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Qorvo Special Edition

# RF Filter Technologies for Dummies

A Wiley Brand

**Learn:**

- The basics of filter technology
- How temperature impacts filter performance
- About surface acoustic wave (SAW) and bulk acoustic wave (BAW) filters
- Key filter packaging technologies from Qorvo

**Larry Miller**

## About Qorvo

Qorvo (NASDAQ: QRVO) is a leading provider of core technologies and RF solutions for mobile, infrastructure, and aerospace/defense applications. Qorvo was formed following the merger of RFMD and TriQuint and has more than 6,000 employees worldwide dedicated to product and technology leadership that enables the world's leading companies to solve their most difficult technical challenges. Qorvo has the industry's broadest portfolio of products and core technologies, offering complete solutions and system-level expertise for mobile devices; communications and network infrastructure; and avionics, space, and defense systems. The company has world-class ISO 9001-, ISO 14001-, and ISO/TS 16949-certified manufacturing facilities, and is a DoD-accredited "Trusted Source" (Category 1A) for GaAs and GaN foundry services. For the industry's leading core RF solutions, visit www.qorvo.com.

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## Qorvo Special Edition

**by Larry Miller**

For Dummies®
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# Introduction

The proliferation of 4G LTE networks and the ubiquitous nature of Wi-Fi are driving a dramatic increase in the number of radio frequency (RF) bands that smartphones and other mobile devices must support. These bands need to be isolated within each device using filters to avoid interference and dropped calls. This is becoming more difficult as governments throughout the world increasingly allocate limited spectrum next to existing bands, often with minimal or nonexistent guard bands. As a result, filter selection has become a key consideration for designers of next-generation smartphones and mobile devices.

This book explains the various filtering technologies that are available to address different filtering challenges and how these solutions have evolved to become key enablers of the global LTE transition.

## Foolish Assumptions

It's been said that most assumptions have outlived their uselessness, but I assume a few things nonetheless.

First, I assume you have an interest in the wireless industry and filter technologies. If so, this is the book for you! If not, keep reading anyway — I'll change your mind!

Next, I assume you're a design engineer, manager, salesperson, customer, supplier, investor, or just someone who needs to know more about filter technologies. As such, this book is written for both technical and nontechnical readers.

## Icons Used in This Book

Throughout this book, I occasionally use special icons to call attention to important information. Here's what to expect:

This icon points out information that may well be worth committing to your nonvolatile memory, your gray matter, or your noggin — along with anniversaries and birthdays!

You won't find a map of the human genome here (or maybe you will, hmm), but this icon explains the jargon beneath the jargon and is the stuff legends — well, nerds — are made of.

Thank you for reading, hope you enjoy the book, please take care of your writers! Seriously, this icon points out helpful suggestions and useful nuggets of information.

# Beyond the Book

Although this book is chock-full of information, I can only cover so much in 24 short pages. So, if you find yourself thinking, "Gosh, this is an amazing book — where can I learn more?," just go to `www.qorvo.com` and `www.triquint.com`. There, you can read more about Qorvo's filter solutions, download technical papers and datasheets, watch helpful videos, and much more!

# Where to Go from Here

If you don't know where you're going, any chapter will get you there — but Chapter 1 may be a good place to start. However, if you see a particular topic that piques your interest, feel free to jump ahead to that chapter. Each chapter is written to stand on its own, so feel free to start reading anywhere. Read this book in any order that suits you (though I don't recommend upside down or backward).

# Chapter 1

# The Basics of RF Filters

### *In This Chapter*

- Getting to know filters
- Understanding the correlation between quality factor and insertion loss
- Keeping cool about temperature variation
- Taking the complexity out of duplexing

In this chapter, you learn about radio frequency (RF) filters: what they are and why they're necessary, their different types and designs, important factors that affect performance, and how duplexing comes into play.

## Defining Filters

The rapid growth in mobile wireless data and 4G LTE networks has created an ever-increasing requirement for new spectrum bands to accommodate wireless traffic. Whereas 3G networks used only about five bands, there are already over 20 4G LTE bands and this number could rise to more than 40 in the near future.

Though it's not practical to support all worldwide bands in a single smartphone, a feature-rich model for international use may need to filter transmit and receive paths for 2G, 3G, and 4G in up to 15 bands, as well as Wi-Fi, Bluetooth, and global navigation satellite system (GNSS). Such a phone may require as many as 30 to 40 filters. The situation is likely to become even more complex with next-generation high-end smartphones requiring even more filters.

