DESIGN GUIDE

Apollo Bluetooth Low Energy SoC RF Front-End Filter

Ultra-Low Power Apollo SoC Family

A-SOCAPG-DGGA02EN v1.0

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Revision History

Revision	Date	Description
1.0	April 8, 2024	Initial release

Reference Documents

These reference documents can be accessed on the Ambiq Website and/or Content Portal.

Document ID	Description
A-SOCAPG-ANGA01EN	Apollo BLE SoC Impedance Matching Application Notes

*Indicates to use the latest version of the document.

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1

Overview

RF filter plays an important role in radio systems to ensure efficient signal transmission and reception respectively. RF filters remove unwanted frequency components from a signal while preserving desired frequency components. RF filter design requires a deep understanding of RF concepts, AC circuit analysis and practical engineering considerations as per desired filter type and its specifications.

For radio devices operating at 2.4GHz ISM band such as Bluetooth capable products, RF filters are mainly used for harmonic suppression and out-of-band interference rejection, especially when the application demands higher transmit power level (e.g., output more than +10 dBm). That's because the harmonic levels will increase nonlinearly as the fundamental power level increased, which may result in potential risk in regulatory compliance. As widely known, for devices operating within 2.4GHz ISM band the ETSI EN 300 328 standard requires harmonic limit of -30 dBm EIRP while the U.S. FCC standard requires much stricter with a limit of -41.2 dBm EIRP. Thus, RF filters are always necessary for wireless products to pass a wide range of radio certification testing.

SECTION

2

RF Filter Basics

Generally, filters used in electronics may be divided into two main categories: passive and active types. Passive filters are composed exclusively of passive components like resistors (R), inductors (*L*), and capacitors (*C*). Active filters are implemented using a combination of passive and active components like transistors and require extra power supply. Op amps are frequently used in active filter designs. These can have high Q factor and can achieve resonance without the use of inductors. However, their upper frequency limit is limited by the bandwidth of the op amplifiers[1].

RF filter is one kind of passive filters designed to operate on signals in the tens of MHz to GHz frequency ranges (HF band and above). Only the reactive elements (e.g., inductors (*L*) and capacitors (*C*) are used in RF filter and the number of reactive elements determines the order of the filter. The frequency band over which the RF filter passes through is called passband, and the frequency band it rejects is called stopband.

2.1 Basic Types of Filters

There are four basic types of filters defined based on their functions. Each type rejects or accepts signals in a different way, and by using the correct type of RF filter it is possible to accept the required signals and block those unwanted frequency components[2].

1. Low-Pass Filter (LPF)

   As shown in Figure 2-1 on page 8, one ideal LPF only allows all frequencies below a certain frequency (usually called as cutoff frequency or corner frequency where it corresponds to the point with 3 dB drop in amplitude response) to pass through while rejecting all other frequency components above it. The actual roll-off rate is dependent mainly upon the order of the filter.

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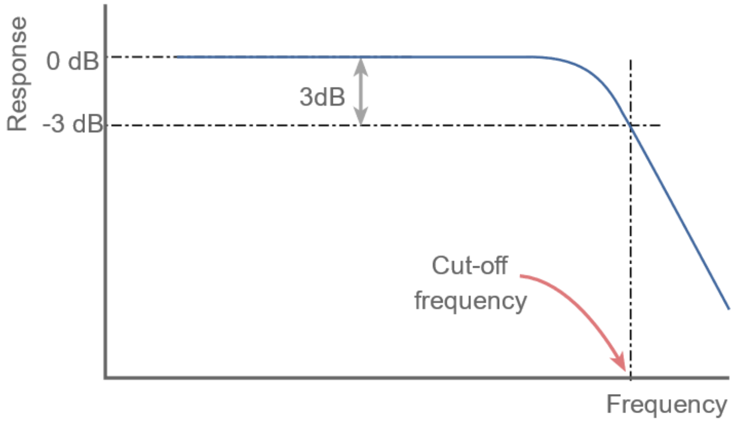
[1] https://en.wikipedia.org/wiki/Electronic_filter

[2] https://www.murata.com/en-global/products/filter/lcfilter/overview/basic

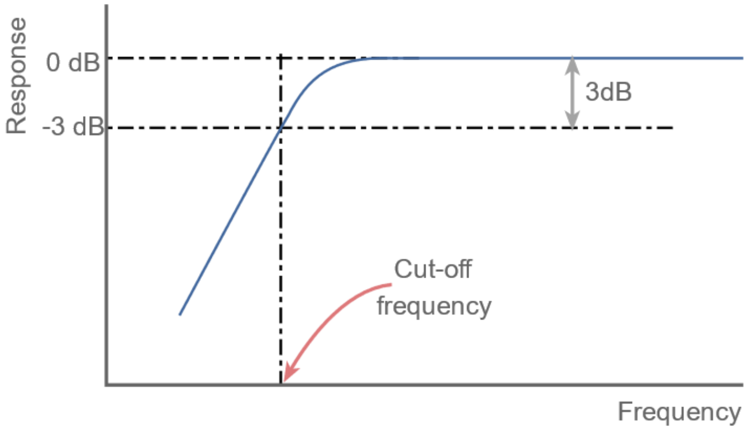
Figure 2-1: Typical Frequency Response of LPF



2. High-Pass Filter (HPF)

   As shown in Figure 2-2, HPF only allows all frequencies above the cutoff frequency to pass through while rejecting all others below it (opposite of LPF). It's nominally flat in passband, and below the cutoff frequency the frequency response falls away at a roll-off rate determined by the order of the filter.

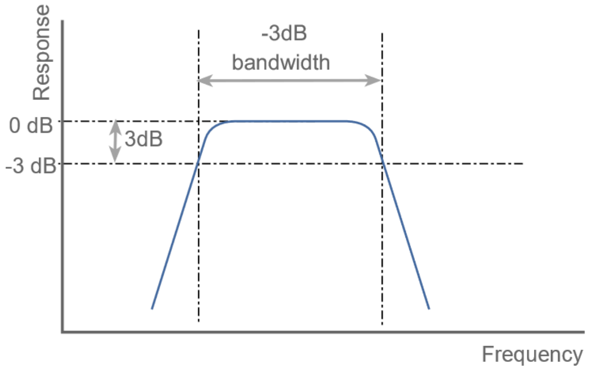
   Figure 2-2: Typical Frequency Response of HPF



3. Band-Pass Filter (BPF)

   As shown in Figure 2-3 on page 9, BPF only allows passing through signals within certain frequency range. Thus, it refers to two cutoff frequencies: the lower and the upper cutoff frequency. The frequency components below the lower cutoff frequency and above the upper cutoff frequency will be attenuated while the frequency components within the passband will be passed through.

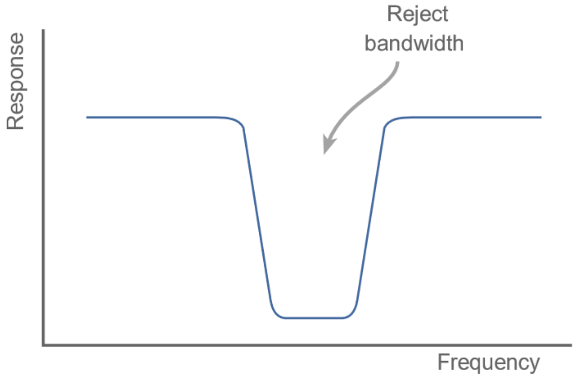
Figure 2-3: Typical Frequency Response of Band-Stop Filter



4. Band-Stop Filter

   As shown in Figure 2-4 the band-stop filter or also called band-reject filter is the opposite of a band pass filter, since it rejects signals within a certain frequency band. This form of RF filter is often used to remove unwanted signals that are known to exist in a system. Sometimes the stop-band filter is also called notch filter if the stopband is narrow enough.

