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INVITED PAPER

MMIC Filter Advancements Drive New Tools

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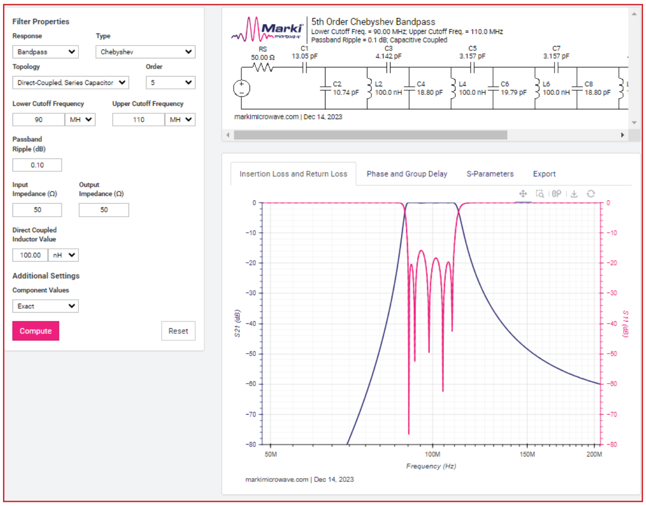
Integrated circuits have redefined electronics in many areas, but not microwave filters until recently. Bringing the power of MMIC fabrication technology to bear on filtering applications has inspired the development of new tools and new ways of thinking about classic problems. This article discusses advancements in software tools and filter hardware, along with applications where both are valuable.

TOOLS OF THE TRADE: THE MMIC FILTER SOFTWARE STACK

In contrast to most broadband components, fixed filters are generally custom-designed for a system with sometimes vaguely defined performance specifications that may shift frequently. Increasingly, customer requirements are driven more by size than rejection requirements. Frequently, filters solve an unanticipated design problem, often stemming from the frequency plan or previous component choices. The filter business and manufacturing process require speed at every step. Once specifications are agreed upon, the design, fabrication and characterization of the filter must happen quickly. However, since fixed filters are passive and linear, the characterization consists of measuring a single two-port S-parameter. To address this new paradigm with maximum speed, new tools are required. Software tools that automate key steps in the design and commercialization processes are necessary to prevent repetitive and time-consuming work.


Filter Properties
Response: Bandpass
Type: Chebyshev
Topology: Direct-Coupled, Series Capacitor
Order: 5
Lower Cutoff Frequency: 90 MH
Upper Cutoff Frequency: 110 MH
Passband Ripple (dB): 0.10
Input Impedance (Ω): 50
Output Impedance (Ω): 50
Direct Coupled Inductor Value: 100.00 nH
Additional Settings
Component Values: Exact

5th Order Chebyshev Bandpass
Lower Cutoff Freq. = 90.00 MHz; Upper Cutoff Freq. = 110.0 MHz
Passband Ripple = 0.1 dB; Capacitive Coupled
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Fig. 1 Fifth-order Chebyshev bandpass filter synthesis.

Step 0: Theoretical Definition with LC and Microstrip Filter Design Tools

Before initiating a MMIC filter design, filter designers investigate what is theoretically possible and what kind of inductances and capacitances are necessary to realize these filters. Marki Microwave does this with analytical filter design tools that the company has made publicly available. The LC filter design tool uses equations from fundamental filter research to calculate the theoretical performance of many different types of filters (Chebyshev, Butterworth, Elliptical, etc.) of different orders at given cutoff frequencies. A representative output of this design tool is shown in ***Figure 1***.

The microstrip filter design tool goes a step further and calculates the actual layout of a planar microstrip filter in a more limited

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number of topologies (Chebyshev and Butterworth). It calculates the scattering parameters for this structure using mathematical models. Tools like these allow a designer to quickly develop an intuition for what is possible in the filter space.

