Between the Amplifier and the ADC: Managing Filter Loss in Communications Systems

Filtering plays an essential part in nearly all communications systems. Removing unwanted signals is part of system design to eliminate unwanted noise or distortion. The signal presented to the analog to digital converter should have no spurs or distortion products, especially outside the desired Nyquist band. Noise and distortion spurs that may be safely outside the band of interest may not remain outside of that band after the ADC sampling process folds them around the sampling frequency.

The primary targets for the final analog filter are broadband noise and harmonic distortion spurs. Broadband noise, in particular, can be problematic since the bandwidth of many ADCs is typically several times the bandwidth of the signals to be processed. Likewise, harmonic spurs from the upper end of the band of interest are typically still within the input bandwidth of the ADC, even though they are far removed from the signal band. If not filtered out these spurs and noise can fold back onto weaker desired signals and mask them.

Designing a filter to pass the desired frequencies is fairly easy. However, one of the largest drawbacks to real filter implementations is the loss of signal through the filter, or insertion loss. This signal loss contributes dB for dB to the ADC noise figure. What may be even worse is that the amplifier driving the ADC will generate distortion at multiples of the filter loss. For example, if a filter has 7dB of loss the amplifier needs to drive a signal 7dB stronger. This will result in second order products with 14dB higher levels and 3rd order products will be 21dB worse. Some of these distortion products (intermodulation in particular) cannot be filtered out, so keeping filter loss to a minimum is critical to system performance.
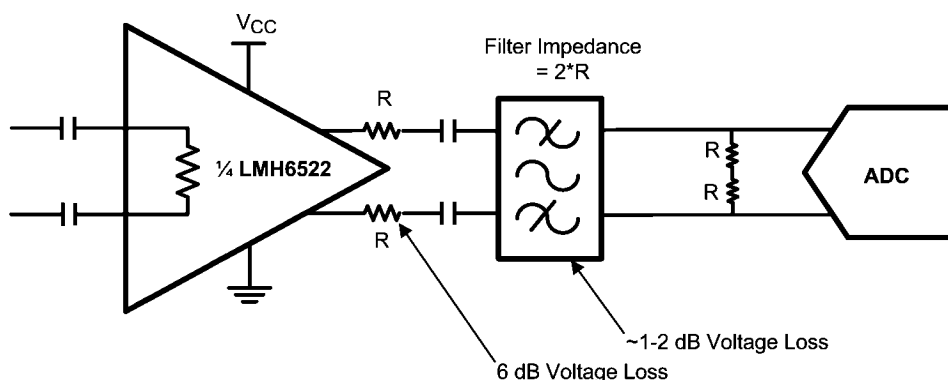

FIGURE 1. Filter-Related Losses

Component Selection for Lowest Losses

One of the first steps of filter optimization is the selection of the center frequency and the bandwidth of the filter. Once this step has been completed the task becomes one of putting the filter elements on the printed circuit board (PCB). PCB design is critical to filter performance, but even before we get to this stage we usually select both the component values and the component sizes we would like to use, this way we can allocate PCB space for the various components. As will be described later, it is very important to choose the filter components first, then make the necessary space available on the PCB, rather than trying to squeeze your filter into the space you have left at the end of the design. The components selected will be critical to the performance of your filter.

INDUCTORS

Most passive filter designs rely heavily on LC circuit elements. Of all the elements in a filter the inductors probably deserve the most attention. Inductors are usually larger and more expensive than the capacitors and resistors used in a given filter. Often inductors are available only in 10% or 5% values as well. By choosing the inductor first the capacitor values can be chosen to help make up for the more limited selection of inductor values. One thing that becomes clear when one is shopping for inductors, though, is that the physical construction of the inductor presents performance compromises that are more severe than found with the capacitors and resistors that will be used for the filter. For a given value of inductance the inductors available are usually in a package size larger than you would prefer. Taking into account frequency limitations and parasitic effects, though, the smaller sizes offered are often unsuitable for the frequency of operation, and using the wrong components can significantly increase the voltage losses inside the filter.

When selecting an inductor you really need to focus on a few key parameters. The first, of course, is the inductance. When looking for inductors of a given value, keep in mind, that of all passive components inductors have the most constraints with respect to the physical size of the device. While a 100pF capacitor can be found in nearly every footprint, for example, inductors are far more limited. For example, in the CoilCraft catalog for an inductor sized 0.080" x 0.050" one series of inductors is available from 2.5 to 51 nH while another series is available from 0.11 to 22 µH.(*Note 1*) While this may seem to be a very large range of values, what may not be clear is that the inductor could be specified at a frequency completely

different than the frequency at which you intend to use the inductor. For example: The CS series of inductors from Coil-Craft use frequencies of 250 MHz to 25 MHz to specify the L values, while the LS series are specified at frequencies of 2.5 MHz to 7.9 MHz.

