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Filter Technologies for Advanced Communication Systems

Systems offering large bandwidths through carrier aggregation and ubiquitous coverage through the massive overlapping of microcells will present both in-band and out-of-band interference that must be managed or eliminated. Likewise, implementation of massive multiple-in-multiple-out (MIMO) will require compact filtering technology that mitigates the adverse impact of out-of-band interference on the uplink sum rate of maximum-ratio combining (MRC) receivers. This white paper examines the filter design challenges brought on by adopting these new technologies, the factors driving the physical, electrical, and cost restraints for 5G filters, and the supporting simulation technology that will help designers physically realize these components.

Mobile Device Filter Technology

4G (LTE) smartphones support in excess of 30 bands, requiring over 60 filters, many in the form of multiplexers. This number of filters consumes significant space and commands the largest share of the RF expense in the mobile ecosystem, putting considerable cost pressures on component manufacturers. The majority of these components are based on surface acoustic wave (SAW) or bulk acoustic wave (BAW) technology. At the lower frequency range, SAW filters meet the requirements for low insertion loss and excellent rejection, covering broad bandwidths at a fraction of the size of traditional cavity and even ceramic filters. Meeting these requirements with the increase in frequency up to 6GHz and mllimeter-wave (mmWave) bands is proving to be a challenge for these filter technologies.

A conventional filter stores the energy in the charge on capacitors and current in inductors, whereas BAW and SAW filters store the signal in acoustic resonators. As the name implies, surface acoustic waves propagate in the lateral direction with the shape and center frequency of the passband determined by the pitch, line width, and thickness of the interdigital transducers (IDT) (Figure 1).

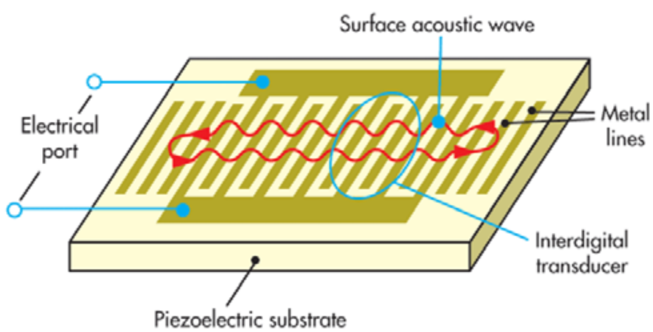

Figure 1: Basic structure of a SAW filter

Because they are fabricated on wafers, SAW filters can be created in large volumes at low cost and filters/duplexers for different bands can be integrated on a single chip with little or no additional fabrication steps. Their key advantages are low cost, good relative bandwidth, and flexible port configurations.

However, due to the degradation in selectivity at higher frequencies, SAW filters have limited use above ~2GHz and are mostly used for applications with modest performance requirements such as global system for mobile communication (GSM), code-division multiple access (CDMA), and 3G receiver front-ends, duplexers, and filters. SAW devices are also highly sensitive to temperature as the stiffness of the substrate material decreases with higher temperatures, resulting in a diminished acoustic velocity and degraded RF performance. Typically, SAW filters operate in the mobile environment from 600MHz to 2GHz, whereas BAW filters operate between 1.5GHz and 6GHz, putting them in the range for the lower 5G bands.

Temperature-compensated SAW (TC-SAW) filters are fabricated using a more complex and costly layer structure to increase the substrate stiffness at higher temperatures and extend their operating range. Since the process doubles the number of required mask layers, TC-SAW filters are more expensive to manufacture, but they are still less expensive than BAW filters. In comparison, BAW filters require about 10 times more processing steps than SAW filters. While BAW technology yields approximately four times more parts per wafer, it still has a higher cost per filter compared to SAW[1]

[1]Robert Aigner, "SAW, BAW and the future of wireless", EDN (edn.com/Home/PrintView?contentItemId=4413442)

BAW filters fall into two general architectures, solidly mounted resonators (SMRs) and film bulk acoustic resonators (FBARs). With BAW filters, an electric field excites an acoustic wave, which travels in a vertical direction through the body of a piezoelectric substrate, as shown in Figure 2. The resonant frequency is determined by the thickness of piezoelectric layer, which must be controlled to high accuracy. The result is a device with lower loss, higher Q, better power handling, and sharper corners (greater selectivity) compared to SAW filters operating at the same higher frequencies.