While powerful and fast, the drawback of these tools is that they only provide theoretical results. When fabricated, the filters created by the microstrip and LC filter design tools will not match the design tool results. The design tools do not account for parasitics of the inductors and capacitors, loss in the components and transmission lines and especially, coupling between different structures. The real-world performance of the filter will not match the simplistic simulation. To achieve better results, further design optimization in a more realistic circuit solver is necessary. For optimal performance, retuning with a sophisticated circuit solver may be required.

Step 1: Topology Definition

Once the theoretical possibilities are understood, the next step is to find the best physical layout to implement in a MMIC structure. This requires researching previously published filter designs, experimenting with different coupling structures and possible circuits in a schematic-level circuit solver, along with exploring different implementations of the circuit in a 3D finite element method (FEM) electromagnetic solver. While standard optimization tools can be used, this is mostly a manual, analog process. The result of this process is not a specific filter design, however, but a topology. A filter topology is the essential, scalable geometry of a filter circuit implemented in a MMIC structure that can be scaled and re-optimized to change the center frequency and bandwidth while maintaining the basic artwork. A given topology will have 10 to 20 design variables that can be continuously varied, leading to millions of potential geometries. Only a small number of these geometries yield a useful filter. Beyond a specific constrained solution space of these design variables, the design is not viable due to unmanufacturable geometries or unacceptably high unit-to-unit variance. Within that useful filter range, however, many designs can be realized with first-pass success.

Step 2: Automatic Design

To realize a specific filter geometry, a designer starts with the base topology and a rough calculation to estimate a seed value for the 10 to 20 design variables. The designer then solves using the seed values in 3D and takes the output to iterate closer to the optimal filter design. This iterative process uses a combination of software tools to refine initial estimates.

Marki uses HOTMESS, a combination of an automatic 3D filter optimizer and a proprietary machine learning algorithm, to automate and optimize the process of creating a set of filters to meet requirements. There are two keys to this tool:

- The 3D FEM solver is relatively slow, taking minutes to hours to solve, so automating the process allows around-the-clock optimization of filters.
- The optimization routine is not blind. It uses the "incorporating prior knowledge" machine learning concept. Unlike a simple gradient solver, HOTMESS solves for the required circuit effect first, improving with each cycle.

Due to these properties, HOTMESS can solve for every achievable percentage bandwidth and center frequency for a given filter topology. ***Figure 2*** illustrates that a filter design should more appropriately be thought of as a matrix of center frequency and passband combinations.

Step 3: Design a Filter Instantly

HOTMESS can provide a solution for nearly every filter topology, but this only addresses the design aspect of the problem. To address the manufacturing aspect, HOTMESS is paired with Prodigy™ Filter Designer to arm filter designers with as much information as early as possible before they develop a filter procurement specification. The publicly available Prodigy™ Filter Designer allows a user to design a filter at any center frequency and bandwidth within the operating range of a given topology. The Prodigy™ Filter Designer interface is shown in ***Figure 3***.

In the Prodigy™ Filter Designer interface, a user selects the desired filter topology, center frequency and bandwidth. The interface then shows an insertion loss and return loss simulation for the selected filter design. This interface is very similar to the LC filter and microstrip filter solvers described earlier, but the underlying math is very different.

In contrast to the ideal filter prediction given by the mathematical models, Prodigy™ Filter Designer creates a real filter, with known design variables and size. Most importantly, Prodigy™ Filter Designer uses machine learning to calculate the real S-parameters of the filters with all the effects like metal loss, parasitics and cross-coupling. This design and its Touchstone file are immediately available to system designers so they can incorporate actual filter performance at the initial stages of a system design.

