Active filters using current-feedback amplifiers

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Introduction

The use of filters in circuit design is very common. They can be found in circuits such as anti-aliasing for analog-to-digital converters (ADCs), image rejection for digital-to-analog converters (DACs), intermediate frequency (IF) stages in communications systems, and even simple bandwidth limiting. However, when the frequency of interest is higher than a megahertz or two, using a current-feedback (CFB) amplifier to perform the task of filtering may be a good choice.

A CFB amplifier has some attributes that make it especially suited as a very high-frequency filter. These include the essentially limitless gain-bandwidth product, an inherently low voltage noise at the expense of more current noise, and the capability for exceptionally high slew rates.

CFB to VFB compensation

One key difference between a voltage-feedback (VFB) amplifier and a CFB amplifier is that the VFB amplifier can use a very wide resistance in the feedback path and maintain a common frequency response characteristic. A CFB amplifier relies on the feedback-path impedance to compensate the amplifier and thus does not have nearly the flexibility in resistance that a VFB amplifier inherently possesses. With a VFB amplifier, placing a capacitor in the feedback path will simply cause a pole to form—hence creating a first-order filter. Doing this to a CFB amplifier, however, will cause the amplifier to oscillate. Why is this? Exploration of this subject can be found in several application reports (see References 1–3) and will not be repeated in this article.

The most simplistic explanation of how a CFB amplifier is compensated is shown in Figure 1. There is much more to the CFB amplifier than a simple RC filter and a buffer, but this is an easy way to see how the amplifier behaves. The capacitor (C) is internal and fixed, while the resistor (R) is external and can be visualized as the feedback resistance. Just like a true RC filter, as R increases, there is more compensation and the bandwidth decreases; but if R is decreased too much, the bandwidth will increase to such a point that the buffer's own transistor frequency effects (f_t) will come into play and cause instability. It is easy to see that adding a capacitor in parallel with R cancels out the C compensation, leading to oscillations.

Reference 4 discusses how to make a CFB amplifier work even though there may be a capacitor in the feedback loop.

Figure 1. Simplified compensation of a CFB amplifier
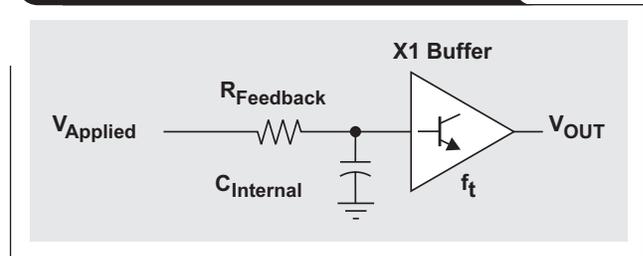
This same technique allows for the construction of any type of active filter required. To see the advantages of the CFB amplifier more clearly, a set of second-order, 0.5-dB-ripple Chebyshev filters was constructed with a corner frequency of 40 MHz at gains of ±2 and ±5.

The Sallen-Key filter with gain = +2

The Sallen-Key filter is inherently suitable for CFB amplifiers due to the feedback loop essentially being isolated from the filter loop. This circuit allows for any resistance to be used in the feedback loop without directly affecting the frequency characteristics. A detailed analysis of the Sallen-Key filter can be examined in Reference 5. Realizing a design that has proper component values can be quite time-consuming. To help simplify the process and to minimize the chance of miscalculations, Texas Instruments (TI) has developed a filter design program called FilterPro™. FilterPro is available for download at no cost from TI's Web site (go to www.ti.com and enter *FilterPro* in the Search Keyword field). The program allows for an easy realization of the desired filter with industry-standard component values and shows the expected frequency response of the filter.

One drawback of this tool is that it uses ideal amplifiers. In the real world, amplifiers have their own bandwidth limitations that can alter the frequency response of the filter. As a general rule of thumb, it is desirable to have the bandwidth of the amplifier at least 10 times higher than the filter's corner frequency. Some of the test results presented later on in this article will show how the amplifier bandwidth can alter the filter's response.

The 40-MHz, second-order, 0.5-dB Chebyshev filter with a forward gain of +2 V/V (+6 dB) was constructed with

the THS4271 (see Figure 2). The THS4271 is a unity-gain stable VFB amplifier with a 390-MHz bandwidth at a gain of +2. The same filter was also realized with the THS3201— a CFB amplifier with a 725-MHz bandwidth at a gain of +2 (also shown in Figure 2).

All tests were run with ±5-V power supplies and were constructed on printed circuit boards (PCBs) with proper high-speed layout techniques and bypassing. One issue with all of these filters is that the input impedance is not fixed and can change drastically from dc up to well beyond the filter's response. It is easy to see that, at dc, the input impedance is determined by the amplifier's input imped-ance in parallel with the 100-Ω termination resistor. For both the VFB and CFB amplifiers, the noninverting input impedance is typically much greater than several megohms and can effectively be ignored at low frequencies.