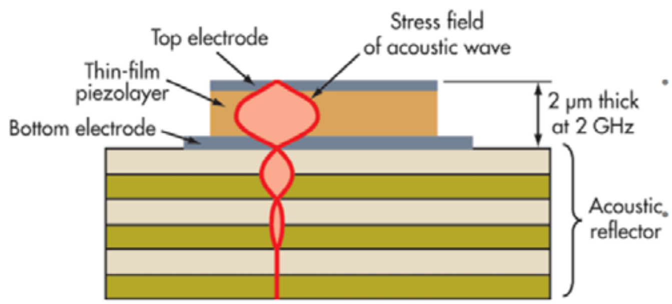

Figure 2: Cross-section of a BAW device

In the case of FBAR filters, the resonator is surrounded by an air interface created through etching or micro-machining. In contrast, acoustic reflectors below the bottom electrode of BAW-SMR filters allow them to be optimized for wideband performance in frequency regions where FBAR filters are more technically challenged. Although BAW-SMR and FBAR filters are more expensive to manufacture, their performance advantages are better suited for most LTE bands in addition to the PCS band, which has a narrow transition range of only 20MHz between transmit and receive paths.

The construction of both BAW filter types allows them to handle higher RF power levels than SAW filters. They have less temperature variation than SAW devices, although not as good as a TC-SAW. The silicon dioxide (SiO_2) used in the reflector reduces the overall temperature drift of BAW significantly below what either traditional SAW or FBAR filters can achieve. Since the BAW-SMR resonator sits on a solid substrate, it can dissipate heat more effectively in comparison to FBAR, which dissipates heat laterally through a much smaller edge surface. This allows BAW devices to achieve higher power densities, allowing devices to handle upwards of 10W, ample power for small-cell base station applications.

Various manufacturers use the Cadence® AWR Design Environment® platform, specifically Microwave Office® circuit design software and AXIEM® and Analyst™ electromagnetic (EM) simulators to support their SAW/BAW filter design activity. With customized simulation libraries that implement acoustic wave filters using mathematical models directly in Microwave Office software, filter designers are able to focus on the combined electrical performance of the SAW/BAW devices with any off-chip resonators and electronic packaging.

Some of these devices have been implemented as parameterized cells (PCells) along laminate and low-temperature co-fired ceramic (LTCC) design kits for further product development and module integration. For SAW/BAW filter designers, AWR® software offers:

- Complete front-to-back design flow in one integrated tool
- Integrate acoustic to electrical models
- Polymorphic/dynamic model support
- Sophisticated interconnect routing and modeling
- EM stackups with built-in shape preprocessing
- Integrated ACE automated circuit extraction and AXIEM and Analyst EM simulators
- Multitechnology device/module design flow

Spectrum and Architecture

Each FCC RF band for 5G of 3.5-6GHz, 27-40GHz, and 64-71GHz presents its own set of issues and solutions for components in the radio design. As a result, this significantly expanded spectrum is expected to result in a greater diversity of filter solutions than those serving the current mobile communication bands.

With 5G, the need for bandwidth has motivated the 3rd Generation Partnership Project (3GPP) to push for advances in radio access technology into the mmWave spectrum, as well as select unused bands between frequencies that have been authorized for public safety and defense applications. As radio technology evolves, planners will look to maximize the use of this very valuable spectrum by limiting the unused space (guard bands) between adjacent bands, as shown in Figure 3.

