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The Wideband Challenge for RF Filters and SWAP-C

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Abstract

There is a continuously evolving, unmet need for RF (Radio Frequency) Filters that operate contiguously over multiple frequency octaves or bands. Unlike traditional switched filter banks, these new filters require similar levels of RF performance but with more filters and a smaller overall footprint. Legacy systems typically operate over a sub-octave and filters meant to break down information from the aperture to sub-bands (octave wide) or a little less. These wideband filters, pre-LNA (low noise amplifier), were minimal loss but very large. This paper will examine two new solutions to miniature, wideband, and contiguous filtering, their different capabilities, and where the new filter technologies can enable new overall system capabilities. The commercial (cell phone) vs DoD (Department of Defense) requirement differences which drive very different needs for RF filters highlight the SWAP-C (Size, Weight, and Power – Cost) challenge as wideband, contiguous vs. not, is considered.

Keywords: RF, filters, tunable, switches.

The RF (Radio Frequency) spectrum is a very crowded operational space.

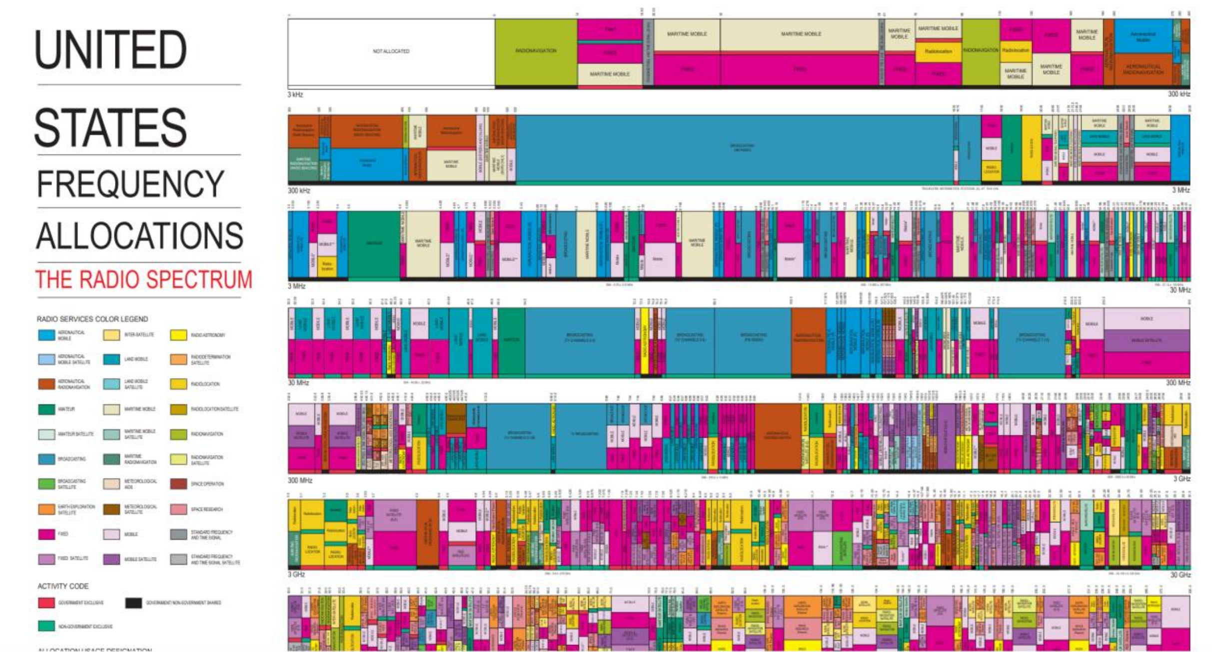


Figure 1: US Frequency Allocation Chart [1]

This chart is a snapshot-in-time portrayal [https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf] of the spectrum governed by the FCC (Federal Communications Commission) and NTIA (National Telecommunications and Information Administration), which regulates interstate and international comms by radio, tv, wire, satellite, and cable [2] in the United States of America. The FCC handles complaints and monitors "traffic," while NTIA generates policy. This crowded frequency spectrum keeps one band isolated from the next through filtering.

