Lattice Semiconductor Corporation

Expanding Frequency and Gain Ranges of the ispPAC®10 and ispPAC20

Introduction

The ispPAC family of analog components from Lattice Semiconductor promises unsurpassed flexibility in many general-purpose analog signal-processing applications by bringing in-system-programmability (ISP™) to the circuit designer. Analog integrated circuits are designed and simulated in Windows®-based, PAC-Designer® software and downloaded to the device to change characteristics as well as circuit topology in milliseconds – directly on the printed circuit board. In-system-programmability allows a designer to immediately evaluate design changes in solid state and allows field upgrades to be accomplished with installed hardware. Configuration data is stored in non-volatile E^2CMOS® memory enabling a device to retain circuit designs while power is turned off. The configuration memory is accessible dynamically as well to change circuit response and function, giving designers true in-system programmability.

Analog building blocks with programmable characteristics replace traditional analog components such as op amps, active filters and comparators, eliminating the need for most external resistors and capacitors. Building blocks are internally connected through an analog routing pool that allows for the blocks to act independently or for cascading and paralleling of multiple stages.

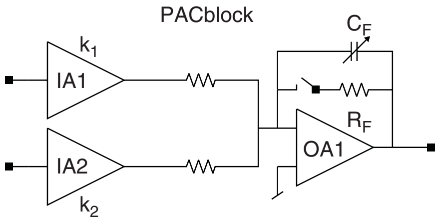
In this application note, we describe how to move the filter range of the ispPAC10/20 to lower frequencies, proportional to the ratio of external resistors. The same technique can be used to increase the gain range of the PACblock™ modules. Measurement results will demonstrate that the frequency can easily be reduced to 10Hz while the gain for a single PACblock can exceed 6000V/V. Additional benefits of this technique include lower input-referred offset and noise, higher SNR and a true rail-to-rail output signal swing.

Overview

The ispPAC10 and ispPAC20 contain multiple PACblocks, such as the one shown in Figure 1. Each PACblock features two instrumentation amplifiers (IA) with built-in gain steps from 1-10 and an output amplifier (OA) with a built-in lowpass filter from 10kHz to 550kHz.

The OA's feedback path contains a programmable feedback capacitor (C_F) and a fixed resistive element (R_F) which can be switched in or out. To configure the PACblock as a regular amplifier, the feedback resistor R_F must be closed. The bandwidth of this amplifier is determined by the product $R_F * C_F$. Programming C_F for different values implements precision lowpass filters in the range of 10kHz (max. cap value) to 550kHz (min. cap value).

Figure 1. Basic PACblock



For the gain and frequency range mentioned above, there is no need for any external components. However, it is possible to achieve programmable gain ranges exceeding the built-in ranges by orders of magnitude by adding external resistors to a PACblock. Furthermore, the programming features of the PACblocks stay fully intact, meaning that the tuning or modification of the device's gain or bandwidth is still available at virtually no loss of accuracy. The programming of the gain settings, feedback path, capacitor values and internal analog routing pool (ARP) between PACblocks and all other features remain fully configurable through nonvolatile on-chip E^2CMOS memory. As usual, the device configuration is set by software and downloaded via a JTAG download cable.

The following discussion will focus on how to connect the external components in order to achieve the gain and frequency expansion mentioned above.

External Feedback

Figure 2a shows conceptually how the external resistor feedback needs to be applied to achieve frequency and gain scaling. For clarity, the first schematic is shown as a single-ended circuit (the differential case will be discussed later). To understand the operation, note that the internal feedback resistor R_F has been disabled (switch is open) and instead IA2 is used as the feedback. This technique, described in application note AN6007, *In-System Programmable Gain with Fractional Gain Adjustments*, is used to achieve gains such as 3/4 or 8/3 and so on, as determined by k_1/k_2. In addition to using IA2 as feedback, the feedback signal is attenuated by the ratio of R_2/R_1.