A filter removes unwanted frequency components from a signal while preserving desired frequency components. There are four basic types of filters that accept or reject signals in different ways (see Figure 1-1). The different types are defined as

- **Low pass:** Allows all frequencies below a certain frequency to pass while rejecting all others (opposite of high pass)
- **High pass:** Allows all frequencies above a certain frequency to pass while rejecting all others (opposite of low pass)
- **Band pass:** Allows all frequencies between two frequencies to pass while rejecting all others (opposite of band stop)
- **Band stop (or band reject):** Rejects all frequencies between two frequencies while passing all others (opposite of band pass)

TIP

Band stop and band reject filters are also known as notch filters.

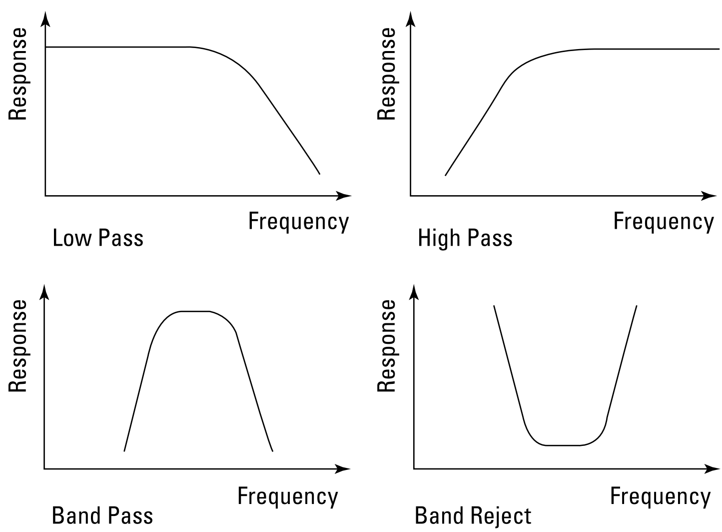


**Figure 1-1:** Basic filter types.

Filter construction varies by application, with size, cost, and performance the major variables. Here are some example filter constructions:

- **Discrete inductor-capacitor (LC) filters** are low-cost structures of moderate performance and size. The LC elements are sometimes implemented as printed structures on substrates called an integrated passive device (IPD).
- **Multilayer ceramic filters** are low to moderate cost and have similar performance to LC filters. Their footprint is generally reasonable, but their thickness is becoming an issue as mobile applications emphasize thinner and thinner designs.
- **Monoblock ceramic filters** are much higher performance than multilayer ceramics and also more expensive. They're also physically larger and usually aren't suitable for mobile applications.
- **Acoustic filters** have the capability to meet both low and high frequencies up to 6 GHz, are small in size, and offer the best performance and cost for complex filter requirements. Acoustic filters are the most common filter construction for mobile devices.
- **Cavity filters** are used in infrastructure applications only. They can achieve good performance at reasonable cost but are large.

Filters can be designed to meet a variety of requirements. Although they use the same basic circuit configurations, circuit values differ when the circuit is designed to meet different criteria. In-band ripple, fastest transition to the ultimate roll-off, and highest out-of-band rejection are some of the criteria that result in different circuit values.

REMEMBER

Filters allow only particular frequencies or bands of frequencies to pass through and are, thus, an essential tool for RF design engineers.

Figure 1-2 shows a typical filter response, as well as some key design considerations for both bulk acoustic wave (BAW) and surface acoustic wave (SAW) technologies (which are discussed in Chapter 2). The figure shows where the rejections and insertion loss specifications are derived in the filter's response. As you can see from the figure, the passband width is the area in which the device passes the signal occupying the desired frequency band. The rejection is shown by those frequency ranges minus the passband.