The commercial challenge of filters will only increase as technology strives to become smaller, less expensive, and able to support a variety of capabilities instead of just one; while overall, the requirements of the filters are becoming more complex. This difficulty becomes exacerbated as the FCC auctions more of the frequency spectrum. As cell phones progress from 5G to 6G and, ultimately, 7G, prime slices of the frequency spectrum are needed to operate. These pieces of the spectrum are taken from other existing bands and are incredibly lucrative as a block of C-Band (3.7 GHz) raised over $81 Billion dollars and following a block needed for 5G wireless raised over $21.8 billion dollars [3].

One example of the importance of filters and their impact on these blocks of the spectrum can be found in the LightSquared vs. GPS spectrum feud. As LightSquared built a 4G LTE network with a plan to cover much of the US by 2015, it encountered a problem with the immediately adjacent frequency band of 1559-1610 MHz, used for GPS satellites and receivers. Since the power level of the terrestrial LTE network is far greater than the GPS signal from space, the concern is that the GPS signal could be impeded. The FCC and NTIA ruled that LightSquared could proceed, yet it was apparent that this would not be an issue if GPS used the proper filters to block interference from adjacent bands. At an estimated cost of 11 cents per filter in both the satellite and receiver [4] this would not have been an issue.

A brief primer on filters reminds us that there are four basic filter shapes: a high pass, low pass, band pass, and band reject or notch filter.

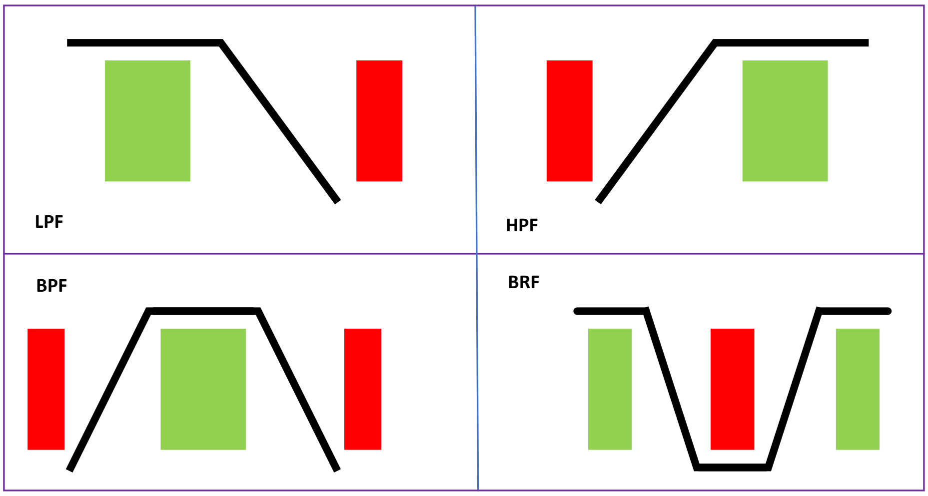


Figure 2: Filter Shapes with Pass/Fail Regions

A filter's fundamental goal is to pass a signal or set of signals and reject any unwanted noise or spurs. In order to achieve this goal, a filter shape is selected based on the requirements to be met by the following set of filter parameters: center or cutoff frequency (Hz), insertion loss (dB), ripple (degrees), Bandwidth (Hz), shape factor, and rejection (dBc).

