

Introduction

This application note describes how to use the ispPAC10 to build precision continuous-time third and fourth order lowpass ladder filters. In-system programmability (ISP™) enables programming, verification and reconfiguration directly on the printed circuit board using the IEEE standard 1149.1 compliant serial port. Butterworth and Chebyshev filter types with cutoff frequencies between 17 kHz - 100 kHz are realizable.

The ispPAC10 (Figure 1) contains four integrated programmable analog modules known as PACblocks and a programmable interconnect system. Each PACblock emulates a collection of instrumentation amplifiers, op amps, resistors and capacitors. Because of the flexibility of the ispPAC10, a filter's characteristics can be adjusted using software without the use of external components.

Due to the lossless nature of their reactive LC components, doubly-terminated passive ladder filters minimize the sensitivity of the transfer function to changes in element values due to temperature, manufacturing tolerances, etc. An important class of active filters is based

Figure 1. ispPAC10 Block Diagram

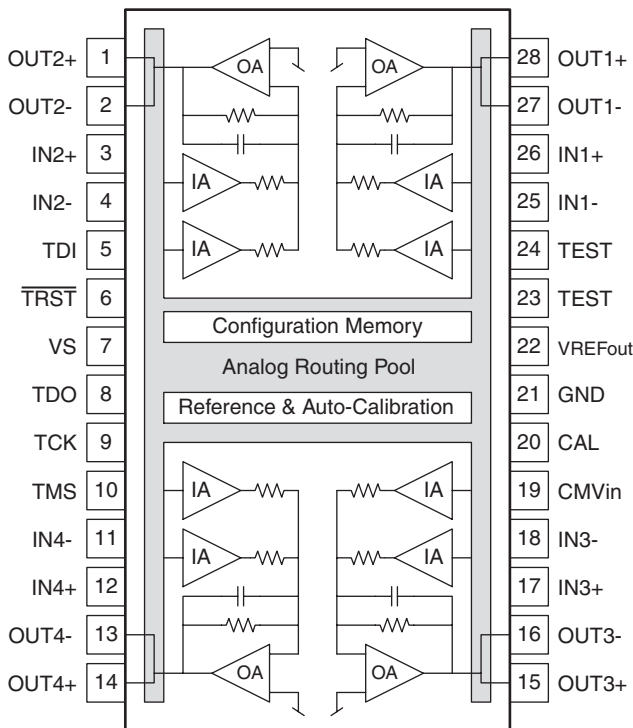
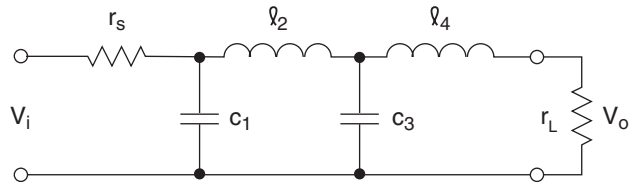


Figure 2. Fourth Order Ladder Filter



upon topologies that use active RC equivalents to realize a passive LC ladder filter. The challenge is to realize an active inductor, and two approaches are commonly used: component simulation, which uses GICs (Generalized Immittance Converters) to model inductors, and operational simulation, which simulates the branch currents of a network as voltages. The latter approach allows the use of RC op amp integrators with time constants proportional to the inductors and capacitors in the filter network. These two techniques are discussed in detail in Reference 1.

The doubly-terminated all-pole lowpass ladder topology is shown in Figure 2. In operational simulation, active integrators are used to simulate inductors and capacitors, while summers are used to implement Kirchhoff's equations, as shown in Figure 3. A one-to-one correspondence is maintained between the L's and C's in the passive circuit and the integrators in the active implementation. Because of this correspondence, the active structure maintains the low component sensitivity of the passive ladder filter.