At extremely high frequencies, the capacitances of the amplifier input (a few pF), the PCB (a few pF), and the package (about a pF) reduce the amplifier's effective input impedance; but the external 27-pF and 47-pF capacitors should be the dominant capacitors in the system. Since the impedance can never be properly matched, it was deter-mined to set the termination for all of these filters to give approximately 50 Ω of impedance at the corner frequency of 40 MHz.

A very important consideration when capacitor compo-nent values are chosen is to keep the capacitance above a minimum of 10 pF. This is to reduce the effects of all the stray capacitances in the system. It will be shown that it is not always possible to meet this goal. In these cases it is best to try to measure the amount of stray capacitance on the PCB and to readjust the capacitor value accordingly to reach the proper design value. Another generally accepted method is simply to use the next lower standard capacitor value, such as 3.3 pF instead of 3.9 pF.

The results of testing the VFB and CFB amplifiers in Figure 2 are shown in Figure 3.

Both of these responses show that there is about a 0.75-dB ripple rather than the desired 0.5-dB ripple. However, this is a fairly reasonable response considering component tolerances, parasitics, and the sheer fact that this is at 40 MHz with a gain of 2.

Since both amplifiers behave similarly, using either one seems reasonable; but the key difference between the two is not actually seen here. The CFB amplifier's capability of very high slew rates compared to the VFB amplifier will translate to a better high-amplitude response and a better distortion characteristic at the higher amplitudes. Using the simple formula

$$f = \frac{\text{Slew rate}}{2\pi V_{\text{PEAK}}}$$

shows that with a 5-V_{PP} signal at 40 MHz, the slew rate must be at least 628 V/µs. Both the THS4271 (1000 V/µs) and the THS3201 (5200 V/µs) certainly have the capability to reproduce this type of signal; but with the CFB amplifier's 5× slew-rate advantage, its odd-order distortion should be better.


Figure 2. Sallen-Key 40-MHz filter with gain = +2 V/V

(a) Using VFB amplifier (THS4271)

(b) Using CFB amplifier (THS3201)
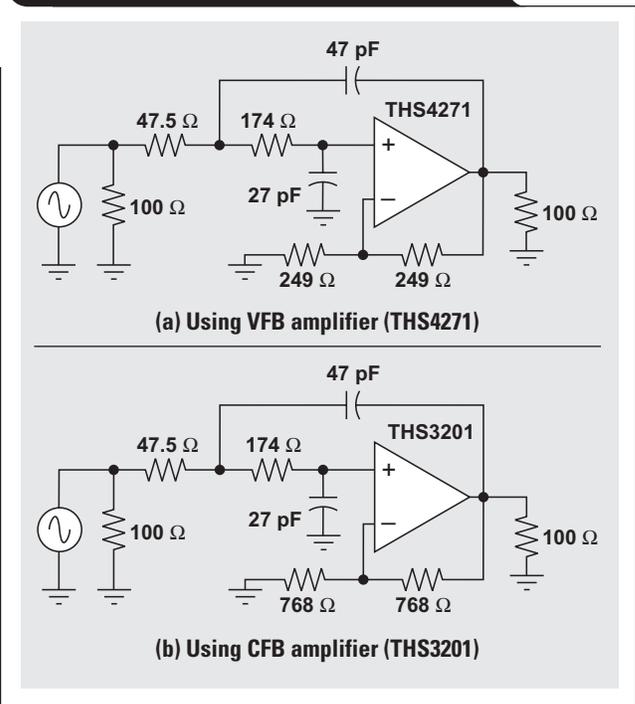
**Figure 3. Sallen-Key filter responses with gain = +2 V/V**
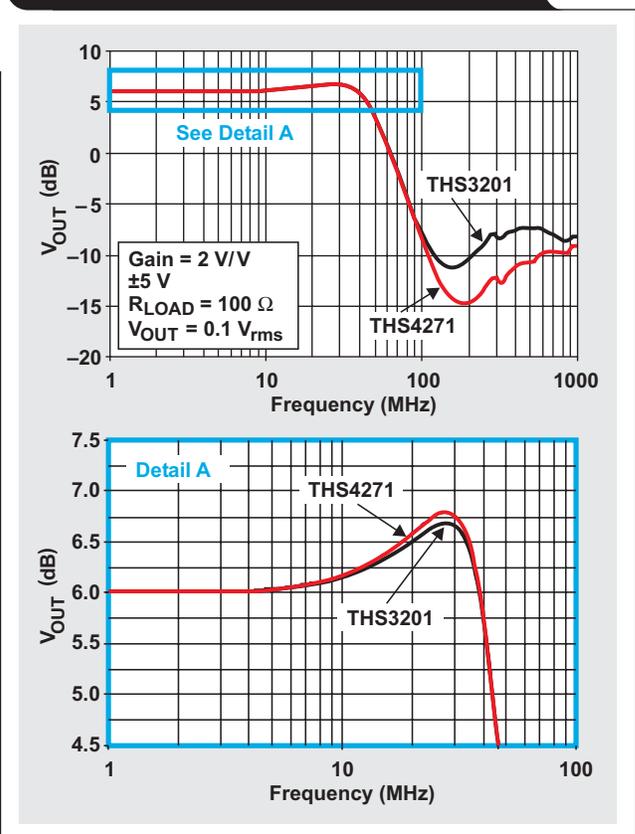
Another interesting result is that there is at best an 11-dB rejection (input referred) with the THS3201 and almost a 15-dB rejection with the THS4271. These responses are actually within reason for a Sallen-Key filter. The Sallen-Key filter topology requires the amplifier to have a very low output impedance within the rejection band. The 47-pF capacitor connecting between the input and the amplifier output is also an excellent high-frequency path for the input signal. If the amplifier does not have the bandwidth and low output impedance to perform well at these very high frequencies, it cannot reject the high-frequency content and the signal passes through the system.

