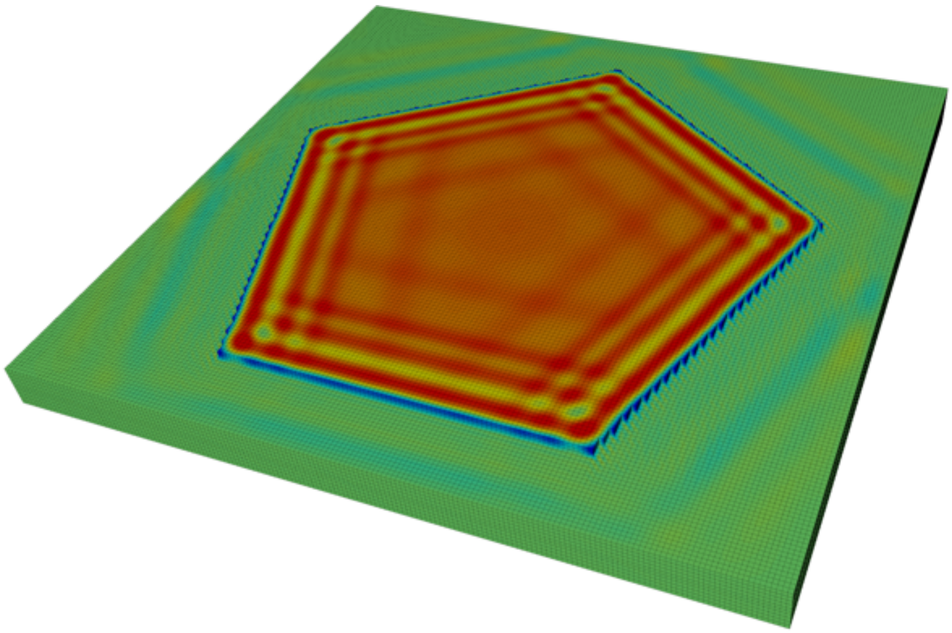
DESIGN AND OPTIMIZATION OF FBAR FILTERS TO ENABLE 5G

MEMS and Sensors Whitepaper Series

This white paper is part of a series of MEMS and Sensors topics from OnScale.



Whitepaper Topics: 5G, RF, RF filter, MEMS, surface acoustic wave (SAW), bulk acoustic wave (BAW), film bulk acoustic resonators (FBARs), finite element analysis (FEA), acoustic filters, analog filters, massive multiple-input multiple-output (MIMO), mobile network

About Us: OnScale's multi-physics solvers have been at the cutting edge of product design and analysis for over 30 years. Heavily used by leading global companies and universities, OnScale CAE and Cloud HPC solutions allow engineers of all fields to run accurate simulations in drastically reduced time-frames, driving the need for physical prototypes down and accelerating product design cycles.

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Introduction

While 4G LTE and LTE-Advanced technologies are still being deployed worldwide, the next generation in wireless communication promises a paradigm shift in throughput, latency, and scalability. By 2025, the emerging wireless 5G market is expected to reach a total value of $250B[1]. 5G is projected to be 100 times faster than 4G LTE and 10 times faster than Google Fiber (a physical connection). To put this into perspective, a high-definition movie will take less than a second to download on 5G, compared to 10 minutes on 4G LTE. Data rates will be further improved by using massive multiple-input multiple-output (MIMO) technology that originally were designed for use in IEEE 802.11n Wi-Fi networks. Multiple antennas will be used to increase data rates and range compared to single antenna systems while using the same amount of power. This might very well be the beginning of the end for cable companies providing a physical cable to the home.

The increased data rates of 5G are expected to boost emerging technologies such as autonomous vehicles, mixed reality (virtual reality and augmented reality), and the Internet of things (IoT). Autonomous vehicles, for instance, will require data to and from a vehicle much faster than today's LTE mobile networks can provide. Modem chips that can handle gigabits per second will be required for vehicles to communicate to each other and their surroundings for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, collectively known as V2X. V2X is expected to use a short-range wireless communication technology that allows a vehicle to interact with other parts of the traffic including streetlights, buildings, cyclists, and even pedestrians. It will require seamless and fast communication solutions in complicated urban environments and will create an entirely new market for modems and analog filters.

