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How Digitally Tunable Filters Enable Wideband Receiver Applications

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Abstract

In today's multichannel, wideband multioctave tuning RF receivers, it is often necessary to eliminate unwanted blockers to preserve the fidelity of signals of interest. Filters have played an essential role in reducing these unwanted signals, particularly in the receiver RF front end and local oscillator (LO) portions of these systems. This article will explore filters within RF signal chains, discuss the concept of blocker signals, review traditional filtering technologies, and conclude with the latest product solutions for optimizing signal chain performance.

Introduction

With the goal to continuously reduce size, weight, power, and cost, while increasing or maintaining performance, it has become necessary for RF system designers to evaluate each component in the signal chain and look for opportunities to innovate. As filters have traditionally consumed large amounts of area, they are an obvious area to explore size reduction.

At the same time, receiver architectures are evolving with the ability for analog-to-digital converters (ADCs) to sample at higher input frequencies. With a higher ADC input frequency, the constraints placed on filters in the signal chain have changed. In general, this trend means a relaxation of rejection requirements for filters, which opens them up to further size and tunability optimization.

To start this exploration, a general overview of RF signal chains and definitions can assist in explaining where and why filters are needed. Further, a review of traditional technologies can give insight into the status quo. Then, by comparing these traditional technologies vs. the latest product solutions, it becomes clear how system designers can easily achieve their goals.

RF Signal Chain Overview

A typical wideband signal chain covering 2 GHz to 18 GHz is shown in Figure 1. The basic theory of operation of this signal chain is the following. The antenna receives a broad spectrum of frequencies. There is a series of amplification, filtering, and attenuation control (the RF front end) before the frequencies are converted to an IF signal that the ADC can digitize. The filtering functions in this block diagram can be divided into four main categories:

- Preselector suboctave filtering
- Image/IF signal rejection
- LO harmonics
- Antialiasing

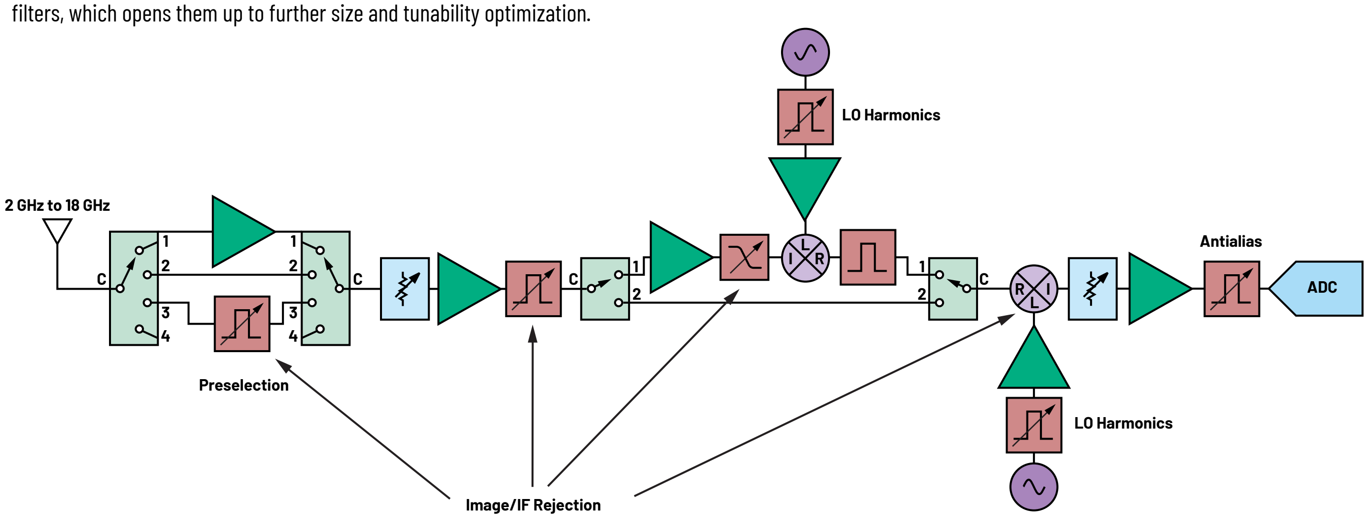

Figure 1. 2 GHz to 18 GHz receiver block diagram.

