SPECTRUM CONTROL

Whitepaper

Solving Modern Spectrum Management Challenges with Custom Microwave Filters

Abstract

In the rush to deploy the latest radar or radio technology, spectrum management is often an afterthought. However, spectrum regulations, cosite interference, and external interference can often render even the most sophisticated communications or sensing system inoperable. This is equally true for commercial wireless communications as it is for satellite/aerospace communications and sensing, as well as military/defense radar and communications. As spectrum management issues are often discovered after deployment has begun, redesigning of a system is likely far too expensive and would incur unacceptable delays. Hence, the solution is to commission customer microwave filter solutions that mitigate interference and overcome EMC performance issues.

Introduction

RF/microwave/millimeter-wave filters are a key enabling technology for existing and emerging wireless applications. Filters are also essential in protecting the spectrum from unnecessary interference and ensuring that critical frequency bands are guarded from existing and emerging wireless services. Filters are found throughout the wireless system/devices signal chain, and are especially important at the output of transmitters and the input of receivers, where they attenuate out-of-band signals and improve the signal quality, or just reduce the interference power level.

As the bulk of the efforts associated with spectrum management and compliance with standards is usually performed near the end of a design cycle filters for spectrum management are often an afterthought or an after-the-fact. This is because some devices or systems may pass compliance testing but may still be found to deviate from the standard and generate interference or face interference from other wireless devices in their installed environment.

Hence, there is sometimes a need for sourcing custom filter solutions for improving a device/systems frequency response. This whitepaper describes several emerging and accelerating trends that are impacting spectrum management for the United States, and around the world. Furthermore, this whitepaper describes key aspects of filter performance, performance tradeoffs, filter technology tradeoffs, and what type of custom filter products are available to solve existing and new spectrum management challenges.

Microwave/Millimeter-wave Filter Trends

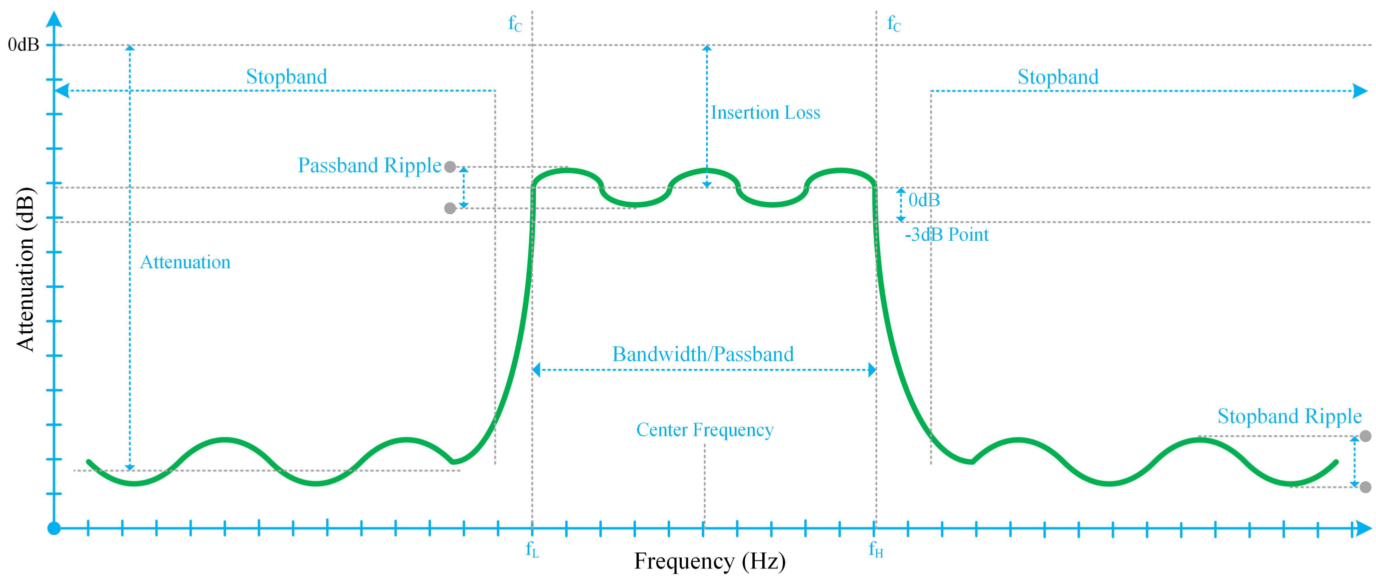
Wireless services and technologies are proliferating around the globe. From defense to consumer applications, the operational frequencies of wireless services are expanding throughout the sub-6 GHz and emerging into millimeter-wave frequencies like never before. This rapid expansion, mixed with the increased spectrum congestion and interference concerns for critical systems in the sub-6 GHz spectrum, is leading to many applications researching technologies operating in the higher millimeter-wave spectrum. The rapid development of higher bandwidth and lower latency technogies is also piquing the interest of technology developers and defense contractors in developing high-reliability /mission-critical wireless technologies for defense and industrial systems.