While Prodigy™ Filter Designer can display every achievable filter for a given topology, it does not display the best achievable performance for a given filter specification. Where the performance of the filter

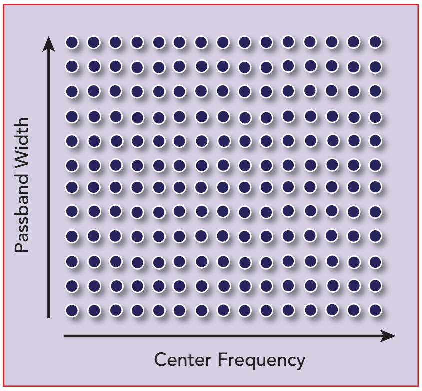
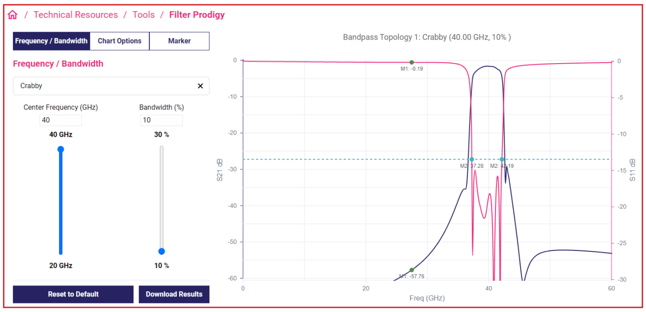


Fig. 2 Filter topology matrix.



Crabby

Center Frequency (GHz) 40

Bandwidth (%) 10

Fig. 3 Prodigy™ Filter Designer user interface.

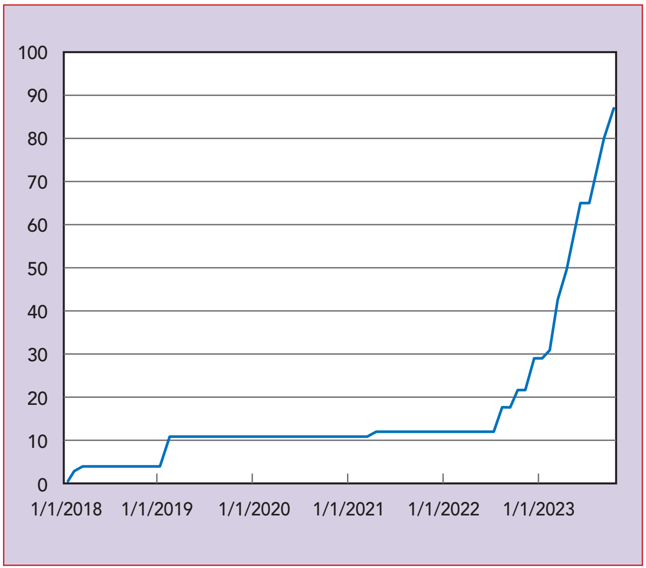


Fig. 4 **Marki MMIC filter catalog.**

is sufficient, the Prodigy solution will be a cost-effective solution. When the Prodigy solution does not meet the requirements, there are trade-off techniques among rejection, size and insertion loss that can be considered.

Step 4: Optimize Cost and Prototyping Speed

Since implementing these new MMIC filter models that allow filter designs to be developed quickly and at scale, the library of in-stock filter designs at Marki has grown quickly. This can be seen in ***Figure 4***. The anticipation is that there will be hundreds of filter designs in production by the end of 2024.

Since each filter has its unique combination of center frequency and rejection shape, finding the optimum filter for a given requirement becomes challenging. This challenge is further compounded for applications that need a series of filters for harmonic cleanup or switched filter banks. A filter search tool has been developed to address this issue. A user inputs passband and rejection performance requirements and the filter search tool cycles through all available catalog products and displays the best match. If no filter is found that meets the desired specifications, the closest available match can be found using the "partial match" match option. While the type (lowpass, highpass or bandpass) of filter can be a selection criterion, leaving this option generic can expand the pool of possible solutions. ***Figure 5*** shows the user interface and the output of the filter selection search tool.