Figure 2a. Single-ended Schematic for External Feedback

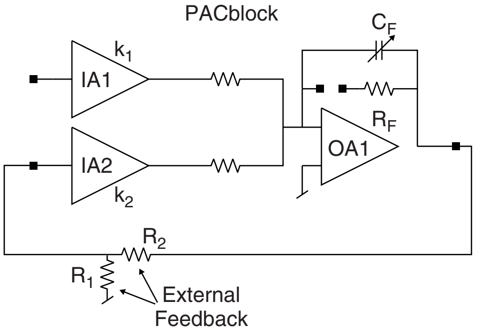
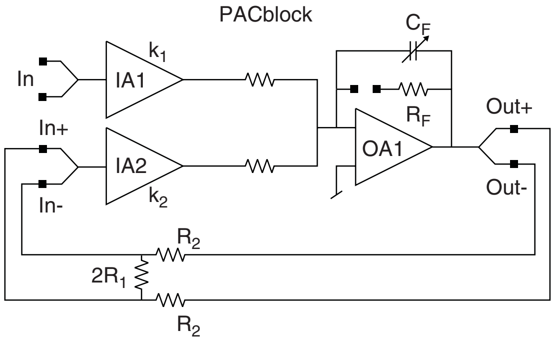


Figure 2b: Differential (real) scheme used in ispPAC10 and ispPAC20



As a result, the feedback is not as "strong" and thus the output amplifier OA1 has to provide more output voltage to make up for that attenuation. Consequently, the higher the attenuation (i.e., the weaker the feedback), the higher the gain from input (In) to output (Out). Note that both k_1 and k_2 (the gains of the two IAs) are still fully programmable and so is C_F.

The exact equation for the new gain is:

$$|A_{dc}| = |V_{out} / V_{in}| = \left|\frac{k_1}{k_2}\right| \left(1 + \frac{R_2}{R_1}\right) \qquad (1)$$

For example, if the attenuation factor R_2/R_1 is 9, then the resulting programmable gain range would *increase* by 10x (the IA's 1x-10x gain range becomes 10x-100x). The effectively "weaker" feedback equates to a higher feedback resistor value, so it is not a surprise that the filter frequencies are affected by the external feedback as well. In fact, for the example shown, the corner frequencies of the lowpass filter are *decreased* by a factor of 10x (10kHz-550kHz becomes 1kHz-55kHz). Note that the polarity of IA2's gain (k_2) must be negative for the circuit to be functional.

Before going into more detail, it is worth pointing out that in reality the PACblocks of the ispPAC10/20 are fully differential and not single-ended. Hence, the second schematic (Figure 2b) shows the actual differential arrangement. The differential nature of the signal also requires the resistor value R_1 to be doubled (referred to as $2R_1$ in the schematic).

Rail-to-Rail Output Swing

The technique of using external feedback can also increase the output signal range. Consider that the resistive feedback element R_F is actually an active circuit whose inputs cannot swing rail-to-rail. Thus, for configurations that use the internal R_F, the PACblock output swing is limited to 1-4V (= 6Vpp diff). However, when using external resistors for feedback attenuation, that limitation no longer applies as long as the attenuated signal going back into IA2 is smaller than 1-4V. For most practical applications, the external resistor ratio will exceed 1.7:1 and therefore the output signals can swing very close to the supply rails without affecting distortion. The measured data (Figure 3) shows that the very low distortion of the PACblocks can be maintained safely within 200mV of each power rail. This is equivalent to a differential output amplitude of more than 9.6V peak-to-peak!

Design Example

Suppose an amplifier with a programmable bandwidth in the range of 100-1kHz is desired. Since the lowest frequency normally is 10kHz, we need a scaling factor of 100. This means R_2/R_1=99. Practical nearest values would be R_2=100kOhm, $2R_1$=2kOhm, k_2=-1.