The Sallen-Key filter with gain = +5

The next step was to see how the responses change with a gain change from +2 V/V (6 dB) to +5 V/V (14 dB). A VFB amplifier's bandwidth will decrease as the gain increases and should start showing effects on the frequency response of the filter. The THS4271 at a gain of +5 V/V has a bandwidth of about 85 MHz, only about 2× the desired corner frequency of the filter. On the other hand, a CFB amplifier can have a much higher bandwidth with a simple reduction of the feedback resistance; think of it as decompensating the amplifier. The THS3201 at a gain of +5 V/V will have

about a 540-MHz bandwidth. FilterPro realized the filters shown in Figure 4.

Notice that the component values for the negative feedback path can be chosen arbitrarily from the filter components. Only the ratio must be maintained to achieve the proper filter feedback. This allows the CFB and VFB amplifiers to utilize their own "optimum" resistor values in the system. The responses, shown in Figure 5, have considerably more peaking than the desired 0.5-dB ripple. Again, some of this peaking is caused by the component tolerances; but a big influence is the amplifier's reduced bandwidth capability. The VFB amplifier (THS4271) shows almost 2 dB of peaking along with a –0.5-dB point at 34 MHz, deviating considerably from the target specification.

The CFB amplifier (THS3201) has about 1.25 dB of peaking, but its –0.5-dB point is at about 44 MHz. The fact that the bandwidth is about 13× the filter's corner frequency strongly suggests that component tolerances are a highly influential factor in the filter response.

Once again, the amount of rejection remains about the same between the design with a gain of +2 V/V and that with a gain of +5 V/V. This means that the amplifier's frequency characteristics are a major factor in the design, as originally expected.

Figure 4. Sallen-Key 40-MHz filter with gain = +5 V/V

(a) Using VFB amplifier (THS4271)

(b) Using CFB amplifier (THS3201)
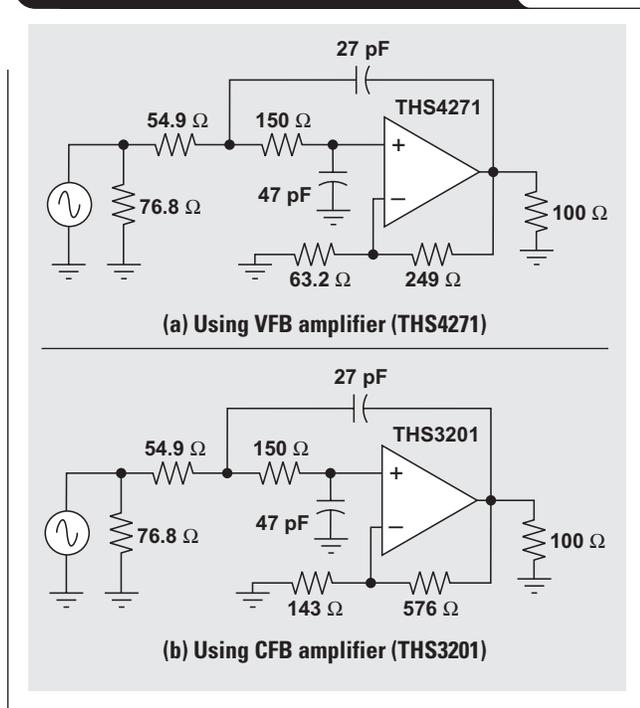
Figure 5. Sallen-Key filter responses with gain = +5 V/V
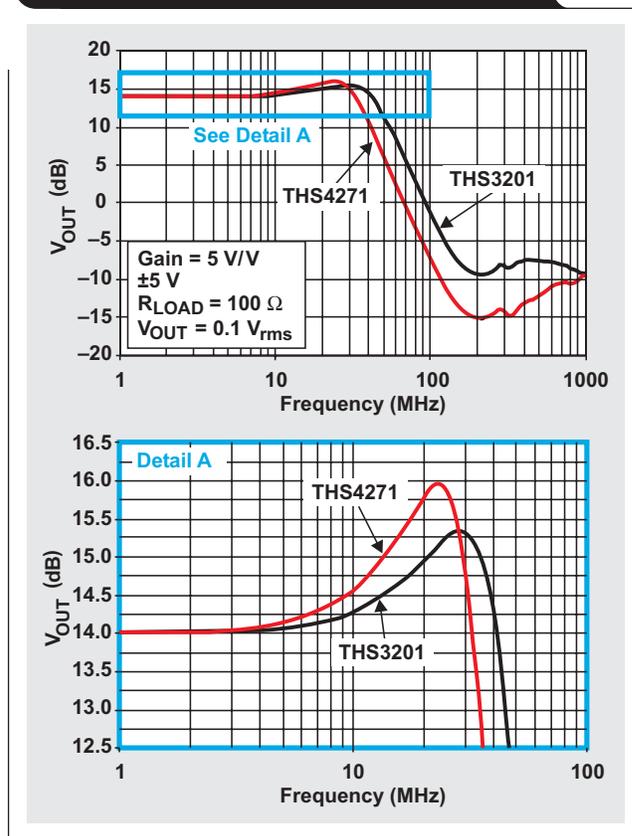
Another key point that should be made is that the noise of a CFB amplifier at gains typically higher than 3 V/V can easily be lower than the noise of a VFB amplifier. This is because the CFB amplifier inherently has low voltage noise and because, as the optimum feedback resistance decreases at higher gains, the noise contribution from the CFB's inverting current noise also decreases. On the other hand, a VFB's dominant noise component stems from the voltage noise, which becomes directly multiplied by the gain of the amplifier.