Filter Requirements

Lower Cutoff (MHz): 38000
Upper Cutoff (MHz): 40000
Passband Definition: 3dB Cutof

	Start Freq. (MHz)	Stop Freq. (MHz)	Rejection (dB)	Ins. Row	Del. Row
1	9000	11000	30		

☐ Ignore Rejection Requirements

Response: Bandpass
Package Type: Any

Results Settings

☐ Show All Filters
☐ Include Partial Match

☐ New Products

Search by Part Number

Part Number	Center Frequency (GHz)	Lower -3dB (GHz)	Upper -3dB (GHz)	Response	Package Type	Package Size	Datasheet	S-parameters	Product Lifecycle
FB-3300	32.98	25.69	40.27	Bandpass	Connectorized	27.94 X 18.80 mm	Datasheet	s2p	Released
MFB-3300	33.10	25.36	40.86	Bandpass	Bare Die	3.13 x 1.25 mm	Datasheet	s2p	Released
MFB-3450	33.71	22.23	45.18	Bandpass	Bare Die	1.25 x 1.25 mm	Datasheet	s2p	Released
MFB-3475U	34.17	27.81	40.53	Bandpass	Connectorized	14.22x13.21mm	Datasheet	s2p	Released
MFB-3475	34.71	28.55	40.89	Bandpass	Bare Die	1.25 x 1.25 mm	Datasheet	s2p	Released
MFBC-00007PSM	34.98	29.50	40.46	Bandpass	Surface Mount	5x5 mm	Datasheet	s2p	Released
MFBC-00016PSM	35.82	29.56	42.07	Bandpass	Surface Mount	5x5 mm	Datasheet	s2p	Released
MFBP-00022CH	35.91	29.98	41.84	Bandpass	Bare Die	2.40 x 2.40 mm	Datasheet	s2p	Released
FB-3700	37.21	31.26	43.18	Bandpass	Connectorized	20.32 x 14.99 mm	Datasheet	s2p	Released
FB-4000	40.08	33.38	46.78	Bandpass	Connectorized	20.32 x 14.99 mm	Datasheet	s2p	Released
MFBC-00017M	42.01	34.08	49.94	Bandpass	Connectorized	39.98 x 20.83 mm	Datasheet	s2p	Released
MFBC-00017CH	42.03	34.11	49.94	Bandpass	Bare Die	2.20 x 2.20 mm	Datasheet	s2p	Released
MFBC-00008CH	44.17	36.07	52.28	Bandpass	Bare Die	2.20 x 2.20 mm	Datasheet	s2p	Released
MFBC-00008M	44.20	36.27	52.13	Bandpass	Connectorized	39.98x20.83mm	Datasheet	s2p	Released
MFB-5350	50.22	33.45	66.99	Bandpass	Bare Die	3.13 x 1.25 mm	Datasheet	s2p	Released

Fig. 5 **Filter search tool and the results.**

FILTER APPLICATIONS

Figure 6 shows the performance of filters with a similar center frequency and bandwidth, but different trade-offs in terms of size, insertion loss, close-in rejection and far-out rejection. The first result in Figure 6 is a legacy laminate filter in a connectorized module and the rest are MMIC filters released after 2020. Each of the MMIC filters utilizes a new topology developed to meet a new system requirement. ***Table 1*** shows selected characteristics of the filters in Figure 6.

Switched Filter Banks

Switched filter banks (SFBs) are a common application for MMIC filters. An SFB is commonly found in wideband receivers and wideband LO generators and synthesizers. MMIC filters are particularly well suited for use in SFBs for two reasons. First, SFBs use many filters, so the size advantage of a MMIC filter is multiplied by the number of filters in the bank. A reduction of 100 mm² on a single filter translates to a size reduction of 8 cm² on an 8-channel SFB and that is significant. Secondly, the cost of creating a new MMIC filter is dominated by the mask for the reticle and the first wafers. Mask production is a slow, serial and expensive process performed with electron beam lithography. Since four to eight filters can share a single mask, the major cost of developing the filters is split among the entire bank of filters.