   Figure 2-4: Typical Frequency Response of Band-Stop Filter



Besides, RF filters can also be classified by their construction and the technology used to make them. In general, most RF and microwave filters are often made up of one or more coupled resonators, and thus any technology that can be used to make resonators can also be used to make filters. The unloaded quality factor of the resonators being used will generally set the selectivity the filter can achieve[1]. RF Filter construction varies by application, with size, cost, and performance being the major variables. Hereunder are some typical filter technologies and constructions used for RF and microwave applications:

Lumped element LC filters, also called *discrete LC filters,* are the simplest resonator structure consisting of parallel or series inductors and capacitors. They have the advantage of being very compact and easy-to-achieve, but the low quality factor will lead to relatively poor filtering performance. LC filters are commonly used in

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[1] https://en.wikipedia.org/wiki/RF_and_microwave_filter

consumer wireless electronics since engineers often combine them with impedance matching network when designing RF front-end circuits.

Planar filters, also known as *distributed element filters*, are made of planar transmission lines such as microstrip, stripline and coplanar waveguide. They are used in many scenarios of the same applications as lumped-element filters. The distributed-element model is suitable for higher operating frequencies but also requires more room than lumped-element model. Planar filters are often found in professional instruments and equipments and dedicated RF/MW components.

Cavity filters are applicable to infrastructure applications such as base station and radar systems since they can offer high power capacity but with relatively larger size. They can achieve a significantly high quality factor as well as increased performance stability at closely spaced frequencies (down to 75 kHz) by increasing the internal volume of cavities.

Dielectric filters are made of various dielectric materials and formed by repeated total reflection of EM waves inside the dielectric. High-dielectric constant materials may be used to reduce the overall size of the filter. One commonly used type of dielectric filters is LTCC (Low Temperature Co-fired Ceramic) filter that is made of multilayer ceramics. With low-loss dielectric materials, dielectric filters may offer significantly higher performance than LC filters.

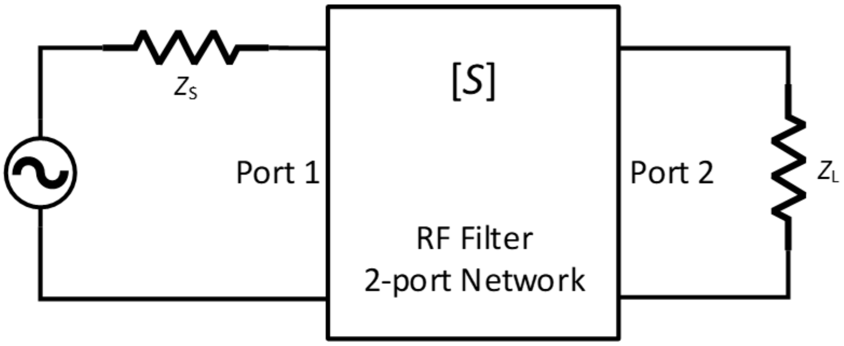
Electroacoustic filters are made of piezoelectric materials and take advantage of piezoelectric effect. Since acoustic wavelength at a given frequency is several orders of magnitude shorter than the electrical wavelength, electroacoustic filters are generally smaller by size and weight than cavity and dielectric filters. Electroacoustic filters are the most common used filter construction for cellular applications since they can solve complex multi-frequency coexistence and filtering problems in modern mobile devices. Most of electroacoustic filters are using thin film technologies such as surface acoustic wave (SAW), bulk acoustic wave (BAW), and thin-film bulk acoustic resonator (FBAR) based structures.

There are different types of RF filters. Consideration must be given to the specific filter type and topology that meets the design requirements. Factors such as operating frequency range, available component values, and size/cost constraints influence the choice between distributed element filters and lumped LC filters. Off-the-shelf multilayer ceramic filters can also offer compact and quick solutions for specific applications. If designing a custom filter, the options include microstrip distributed structures or lumped passive LC structures. In cases where size is a constraint and the frequency is below 3 GHz, and when working with cost-effective consumer-grade FR-4 PCBs, it is typically advisable to select LC lumped filter types instead of distributed structures.

2.2 RF Filter Topology

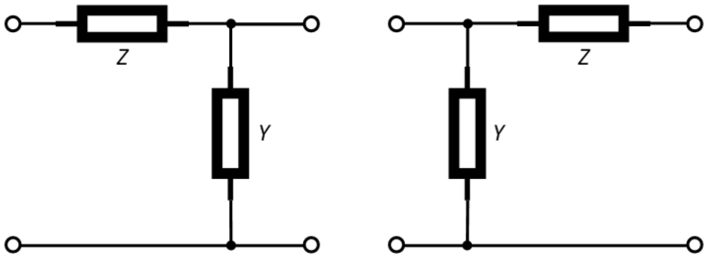
As shown in Figure 2-5, RF filters can be regarded as passive two-port networks called "sections" where S-parameters can be used to analyse them. RF Filter topology defines the manner in which passive components are connected.

Figure 2-5: RF Filter Defined by 2-Port S-Params Network



There is no formal definition of a "section" except that it must have at least one series element (expressed by impedance Z) and one parallel element (expressed by admittance Y). Sections are invariably connected in a "cascade" or "daisy-chain" way, which consist of additional copies of the same section or of completely different sections. The rules of series and parallel impedance would combine two sections consisting only of series components or shunt components into a single section[1]. As shown in below three figures respectively, there are three basic topology forms for passive RF filters, including the L-section, T-section, and Π-section.

Figure 2-6: L-Section Topology



As shown in above Figure 2-6, L-section is the simplest topology form consisting of two elements, one in series connection and the other in parallel connection. RF Filters designed using network synthesis methods usually repeat the asymmetrical L-section topology though component values may change in each cascaded L-section. The symmetrical T-section and Π-section are built from the combination of two back-to-back L-sections. It can be seen that the T-section has two series elements and only one shunt element while the Π-section has two shunt elements and only one series element. The components can be chosen symmetric or not, depending on the required frequency response characteristics.

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[1] https://en.wikipedia.org/wiki/Electronic_filter_topology

Figure 2-7: T-Section Topolgy

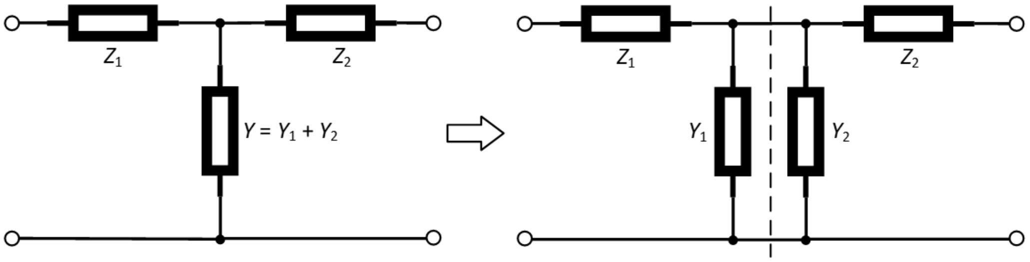
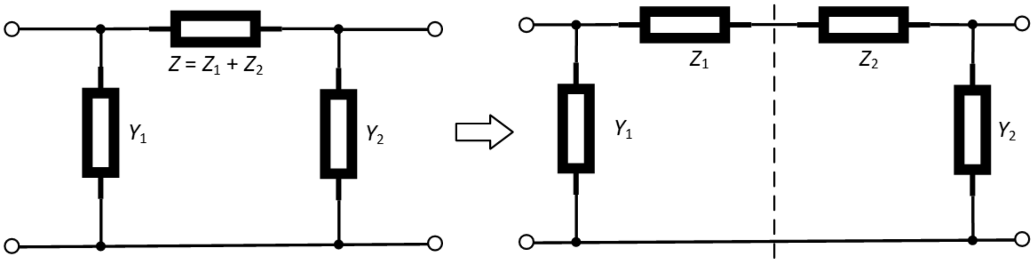
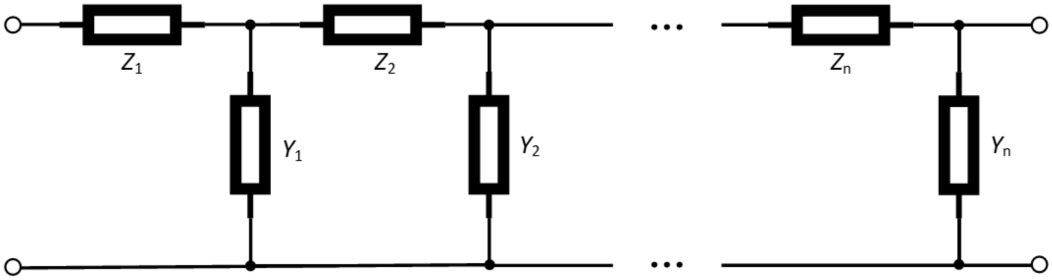


Figure 2-8: Π-Section Topology



More elements are required when it is desired to improve some parameters of the filter such as stop-band rejection or slope of transition from pass-band to stop-band. As shown in Figure 2-9, multiple-element filters are usually constructed as a ladder network that can be regarded as a continuation of the L-sections, T-sections, or Π-sections designs of filters.