There are three main trends currently impacting microwave and millimeter-wave spectrum management, emerging 5G technologies, a millimeter-wave migration, and the growth of mission critical applications using wireless communications and sensing technology. Essentially, sub-6 GHz 5G technologies up to 5 GHz are beginning to be deployed around the world, with planned wide scale urban and factory deployments of millimeter-wave 5G technologies. Furthermore, other wireless communication technologies are also seeing greater adoption and further cluttering the spectrum below 6-GHz. This is causing many sensitive applications and critical applications to evaluate higher frequencies for their applications to avoid the clutter, enable higher bandwidth use cases, and ensure reliable and low-latency operation.

Hence, the threat of spectrum clutter and interference, along with the potential benefits of higher bandwidth and higher frequency bands, is encouraging research and development of a variety of applications well into the millimeter-wave frequencies. This is also leading to the reforming of several use cases, some requiring strict spectrum management guidelines, and some that even the U.S. Department of Defense (DoD) and other agencies are concerned that they may threaten national security due to the potential for interference of critical radio-navigation services.

Filter Performance Parameter Overview

Though designing a filter that meets certain performance criteria may be challenging, specifying a filter just requires an understanding of the performance budgets of a signal chain and/or what type of interference may need to be mitigated. The following is a description of several of the top filter performance parameters to keep in mind when specifying a filter.



A bandpass filter response diagram

Insertion Loss & Attenuation/Rejection

The insertion loss or attenuation/rejection of a filter is the amount of signal energy lost as a signal passes through the filter. Insertion loss is typically referencing the signal loss through the passband while attenuation/rejection is generally used to refer to the relative signal loss in the stop band(s) compared to the passband. It is generally desirable to have a filter response with limited insertion loss and attenuation adequate to reduce signal levels in the stopband to a maximum specified signal power.

% Bandwidth

Percent bandwidth (%BW) is a relative figure of merit that compares the passband bandwidth to the center frequency. This is frequently calculated as the passband bandwidth in hertz divided by the center frequency in hertz.

Passband Frequency (Bandwidth)

The passband frequency range is the portion of a filter’s response where the signal loss is the lowest. The passband, or bandwidth, of a filter is usually measured from the cutoff frequency points where the insertion loss of the filter degrades by -3dB from the lowest loss (cutoff frequency).

Stopband Frequency

The stopband frequencies, or stopband, is the frequency range where the filter’s response provides the highest attenuation, or the desired minimal rejection. Generally, the stopband(s) are only referred to within the filter's specific frequency operation range, as some filter technologies may experience a degradation in attenuation beyond the operating frequency range that leads to attenuations above the desired minimum rejection.

Passband and Stopband Ripple

The passband and stopband ripple is a measure of the deviation of the passband and stopband response from the average passband or stopband response, respectively. Some applications may require ripple specifications, usually in the passband, that meet a certain level of “flatness” to ensure the signal amplitude of passband signals is consistent as possible.

Group Delay

The group delay is the amount of time it takes for a given signal to travel through a filter. Ideally, a signal of a finite time duration would travel through the filter with the same time delay, regardless of frequency, to avoid signal distortion. In real filters, there is a frequency dependent time delay, a phenomenon known as group delay.

Peak Power and/or CW/average Power

Depending upon the filter technology and design, there is a maximum peak power handling and maximum continuous wave/average power handling capability. Exceeding this maximum may result in derating of the filter performance, permanent degradation of the filter response, or filter failure.

Technology

There are a variety of filter technologies, each with its benefits and drawbacks. Generally, the other specifications of the filter provide boundaries and limit the selection of certain filter technologies into a practical few. For instance, cavity filters tend to exhibit good insertion loss, rejection, and power handling, but also tend to be larger and heavier than other filter technologies.

