The 5G Effect on RF Filter Technologies

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ABSTRACT

A great deal is being written about the next generation mobile standards, "5G". As with the early stages of previous generations, it is hard to clearly see the direction forward. The intersection of technological obstacles, economic realities and political forces produces a path that is not only difficult to predict but curiously interesting in retrospect. Even with this history we press on and predict – it is our way. Even with all the publications on 5G and its many technical challenges there is a dearth of information on the RF filters required. This is somewhat surprising as filters have become a major part of the radio in a mobile phone. State of the art smartphones now contain more than 60 filters and command the largest share of the RF wallet. The key starting point is the proposed new RF bands that will be used for 5G. The FCC has recently proposed band sections between 3.5-6 GHz, 27-40 GHz and 64-71 GHz. As anyone familiar with radios in these areas knows, each band commands its own set of issues and solutions. The span of filter solutions for 5G will be more diverse than in the current mobile technology bands.

CURRENT FILTER MOBILE ENVIRONMENT

The latest, advanced smartphones continue to add frequency bands in each phone to the point where 30+ bands [1] are not uncommon. This presents the reality that over 60 filters, many in the form of duplexers, are operating in your pocket. The vast majority of these filters are acoustic filters in the form of surface acoustic wave (SAW) and bulk acoustic film (BAW) technologies. BAW filters fall into two general architectures, solidly mounted resonators (SMR) and film bulk acoustic resonators (FBAR). Also, both SAW and BAW devices have temperature compensated (TC) versions and will often see TC used as a descriptor prefix e.g. TC-SAW.

Filters fundamentally work by storing enough of a signal to determine the rate of change of the signal, allowing one frequency to be differentiated from another. Digital signal processing (DSP) filters do this by converting the signal with an A/D converter to a digital sequence stored in local memory. The math processor can then operate on the data, removing the unwanted frequencies and allowing the desired frequencies to be reconstituted. Analog filters effectively do the same thing, storing the signal, not in digital words, but in stored energy. A conventional RLC filter stores the energy in the capacitors and inductors, BAW/SAW filters in acoustic resonators and with waveguide/cavity filters in the EM resonance in the transmission lines or the cavity.

SAW and BAW filters have emerged as the technologies of preference over other approaches such as ceramic, dielectric and lumped element filters by achieving high performance, small form factor and low costs simultaneously. High performance of a bandpass filter is characterized by a high quality factor (Q), low insertion loss (IL), high return loss (RL) and high out-of-band rejection. Acoustic filters achieve this by converting the RF signal from an electromagnetic (EM) wave with a high propagation velocity to an acoustic wave with a low propagation velocity with the use of a piezoelectric material such as quartz, AlN, $LiNO_3$ or $LiTaO_5$. This reduces the signal propagation velocity by a factor of 20,000 to 50,000 transforming the wavelength from centimeters to microns. This allows the signal to be "stored" and "sampled" sufficiently to differentiate a desired frequency in a very compact space. Of course, these acoustic filters are analog, where the signal energy is stored in a resonant element with a characteristic Q. Q is the amount of energy stored in the resonator divided by the parasitic energy lost and, for acoustic filters, range from 500 to 4000. Of course, the signal is not discretely sampled in the sense of a DSP but it's a good way to visualize it.

Typically, SAW filters operate in the mobile environment from 600 MHz to 2 GHz and BAW filters range from 1.5 GHz to 3.5 GHz [2]. SAW filters, in general, are less expensive than BAW filters due to BAW's more complex process costs. SAW filters have performance issues above 2 GHz due to parasitic losses that do not affect BAW filters until higher frequencies. BAW filters below 1.5 GHz get larger in size, higher in process costs and have lower performance advantages than a SAW filter at the same frequency. So, neither technology can fully displace the other - although they try.

An additional complication for filter designers is the emergence of carrier aggregation (CA). CA is the ability to transceive multiple bands at the same time. This provides a faster user experience and more flexibility for the mobile provider. However, it required the design of triplexers, quadplexers and even hexplexers where the elemental filter component needs to have compatible impedances with the other frequencies in the aggregation. This is a severe design challenge.