Modern modems like the ones used in mobile phones are compatible with multiple transmission bands, including 3G, 4G LTE, Wi-Fi, and Bluetooth. To avoid cross talk and optimize the quality and throughput of each band, a dedicated analog filter is used for each of the bands. Surface acoustic wave (SAW) filters are primarily used for 2G and frequencies below, while bulk acoustic wave (BAW) filters are used for 3G and above. One BAW filter type is called a film bulk acoustic resonator (FBAR). These filters are made from piezoelectric material sandwiched together to create a network of resonating structures that resonate in the frequency range of 100 MHz to 10 GHz. FBARs are highly complex devices and are challenging to design since there are physical parameters (i.e. geometry and materials) as well as electrical properties to consider. OnScale has developed a fully cloud-enabled simulation product optimized for multi-domain simulations of piezoelectric devices such as FBARs. This paper will focus on how FBARs can be efficiently and effectively simulated using OnScale Cloud CAE to reduce cost, risk, and time to market.

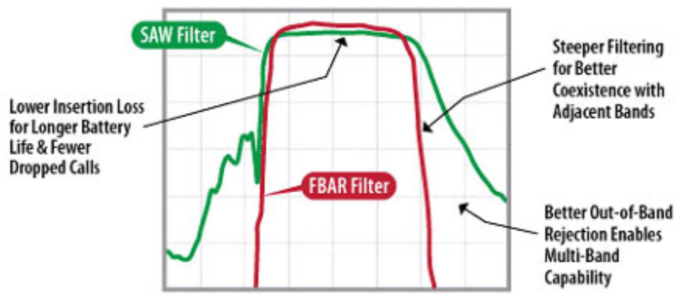
[1] "5G Wireless Market Worth $250 Billion by 2025: $6 Billion Spend Forecast on R&D for 2015-2020", PR Newswire, March 2016

Development of FBARs for 5G

SAW filters have been used in mobile phones for 20 years, but it was not until 2001 that BAW and FBAR filters were introduced into the market. While more complex and more expensive to fabricate, these filters are ideal for applications that require higher performance than SAWs. An FBAR filter generates a bulk wave inside a piezoelectric thin film that is sandwiched between two electrodes. A high-frequency signal is applied to the electrodes and an acoustic wave resonates in the structure at a designed frequency determined primarily by the shape and thickness of the piezoelectric thin film.

***Table 1:** FBAR Filter Fact Sheet (Source: EDN)*

Advantages over SAW



Filter Type	Bandpass
Frequency Band	> 3 GHz
Acoustic Wave Velocity	11,300 m/s (typ)
Piezoelectric Material	AlN, ZnO
Packaging	e.g. 1.1x1.4 mm^2 footprint, flip-chip

FBAR filters are a type of bulk acoustic wave (BAW) filter with superior performance and steeper rejection curves compared to surface acoustic wave (SAW) filters. FBARs feature lower insertion loss (0.3 dB to 0.5 dB), which equates to significantly lower current consumption and, as a result, extended battery usage for handheld electronic devices. FBARs use piezoelectric thin films with thicknesses from micrometers to tenths of micrometers and resonant frequencies between 100 MHz and 10 GHz. Two common piezoelectric materials used for the thin film are aluminum nitride (AlN) and zinc oxide (ZiO), with reports of PZT being tested as well. The structure of the FBAR is made by forming cavities in the silicon substrate, which can be effectively performed using deep reactive ion etching (DRIE) or by using sacrificial layers. It is in these cavities where the acoustic waves resonate when the FBAR filter is in use. While FBARs can process higher frequencies than SAWs and are more resilient to static electricity, controlling the thickness of the deposited piezoelectric layers during fabrication is very challenging. Figure 1 shows a cross-section of an FBAR filter with piezoelectric layer suspended above an etched cavity.

