The Linley Group

MOBILE CHIP report

Insightful Analysis of Mobile System Design

FBAR Gets Excellent Reception

Superior Performance of Avago RF Chips Sweeps Flagship LTE Phones

By Sanjay Sethi (July 27, 2015)

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Although most smartphone reviewers focus on processor speed, users are more worried about getting five bars of cellular reception whenever possible. Reception depends on the quality of the RF (radio frequency) subsystem, which in turn depends on a critical but unglamorous component: the RF filter. Using its unique film-bulk-acoustic-resonator (FBAR) technology, Avago delivers the best filters in the industry, and it has the flagship design wins to prove it. As the rapid transition to LTE drives tremendous growth in FBAR shipments, competitors are eying this market in hopes of getting a piece of the pie.

At its most basic, the RF filter passes wanted frequencies and rejects unwanted frequencies (for band selection and coexistence with other services), and it's instrumental in allowing the many receivers in a phone to process only the intended signal. Previously, phones operated primarily over a small number of frequency ranges specific to a given region of the world. Today, manufacturers want to build global phones that can function across different regions and different carriers. The more frequency bands a phone needs to support, the more filters it requires.

As Figure 1 shows, a typical LTE phone needs multiple RF filters, each tuned to a specific band. For each supported band, the phone normally requires a transmit filter and a receive filter, plus another receive filter for the second (diversity) antenna. Other radios, such as Bluetooth, GPS, and Wi-Fi (not shown), require additional filters. For a high-end phone that supports 15 bands, the total number of filters can approach 50. Increased band count and a future shift to 4x4 MIMO could raise this number to 100 by 2020. Mainstream LTE phones use fewer filters, and 2G/3G phones require only a handful.

In early cellular generations, filtering requirements were simple and could be adequately handled using SAW (surface acoustic wave) filters. During the evolution of CDMA and 3G, Avago found that its FBAR technology was well suited to more-challenging filter requirements. To take advantage of LTE, smartphones have become more complex.

As a result, phone manufacturers have expanded their use of FBAR technology. In 2014, Avago's Wireless Communications business generated $1.69 billion in revenue, nearly doubling in size from the previous year. FBAR-related products contributed the vast majority of this revenue. Avago filters appear in the Apple iPhone 6 and Samsung Galaxy S6, as well as flagship smartphones from HTC, Huawei, LG, Xiaomi, and others. The company's wireless business will grow after its acquisition of Broadcom (see *NWR 6/22/15,* "Breaking Down Broadcom").

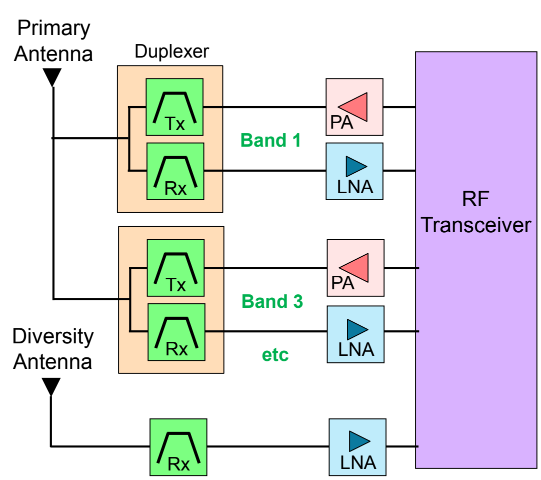

Figure 1. Typical LTE RF subsystem. Each band requires transmit and receive filters on the primary antenna and an additional receiver filter on the diversity/MIMO antenna. A high-end LTE phone may support 15 bands.