The most straightforward application of MMIC filters for SFBs is the filtering of harmonics following a fre-

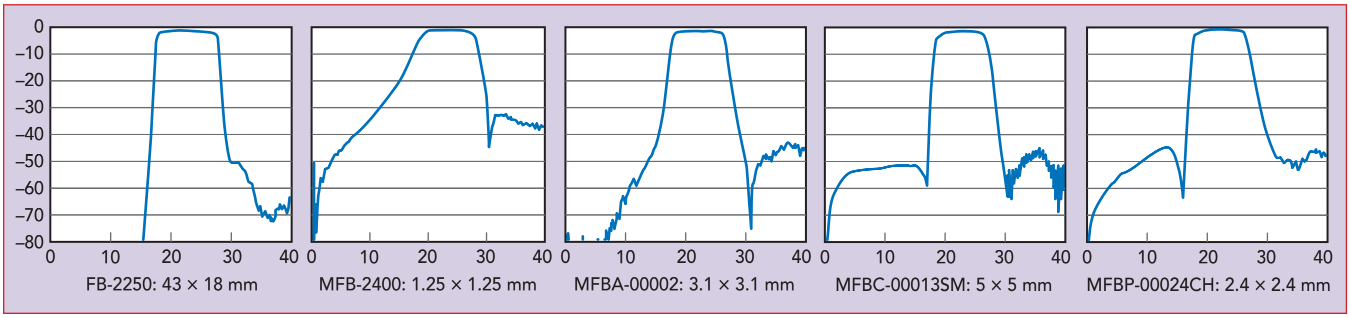
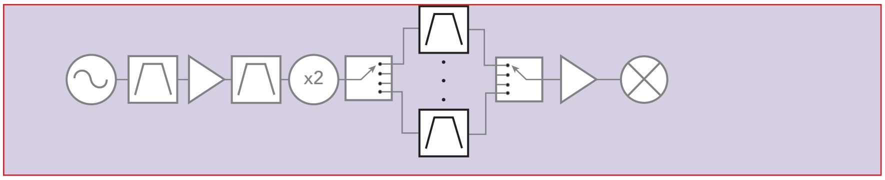


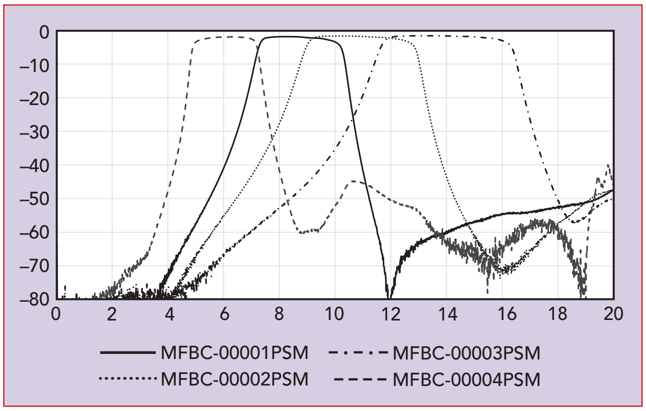
Fig. 6 **Filter trade-offs affect performance.**

TABLE 1
FILTER DETAILS

Part Number	Package	Size (mm)	Insertion Loss (dB)	40 dBc Rejection Offset (%)
FB-2250	Module	43 x 18	1.5	8
MFB-2400	Chip	1.25 x 1.25	1.3	63
MFBA-00002CH	Chip	3.1 x 3.1	1.7	16
MFBC-00013SM	QFN	5 x 5	1.4	10
MFBP-00024CH	Chip	2.4 x 2.4	1.4	12



▲ Fig. 7 **SFB in a transmit lineup.**



▲ Fig. 8 **Retuning filter designs for different bands.**

quency multiplication block. ***Figure 7*** shows the lineup for an SFB after a frequency doubler, along with the placement of the filters. With applications going higher in frequency, the multiplication block could be a doubler, tripler or quadrupler.

Marki doublers achieve harmonic suppression performance of 40 to 60 dBc across several octaves of bandwidth, however, this performance may not meet the requirements of high performance electronic warfare and instrumentation LO generators. Because the harmonic spurs are always separated from the desired tone by a fixed ratio and not a fixed frequency, a constant percentage bandwidth filter bank is required. Fortunately, this design is straightforward in a MMIC filter using a single filter topology since the basic design can be scaled and retuned to move the center frequency as shown in ***Figure 8***.