Size & Weight

Every application has size and weight requirements based on the platform and installation of the system. Certain filter design choices, specifications, and filter technology impact the size and weight of a filter, which provides some limitations to what is practical and will meet size/weight specifications. For instance, printed and SAW filters are generally smaller than other filter technologies, but exhibit lower power handling and have lower performance than other larger and heavier filter technologies.

Cost

The various filter technologies all present different cost parameters. Moreover, the design complexity and material decisions of a filter also influence the overall cost of a custom filter project and the price-per-filter. A project's budget will determine what filter technologies and other performance limitations.

Microwave Filter Performance Trade-offs

Like with any practical RF components, when designing or determining performance priorities, there are trade-offs to consider with microwave/millimeter-wave filters. Essentially, each of the key performance parameters of filters are related to the other parameters. Hence, specifying a single filter performance parameter often also sets limitations on other performance parameters, which further depend on the complexity, typology, and technology of the filter. The following is a brief discussion of several of the trade-offs to consider while prioritizing key filter performance parameters.

Insertion Loss Versus Q-Factor

Generally, the insertion loss in the passband of the filter response is proportionally related to the Q-factor. A filter with a higher Q-factor will also exhibit a better insertion loss metric (closer to 0 dB). As the Q-factor of a filter drops the insertion loss also drops, though not in a linear relationship as the insertion loss lowers more rapidly for lower Q values. Moreover, a filter with a lower Q-factor will also exhibit more "rounded" corners of the passband, i.e. less "sharpness". Aside from having lower insertion loss at the passband edges causing potential issues with modulations that require consistent amplitude in the passband, other modulations that use the entirety of the passband will also experience signal integrity issues with roll-off in the passband.

Rejction Attenuation Versus Insertion Loss

In the case of most filters, rejection and insertion loss are related in that achieving a greater rejection also comes at the cost of lowering the insertion loss (more negative dB). As a higher insertion loss is typically desirable, the highest acceptable rejection is what often dictates the insertion loss and may require a designer to choose various typologies or technologies that enable an acceptable insertion loss and rejection figure.

Phase Group Delay Versus Rejection Attenuation

The group delay of a filter is highly affected by the filter typology and other filter performance factors. Generally, the higher the order a filter, the greater the group delay. Hence, if a greater order of filter is used to enhance the rejection, the group delay is also being increased. Depending on the application, a designer may need to limit the filter order, and hence rejection and selectivity, to ensure the group delay stays below a desired limit

Group Delay Versus % Bandwidth

The group delay is also generally related to the % Bandwidth and selectivity. A narrower filter will generally have a higher group delay than a broader filter with lower selectivity. Therefore, group delay may be a limiting factor in how narrow a filter can be designed for a given application.

Selectivity Versus % Bandwidth Versus Insertion Loss

Designing filters with wide bandwidths and "steep skirts", or more selectivity, has a directly negative impact on insertion loss performance of a filter. Hence, insertion loss must be sacrificed to enable wider bandwidths with high selectivity. A higher insertion loss means lower signal power at the output of the filter and may require additional signal amplification before the filter to compensate for this loss. As increasing the signal strength also increases the noise and introduces non-linearities, there are other considerations to compensate for high insertion loss in a filter.

Ripples Versus Selectivity

High selectivity and low ripples are generally desirable in a filter. However, ripple and selectivity generally scale together, so to achieve greater selectivity requires increasing the ripple variation. As this is undesirable, a critical ripple figure may limit the selectivity of the filter design.

% Bandwidth & Center Frequency Versus Cost

Generally, the closer the stopband is to the center frequency of the filter, the more complex a filter topology is required. The more complex a filter is, the greater the component count, assembly difficulty, quality testing, and other factors that ultimately impact the design and production time and cost. This is also the case for filters with a higher center frequency, as the higher the center frequency requires greater precision design, machining, and quality practices. In some cases, achieving a higher center frequency may also require the use of specialized materials, which can further increase cost and lead time.

Size Versus Power Handling

In order to handle higher average power ratings, a filter typically requires a larger footprint than a lower power handling version. The larger footprint also generally involves greater component and overall filter size and weight. To accommodate higher power handling other filter performance factors may also need to be sacrificed depending on the type of filter technology used.