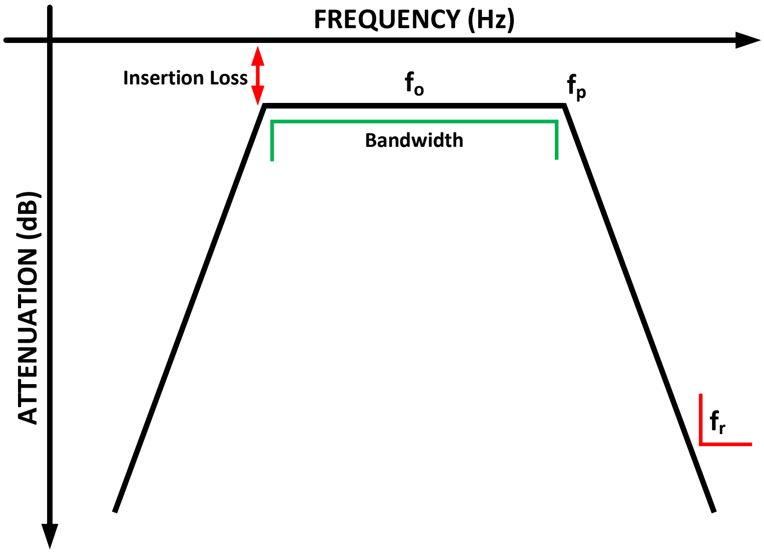


Figure 3: Filter Parameters and Terminology

Where f_o is the center frequency, f_p is the pass band edge, f_r is the first rejection frequency, Bandwidth is defined as the 1dB / 3dB / etc. bandwidth, Insertion loss is the power or attenuation loss from 0 dB to f_o, and shape factor is the ratio of the rejection edge to the passband edge:

Shape Factor = f_r / f_p

RF filters can be defined in two primary types, amplitude, and phase. Amplitude filters, such as Butterworth, Chebyshev, and Cauer, typically address passband flatness and stopband roll-off. Based on the number of poles, each of the three filter types trade ripple in the passband for amplitude rejection. Phase filters, such as Bessel or Gaussian filters, support linear phase functions in which the filter has a constant group delay in passing a wave and removing high-frequency noise while minimally impacting stopband rejection. For this paper, amplitude filters will be the focus.

Overall, the RF filters can directly impact the system's dynamic range and linearity. When looking at super heterodyne vs. direct sampled systems, overall SWAP-C (Size, Weight, and Power and Cost) comparing the number of filters to their required footprint and placement in the system are critical parameters to consider. A ***superhet*** system

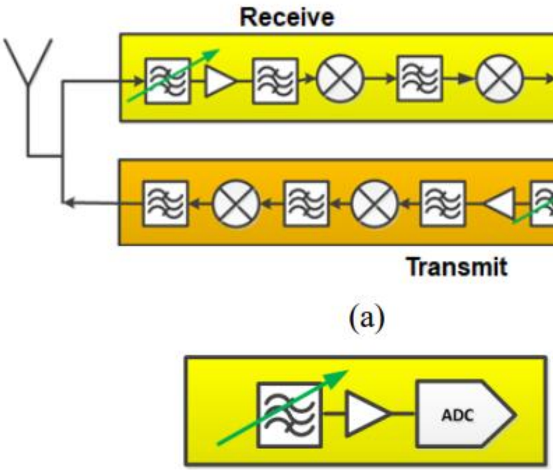


Figure 4: (a) Typical Reference Super Hetrodyne Topology, (b) Direct Sample Topology [5]

It has an initial filter between the aperture and the LNA (low noise amplifier), generally an octave sub-dividing switched filter bank. This filter has shallow insertion loss but wider percent bandwidths. The ***superhet*** is also identified by an ***up/down*** convert or two mixers, each followed by a high-performance IF filter to utilize narrow band pass filter functions. The overall size of this kind of assembly is driven by both the switch filter bank and the two IF filters, along with the LO generator. Switching to a direct sampled system offers the advantage of a more compact receiver architecture that allows significant flexibility in the digital manipulation of received signals. The challenge is that without the mixers to separate and isolate all of the close-to-carrier interferers, the filters in a direct sampled system need to be narrower in percent bandwidth, contiguous, and able to cover the same or broader overall frequency range, but small enough to be of reduced size.