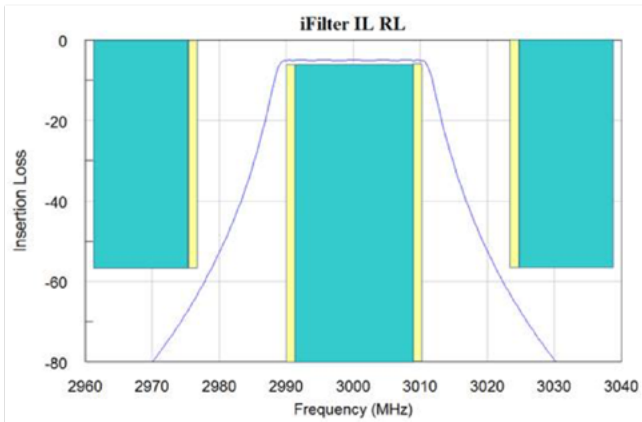

Figure 3: General filter S21 frequency mask showing passband and guard bands as simulated in Microwave Office software

High-performance filtering is critical as spectral crowding increases the need for interference mitigation and bandwidth utilization drives the need to reduce or even eliminate guard bands. Supporting technology will require very low loss, raising the filters with exceptionally steep filter skirts (high selectivity), high rejection, and very little temperature drift. In addition to these stringent requirements, increased parasitics and substrate losses associated with the filtering device and its packaging (laminate) at mmWave frequencies will most certainly degrade performance unless properly addressed.

For the 3.5-6.0GHz 5G bands, the frequencies are close enough to the current mobile high band that systems can employ a similar set of radio solutions. While the higher (6GHz) frequencies will challenge the performance levels for current off-the-shelf components, the basic radio architectures employed in current systems are expected to work. From a filter perspective, the incremental higher frequency will be an additional barrier to SAW filters, which already struggle at the 2.5GHz band. This leaves the field open for BAW and TC-BAW filters. However, the performance degradation of the current BAW technology at higher frequencies may disqualify these types of filters as well.

Filter technology is driven by size and integration concerns, which is influenced by the system architecture. To illustrate, consider the receiver portion of a 4G base station that could be configured along two main architectural paths: an intermediate frequency (IF) sampling receiver with heterodyne mixing stages down-converting the carrier frequency to the IF sampled by the analog-to-digital converter (ADC) and a direct down-conversion receiver in which the carrier frequency is converted through quadrature demodulation into two baseband signals for digital conversion.

Because each of the radio blocks represent a discrete or lightly integrated component, the heterodyne architecture offers certain flexibility, allowing a relatively straightforward design to be easily modified for different wireless standards and carrier frequencies. While the architecture is robust and well documented, designers must still address a number of concerns that will impact the filtering. These concerns include device linearity (spurious products from nonlinear components), size constraints, and complexity. Due to the large number of discrete components required, heterodyne systems can consume large board areas and become cost challenging with low-volume components.

These drawbacks are multiplied when designing multiple antenna systems. The challenge of addressing space and cost pressures is compounded by the complexities introduced with the architecture advances of carrier aggregation, phased array antennas, and massive MIMO. As a result, the design and product development effort becomes a formidable task requiring considerable engineering support starting with simulation.

Visual System Simulator™ (VSS) system design software helps designers tackle these challenges with the ability to investigate different architectures and study the impact of individual component specifications on the overall system performance. Combined with Microwave Office software and AXIEM and Analyst EM simulators, designers have a seamless path from initial system architecture development to component specification to physical realization and verification.

A standard example featuring a preconfigured single conversion heterodyne receiver and a direct-conversion receiver illustrates two popular architectures, providing system designers with an excellent guide to developing their own virtual system design bench, as shown in Figure 4. The received signal in each case is made up of a 16 quadrature amplitude modulation (QAM) signal at 27GHz (close to the 28GHz band used by Verizon for 5G) along with an image signal at 7GHz. The same image rejection and low-pass filters (LPFs) are used in both the single conversion heterodyne and direct conversion top-level systems.

