic Bands

Results from Fig. 8 indicate the existence of two parasitic bands occurring around $2f_0$ and $3f_0$ that must be considered if signal suppression at filter harmonic frequencies is important for system design. The occurrence of the parasitic bands can be explain by the periodicity in the characteristics of transmission line elements as the frequency doubles, triples, etc. In other words, quarter wavelength lines at fundamental frequency of the filter become half wavelength long at $2f_0$, and three quarter wavelength long at $3f_0$. Due to the construction of the filter, the signal from the input port can pass through the filter to the output port at these frequencies. This unwanted transmission results in the occurrence of spurious (parasitic) bands. Plots of the magnetic field distribution, illustrating the effects described, are presented in Fig. 9-11.

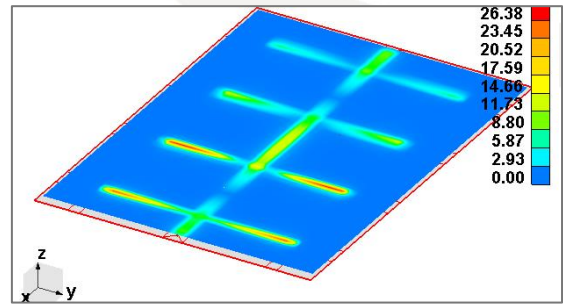


Figure 9. Magnetic field distribution box at f_0 .

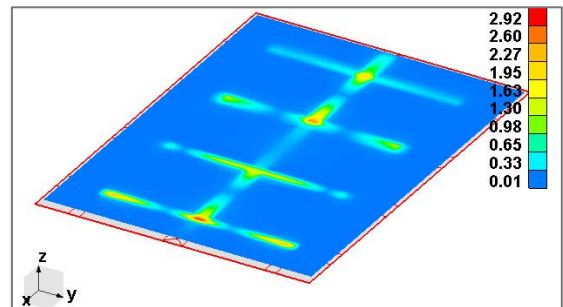


Figure 10. Magnetic field distribution around $2f_0$.

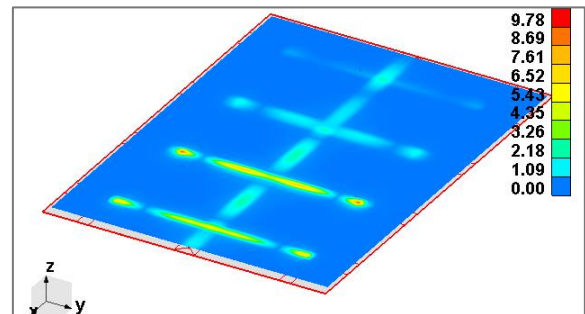


Figure 11. Magnetic field distribution around $3f_0$.

Filter inside Metallic Box

For most engineers a filter design may end at the stage where filter S parameters from Fig. 6 have been achieved. Indeed, it may seem that all of the specifications are met and the design is finished. The usual practice would be to proceed immediately to prototype fabrication and measurement. Usually the fabricated printed circuit board (PCB) will be attached to a metal base, coaxial-to-microstrip connectors connected to input and output ports, and measurements of the assembled circuit carried out using a network analyzer. With a well-controlled manufacturing and following good measuring practice, the measured performance of the fabricated filter sample will fall very close to the results shown in Fig. 8.

However, in microwave systems, filters are rarely used without metal housing which helps maintaining signal integrity and interference from other circuit or a system. Therefore, although the design of the filter may seem complete after finishing the steps described so far, the final check should include the simulation of the filter shielded inside a metal box. The WIPL-D Pro EM model of the filter circuit in a metallic box can be easily

built starting from the circuit shown in Fig. 7. By adding several nodes (e.g. simply by copying nodes from the top of the substrate and altering z coordinate to a value of the height of the box H) and creating additional metal plates, a complete metallic box can be created.

For the particular filter design example on hand, the height H of the box and length L of both, the substrate and the box, have been defined symbolically to enable the study of various effects as the size of the enclosure changes. Within the box, the filter is placed asymmetrically with respect to the y coordinate. The illustration of the filter inside the metal box is presented in Fig. 12 at a stage where a top cover is still not completely built, so that the interior of the box with a filter can be illustrated.