The broad range between the smallest and largest detectable signals, without a notable detected distortion, is called SFDR (Spur Free Dynamic Range). The lower end of this range can be limited by noise, calculated through NF (noise figure), and the higher end of the spectrum is determined by TOI (Third Order Intercept). RF filters in receive systems, ***superhet*** or directed sampled, can impact the system noise figure and the third-order intercept.

The ***superhet*** block diagram, shown above, can be used as an example of a cascade noise figure, highlighting the critical need for both filter placement in the system as well as its insertion loss.

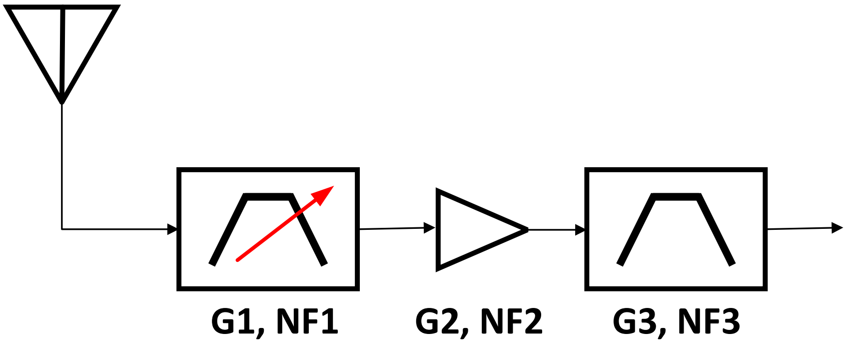


Figure 5: Front End Noise Figure Calculation Graphic

In this case, the cascaded NF for the system is represented as:

NF = (G1*NF1) + (NF2 – 1)/G1 + (NF3-1)/(G1G2)+ ...[6]

But because the filter is before the LNA (Low Noise Amplifier) and not reduced by the gain of the LNA, G1 is 1, so the same equation can be shown as:

NF = NF1 + (NF2 – 1)/G1 + (NF3-1)/(G1G2)+ ... [6]

NF1 represents the noise figure of the RF filter; since the filter is passive, the insertion loss is the NF1, so if the filter has a -3 dB insertion loss, it contributes 3 dB to the overall system noise figure. The straightforward solution would be to add gain to that filter to minimize or eliminate its impact on the system noise figure, but that would negatively impact the IIP3 / TOI of the system and the overall dynamic range. When examining third-order spurs in a system, their power level increases by 3 dB; for every 1 dB, the input signal increases. Another way of looking at this is that for every dB of gain put back into the pre-LNA filter, third-order harmonics will increase by 3 dB. IIP3 can be calculated from the plot:

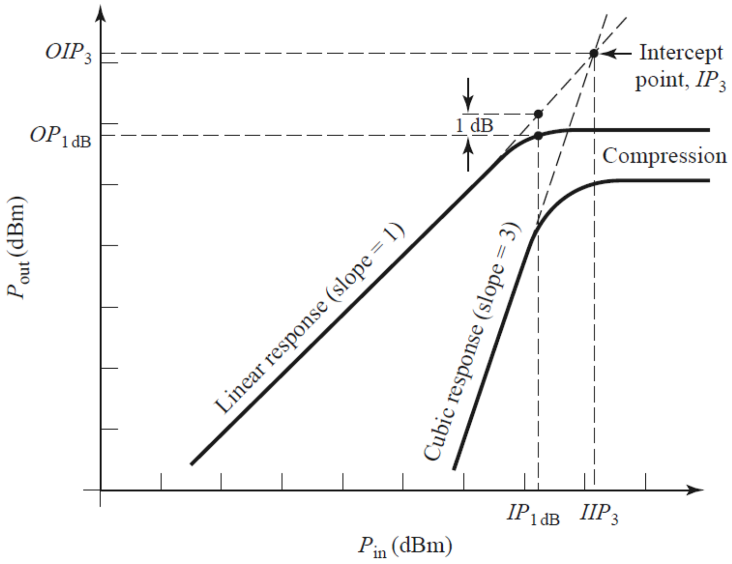


Figure 6:TOI Plot [7]

A low NF and a high IIP3 maximize the overall system dynamic range for the ***superhet*** or directly sampled receiver. The need for filters to be contiguous and (passive) low loss while meeting the filtering requirements of the systems is a complex trade to maximize dynamic system range.

