

Expanding the usability of current-feedback amplifiers

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Introduction

Although current-feedback (CFB) amplifiers have been around as long as the widely utilized voltage-feedback (VFB) amplifiers, their acceptance has been sporadic. One of the reasons for this is quite simple—they have a different name and therefore must be difficult and very hard to use. This is simply not true. There are numerous papers^{1, 2, 3} comparing the differences between the two amplifier types that show they are more similar to each other than different. In fact, for numerous circuits, a CFB amplifier may actually yield better results due to its inherent slew-rate advantage, lack of a gain-bandwidth product, and reasonably low noise for the performance.

Almost every paper written about CFB amplifiers cautions readers that placing a capacitor directly in the feedback path, without any resistance in series, will cause the CFB amplifier to oscillate. This is true, as the compensation of the amplifier is tied directly to the feedback impedance. Since a capacitor has low impedance at high frequencies, this essentially places a short in the feedback path that inadvertently defeats amplifier compensation, resulting in instability.

Because of this limitation, there are a handful of common circuits that are not recommended for use with a CFB amplifier. These include integrators, some types of filters, and special feedback-compensation techniques. But what if there was a way to make these circuits work? And what if the solution was as simple as adding a single component? This would make it feasible to implement a CFB amplifier for just about every application for which a VFB amplifier could be used, with the benefits of the CFB amplifier.

Compensation

This article does not explain the compensation theory of VFB and CFB amplifiers, as there are many papers written on this topic. The only thing that is important is that there must be resistance, or impedance, in the feedback path at the open-loop intersection point to make the CFB amplifier stable.

Figure 1 shows a traditional VFB amplifier, a THS4012, configured in a noninverting gain of +5 with a simple low-pass gain filter set at approximately 1 MHz by the straightforward $1/(2\pi R_F C_F)$ formula.

If a CFB amplifier like the THS3112 is simply dropped into this circuit, it *will* oscillate and the circuit will become useless. A method of compensating the CFB amplifier in this circuit is to insert a resistance, or impedance (Z), in the feedback path as shown in Figure 2.

It can easily be seen that regardless of the impedance of the feedback path represented by R_F and C_F , the impedance Z is in the amplifier's feedback loop dictating the compensation of the amplifier. The interesting thing about this configuration is that the feedback resistance (R_F), which normally dictates the compensation of the

Figure 1. VFB test circuit

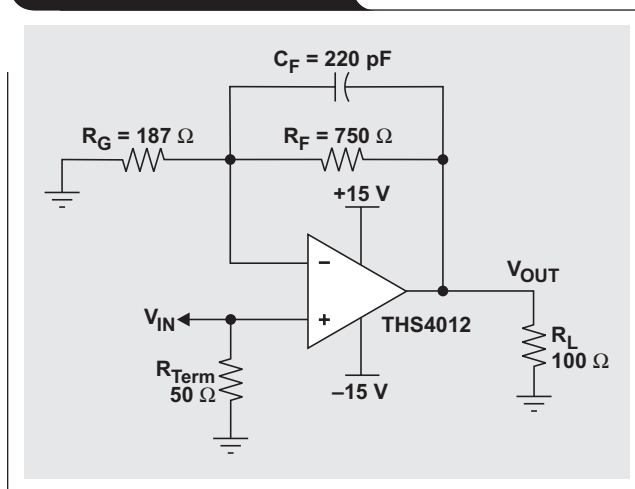
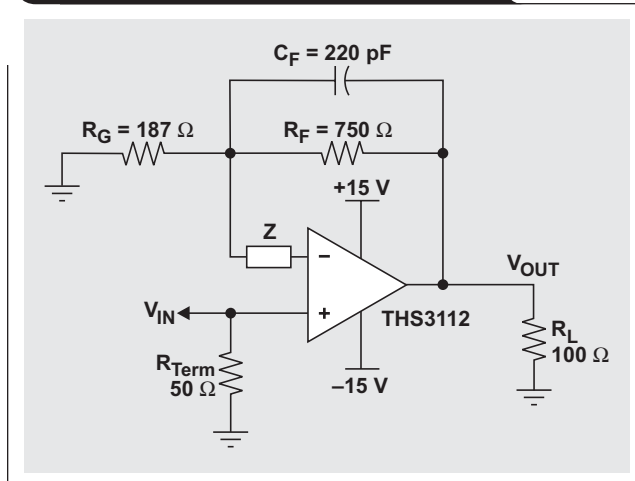