One last issue that must be addressed is that there are decompensated VFB amplifiers available that may be better suited for higher-gain systems—such as the OPA843, OPA846, and OPA847, with a minimum gain of +3 V/V, +7 V/V, and +12 V/V, respectively. These amplifiers typically have a reduced voltage noise as the minimum gain is increased, along with a higher slew rate and a higher gain-bandwidth product. They are certainly viable alternatives that may find success in many higher-gain filter designs; but, for an all-in-one amplifier solution, a CFB amplifier is very versatile.

The multiple-feedback filter with gain = –2 V/V

The next most commonly used filter is the multiple-feedback (MFB) filter, also known as the Rauch filter. One advantage of the MFB filter is its reduced sensitivity to component variation. This is important when real-world capacitors can easily have ±15% temperature variances, +5/–10% variances over frequency, and ±10% variances over operating voltage. The same 0.5-dB-ripple Chebyshev design was done with FilterPro with a gain of –2 V/V (+6 dB with a 180° phase shift) and is shown in Figure 6a for the THS4271.

There are some drawbacks to the MFB design. First is the obvious fact that the capacitor value in the feedback path is very small—10 pF. Even using very small resistor values around the amplifier did not help increase the capacitor value very much. Another possible issue is that, in the inverting configuration, the amplifier's noise gain is +1 higher than before. What this means is that the bandwidth of the amplifier is approximately equal to the gain-bandwidth product divided by the noise gain. Noise gain is always referred to the noninverting terminal and thus has a gain of $1 + R_f/R_g$. For this design with a gain of –2 V/V, the noise gain is +3 V/V, reducing the effective bandwidth even more than the non-inverting Sallen-Key design. Note that when operating well above the filter's corner frequency, the feedback capacitor essentially becomes a short, resulting in an amplifier noise gain of +1. For this reason, using a decompensated VFB amplifier is not suggested without special techniques.

Can this topology be used with a CFB amplifier? There is a capacitor directly in the feedback loop, and traditional thought suggests that there is no way to use a CFB amplifier. The method outlined in Reference 4, however, makes it possible to use an MFB circuit with a CFB amplifier. For this test a Murata BLM18HG471SN1 ferrite chip was chosen, as its impedance is about 650 Ω at 700 MHz and about 600 Ω at 1 GHz. The key reason for using a ferrite chip is its low impedance—and hence low noise—at low frequencies while still maintaining enough impedance at high frequencies to keep the amplifier stable. Keep in mind that this chip has about 200 Ω of impedance at 20 MHz and about 100 Ω at 6 MHz, so the contribution of inverting current noise must be considered in the total noise of the system. The final design of the MFB circuit with the THS3201 CFB amplifier is shown in Figure 6b.

