Application Note

Cavity-Based Helical Resonator Bandpass Filters Designed With Parameterized Project Template in NI AWR Software

Overview

This application note describes the design process for a low-cost family of ultra high-frequency (UHF) cavity-based helical resonator bandpass filters for a cable television (CATV) component test switched filter bank. Cavity-based filter performance is determined entirely by geometry. Even though the filter structures are tuned, it can be challenging to size all the component geometries such that the tuning elements are effective to meet the desired synthesized response, hence a tool such as NI AWR Design Environment™ - inclusive of Analyst 3D EM simulator - greatly assists.

3D EM geometry creation and simulation for cavity-based filters, including tuning elements, is generally very time intensive. With one integrated project, new designs could be rapidly explored through changes in a small number of key global parameters. By leveraging parameterized 3D EM building blocks for cavities and resonators in the filter, as well as port tuning techniques, the synthesis and design stages were simplified and the design was then highly re-usable. A key element of the low cost, fast filter implementation was the unique construction of the filter cavities using double clad printed circuit board (PCB) material. The cavities and enclosure were cut out using an LPKF PCB milling machine driven from a parameterized set of fabrication files and assembled like a planar die cut model airplane.

NI AWR Design Environment software, specifically Microwave Office circuit design software, was used to create a complete “synthesis to implementation” process for the entire filter design including the generation of fabrication files. A hierarchical modeling approach was used for the cavities that included optimization of the circuit model in Microwave Office and verification using Analyst EM simulation. Once the template project was created, the entire process of designing for a new filter frequency could be undertaken in less than a day due to the tightly integrated project environment. First pass success was achieved on three different frequency filter designs, as well as a large reduction in time for 3D EM structure creation of the filter family due to the cascadable building block nature of Analyst PCells.

PCell Building Blocks

A hierarchal approach to the filter design project was adopted utilizing parameterized 3D PCells within Analyst. A core set of global parameters completely specifies the filter physical dimensions. Figure 1a shows the first two sections of the complete filter model in the 2D layout editor captured as a cascade of parameterized 3D PCells. Figure 1b shows the corresponding 3D representation of the complete filter model. Coaxial SMA feeds exist on wave ports 1 and 2. Lumped ports 3 through 7 are used to implement the port tuning techniques described later.

Figure 1: 3D PCells cascaded together in a 2D layout (a) alongside corresponding 3D for whole filter model (b).
The entire filter was implemented with only three core parameterized building blocks consisting of a helical resonator coil, slot aperture coupling, and SMA bulkhead launch with adjustable endpoint resonator tap wire. Figure 2 shows these building blocks individually.

(a) Helical resonator coil (b) Slot aperture coupling (c) SMA bulkhead launch

The 3D PCells were drawn using the Analyst 3D editor and the relevant parameters used in construction were exported into Microwave Office (Figure 3).

(a) (b) (c)

Figure 2. Three core parameterized building blocks within the filter: helical resonator coil (a), slot aperture coupling (b), and SMA bulkhead launch (c).

The 3D PCells were drawn using the Analyst 3D editor and the relevant parameters used in construction were exported into Microwave Office (Figure 3).

(a) (b) (c)

Figure 3. Parameters used in construction of the filter were exported back into the Microwave Office 2D environment.
Design Flow

The design and manufacture of this filter presented a number of challenges, as is typical of this type of filter design. First, the filter was designed using ideal elements and traditional filter theory. Optimizations were carried out to get the required response. The first challenge was to get the ideal filter response into an actual physical, cascaded cavity filter topology. EM simulation using Analyst was heavily used as it offers several advantages for this type of project, particularly the ability to create 3D parts as PCells that can be repeatedly used in the final layout. This made model creation faster and easier, as the steps from individual cavity design to the final five cascaded sections involved connected similar shapes. The shapes were created using parameters so that the actual geometries could be quickly changed, without having to redraw the structures in a 3D layout editor.

The design process for coupled resonator band pass filters is well addressed in literature [1] to [3] and can be summarized as follows for a helical resonator implementation.

1. Calculate filter order for desired response, such as Chebyshev or Bessel, based on passband ripple and stopband rejection requirements.
2. Calculate the coupling coefficients between filter input, resonators, and output. Convert the coupling coefficients into coupling bandwidths that can be easily measured with the simulator or on the bench.
3. Design a helical resonator and cavity physical implementation whose filter center frequency based dimensions are the best trade off between unloaded Q, performance dimensional sensitivity, and cavity size.
4. Choose an input and output resonator to connector launch coupling configuration. Choices are E-field with direct resonator tapping or H-field with magnetic coupling loops.
5. Choose an inter-resonator coupling method such as slot style aperture coupling and create a mapping between slot dimensions and the resulting coupling bandwidths so that the nominal slot size between each cavity can be defined based on the synthesized coupling coefficients from Step 3.
6. Build the filter with tuning elements on all resonators and coupling elements.
7. Tune the filter and validate design.

A Microwave Office project template with user folders was created for this design flow utilizing hierarchal techniques and parameterization, as shown in Figure 4. A separate project was then created with this template for each of the design frequencies of 215, 380, and 540 MHz.

Figure 4: Design flow captured in user folders.
Ideal Filter Prototype

An ideal filter prototype model was created with inverter coupled resonator elements in a linear schematic to prove that the derived coupling coefficients were correct. The ideal filter model was also used to derive the group delay responses required for the latter filter tuning steps.

Equations as a function of fractional bandwidth, impedance, and frequency scaling for deriving the coupling coefficients were directly added to the schematic, as shown in Figure 5. The $g_0$ to $g_N$ were calculated from the passband ripple value of the desired order Chebyshev response. The resonator loss element was determined from the resonator impedance and unloaded Q derived from Section 2, as well as the resonator slope factor.