Figure 2. CFB test circuit with simple modification



amplifier, can now be essentially any resistance desired. The reader should keep in mind that this is still a high-speed amplifier with speeds over 100 MHz; so the feedback resistance should always be kept less than a few kilohms to minimize the effects of parasitic capacitances on the overall circuit. Conversely, minimizing the resistance too much will place too much of a load on the amplifier, typically degrading performance.

One of the drawbacks of adding the impedance Z in this manner is that the summing node at the inverting terminal is now separated from the virtual summing node. This can

introduce errors into the system due to the bias current and the dynamic signal current flowing through this impedance; but these effects are reasonably small as long as the impedance is minimized.

Adding impedance Z can affect input offset voltage due to the dc input bias current, which is typically 1 to 10 μA , multiplied by the impedance Z . This resulting voltage gets multiplied by the noise gain of the circuit. Additionally, when a signal appears at the output, the CFB amplifier (as the name implies) relies on an error current flowing through the inverting node through the impedance Z , producing a signal error. However, since the transimpedance of most CFB amplifiers is well over 100 $\text{k}\Omega$ and sometimes as high as several megohms, this error is also minimized if the impedance is kept low. The drift of this circuit now also relies on the temperature characteristics of impedance Z and should not be used as a precision amplifier; but most CFB amplifiers are not used as precision amplifiers anyway due to their inherent topology limitations. Overall, these issues are minimal and, for most systems, can be effectively ignored in favor of the CFB amplifier's advantages as previously stated.

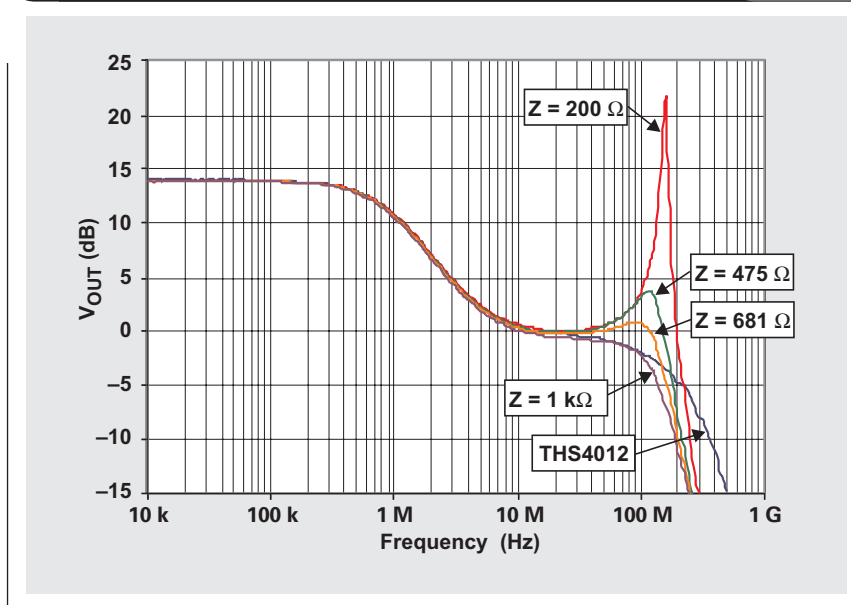
Testing with different Z values

The easiest way to see if the circuit is stable is to use a network analyzer frequency sweep. Instability can typically be seen as sharp rises in the frequency response at the amplifier's bandwidth limitations. If the peaking is smooth, or there is no peak, then the amplifier should be stable. Figure 3 shows the frequency response of the system with different values of resistors for the variable Z .

The response of the THS4012 is also shown for reference to easily compare the performance of the two systems. It is interesting that no matter what resistance is used for Z , the responses below 20 MHz look identical to each other. This is the ultimate goal of this configuration—no differences in signal performance. For the stability part of the circuit, the area above 20 MHz must be examined.