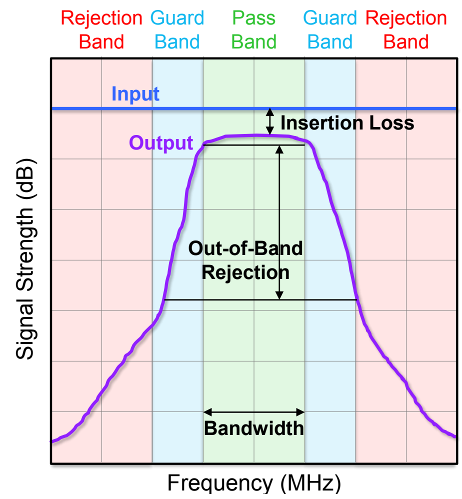

Figure 2. Frequency response of a hypothetical bandpass filter. The filter passes as much signal as possible within the desired band while reducing signal levels at frequencies outside that band.

RF-Filter Basics

A filter is a circuit element that converts an input signal to an output signal according to its frequency. Cellular devices require bandpass filters, which function as in Figure 2 shows. If the frequency is in the desired (pass) band, the output signal level is very close to the input signal level, with a small reduction called the insertion loss. The output signal drops rapidly in the intermediate area known as the transition or guard band, and it should be as low as possible for all other frequencies. The difference between the minimum signal level in the pass band and the maximum signal level in the rejection band is called out-of-band rejection.

A good filter should have minimal insertion loss, since any loss degrades the signal, reducing the sensitivity of the receiver and wasting power when transmitting. It should also have high out-of-band rejection, minimizing interference by attenuating out-of-band signals. A steep slope in the filter response increases out-of-band rejection; because the shape of this curve resembles a woman's skirt, a good design is said to have a steep filter skirt. The temperature coefficient of frequency (TCF) defines the change in the frequency with temperature and is generally measured in parts per million (ppm) per degree.

LTE can operate in more than 40 bands ranging from 700MHz to 3,600MHz (see *MCR 3/31/14*, "New Products Level LTE Playing Field"), although a single phone typically implements 6 to 15 bands. Each band comprises 10–120MHz of spectrum, which is further subdivided into channels. A receive (Rx) filter allows the cellular subsystem to detect a signal in a specific band while reducing interference from other bands. The transmit (Tx) filter reduces unwanted (out-of-band) emissions before sending a signal.

A duplexer is a three-port component that filters RF signals at the point closest to the antenna, as Figure 1 shows. By implementing two filters in the same circuit, it allows simultaneous transmission and reception in the same band. The duplexer reduces the complexity, size, and cost of the RF subsystem. Adding filters to the device can extend this concept to triplexers, quadplexers, and so on (generically called multiplexers).

When operating in the more common full-duplex (FDD) mode, an LTE device can transmit and receive simultaneously on different frequencies. If these frequencies are near each other, the Tx and Rx filters must together prevent the transmitted signal from interfering with the received signal—a phenomenon called self-desense. This situation can require 50–60dB of isolation for full-speed operation. TDD systems, which alternately transmit and receive (at different times), have less stringent filtering requirements (20–40dB).

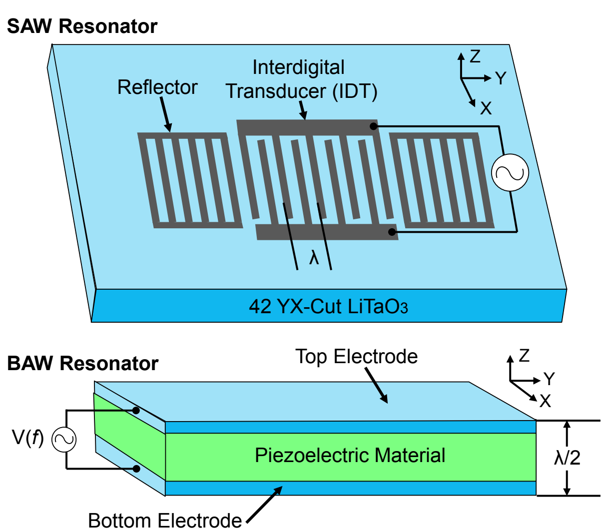

Figure 3. Comparison of SAW and BAW resonator designs. A SAW resonator conducts waves across the surface, whereas a BAW resonator keeps the waves in a vertical direction.