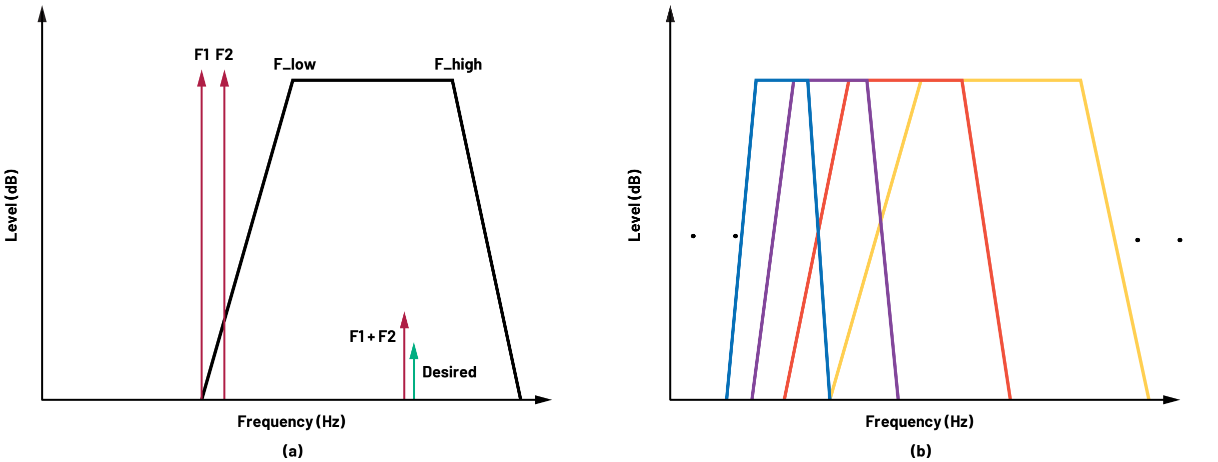

Figure 2. (a) Suboctave preselection mitigates IMD2 issues; (b) filter bands become wider as frequency increases.

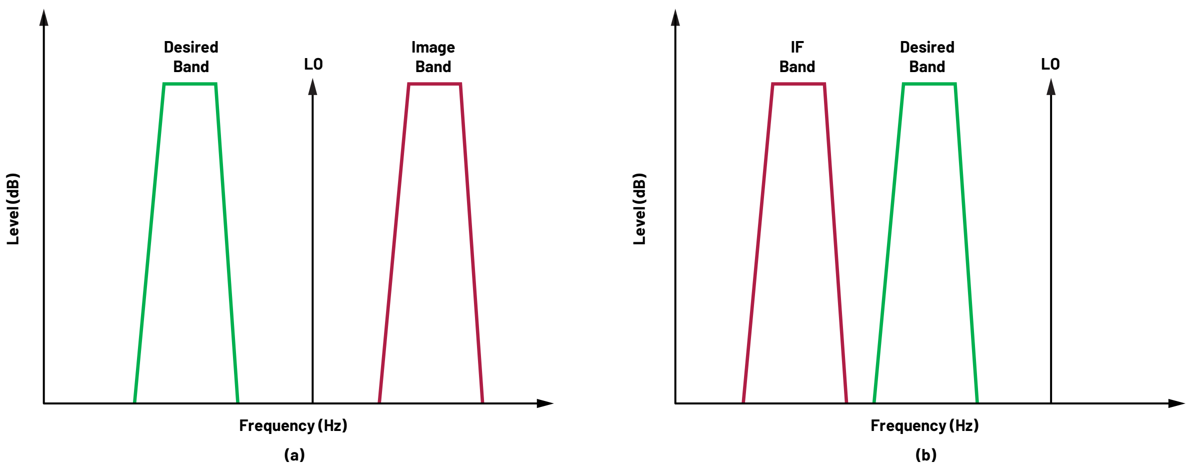

Figure 3. (a) An image band and (b) an IF band must be rejected before the mixer.

The preselector suboctave filtering needs to be near the beginning of the signal chain and is used to address second-order intermodulation distortion (IMD2) spurs that can show up in the presence of interferer signals (also known as blockers). This occurs when two out-of-band (OOB) spurs add or subtract and create a spur that falls in band, potentially masking a desired signal. A suboctave filter removes these interfering signals before they can hit a nonlinear component in the signal chain (such as an amplifier or mixer). Often, the absolute bandwidth requirement for the suboctave filter becomes narrower as the center frequency reduces. For example, the first band in a 2 GHz to 18 GHz signal chain may only cover 2 GHz to 3 GHz and would need good rejection at 1.5 GHz on the low-side (F_high/2) and at 4 GHz on the high-side (F_low × 2), whereas the highest band in the signal chain may cover 12 GHz to 18 GHz, with good rejection at 9 GHz on the low-side and at 24 GHz on the high-side. These differences mean many more filters are needed to cover lower frequencies bands than high frequency bands. A frequency spectrum example of the preselector filtering is shown in Figure 2.

The image/IF rejection filtering is typically further down the signal chain, between the LNA and the mixer. It is used to reject the image frequencies and unwanted IF frequencies. The image is a frequency band that, when present at the mixer input, will generate signals equal in amplitude to the desired signals at the mixer output. Image mitigation can be achieved from several components in the signal chain, such as preselector filters, dedicated image reject filters, and image rejection from single-sideband (SSB) mixers. IF signal rejection is required to knock down spectrum at IF frequencies before the mixer to avoid them from leaking directly across the mixer and showing up as unwanted spurs. A frequency spectrum example of the unwanted image and IF bands is shown in Figure 3.

Depending on the circuitry used to generate the LO, filtering requirements may vary at this point in the signal chain. The desired signal feeding the LO port of the mixer is a clean sine wave or a square wave. Often, the LO circuitry creates subharmonics and harmonics of the desired LO signal. These unwanted signals (see Figure 4) need to be rejected before they reach the mixer to avoid generating unwanted MxN spur products. If the LO signal is at a single frequency, then a fixed band-pass filter is sufficient and can be optimized to pass only the desired signal. In wideband signal chains, a tunable LO signal is usually implemented and therefore requires either a set of switched filters or a tunable filter.