Traditional switched filter banks for ***superhet*** receivers traded size for performance to meet DoD (Department of Defense) related filter requirements that ultimately roll-up to dynamic range constraints. These filter banks (Figure 7) were typically sub-octave (%BW > 20%), large assemblies that prioritized the lowest possible insertion loss so that the impact on noise figures was minimal.

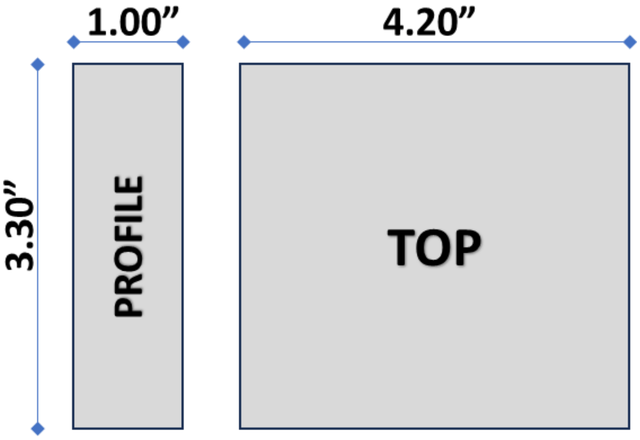


Figure 7: Typical COTS Switched Filter Bank

Cell phones also need low loss filters, but the intent is more to limit the need for signal amplification, which requires more parts, consumes more power, and takes up more footprint. For cell phones, small size and low cost are critical. If the filters do not have low loss, the circuit would need to add an amplifier to recover the loss. The implications of this parts are significant, as it’s another part per phone to purchase, it consumes power which leads to faster battery drain or a new battery development effort, and changes in linearity, which may impact the built in antennas. Ultra-high-volume needs would most likely pay a heavy financial penalty for adding amplifiers. Due to the differences in both Bandwidth and frequency, filters for cell phones are primarily acoustic technology as opposed to DoD filters which use more waveguide, planar, and chip and wire components.

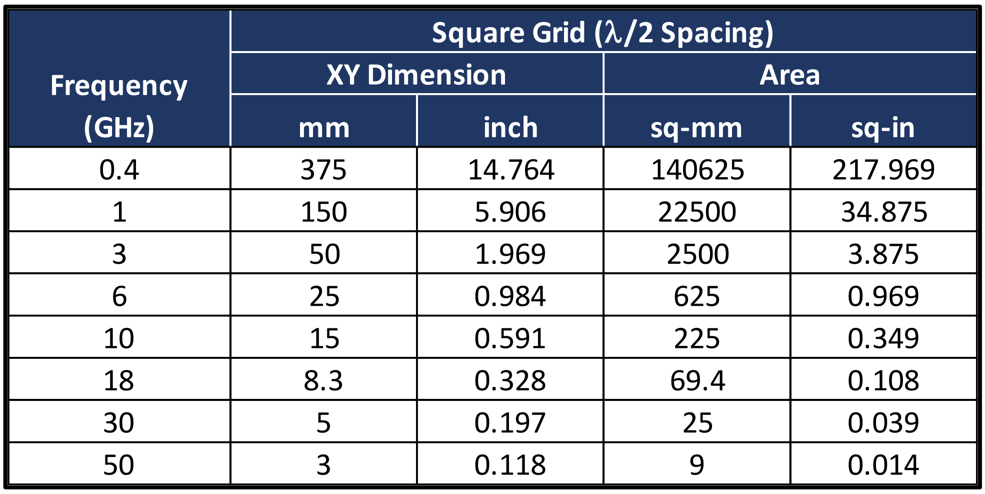
Another difference between the commercial cell phone filter needs that stands opposite of the DoD requirements is continuous or contiguous coverage. Cell phone bands operate over multiple frequencies, but have gaps, more the higher in frequency past 4 GHz, in-between filters which do not filter out the spectrum.