SAW and BAW Filters

RF filtering in handsets is dominated by surface-acoustic-wave (SAW) and bulk-acoustic-wave (BAW) filters. Acoustic resonators form the core of both. These devices experience acoustic-wave propagation, vibrating at a resonant frequency related to their dimensions and mechanical properties. In a sense, the resonator behaves as an acoustic cavity, trapping the wave in the medium. A surface acoustic wave is an elastic wave that travels along the surface of a crystal substrate in the *y* direction, and a bulk acoustic wave is an elastic wave that travels inside solid material in the *z* direction, as Figure 3 shows.

Resonators are combined in an electrical circuit called a ladder filter. Each "rung" of the ladder comprises two resonators, one connected in series and the other connected in shunt. Adding rungs improves rejection but also increases insertion loss. Some filter designs also include inductors or capacitors. The parameters of the resonators and the added components determine the skirt shape, out-of-band rejection, and impedance of the filter.

A resonator's Q factor specifies the ratio of the energy stored to the power dissipated; a high Q indicates the resonator loses little energy per cycle. A filter built with high-Q resonators has a steep filter skirt. BAW resonators have demonstrated better Q values than SAW resonators. Q values of 2,000 to 3,000 represent the state of the art for BAW resonators at 2GHz. In contrast, the best SAW filters achieve 1,000 to 1,500.

In addition, BAW filters have better power handling, since they are based on a parallel-plate capacitor rather than the SAW filter's long narrow interdigital fingers (IDTs). BAW filters also have less frequency drift with temperature. Furthermore, SAW filters are difficult to push beyond 2GHz, because their power density increases with the cube of the frequency.

The major advantage of a SAW filter is lower cost: it can be manufactured using one or two layers of thin-film metal deposition and one or two photomask layers. BAW filters, in contrast, need about 10 mask layers and many deposition layers. Another advantage of the SAW filter is that it can act as a balun (a device with single-ended input and balanced output). Also, the IDT pitch can vary depending on the mask layout, allowing resonators of significantly different frequencies on the same die.

FBAR and SMR-BAW Technologies

BAW filters are manufactured using two technologies: FBAR (also called free-standing membrane) and SMR (solidly mounted resonator). The fundamental difference between FBAR and SMR is the means by which the acoustic energy is trapped, as Figure 4 shows. FBAR uses an air cavity between the bottom electrode and the carrier wafer. SMR creates a Bragg reflector underneath the bottom electrode using a stack of roughly λ/4 thin-film layers with alternating low and high acoustic impedance (where λ is the wavelength of the target frequency).

An SMR device can be manufactured using traditional VLSI processing, whereas an FBAR filter is more like a MEMS device and thus can be complicated to manufacture. But the latter approach provides better effective coupling than the former ($k_{T\,EFF}^{\,2}$ of 6.9% versus 6.5%, or about 4MHz wider bandwidth at 2GHz), because the air/electrode interface traps more acoustic waves than the Bragg reflector. SMR can provide a better TCF than FBAR (–18ppm/°C versus –27ppm/°C, or about 2MHz less frequency shift from –40°C to +80°C at 2GHz), since the SiO_2 layers in the Bragg reflector have a positive TCF, which offsets the negative TCF of the other layers.

Manufacturing Challenges

The key to making acoustic filtering (e.g., SAW and BAW) devices is the use of piezoelectric materials as the medium and the use of transducers to convert between electrical signals and acoustic waves. The application of an electric field to a piezoelectric material produces mechanical stress or force. An inverse effect produces an electric field through imposition of a stress on the material. For BAW, the piezoelectric thin-film material that best balances performance and manufacturability is aluminum nitride (AlN).

Two unique and challenging processes for manufacturing thin-film BAW devices stand out. The first is piezoelectric-film deposition. This process must yield a highly uniform and textured crystalline film to provide strong coupling that is repeatable and uniform. The coupling coefficient cannot be trimmed, and its nonuniformity can become a major hazard to the yield.