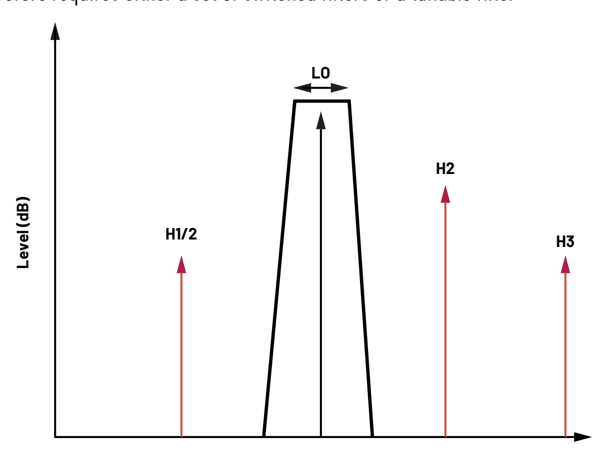

Figure 4. LO harmonic filtering.

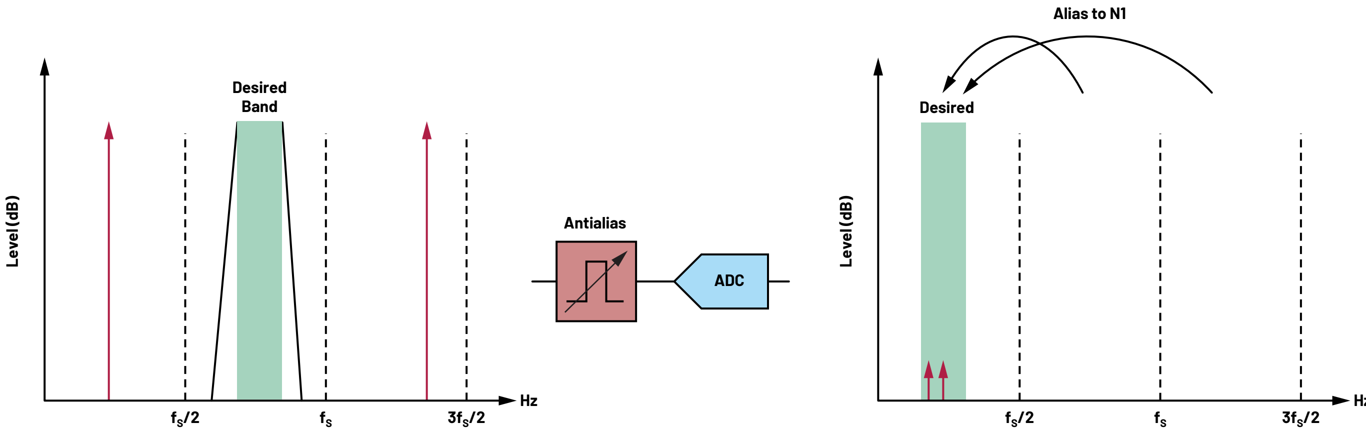

Figure 5. Aliasing in the ADC can cause interfering signals to show up in a band if there is insufficient rejection.

When sampling with an ADC, the system designer needs to select which Nyquist zone to digitize. The first Nyquist zone ranges from DC to $f_S/2$ (where f_S is the sample rate of the ADC). The second Nyquist zone is from $f_S/2$ to f_S and so forth. Antialiasing filters are used to reject interferer signals in Nyquist zones adjacent to the desired Nyquist zone. Interferers at this location in the signal chain can come from various sources, such as the MxN spurs generated in the mixer, the downconverted signals adjacent to the desired signals, or from harmonics generated in the IF signal chain. Any unwanted signals that are input to the ADC will alias into the first Nyquist zone when performing digitization. A frequency spectrum example of the unwanted aliasing signals is shown in Figure 5.

Blocker Signals

In RF communications systems, a blocker is a received and unwanted input signal that degrades the gain and signal-to-noise-and-distortion (SINAD) ratio of the desired signals of interest. A blocker can be a signal that masks the desired signal directly or creates spurious products that mask the desired signal. These unwanted signals could be the result of unintentional or intentional interference. In the former case, it comes from another RF communications system operating in the adjacent frequency spectrum. In the latter case, it comes from nefarious electronic warfare (EW) systems designed to intentionally disrupt RF communication or radar systems. A frequency spectrum example of a blocker signal and a desired signal is shown in Figure 6.

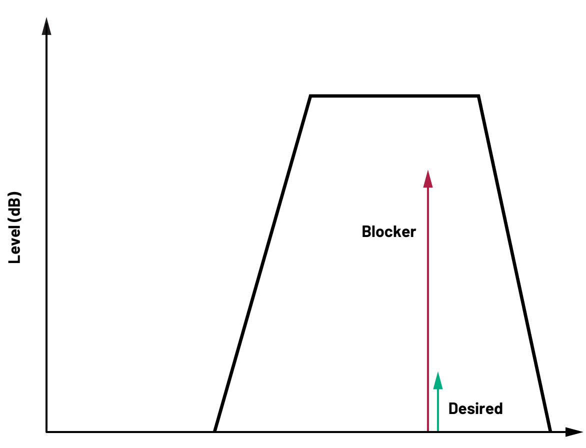

Figure 6. Desired and blocker signals.