Pre-selection Filter

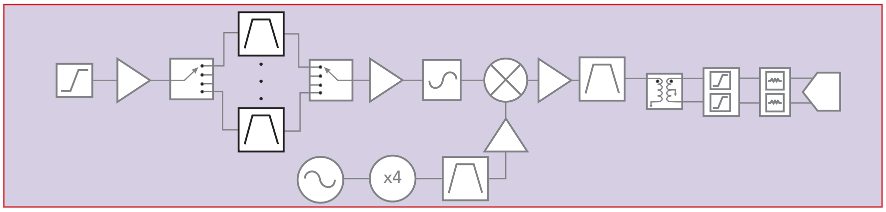
The pre-selection filter is another common SFB application. This function appears at the front end of a wideband receiver as shown in ***Figure 9***. These filters typically come after the limiter and low noise amplifier (LNA) or they may be switched with the LNA to reduce the nonlinear harmonics created by the signal before frequency conversion or further signal processing. While these pre-selection filters can be constant percentage bandwidth when second-order intermodulation distortion (IP2) is a major limitation, frequently they are a fixed bandwidth to maximize the Nyquist zone of the ADC at the end of the receive chain. ***Figure 10*** shows a series of four GHz filters that can be combined with SP4T switches on either side to create a four-channel 2 to 18 GHz pre-selection filter. While constant percentage bandwidth filters can easily be realized as MMICs by scaling the circuit, constant bandwidth filters offer a different set of challenges. This is particularly evident at low frequencies where filter bandwidths can be more than an octave. The performance of this 2 to 18 GHz pre-selection SFB is shown in Figure 10.

CASCADING FILTERS

A solution for multi-octave filters is to cascade lowpass and highpass filters. This sounds straightforward, but not all filters can be cascaded and maintain satisfactory performance. A key attribute to success is ensuring that the lowpass and highpass filters have good out-of-band performance. Lowpass filters must have good high frequency response, which means a flat passband. Highpass filters must have good out-of-band performance, maintaining good rejection out to 40 GHz and beyond without bandpass filter reentrant mode issues.

There are several advantages to creating bandpass filters from highpass/lowpass filter combinations. The technique allows for arbitrarily wide percentage bandwidths, making 2 to 18 GHz filters as easy as 2 to 6 GHz filters. The highpass and lowpass filters can be designed and optimized independently, allowing for rapid design of a complete set of filters at regular steps. Lumped elements can be used in MMIC highpass and lowpass filters, allowing for a small die size. In theory, the combination highpass/lowpass filter can be in separate, well-matched packages placed close to each other.

However, not all filters can be cascaded. This technique is useful for improving the rejection of bandpass filters. When a requirement calls for a steeper rejection than a single filter can provide, a cascade filter may be the solution. However, precautions need to be taken because bandpass filters are



▲ Fig. 9 **SFB used as a pre-selection filter.**

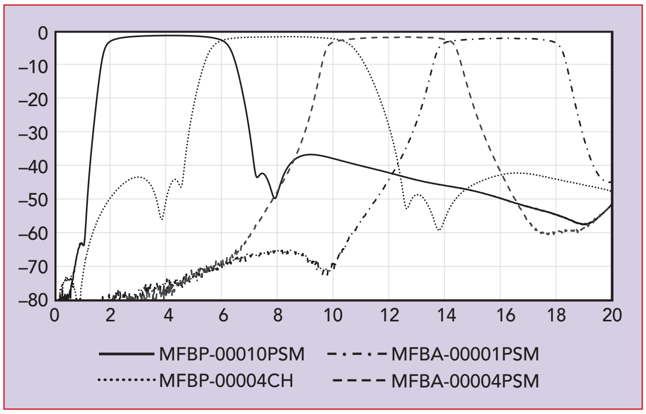


Fig. 10 2 to 18 GHz SFB performance.

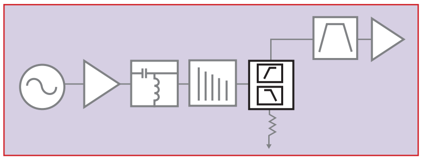


Fig. 11 NLTL terminated with a diplexer.