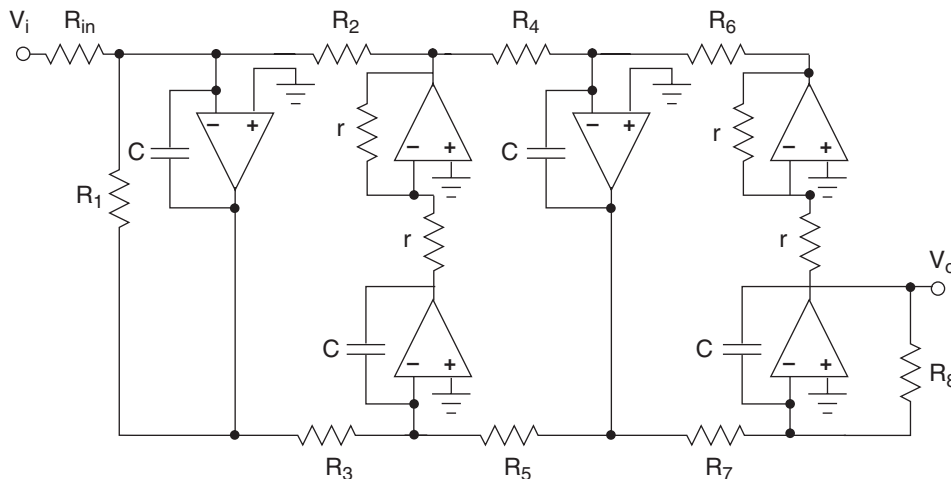
ispPAC10 Implementation

Fundamentally, a PACblock can be represented as a differential output integrator with differential summing inputs, programmable (positive and negative) gain and an optional feedback resistor to implement a lossy integrator. Within a finite range required by the discrete capacitor arrays and integer gain steps, each pole of a 17 kHz - 100 kHz passive ladder filter can be implemented in a PACblock. With four PACblocks in the ispPAC10, a fourth-order filter can be implemented.

The challenge in any filter design is tuning: establishing the parameter values necessary to realize a desired filter characteristic. Because this implementation uses integrators to simulate the operation of the inductors and capacitors, the integrator values can be found by equating the L's and C's of the passive structure to the corresponding integrator time constants in the active

ispPAC10 Precision Ladder Filter Generation

Figure 3. Fourth Order Ladder Filter, Active Implementation



implementation. Ideally, all passive ladder filters can be implemented in this manner because RC op amp circuits simulate the passive components. However, because of the discrete nature of the PACblock gain and capacitance (i.e. R and C), not all L and C values can be simulated within the ispPAC10. To simplify the selection of available realizable filters, a macro has been developed for use with the PAC-Designer® software. This will now be described in greater detail.

Ladder Macro

The ispPAC10 is configured using PAC-Designer™, a Windows®-based design tool. As an alternative to designing a ladder filter manually, a macro has been created which turns the design process into a series of choices: filter type, ripple (if any) and cutoff frequency. Once these choices are made, click the generate schematic button and PAC-Designer will implement the chosen filter. The macro ‘Ladder’ can be accessed through the Tools ⇒ Run Macro menu in the PAC-Designer software. This brings up a dialog box similar to Figure 4. Select the ‘Ladder.exe’ macro and click ‘OK.’

Now a screen similar to Figure 5 will appear. There are several filters from which to choose under the Ripple column. Choosing one of these filters then brings up a selection of available cutoff frequencies for that particular filter.

Filter Types

From Figure 5, it can be seen that there are three filter types available from the Ladder Macro: Chebyshev, Butterworth and Unity Gain. All filters are fourth order except for one third-order Butterworth type (this is evi-

Figure 4. PAC-Designer Macro Dialog

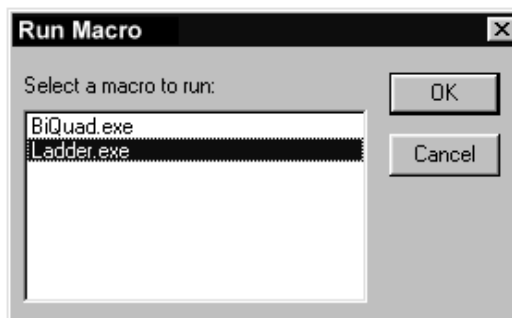
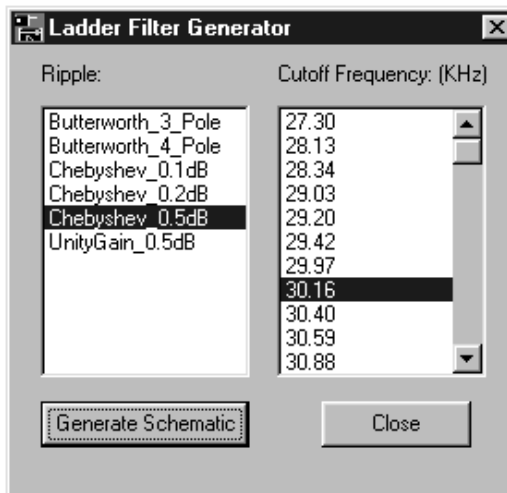