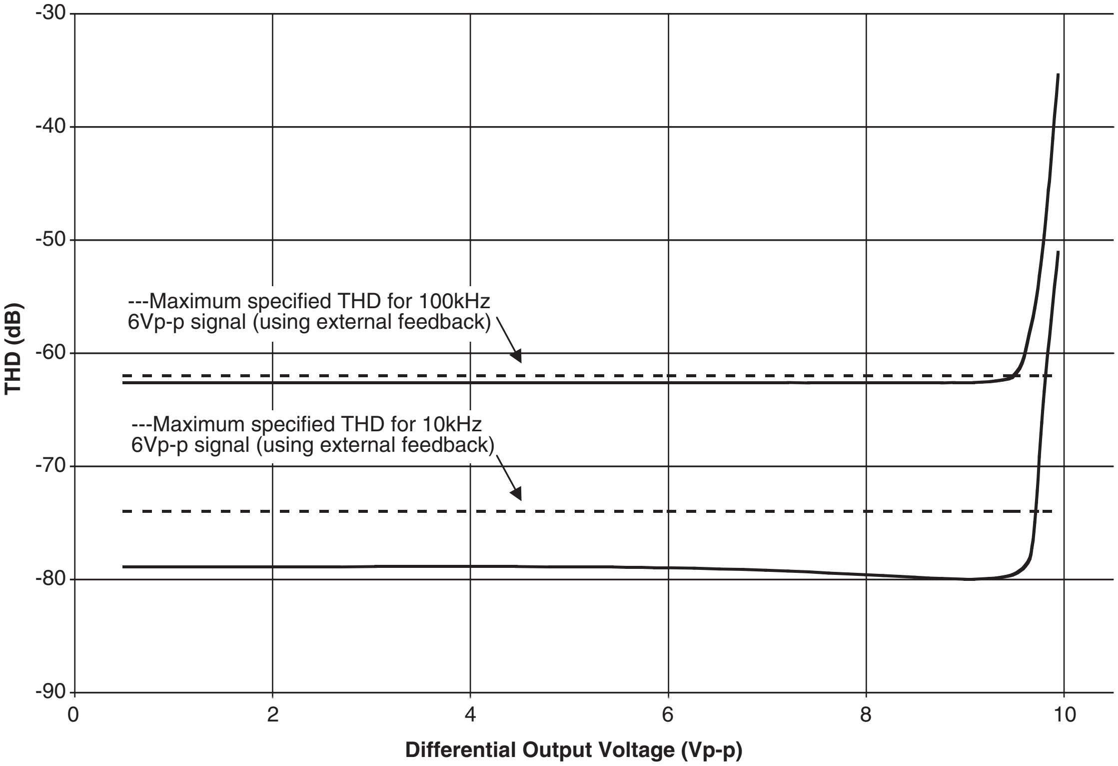
For the capacitor values available, the new frequency range then becomes 100Hz-1.06kHz programmable in 122 precise steps.

The new gain range is increased by the same scaling factor of 100. Hence, by changing k_1 from 1-10, the overall input-to-output gain range is 100-1000, programmable in 10 precise steps. Note that the gain can be reduced, increased or fine-tuned by using additional PACblocks. See application note AN6007, *In-System Programmable Gain with Fractional Gain Adjustments*.

Design Guidelines

The design guidelines for choosing proper values of the external resistors are fairly simple. Consider that the resistive load seen by the output amplifiers (OA) is about R_1+R_2 in addition to any other load it might drive. Keeping those feedback resistor values in the 10KΩ range or

**Figure 3: Distortion Performance when using external feedback
(k_1 = 1, k_2 = -1, R_2 = R_1 = 10KΩ, and CF = 1.07pF)**



higher will minimize the extra loading of the OAs. However, choosing very large values for R_1 can cause instabilities because of the phase shift caused by R_1 and parasitic capacitance on the input of IA2. Again, those values are not critical and generally present no real problems. In general, values in the 1-100KΩ range for R_1 will be a good choice.