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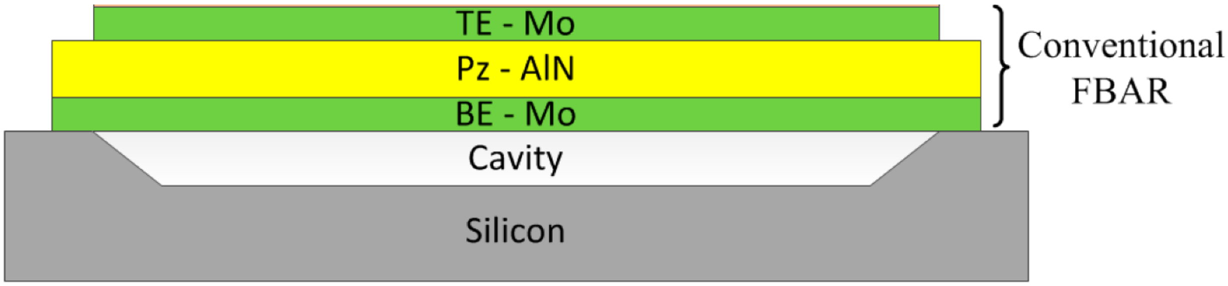

Figure 1: *FBAR filter model cross-section (Source: MDPI).*

A range of different shapes and sizes can be used depending on the performance requirements, with early designs using square shapes and more advanced designs using pentagons. Figure 2 (left) shows a layout of a pentagonal FBAR resonator. This has been imported into OnScale's platform from a GDSII file and modeled using OnScale's cloud solver. A rendering of the resulting device is shown in Figure 2 (right).

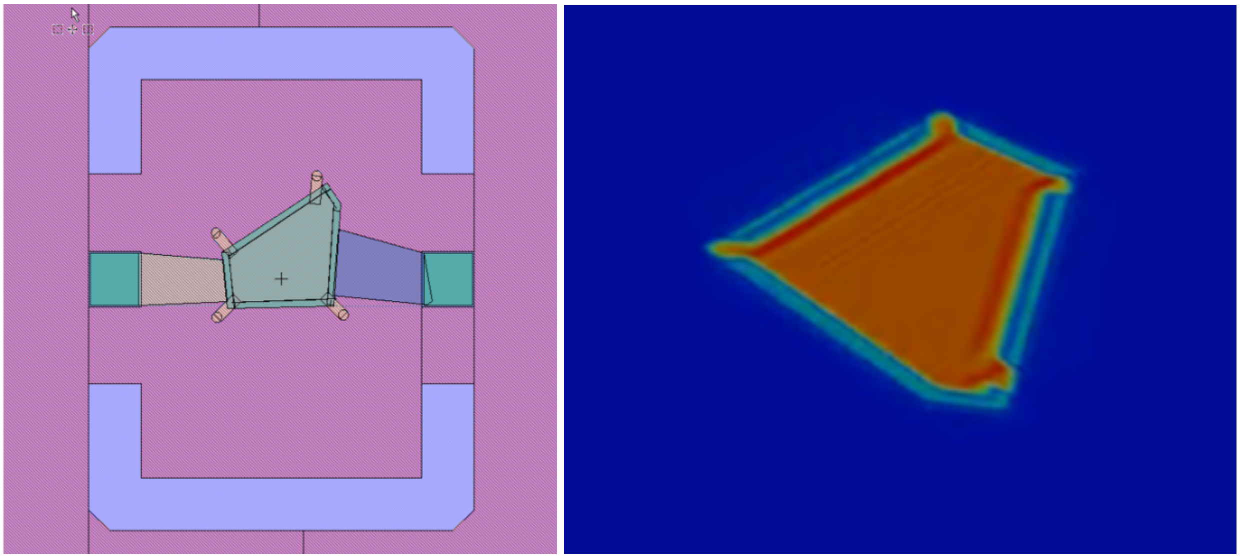

Figure 2: *GDSII import and simulation of a pentagonal FBAR filter (Source: OnScale).*

Designing FBARs Using FEA

The main purpose of modeling and simulating FBARs is to minimize the number of fabrication runs and speed up time to market. FBARs are intricate devices that operate in both the electrical and mechanical domains, which are coupled through piezoelectric physics. Complex acoustic wave propagation must be studied to minimize spurious modes and maximize key performance indicators (KPIs). Months of simulation time can be saved, and the number of prototype runs reduced, through enhanced FEA simulation and optimization. Detailed simulations also enable quick troubleshooting of existing design and process issues. This is particularly important because fabrication of FBARs is challenging and small imperfections and process variations can impact the performance.