The second manufacturing hurdle is the wafer-level frequency and layer-thickness trimming. For some applications, the three-sigma (3σ) frequency accuracy must be 0.1% (or 2MHz at 2GHz). To meet this target, the uniformity of the deposited thin films must be roughly 0.1% as well. But the best thin-film-deposition system achieves 3σ uniformity across the wafers of no better than 2% (40MHz at 2GHz). To overcome this limitation, equipment vendors have developed a trimming process. It takes a few minutes to trim one wafer (a six-inch wafer typically contains more than 10,000 filter die).

Thin-film BAW technology is compatible with any wafer processing, including silicon and gallium arsenide (GaAs). This flexibility allows integration of both active elements and filtering on the same chip. SAW devices are commonly constructed on a $LiTaO_3$ crystal substrate that cannot directly integrate other components.

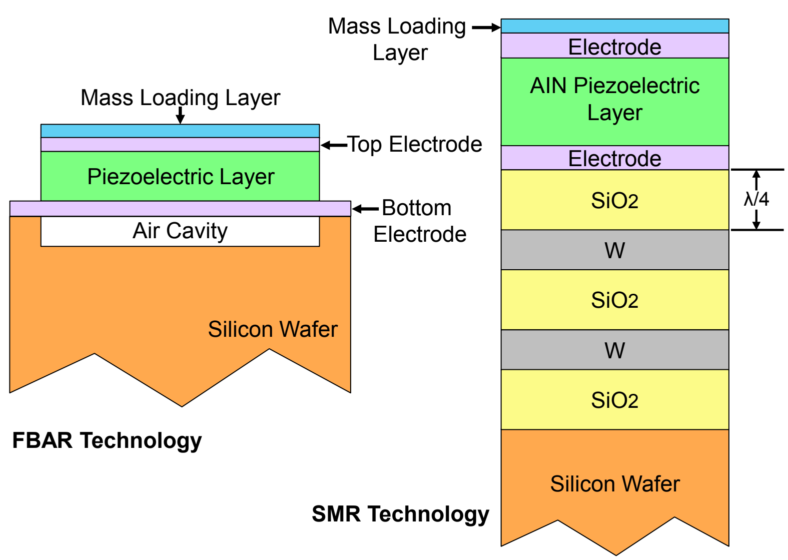

Figure 4. Comparison of FBAR and SMR structures. An FBAR resonator contains an air cavity that forms a drum-like structure. An SMR design instead uses layers of silicon dioxide (SiO2) and tungsten (W) to reflect sound waves.

Avago FBAR Technology

An early pioneer in MEMS technology, Hewlett-Packard (which spun off Agilent and later Avago) began research on FBAR technology in 1993. FBAR requires a free-standing membrane that connects to the substrate along its edge only. In early versions, membrane cracking was a chronic problem. Rich Ruby, director of the FBAR project at Hewlett-Packard (now Avago), said the films would "roll up like cigarette paper." Ruby and his team eventually solved this problem, and Avago now successfully manufactures more than one billion FBAR filters per quarter. No other supplier has brought this technology to mass production.

Perhaps the most important advantages of FBAR technology are its steep filter skirts and superior out-of-band rejection, as Figure 5 shows. These features are important to LTE because of the narrow gap between transmit and receive frequencies in many FDD bands. Newer LTE phones implement carrier aggregation (CA), which increases data rates by operating in more than one frequency band simultaneously (see *MCR 6/30/14,* "LTE-Advanced Gets CoMPed"). Since multiple bands are active at the same time, the opportunities for interference multiply. Each operator allows specific band combinations. Those involving adjacent bands are particularly difficult to implement; without high-quality filters, they will suffer low data rates (eliminating the benefit of CA) or may not work at all.