Figure 2-9: Ladder Network Composed of Cascaded L-Sections



2.3 Network Synthesis Method

In signal processing, network synthesis filters are filters designed by the network synthesis method. The network synthesis method starts with a required transfer function and then expresses that as a polynomial equation of the input impedance of the filter. It has produced several important classes of filter including the Butterworth filter, the Chebyshev filter, the Elliptic filter, and more. It was originally intended to be applied to the design of passive filters, but its results can also be applied to implementations in active filters and digital filters. The purpose of the method is to obtain the actual component values from the polynomial expansions representing the transfer function[1].

The class of network synthesis filters refers to the class of polynomials from which the filter is mathematically derived. The order of the filter is the number of filter elements present in the filter's ladder implementation. Generally speaking, the higher the order of the filter, the steeper the cut-off transition between passband and stopband.

The *Butterworth filter* is a type of filter designed to have a frequency response that is as flat as possible in the passband. It is also referred to as a maximally flat magnitude filter, which means that the response in the frequency domain is the smoothest possible curve of any class of filter of the equivalent order.

The frequency response of an ideal Butterworth filter is maximally flat (e.g., has no ripples) in the passband and rolls off towards zero in the stopband. When viewed on a logarithmic Bode plot, the response slopes off linearly towards negative infinity. A first-order filter's response rolls off at –6 dB per octave (–20 dB per decade). A second-order filter decreases at –12 dB per octave (–40 dB per decade), a third-order at –18 dB (–60 dB per decade) and so on. Butterworth filters have a monotonically changing magnitude function with the angular frequency ω, unlike other filter types that have non-monotonic ripple in the passband and/or the stopband[2].

Compared with other filter types, the Butterworth filter rolls off more slowly around the cutoff frequency than them, but without ripple in pass-band. For applications requiring faster transition from passband to stopband, it will often require a higher order to implement a particular stopband specification. The Butterworth filters also have a more linear phase response in the passband than other filters can achieve.

The *Chebyshev filter* has a faster cut-off transition than the Butterworth filter, but at the expense of there being ripples in the frequency response of the passband. There is a compromise to be had between the maximum allowed attenuation in the passband and the steepness of the cut-off response. This is also sometimes called a Type I Chebyshev, the Type II Chebyshev being a filter with no ripple in the passband but ripples appear in the stopband[3].

Chebyshev filters have the property that they minimize the error between the idealized and the actual filter characteristic over the operating frequency range of the filter, but they achieve this with ripples in the passband. Because of the passband ripple inherent in Chebyshev filters, filters with a smoother response in the passband but a more irregular response in the stopband (e.g., the Type II Chebyshev filters) are preferred for certain applications.

The Chebychev filter using LC combinations provides the fastest transition from passband to stopband. The fast transition between pass-band and stop-band

[1] https://en.wikipedia.org/wiki/Network_synthesis_filters

[2] https://en.wikipedia.org/wiki/Butterworth_filter

[3] https://en.wikipedia.org/wiki/Chebyshev_filter

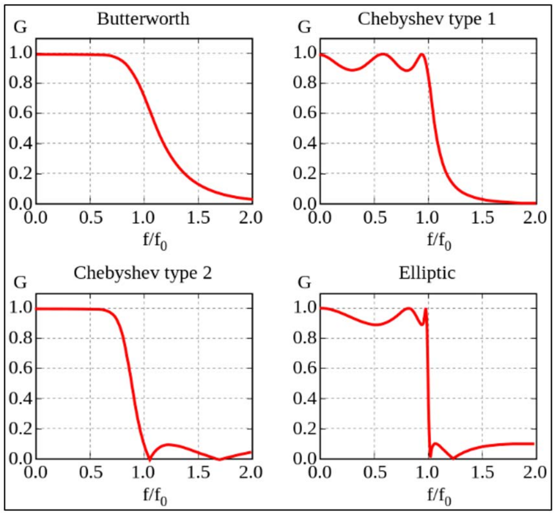
comes at the price of in-band ripple, and this may not make it acceptable for all applications. However, the Chebyshev filter is still widely used and popular in many RF applications where ripple may not be such an issue, since the steep roll-off is used to advantage to provide significant levels of reduction of unwanted out of band spurious emissions such as harmonics or intermodulation products. The fast transition between pass-band and stop-band enables the best attenuation of unwanted signals to be achieved.

The *Elliptic filter* (also known as *Cauer filter*) is a signal processing filter with equalized ripple behavior in both the passband and the stopband. The amount of ripple in each band is independently adjustable, and for the given values of ripple (whether the ripple magnitude is equal or not), no other filter classes of equal order can have a faster transition in amplitude response between the passband and the stopband. Alternatively, one may give up the ability to adjust independently the passband and stopband ripple, and instead design a filter which is maximally insensitive to component variations[1].

The elliptic filter has a faster transition from the passband to the stopband than any other class of network synthesis filter. According to the ripple characteristics presented in the passband and stopband, the elliptic filter can be transformed into other filter classes. As the ripple in the stopband approaches zero, the elliptic filter will become a type I Chebyshev filter. As the ripple in the passband approaches zero, the elliptic filter will become a type II Chebyshev filter and finally, as both ripple values approach zero, the elliptic filter will become a Butterworth filter.

The following Figure 2-10 shows a comparison of the amplitude response (gain) between Butterworth, Chebyshev (type I and type II), and Elliptic filters. Note the filter examples used in this illustration are all fifth-order low-pass filters. As is clear from the figure below, the elliptic filter has sharper transition than all the others but shows ripples within the whole bandwidth[2].

Figure 2-10: Comparison of Amplitude Response for Different Filter Classes



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[1] https://en.wikipedia.org/wiki/Elliptic_filter

[2] https://en.wikipedia.org/wiki/Electronic_filter

2.4 RF Filter Characteristics

Designing RF filters requires careful consideration of various factors and parameters to achieve the desired performance. Some terms often used to characterize RF filters are explained below[1].

- **Orders**: For high-pass and low-pass filters, the order is the sum of the number of reactive elements such as capacitors and inductors used in the filter. For band-pass or band-stop filters, the order is the total number of series or parallel resonators composed of LC components.
- **Cutoff frequency / Bandwidth**: As mentioned previously, the cutoff frequency of the filter is defined as the point at which the amplitude response falls to 50% (e.g., -3 dB) of the amplitude within passband. The cutoff frequency is sometimes referred to as the half power or -3 dB frequency. For band-pass filters there are two cutoff frequencies: lower and upper respectively. Bandwidth is defined as the frequency range of passband, corresponding to the cutoff frequency in low-pass filter and the difference between upper and lower cutoff frequency for a band-pass filter.
- **Return Loss (S_{11})**: Return loss (abbreviated as RL) is used to measure the amount of the signal power reflected by the filter when the signal is input to the filter, expressed in dB. Sometimes, the VSWR can be used to indicate the input reflection characteristic of the filter. Both VSWR and RL can be defined in terms of the magnitude of the input reflection coefficient Γ_{in}, (e.g., the magnitude of S_{11} parameter if two-port network model was used for analysis).

$$VSWR = \frac{1 + |\Gamma_{in}|}{1 - |\Gamma_{in}|} = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

$$RL(dB) = -20 \log|\Gamma_{in}| = -20 \log|S_{11}|$$

- **Insertion Loss (S_{21})**: Insertion loss (abbreviated as IL) is used to measure the attenuation amount of signal power in the passband when the signal passes through the filter, expressed in dB. On the other hand, the variation of insertion loss also refers to the magnitude of passband ripple or passband flatness in other words. Insertion loss can be expressed as S_{21} parameter if the two-port network model was used for analysis.

$$IL(dB) = -20 \log|S_{21}|$$

  Return loss and insertion loss are related characteristics, and RF filters with good insertion loss characteristics tend also to have good return loss characteristics.