Performing the numerical analyses described above are monumental tasks for legacy solvers, particularly in full-3D, where the number of meshed elements can balloon into the millions. These legacy solvers use memory-intensive frequency-domain approaches and general formulations that are better suited for commodity mechanical modeling than the high-performance, multi-physics device space occupied by FBARs. In contrast, OnScale utilizes a highly efficient time domain solver which offers several advantages over traditional approaches. The efficient use of memory allows larger and faster simulations, enabling the investigation of key parameters and effects such as electrical impedance, insertion loss, Q value, coupling constant, resonant frequency, lateral modes, coupling to substrate, energy flux, and loading caused by electrodes. In the following section, we will describe a direct comparison of the modeling performance of OnScale versus an exemplary legacy solver that is still being used by a substantial number of companies in the 4G resonator market.

OnScale vs. Legacy Solvers

A simple square-shaped FBAR filter will be used as an example for the simulation and optimization model (Figure 3). The design comprises an AlN piezoelectric layer with material properties input from full stiffness, piezoelectric, and permittivity tensors (Q = 3,000). The electrodes are made of molybdenum and the substrate is silicon with simple fixed boundary conditions. The design frequency is ~1.85 GHz. A 1D model will be used for a fundamental stack design, followed by a 2D model for initial analysis or parasitic modes, and a 3D model for final performance evaluation. 1D Models are an efficient tool for evaluating fundamental FBAR performance, determining the effect of material property changes and predicting the loading caused by electrode layers. 2D models provide valuable information about parasitic lateral modes and executing rapidly to allow many designs to be evaluated, and 3D models allow the full FBAR design to be assessed, providing information on the effect of mounting conditions and topology on final performance.

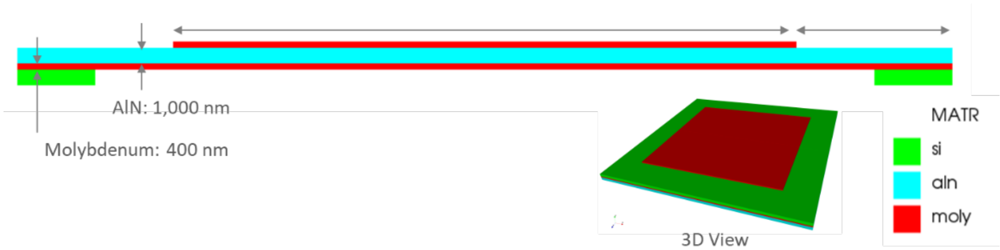

Figure 3: *Square FBAR design example (Source: OnScale).*

Using a mesh size of 200 nm to properly capture the shape of the acoustic waves with a wavelength of 1.5 um, the 2D model has a manageable 5,000 elements to account for. In 3D, however, over 2.5 million elements must be solved at each frequency/time step. Legacy solvers are incapable of addressing the final and most crucial step in the design process because they lack the efficiencies of OnScale's numerical algorithms and meshing techniques. A direct runtime comparison between OnScale and the leading legacy solver was performed using the square FBAR design in 3D. Table 2 clearly captures the advantages of using OnScale, where both the solve time and RAM requirements were reduced by a factor of 99%.

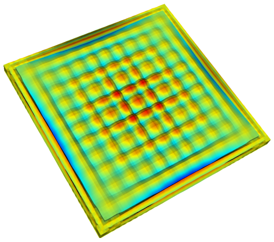

Figure 4: *3D model of a resonating FBAR (Source: OnScale).*

Table 2: *Performance Comparison*

	Legacy[2]	**OnScale**
RAM	600 GB	3 GB
Solve Cycles	200 frequencies	3,000 cycles
Solve Time	1,000 h	10 h

[2] R. Thalhammer & J. D. Larson, "Finite Element Analysis of BAW Devices: Principles and Perspectives," 2015 IEEE International Ultrasonics Symposium (IUS), Taipei, 2015, pp. 1-10.