Figure 6. MFB 40-MHz filter with gain = –2 V/V

(a) Using VFB amplifier (THS4271)

(b) Using CFB amplifier (THS3201)
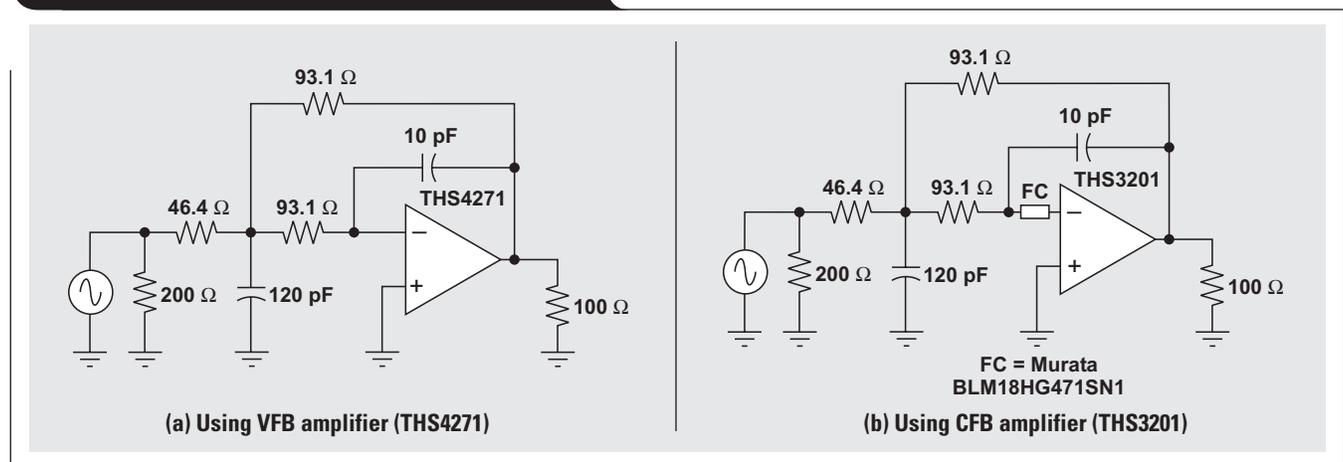
The frequency responses of these systems, shown in Figure 7, reveal an excellent reason to use the MFB filter—the out-of-band attenuation is far superior to the Sallen-Key response, by about 20 dB. This superiority is due to the inherent RC filter (46.4 Ω and 120 pF) to ground at the input of the MFB filter. The filter shunts the input signal to ground even if the amplifier is running out of bandwidth.

Figure 7 also shows that the VFB amplifier has a much better filter response with a 0.5-dB ripple and a corner frequency of 36 MHz. The CFB amplifier has nearly a 2-dB ripple and an extended corner frequency of 44 MHz. Since exactly the same components were swapped from one test PCB to the other, component variations can be ruled out as the main contributor to this excess peaking. Additionally, the bandwidth of the THS3201 is over 600 MHz with a gain of –2 V/V, minimizing the effects of amplifier bandwidth interactions; and the THS4271 has only about a 220-MHz bandwidth at a gain of –2 V/V. This leaves the ferrite chip's interaction with the amplifier as the only probable cause of this peaking.

The impedance of the ferrite chip increases with increasing frequency. Since the CFB amplifier's compensation is dictated by the feedback impedance, this will have a direct impact on the amplifier's characteristics. The true test of this impact was to replace the ferrite chip with pure 750-Ω and 249-Ω resistors, whose responses are shown in Figure 8. It is interesting to note that as the frequency increases, the response of the ferrite chip approaches that of the 750-Ω resistor. This makes sense, since the ferrite chip's impedance is about 700 Ω at its peak.

It is also noteworthy that the 249-Ω resistor allows the amplifier to remain stable. We would expect the THS3201 to need at least 600 Ω of impedance to be stable with a gain of –1 V/V. The reason it remains stable with 249 Ω of impedance is that the 10-pF capacitor has some impedance at 750 MHz. Remember that in the real world, a capacitor has an associated inductance that causes its impedance to increase at high frequencies. Add this impedance to the amplifier's output impedance, and the real resistor value in an inverting configuration does make the amplifier stable. The response at about 400 MHz shows some aberrations, which implies that stability is starting to be a bit of a concern. With –30 dB of attenuation at this point, however, the system will remain stable; as one of the conditions for instability is that the amplitude must be greater than 0 dB.