Many RF components exhibit weakly nonlinear memoryless behavior. This means they can be approximated by a low order polynomial. For example, a wideband frequency amplifier could be modeled by the odd-order polynomial that includes only the first-order and third-order terms:

$$y(t) \approx \alpha_1 x(t) + \alpha_3 x^3(t) \tag{1}$$

When there are two incident signals present at the input of the amplifier, within the operating frequency range, as might be the case with a desired signal, ω_1, and a blocker signal, ω_2, the input signal can be described as:

$$x(t) = Acos(\omega_1 t) + Bcos(\omega_2 t) \tag{2}$$

Substituting the input equation into the odd-order polynomial results in an output of:

$$y(t) \approx \left(\alpha_1 + \frac{3}{4}\alpha_3 A^2 + \frac{3}{2}\alpha_3 B^2\right) Acos(\omega_1 t) + \ldots \tag{3}$$

When the amplitude of the desired signal is much less than the blocker signal, A << B, then the polynomial in Equation 3 further reduces to:

$$y(t) \approx \left(\alpha_1 + \frac{3}{2}\alpha_3 B^2\right) Acos(\omega_1 t) + \ldots \tag{4}$$

Given the simplification in Equation 4, the desired signal amplitude is now a strong function of the blocker signal amplitude, B. Since most RF components of interest are compressive, the alpha coefficients must be of opposite sign,[1] such that $\alpha_1\alpha_3 < 0$. The result of the two statements mentioned previously is consequential, in that the gain of the desired signal goes to zero for large blocker signal amplitudes.

Filter Definitions

To solve the problem of unwanted signals in RF communications systems, engineers have relied upon filters to reduce these signals and preserve the desired signals of interest. In simple terms, a filter is a component that allows the transmission of frequencies within a pass band and rejection of frequencies in a band-stop.[2]

Usually, the insertion loss (dB) of a filter can be described as either low-pass, high-pass, band-pass, or band-stop (notch). This nomenclature refers to the allowable pass-band frequency response plotted vs. increasing frequency. Filters can further be categorized by their frequency response shape, such as pass-band ripple, stop-band ripple, and how fast they roll-off vs. frequency. For illustrative purposes, Figure 7 shows the four primary filter types.

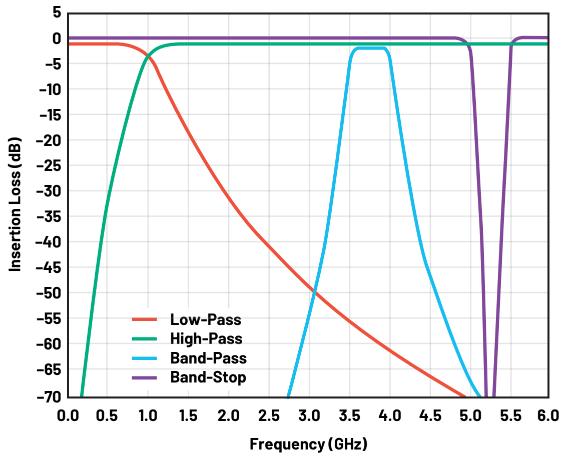

Figure 7. Filter shapes by type.

Besides insertion loss, another important characteristic of filters is group delay, which is defined as the rate of change of transmission phase with respect to frequency. The units of group delay are time (seconds), and therefore this metric can be thought of as the transit time for a particular signal through the filter. The transit time by itself for a single frequency is typically of little consequence, but when a wideband modulated signal passes through a filter, the flatness of the group delay becomes important because it can distort the signal by introducing different time delays in the received signal. The equation for the group delay is given in Equation 5 where Θ is the phase and f is the frequency:

$$Group\ Delay\ (s) = gd = -\frac{d\theta}{df} \times \frac{1}{360} \qquad (5)$$

Classical filter types with distinct insertion loss and group delay characteristics are Butterworth, Chebyshev, elliptic, and Bessel. Each one is usually defined by an order number that describes how many reactive elements are in the filter. The higher the order number, the faster the frequency roll-off.

When considering similarly ordered filters, the Butterworth style offers a maximally flat pass-band response at the expense of frequency roll-off, whereas a Chebyshev filter has good frequency roll-off with some pass-band ripple. An elliptic filter (sometimes called the Cauer-Chebyshev) has more frequency roll-off than a Chebyshev filter, but consequently ripple in both the pass band and the stop band. The Bessel filter has maximally flat frequency and group delay responses, although with the worst frequency roll-off performance. For illustrative purposes, Figure 8 shows the ideal insertion loss and group delay for a fifth-order low-pass filter with a 3 dB frequency ($f_{3\ dB}$) of 2 GHz, allowable pass-band ripple of 1 dB, and stop-band ripple of 50 dB.

For systems where maintaining constant phase across frequency is important, such as radar systems, the group delay flatness across the band of interest is critical to avoid unexpected phase deviations on the pulse being received. Given that received signals can span 1 GHz or more, the group delay flatness across a wide bandwidth should be minimized. A rule of thumb is to keep the group delay flatness to <1 ns but this will depend on the system's tolerance for the phase deviation. The plots in Figure 9 show an example of a filter with a group delay flatness of 2.24 ns and 0.8 ns, respectively. Observation of the plots shows a much more consistent phase change across frequency for a flatter group delay.