An example of the value that FBAR filters offer is in the use of Band 13 in the U.S. This spectrum, employed by Verizon for LTE service, is only 2MHz away from a new public-safety-radio (PSR) band. To avoid interfering with PSR operation, the LTE standard can require handsets operating in Band 13 to drastically reduce transmitted power. Such a power reduction has a major impact on network efficiency, reducing the range, as well as on the quality of service, greatly decreasing data throughput or even dropping calls. By combining a temperature-compensated FBAR duplexer that offers extremely fast roll-off with a highly linear power amplifier in an integrated front-end module

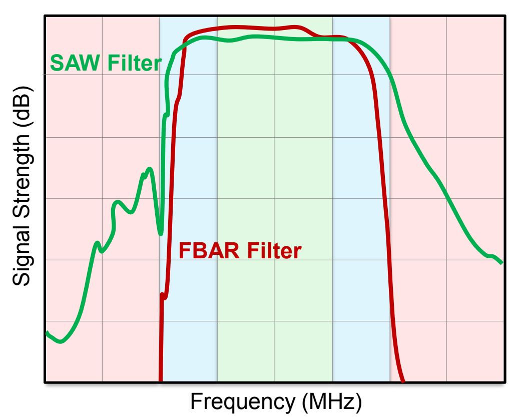

Figure 5. BAR versus SAW frequency response. FBAR has a lower insertion loss, steeper filter skirt, and better out-of-band rejection than SAW. (Source: Avago)

(FEM), Avago created a product that allows Band 13 handsets to operate at full power without interfering with PSR.

FBAR also has a lower insertion loss than typical SAW filters. This factor compensates for the higher losses associated with combining multiple bands in an LTE radio front end. Cell coverage improves because the phone can detect weaker signals that might otherwise result in poor reception or dropped calls. This effect can also improve real-world data rates; a stronger signal enables a more efficient modulation (e.g., QAM-64 instead of QAM-16). The end result is a better user experience and higher data capacity per cell site.

FBAR Improves Battery Life, Coexistence

Battery life is often benchmarked and compared across phones. On the transmit side, FBAR's lower filter insertion loss means less output power is needed for the same radiated power at the antenna, increasing battery life. For example, in a handset with a reference output of 450mA, a 0.5dB improvement in insertion loss saves 50mA. For a user that uploads 1GB of LTE data per month at 2Mbps, however, the transmitter is active less than five minutes per day, saving less than 4mAh of a typical 1,600mAh smartphone battery (2%).

Envelope tracking is a popular power-saving technique in which the supply voltage applied to the power amplifier (PA) is constantly adjusted to keep the PA operating at peak efficiency for the given instantaneous output-power requirements (see *MCR 11/24/14,* "What Is Envelope Tracking?"). But the switched-mode supplies that generate the time-varying power also generate noise, which appears as amplitude modulation on the output RF signal. This noise has a wide bandwidth and thus interferes with adjacent channels. It is particularly problematic for FD-LTE, where transmitted noise in the receive channel masks the received signal. FBAR filters provide the high out-of-band rejection and skirt roll-off needed to meet the receiver-sensitivity and adjacent-channel-selectivity (ACS) requirements.

FBAR filters can also reduce interference with Wi-Fi. As an example, the transmit frequency of European LTE Band 7 (2.50–2.57GHz) is located just above the frequencies that Europe assigns to Wi-Fi (2.401–2.488GHz). When using a smartphone as a Wi-Fi hot spot, for example, Wi-Fi operates simultaneously with LTE. Without superior filtering, the Wi-Fi transceiver can be overwhelmed by LTE transmission on Band 7. Serving in conjunction with an Avago ACPF-7124 Wi-Fi coexistence filter, the Avago ACMD-6107 duplexer provides sufficient protection to allow operation on even the highest-frequency Wi-Fi channels without interference. Competing filters with lower out-of-band attenuation can render the upper Wi-Fi channels unusable.

The vast majority of phones also support GPS and other location services. Because GPS signals are very low power (between –125dBm and –150dBm), any other signal in close proximity to the GPS frequency will desensitize the receiver. The steep filter skirt and wideband attenuation of the ALM-GN001 prefilter/low-noise-amplifier (LNA) module provides excellent out-of-band blocking of cellular and Wi-Fi signals, improving location accuracy.