Filter Technology Tradeoffs

Over the last several decades, many resonator technologies have emerged. With the advent of PCB technology and semiconductor technology, additional resonator technologies have also become viable. With appropriate design and fabrication practices, these resonator technologies can be used as the backbone of microwave/millimeter-wave filters. What is crucial for all

	Lumped Element	Cavity	Ceramic (Coaxial)	Tubular	Waveguide	Suspended Substrate	Printed (Planar)	SAW
								
Frequency Range	0.1 MHz 8 GHz	300 MHz 30 GHz	500 MHz 4 GHz	30 MHz 20 GHz	2 GHz 50 GHz	500 MHz 40 GHz	500 MHz 20 GHz	20 MHz 2600 MHz
Performance	Medium	High	Medium	High	High	Medium High	Low	Medium
Size	Small	Medium to Large	Small	Medium to Large	Medium to Large	Medium to Large	Small	Small
Unit Cost	$$	$$	$	$$	$$$	$$$	$	$$
Power Handling	Medium	High	Medium	High	High	Medium	Low	Low

NOTE: These are general guidelines. Parameters may vary depending on specific requirements.

filter selection guide

high performance and high frequency filters is tolerance, reliability, and thermal stability.

However, each filter technology comes with their own nuanced electrical and physical characteristics. These factors lend certain filters advantages in some applications and disadvantages for others. The following is a brief introduction to filter technologies commonly used for microwave/millimeter-wave applications.

Cavity

Cavity filters are typically constructed of a conductive housing with quarter-wavelength metal metallic resonators inserted in the housing, which traps and air dielectric. The air dielectric and solid conductive housing and resonator construction enables Cavity filters to handle very high power. With precision machined components, Cavity filters can be made with very low insertion loss, high performance, and can readily be scaled for medium to large quantity manufacture.

Cavity filters can be made to accommodate narrow bandwidth to wide bandwidths depending on the configuration or can be made to have extremely rapid transition bands (steep skirts). Cavity filters are most often configured as coaxial connectorized models but may also be implemented with waveguide inter-connect. As the signal path of a Cavity filter is surrounded by shielding conductors, this type of filter minimizes interference from external signals. This type of filter tends to be much larger and heavier than comparable ceramic filters but is a highly versatile technology that can be readily customized due to its all metal construction.

Filter Types Compatible With Cavity Filters

- Band-pass
- Band-stop (notch filter)

Cavity Filter Responses

- Chebyshev
- pole-placed

Key Attributes of Cavity Filters

- 400 MHz to 40 GHz *Spectrum Control specific capability
- Low insertion loss & high rejection
- High selectivity Chebyshev and pole-placed responses
- Temperature stable options
- High power handling capability
- 0.1 to >60% bandwidth Low profile designs available
- Drop-in designs to 20 GHz
- Low intermodulation products
- Bimetallic resonators for superior temperature stabilization *Spectrum Control specific capability

Lumped-Element or Discrete LC Filters

Lumped-Element, or inductor-capacitor (LC) filters, are constructed of series and parallel resonant combinations of inductors and capacitors. As these filters use resonant structures that are based on inductors and capacitors, whose size dictates their frequency behavior, the size of a Lumped-Element filter is determined by the operating frequency. Hence, in some low frequency applications, these filters may be impractically large, or for higher frequencies the small size of the components may not be practically fabricated.

The versatility of Lumped-Element filters enables custom designs to address application specific needs, such as low insertion loss, high power handling, compact size, specific geometries, etc. Lumped-Element filters are limited in Q-factor by the inductors and capacitors in the design and are not easily designed to meet narrow bandwidths due to internal coupling between components. These filters may be designed with steep skirts, however, and can be fabricated as very high order filter designs.

Filter Types Compatible With Lumped-Element Filters

- Low-pass
- High-pass
- Band-pass
- Band-stop
- Diplexer

Lumped-Element Filter Responses

- Chebyshev
- Elliptical
- Vessel
- Butterworth
- Constant-impedance
- Constant Group Delay

Key Attributes of Lumped-Element Filters

- 300 kHz to 10 GHz operating frequencies *Spectrum Control specific capability
- DC to 20 GHz
- Versatile topologies and transfer functions
- Good for moderate to very wide bandwidths
- Can be connectorized surface mount (high frequency applications) for drop-in
- Easily multiplexed
- Temperature stable options
- RoHS compliant

Ceramic

Ceramic filters are constructed of quarter-wavelength ceramic resonators, whose size depends on the dielectric constant of the ceramic material used. The temperature stability of a ceramic filter also depends on the dielectric constant of the resonant, hence more thermally stable Ceramic filters tend to be larger in size. Ceramic filters exhibit good insertion loss, small size, and can be cost-effectively produced in mass quantities. Ceramic filters generally to be low power components and are relatively fragile compared to other filter technologies.