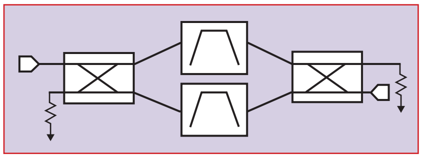


Fig. 12 Balanced filter block diagram.

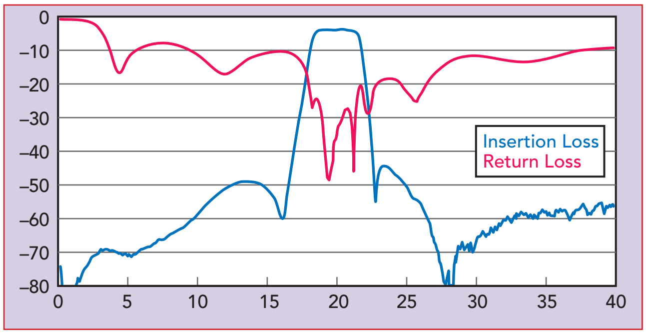


Fig. 13 MFQH-00001CH performance plots.

reflective. This and other challenges can be addressed with reflectionless filters.

REFLECTIONLESS FILTERS

Classic filters function as mirrors outside of the passband. This may present an issue for frequency conversion functions like mixers, doublers and nonlinear transmission lines (NLTLs) because the strongest tone, (the LO, image or the fundamental input) is not the desired tone. Reflections of these high-power tones back into a frequency conversion device may cause unpredictable responses due to nonlinearities in the device. There are at least two solutions that may be appropriate for these issues. The best choice will depend on the specifics of the application:

Terminated Diplexers: A diplexer is a device that routes signals to specific output ports based on frequency. A bias tee is a simple and extreme example of a diplexer; most diplexers have a higher crossover frequency. When one side is terminated in a 50 Ω load, it will function as a highpass or lowpass filter where the common port has good return loss across the band. The diplexer design will determine the return loss performance of the highpass and lowpass ports. This approach can be an excellent termination for an NLTL or other multiplier chain since the low frequency fundamental tones can be eliminated. ***Figure 11*** shows a block diagram of a diplexer terminating an NLTL to reduce reflections.

Balanced Filters: To create a reflectionless, balanced circuit requires two identical subcircuits connected with quadrature hybrids. By combining MMIC filter technology and quadrature hybrid designs, designers can create reflectionless bandpass filters with good return loss across a wide bandwidth. The major benefit of this technique is that it is simple and can be realized on a single chip, with only a slight increase in chip area. The block diagram of this design approach is shown in ***Figure 12*** and ***Figure 13*** shows the actual performance of a Marki MMIC reflectionless bandpass filter.

VARACTOR-TUNABLE FILTERS

The ideal solution for many RF systems has long been tunable filters. If an ideal tunable filter were available, it would dramatically reduce the complexity, size and cost of many RF systems. There are many types of tunable or switchable filters available using various techniques. Varactor-tuned filters use fixed inductors with varying capacitors to move the values of the resonators. While these filters have found wide acceptance, tunable bandpass fil-

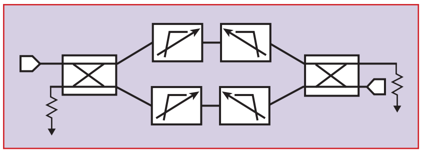


Fig. 14 Varactor-tunable bandpass filter.