Finding a component with the correct value of inductance is less than half the battle. One key parameter that is often misunderstood is the Self resonant frequency (SRF). This represents, ideally, the highest frequency at which the inductor is really an inductor. At the self resonant frequency, the inductor has equal amounts of inductive and capacitive reactance. Depending on your application you may be able to use the inductor up to this frequency or slightly beyond. At the very least make sure to model the filter with realistic parasitic values to see if the parasitic capacitance causes the filter to loose performance above the SRF.

When looking at inductor specifications at the signal frequency, don't forget to research the component performance in the stop band. Having good pass-band performance is important, but having good stop band performance is important as well. The stop band can easily extend well beyond the passband frequency.

In filter design many portions of the circuit are composed of dipoles. The dipole is a circuit element where a capacitor and inductor form a resonant pair that contribute to the frequency response of the circuit. At and near the resonant frequency of these dipole elements there are large currents flowing in the circuit. In order to keep resistive losses low the circuit element must have a good quality factor or "Q". The Q of an inductor is defined as the ratio of the resistive losses to the inductive reactance. Q must be measured at the frequency of interest because both the inductive reactance and the resistive losses are frequency dependent. Most inductor manufacturers will chart Q vs frequency for their inductors. As a rule of thumb, it is easier to get a high Q inductor when using a physically larger component. This is primarily due to the ability to use a thicker conductor for the inductor to achieve lower resistance.

Many times, for a given inductor size there will be several construction methods to choose from. Wire wound inductors can have an air core or ferrite core. The conductor can be wire wound, thin film or lithographic. Some inductors offer shielding. Other options may include low temperature co-fired ceramic (LTCC) or other more exotic construction methods. Generally speaking, if the inductor has a satisfactory L, Q and SRF the construction method is not a concern.

CAPACITORS

We looked at inductors first since they are usually the hardest component to select. The capacitors are, of course, equally critical to the filter design; however, they are usually much easier to select. The key parameters of a capacitor are very similar to those of the inductors. Capacitors also have quality factor and self resonant frequency metrics and they should be selected to equal or exceed the values you used to choose the inductor.

One recent trend in capacitors is to shift the side plates to the long side of the capacitor to gain a much higher Q for a sim-ilarly sized capacitor of the more conventional construction. AVX corporation, for instance offers 0204 and 0508 sized capacitors which cut parasitic inductance and resistance (*Note 2*).

When selecting filter capacitors it's also a good time to revisit your supply bypass capacitors for the amplifier and ADC. New low loss, high SRF technology will be equally valuable on decoupling capacitors. In order to make the best use of the new capacitor technology it will be very important to ensure that the decoupling capacitors are close to the amplifier or ADC pins. Vias should be avoided if possible due to the inductance they add. Power supply decoupling is really just a fancy name for a low pass filter you place on the device power pins, and before the PCB design is complete is a good time to make other design changes.

Selecting good components with appropriate values and good performance will help keep the power lost in the components to a minimum. If your filter is nearly ideal due to high Q inductors and capacitors and you still find your system performance coming up short there may be some other alternatives for your system to cut the filter related losses. These techniques are described in the following sections.

Note 1: http://www.coilcraft.com/smind.cfm

Note 2: http://www.avx.com/docs/catalogs/lga2t.pdf

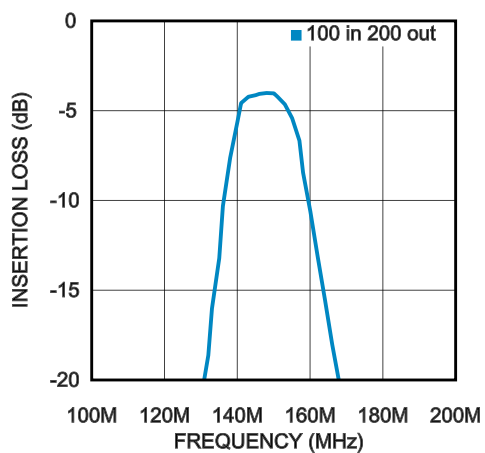# Filters

IMPEDANCE TRANSFORMATION

When you design an LC filter you normally chose a characteristic impedance for the filter. High-impedance filters tend to be susceptible to noise and parasitic PCB capacitance. High-impedance filters also may have undesirably low values for the capacitors. Designing a low impedance filter usually gives better capacitor values and gives a filter that is less influenced by PCB capacitance. Filters with very low characteristic impedance, however, may be difficult or impossible to drive, due to the currents required. Most communications systems have settled on the range of 50Ω to 400Ω as reasonable impedances for IF filters. For example, the ADC16DV160 has been tested with filters that range from 100Ω to 400Ω with good results.