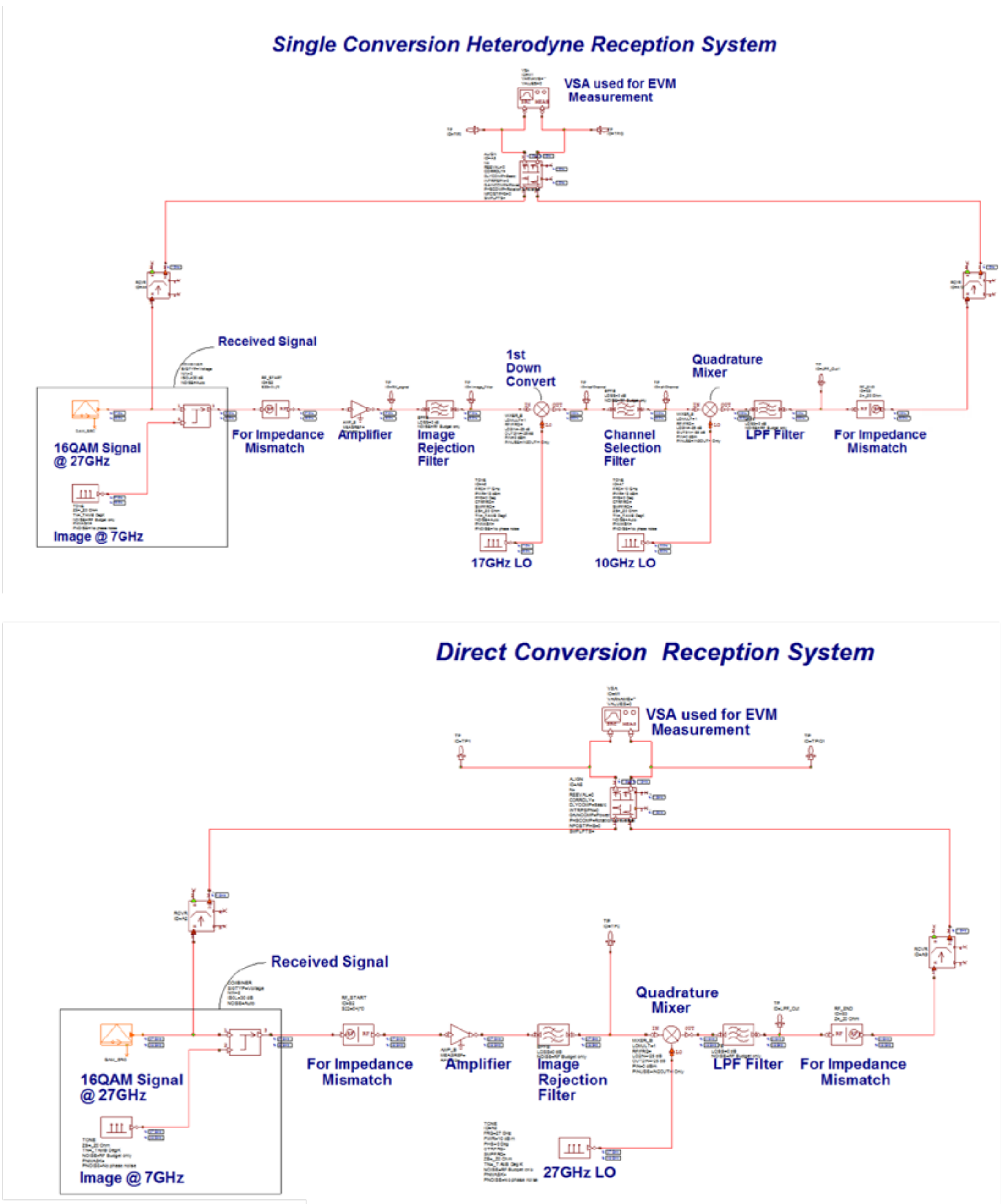

Figure 4: Two different system architectures in standard VSS example illustrate (filter) component specification impact on system performance for both heterodyne (top) and direct-conversion receivers (bottom)

The desired response of the filter (low-pass Butterworth) used in both of these systems is easily defined by the user with real-time visual inspection through the property definition dialog box shown in Figure 5. Designers specify the expected or desired filter characteristics based on information from vendors or on system requirements that can then be passed along to the filter manufacturers. Alternatively, designers can substitute real measured data or data from circuit/EM level (physical model) simulation directly into a system analysis.