Lastly, the quality factor (Q factor) of reactive elements used to design filters is an important attribute that can impact performance. The quality factor is defined as the ratio of reactive impedance to the series loss resistance for a particular circuit element. It is a function of the technology process and the physical area used for implementation. Higher quality factors allow for sharper frequency responses and less insertion loss.

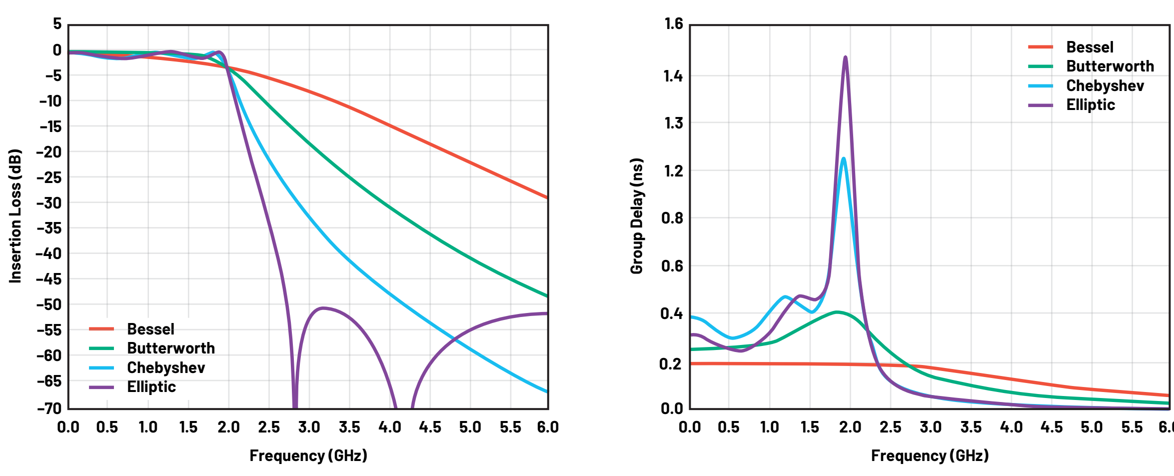

Figure 8. Insertion loss and group delay for fifth-order low-pass filters.

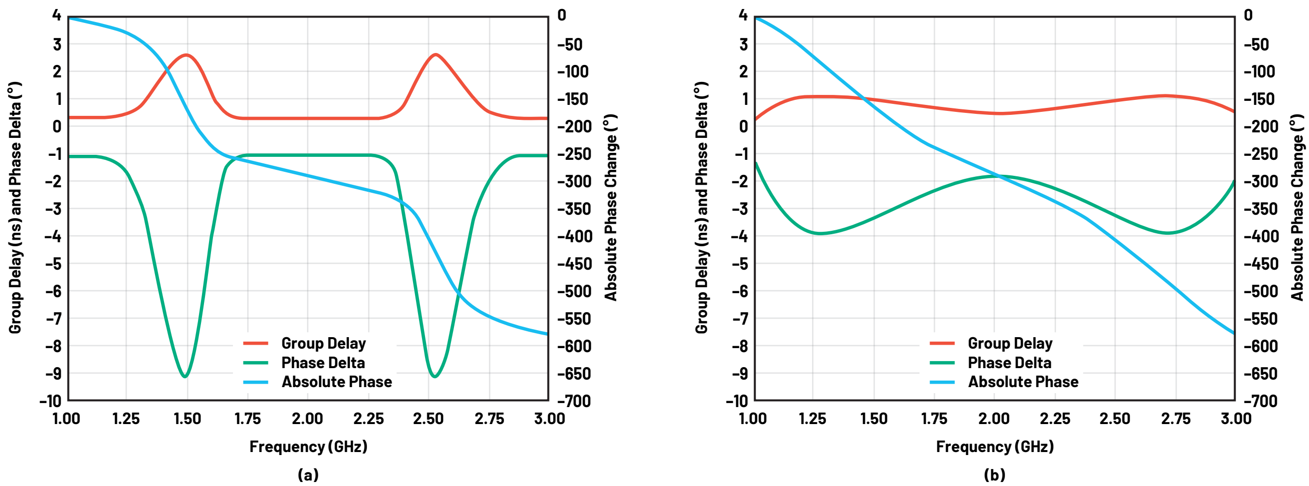

Figure 9. The group delay flatness affects the deviation from the linear phase: (a) showing 2.24 ns group delay flatness vs. (b) showing 0.8 ns flatness resulting in more consistent phase change vs. frequency.

Traditional Filter Technologies for RF Communications

When designing a filter for RF communications systems, there are a variety of technologies available to implement the classical filter types. Traditionally, RF engineers relied upon discrete lumped element implementations with surface-mount components or distributed element filters containing transmission lines printed on PCB materials. However, in recent years, filters have been designed on semiconductor processes that allow for precise temperature stable reactive components with improved quality factors. Additionally, the semiconductor processes allow for switched and tunable reactive elements that can be more challenging to implement in the discrete lumped element implementations. There are other technologies as well, such as the bulk acoustic wave (BAW), surface acoustic wave (SAW), low temperature cofired ceramic (LTCC), cavity filters, or ceramic resonators.