Filter Types Compatible with Ceramic Filters

- Band-pass
- Band-stop (notch filter)

Ceramic Filter Responses

- Chebyshev

Key Attributes of Ceramic Filters

- 400 MHz to 6 GHz *Spectrum Control specific capability
- 1 to 10% bandwidths
- 2 to 6+ sections with custom packages available
- Low cost and small size
- Good insertion loss relative to size
- Surface mount only (small size)
- Open frame or hermetically sealed for Hi-Rel applications
- Temperature stabilizing elastomers *Spectrum Control specific capability

SAW

Surface acoustic wave (SAW) filters are constructed of a piezoelectric crystal coupled with multiple conductors that are designed to resonate as designated frequencies. A SAW filter's response is determined by the number of electrodes and the geometry of the design and can be made to reach narrow bandwidths with very low group delay. Compared to other filter types, SAW filters have inferior insertion loss and power handling, but are much smaller and can be made inexpensively in mass quantities with an automated fabrication process.

Filter Types Compatible with SAW Filters

- Band-pass
- Duplexer

SAW Filter Responses

- Chebyshev

Key Attributes of SAW Filters

- Frequencies from 20 MHz to 2600 MHz *Spectrum Control specific capability
- Made using photolithographic processes i.e. not hand-made
- Extremely small size
- Through-hole and surface mount package options
- 0.04 to 60% bandwidths
- Hermetically sealed
- Can be made for low loss <2 dB
- Shape factors below 1.10:1
- Can be readily customized for a variety of application specific requirements

Suspended Substrate

Suspended Substrate filters are constructed using a printed circuit technology, which is highly versatile and can be used for both broadband and narrowband applications. Being a printed circuit technology, surface mounted and through hole PCB components can be readily integrated into the design, enabling combination filter technologies, such as adding lumped-element filter components.

Filter Types Compatible with Suspended Substrate Filters

- High-pass
- Low-pass
- Broadband Band-pass
- Multiplexers

Suspended Substrate Filter Responses

- Chebyshev
- Elliptic

Key Attributes of Suspended Substrate Filters

- 2 GHz to 40 GHz *Spectrum Control specific capability
- Higher Q than other planar technologies
- Hermetic designs possible
- Small size and compact form factor
- Ideal for broadband multiplexing
- Well suited to high shock and vibration applications
- Highly repeatable and ideal for matched filter applications
- Easily integrated with other components in IMAs
- Immersion silver plating for very low loss designs

*Spectrum Control specific capability

Tubular (Coaxial)

Tubular filters are precision machined mechanical structures with captivated high and low impedance transmission line elements terminated in coaxial connectors. This type of filter tends to be linear and comparatively narrow in construction, which is well suited to in-line installation with coaxial cable assemblies. The characteristic impedance of the tubular filter transmission line is tuned to yield the desired filter response, which is either low-pass or band-pass. These filters can be made comparatively mechanically rugged and tend to be very thermally and electrically stable. As Tubular filters can be made to handle high input powers, they are commonly used to suppress harmonics and high frequency interference as output filters for low and medium power transmitters.

Filter Types Compatible with Tubular Filters

- Low-pass
- Band-pass

Tubular Filter Responses

- Chebyshev

Key Attributes of Tubular Filters

- Frequencies from 30 MHz to 20 GHz *Spectrum Control specific capability
- Broad stopbands
- Low loss and high rejection
- High repeatability
- Ideal for harmonic rejection
- 2 to 50% bandwidths
- High power handling (designs to 5000 watts)
- Mature technology
- Low VSWR
- Temperature Stable

Printed (Planar/Microstrip/Stripline)

Printed filters are constructed of planar transmission lines developed on a substrate, such as common PCB substrates or precision microwave substrates. The performance of a Printed filter largely depends on the behavior of the substrate, which also impacts the size of the filter relative to the operating frequencies. Hence, there are generally size constraints that limit the use of microwave filters that are too low in frequencies and are too large, or the fabrication process isn't precise enough to practically fabricate a high frequency Printed filter.