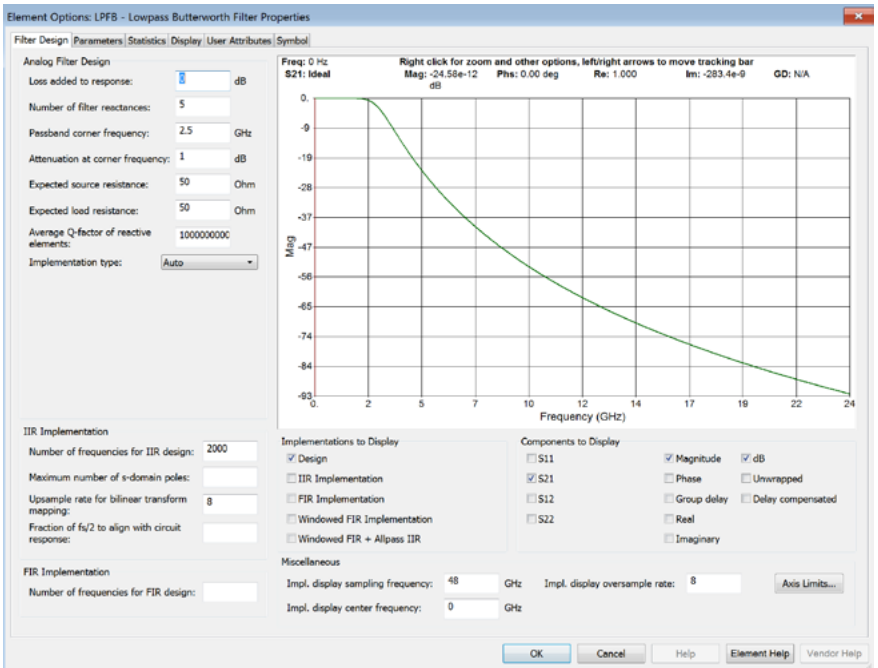

Figure 5: Properties definition for LPF element used in heterodyne and direct-conversion system architectures

Two alternative radio approaches gaining attention include cognitive and reconfigurable software defined radios (SDRs) and tunable filters. With SDRs, all the filtering is done after the analog-to-digital conversion (ADC) on the receive side and before the ditigal-to-analog conversion (DAC) on the transmit side. The current state of the art in silicon can address the filtering, however this approach consumes tens of watts of power in contrast to passive filters, which consume zero power. In addition, the front-end amplifier would be vulnerable to any potentially strong out-of-band signals and the ADC would be converting the entire received spectrum. A tunable band select filter before the LNA would address out-of-band signals, while a tunable anti-aliasing filter before the ADC would greatly improve the power efficiency.[2]

In addition to the use of CA and mmWave spectrum, 5G networks make use of greatly improved antenna array technology, requiring additional filter solutions. Massive MIMO, which may contain 100 or more antenna elements, can offer an order of magnitude improvement in spectral efficiency (60-110 of bit/s/Hz/cell, under ideal conditions, compared to ~ 3 bit/s/Hz/cell) over a 4×2 MIMO.[3]

One concern for massive MIMO implementation is the complexity and quantity of components per RF chain, including broadband high-resolution ADCs and DACs, highly linear power amplifiers (PAs) with linearizing control circuits, and a large number of filters with strong out-of-band suppression to address any interfering signals. Reducing interference as early as possible in the receiver chain is a favorable approach for achieving the objectives of MIMO antennas, simultaneously increasing interference robustness while decreasing power consumption.