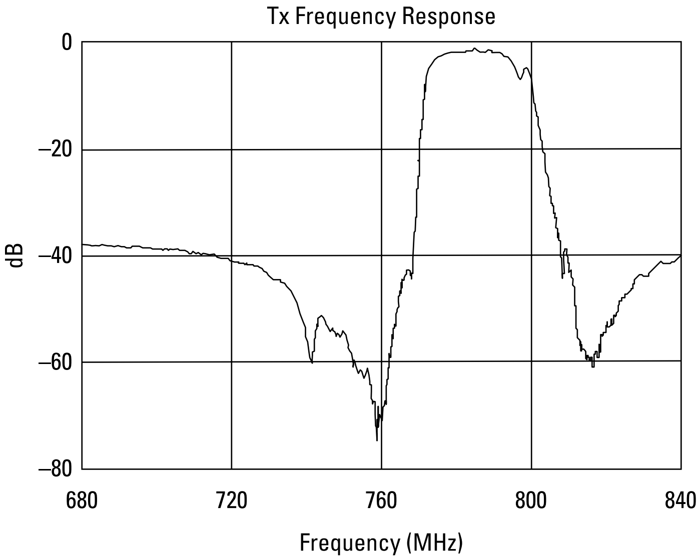


**Figure 1-2:** A typical filter response.

TIP

See the nearby sidebar, "RF Filters 101: A tutorial," for more filter parameters.

# The Relationship Between Q Factor and Insertion Loss

The insertion loss of a filter is determined by multiple factors. Among these are the filter bandwidth relative to center frequency, the order of the filter, and the quality factor (Q factor) of the resonators that make up the component.

Figure 1-3 shows the attenuation characteristics for an acoustic filter for four different values of resonator Q. The Q values are 3000, 1500, 1000, and 700.

## RF Filters 101: A tutorial

In case your knowledge of electronics is a bit rusty, here's a brief tutorial on some of the more important terms and concepts to help refresh your memory.

**Attenuation:** An amplitude loss, usually measured in decibels (dB), incurred by a signal after passing through an RF filter.

**Cutoff:** Normally taken to be the point at which the response of the filter has fallen by 3 dB.

**Group delay:** The derivative of a filter's phase with respect to frequency. Group delay, measured in time (in seconds), can be thought of as the propagation time delay of the envelope of an amplitude modulated signal as it passes through an RF filter.

**Insertion loss:** Loss of signal power resulting from the insertion of a component.

**Isolation:** Separation of one signal from another to prevent unintentional interaction between them (for example, transmit and receive interaction).

**Q factor:** The "quality" factor is a measure of the selectivity of a resonant circuit described as the ratio of stored versus lost energy per oscillation cycle.

**Passband:** The region through which the signal passes relatively unattenuated.

**Ripple:** The variation of insertion loss in the passband.

**Selectivity:** A measurement of the capability of the filter to pass or reject specific frequencies relative to the center frequency of the filter. Selectivity is usually stated as the loss through a filter that occurs at some specified difference from the center frequency of the filter.

**Stopband:** A band where the filter has reached its required out-of-band rejection, defined as a required number of decibels.

The figure shows some clear trends:

- Loss increases as the Q factor drops and increases more rapidly for lower values of resonator Q.
- The edges of the passband become more rounded and the passband narrower as the Q decreases. Note how each successively lower Q plot fits inside the previous.
- The loss at the passband edges increases more than loss in the middle of the band. This poses a serious problem for modulations that go right to the edge of the passband.

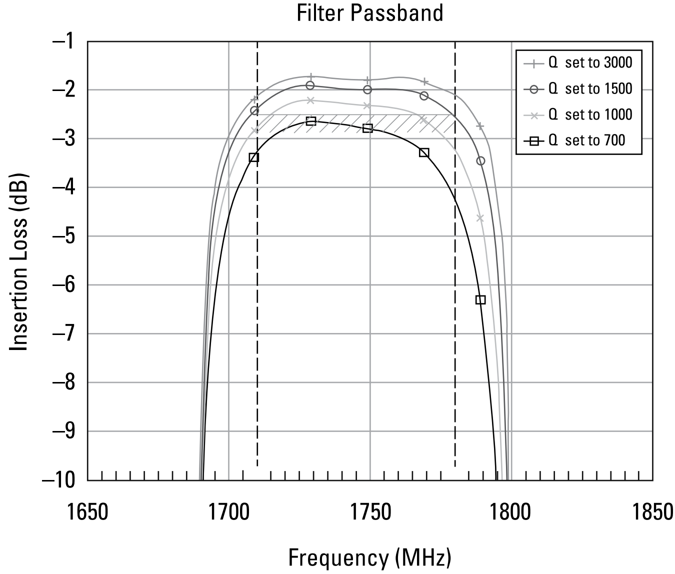


**Figure 1-3:** Attenuation characteristics of an acoustic RF filter with different resonator Q values.

Narrow modulations such as GSM (200 kHz) and CDMA (1.25 MHz) will suffer the most sensitivity loss at the band edge due to this effect, while WCDMA (3.84 MHz) will suffer less. LTE results depend on the system bandwidth, with narrower bandwidths more affected. The need for sharp corners at the passband edges has been a historic driver of the need for higher-Q filter structures such as BAW.