The ramifications of this performance gap with legacy solvers are that critical design decisions are made based on an incomplete analytical understanding at best, and complete guess-work at worst. Expensive MPW prototype runs are used in lieu of fundamentally sound models of the device, and the 2nd and 3rd order effects that can only be captured with a full 3D model, such as coupling between resonators (in a ladder filter), packaging effects, and thermal stress, are studied empirically at great cost. OnScale delivers the necessary computational efficiencies to bring the full power of an HPC cluster to bear on the FBAR design process. But solving a single model can only provide so much insight into a design space with thousands or millions of degrees of freedom. To address this, it is also necessary to have the capability to leverage more computing power than is typically available using internal computing resources.

OnScale Cloud CAE as a Force Multiplier: Case Study

There are several ways that a simulation study can be accelerated to use less time and thereby increase the coverage and understanding of a given design space prior to prototyping. One method is to use Cloud Computing to run a range of models in parallel, allowing batch jobs to be completed rapidly. Another method is the use of MPI to allow simulations to be broken down through domain decomposition and shared between computing resources. Combining these two approaches offers enormous increases in speed (over 50X). In this section, we investigate a massively parallel optimization study of a pentagonal resonator FBAR design using OnScale Cloud and a genetic algorithm implemented in MATLAB.

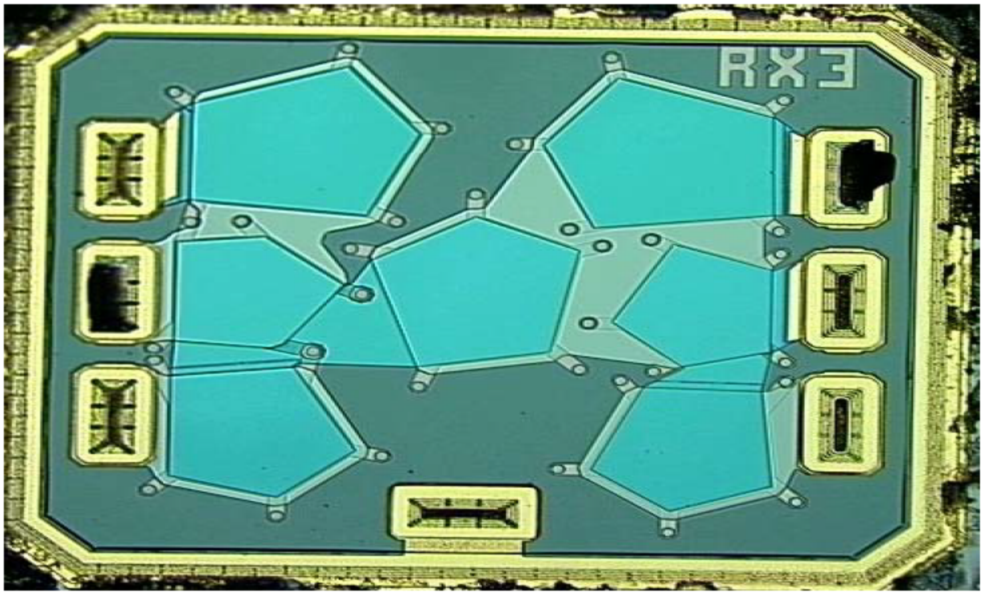

Figure 5: *Die photo of an FBAR employing multiple pentagonal resonators.*[3]

[3] R. Ruby, "A decade of FBAR success and what is needed for another successful decade," 2011 Symposium on Piezoelectricity, Acoustic Waves and Device Applications (SPAWDA), Shenzhen, 2011, pp. 365-369.

Study Setup

Resonators with non-parallel sides support weaker lateral resonances than ones with parallel sides, such as in the previous example. Both quadrilateral and pentagonal designs are being explored in the industry to optimize the simple square FBAR. An arbitrary pentagonal top electrode is added to the 3D FBAR model with the goal of reducing spurious resonances. Using simple trigonometry, an arbitrary pentagon is created with seven input variables. The model is fed into an analyzer together with the design input variables. Keeping the area of the arbitrary model constant makes it easy to compare performance between different models. To simplify the study, the piezoelectric coupling was turned off to make the model purely mechanical. The device was excited with a pressure load applied to the top electrode to simulate the thickness mode vibration of the device. The device size was scaled down to an area equivalent to 50x50 µm and the design fitness was assessed by calculating the average lateral wave velocity while trying to minimize the peak in band frequency components. These simplifications represented a 10X computational speed increase and are accepted approximations in the industry for large scale conceptual design exploration.