From a size and loss standpoint, acoustic filters, SAW (Surface Acoustic Wave) and BAW (Bulk Acoustic Wave) seem like ideal filters for DoD technology. Driving requirements such as max frequency (around 6 GHz), power handling less than 1 W, and limitations in extending %BW past 10% have limited the use of acoustic filters in DoD applications. Innovation of new filters is primarily in the commercial (cell phones) area as opposed to DoD work simply because of the money available. One example shows a typical ***superhet*** system in the DoD environment may require 100 to 1000 filters for the lifecycle of that hardware. Direct sample receivers use more, around 10,000 filters per lifecycle. By comparison, a typical cell phone filter will be used over a billion times per year. [8]

As cell phones move further into 5G and 6G frequency plans, their frequency plans are expanding past typical 3G and 4G LTE spectrums, pushing the acoustic technology. Recently, DARPA released a program called COFFEE [9] which addresses needs from 2-18 GHz. This effort has multiple technology efforts, but several are using acoustic technology past what traditional acoustic limitations set. Several companies, Northrop Grumman and Acoustics, are pushing acoustics well into Ku-Band (12 – 18 GHz), where typically limited closer to 4 GHz. The target is a minimal footprint but high-performance device assembly.

What is the wideband challenge for RF Filters? For commercial applications, filters need to be very small, narrow Bandwidth, high performance, and very inexpensive. For DoD filters, filters need low insertion loss, more selectivity, more attenuation, varying bandwidths, larger filters (filter bank), and across a broader spectrum; but also, be smaller in size and cost than ever.

Size over frequency, mainly when limited to elements, is constrained by the highest frequency.



Frequency (GHz)	Square Grid (λ/2 Spacing)			
	XY Dimension		Area	
	mm	inch	sq-mm	sq-in
0.4	375	14.764	140625	217.969
1	150	5.906	22500	34.875
3	50	1.969	2500	3.875
6	25	0.984	625	0.969
10	15	0.591	225	0.349
18	8.3	0.328	69.4	0.108
30	5	0.197	25	0.039
50	3	0.118	9	0.014

Figure 8: On-Grid Size by Frequency

As shown in Figure 8, the upper-frequency extent of the RF sensor will set the element grid spacing and, therefore, an available footprint for the filter assembly. Another way to look is by log chart.