Figure 7. MFB filter responses with gain = –2 V/V
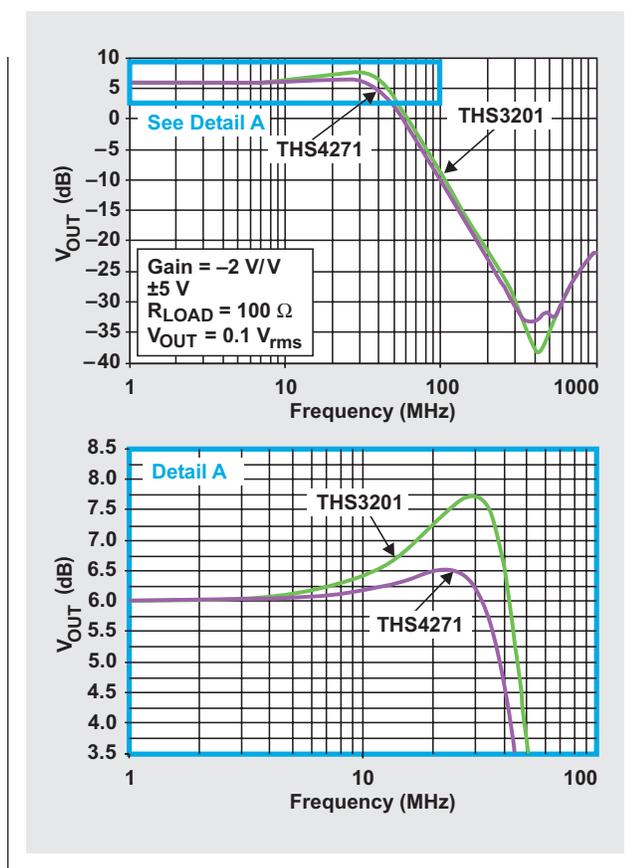
Figure 8. CFB amplifier MFB responses with resistors and gain = –2 V/V
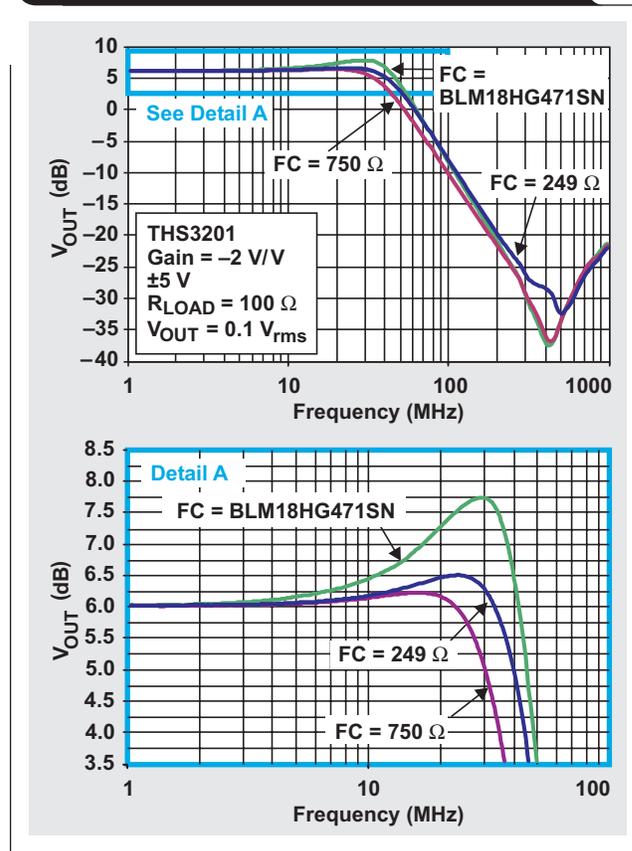
It is obvious that the ferrite chip's impedance characteristics directly impact the system. The use of other types of ferrite chips was explored, and their responses are shown in Figure 9. From this plot it appears that using the BLM18BD121SN chip with only 120 Ω of impedance at 100 MHz performs the best. This chip has a maximum impedance of 300 Ω at 800 MHz, which resembles the 249-Ω resistor's high-frequency characteristics at 400 MHz; but, again, having substantial attenuation will help keep the system stable.

The multiple-feedback filter with gain = –5 V/V

The last circuit explored was the same MFB topology except with a gain of –5 V/V. As we know, this implies a noise gain of +6 V/V; but the impact on amplifier bandwidth is negligible between these two gains and should not be a concern. Figure 10 shows the circuits used to test this configuration.

The obvious concern about this design is the 3.3 pF in the feedback path. Stray capacitance can easily influence the circuit relative to the capacitance value. It is possible to lower the resistor values around this, but a value of 10 pF would cause the input resistance to change from 53.6 to 15.8 Ω, placing too large a load at the rejection band of the filter. Needless to say, the filter was used as shown in

Figure 9. CFB amplifier MFB responses with other ferrite chips and gain = –2 V/V

Figure 10. MFB 40-MHz filter with gain = –5 V/V

(a) Using VFB amplifier (THS4271)