Figure 5. Ladder Filter Generator Macro Example Selection



ispPAC10 Precision Ladder Filter Generation

Figure 6. Available Filter Types

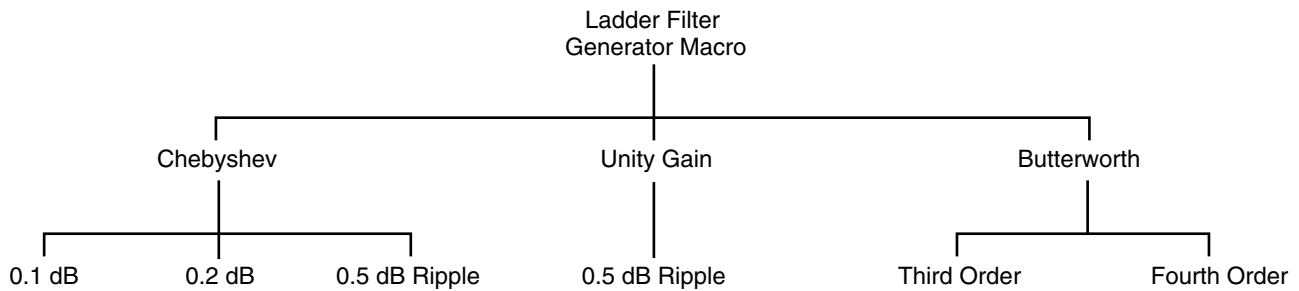
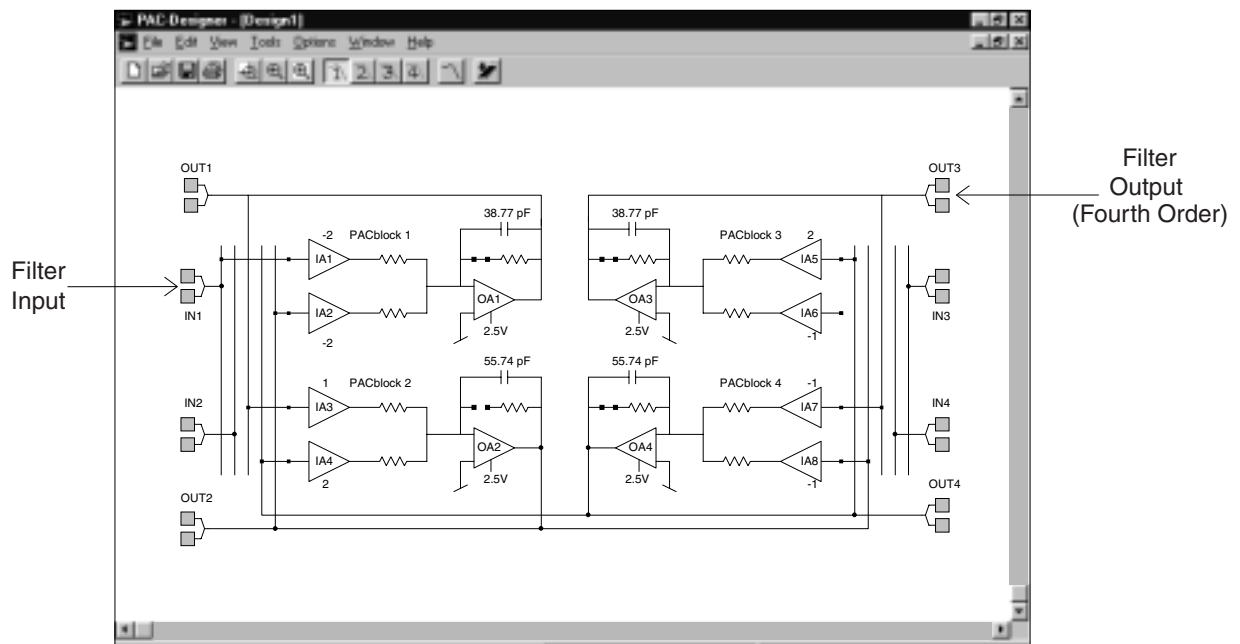


