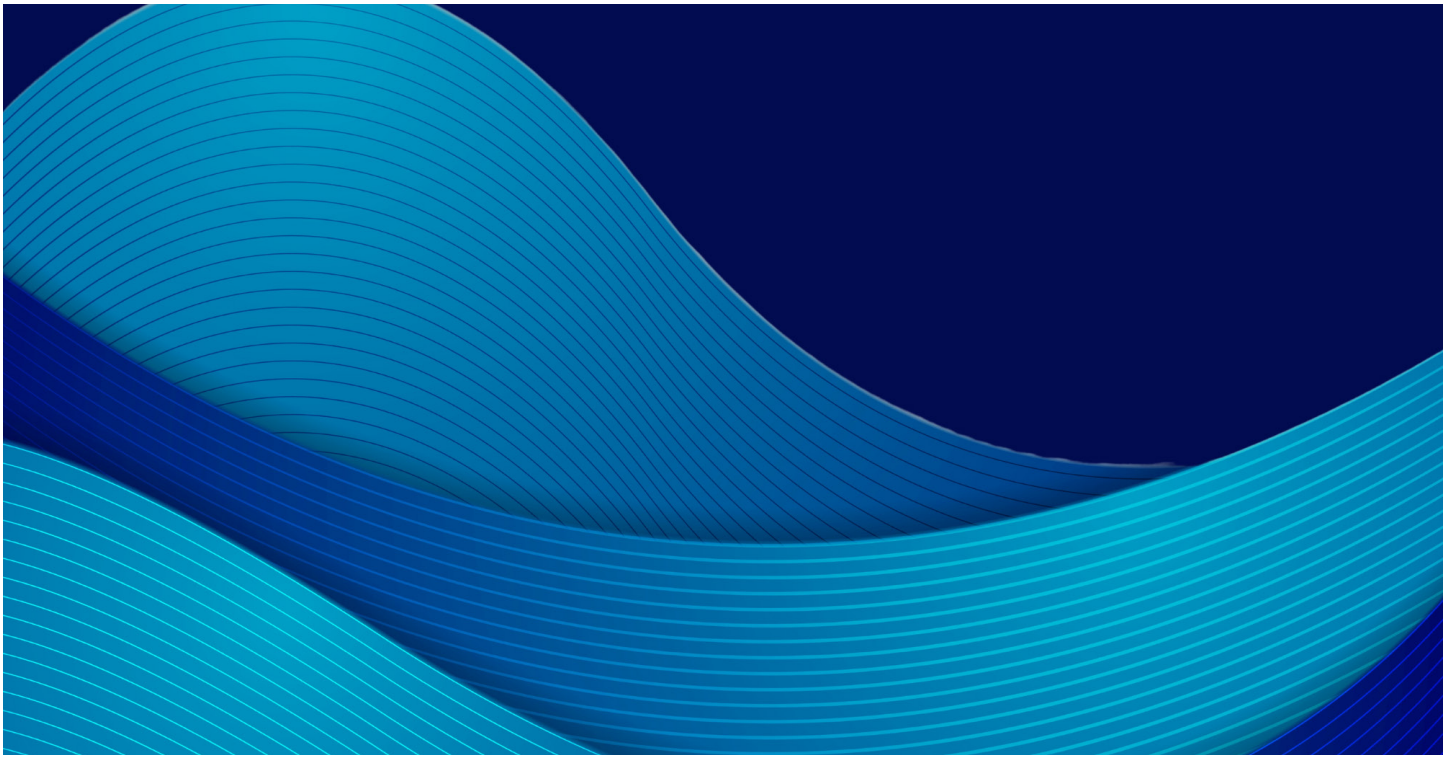
WHITE PAPER

knowles

IMPLEMENTING HIGH-PERFORMANCE FILTERS IN MILLIMETER WAVE APPLICATIONS

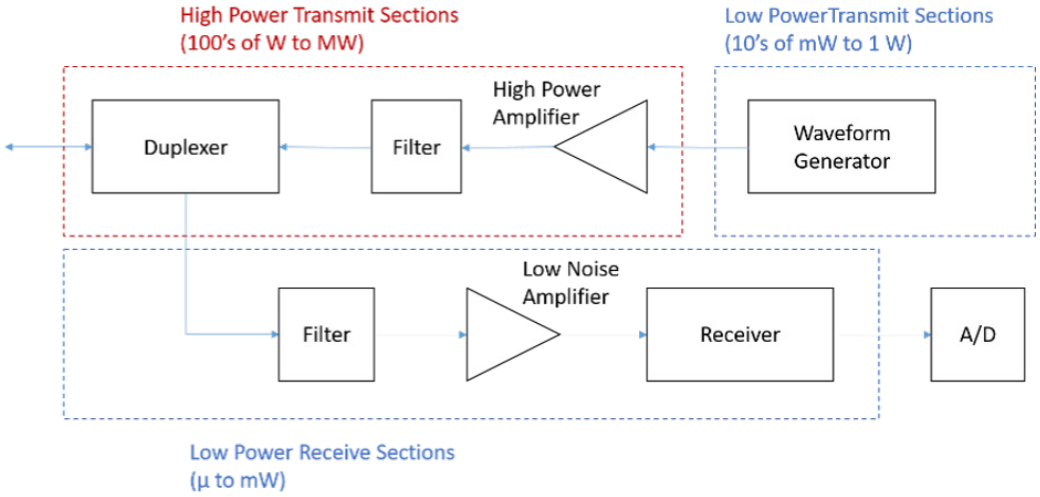
Peter Matthews, Director of Technical Marketing, Knowles Precision Devices