- **Out-of-band Rejection** or **Out-of-band Attenuation**: Out-of-band Attenuation is often used to represent the amount of reduction of signal power within

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[1] https://www.wiley.com/en-sg

stopband, especially at some frequencies of interest such as harmonics, expressed in dB. It shows the suppression ability of the filter to unwanted frequency signals.

When the filter design focuses on insertion loss, there will be a tendency for attenuation characteristics to suffer. For this reason, maintain a balance or trade-off between in-band insertion loss and out-of-band attenuation when designing an RF filter for practical application.

- **Quality Factor**: Q factor describes the selectivity of the band-pass filter and related to bandwidth, which generally defines the ratio of the average stored energy to the energy loss per cycle at the resonant frequency. It's commonly considered the power loss as consisting of the power loss associated with the external load and the filter itself, the resulting quality factor is named loaded Q. It can be expressed as follows[1]:

$$Q = \omega \frac{average\ stored\ energy}{energy\ loss\ per\ cycle}\bigg|_{\omega=\omega_c} = \frac{f_c}{BW_{3dB}}$$

  where f_c is the center or resonant frequency of the filter, and BW_{3dB} is the 3 dB bandwidth of the filter. It can be seen that Q factor is inversely proportional to filter bandwidth.

- **Shape Factor**: This factor describes the sharpness of the filter frequency response by taking the ratio between the 60 dB and the 3 dB bandwidth. The higher the shape factor, typically the closet the filter is to theoretical performance. The shape factor of an ideal band-pass filter is equal to 1 which means its passband shape is close to one rectangle[1].

$$SF = \frac{BW_{60dB}}{BW_{3dB}}$$

- **Group Delay:** Group delay is a measure of how different frequency components of a signal (which consists of sine waves at various frequencies) are delayed in propagation time when passing through the filter. It characterizes the dispersion characteristics of the filter. Group delay is a derivative of the filter's phase with respect to frequency and expressed in units of time (seconds)[1].

$$t_g = \frac{d\phi(\omega)}{d\omega}$$

- **Power Capacity**: Power capacity defines the maximum power of the passband signal that can be handled by the filter. Ensuring the filter can handle the incoming power is critical. Assessing the filter's power-handling capabilities guarantees its reliability and sustainability when subjected to varying power inputs.

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[1] https://drive.google.com/file/d/1KytkPX0f7uzMQYm7cPSlLfMTxwpmwpw7/view?pli=1iew?usp=sharing&pli=1

SECTION

3

LC Filter Design Examples

As mentioned previously, RF filters are often used to suppress harmonics at higher frequencies to meet various radio certification requirements. Specifically, for 2.4 GHz Bluetooth application based on Apollo Blue series Bluetooth Low Energy SoC, the need to take into account how to decrease the emission levels at 2nd harmonic (frequency rang: 4.8 to 5 GHz) and 3rd harmonic (frequency range: 7.2 to 7.5 GHz) must be considered. It's obvious that only low-pass and band-pass filters are suitable for harmonic rejection.

On the other hand, one also needs to consider whether the RF filtering function can be associated with the LC impedance matching network, thereby reducing the number of discrete components used and saving PCB space. Therefore, the basic principle for designing RF filters is to use as few numbers of LC components as possible to achieve expected performance.

This section will introduce how to design appropriate discrete LC filters used for 2.4 GHz Bluetooth applications. There are many free online design tools that can be used to design and analyze various type of discrete LC filters. A one web-based LC filter design tool[1] will be used as an example in this section to illustrate how to design applicable LC filter based on specific application.

3.1 Basic Design Steps

This section describes the basic guidelines on the step-by-step process of starting an RF filter design to provide insights into how RF filter design starts: selecting the filter response, transfer function, structure, and evaluating its capabilities, and more[2].

- **Specifying the Required Filter Response**

  To begin the filter design process, it is essential to determine the desired response type: low-pass, high-pass, band-pass, or band-stop. Each response

[1] https://markimicrowave.com/technical-resources/tools/lc-filter-design-tool/

[2] https://www.ee-diary.com/2023/05/basic-steps-in-designing-rf-filters.html

type serves different filtering purposes and sets the foundation for subsequent design decisions. As mentioned above, the low-pass and band-pass response types are appropriate for our purpose.

- **Selecting the Applicable Transfer Function**

  The two most common filter classes in RF design are Butterworth and Chebyshev filters. As described previously, the Butterworth filter provides a flat passband response without any ripple, while the Chebyshev filter offers excellent amplitude roll-off characteristics during transition from passband to stopband. Understanding the characteristics of these filter classes helps in selecting the appropriate transfer function for the specific design. Chebyshev filters exhibit amplitude and return loss ripple within their passbands, but they offer a remarkable amplitude roll-off of approximately 10 dB/octave/order, depending on the selected ripple design amplitude. For a predictable 50-Ω output impedance, Chebyshev filters should always have an odd order.

  On the other hand, Butterworth filters have a flat passband response without any amplitude ripple and an amplitude roll-off of 6 dB/octave/order. The elliptical filter exhibits a highly sharp rejection response, but it is generally limited to frequencies below 1 GHz due to its sensitivity to component variations that may degrade its RF performance.

- **Determining Filter Types and Topologies**

  There are different types of RF filters technology. Consideration must be given to the specific filter construction and topology that suits the design requirements. Factors such as frequency range, component variation sensitivity, and size constraints influence the choice between microstrip distributed filters and lumped passive LC filters. Dielectric filters can also offer compact and quick solutions for specific applications but with much higher cost.

  If designing a custom RF filter, the options include distributed-element structures or lumped-element LC structures. In cases where size is a constraint condition and the operating frequency is below 3 GHz, and when working with cost-effective consumer-grade FR-4 PCBs, it is typically advisable to select lumped-element LC filter types instead of distributed structures.

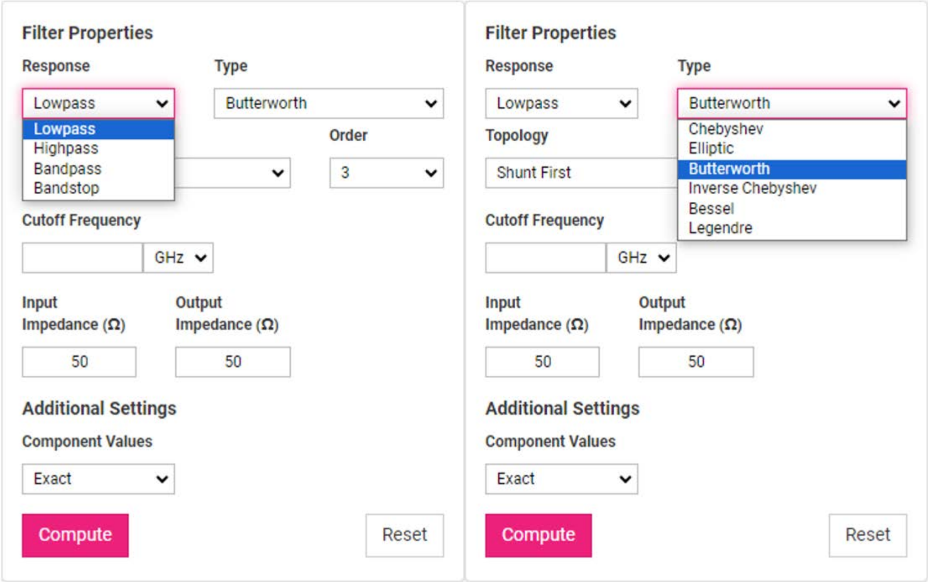
- **Evaluating Filter's Actual Performance**

  Finally, to ensure the RF filter meets the desired performance criteria, it is important to evaluate its capabilities by practical testing. This includes measuring S-parameters that represent return loss, insertion loss and out-of-band attenuation by using network analyzer, verifying the ultimate RF performance by using spectrum analyzer or wireless tester after they are mounted on PCBs.