Examining the circuits in Figures 1 and 2 shows us that the feedback impedance is dictated by the capacitor C_F . Above 20 MHz, this impedance is very small—essentially creating a short from the output to the summing node. This configuration is commonly referred to as a unity buffer with the signal gain set to 1. The data sheet for the THS3112⁴ recommends that, in a gain of +1 under the circuit conditions utilized, the feedback resistance be 1 $\text{k}\Omega$. Thus, it is no surprise to see that when $Z = 1 \text{ k}\Omega$, the response looks very smooth and well behaved, indicating a very stable system. However, when $Z = 681 \Omega$, the response also looks very reasonable and helps minimize the potential issues

Figure 3. Frequency responses with resistors (gain = +5)



stated previously. This shows that there is a reasonably wide range of acceptable values for Z and does not imply that the selection for Z is highly critical. Figure 3 also illustrates a common trait for current-feedback amplifiers—as the feedback impedance is decreased, the peaking will increase. If the impedance is too low, there is a good chance that the circuit will become unstable and oscillate, as illustrated by the response when $Z = 200 \Omega$.

Output noise

One element that may be very important in a system is the output noise. Adding a resistance in the manner discussed only makes the output noise worse. The inverting current noise of the amplifier goes through the resistance at Z and creates a voltage noise. This noise then becomes multiplied by the circuit's gain, which is frequency-dependent.

For a CFB amplifier, the inverting current noise is typically the highest noise component of the amplifier. Although the CFB amplifier voltage noise is inherently very low, typically less than $3 \text{ nV}/\sqrt{\text{Hz}}$, the inverting current noise of most CFB amplifiers is generally around $15 \text{ to } 20 \text{ pA}/\sqrt{\text{Hz}}$. The noninverting current noise is only noticeable if the source impedance is high. Using a $50\text{-}\Omega$ environment minimizes the noninverting current noise.

The THS3112 was designed to have very low noise. The voltage noise is $2.2 \text{ nV}/\sqrt{\text{Hz}}$, the noninverting current noise is $2.9 \text{ pA}/\sqrt{\text{Hz}}$, and the critical inverting current noise is a low $10.8 \text{ pA}/\sqrt{\text{Hz}}$. However, multiplying the inverting current noise by $1 \text{ k}\Omega$ and then multiplying by the gain can alone produce a very substantial output noise of about $54 \text{ nV}/\sqrt{\text{Hz}}$ in the pass band. To quantify the output noise of the system, the circuits shown in Figures 1 and 2 were tested for output

noise (see Figure 4). For comparison, the THS4012, with a respectable voltage noise of $7.5 \text{ nV}/\sqrt{\text{Hz}}$ and both current noises of $1 \text{ pA}/\sqrt{\text{Hz}}$, is also shown in Figure 4.

Note that the output noise of the THS4012 is the same as when using the THS3112 with $Z = 475 \Omega$. Again, these responses are just like those of a VFB amplifier in the traditional configuration, showing that the basic functionality is sound—there are no differences between a VFB amplifier and this configuration. Figure 4 shows that although using $Z = 1 \text{ k}\Omega$ produces a very stable amplifier, the output noise is $20 \text{ nV}/\sqrt{\text{Hz}}$ higher than that of the THS4012.

Figure 4. Output noise (gain = +5)