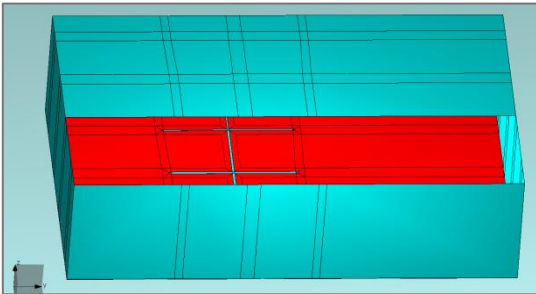


Figure 12. A complete filter within a metallic box (top cover partially removed for illustration).

Results of the simulation for three different box heights are presented in Fig. 13 and compared with the S21 obtained without metal enclosure, i.e. for the filter presented in Fig. 7. The first box height of H1=5 mm approximately corresponds to the minimum recommended box height when working with microstrip circuits as it is around twenty substrate heights. Second height of H2=20 mm corresponds to the typical box size used when a number of a circuits used in a system must be integrated within the same box, e.g. power amplifier, circulator, etc. These components may come bulky at the operating frequency of 1.7 GHz and therefore may require a box height in that range. The height H3= 50 mm corresponds to an oversized box. As will be explained later, oversizing a box can lead to significant problems.

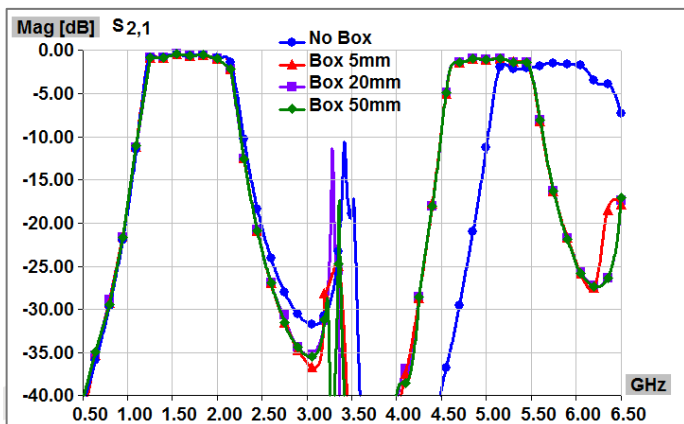


Figure 13. Comparison of filter S21 for unshielded filter and filter with shielding for three different box heights.

Comparison of the traces from Fig. 13 leads to three important conclusions. Firstly, when the filter is put in a metal box, both of the harmonic parasitic bands are shifted down in frequency. The bandwidth of the second parasitic band around $3f_0$ becomes significantly reduced. The insertion loss in this parasitic band is also reduced if a metal enclosure is applied. Secondly, the frequency shift of the first parasitic band around $2f_0$ causes the slope of the higher band edge at the fundamental band to become sharper. Finally, the height of the box has a minor effect on S21. In all simulations the box width has been kept at the same value, $W=110$ mm, while the box length L has been set to 85 mm, 375 mm and 205 mm for the box heights of 5mm, 20 mm and 50 mm respectively.

The effects of the metal enclosure can be easily explained if the analysis of the filter from Fig. 7 is repeated with radiation analysis options adjusted to capture the unwanted radiation of the filter. The radiation pattern at the frequency around $3f_0$ is plotted in Fig. 14. It can be concluded that a significant radiation occurs for the unshielded case causing the shift in resonant frequencies of the resonators and radiation loss. The shift in resonance frequencies of the resonators directly translates into frequency shift of the parasitic band, while the radiation loss is responsible for increased insertion loss. Adding a metal enclosure eliminates both of the effects and results in centering of second parasitic band at approximately $3f_0$.

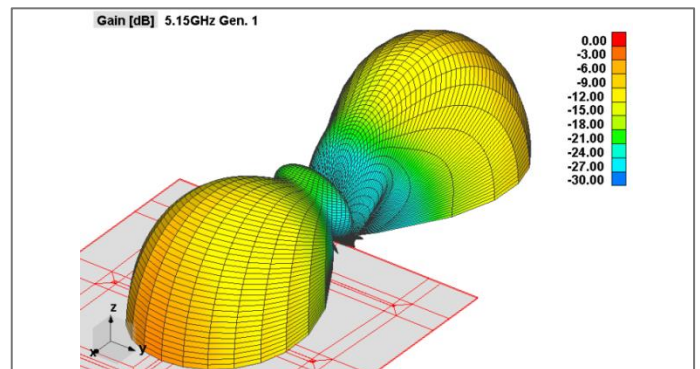


Figure 14. Radiation pattern of unshielded filter from Fig. 7 around frequency $3f_0$.