3.2 Design Tool Introduction

LC Filter design tool[1] is a free online application for lumped LC filter analysis, where one can calculate LC filters circuit values with low-pass, high-pass, band-pass, or band-stop response as well as select different transfer functions such as Butterworth, Chebyshev, Elliptic filter type, and more.

Figure 3-1: Design Parameter Input Window of LC Filter Design Tool



Filter Properties

Response: Lowpass

Type: Butterworth

Order: 3

Input Impedance (Ω): 50

Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

Filter Properties

Response: Lowpass

Type: Butterworth

Topology: Shunt First

Input Impedance (Ω): 50

Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

As shown in Figure 3-1, the meanings of each item in the *Filter Properties* window are explained as follows:

- **Response**: Four basic filter response types: low-pass, high-pass, band-pass and band-stop.
- **Type**: Users can select various network synthesis methods (e.g., different amplitude response characteristics) to implement different transfer function, such as previously mentioned Butterworth, Chebyshev type I or type II, Elliptic, and more.
- **Topology**: It indicates the manner in which passive components are connected in the filter. There will be different options for different filter response type. For low-pass and high-pass filters, only two options are given to indicate if the first component connects in series or shunt. However, there are more options for band-pass filters since they have multiple topologies.
- **Order**: The total number of reactive components (for low-pass and high-pass filters) or LC resonator branches (for band-pass and band-stop filters) used in filter design, up to 20.

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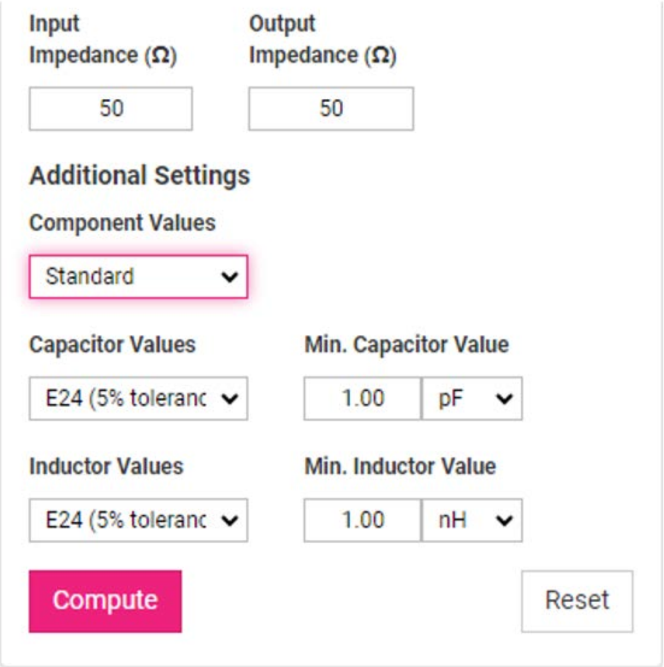
[1] https://markimicrowave.com/technical-resources/tools/lc-filter-design-tool/

- **Cutoff Frequency**: Usually the frequency at which the amplitude response of the filter has fallen by 3dB from passband level. Only one value for low-pass and high-pass filter types but two values for band-pass and band-stop filters.
- **Input Impedance & Output Impedance**: The default impedance value is 50 Ω but users can also set arbitrary input and output impedances.
- **Component Values**: Two options are given: exact or standard component value. By default, LC filters will be synthesized with exact components values and show ideal frequency response. However, actual mass-produced components have values limited to a set of standard component values and bounded below by some minimum. Moreover, they are subject to manufacturing tolerances and temperature variations. Consequently, when implementing the simulation design, actual component values often differ from the simulated values and may negatively impact the filter performances. Thus, to model the filter sensitivity to these variations, users can limit the capacitance and inductance to standard E series of preferred values[1], and also set their minimum values as shown in Figure 3-2.

Figure 3-2: Additional Settings for Standard Component Values


Input Impedance (Ω): 50
Output Impedance (Ω): 50
Component Values: Standard
Capacitor Values: E24 (5% toleranc
Min. Capacitor Value: 1.00 pF
Inductor Values: E24 (5% toleranc
Min. Inductor Value: 1.00 nH

At last, export the auto-generated filter design to detailed S-parameter files or time-domain files for further accurate analysis, that enables us to modify the circuit and edit component values, run S-parameters analysis, simulate the effects of finite Q factor possessed by inductor and capacitor in engineering, run transient response analysis, and more.

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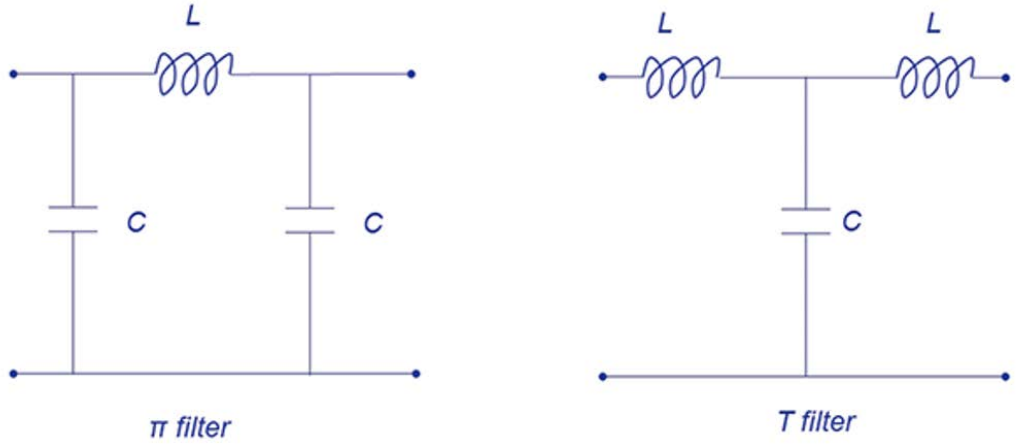
[1] https://en.wikipedia.org/wiki/E_series_of_preferred_numbers

There are two types of circuit simulators that the LC filter design tool can export to: LTSpice[1] and Qucs[2]. They are both free available online and for more information visit their websites.

3.3 Low-Pass Filter Design Example

As described in the *Apollo BLE SoC Impedance Matching Application Notes v1.0*, the L-type, Π-type or T-type topology with low-pass structures are recommended to use in RF front-end matching network. Thus, the optimal choice is to design one low-pass filter combined with off-the-shelf matching network. As mentioned previously, the filter order is equal to the total number of reactive components used in low-pass filters. The configurations of 3-order Π and T low-pass filters are given in Figure 3-3. Next, use Butterworth and Chebyshev methods respectively to design 3-order low-pass filter and check if they meet design expectations.

Figure 3-3: The Low-Pass Π-Type and T-Type Filter Topology



RF filter design objectives are determined based on practical application requirements at the initial stage. In most cases the design goals need to be adjusted or modified dynamically depending on original RF test results. The first design principle is to ensure the insertion loss within operating frequency range should be as low as possible while the attenuation at harmonic frequencies should be as much as possible. For Bluetooth applications, take several filter characteristic parameters below as design expectations at first.