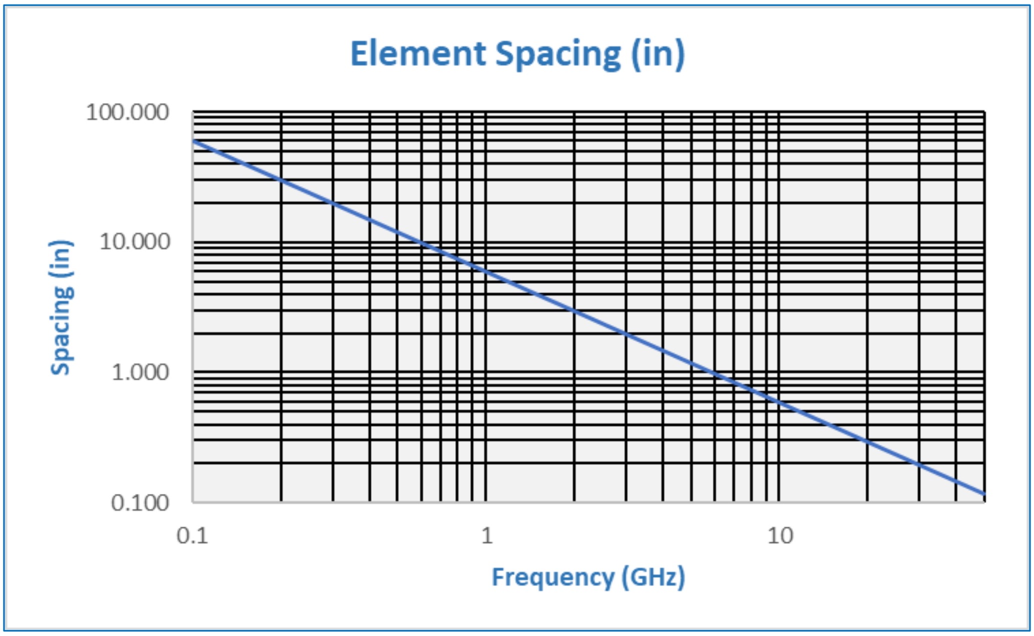
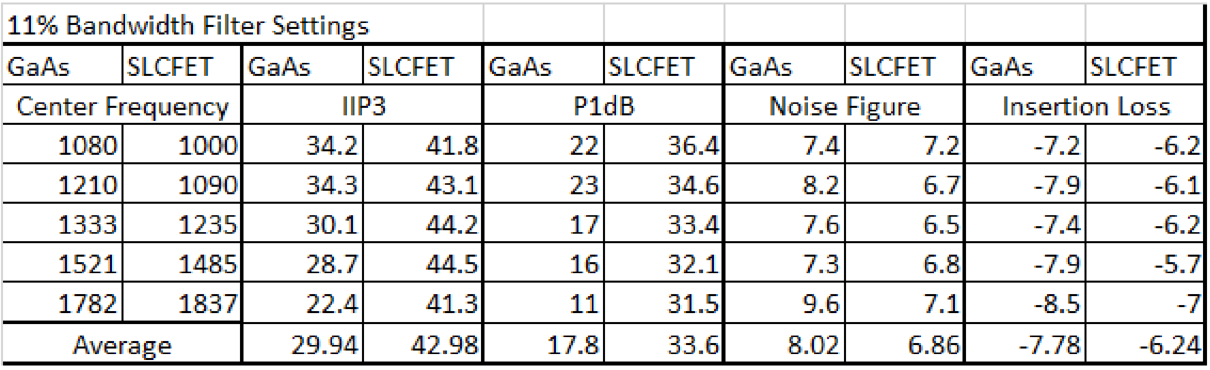


Figure 9: On-Grid Element Spacing

For a single-octave or narrowband system, this is not so much of an issue as a multi-octave or wideband system. Suppose the system is operating at 6 GHz with a grid of 625 mm^2, compared to a system running from 1 to 18 GHz, where the footprint is established by the 18 GHz grid (69.4 mm^2) but must fit 1 GHz at 22500 mm^2. Waveguide and planar filters have dimensions set by frequency wavelength (ʎ); nothing will serve on the grid.

Two new technologies are actively working to solve the wideband RF problem of fitting on-grid, SLCFET-based filters and the ARABIKA (Acoustic Resonator Multi-Mode Based Densely Integrated S-Ku Filters for Advanced RF Systems) solution to DARPAs COFFEE. SLCFET [12] is a technology enabler integrated into filter technology. Initial designs are accomplished across two octaves [9] 0.5 to 2.0 GHz demonstrated contiguous, constant bandwidth filters. Follow on works showed reconfigurable bandwidth filters from 1-2 GHz. Compared to a GaAs version of the same filter, there were significant improvements in IIP3, Insertion Loss, Noise Figure, and P1dB.