REMEMBER

GSM is a 2G standard for cellular data networks. CDMA and WCDMA are 2G/3G standards for cellular data networks.

Drift due to temperature variation (discussed later in this chapter) will worsen the problem of the modulated signal coming close to the passband edge, unless temperature-compensated processes — such as Qorvo's LowDrift or NoDrift filter processes — are used.

Widening the lower-Q filter's response curve to improve the insertion loss problem may be tempting, but it will result in reduced selectivity to nearby interference. This selectivity degradation is not acceptable for many demanding filter applications.

TIP

Learn more about SAW and BAW filters in Chapter 2 of this book. You can also explore more details on Qorvo's LowDrift and NoDrift SAW and BAW technology in *RF Filter Applications For Dummies.*

# The Impact of Temperature on Filter Response

Temperature drift has become an increasingly important issue as the frequency spectrum becomes more crowded. High selectivity is required to minimize insertion loss and ensure rejection of adjacent bands.

The key performance parameters for filters are low loss to the desired signals in the passband and sufficient attenuation of undesired interference in the stopband. These parameters need to be met across a broad range of environmental and production variations. The historical solution has been to build allowances for each of these into the design based on knowledge of the process variation.

For some challenging filtering applications, the temperature drift of the filter may be in the range of the width of the transition band between the passband and stopband. This makes the design of filters to address these needs very difficult, if not impossible. The solution to this problem is to design the filters using an advanced fabrication process that greatly reduces change with temperature.

# The Role of Duplexing

*Duplexing* enables two-way communications over a single communications channel. There are two basic modes of duplex operation:

- **Half duplex:** The communicating parties take turns transmitting and receiving. While one party is transmitting, the other is receiving.
- **Full duplex:** The communicating parties can transmit and receive simultaneously. Full duplexing is achieved through *frequency division duplexing* (FDD) or *time division duplexing* (TDD).

## Frequency division duplexing

FDD uses two separate frequency bands or channels to achieve full duplex communications. The two bands are physically separated in frequency (called a *duplex gap*) to prevent interference.

Here are the primary advantages and disadvantages of FDD:

- **Advantages:** Latency is extremely low, and the full capacity of the band or channel can be used.
- **Disadvantages:** A symmetric pair of frequencies is required within the desired band for transmit and receive. FDD also requires more frequency spectrum than TDD.

## Time division duplexing

TDD emulates full-duplex communication over a half-duplex link, using a single frequency band for both transmitting and receiving. TDD assigns rapidly alternating time slots to transmit and receive operations of the communicating devices. Although TDD transmissions are actually concurrent rather than simultaneous, the intermittent nature of the communication is imperceptible to the communicating parties due to the high speeds at which TDD occurs.

The primary advantages and disadvantages of TDD are the following:

- **Advantages:** TDD operates over a single frequency, and transmit and receive time slots don't have to be symmetric.
- **Disadvantages:** Switching between transmit and receive operations causes some latency compared to FDD. Additionally, precise timing and synchronization are required to ensure time slots don't interfere or overlap.

TIP

In some applications, asymmetric time slot allocation can be dynamically assigned to automatically adjust to changing transmit and receive requirements.

Today, FDD is more widely used in 4G LTE networks. However, as the limited frequency spectrum becomes increasingly crowded, TDD is likely to be adopted more in the future due to its use of only a single frequency range.

# Chapter 2

# All about Acoustic Filters

### In This Chapter

- Understanding surface acoustic wave technologies
- Using bulk acoustic wave filters for higher-frequency applications

Acoustic filter technologies continue to evolve to meet the challenges of the global transition to 4G networks. In this chapter, you find out about surface acoustic wave (SAW) and bulk acoustic wave (BAW) filter technologies, which are used to solve many of today's toughest mobile device filtering problems.