Trade-offs exist with each approach and technology:

Lumped LC filters are implemented with surface-mount inductors and capacitors on a PCB. The benefit is the ease of assembling and then changing the performance of the filter by swapping out values.

Distributed filters are designed as resonant pieces of a transmission line implemented on a dielectric (either integrated into the PCB or standalone on a separate dielectric) and are oriented to behave as quasi-inductors or quasi-capacitors in some frequency range. They exhibit periodic characteristics. In some cases, lumped components are added to improve/miniaturize the distributed filter.

Ceramic resonator filters use multiple ceramic resonators (which are a distributed element) that are coupled via lumped elements. The coupling element is typically a capacitor but sometimes inductors are also used. This type of filter is a hybrid of distributed and lumped elements.

Cavity filters are implemented with distributed elements (rods) enclosed within a conducting box. They are known for being able to handle high amounts of power with little loss but at the expense of size and cost.

BAW and SAW technologies can provide excellent performance but they tend to be frequency selective and not suitable for wideband applications.

LTCC filters are implemented by combining many layers of distributed transmission lines within a ceramic package, which is similar to a distributed filter and can serve a number of applications but are fixed. Since they are 3D stacked, they end up taking little space on the PCB.

Lastly, filters integrated into semiconductors support a wide frequency range with recent advances in semiconductor performance. The ability to easily integrate digital control elements into these components aids in the adoption into software-defined transceivers. In general, the trade-off between performance and integration provides a compelling value to designers of wideband systems.

Table 1. Filter Type Comparison

	Frequency Range	Tunability	Size	Cost	Q-factor
Lumped LC	<6 GHz	Difficult to implement	Medium	$	Medium
Distributed	<50 GHz	Fixed	Medium	$$	Medium/high
Ceramic Resonator	<6 GHz	Fixed	Large	$$	High
Cavity	<40 GHz	Fixed	Large	$$$	High
SAW/BAW	<6 GHz	Fixed	Small	$	High
LTCC	<40 GHz	Fixed	Small	$	Medium
Semiconductor	<50 GHz	Digital tuning integrated	Small	$$	Medium

Latest Filter Solutions

Analog Devices has developed a new family of digitally tunable filter products that utilize an enhanced semiconductor process along with industry friendly packaging techniques. This technology results in small, high rejection filters that alleviate the blocker issues that arise in a receiver. These filters are designed to be highly configurable by standard serial to parallel interface (SPI) communication, with fast RF switching speeds. Additionally, ADI has incorporated a 128-state lookup table within each chip to allow for quickly changing filter states for fast frequency hopping applications. The combination of fast tuning with high rejection and wide frequency coverage enables the next generation of receiver applications operating in adverse spectral environments.

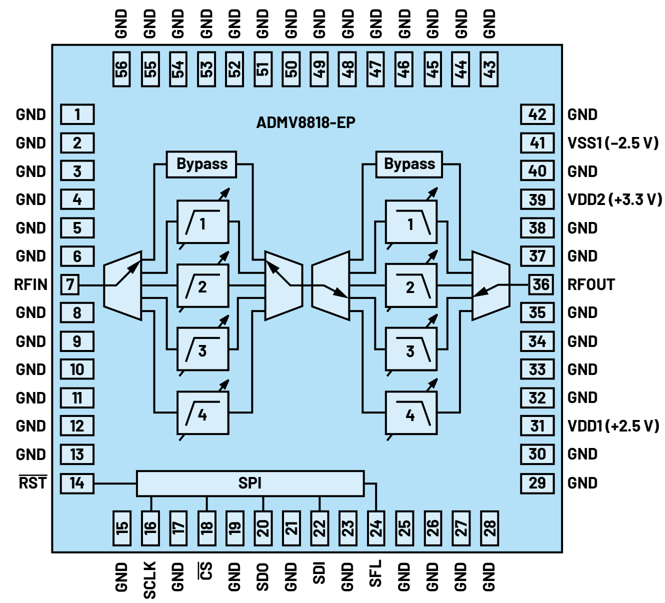

Figure 10. ADMV8818 functional block diagram.