Figure 7. PAC-Designer Fully Implemented ispPAC10 Fourth Order Ladder Filter



dent from its name in the macro screen). See Figure 6 for the available filter types. Referring to Figure 7, the input for all filters is input one (IN1); the output for all fourth order filters is output three (OUT3) and the output for the third order Butterworth filter is output four (OUT4). In the case of the third order filter, the unused PACblock (PACblock 3) is available for other uses.

The Chebyshev filters, available in the PAC-Designer macro, are classical Chebyshev types with equiripple passband and monotonically increasing attenuation in the stopband. The choices are passband ripple of 0.1dB, 0.2dB or 0.5dB. Within each ripple type, a number of cutoff frequencies are available. The cutoff frequencies differ for each filter type due to the discrete nature of the available ispPAC10 gain and capacitor values.

As mentioned above, third and fourth order Butterworth filter types are available. They have nominal 6dB insertion loss and a variety of available cutoff (-3dB) frequencies.

The Unity Gain filter is an equiripple lowpass filter, similar to a fourth order Chebyshev filter with 0.5dB ripple, but with a nominal 0dB insertion loss at DC.

In the Ladder Filter Generator dialog box, select the desired filter type (Ripple) and cutoff frequency and click on 'Generate Schematic.' Figure 7 shows an example of a fourth-order Chebyshev filter implementation with 0.5dB ripple, tuned to have a -3 dB frequency of 30.16 kHz.

The insertion loss for each of the available filters differs and is generally not 0dB. In these implementations, the

ispPAC10 Precision Ladder Filter Generation

only independent control for the filter's insertion loss is the gain value of the input PACblock. Specifically, changing the gain of IA1 in PACblock 1 proportionally changes the gain of the filter. However, increasing the gain value of IA1 to reduce the filter's insertion loss also affects the filter's input dynamic range, as explained in the Input Range Limits section below. If a filter with 0dB insertion loss is required, use either the Unity Gain 0.5dB ripple filter or modify one of the Butterworth types to have 0dB insertion loss by setting the gain of the input PACblock's IA1 to two.

PAC-Designer contains a gain/phase simulator that can display up to four transfer functions. The simulator is accessible through the Tools menu or the simulator icon in the toolbar. The simulator enables the user to easily verify the response characteristics of any of the filters. When running the simulator, be sure to set either V_{OUT3} or V_{OUT4} (depending on the filter type) as the simulator's output node in the Simulator Options dialog box (invoked with Options ⇒ Simulator).

Input Range Limits

Ideally, the overall filter and each stage of the filter should have 0dB insertion loss. Under this condition, the input range would be the full dynamic range of the ispPAC10. However, in this implementation, a PACblock's gain affects both the signal gain and a pole location within the filter. There are only integer PACblock gain steps of one to ten available, and the values in the filter implementations were chosen to provide the pole locations necessary for the particular filter type. These gain values do not necessarily result in 0dB insertion loss for each stage,

thus the filter's maximum input level may need to be less than full scale to prevent an internal node from clipping.

Table 1 gives the input range for each filter type in terms of the ispPAC10 full scale input level. Full scale (FS) is defined as $6V_{PP}$, the maximum recommended input level for specified THD for a PACblock.

Note again that for all filter types, the change in the insertion loss of the filter is directly proportional to the change in the gain of the input stage. Changing this gain does not change any of the filter's frequency characteristics. Changing any other PACblock gain or any capacitor will modify the filter's characteristics. All this is easily verified using the simulator within PAC-Designer.