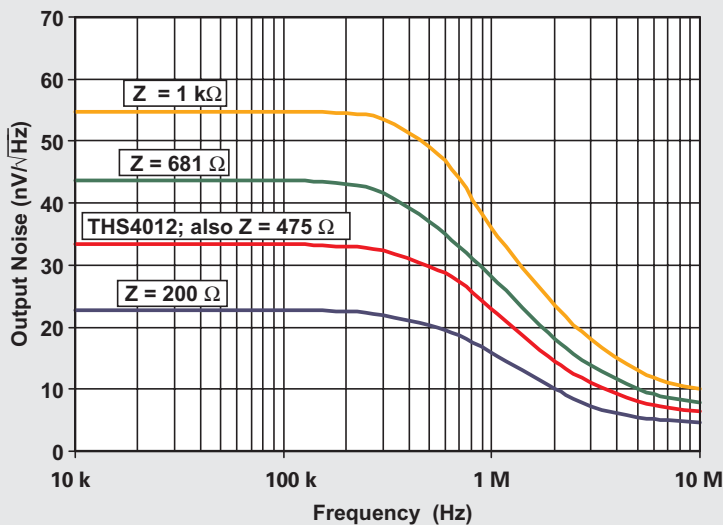
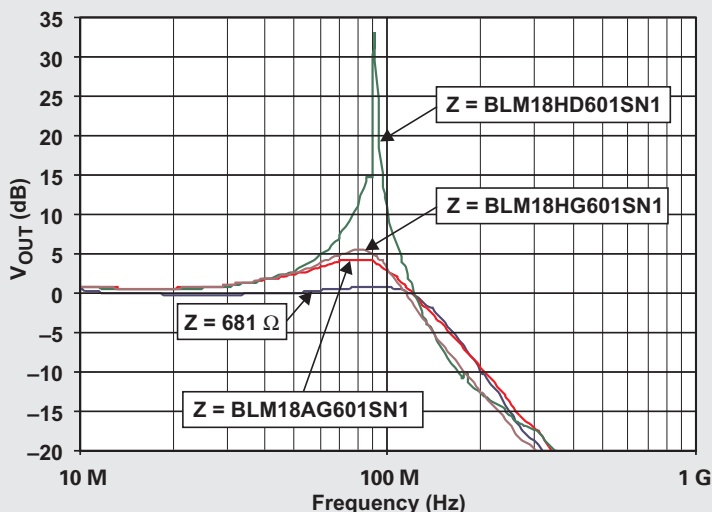


Figure 5. Frequency responses above 10 MHz with ferrite chips (gain = +5)



Keep in mind that the THS3112 has very low overall noise but that many other CFB amplifiers will probably produce much higher noise. The only way to get around this is if the unity-gain stability of the amplifier requires a very small resistor of, say, only 500Ω or less. But what if there was another way to make the CFB amplifier stable *and* have low noise at the same time?

Fundamentally speaking, the circuit needs high impedance within the feedback path only at the amplifier's bandwidth limit. At frequencies below this point, it really does not matter what the impedance is, and the amplifier will work fine. The issues stated previously are also minimized, resulting in an even better system than one using pure resistors.

The first solution that comes to mind is to use an inductor. Inductors have low impedance at low frequencies and high impedance at high frequencies—exactly what is desired; but their relatively large size and high cost are generally considered prohibitive. An alternative component that minimizes these disadvantages and still functions the same is the ferrite chip.

Testing with ferrite chips used for Z

Ferrite chips have been available for several years, are relatively low-cost, and are available in very small sizes—0402 and larger. Although several manufacturers produce ferrite chips, testing was done with what was available in the test lab—ferrite chips from Murata's BLM series. Examining the impedance characteristics of these ferrites revealed several possible components that could be utilized.

The first factor in determining the proper component was the ferrite's impedance at the amplifier's bandwidth limit. For the THS3112, this implied an impedance of at least 600Ω at about 150 MHz to meet stability. This can vary, as the first test results showed (see Figure 3).

Additionally, the Q of the ferrite chips varies from grade to grade. Some have a low Q with a fairly smooth rise to the resonance point that then subsides due to inherent properties and parasitics, while other chips have a relatively high Q with a sharp rise and fall in impedance associated with them. Although either style may meet the impedance requirements, testing was required to see if this Q had an effect on the circuit. Again, the best way to show the results was to graph the frequency response of the system, as shown in Figure 5. The responses below 10 MHz were all identical to the original configuration. This figure concentrates on the stability portion of the responses above 10 MHz . For comparison purposes, the $681\text{-}\Omega$ pure-resistance response is shown.

Although all of these ferrite chips have the same impedance at 100 MHz (600 Ω), they produced different results. The HD series high-Q chip shows a very narrow and large peak that will most likely result in instability and oscillations. The AG and HG series low-Q chips both performed about the same, and either one would probably produce acceptable results. The only difference is that the HG series has impedance at higher frequencies and would probably be better suited for use with very high-speed CFB amplifiers such as the OPA685 or the THS3202.