11% Bandwidth Filter Settings									
GaAs	SLCFET	GaAs	SLCFET	GaAs	SLCFET	GaAs	SLCFET	GaAs	SLCFET
Center Frequency		IIP3		P1dB		Noise Figure		Insertion Loss	
1080	1000	34.2	41.8	22	36.4	7.4	7.2	-7.2	-6.2
1210	1090	34.3	43.1	23	34.6	8.2	6.7	-7.9	-6.1
1333	1235	30.1	44.2	17	33.4	7.6	6.5	-7.4	-6.2
1521	1485	28.7	44.5	16	32.1	7.3	6.8	-7.9	-5.7
1782	1837	22.4	41.3	11	31.5	9.6	7.1	-8.5	-7
Average		29.94	42.98	17.8	33.6	8.02	6.86	-7.78	-6.24

Figure 10: GaAs vs. SLCFET Filter Performances

Unlike COTS (Commercial Off the Shelf Technology) parts, this is a filter bank with hundreds of filter channels, contiguous coverage across the band, low insertion loss, and by comparison, small at 6mm x 6mm. Wideband or multi-octave coverage is possible, as demonstrated in [11], as switched filter banks can be combined with SLCFET switches to cover large blocks of the RF frequency spectrum.

The ARABIKA approach is a developmental approach using a type of acoustic resonator that resonates at frequencies higher than 6 GHz. Preliminary results have already demonstrated high Q resonance at 18 GHz.

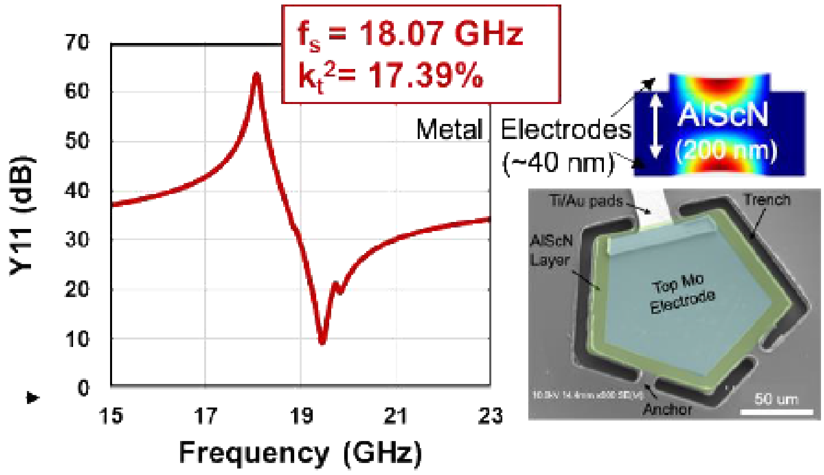


Figure 11: 18 GHz Acoustic Resonance [12]

The final, on-grid solution is a trade between performance and size. The SLCFET-enabled reconfigurable filters are a modular approach to reconfigurable bandwidths and dynamic frequency selections, the ability to switch in more filters to cover more comprehensive frequency spectrum coverage, and (control allowing) hundreds to thousands of filter options from 5% bandwidths up to 100% bandwidths. Conversely, the acoustic solution in ARABIKA offers fewer filters at a better insertion loss, better selectivity/attenuation, and a 2-18 GHz on-grid solution. Both solutions offer contiguous coverage from their respective start to stop frequencies. The SLCFET enabled device set is dynamic in both center frequency and bandwidth through the tuning range, while the acoustic solution is currently only dynamic in position in frequency.

Conclusions

Wide-band, multi-octave spectrum needs bring a significant challenge to the existing RF filter device technology. Constraints traditionally applied to single filters and sub-octave switched filter banks are now being applied to tens and hundreds of filters. This solution set will vary based on market, as the DoD and commercial industry are looking for small filters, but with significantly different requirements from cost to bandwidth. Advances have been made in both areas, but the overall need for the DoD presents an increased challenge which is only starting to be addressed.

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