This type of filter may be printed directly on the main board of a device, a daughter board, inserted as a surface mount component, or as a connectorized addition. Hence, these filters are relatively inexpensive to produce in large quantities. Typically. Printed filters exhibit adequate insertion loss and rejection

Filter Types Compatible with Printed Filters

- Band-pass
- Band-stop (notch filter)
- Low-pass
- High-pass

Printed Filter Responses

- Chebyshev
- Elliptical
- Bessel
- Butterworth

Key Attributes of Printed Filters

- Frequencies from 500 MHz to 20 GHz *Spectrum Control specific capability
- Very small size surface mount, drop-in, or connectorized packages
- Low cost
- Readily mass manufactured using automated processes
- Easily customized for application specific requirements

Waveguide

Waveguide filters are constructed of waveguide sections with precision placed metallic rods or E-/H-plane inserts within the waveguide. Precision mechanical construction enables waveguide resonator elements with extremely high Qs, comparable to cavity filters. Waveguide filters tend to exhibit very low insertion loss and high power handling, as the only components of these filters is air and precision metal.

Additional heat sinking structures can be directly machined into the body of a waveguide filter, further enhancing the power handling capability of this filter technology. Due to the banded nature of waveguide structures, waveguide filters yield relatively low % bandwidths, and can only be made in band-pass or band-stop configurations. Waveguide to coaxial adapters can be integrated into a waveguide filter, eliminating the need for additional adapters.