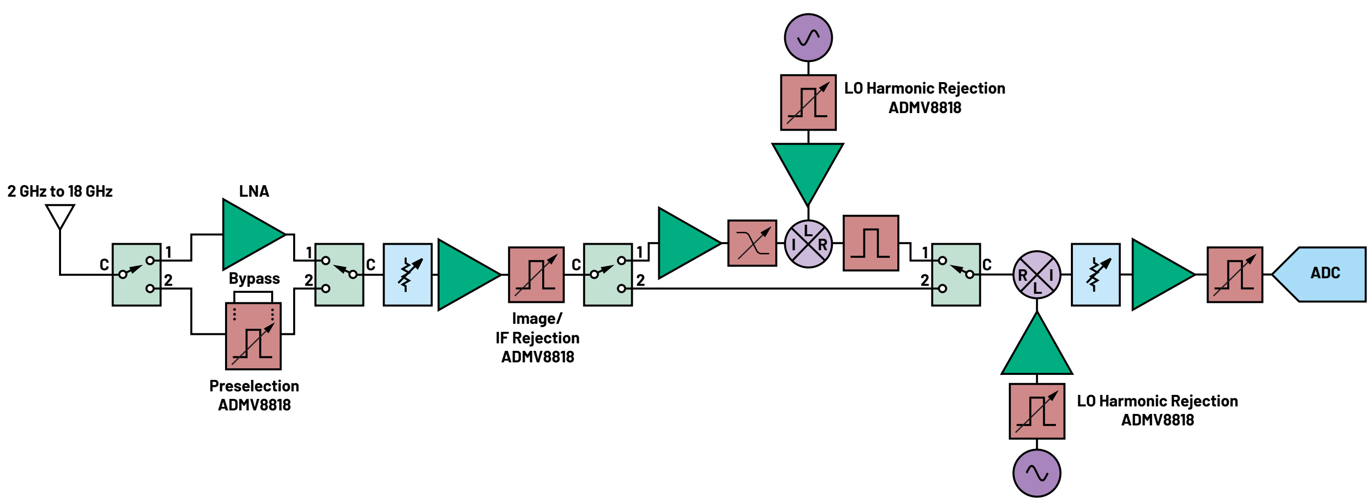

Figure 11. A block diagram of a 2 GHz to 18 GHz receiver using ADMV8818 as a preselector and image filter.

The latest products to be introduced using this technology are the ADMV8818, which has four high-pass and four low-pass filters operating from 2 GHz to 18 GHz, and the ADMV8913, which has a high-pass filter and low-pass filter operating in the 8 GHz to 12 GHz frequency range.

The ADMV8818 is a highly flexible filter in a 9 mm × 9 mm package that can achieve tunable band-pass, high-pass, low-pass, or bypass response between 2 GHz and 18 GHz. The chip consists of two sections: the input section and the output section. The input section has four high-pass filters and an optional bypass that is selectable by the two RF_{IN} switches. Similarly, the output section has four low-pass filters and an optional bypass that is selectable by the two RF_{OUT} switches. Each of the high-pass and low-pass filters are tunable with 16 states (4 bits of control) to adjust the 3 dB frequency ($f_{3\,dB}$). Figure 10 shows a functional block diagram of the ADMV8818.

Thanks to its rapidly reconfigurable flexible architecture and small form factor, the ADMV8818 provides full coverage over the 2 GHz to 18 GHz band without any dead zones. The ADMV8818 can be configured as a suboctave preselector filter, image, or IF filter. When configured in a signal chain as shown in Figure 11, the receiver can maintain high sensitivity with the ability to switch to the ADMV8818 as a preselector in the presence of a larger OOB signal.

For example, if a signal of interest is being received near 9 GHz but a strong OOB blocker is present at 4.5 GHz, then that blocker signal can cause harmonics to show up near the desired 9 GHz signal, preventing operation. Configuring the ADMV8818 as a 6 GHz to 9 GHz band-pass filter would allow for a wideband signal to pass through while properly knocking down the level of the blocker before it can cause harmonic issues to crop up in the nonlinear elements of the signal chain. An S-parameter sweep of the ADMV8818 configured for this case is overlaid with blockers and shown in Figure 12.

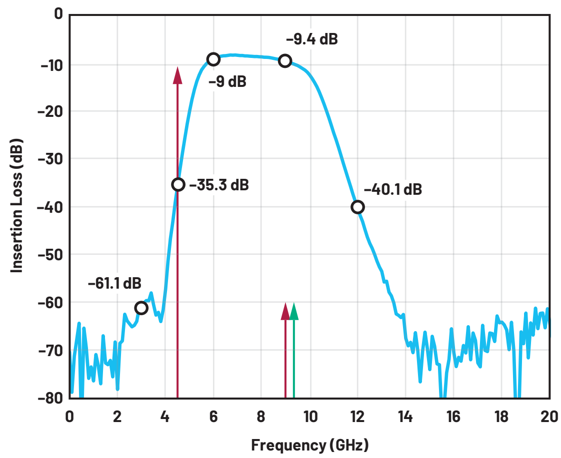

Figure 12. ADMV8818 configured as a 6 GHz to 9 GHz band-pass filter. The filter rejects F2 – F1, F1 + F2, F/2, and F × 2 spur products.

A size comparison of a typical 2 GHz to 18 GHz preselector block is shown in Figure 13. In this comparison, the switched fixed filter preselector bank is implemented with distributed filter technology on a ceramic substrate. The size is estimated based on commercially available filter technology. Eight-throw switches are included in the estimate to compare equivalent functionality. The tunable BPF shown is the ADMV8818 that covers the same frequency range and offers full tuning flexibility over the switched filter bank. The area savings of the ADMV8818 vs. a switched filter bank is greater than 75%. The preselector functionality in a receiver signal chain typically takes up a sizeable portion of the overall size of the system, so this area savings are critical in size limited EW systems that have the flexibility to trade off size with performance.