LIKELY 5G SPECTRUM

The FCC has recently proposed band sections between 3.5-6.0 GHz, 27-40 GHz and 64-71 GHz for the emerging 5G application [3]. These have been mostly harmonized with the frequencies with the 2015 World Radiocommunication Conference (WRC-15) giving hope for a more straight forward world compatible phones. These bands provide more than10X in total bandwidth over the entire existing mobile spectrum. This is necessary to achieve the aggressive performance goals of 5G. The challenge is that for the new mmW frequencies above 20 GHz many of the current mobile radio solutions are either seriously challenged or technologically infeasible. The specific band specifications are yet to be determined but, if history is any teacher, the standards will push to the edge of capability of filter design to preserve as much bandwidth as possible.

EFFECT ON RADIO ARCHITECTURE

The direct conversion radio architecture or "zero IF" technology used for current mobile devices exists because of the ability of very fast CMOS transceivers to process RF signals directly as shown in Fig. 1. This architecture provides a simplified set of components and provides for a highly linear output, which is necessary for the complex modulation protocols used. The effect on band filters has been, in many cases, very difficult performance specifications, but the reward for filter manufactures is that two filters or one duplexer is required for each band. For early 3G phones with 3 or 4 bands this was not a big issue, but now 4G phones with over 30 bands have resulted in a rapid expansion of the filter demand and commanding the top share of the RF front end wallet. For frequencies below 6.0 GHz this approach is extensible with the current state of transceivers. As for new mmW frequencies deployed, the ability to directly receive these higher frequencies become problematic.

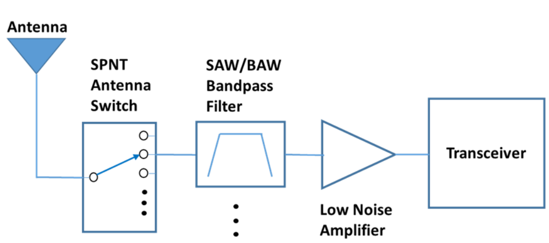

Fig. 1. Simplified Direct Conversion or Zero IF receiver block diagram.

To accommodate the mmW frequencies we need to return to the classic super-heterodyne radio architecture as shown in Fig. 2. Although robust and well understood it produces challenges of linearity and complexity. When you marry these limitations with the architecture advances of carrier aggregation, phased array antennas and massive MIMO (multiple input, multiple output) features, the design challenges compound [4]. All these create a complex landscape for the filter components.

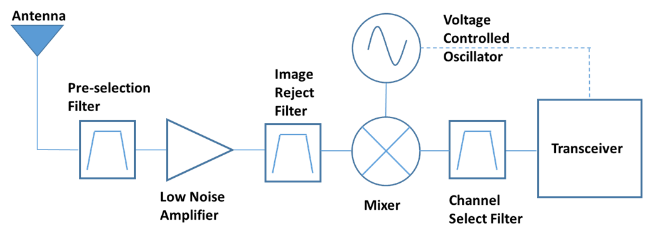

Fig. 2. A simplified Super-heterodyne receiver block diagram.

FILTERS FOR 5G FOR FREQUENCIES LESS THAN 6 GHZ

For the new 3.5-6.0 GHz band, the frequencies are close enough to the current mobile hi-band that one would expect a similar set of direct conversion radio solutions. The higher frequencies add stress to the stock hi-band radio components performance, but the basic direct conversion radio architecture is expected to hold. From a filter perspective the incremental higher frequency will be an additional barrier to surface acoustic wave (SAW) filters which already struggles at the 2.5GHz band. This leaves the field open for BAW and temperature compensated BAW (TC-BAW). However, the effect of the higher frequency has its effects on BAW filters as well. The acoustic losses dramatically increase with f^2 as shown in Fig 3.