FC = Murata BLM18HG471SN1

(b) Using CFB amplifier (THS3201)
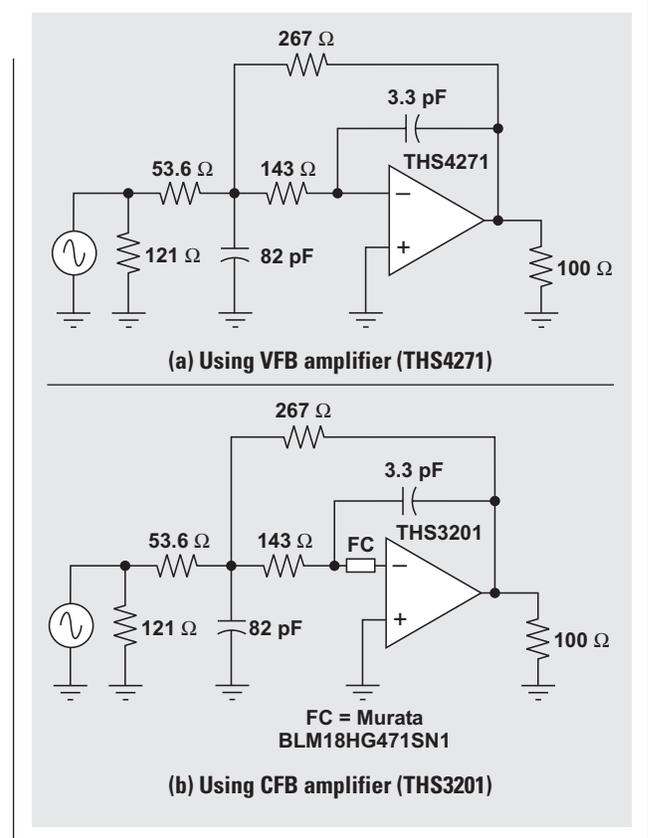
Figure 10. Figure 11 shows the responses, which are pretty much what is expected. The VFB amplifier does not have enough bandwidth to create a 40-MHz filter properly and rolls off prematurely, resulting in a corner frequency of 23 MHz.

The CFB amplifier exhibited peaking of only about 1.25 dB and a corner frequency of 34 MHz. As stated previously, the interaction of the ferrite chip and the amplifier comes into play. Just as the response of the CFB amplifier MFB design with a gain of –2-V/V showed an interaction with the ferrite chip's impedance, so did the design with a gain of –5 V/V, which exhibited similar results as shown in Figures 12 and 13. The best response was achieved when the impedance of the chip was very low at the pass-band corner frequency and increased to at least 250 Ω at 400 to 500 MHz.