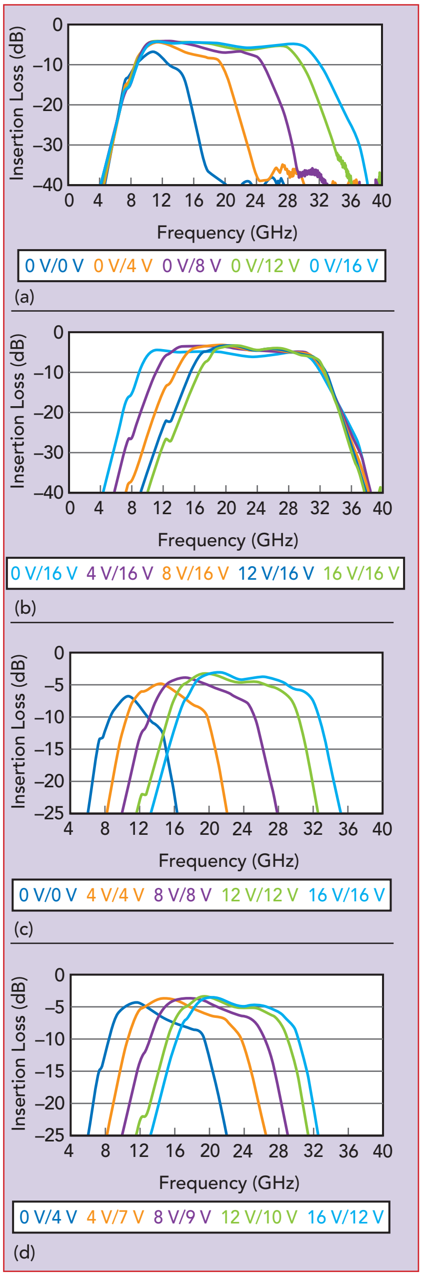


Fig. 15 (a) Insertion loss sweeping lowpass. (b) Insertion loss sweeping highpass. (c) Insertion loss constant percentage bandwidth. (d) Insertion loss constant bandwidth.

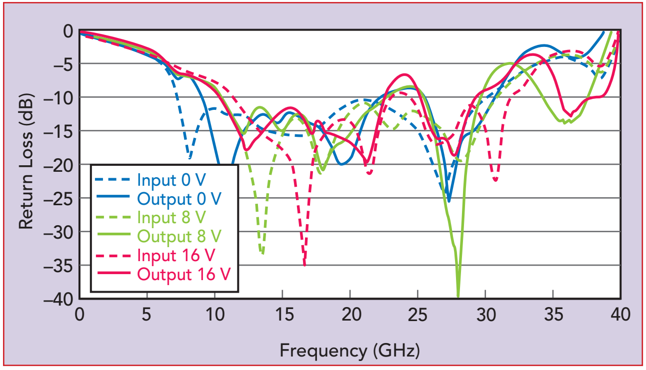


Fig. 16 Insertion loss constant bandwidth.

ters are only capable of fixed percentage bandwidth tuning, which creates challenges. Also, the return loss of varactor-tuned filters tends to suffer across the tuning range due to the detuning of the filter structures.

To overcome these limitations, many of the previously described techniques can improve the state-of-the-art in varactor-tuned filters. Marki solves the challenge of fixed percentage bandwidth tuning by designing separate highpass and lowpass filters that are tuned independently. Without these separate, independent tuning voltages, the best result is roughly fixed percentage bandwidth filters.

To overcome the challenge of detuning filters that degrade return loss, Marki designers embed a high-pass/lowpass cascade in a balanced structure to provide good return loss regardless of the tuning state. This approach results in a versatile and effective filter for size-constrained applications that can sacrifice some rejection and insertion loss performance. ***Figure 14*** shows the block diagram of this varactor-tunable bandpass filter approach.

The following charts show the performance of Marki's MFBT-00003PSM varactor-tuned bandpass filter and they illustrate some of the concepts previously discussed. ***Figure 15a*** and ***Figure 15b*** show the insertion loss as the independent control voltages are swept. ***Figure 15c*** and ***Figure 15d*** show insertion loss for constant percentage bandwidth and constant bandwidth applications. ***Figure 16*** shows the return loss for different bias conditions.

CONCLUSION

Size and channel density requirements for high performance RF circuits pressure designers to minimize the footprint without sacrificing performance. When size is the primary concern, MMIC fixed and tunable filters offer significant size reductions and improved economics for applications where multiple filtering states are necessary. Innovation from companies like Marki in both automated design flows and filter performance enables a viable business model for high performance MMIC filters in the low volume and high-mix market applications. ■