As many aerospace and defense and satellite communication applications face new requirements to perform increasingly complex tasks with unwavering precision and reliability, the wider bandwidths and faster speeds available in the millimeter wave (mmWave) portion of the RF spectrum are becoming increasingly attractive. But as with any technology shift, this presents new challenges for RF engineers as they look to implement sufficient high-performance RF filtering at mmWave bands. In this white paper, we aim to help engineers address these challenges by exploring some of the aspects to consider when selecting filtering technology.

An Overview of the Jobs and Characteristics for mmWave Filters

In general, filters are responsible for solving a variety of problems in a receiver or transmitter. Let's look at a radar as an example device. In a radar, you can think of a filter as the problem-solving assistant that comes along and tidies up different messes that are either outside the radar or made by components in the radar itself. While modern radar systems have multiple functions contained in single module or circuit card, the functional diagram below breaks out the functions here for ease of understanding.



For mmWave radar applications specifically, filters must cover the Ka band (26.5 – 40 GHz), which can be used for activities such as active radar homing in missiles systems. These filters also must have high fractional bandwidth and high selectivity. Additionally, low-loss filtering is important to preserve noise figure, and component size is also a key factor in practical mmWave front end designs. In phased array antennas the elements must be sufficiently close together to avoid generating grating lobes – and half wavelength spacing for mmWave frequencies amounts to a few millimeters.

The insertion loss of a filter can be impacted by a range of factors. These include filter percent bandwidth, overall rejection, and quality factor (Q factor). The Q factor of a resonator is expressed as the ratio of stored versus lost energy per oscillation cycle. Overall losses through a filter increase as Q factor drops and will increase more rapidly with frequency for lower values of resonator Q. As a result, the edges of the passband become more rounded, and the bandwidth narrows as the Q decreases.

Selectivity is another way of talking about Q factor, and a measurement of the capability of the filter to pass or reject specific frequencies relative to the center frequency of the filter. Selectivity is typically stated as the loss through a filter that occurs at some specified distance from the center frequency. A filter with high selectivity exhibits high slope in the transition from pass to stop. Selectivity is crucial in environments where adjacent channels are close together. High selectivity enables designers to make good use of available bandwidth.

Since a resonator's bandwidth is inversely proportional to its Q, balancing Q with bandwidth is important in a filter design that seeks to maximize percent bandwidth, or the bandwidth of a system relative to its center frequency. One of the desirable attributes of the mmWave spectrum is the ability to access large amounts of bandwidth (and hence increased data rates). To have a radio access system bandwidth limited because of available filter technology is not desirable.

Key Filter Technologies for mmWave

At the frequencies of interest, the main filter implementation technologies available are waveguide, cavity, and planar. Below is a high-level overview of each of these filter types.

Waveguide filters: These filters are characterized by high power handling capability up to 90GHz, leading to their wide adoption in radar applications, and low loss given that the waveguide itself is a low loss medium.

Cavity filters: These filters are a very common option for the 40 MHz to 960 MHz frequency range and can offer high selectivity under high power up to 40GHz. Cavity filters can achieve good performance but are physically large and usually only seen in infrastructure applications, such as for additional filtering at a cell site.

Planar filters: These filters are manufactured by creating flat 2D resonators with patterns of strip elements on a dielectric substrate, and depending on the filter topology, can offer high Q and a reasonable approach to achieving high performance in a small footprint when compared with discrete lumped element designs.

In a planar lumped element approach, the filter's transmission lines are printed in various configurations, depending on the required performance and filter elements are realized through discrete resistive, capacitive, and inductive elements. On the other hand, planar distributed element filters rely on carefully distributed transmission lines to create resonant structures and can be designed to tighter tolerances than a lumped element filter. In general, distributed element designs are more practical than lumped element designs at increased frequencies.

Given the needs stated above for small form factor filter implementations, planar filters are currently one of the best options for mmWave application filtering. In the remainder of this paper we will explore some of the features of this filter technology.

Planar Filter Implementation at mmWave

The structure of planar filters is very similar to that of a printed circuit board (PCB), but with the key distinction that the metal conductor patterns printed on the solid dielectric substrate are there to create resonators rather than just interconnects. The metal circuit patterns of strip elements are placed on a solid dielectric insulating layer with a metal ground layer below the dielectric.

The fields surrounding the strip permeate two different media, with part of the field in the substrate and another in the air above the strip. The higher permittivity of the dielectric substrate causes the E-field to concentrate in the substrate, meaning field losses due to material choice become a factor. Standard PCB materials like FR4 can be used below 1GHz for low Q filters. Lower loss and increased Q can be found by using ceramic materials.