Notice that the pure resistance has a lower response peak than the ferrite chips. Coupled with the fact that the HD series has a high Q and a high peak, this implies that the slope of the impedance at the amplifier's bandwidth is a factor for stability. This makes a lot of sense; as it is well known that for any amplifier, if a zero intersects the amplifier's open-loop response at a rate of closure of 40 dB/decade, large peaking and oscillations will most likely result.⁵ For this circuit configuration, if the impedance of Z has a large slope that intersects the transimpedance curve at essentially a rate of closure of 40 dB/decade, peaking and oscillations also will most likely occur. By comparison, a resistor intersects the transimpedance curve at a rate of closure of 20 dB/decade, resulting in a stable response. Even though the low-Q ferrite beads have some slope related to their impedance, the rate of closure is much lower than 40 dB/decade, providing improved stability. Nevertheless, minimizing this intersection rate of closure as much as possible should produce acceptable results.

To further expand on the usefulness of the ferrite chips, more testing was done utilizing the AG series in the circuit, as shown in Figure 6.

This figure shows that, just like the results for the pure resistor, the higher the impedance is, the lower the peaking.

How does this affect the output noise of the system? Figure 7 shows the output noise when the ferrite chips were used, along with the output noise of the THS4012 and some of the original resistor configurations.

As expected, due to the low frequency impedance of the ferrite chips, the noise is extremely low. This noise was the same regardless of which ferrite was used. If noise above 10 MHz was important, the impedance of these ferrite chips would start to increase the output noise to the same extent as resistors. These tests show that there are several advantages of using ferrite chips over resistors.

Figure 6. Responses with AG series ferrite chips (gain = +5)

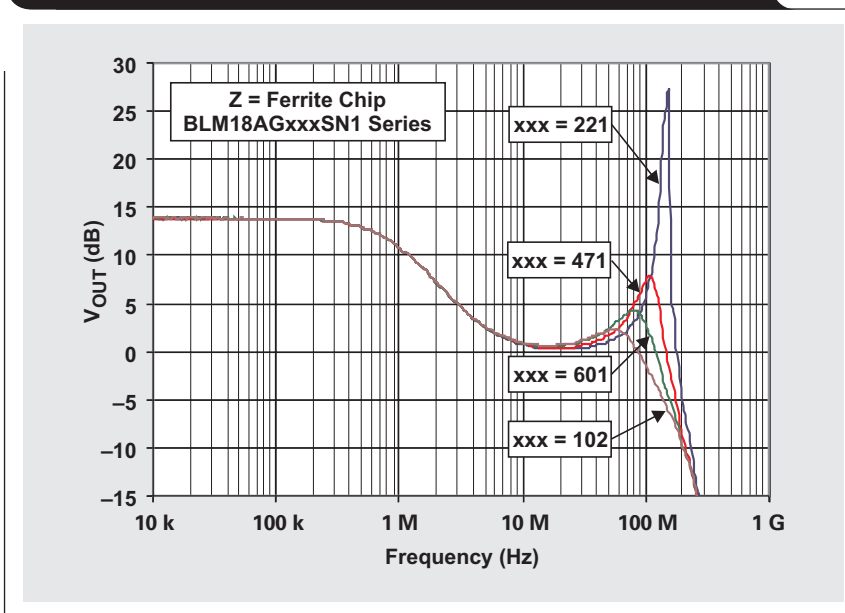
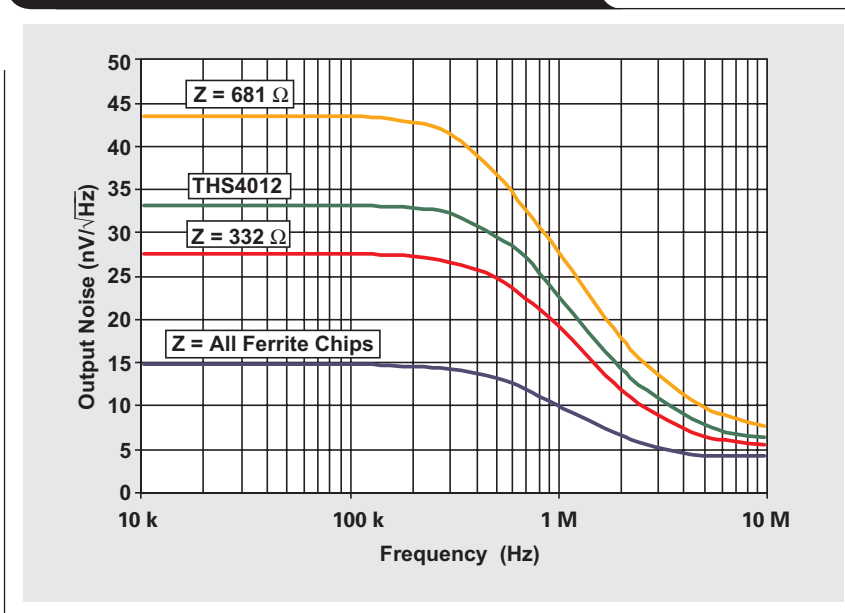