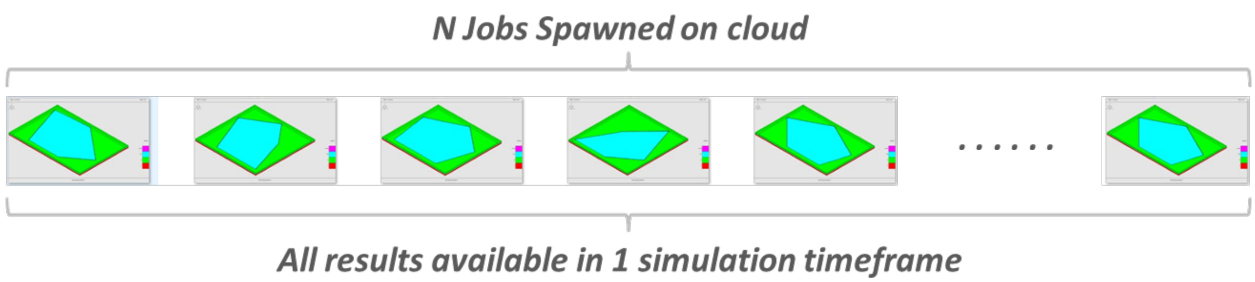

Figure 6: *Parallel design study on the cloud (Source: OnScale).*

Study Results

The model was run for 52 generations and a total of 3,640 designs were investigated. It ran for a total of 68 hours and utilized 8.67 GB of memory. The simulation tool was connected to MATLAB's Global Optimization Toolbox, which allowed various parameters to be tracked during the run including the current best design. The optimal designs were found to have edges angled to the substrate edges to avoid strong reflections, whereas the worst design had three edges close to parallel with the substrate causing increased lateral mode activity. These results can be seen in Figure 7, where the best pentagonal design shows a significant reduction in ripple when compared to the square device, which was the starting point for the exercise. It is important to note that each of the 3,640 designs were simulated in full 3D, a study that would take a legacy solver nearly a year to complete on the same computing resources. The results provided below are indicative of the type of results that can be achieved with FEA for a simple representative example, however further design space exploration is required in this specific case.