Expanding the Programmability

In addition to programming k_1 (the "forward" gain in Figure 2), the "feedback gain" k_2 can be reprogrammed as well, thus affecting both gain range and frequency range in 10 additional steps. For example, if the external attenuation were 9:1, then one could shift both gain and frequency ranges by programming k_1 and k_2 from 1-10, resulting in 1kHz-550kHz for the filter range (1,270 steps) and in 1-100x for the gain range (100 steps), all accomplished without changing an external component.

Pushing the Extremes

Now that we have explored the principles of shifting gain and frequency ranges, the question is how far one can go with this technique. First of all, note that accuracy of gain or frequency settings doesn't suffer. Given that precision resistors of 1% or better are quite inexpensive, one can achieve large attenuation ratios rather easily and with high accuracy. In that case, the accuracy of the programmable gains and frequencies in the PAC devices are not affected, since the additional error contributed by the resistor matching can be kept very small.

If we consider pushing the gains or frequencies to extremes, one should expect to run into certain limitations. The maximum gain per PACblock is ultimately limited by the open-loop gain of the OA amplifier which exceeds 10,000V/V or 80dB. At that gain level, one must consider that noise and offset internal to the amplifiers will be amplified to a level noticeable in the output signal. For example, if the input referred offset of a PACblock is 50µV, then an amplification by 10,000 results in an output-referred offset of 500mV.

To achieve a gain of 10,000, the attenuation factor would have to be 1000:1 (or, 999:1 to be exact). Hence, the lowest bandwidth of a PACblock would be reduced to 10Hz. Because the noise level internal to the PACblock is not a function of external feedback, the S/N ratio would be very high, considering the small bandwidth of the resulting amplifier. For the case described here, one can expect to achieve 110dB SNR.

Measured Gain and Frequency Range

For various external resistor ratios, gains and corner frequencies were measured and these are shown in Figure 4. The lower line shows the lowest filter bandwidth resulting from the largest value of C_F, and the gains achieved for those corner frequencies. One can see that shifting the lower frequency from normally 10kHz down to 1kHz (or, a factor of 10x) increases the gain of the PACblock by 10x, or 20dB. To further lower the frequency to 100Hz, the gain increases to 100x, or 40dB and so forth.

The upper line shows the highest bandwidth achievable when C_F is at its smallest value. For example, let's use the previous case of a gain of 20dB, which resulted in a minimum bandwidth (filter setting) of 1kHz (for C_F at maximum value). By programming C_F to a smaller value, the filter bandwidth could be increased. Drawing a horizontal line from the 20dB/1kHz point over to the other line reveals that the maximum bandwidth has also been reduced by the same 10x factor and is now 55kHz. In other words, for any given gain, the user can program virtually any filter bandwidth within the two limits given by the lines in the graph. The fact that the measurement points fall accurately on the straight line dictated by theory indicates that the device performs accurately over a large gain and frequency range.

