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Implementing High Performance Filters in Millimeter Wave Applications

INTRODUCTION

The advent of fifth generation (5G) communications brings an increased interest in Millimeter Wave (mmWave) technologies. Among the technology challenges engineers will face is how to implement sufficiently high-performance RF filtering in mmWave applications. This article will look at some of the aspects to consider in selecting a filter technology.

FILTERS FOR 5G MMWAVE

Filters for 5G mmWave applications will need to be able to cover the near term licensed bands such as those at 28 GHz and 38 GHz with the addition of the unlicensed spectrum up at 60 GHz. The interest in these frequencies stems from the availability of contiguous spectrum. Bands in the mmWave spectrum allow wide carrier bandwidths in the range of 400 MHz and systems are being designed to take advantage of Carrier Aggregation (CA), allowing them to support over 1 GHz of instantaneous bandwidth. Filters with high fractional bandwidth and high selectivity will be required, since CA relies on high isolation between Tx and Rx paths. Low loss filtering is important to preserve Noise Figure, and component size will be a key enabling 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 the 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 and high selectivity enables designers to make good use of available bandwidth.

Since a resonators bandwidth is inversely proportional to its Q, balancing Q with bandwidth is important in a filter design that seeks to maximize Percent

Bandwidth. Where Bandwidth is the width of the passband of a bandpass filter and is expressed as the frequency difference between lower and upper 3 dB points, Percent Bandwidth (or Fractional Bandwidth) is a common relative merit that compares bandwidth with carrier frequency. Commonly calculated as 3dBW/(Center Frequency). Percent Bandwidth is likely to be an important consideration in 5G mmWave applications. 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.

At the frequencies of interest, the main filter implementation technologies available are Waveguide, Cavity and Planar.

Waveguide 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 are a very common approach in the 40 MHz to 960 MHz frequency range and can offer high selectivity under high power up to 40GHz. They 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 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 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. 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. 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 5G mmWave applications and in the remainder of this article we will explore some of the features of this filter technology.

PLANAR FILTER IMPLEMENTATION

The structure of Planar Filters is very similar to that of a printed circuit board, 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 in ceramic materials.

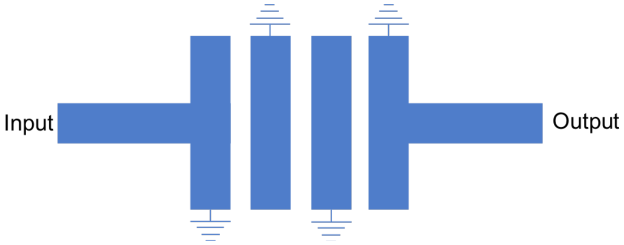
The width of a strip element, the dielectric constant of the substrate and its thickness determine the characteristic impedance. Changing the characteristic impedance (by changing the structure of the strip element) creates a discontinuity in transmission characteristics, and it is this effect that is 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.

End-Coupled. This filter consists of sections of transmission line a half wavelength long at the center frequency f0 of the bandpass filter which 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 consequence, this topology has the advantage of wider bandwidth compared to the end coupled approach.

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



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

There are many more variations on this for constructing bandpass as well as lowpass and highpass filters out of stripline. A defining characteristic of all is that the choice of substrate can make a significant impact on the performance characteristics of the filter, regardless of the topology that 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 appplications to begin with, which is 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 vaccum, ν = frequency and ε_r = dielectic constant

As we increase dielectric constant values we can significantly reduce the wavelength of the EM 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 filters 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. Amongst the most important are losses 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:

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

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 has grown to be a critical issue. 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 filters ability to remain in specification over a range of operating temperatures.

At mmWave frequecncies antenna pitch and component size are reduced. Planar transmission line filters take advantage of the same reduction in size due to reduced wavelengths.

CONCLUSION

Selecting a substrate material with which to implement a planar transmission line filter becomes an important design choice in itself. At Knowles Precision Devices, the DLI filter technology team 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 5G mmWave.