- Return loss within operating band (2.4 ~ 2.5 GHz): lower than -20 dB at least
- Insertion loss within operating band (2.4 ~ 2.5 GHz): lower than 0.5 dB
- Suppression at 2nd harmonic (4.8 GHz): greater than 10 dB at least
- Suppression at 3rd harmonic (7.2 GHz): greater than 20 dB at least

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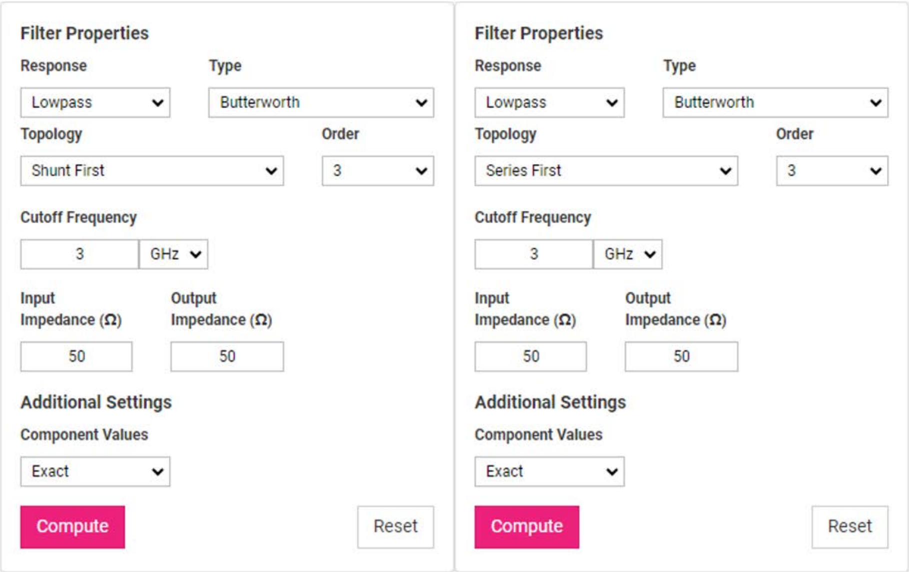
[1] https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
[2] https://qucs.sourceforge.net/

As described above, the return loss corresponds to S_{11} parameter, and the passband insertion loss plus the out-of-band attenuation correspond to S_{21} parameter in a two-port network. Thus, use S-parameters model for analysis.

1. **Butterworth Filter Example**

   Use Π-section and T-section to model the 3-order Butterworth low-pass filter respectively. Considering the Butterworth filter has a slow roll-off rate from passband to stopband, so the cutoff frequency must be set to a higher value to minimize the influence. Otherwise, the insertion loss in operating band will increase and become unacceptable for wanted signals. On the other hand, the out-of-band attenuation will be difficult to meet if the cutoff frequency is set to much higher than operating frequency. Thus, there are always trade-offs between various design requirements. In this example the various parameters in the **Filter Properties** window are set as shown in Figure 3-4. *Shunt First* in the topology box means Π-section config and shown in the left half, while *Series First* means T-section config and shown in the right half.

   Figure 3-4: Parameter Settings for 3-Order Low-Pass Butterworth Filter

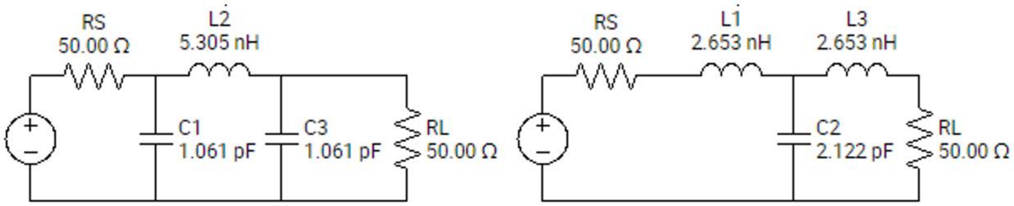


Filter Properties
Response: Lowpass
Type: Butterworth
Topology: Shunt First
Order: 3
Cutoff Frequency: 3 GHz
Input Impedance (Ω): 50
Output Impedance (Ω): 50
Additional Settings
Component Values: Exact

Filter Properties
Response: Lowpass
Type: Butterworth
Topology: Series First
Order: 3
Cutoff Frequency: 3 GHz
Input Impedance (Ω): 50
Output Impedance (Ω): 50
Additional Settings
Component Values: Exact

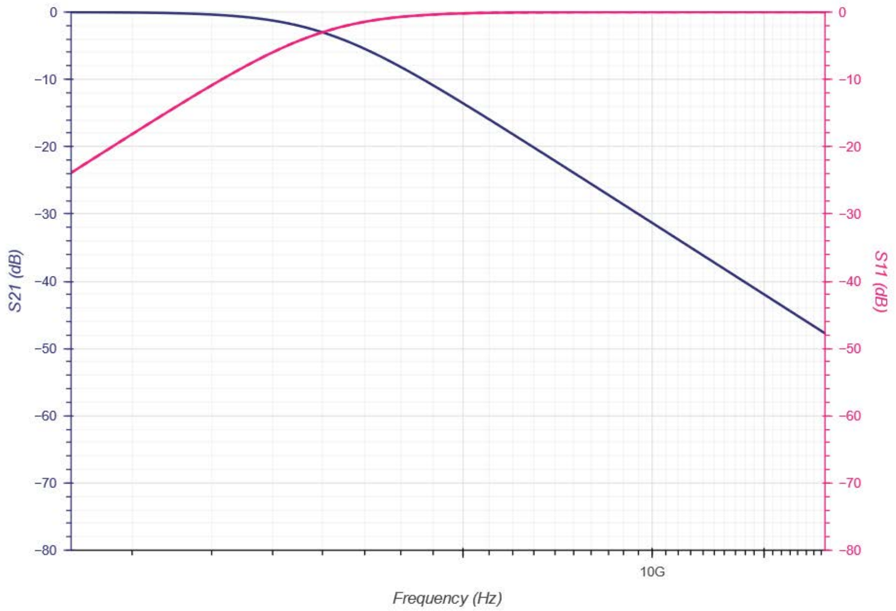
   Then click **Compute**. The discrete LC filter circuit schematic will be generated as shown in Figure 3-5 respectively. Note these LC component values are calculated as exact and ideal ones, so replace them with the closest capacitor and inductor standard values in practice.

   Figure 3-5: Derived Butterworth Filter Schematics for Π-Section and T-Section



As shown in Figure 3-6, the S_{11} and S_{21} frequency response curves are also auto-generated by simulation settings accordingly. The simulation results are basically consistent for Π-section and T-section. Observed from the S-parameters response curves, the cutoff frequency is located at the cross point of S_{11} and S_{21}curves. The S_{21} curve indicates insertion loss within operating frequency range exceeded 1 dB and was higher than expected although the suppression at harmoni frequencies just meet design requirements. Meanwhile, the S_{11} within operating band was greater than -10 dB which means the return loss was too high.