As the number of MIMO basestation antennas (M) increases, studies have shown that the necessary out-of-band attenuation provided by the bandpass filters (BPFs) increases proportionately to the square root of the M.[4]

This implies a practical limit on the number of broadcast satellite (BS) antennas due to the increase in BPF design complexity and power consumption. Insufficient out-of-band attenuation would result in aliasing of the filtered out-of-band interferers into the useful band at the output of the ADC, thereby corrupting the received baseband signal.

[2]Steven Mahon, "The 5G Effect on RF Filter Technologies", IEEE Transactions on Semiconductor Manufacturing, Volume: 30, No. 4, November 2017 .
[3]Emil Bjorson, "How much does Massive MIMO Improve Spectral Efficiency", ma-mimo.ellintech.se/2016/10/18/how-much-does-massive-mimo-improve-spectral-efficiency.
[4]Sudarshan Mukherjee and Saif Khan Mohammed, "How Much Bandpass Filtering is Required in Massive MIMO Basestations?", IEEE Transactions on Vehicular Technology, Volume: 66, Issue: 5, May 2017.

Physical Design at mmWave

Taking advantage of mmWave spectrum will require addressing poor individual component performance and the technological challenges of applying current mobile radio solutions above 20GHz. Compounding these issues, when the mmWave specific bands are defined, the standards will most likely require the filters to preserve as much bandwidth as possible, calling for high selectivity.

FBARs operating in frequency range of 5-20GHz have been reported in literature.[5]

These filters offer low insertion loss for decent system performance and can be designed integrated with monolithic microwave IC (MMIC) and other technologies to reduce cost and size and provide low-power consumption. In general, the use of mmWave frequencies will likely require different filter technology than the acoustic wave filters currently used in mobile devices at cellular frequencies. Due to the need for RF chain optimization and proper addressing of the interactions between elements, there will be more integrated approaches for filtering, and the overall jump in complexity for 5G subsystems will place greater demands on design teams.

As frequencies increase toward the mmWave range, the RF wavelength becomes small enough that filters based on EM techniques are feasible. Waveguide and cavity filters are two of the most common high performing filter types between 20GHz and 80GHz. These filters have dimensions in centimeters rather than the required millimeters, however, there are many efforts to miniaturize these filters at mmWave frequencies.

The wavelength size for the EM wave being filtered is still large with respect to the filter's physical size requirements, so it is likely that these mmWave filters will be larger than the lower band acoustic filters, which may be permissible if a different radio architecture can reduce the quantity of filters required. Otherwise, alternative construction must be developed.

Likely candidates are filters based on substrate integrated waveguides (SIW), shown in Figure 6, which offer a planar construction that can be easily incorporated into MMIC, RFIC, and PCB substrates with existing interconnect structures, and have also been demonstrated using standard complementary metal oxide semiconductor (CMOS) technology. Gallium arsenide (GaAs) and indium phosphide (InP) technologies offer better performance than the CMOS process because of higher breakdown voltages and higher electron mobility, as well as high cutoff frequencies (fT) and good noise performance. MMICs also offer high-quality passives. However, major drawbacks of the III-V semiconductor technologies include high cost, a low level of integration, and high-power dissipation.