One common trick with filters is to use the input and output impedances to provide some voltage boost. When there is an ADC on the termination end of a filter you can use voltage gain to offset power loss. The reason this works is that the ADC doesn't measure power. An ADC (to a first order) can't tell the difference between 2 V_{PP} across 100Ωs and 2V_{PP} across 200Ω. Thus a 100Ω in, 200Ω out, filter could give you enough voltage boost to almost offset 3dB of the 6dB voltage loss of the termination resistors. This technique does have some limitations. Filters with more than a 4:1 impedance transformation ratio are difficult to design and will be sensitive to component tolerances.
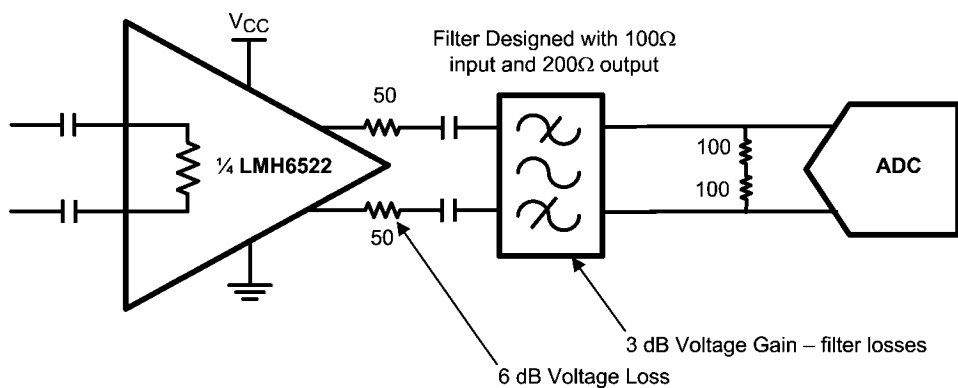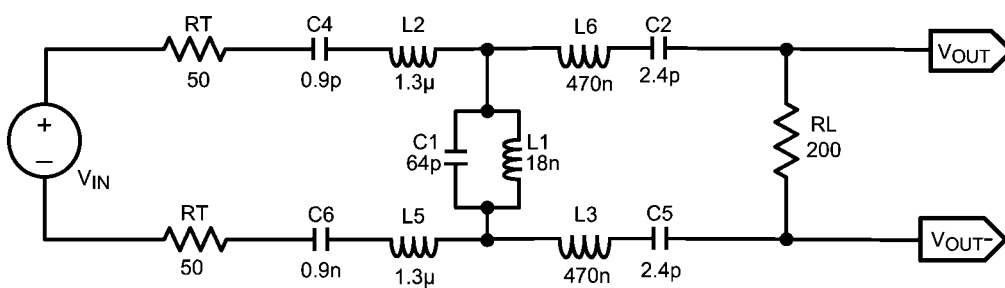
FIGURE 2. Using Impedance Transform To Realize Voltage Gain

FIGURE 3. Frequency Response for Impedance Transform Filter

FIGURE 4. Butterworth Filter with 100Ω Input and
200Ω Output Impedances

FILTER TERMINATION

There is also another option for getting more voltage out of a filter. Filter termination is required for good filter response, however, it is possible to use a filter without matching the impedance of the filter exactly. The degree of filter mismatch will determine the amount of voltage gained and it will also impact the negative effects on the filter response. The exam-ple below shows how the trade off works. It is best to match at least one side of the filter with the design impedance. With an amplifier like the LMH6521 or LMH6522 it is very easy to select the filter driving impedance. The LMH6521/22 ampli-fiers have low output impedance and the filter termination resistors are external so they can be easily changed which makes system optimization easy.
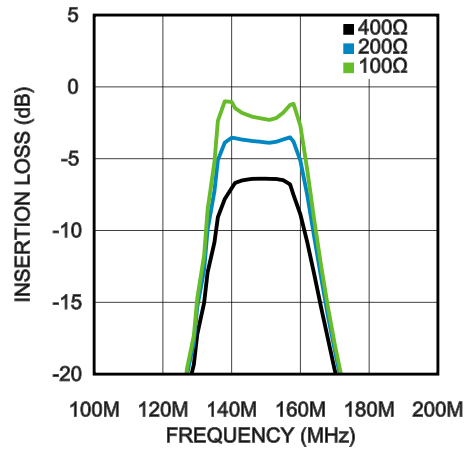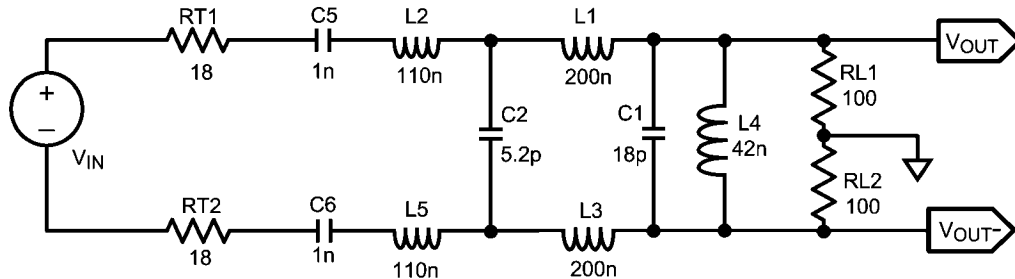