The ADMV8913 is a combination of high-pass and low-pass filters in a 6 mm × 3 mm package, and it is specifically designed for operation in the 8 GHz to 12 GHz frequency range (X band) with low insertion loss of 5 dB. The high-pass and low-pass filters are tunable with 16 states (4 bits of control) to adjust the 3 dB frequency ($f_{3\,dB}$). Additionally, the ADMV8913 incorporates a parallel logic interface that allows for setting the filter states without the need for SPI communication. This parallel logic interface can be quite useful for systems that require fast filter response times because it eliminates time needed for the SPI transaction. A functional block diagram of the ADMV8913 is shown in Figure 14.

Modern X band radar systems, whether they employ mechanically steered antennas or high channel count phase array beams, often rely upon filtering solutions that are compact in size, have low insertion loss, and are easily configurable. The ADMV8913 is ideally suited for this application thanks to its low insertion loss, small form factor, and flexible digital interface options (either SPI or parallel control). These features allow it to be placed close to the front of these systems to ensure optimum performance, while reducing integration complexity.

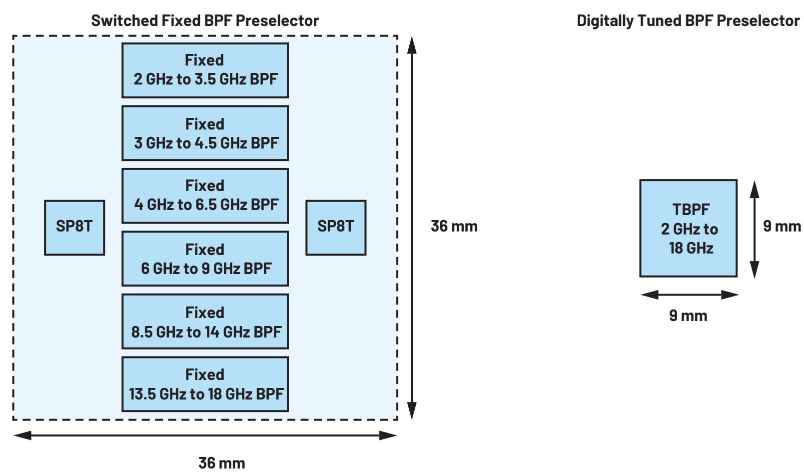

Figure 13. Fixed switched 2 GHz to 18 GHz BPF (left) vs. digitally tunable 2 GHz to 18 GHz BPF (right). The area savings are greater than 75%.

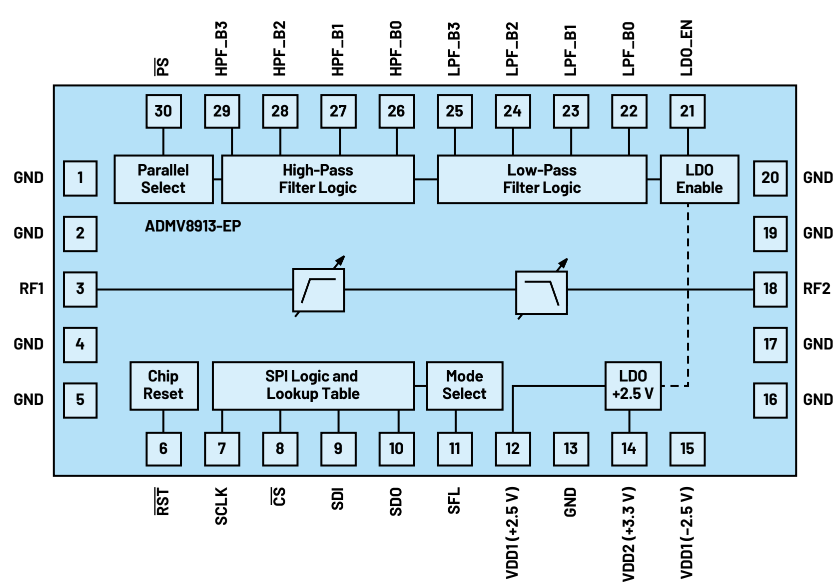

Figure 14. ADMV8913 functional block diagram.

Conclusion

The design considerations for an RF front end for a wideband receiver are numerous. The front end must be designed to handle difficult blocker scenarios, which are unpredictable, while also detecting low level signals. Being able to dynamically adjust the front-end filtering performance to handle these blocker signals is a critical feature for RF front ends. The new digitally controlled tunable filter IC product offerings from ADI provide industry-leading performance with enhanced digital functionalities addressing many front-end applications. These two new products are just the first of many exciting new developments in the digitally tunable filter portfolio. For customers interested in learning more about these product offerings, please visit the Digital Tunable Filters product page to see the latest data sheets or reach out your local representative to discuss a particular end application.

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About the Author

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David Mailloux is a product applications engineer within the RF and Microwave Business Unit at Analog Devices. He received both a bachelor and master of science degree in electrical engineering from the University of Massachusetts Lowell in 2010 and 2012, respectively.

From 2010 to 2015, his experience includes working for Hittite Microwave and Symmetricom (now Microchip Technology). He has experience designing oscillators both at the semiconductor and the module level, and his theoretical background is complimented by adept laboratory practices.

In 2015, he joined ADI as a product applications engineer supporting highly integrated up/downconverters and tunable filter products. Additionally, his technical support areas have included voltage controlled oscillators, phase-locked loops, frequency dividers, and frequency multipliers.