Figure 3-6: The Simulation Results of S_{11} and S_{21} for Butterworth

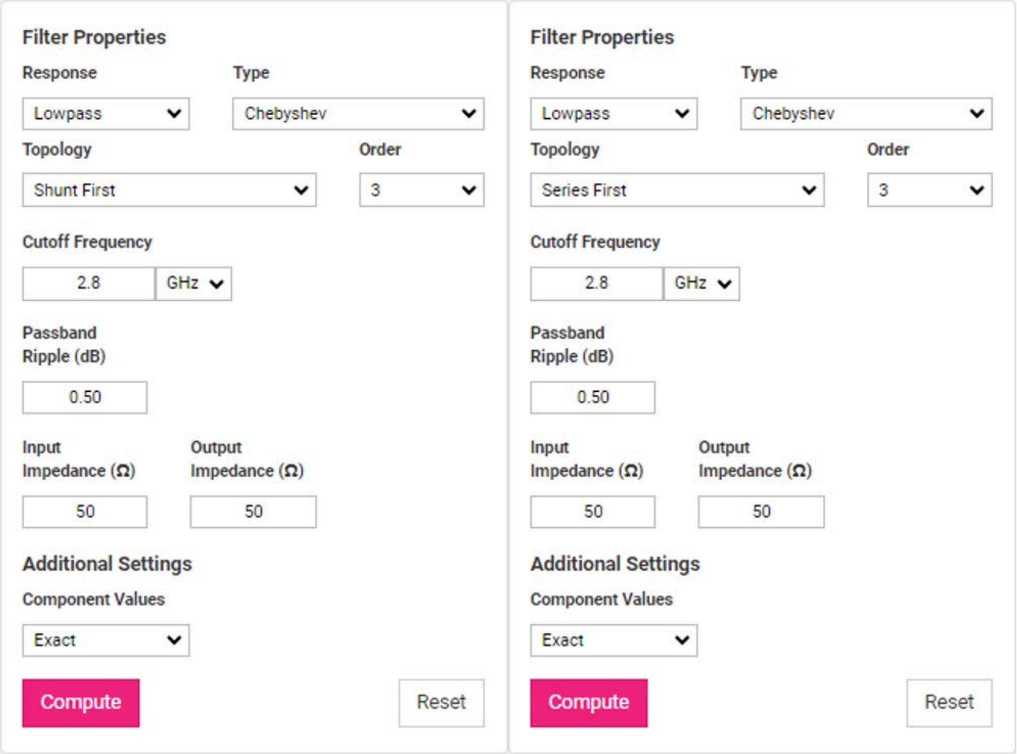


Therefore, the 3-order Butterworth low-pass filter cannot achieve design goals well due to its inherent slow roll-off characteristics. There are two approaches that can improve this situation: one is to increase the order of the low-pass filter, but this means more LC passive components are needed; the other way is to utilize another low-pass filter design methodology.

2. **Chebyshev Filter Design Example**

Like before, create two topologies of Π-section and T-section by using Chebyshev synthesis method for designing a 3-order low-pass filter. Various options are set as shown in Figure 3-7 on page 24, one more item named **Passband Ripple** appears in Chebyshev design type. Note the cutoff frequency here may be set to a lower value than the Butterworth type due to its faster transition from passband to stopband. The two settings are the main differences between Chebyshev and Butterworth filters.

Figure 3-7: Parameter Setting for 3-Order Low-pass Chebyshev Filter



Filter Properties

Response: Lowpass
Type: Chebyshev
Topology: Shunt First
Order: 3
Cutoff Frequency: 2.8 GHz
Passband Ripple (dB): 0.50
Input Impedance (Ω): 50
Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

Filter Properties

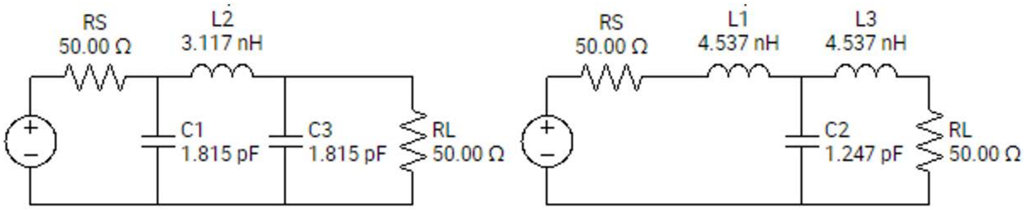
Response: Lowpass
Type: Chebyshev
Topology: Series First
Order: 3
Cutoff Frequency: 2.8 GHz
Passband Ripple (dB): 0.50
Input Impedance (Ω): 50
Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

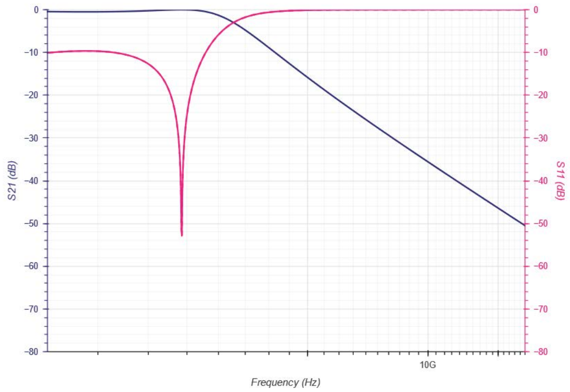
The discrete LC filter circuit schematic will be auto-generated by above simulation settings as shown in Figure 3-8 respectively.

Figure 3-8: Derived Chebyshev Filter Schematics for Π-Section and T-Section



Based on these exact and ideal LC component values, the S_{11} and S_{21} frequency response curves are also auto-generated as shown in Figure 3-9. According to the simulation results, the S_{11} (return loss) within operating band would get lower than -30 dB as well as the S_{21} (insertion loss) would be as low as less than 0.5 dB. In the meantime, the out-of-band attenuation will be lower than -15 dB at 2nd harmonic frequency and less than -25 dB at 3rd harmonic frequency.

Figure 3-9: The Simulation Results of S_{11} and S_{21} for Chebyshev



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As is seen from the comparison above, disregarding the difference of component values the Chebyshev low-pass filter type seems more appropriate for RF applications than the Butterworth structure, since it can reach a better balance between return loss and insertion loss.

The next step is to export the auto-generated filter design constructed by ideal LC component models for further analysis. The export dialog box is as shown in Figure 3-10 on page 26 as mentioned above two kind of circuit simulator tools are supported: LTSpice[1] and Qucs[2]. The purpose of export actions is to model the filter by using the closest capacitor and inductor engineering values and take into account the parasitic effects brought by them when applied to RF applications.

For both of the two circuit simulators, the export dialog will create the corresponding file format they supported respectively, which includes the filter schematics as well as auto-generated simulation settings. Afterwards, modify the exact component values with standard component values available in engineering and select the type of simulation to preform, either being S-parameters or time-domain transient response.

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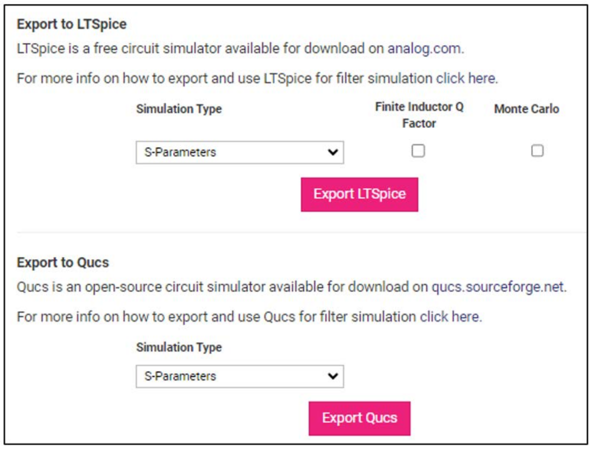
[1] https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html

[2] https://qucs.sourceforge.net/

Figure 3-10: Export Dialog of LC Filter Design Tool



Export to LTSpice

LTSpice is a free circuit simulator available for download on analog.com.

For more info on how to export and use LTSpice for filter simulation click here.

Simulation Type: S-Parameters

Finite Inductor Q Factor ☐

Monte Carlo ☐

Export to Qucs

Qucs is an open-source circuit simulator available for download on qucs.sourceforge.net.

For more info on how to export and use Qucs for filter simulation click here.