Filter Performance

The ispPAC10 has a specified typical pole frequency accuracy of $\pm 1.0\%$. Contrast that to traditional R, L, C and op-amp implementations where component values may vary by 5 to 20%. The precision in the ispPAC10 pole accuracy results in a tighter tolerance for the stopband-to-passband ratio, which may mean that the necessary filter order is less. Precision also means that there is less variation in the passband edge, resulting in greater usable system bandwidth and better signal-to-noise performance.

Performing sensitivity analysis using a $\pm 2.5\%$ pole accuracy yields the results shown in Table 2. Figures 8 and 9 are typical of the distributions seen in the filter parameters for fourth-order Butterworth and Chebyshev (0.5 dB ripple) filters. In all cases, note the small variations of gain, cut-off frequency and ripple.

Table 1. Input Range by Filter Type

Filter	Nominal G1*	Maximum Full Scale Input (V_{PP})**	Maximum Input at Nominal G1 (V_{PP})	Nominal DC Insertion Loss (dB)(V/V)	Filter Output (PACblock Number)
Butterworth – 3 Pole	1	$\frac{FS}{G1}$	6	-6.02 (1/2)	4
Butterworth – 4 Pole	1	$\frac{FS}{G1}$	6	-6.02 (1/2)	3
Chebyshev – 0.1 dB	1	Minimum $\left(\frac{FS}{1.3}, \frac{FS}{G1}\right)$	4.6	-1.32 (6/7)	3
Chebyshev – 0.2 dB	1	$\frac{FS}{G1}$	6	-4.42 (3/5)	3
Chebyshev – 0.5 dB	2	Minimum $\left(\frac{FS}{2.1}, \frac{FS}{G1}\right)$	2.9	-3.52 (2/3)	3
Unity Gain – 0.5 dB	2	Minimum $\left(\frac{FS}{1.7}, \frac{FS}{G1}\right)$	3	0 (1)	3

*G1 is the input gain (IA1) of PACblock 1.