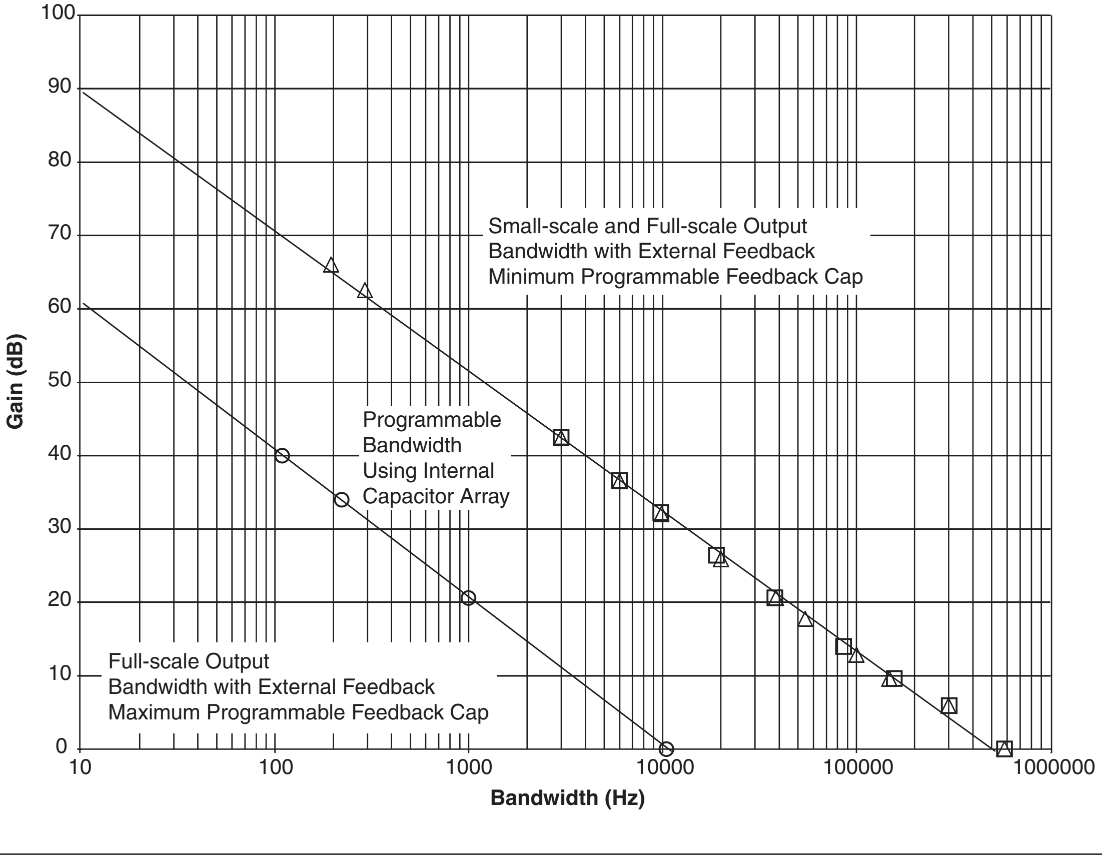
Summary

Using a PACblock device with external feedback can substantially expand the versatility that ispPAC products inherently offer. Precise low-bandwidth configurations can be implemented without the use of bulky external capacitors and the bandwidth can be programmed over a greater than 100x range in 1,270 increments without modifying external components.

High gains beyond 1000V/V per PACblock can be achieved as well. External resistors set the gain range, while the PACblock gains allow in-system programmable change by as much +/-100x in 100 precise steps.

Externally attenuated feedback also allows for true rail-to-rail output signals. Furthermore, signal-to-noise performance increases with lower filter bandwidth. Overall, the use of fixed external resistors greatly expands the gain and filter ranges of the ispPAC10 and ispPAC20 devices without a reduction in performance.

Figure 4. Measured Gain and Filter Bandwidth



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Appendix

The transfer function and gain relationships are shown in Equations 1-3.

Frequency response (where R_F = 250KΩ):

$$H(s) = -\frac{\frac{k_1}{k_2}\left(1+\frac{R_2}{R_1}\right)}{1-\frac{R_F\, s\, C_F\left(1+\frac{R_2}{R_1}\right)}{k_2}} \qquad (1)$$

Gain calculation:

$$|A_{dc}| = |V_{out}/V_{in}| = \left|\frac{k_1}{k_2}\right|\left(1+\frac{R_2}{R_1}\right) \qquad (2)$$

Bandwidth calculation (where R_F = 250KΩ):

$$f_{3dB} = \frac{1}{2\pi}\,\frac{1}{R_F\,C_F}\,\frac{k_2}{1+\frac{R_2}{R_1}} = \frac{k_1}{|A_{dc}|}\left(\frac{1}{2\pi R_F C_F}\right) \qquad (3)$$