Figure 11. MFB filter responses with gain = –5 V/V
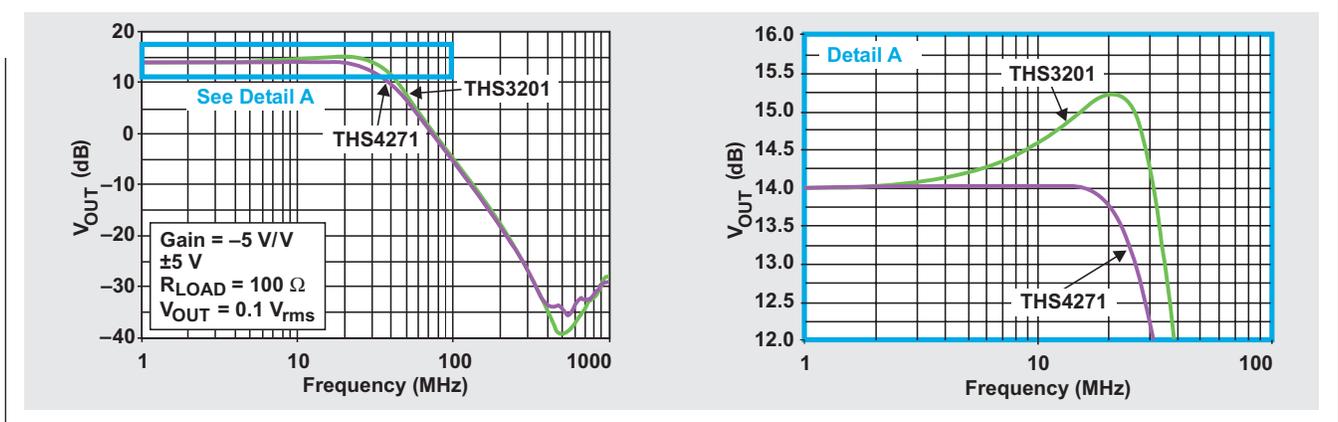
Figure 12. CFB amplifier MFB responses with resistors and gain = –5 V/V
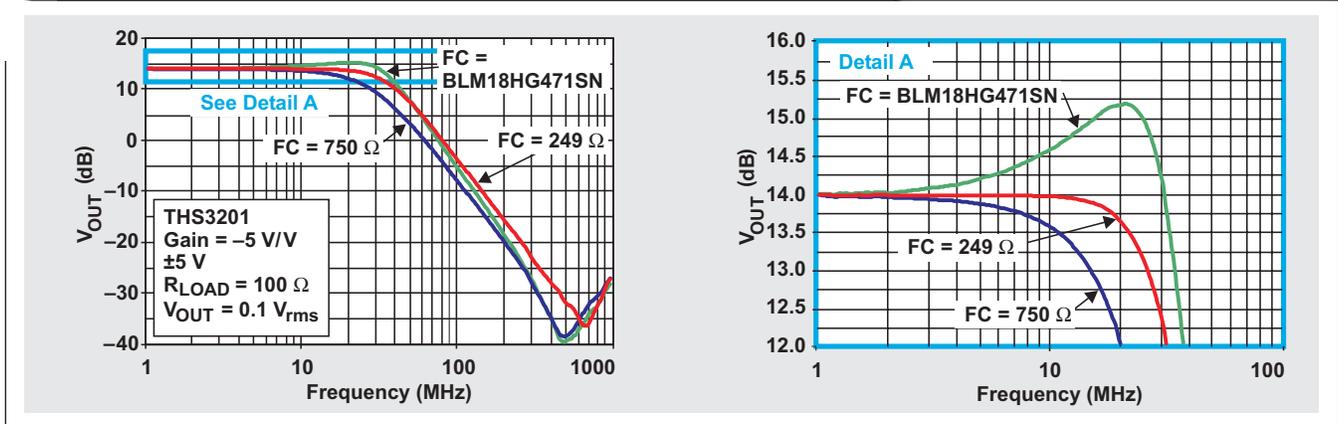
Figure 13. CFB amplifier MFB responses with other ferrite chips and gain = –5 V/V
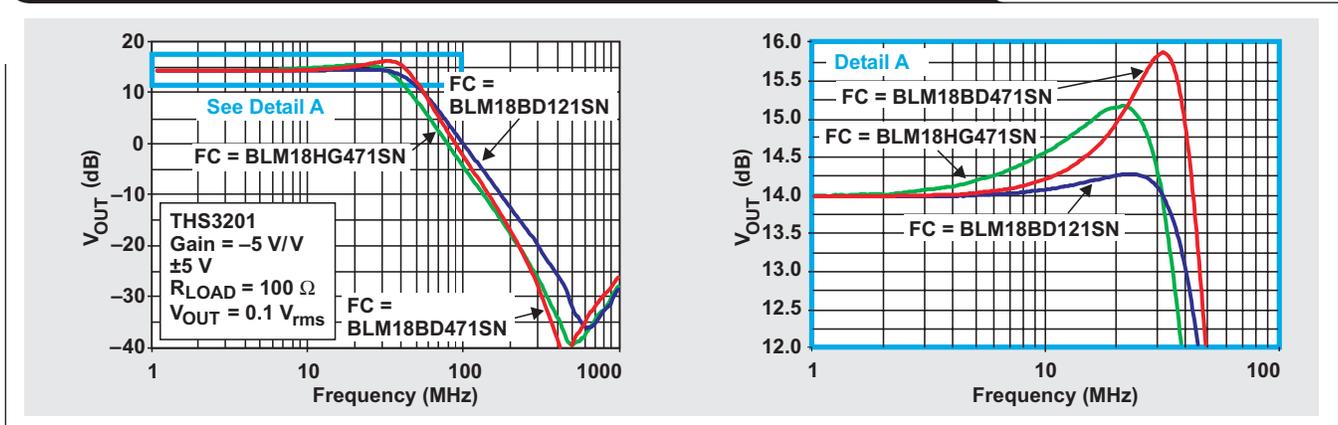
Conclusion

As any circuit dictates, there will always be trade-offs in any design, and filtering is no exception. The MFB filter certainly shows excellent performance in the rejection band, over 20 dB better than the Sallen-Key filter; and its sensitivity to tolerance is much better. However, the use of very small capacitors in the system may limit its overall usefulness as a filter.

The use of a CFB amplifier as a filter certainly has been proven to be functional. The enhanced bandwidth and slew-rate capabilities show even better potential than a VFB amplifier; but the trade-off in the MFB design may be a hindrance to its acceptance as a good high-frequency filter. Nevertheless, independent testing at frequencies lower than 10 MHz has shown excellent results. This makes sense, as the impedance of the ferrite chip typically does not become too high until this point and can be negligible in the system. Coupled with the reduced output noise as the gain increases, the CFB amplifier can be a good choice for the proper application. It is not perfect, and the use of VFB amplifiers may make more sense in the circuit.

Of course, the unity-gain stable VFB amplifier can work with any topology without issue; but the gain-bandwidth-product limitation exists, and the slew-rate capabilities are not nearly as good as those of a CFB amplifier. The VFB amplifier also may not be the perfect building block if multiple gains are required due to the bandwidth reductions at higher gains. Instead, the use of decompensated amplifiers at higher gains for the Sallen-Key filter would be suggested, as this allows higher performance with low noise; but this approach can be used with only limited gain ranges and cannot be used with the MFB filter without the need for its own special compensation techniques.

References

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Document Title   **TI Lit. #**

1. James Karki, "Voltage Feedback Vs. Current Feedback Op Amps," Application Report slva051
2. Anthony D. Wang, "The Current-Feedback Op Amp: A High-Speed Building Block," Application Bulletin sboa076
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5. James Karki, "Effect of Parasitic Capacitance in Op Amp Circuits," Application Report sloa013

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