**FS = $6V_{PP}$.

ispPAC10 Precision Ladder Filter Generation

Figure 8. Fourth Order Butterworth Filter Implementation

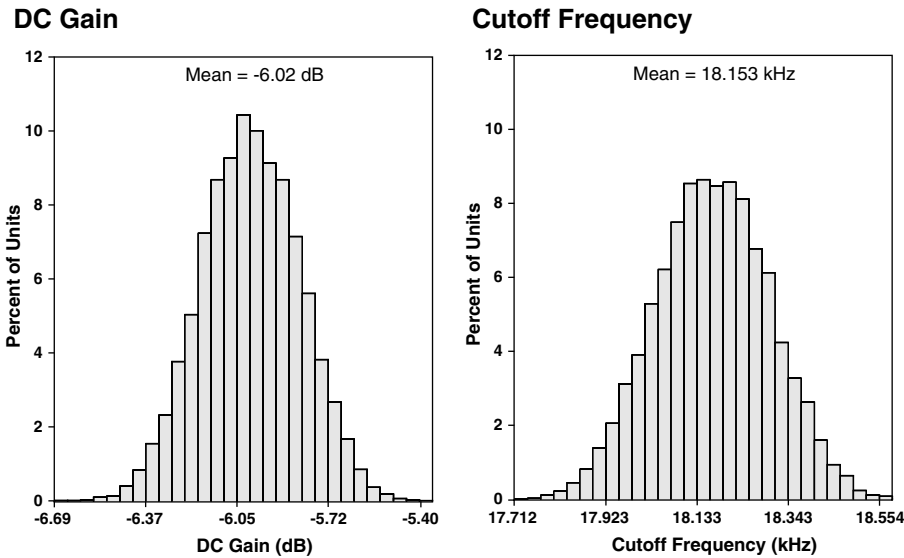


Figure 9. Fourth Order 0.5 dB Chebyshev Variations

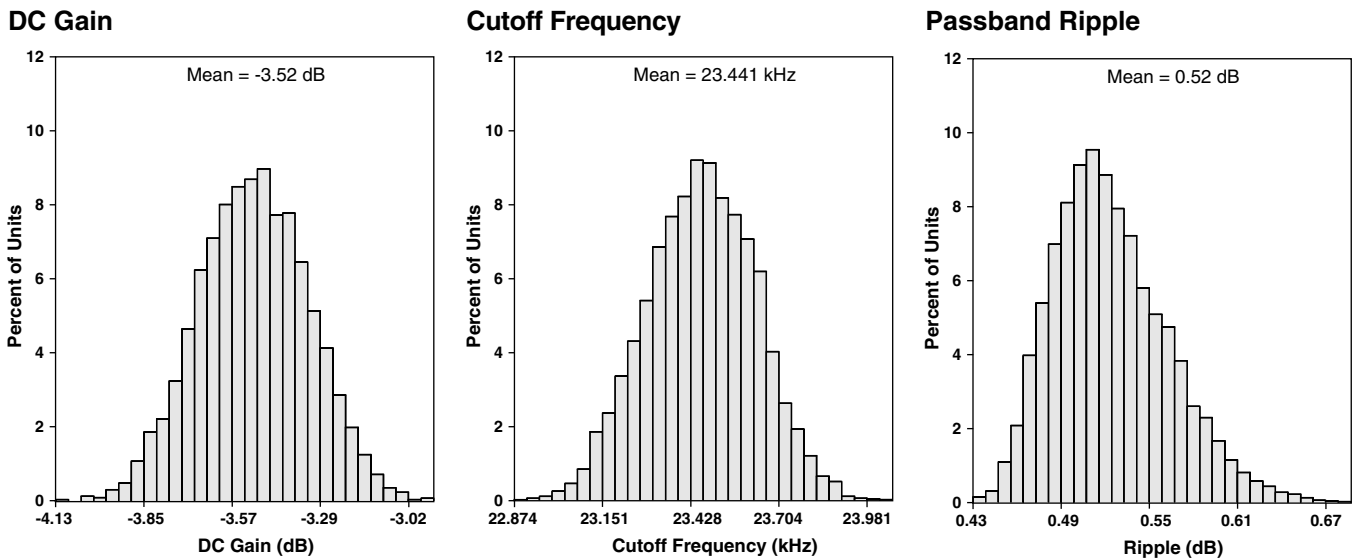


Table 2. Filter Parameter Variation due to ispPAC10 Pole Tolerance of $\pm 2\%$

Filter	Nominal DC Insertion Loss (dB)	Insertion Loss Standard Deviation (dB)	Cutoff Frequency Standard Deviation (%)	Ripple Standard Deviation (dB)
Chebyshev – 0.1 dB	-1.32	0.14	1.15	0.014
Chebyshev – 0.2 dB	-4.42	0.11	0.93	0.019
Chebyshev – 0.5 dB	-3.52	0.11	0.72	0.042
Butterworth – 3 Pole	-6.02	0.08	0.81	—
Butterworth – 4 Pole	-6.02	0.09	0.73	—

ispPAC10 Precision Ladder Filter Generation

Simulation and Results

As previously mentioned, PAC-Designer contains a gain/phase simulator that can display up to four transfer functions. The simulator is accessible through the Tools menu or the simulator icon in the toolbar. Figure 10

provides the simulation results of the filter in Figure 7 while Figure 11 shows the actual measurements taken with a network analyzer. In the actual measurements, notice at high frequencies the excess phase in the phase plot and the existence of a noise floor in the magnitude plot.