## SAW: Mature But Still Growing

SAW filters are widely used in 2G and 3G receiver front ends, duplexers, and receive filters. SAW filters combine low insertion loss with good rejection, can achieve broad bandwidths, and are a tiny fraction of the size of traditional cavity and ceramic filters (discussed in Chapter 1).

Because SAW filters are fabricated on wafers, they can be created in large volumes at low cost. SAW technology also allows filters and duplexers for different bands to be integrated on a single chip with little or no additional fabrication steps.

The *piezoelectric effect* that exists in crystals with a certain symmetry is the "motor" as well as the "generator" in acoustic filters. When you apply a voltage to such a crystal, it will deform mechanically, converting electrical energy into mechanical energy. The opposite occurs when such a crystal is mechanically compressed or expanded. Charges form on opposite faces of the crystalline structure, causing a current to flow in the terminals and/or voltage between the terminals. This conversion between electrical and mechanical domains happens with extremely low energy loss, achieving exceptional efficiency in both directions.

In solid materials, alternating mechanical deformation creates acoustic waves that travel at velocities of 3,000 to 12,000 meters per second. In acoustic filters, the waves are confined to create standing waves with extremely high-quality (high-Q) factors of several thousand. These high-Q resonances are the basis of the frequency selectivity and low loss that acoustic filters achieve.

In a basic SAW filter (see Figure 2-1), an electrical input signal is converted to an acoustic wave by interleaved metal interdigital transducers (IDTs) created on a piezoelectric substrate, such as quartz, lithium tantalite ($LiTaO_3$), or lithium niobate ($LiNbO_3$). Its slow velocity makes it possible to fit many wavelengths across the IDTs in a very small device.

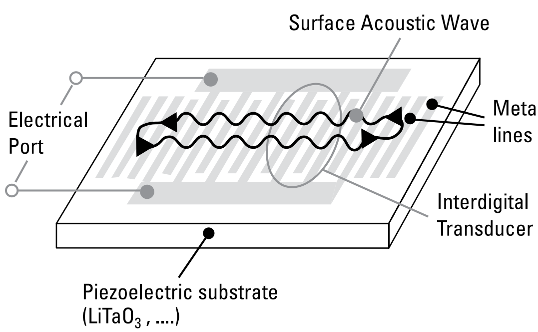


**Figure 2-1:** A basic SAW filter.

A key advantage of SAW is its capability to optimally meet standard filter applications up to 1.9 GHz, including several standard bands such as GSM, CDMA, 3G, and some 4G bands. Additionally, techniques such as wafer level packaging (discussed in Chapter 3) are being used to shrink SAW filters, allowing the integration of filters and duplexers for multiple bands onto a single chip. This is becoming increasingly important as smartphones incorporate more functions.

SAW filters, however, have limitations. Above about 1 GHz, their selectivity declines; at about 2.5 GHz, the use of SAW is limited to applications with modest performance requirements.

SAW is also very temperature sensitive. The stiffness of the substrate material tends to decrease at higher temperatures and acoustic velocity diminishes. A SAW filter's response may shift downward by as much as 4 MHz as temperature increases. This limitation has become more significant as guard bands become narrower and consumer devices are specified to operate across a wide temperature range (typically, –20°C to 85°C).

An alternative approach is to use Qorvo's LowDrift and NoDrift SAW filters, which include overcoating of the IDT structures with layers that increase stiffness at higher temperatures. Although an uncompensated SAW device typically has a temperature coefficient of frequency (TCF) of about –45 parts per million per degree Celsius (ppm/°C), LowDrift SAW filters reduce this to –15 to –25 ppm/°C. For the most stringent applications, NoDrift SAW reduces this even further to essentially 0 ppm/°C. However, because the process doubles the number of required mask layers, LowDrift and NoDrift SAW filters are more complex and, thus, more expensive to manufacture — but still less expensive than BAW filters. I talk more about Qorvo's LowDrift and NoDrift SAW and BAW filters in *RF Filter Applications For Dummies.*

# BAW: High Performance

Although SAW and Qorvo's LowDrift and NoDrift SAW filters are well suited for applications up to about 1.5 GHz, BAW filters generally deliver superior performance (higher Q) with lower insertion loss at higher frequency levels.

With BAW technology, it is possible to create narrowband filters with exceptionally steep filter skirts and excellent rejection. This makes BAW the technology of choice for many challenging interference problems. BAW delivers these benefits at frequencies above 1.5 GHz, making it a complementary technology to SAW (which is most effective at lower frequencies). BAW can address frequencies up to 6 GHz and is used for many of the new LTE bands above 1.9 GHz. BAW is also highly effective for LTE/Wi-Fi coexistence filters.