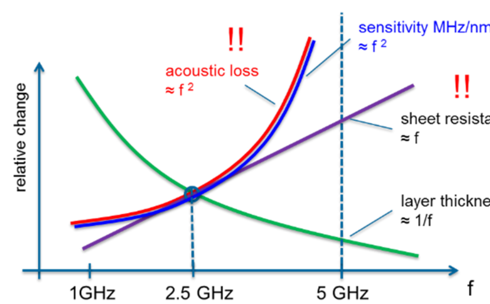

Fig. 3. BAW losses as frequency increases [Courtesy of Qorvo]

FILTERS FOR 5G FOR FREQUENCIES GREATER THAN 20 GHZ

At mmW frequencies the acoustic filters run into catastrophic issues with increased acoustic losses and unrealistic scaling dimensions. The advantage of converting the RF electromagnetic (EM) wavelength to a smaller sound wavelength comes back to bite you as frequencies approach

10GHz, However, the RF wavelength starts getting small enough that filters based on EM techniques are feasible.

The existing high performing filters for the frequencies between 20 GHz and 80 GHz usually fall into two architectures - waveguide filters or cavity filters. For most mmW radios these filters have dimensions in centimeters rather than the required millimeters. However, the market pull that is starting is creating efforts on many fronts to miniaturize mmW filters [5]. The advantage of waveguide filters is that planar versions can be incorporated in substrates with existing interconnect structures and have been demonstrated on standard CMOS technology [6]. The unknown is if the performance on existing substrate technologies will produce sufficient filter attributes or if a custom, optimized substrate technology will be required.

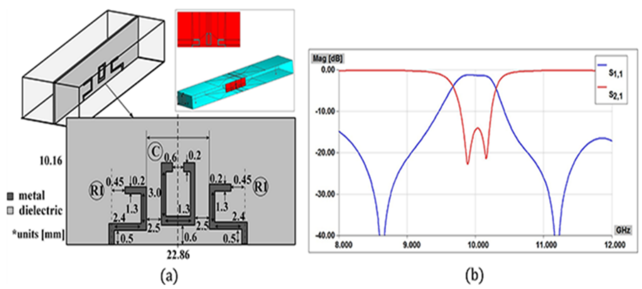

Fig. 4. Waveguide filter example [7]: (a) 3D model; (b) amplitude response.

Cavity filters usually suffer from an even larger form factor challenge than planar waveguide filters. They, however, provide the most design latitude to optimize the filter attributes and power handing. As with planar waveguide, there are efforts to miniaturize cavity filters [9] and it remains to be seen if it can meet all the required goals and may be particularly challenged with cost.

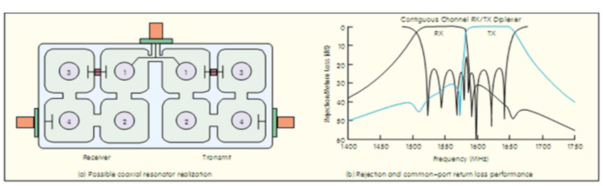

Fig. 5. Cavity diplexer: (a) diagram; (b) amplitude response.

Both planar waveguide and cavity filters have a difficult challenge reaching the small size for mobile systems. The wavelength size for the EM wave being filtered is large with respect the size requirements so it is likely that these mmW filters will be larger than the lower band acoustic filters. However, the quantity of filters needed for the radio is much less due to the radio architecture challenges noted before.

MOBILE FILTER MANUFACTURERS

The dramatic increase in filter content in advanced 4G LTE smartphones has placed significant demands on the manufacturers of precision SAW and BAW bandpass filters. All of the major suppliers have had to add significant manufacturing capacity, sometimes multiple times to keep up with demand. Several suppliers have had to publicly announce that front-end module production was limited by either internal or external filter supply constraints. No fun.

The large producers of SAW devices include Murata, Skyworks (from Panasonic), RF360 Holdings (Qualcomm/TDK-EPCOS joint venture), Qorvo and Taiyo Yuden, in addition to several other of small SAW manufactures across the globe, some offering foundry services. This gives the module producers the flexibility of external and internal sources. A standard SAW process is well understood and difficult to differentiate in the marketplace; however, as performance demands increase, requiring approaches such as TC and higher frequencies, advanced SAW process get more complex and there is opportunity to differentiate between manufactures. The penalty is that the historic cost advantage SAW has had over BAW will erode as the advanced SAW processes are developed.