Figure 10. PAC-Designer Lowpass Simulation Result

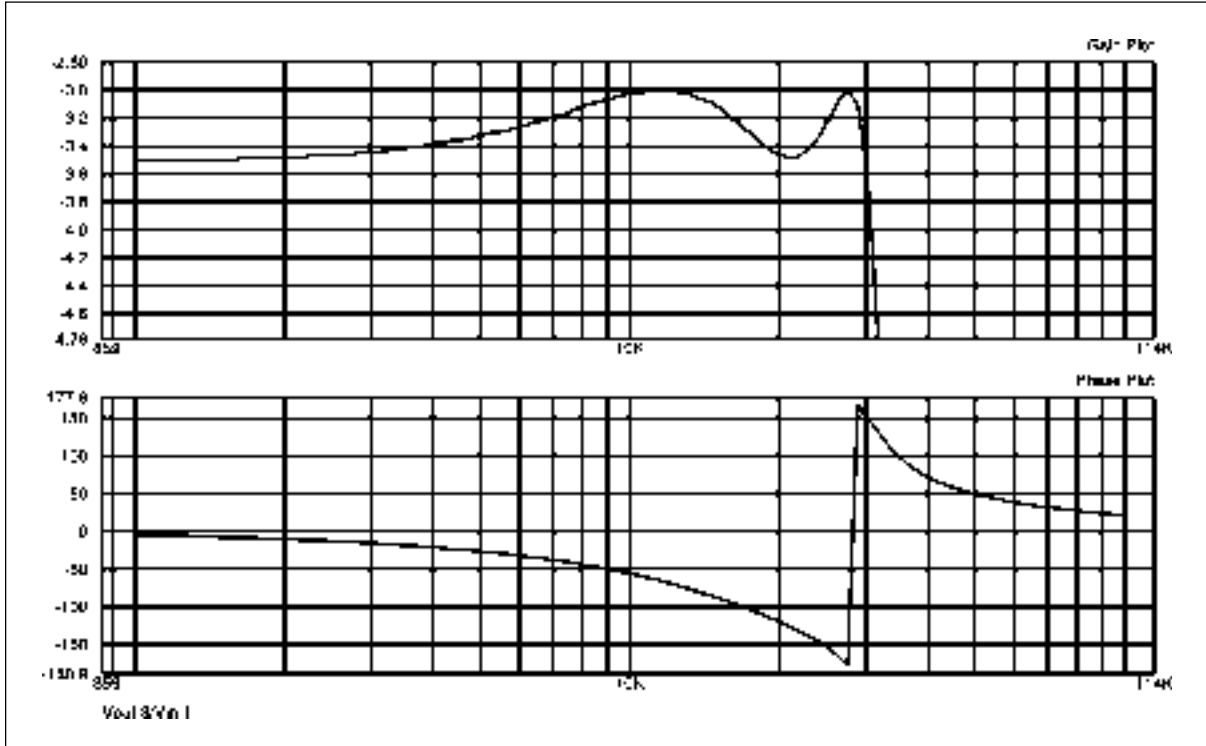
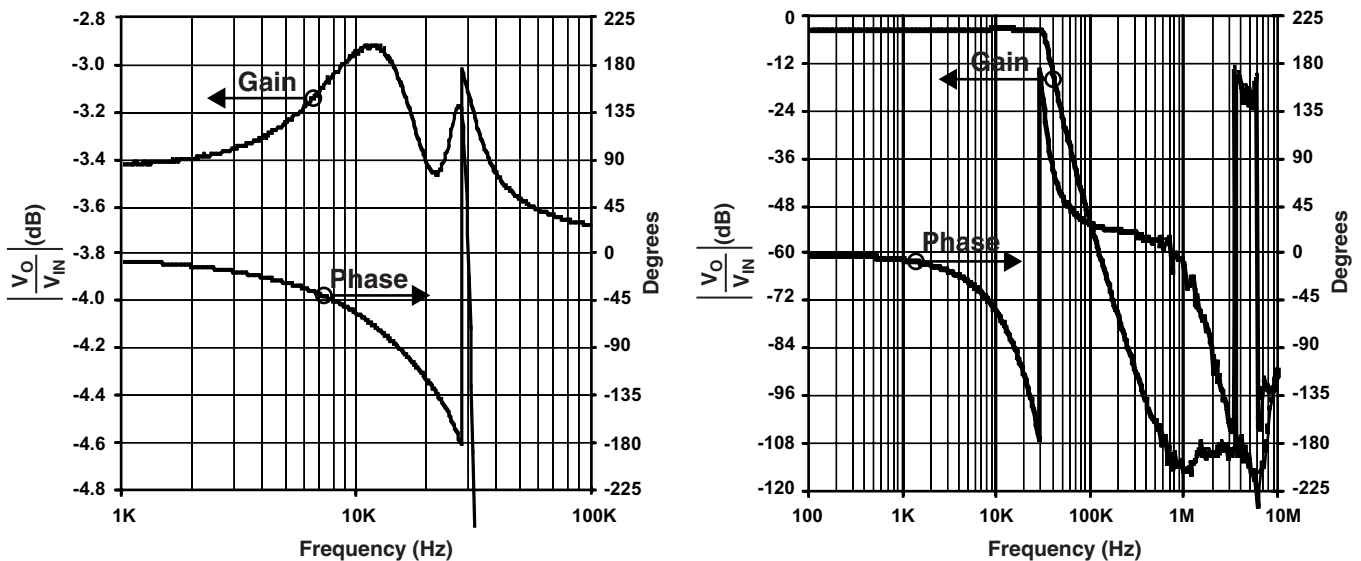