If the size of the box becomes too large, some additional effects arising from the presence of a metal box may come into play. For the box length $L=375$ mm, width $W=110$ mm and height $H_3=50$ mm, a box self-resonance may interfere with the filter performance. S21 of the filter when put inside such a box is given in Fig. 15. A new transmission peak occurring at 3.73 GHz can be observed.

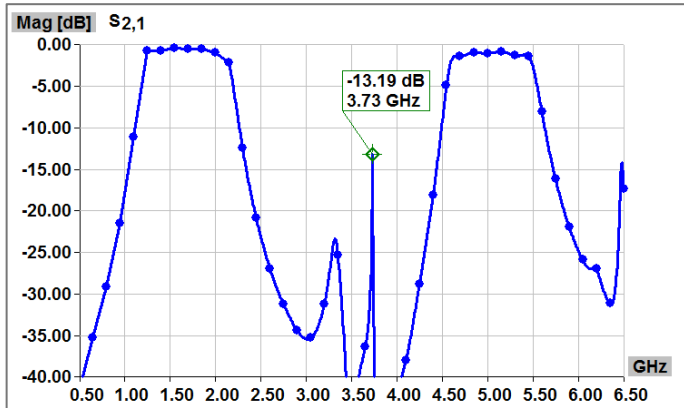


Figure 15. S21 of the filter when placed in an oversized metallic box.

The reason for the new peak to appear can be found if a field pattern is plotted using Near Field option from WIPL-D Pro. The field plot is presented in Fig. 16. It can be observed that the whole filter circuit is laying within one of the four resonance maxima (second from the left) of the electric field which causes the ports of the filter to be strongly coupled and resulting in an additional transmission peak at the box self-resonance frequency. The effect of such a resonance within a large metallic box should be studied before the box is designed and proper measures for avoiding the detrimental influence to a system performance prepared before the system is integrated within a box. The measures can typically include simple steps, such as putting absorbing material at the top cover of the box, shaping the box differently, or adding additional metal patterns in order to completely eliminate the resonances or to shift them to higher frequencies where they will not cause any problems.

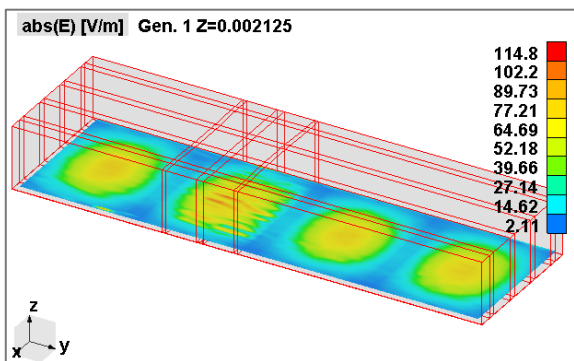


Figure 16. Electric field pattern inside an oversized box indicating the existence of box modes around frequency of 3.65 GHz.

Conclusion

The accurate and efficient design of a microstrip bandpass filter can be easily accomplished when using WIPL-D design suite as it integrates microwave circuit, EM, radiation and near-field analysis within a single design environment. Moreover, the built-in tool, Filter Designer, allows for direct synthesis of a microstrip filter circuit based on the specification selected by a designer through user-friendly, wizard-like interface.

The filter comprising analytic microstrip elements can be optimized to meet the specifications and then smoothly transferred to refine the design using EM analysis as an automated transfer of schematic to a 3D EM component is available with a single mouse click. The EM model obtained resembles the shape of microstrip conductor pattern as implemented in the schematic. Nonetheless, it can be used reliably for circuit simulation and optimization. In addition, the model can be adjusted to rectangular shape with very little effort, or a metallic box can be added to enclose the filter and study the effects of the shielding to the filter performance.

The introduction of the metallic shield can change the performance of the filter. This is an important fact to have in mind as the good performance of an unshielded filter, verified by EM simulations or by measurements, can be significantly changed when it is put in the metal box. The effects occurring in the box can alter the performance related to fundamental and especially to parasitic bandwidths as they may shift in frequency due elimination of the radiation, or a new parasitic transmission band may appear due to the self-resonances of the box. If this is the case, the effectiveness of several techniques to suppress the box modes can be tested and the best solution selected and applied immediately at simulation stage without expensive and time consuming rework once filter samples have been made.