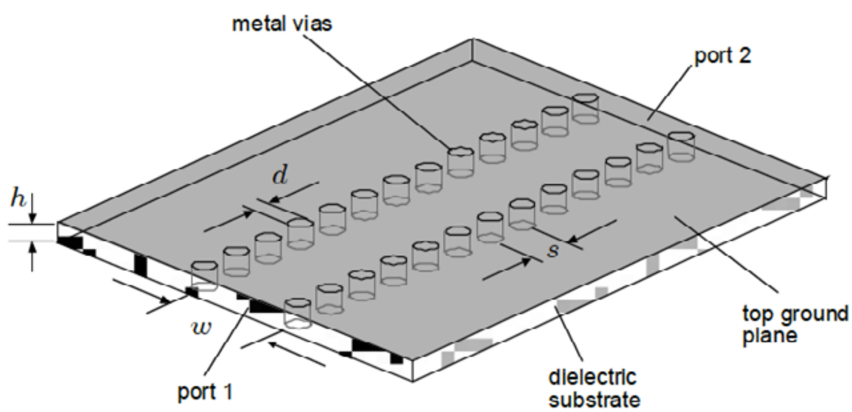

Figure 6: Typical construction of an SIW

The main advantages of CMOS include low cost, integration of digital, analog, and RF functionality into a single IC, a plentiful number of manufacturers, and cutoff frequencies beyond 100GHz. Because of the low resistivity of silicon (Si) substrates (typically 10Ω-cm) and metal losses, on-chip passive components exhibit low quality factors (Q factors) and suffer from high losses in mmWave circuits, degrading BPF insertion loss and out-of-band rejection.

[5]K. Umeda, H. Kawamura, M. Takeuchi, and Y. Yoshino, "Characteristics of an AlN-based bulk acoustic wave resonator in the super high frequency range," Vacuum, vol. 83, no. 3, pp. 672–674, 2008 ,7

[6]N. I. M. Nor, K. Shah, J. Singh, N. Khalid, and Z. Sauli, "Design and analysis of film bulk acoustic wave resonator in Ku-band frequency for wireless communication," in Proceeding of SPIE, Active and Passive Smart Structures and Integrated Systems 2012, 83411R, vol. 8341, 2012.

The size of a mmWave passive filter based on distributed transmission (example filter in Microwave Office software is shown in Figure 7) is smaller than a filter at microwave frequencies, supporting integration with other circuits on a single chip. The Q factor of a monolithic transmission line (TL) is directly proportional to the square root of its operating frequency. As a result, the Q factor of a TL is enhanced with increasing frequency. Consequently, TLs are broadly used and preferred as resonators for mmWave passive filter design. At mmWave frequencies, reactive elements required for matching networks and resonators become very small. Quasi-transverse EM (quasi-TEM) TLs are easily scalable in length and can realize small reactances.

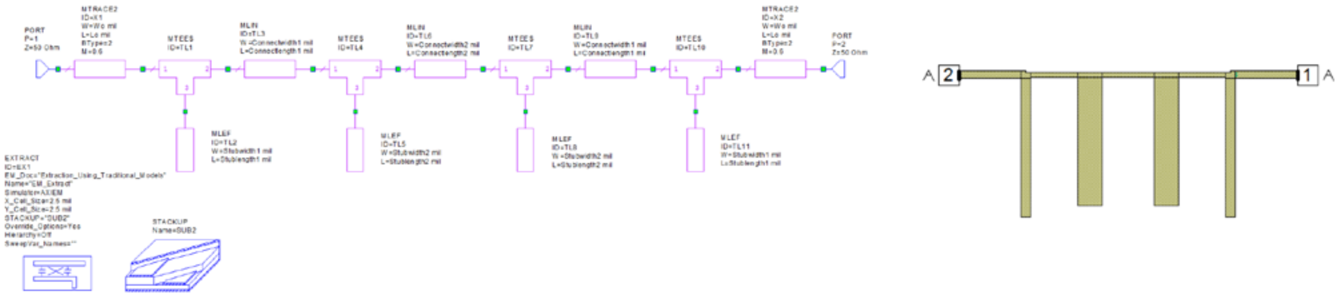

Figure 7: Microstrip bandpass filter example based on transmission lines and open-circuited stubs that reduces in size at mmWave frequencies

Conclusion

For 5G/6G filter designers, the challenges are compounded by an increase in potential interferers due to the adoption of massive MIMO and network cell densification, guard bands that are reduced or eliminated, and carrier aggregation demands of greater selectivity and mmWave spectrum. As current radio and acoustic filter technologies struggle with performance at these higher frequencies, designers will need to explore a wide range of alternatives. Simulation software, which includes system, circuit, and EM analysis, will play a critical role in the success of these new filter technologies.

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