BAW filter size also decreases with higher frequencies, which makes these filters ideal for the most demanding 3G and 4G applications. In addition, BAW design is far less sensitive to temperature variation even at broad bandwidths.

Unlike SAW filters, the acoustic wave in a BAW filter propagates vertically (see Figure 2-2). In a BAW resonator using a quartz crystal as the substrate, metal patches on the top and bottom sides of the quartz excite the acoustic waves, which bounce from the top to the bottom surface to form a standing acoustic wave. The frequency at which resonance occurs is determined by the thickness of the slab and the mass of the electrodes. At the high frequencies in which BAW filters are effective, the piezo layer must be only micrometers thick, requiring the resonator structure to be made using thin-film deposition and micro-machining on a carrier substrate.

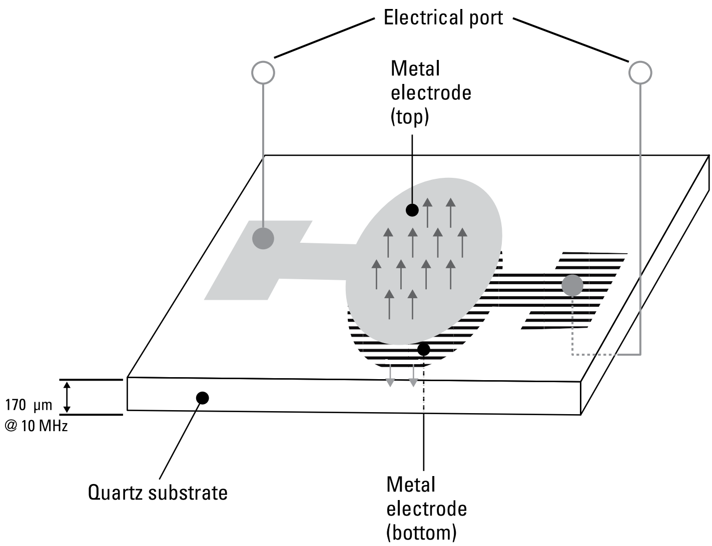


**Figure 2-2:** A basic BAW filter.

To keep the waves from escaping into the substrate, an acoustic Bragg reflector is created by stacking thin layers of alternating stiffness and density. The result of this approach is called a *solidly mounted resonator BAW* (BAW-SMR).

TECHNICAL STUFF

A Bragg reflector is a structure formed from multiple layers of alternating materials with varying refractive index.

An alternative approach, called a *film bulk acoustic resonator* (FBAR), etches a cavity underneath the active area, creating suspended membranes. Figure 2-3 compares BAW-SMR and FBAR filter designs.

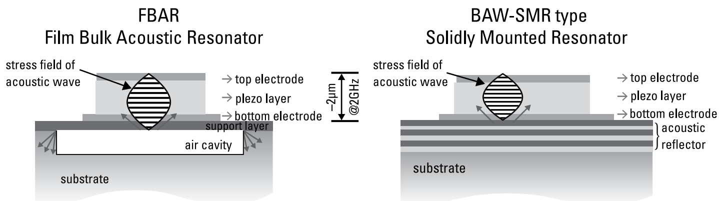


**Figure 2-3:** BAW filter technologies.

Both types of BAW filters can achieve very low loss because the density of their acoustic energy is very high and the structures trap acoustic waves very well. Their achievable Q is higher than any other type of filter of reasonable size employed at microwave frequencies: 2,500 at 2 GHz. This results in superb rejection and insertion loss performance, even at the critical passband edges.

The fundamental difference between FBAR and BAW-SMR is in how acoustic energy is trapped. For FBAR, the air/crystal interface on both faces of the resonator ensures that the main mode of interest is appropriately trapped. In BAW-SMR, Bragg reflectors underneath the resonator effectively trap this mode.

Another major difference between FBAR and BAW-SMR is the thermal path for heat generated in the device. In BAW-SMR, the heat has a conduction path into the substrate from which it can be spread. In FBAR, because there is an air gap on each side of the resonator, the thermal conduction path is weaker.