As the number of filters per phone increases, minimizing their size becomes crucial. Avago developed Microcap encapsulation technology, allowing it to sell tiny FBAR filters in chip-scale packages for the most size-constrained applications. FBAR is a bulk material; hence, it offers excellent power handling for its size without requiring the parallel structures typical of SAW filters. In addition, the FBAR device also shrinks in size with increasing frequency, positioning the technology to address new high-frequency LTE bands at 2.5–2.7GHz and 3.5GHz.

A Variety of FBAR Products

As LTE rolled out, the need for superior filtering became evident as the newly allocated spectrum proved challenging. In particular, the 2.3–2.7GHz range contains many coexistence issues primarily between unlicensed 2.4GHz Wi-Fi and the LTE bands that surround it: Bands 7, 40, and 41. Avago offers various products to improve this coexistence, including the ACPF-7124 and ACPF-7424 Wi-Fi filters, the ACPF-8240 Band 40 filter, and the ACMD-6107 and ACMD-6307 Band 7 duplexers.

Owing to the increasing deployment of carrier aggregation (CA), demand for premium filtering has expanded beyond addressing coexistence problems. Avago's CA approach uses single-antenna multiplexing, enabled by FBAR, to minimize signal loss and improve isolation. In addition to simple duplexers, the company offers triplexers, quadplexers, and quintplexers. For example, the ACFM-7024 is a Band 2/4 CA quadplexer that addresses the North American market, whereas the ACFM-2013 is a Band 1/3 quadplexer that addresses China and other Asian countries. Avago is also developing the ACFM-7037, a Band 3/7 quadplexer for Europe. It plans to develop additional multiplexer products as new frequency combinations emerge.

Beyond the aforementioned discrete FBAR offerings, Avago pairs these same filters with its power amplifiers (PAs) to develop front-end-module products called PA duplexers (PADs). For example, the AFEM-7007 is a Band 7 PAD, whereas the AFEM-7413 is a Band 13 PAD. The integrated PAD products reduce solution size and time to market while improving performance. The iPhone 6 Plus, for example, uses the company's A8020 High Band PAD and A8010 Ultra High Band PAD.

Competitors Earn D-Minus on FBAR

SAW and BAW filters have strengths and weaknesses, and for the most part, they complement each other. The number of applications in which they compete against one another is very limited; SAW filters dominate at low frequencies, and BAW filters take the lead at 2.0GHz and above. The latter have better Q factor, power handling, and ESD (electrostatic discharge) resistance, whereas the former are less expensive.

The leading RF-filter suppliers are Avago, Epcos, Murata, Qorvo (formed by the merger of RFMD and TriQuint), Skyworks, and Taiyo Yuden (TY). Of these companies, only Avago is shipping FBAR filters in high volumes. Taiyo Yuden has developed FBAR technology in addition to SAW, but it is not shipping in significant volumes. Skyworks produces both discrete RF filters (SAWs, temperature-compensated SAWs, and SMR-BAWs) and front-end modules, but it mainly targets the lower-frequency segment of the market.

Epcos offers SAW, TC-SAW, and SMR-BAW filters. Murata offers SAW and TC-SAW RF filters, sometimes delivering performance similar to that of Avago's FBAR filters. Qorvo obtained SMR-BAW technology from the TriQuint merger, in addition to SAW filters from RFMD, and it's also developing and selling FEMs that integrate TriQuint RF filters with RFMD PAs. The insertion loss for its SMR-BAW filters, however, can be higher than that of FBAR filters, as Table 1 shows.

SAW filters fall further behind in out-of-band rejection. For example, we compared Avago's ACMD-6307 duplexer for LTE Band 7 and a similar SAW-based duplexer, the SAYFH2G53CC0F0A from Murata. At 25°C, Avago delivers 40dB typical rejection, whereas the Murata part rates at only 20dB (typical). This performance difference (100x) is enormous.