Filter Types Compatible with Waveguide Filters

- Band-pass
- Band-stop (notch filter)
- Diplexer

Waveguide Filter Responses

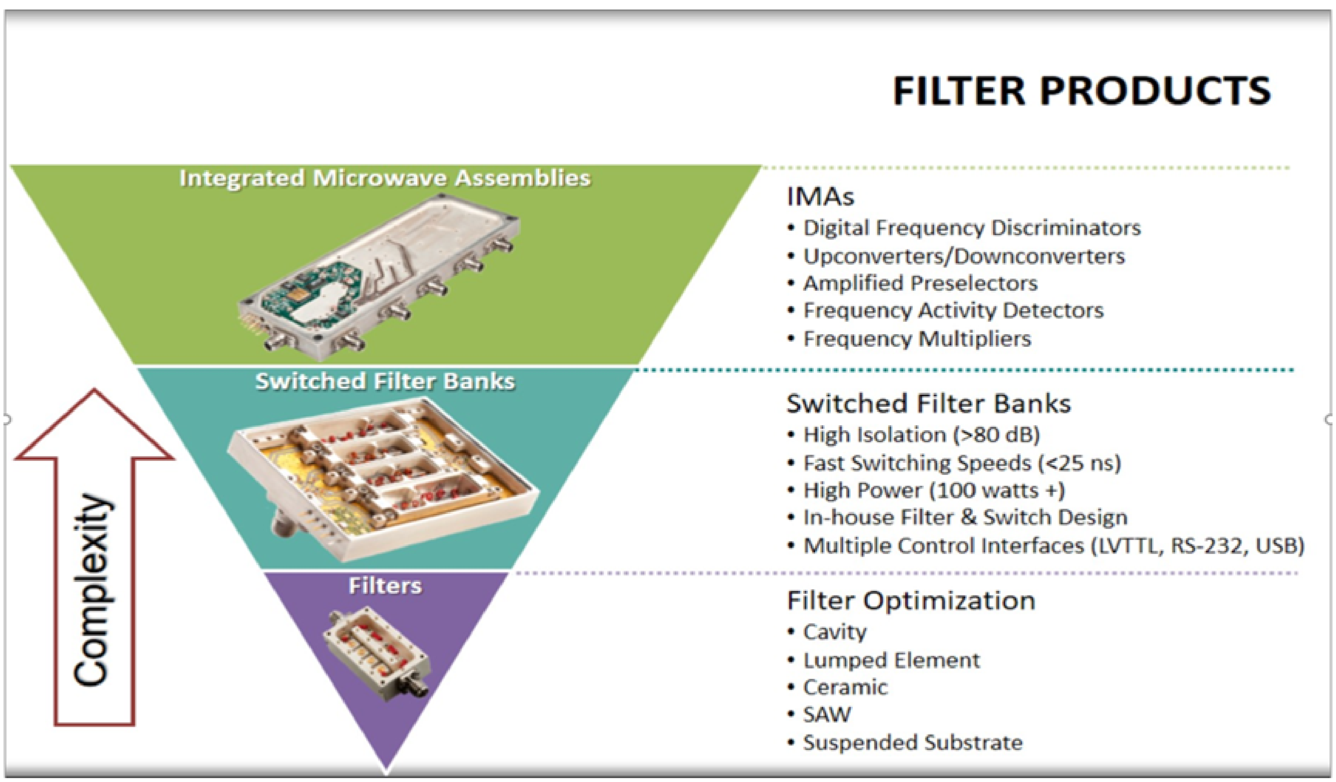
- Chebyshev

Key Attributes of Waveguide Filters

- Frequencies from 2 GHz to 50 GHz
- 0.1 to 10% bandwiths
- Extremely low insertion loss
- High power handling with integral heat sinks
- Can be coaxial connectorized (SMA, TNC, or Type-N) *Spectrum Control specfic capability

Custom Microwave Filter Design Considerations

The following is a brief description of the type of filter solutions commonly available for RF/microwave/millimeter-wave applications. It is the goal of this section to help technical professionals who are researching filter solutions to better understand the nuances of determining the necessary filter parameters and type of filter product they may require while solving a particular design challenge.



Types of Filter Products

There is a hierarchy of filter solutions, which includes an individual filter, a switched filter bank (SFB), or an integrated microwave assembly (IMA). Depending on the requirements of an application, inserting a simple filter designed to address the attenuation specifications of the design may be adequate. In other cases, however, a more complex IMA with integrated active elements, such as amplifiers and detectors, may be necessary to make a design succeed.

Filter

A single filter is a packaged or assembled component with a frequency response that allows a certain range of frequencies to pass (passband) through the devices with minimal insertion loss, and otherwise attenuates signal outside of the frequency band of interest (stop band). A filter is designed to either be a bandpass, bandstop/bandreject, lowpass, or highpass filter, that is either allowing a set range of frequencies pass with minimal attenuation, heavily attenuating a range of frequencies, allowing the lower frequency range pass, or passing the higher frequency range, respectively.

There are several filter technologies that can be employed, mainly cavity, lumped element, ceramic, surface acoustic wave (SAW), tubular, planar, and suspended substrate resonators/filters are the most relevant for performance microwave and millimeter-wave applications. The type of filter technology selected is often based on the response and trade-offs acceptable for the design. The trade-offs and nuances of the various filter technologies is further discussed in the third blog of this series, which can be found here {LINK}.

Switched Filter Bank

When a more complex filter function is required, mainly being able to change the filter response using a switchable control, a switch filter bank (SFB) is specified. SFBs consist of filters and the necessary switching/control elements to allow for the switching of the SFB's frequency response using control signals determined by the chosen control interface(s). PIN Diodes or FET switches are commonly used as the switching elements. SFBs may also be hermetically sealed with inert (Nitrogen) backfill. More advanced SFBs may also include integrated low-noise amplifiers (LNAs) and provide active gain compensation over temperature for applications where signal level stability is critical. SFBs are often used in military, high-end commercial, and research applications that require superior signal integrity, such as electronic intelligence (ELINT), electronic warfare (EW), automotive radar, complex wireless installations, and with RF simulators/test equipment.

Integrated Microwave Assembly

An Integrated Microwave Assembly (IMA) performs much more complex functions than an SFB and is composed of filters and other active elements. Example IMA solutions include digital frequency discriminators, upconverters/downconverters, amplified preselectors, frequency active detectors, and frequency multipliers. For instance, an IMA may perform both frequency response shaping and frequency translation, such as with a frequency multiplier or divider. IMAs are often integrated into precision systems used for a variety of applications, from military, wireless, aerospace, space, and naval. Generally, an IMA is needed in a situation where a compact and high performance component is required to support a system or subsystem function where individual filter, frequency translation, or amplification components are too bulky or their combined performance is too low.

Conclusion

There are now often too many interference and spectrum management concerns to account for to have absolute confidence that a new deployment or new technology will work reliably in the field. Hence, custom filter solutions are becoming increasingly important for the development and deployment of today's generation of wireless communications and sensing systems. Though the process of designing a custom filter is complex and requires skilled engineers, manufacturing capability, and advanced quality control procedures, this process can be made much simpler with the help of a custom filter solutions partner, such as Spectrum Control.

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