REMEMBER

Because BAW filters offer low insertion loss, they help compensate for the higher losses associated with the need to support many bands in a single smartphone. Besides improving signal reception, lower loss also contributes to longer battery life. BAW excels in applications where the uplink and downlink separation is minimal and when attenuation is required in tightly packed adjacent bands.

Although BAW inherently has about half the temperature-drift performance of standard SAW, there are cases where this improvement is not sufficient. To address these applications, Qorvo has created a NoDrift BAW process, which has an essentially zero ppm/°C drift, similar to the performance that NoDrift SAW achieves.

TIP

Learn more about Qorvo's LowDrift and NoDrift SAW and BAW filters in *RF Filter Applications For Dummies.*

# Chapter 3

# Filter Packaging Technologies

### In This Chapter

- ▶ Flipping out over flip-chip technology
- ▶ Recognizing the advantages of wafer level packaging
- ▶ Integrating components for simplicity

In this chapter, you learn about key Qorvo filter packaging technologies and strategic differentiators.

## CuFlip: Copper Flip-Chip

Qorvo's CuFlip interconnect technique is a proprietary, advanced flip-chip technology that uses copper "bumps" to replace wire bonds (see Figure 3-1). CuFlip (pronounced "copper flip") offers several advantages over other methods of connecting radio frequency (RF) components to printed circuit boards in mobile devices:

- **Superior RF performance:** CuFlip doesn't require the signal to travel through the epoxy, thereby improving performance.
- **Design flexibility:** CuFlip enables a more compact design and lower height, resulting in a smaller overall footprint and offering plug-and-play placement of CuFlip-based products in a wide range of configurations (including ultraslim designs).

- **Reduced bill of materials:** The elimination of wire bonds reduces the overall bill of materials, making CuFlip products smaller and reducing board space requirements.
- **Faster manufacturing and assembly:** The uniformity of the copper pillars streamlines product assembly of standard surface-mount components by eliminating the need to match each wire bond. In turn, this reduces cycle time and increases throughput and operations.
- **Lower cost:** This highly repeatable process requires substantially fewer steps compared to wire bond assembly, resulting in higher yields.

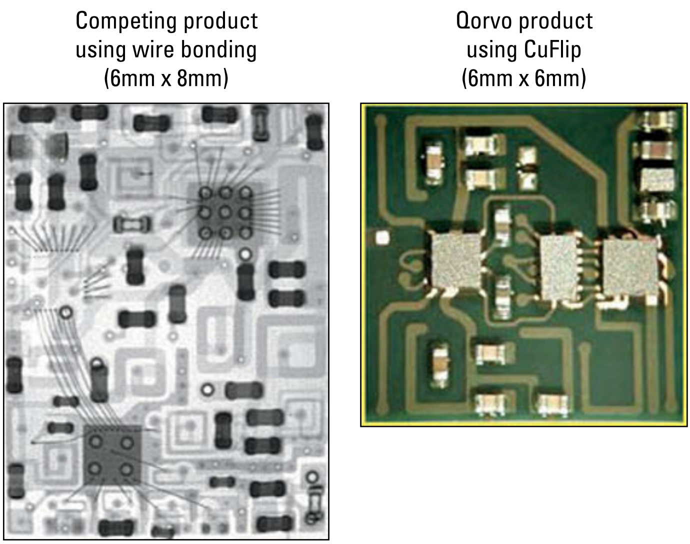


**Figure 3-1:** The CuFlip advantage over wire bonding.

# Wafer Level Packaging

Typical filter packaging consists of filter die encapsulated in a ceramic package. Qorvo's wafer level packaging (WLP) technology eliminates bulky ceramic packages, significantly reduces size, and increases performance (see Figure 3-2).

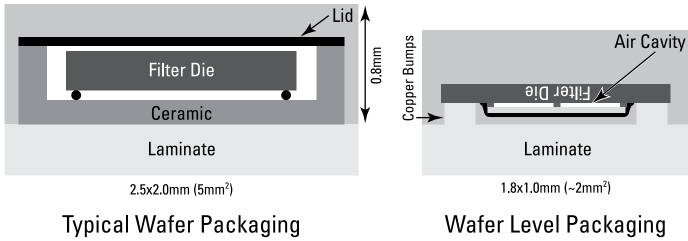


**Figure 3-2:** Typical wafer packaging versus Qorvo's wafer level packaging design.

Qorvo's WLP technology encapsulates the die within a polymer seal to create a protective air cavity around the filter area. This permits high-frequency operation and provides mechanical protection for the filter. In addition, proprietary CuFlip technology (discussed earlier in this chapter) is utilized and the die is flipped upside down so the copper bumps can be placed directly on the laminate. Together, these advances increase system performance and reduce package size considerably, shrinking space requirements by over 50 percent.