Figure 5: Ideal filter schematic with embedded equations.
Resonator
A spreadsheet was created with the helical resonator equations from [1] to obtain starting point dimensions for the helical resonator and cavity. Helix diameter, wire diameter, pitch, number of turns, and resulting cavity dimensions were traded off against optimum overall volume, resonator impedance, and unloaded Q.

The helical resonator and cavity dimensions were fine tuned with Analyst using the loosely coupled 3D model shown in Figure 6a. Note that the variable length tuning screw and coil support structure are included in the model. The plots in Figure 6b illustrate the resonant frequency of the optimized coil and cavity for the 380 MHz filter implementation, with the tuning screw at both minimum and maximum insertion depth and the resulting 20 MHz of tuning range.

Figures 6: Single resonator 3D model (a) and Graph of resonance at extremes of tuning screw insertion (b).

Coupling Component
Figure 7 shows an Analyst 3D model with two cavities and a coupling slot. An inserted tuning screw was created to characterize the inter-resonator coupling bandwidths obtained for various coupling slot dimensions.

Figure 7: Coupling slot 3D model.
The coupling slot width was swept over a practical range dictated by the cavity dimensions and the resulting coupling bandwidths are shown plotted in Figure 8a. In Figure 8b the coupling slot widths required for a particular coupling bandwidth were plotted and a polynomial curve fit performed so that an expression relating coupling slot dimension to required coupling bandwidth could be obtained. This expression was used to size the slot widths of the whole filter model for the coupling bandwidths calculated in the ideal filter prototype section.

![Figures 8: Graphs of Coupling bandwidth (a) versus slot width (b).](image)

**Simulate and Tune the Whole Filter Section**

The objective of this section was to validate that the whole filter model could be tuned to a perfect Chebychev response in the simulator within the range of the implemented tuning elements and adjustments then made if small corrections were required. To achieve this without a large number of time intensive 3D EM simulations, the port tuning techniques of Swanson [4] were leveraged. The port tuning method placed lumped ports at the end of the resonators in the whole filter simulation model, as shown in Figure 9 and the previous Figure 1 (ports 3 to 7). A single Analyst simulation was run to obtain the multi port S-parameters of the nominal model. Fast tuning feedback was achieved in the linear simulator by using ideal ground connected capacitors across the resonator ports to simulate the resonator tuning screws and parallel ideal transmission line elements connected between the resonator ports with variable impedance to simulate the coupling slot tuning screw function. The whole filter was then tuned in the linear simulator, just as it would have been done on the bench, and the degree of deviation of tuning elements from the nominal position was used as a score card for the filter implementation. If any tuning element deviation was unacceptable, then the Analyst whole filter structure model was tweaked and re-simulated. This process took no more than two to three iterations and hence was a huge time improvement over trying to vary tuning elements in multiple full 3D filter simulations.

![Figure 9: Tuning elements for port tuned model.](image)
Ness [5] proposed a single pass tuning technique for coupled resonator filters based on the deterministic group delay response of the input or output port reflection coefficient as each resonator is added individually from input to output. The technique was leveraged in this project for tuning both the simulated filter and the real filter on the bench. Figure 10 shows the overlaid group delay responses as each resonator of the filter was added. These responses, derived from the ideal filter prototype section, were used as a tuning template for each resonator and coupling.

Figure 11 shows the S21 and S11 responses of the linear simulator port tuned filter using the Ness GD method, resulting in the desired Chebychev response and acceptable tuning element deviations from nominal.

Figure 12 shows a set of port-tuned element values for the 380 MHz filter.
Cavity and Enclosure Parameterized Elements

Figure 13 illustrates the use of shape modifiers with hierarchal parameterization to implement one of the planar sections that forms the cavities and filter enclosure. These elements automatically size with the global parameter set of the project file.

Fabrication Files

The filter cavities and enclosure were fabricated with an LPKF PCB milling machine on two separate panels using the hierarchal parameterization elements to generate the fabrication files as illustrated in Figures 14a and b.
Figures 15a and b show the panel artwork from Microwave Office used to create the precut cavity walls, slots, and housing.

Fabricating the Filters
The resulting cavity building blocks were then assembled, as shown in Figure 16, similar to assembling a model airplane from planar die-cut balsa wood pieces.

The helical resonator coils were wound on a 3D printed plastic former from appropriate diameter solid conductor household wire. Final assembly was then carried out by inserting the coils and tuning screws. A wooden dowel was used for mechanically supporting the free end of the coils. Figure 17 shows the assembled 380 MHz filter.

Figure 18 shows the completed 215, 380, and 540 MHz bandpass filters combined into a switched filter bank.
Tuning the Manufactured Filter

The completed filter was tuned using the same method as the simulation model. The group delay responses were exported from Microwave Office to the vector network analyzer (VNA) to be used as tuning templates. All resonators were detuned by shorting the resonator with its corresponding tuning screw. As each succeeding resonator was added to the filter response by releasing the screw, the center frequencies and couplings were adjusted until the group delay matched the template.

Simulated and Measured Results

Typical measured results are shown in Figure 19. Agreement between simulated and measured results was considered excellent. First pass design, construction, and verification of the filters was achieved.

![Figure 19: Measured results of 380 MHz filter perfectly overlaid on the simulated data imported into the VNA.](image)

Conclusion

This application note has described the design and manufacture of a family of helical resonator-based cavity band pass filters that was achieved with first pass success. Extensive use was made of 3D EM simulation to design the coils, cavities, and apertures, as well as a parameterized project template for capturing all steps of the design process. The NI AWR Design Environment platform enabled the designer to work seamlessly between Microwave Office circuit design software and Analyst 3D EM simulator.

References