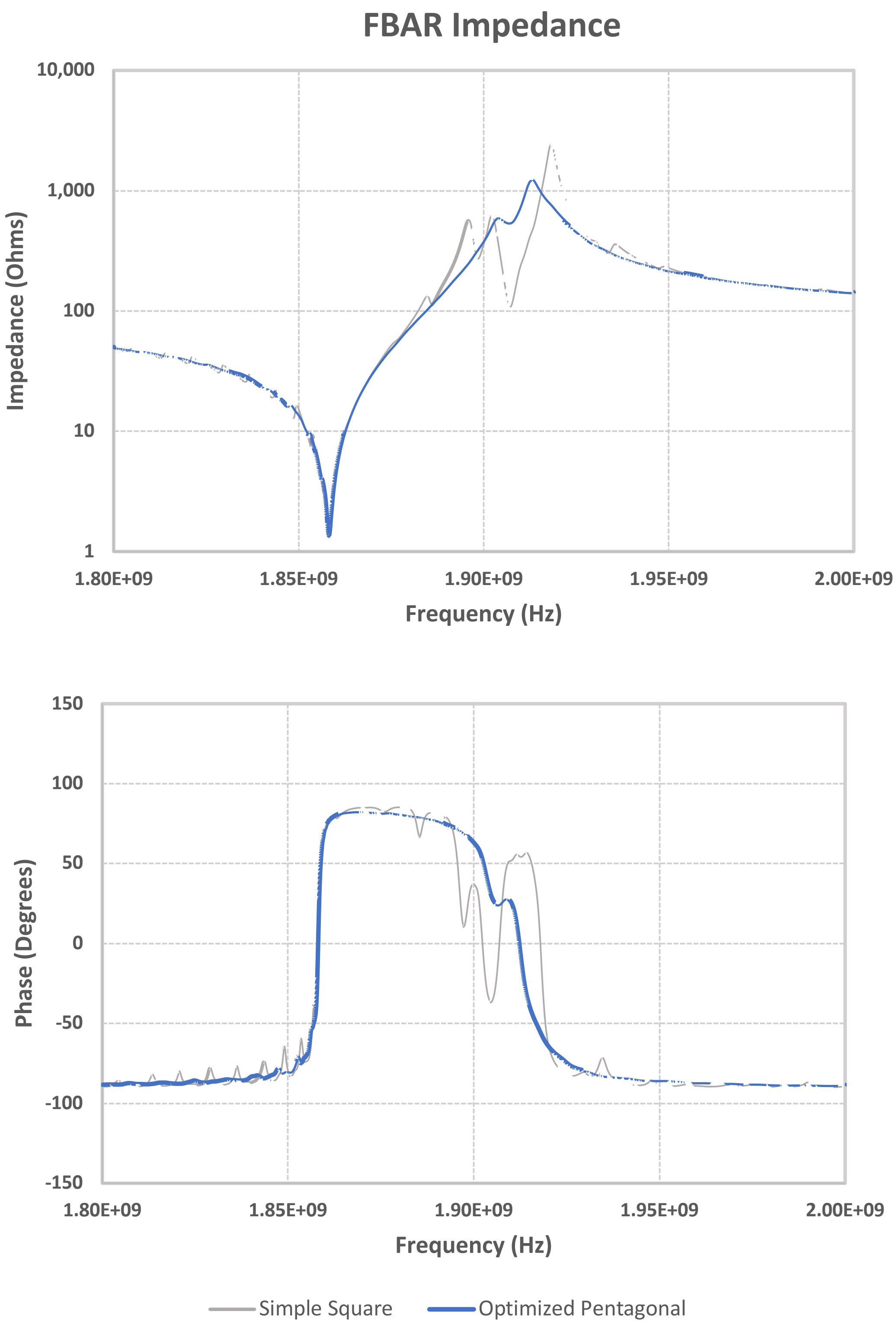

Figure 7: *Comparison of simple square design (gray) and optimized pentagonal design (blue) (Source: OnScale).*

Summary

Despite the lack of standards, 5G is promising faster data rates for mobile phones and will be an enabler for autonomous vehicles and the IoT. The move from 4G to 5G represents orders of magnitude higher data rates at frequency bands beyond 3 GHz. Smartphones are already being challenged with multiple radios operating in frequency bands close to each other, necessitating the use of precision analog filters to effectively isolate bands. SAW filters have been successfully used up to 1.5 GHz, whereas BAWs and FBARs are used for higher frequencies. FBARs are a BAW type that uses thin piezoelectric films to generate acoustic waves in the bulk substrate. This results in superior insertion loss performance and rejection of frequencies outside the band of interest. For these reasons, FBARs are well-positioned to be used in 5G applications. However, legacy CAE tools are incapable of performing complete 3D design studies, which are a critical step in optimizing the design and improving the time to market for these highly complex structures. This paper has demonstrated how FBARs can be simulated using a real-world example of a massively parallel pentagonal resonator design study, highlighting the need to choose the correct CAE tools in order to fully understand a design space and accelerate time to market.

About OnScale: OnScale, the global leader in CAE and Cloud HPC, empowers engineers to accelerate innovation for next-generation products such as 5G smartphones, Internet of Things (IoT) and biomedical devices, and driverless car products. OnScale Cloud combines world-class Computer-Aided Engineering (CAE) multi-physics solvers with the limitless power of cloud High Performance Computing (HPC) to eliminate performance and cost constraints.

About the Author: Dr. Gerry Harvey is the VP of Engineering at OnScale. A numerical scientist, engineer, and FEA expert with over 15 years of industry experience, Gerry helps customers get up to speed with OnScale solutions and maximize the potential of OnScale Cloud.