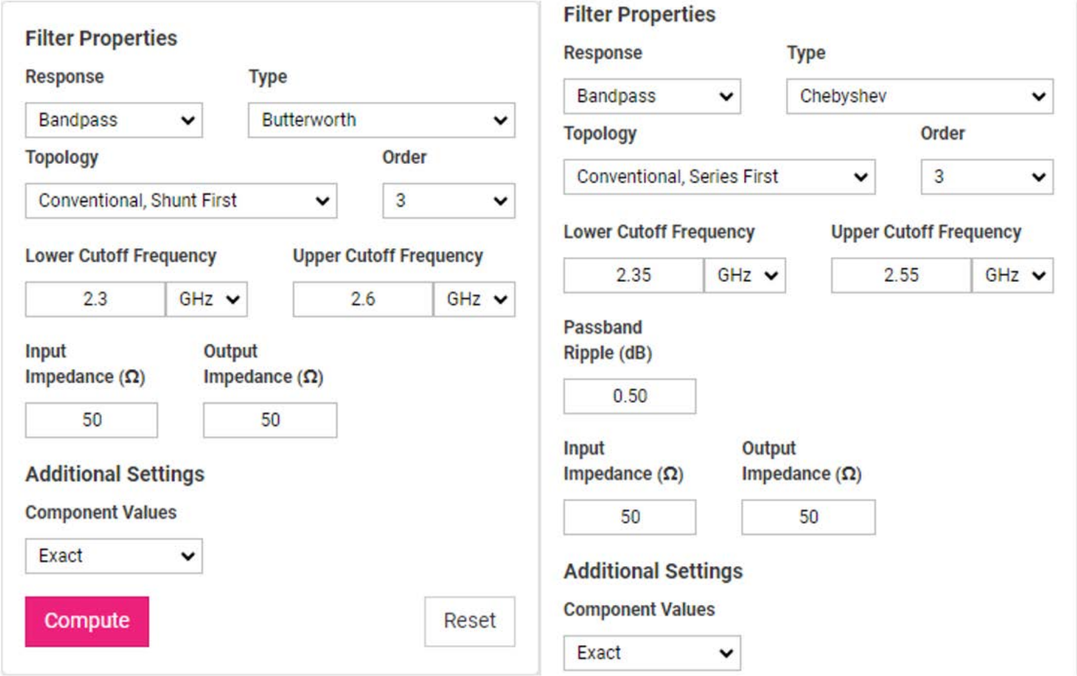
Simulation Type: S-Parameters

3.4 Band-pass Filter Design Example

Compared with low-pass or high-pass filter types, band-pass filters require double the number of components for the same filter order. Thus, band-pass filters composed of lumped LC components are not recommended for those designs with compact board size under normal conditions. There are also other constraint factors, such as practical available component values, that limit the application of discrete LC band-pass filters. Below gives design examples to illustrate these limitations.

Design one 3-order band-pass filter by using Butterworth and Chebyshev method respectively. As shown in Figure 3-11, the Butterworth filter design parameters are set as shown in the left half and the Chebyshev set as shown in the right half.

Figure 3-11: Parameter Settings for 3-Order Band-pass Filter



Filter Properties

Response: Bandpass

Type: Butterworth

Topology: Conventional, Shunt First

Order: 3

Lower Cutoff Frequency: 2.3 GHz

Upper Cutoff Frequency: 2.6 GHz

Input Impedance (Ω): 50

Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

Filter Properties

Response: Bandpass

Type: Chebyshev

Topology: Conventional, Series First

Order: 3

Lower Cutoff Frequency: 2.35 GHz

Upper Cutoff Frequency: 2.55 GHz

Passband Ripple (dB): 0.50

Input Impedance (Ω): 50

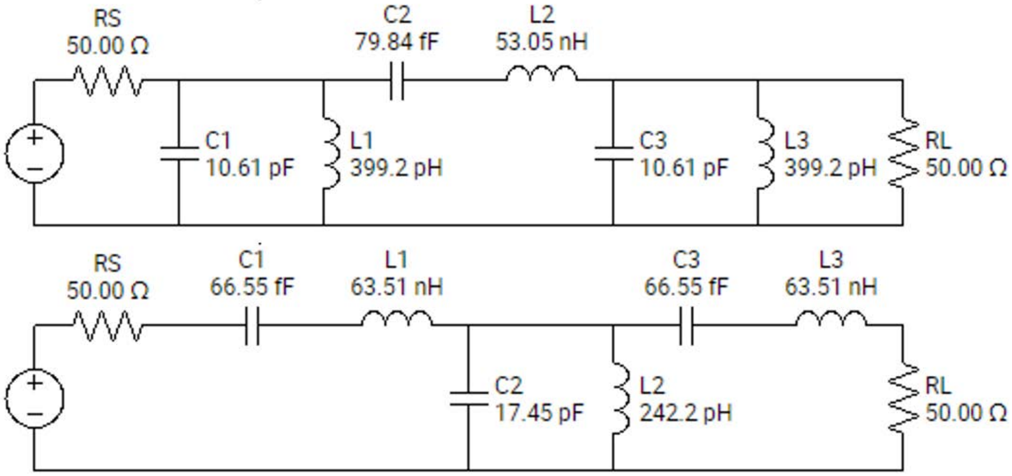
Output Impedance (Ω): 50

Additional Settings

Component Values: Exact

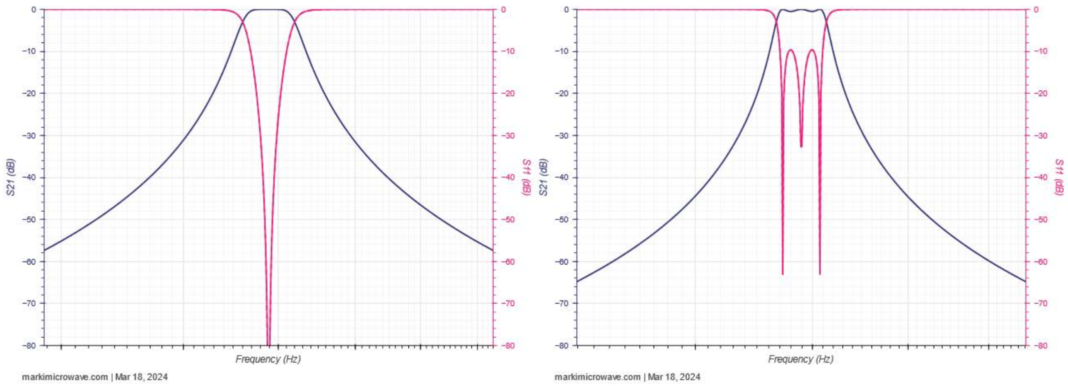
The corresponding band-pass filter schematic auto-generated by above settings are as shown in Figure 3-12 on page 27. It can be seen that the simulated component values, such as capacitors used in series connection and inductors used in shunt connection, are too small and not available in engineering.

Figure 3-12: Auto-Generated Bandpass Filter Schematics for Two Types



The simulated S_{11} and S_{21} frequency response curves are given as shown in Figure 3-13. It seems that the Butterworth type has better return loss and flatness characteristic within passband than the Chebyshev type for band-pass filter applications.

Figure 3-13: Simulation Results of S_{11} and S_{21} for Bandpass Filters



Therefore, in addition to increasing the number of components used, it's difficult for band-pass filters to find actual inductors and capacitors matching or approaching the simulated component values for 2.4 GHz applications. As a matter of fact, in the case of high-frequency and compact applications it is more preferable to directly use the off-the-shelf bandpass filter products (e.g., miniaturized integrated package of distributed-element filters, ceramic filters, electroacoustic filters as mentioned before, and more).

SECTION

4

Conclusion

Starting an RF filter design required careful consideration of various factors, such as filter response type, transfer function selection, filter topology, and evaluating the filter's actual performance such as in-band insertion loss and out-of-band attenuation, and more. As a result, the applicable RF filter designs are always required to compromise among various constraints.

This application note described some filter basics and illustrated how to design an appropriate lumped-element LC filter for 2.4 GHz Bluetooth based applications. It turns out that the low-pass LC filter is the most appropriate type for miniaturization board-level design, since the least number of reactive components associated with impedance matching network can be used to achieve desired and acceptable performance.

However, as can be seen from examples given in the present document, even a well designed LC low-pass filter operating at 2.4 GHz ISM band does not provide very good roll-off characteristic and out-of-band rejection ability. A faster roll-off from the passband to the stopband usually means that the designed filter must be of higher order, which indicates more reactive components should be employed. It’s impossible for consumer electronic products that are getting more and more miniaturized today. In this case the possible solution is to directly use those ready-made RF filter products that have better performance but also more expensive.

Design examples given in the present document are only for reference and modifications must be performed when designing a practical LC filter that is applied in RF systems. Always remember that the basic rule of lumped-element LC filter design is to use as few the number of reactive components as possible once the filter’s capabilities meet design requirements and expectations.

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