Benefits of WLP over traditional packaging methods include

- **Significantly smaller size:** Package size is reduced considerably, which can shrink the amount of printed circuit board (PCB) space an RF device occupies by over 50 percent.
- **Design flexibility:** A smaller footprint offers designers plug-and-play placement of WLP components in a wide range of wireless device configurations.
- **Superior performance:** The sealed air cavity surrounding the die provides the necessary clearance for high-frequency operation, as well as structural support and mechanical protection. Plus, the WLP provides minimal parasitics, reducing power consumption and extending battery life.
- **Lower height for thinner devices:** By eliminating the ceramic package, WLP filters are 0.13 mm thinner, a key consideration in designing today's thinner mobile devices.

# Integration

Qorvo's advanced filtering solutions raise high performance and small size to new levels when integrated with power amplifiers, switches, and other front-end RF components. As the number of bands in smartphones continues to rapidly increase, the trend is to integrate modules that combine premium filters with highly efficient broadband amplifiers to reduce RF size and complexity in smartphones.

Qorvo uses dense packaging technologies — like CuFlip ("copper flip") interconnect services and WLP (both discussed earlier in this chapter) — to combine high-performance broadband amplifiers with premium filters in a simplified integrated solution that speeds time to market for customers (see Figure 3-3).

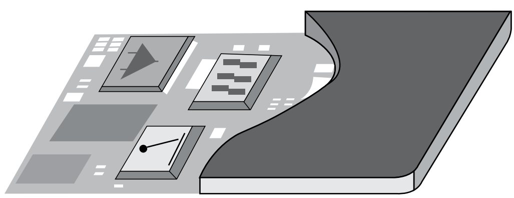

**Figure 3-3:** Integration removes complexity.

REMEMBER

Integration is a key differentiator for Qorvo, which uses high-performance components (in-house design and manufacturing of key module components) in its filters, built with extensive integration expertise (coordinated supply chain, stable processes, and RF module simulation).

## Chapter 4

# Ten Important Facts about Filter Technologies

### *In This Chapter*

- Getting clear on filter technologies
- Gathering the facts you need to know

Here are ten important things to remember about filter technologies:

- Filters remove unwanted frequency components from a signal while preserving desired frequency components.
- The quality factor (Q factor) is one of the main determiners of filter loss. Lower Q leads to higher loss and rounding of the filter corners. This rounding of the corners can be problematic for narrowband modulations.
- The wider the bandwidth and the greater the required selectivity, the more the insertion loss parameter must be sacrificed. The design engineer must balance these characteristics in order to eliminate increasing the power amplifier (PA) output and potential increased current and matching components.
- The most common filter configuration for mobile devices is an acoustic filter — surface acoustic wave (SAW) and bulk acoustic wave (BAW).
- The most common acoustic filter architecture is a ladder configuration, where multiple resonators are connected in a series and shunt arrangement.
- A duplexer with a high isolation between the transmit and receive frequencies is optimal when trying to achieve high sensitivity in a user's wireless system design.

- SAW devices work best at lower frequencies below 1.5 GHz, while BAW technology works best for filter designs above 1.5 GHz.
- In today's mobile environment, the amount of bands required in one device is staggering — and the trend will only increase. Supporting all these bands causes coexistence issues requiring filters to reject bands, such as public safety, global navigation satellite system (GNSS), Wi-Fi, and others. Filters have an important role in allowing coexistence between bands.
- Spectrum allocation for new frequencies requires filters to have much tighter temperature drift. Qorvo's LowDrift and NoDrift filter technology best addresses these temperature drift requirements. NoDrift technologies can produce an essentially zero parts per million per degree Celsius (ppm/°C) characteristic.
- Advanced packaging technologies developed by Qorvo, such as CuFlip (pronounced "copper flip") and wafer level packaging (WLP), enable high performance and high levels of integration. These characteristics will be increasingly necessary as the band count and complexity level of radio frequency (RF) front ends continue to increase.

# Solving LTE Challenges with Advanced Filter Technology