30172307

**FIGURE 5. Butterworth Filter with Different Input Termination Resistance Values —
Filter is designed for 400Ω Input**

CREATIVE FILTER SELECTION

Another option for filter flexibility is the topology of the filter. The filter below has an asymmetric response, incorporates impedance transform and is very forgiving of input impedance termination resistance. From the filter response curves it can be seen that this filter will even give a slight voltage gain while keeping a well-behaved response. This filter topology is par-ticularly well-suited for an anti-alias filter since it provides more attenuation on the high-frequency side of the response. It is on this side that the distortion products fall and in many cases the bulk of the amplifier noise falls into the higher fre-quencies as well.

30172306

FIGURE 6. "Tapped L" Filter
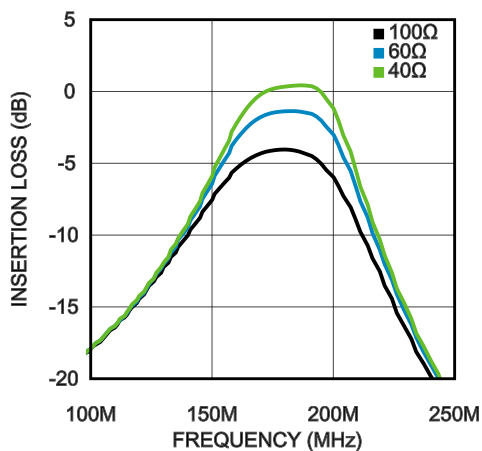
30172308

**FIGURE 7. Various Input Termination Conditions for the Tapped L Filter —
Filter was designed for 100Ω Termination**

ADC Selection

The choice of an ADC can significantly ease the system design. With ever-improving distortion specifications, higher sample rates and noise performance the ADC chosen in a particular application can enable the use of a lower order filter. This filter will have lower loss and will be less susceptible to component variations. Higher ADC sample rates will provide a lot of filter flexibility. For instance, a radio with a 60MHz bandwidth and using a 100 MSPS ADC would gain an additional 25MHz of frequency range by changing to a 150 MSPS ADC. This extra frequency range can be used for filter skirts.

While advancements in high performance, active circuits are making system designs more robust, there is still a need for the use of passive components. Using these filter techniques can make the most of that last passive stage in the signal path.

Notes

TI/NATIONAL INTERIM IMPORTANT NOTICE

Texas Instruments has purchased National Semiconductor. As of Monday, September 26th, and until further notice, products sold or advertised under the National Semiconductor name or logo, and information, support and interactions concerning such products, remain subject to the preexisting National Semiconductor standard terms and conditions of sale, terms of use of website, and Notices (and/or terms previously agreed in writing with National Semiconductor, where applicable) and are not subject to any differing terms and notices applicable to other TI components, sales or websites. To the extent information on official TI and National websites and business social networking media, etc., pertains to both TI and National-branded products, both companies' instructions, warnings and limitations in the above-referenced terms of use apply.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		Applications	
Audio	www.ti.com/audio	Communications and Telecom	www.ti.com/communications
Amplifiers	amplifier.ti.com	Computers and Peripherals	www.ti.com/computers
Data Converters	dataconverter.ti.com	Consumer Electronics	www.ti.com/consumer-apps
DLP® Products	www.dlp.com	Energy and Lighting	www.ti.com/energy
DSP	dsp.ti.com	Industrial	www.ti.com/industrial
Clocks and Timers	www.ti.com/clocks	Medical	www.ti.com/medical
Interface	interface.ti.com	Security	www.ti.com/security
Logic	logic.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Power Mgmt	power.ti.com	Transportation and Automotive	www.ti.com/automotive
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com	Wireless	www.ti.com/wireless-apps
RF/IF and ZigBee® Solutions	www.ti.com/lprf	**TI E2E Community Home Page**	e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

Copyright© 2011 Texas Instruments Incorporated