The BAW supplier landscape is much smaller and restricted with Broadcom (from Avago) and Qorvo (from TriQuint) being the only two volume suppliers in the smartphone arena. Broadcom has the lead position in both volume and filter performance with their FBAR technology. Qorvo holds a significant second position with their SMR technology which is closing the gap in performance with FBAR. Both companies have added significant capacity in the past decade to accommodate the growth. Both have moved their manufacturing from 150 mm to 200 mm wafers and both have recently purchased sizable used silicon wafer fabs to accommodate expected future demand. The barrier to entry for BAW technology is significantly higher than SAW devices due to the complexity of the BAW process. In addition to the intrinsic complexity of the process, both companies have a comprehensive IP profile covering the technology. Between 2009 and 2012, Avago and TriQuint engaged in a significant legal battle on BAW technology patents that ended with a cross-license agreement. During the time both companies doubled their effort to add to their patent portfolio further adding to the barrier to entry. However, the growth of this market is compelling, and Skyworks, RF360 Holdings and Taiyo Yuden have announced their intent to offer BAW based products. An interesting BAW start-up, Akoustis [8], had developed a very high performance BAW technology by using single crystal AlN rather than the polycrystalline AlN used by all other suppliers.

On the mmW front the opportunities are very open. There is no high volume application for mmW radios and most capabilities work in the defense and infrastructure market with modest volumes. One start-up company working a miniature cavity filter capability based on IC wafer processing technology is Nuvotronics [9].

Effects on the Compound Semiconductor Community

Although none of the filter technologies discussed directly involve compound semiconductors (CS), the trade-offs will affect the system design which are full of CS components. The effect on CS components on bands below 6 GHz will be more evolutionary with higher performance capability roughly based on existing architectures. For frequencies above 20 GHz the space is wide open for innovation with the frequencies working in the sweet spot of CS technologies. The need to do some form of up/down conversion of the fundamental carrier frequency opens the CS community to components such as mixers and voltage controlled oscillators at mmW frequencies which are not currently in mobile devices.

Conclusion

The roll out of 5G is still a few years in the future, but the early foundations are starting to form. The third LTE incarnation, LTE Advanced Pro, will incorporate many of the new features such as advanced carrier aggregation and massive MIMO, and can be thought of as "4.5"G. This will all occur with frequencies below 6.0 GHz.

These new features, in addition to the extended frequency above 2.5 GHz, will stress the performance bounds of acoustic filters. BAW filters will likely dominate the 3.5-6.0 GHz as they do in the current 2.5-3.5GHz. The performance challenges will be significant as the frequencies reach to 6.0 GHz. Improved acoustic resonator technology will have to be developed if significant drop in filter performance is to be avoided. SAW filters will continue to use process improvement and their historic cost advantage to encroach on low frequency area that BAW currently enjoys. SAW filters will dominate the new 600-700 MHz bands emerging.

For the mmW frequencies above 27 GHz the mobile filter challenge will be significant. High performance filters for the mmW do exist but most technologies have size and weight issues incompatible with a mobile device. New technologies for miniaturized EM waveguide and cavity filters are starting to emerge. The expected performance of cavity filters should be higher than that EM waveguide filters. However, the EM waveguide filters will have the best opportunity to meet the mobile form factor and cost goals using an optimized thin film process

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Acronyms

BAW: Bulk Acoustic Wave
CS: Compound Semiconductor
DSP: Digital Signal Processing
EM: Electro-Magnetic
FBAR: Film Bulk Acoustic Resonator
IL: Insertion Loss
IF: Intermediate Frequency
LTE: Long Term Evolution
mmW: Millimeter Wave
MIMO: Multiple Input, Multiple Output
RL: Return Loss
RLC: Resistor, Inductor (L), Capacitor
RF: Radio Frequency
SAW: Surface Acoustic Wave
SMR: Solidly Mounted Resonator
TC: Temperature Compensated