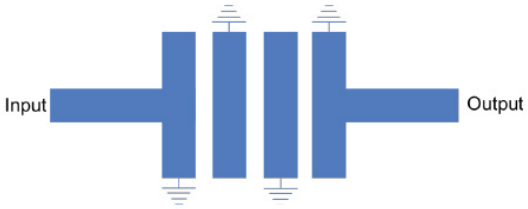
The width of a strip element and the dielectric constant of the substrate and its thickness determine the characteristic impedance. Changing the characteristic impedance by changing the structure of the strip element creates a discontinuity in transmission characteristics. It is this effect that is used to create distributed element systems that mimic the properties of a lumped element circuit. Discontinuities in the transmission line are engineered to present a reactive impedance to the wave propagating through the line, and these reactances can be designed to serve as approximations for lumped inductors, capacitors, or resonators, depending on what is needed for the filter.

A wide range of distributed element filter topologies have been developed. Some common approaches to band-pass filters include end-coupled, parallel-coupled, interdigital, and hairpin. Let's explore each of these options in more detail.

End-Coupled: This filter consists of sections of transmission line a half wavelength long at the center frequency of the bandpass filter that act as resonators and are coupled across capacitive gaps in the transmission line.

Parallel-Coupled: This filter is constructed so that adjacent resonators are parallel to each other along half of their length. This arrangement gives relatively large coupling between resonators, and as a result, this topology has the advantage of wider bandwidth compared to the end coupled approach.

Interdigital: In this topology, each resonator is a quarter wavelength long and is terminated in a short circuit at one end with the other end left as an open circuit, with the orientation alternating.



Hairpin: This filter type is obtained if we imagine folding the resonators in the parallel coupled filter, resulting in a 'U' shape.

There are many more variations for constructing bandpass, as well as lowpass and high pass, filters out of stripline. However, a defining characteristic of all these variations is that the choice of substrate can make a significant impact on the performance characteristics of the filter, regardless of the topology you choose.

The dielectric properties of the substrate have a direct influence on one of the motivating factors for selecting planar filter technology for mmWave applications to begin with – the ability to produce significantly smaller form factor filters compared to the other available technologies. The wavelength of an electromagnetic wave as it propagates through a dielectric medium is given by:

$$\lambda = \frac{c}{\nu\sqrt{\varepsilon_r}}$$

Where: c = speed of light in a vacuum, ν = frequency and ε_r = dielectric constant.

As we increase dielectric constant values we can significantly reduce the wavelength of the electromagnetic wave propagating through the transmission line. Given that the filter consists of resonators of half or quarter wavelength in size, high dielectric substrates allow us to build compact filters.

Q factor, as we have seen, is an important measure of a filter's ability to perform and influences a range of other metrics including insertion loss, selectivity, and bandwidth. Loss of energy in a resonator reduces Q and losses in a microstrip resonator can come from a number of sources.

Some of the most important sources of loss are from the conductor, the dielectric substrate, and radiation away from the stripline. The total unloaded Q of a resonator can be found by adding these contributing losses together, resulting in:

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r}$$

The Q associated with the properties of the dielectric is driven by a property called the dielectric loss tangent, which can be expressed using the following equation:

$$Q_d \geq \frac{1}{tan\delta}$$

Balancing the properties of the substrate to reach the desired filter characteristics involves aiming for both high dielectric constant and low dielectric loss at the frequencies of interest while weighing the desire for sufficiently high Q against the bandwidth requirements of the application.

Further challenges are faced when we consider the temperature characteristics of the substrate, both in terms of temperature stability and coefficient of thermal expansion of the filter substrate compared to that of the host board. Temperature stability of filters is a critical issue, especially at mmWave frequencies. High selectivity is required to minimize insertion loss and ensure rejection of adjacent bands and bandwidth can easily be eaten up by a filter whose edges wander with temperature.

Again, selecting the right substrate here is key, as the temperature coefficient of capacitance drives the filter's ability to remain in specification over a range of operating temperatures. At mmWave frequencies, antenna pitch and component size are reduced. Planar transmission line filters take advantage of the same reduction in size due to reduced wavelengths.

Meeting All Your mmWave Filtering Needs

At Knowles Precision Devices, we have more than 40 years' experience developing high-performance microwave components for military applications. Since selecting a substrate material to implement a planar transmission line filter on is a critical design factor, you can rest assured knowing that our material scientists have engineered a range of dielectric materials that, combined with our advanced thin film manufacturing techniques, allow you to build filter designs that can meet the challenges of mmWave.

As a result, we can supply customers with high-quality RF components for a wide range of critical military communication applications such as radios that rely on UHF communications, GPS devices operating in the L band, and electronic warfare radars that fall in the X, S, and K bands. We also have the expertise necessary to supply components for wideband applications such as receivers that need to operate across an extremely wide range of bandwidths to pick up and understand signals anywhere from 300MHz to 20GHz and beyond.

To learn more about some of the filtering challenges modern aerospace and defense systems face, check out our webinar, *Addressing Filtering Challenges in Digital Broadband Receivers for Electronic Warfare Applications*.