Thus, Avago faces little competition at higher frequencies. Most of the other players are targeting the low- to middle-frequency segments of the handset market, leaving Avago virtually unchallenged in the highly profitable (more than 50% gross margin) FBAR business. Even where SMR-BAW and, perhaps, TC-SAW compete with FBAR, comparison of the technical specifications shows why handset manufacturers prefer FBAR technology.

Taking It to the High End

Even premium phones generally use inexpensive SAW filters for frequencies below 2.0GHz while implementing

	2,300–2,395MHz, 25°C		2,395–2,400MHz, 25°C		2,300–2,400MHz, 85°C	
	Typ	Max	Typ	Max	Typ	Max
Avago ACPF-8240 (FBAR)	1.0dB	2.9dB	1.5dB	2.8dB	N/A	3.3dB
Qorvo 885069 (SMR-BAW)	1.3dB	2.7dB	1.8dB	3.0dB	N/A	3.2dB
Murata SF 2173E (SAW)	N/A	N/A	N/A	N/A	3.0dB	3.5dB

Table 1. Insertion loss of Band 40 filters. N/A=not available. Avago is superior in most cases, particularly for typical operation. (Source: vendor data sheets)

Price and Availability

Avago provides a wide range of FBAR-based filters, duplexers, and multiplexers that are in production. Pricing varies by product, but we estimate the company's average selling price is about $0.40 per filter. For more information, access *www.avagotech.com/products/wireless/fbar.*

FBAR for higher frequencies. A typical phone with 20–30 filters might use 10 FBAR filters. At about 40 cents each, these filters total to about $4 in FBAR content per phone. FBAR technology offers clear advantages in reducing out-of-band signals that can interfere with LTE, Wi-Fi, and GPS radios. These advantages manifest themselves to end users as better cellular reception, greater access to service, higher LTE and Wi-Fi data rates, more-accurate GPS location, and longer battery life.

Premium-phone makers recognize these advantages and have chosen FBAR for their flagship products. Premium devices comprise about 30% of the smartphone market, but this segment is growing slowly if at all. These phones have already moved to LTE, but the number of filters they use will increase as they add bands and eventually move to 4x4 MIMO. As more phones implement carrier aggregation, which benefits from higher-quality filters, FBAR adoption will rise.

Beyond the premium tier, however, cost is the main focus. LTE, even with carrier aggregation, can function without FBAR; in many cases, the bands are far enough apart that inference is low. Operators will encounter fewer problems if they implement only TD-LTE or don't support using the phone as a Wi-Fi hot spot. These problems appear in the form of lower data rates or even connection loss when certain bands are used. In addition, Wi-Fi or GPS performance may occasionally diminish. But such sporadic difficulties are tough to measure or demonstrate to phone reviewers and end users. Furthermore, FBAR's effect on overall battery life is small. Thus, it's difficult for phone makers to charge extra for this feature, so cost-focused vendors will shy away from the added expense.

The premium segment is large enough and lucrative enough that Avago has chosen to focus FBAR solely on this segment. The company's most pressing concern is meeting demand. It manufactures all FBAR products at its own fab in Fort Collins, Colorado, which is converting from six-inch to eight-inch wafers to expand capacity. Avago continues to miniaturize its FBAR filters; although analog designs are not subject to Moore's Law, the company continues to redesign its filters to reduce their size, squeezing more and more onto a single wafer. These improvements will help phone makers add more filters without breaking their RF budget. Avago is also going up the food chain, offering modules that combine power amplifiers with its popular FBAR filters. This approach reduces size and squeezes out the last 0.1dB of insertion loss.

Several filter manufacturers have tried but failed to develop commercially viable FBAR filters. HP, then Agilent, and now Avago each stuck it out and has by sheer dint of innovation and hard work become the world's only high-volume provider of FBAR technology. The barriers to entry are primarily in the manufacturing process; the challenge lies in mass-producing a highly reliable free-standing membrane that can withstand the stresses of being fastened to the underlying silicon substrate at select points on its periphery. Until a competitor can demonstrate high-volume FBAR production, Avago will maintain its lead in this market. ♦