Figure 11. ispPAC10 Chebyshev Lowpass Filter Frequency Response



ispPAC10 Precision Ladder Filter Generation

Summary

The ispPAC10 is a versatile component for performing analog signal processing. Because of its ease of configuration and interconnection, the seemingly simple PACblock can be configured to perform many useful functions. The ladder filters discussed here are one such example. The filters achieve a precision in their frequency characteristics far exceeding that of traditional implementations. A key benefit of the ispPAC10 is the ease in modifying the filter type and parameters, without the need to unsolder the device from a circuit board, made possible by the ISP interface and PAC-Designer software.

Appendix

Fourth Order Transfer Function

The two basic circuits for a PACblock are the lossy integrator and the integrator. As derived in the ispPAC10 data sheet, the transfer function for the lossy integrator is:

$$V_O = \frac{k_1 V_{IN1} + k_2 V_{IN2}}{1 + \frac{sC_F}{2g_{m3}}} \quad (1)$$

and the transfer function for the integrator is:

$$V_O = \frac{k_1 V_{IN1} + k_2 V_{IN2}}{\frac{sC_F}{2g_{m3}}} \quad (2)$$

In these formulas, where g_m is the transconductance value (voltage to current transfer function); g_{mxy} refers to the value of g_m where $x=1, 2$, (the two input amplifiers) or

3 (the feedback element) and y is PACblocks 1-4. The feedback g_m (g_{m3}) is either $2\mu A/V$ or 0 depending on whether the feedback switch is closed or open. The input amplifiers' g_m is equal to $2\mu A/V * k$, where k is the integer gain programmed and displayed in PAC-Designer.

Using this and referring to Figure 7, the transfer function for the (fourth order) ladder filter can be found (Equation 3).

References

1. Sedra, Adel S. and Peter O. Brackett. *Filter Theory and Design: Active and Passive*. Portland, OR: Matrix Publishers, Inc., 1978.
2. Zverev, Anatol I. *Handbook of Filter Synthesis*. New York: John Wiley and Sons, Inc., 1967.
3. Daryanani, Gobind. *Principles of Active Network Synthesis and Design*. New York: John Wiley and Sons, Inc., 1976.

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$$\frac{V_{O3}}{V_{IN1}} = \frac{\left[\frac{16g_{m11}g_{m12}g_{m13}g_{m24}}{C_1C_2C_3C_4} \right]}{\left[s^4 + 2s^3 \left(\frac{g_{m33}}{C_3} + \frac{g_{m31}}{C_1} \right) + 4s^2 \left(\frac{g_{m33}g_{m31}}{C_1C_3} + \frac{g_{m13}g_{m14}}{C_3C_4} + \frac{g_{m21}g_{m12}}{C_1C_2} + \frac{g_{m24}g_{m22}}{C_2C_4} \right) + 8s \left(\frac{g_{m13}g_{m14}g_{m31}}{C_1C_3C_4} + \frac{g_{m21}g_{m12}g_{m33}}{C_1C_2C_3} + \frac{g_{m24}g_{m22}g_{m33}}{C_2C_3C_4} + \frac{g_{m24}g_{m22}g_{m31}}{C_1C_2C_4} \right) + 16 \left(\frac{g_{m12}g_{m13}g_{m14}g_{m21} + g_{m24}g_{m22}g_{m33}g_{m31}}{C_1C_2C_3C_4} \right) \right]} \quad (3)$$