Figure 7. Output noise comparison (gain = +5)



Inverting gain configuration

All of the testing discussed so far was done with the non-inverting gain configuration. This configuration forces the non-inverting node voltage to move proportionally to the input voltage applied. So how does the system work in the inverting gain configuration where the inverting node is held at a virtual ground? The easy answer is that it works

Figure 8. Inverting gain of 5 VFB configuration

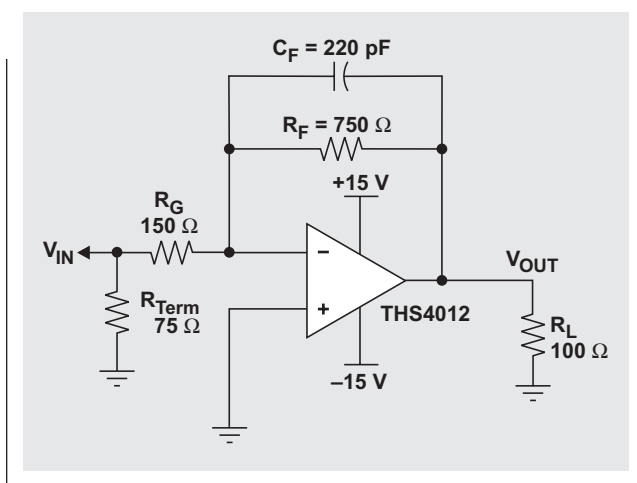
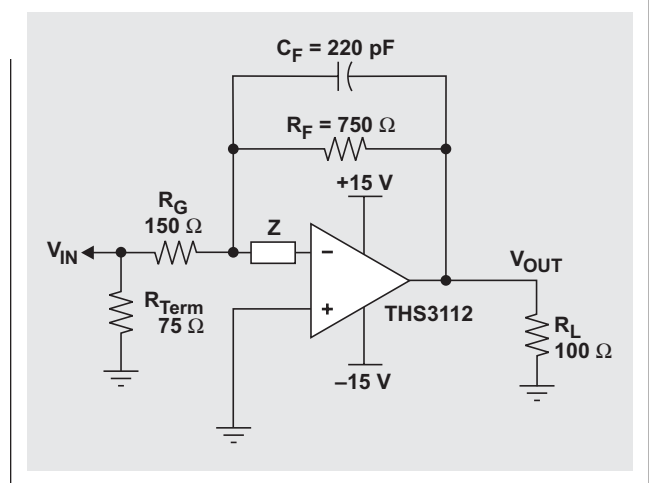


Figure 9. Inverting gain of 5 CFB configuration



exactly the same as before. Figures 8 and 9 show the test circuits for this configuration. The signal gain was kept at a gain of 5.

The same concepts apply for this CFB configuration as for the noninverting configuration. The advantage of this circuit is that the attenuation is not limited to unity gain, or 0 dB, like the noninverting gain circuit. Figure 10 shows the frequency responses of this configuration with varying pure resistor values for Z. The THS4012 response is shown for comparison purposes.

As expected, the responses all look comparable to each other below 10 MHz. Additionally, the resistance values affect the stability and again show that the higher the resistance is, the better the stability. Using a resistance as low as 475 Ω actually shows respectable performance in this configuration. Remember that for oscillations to occur, the

gain must be above unity gain, or 0 dB. As long as the peak is below 0 dB, oscillations should not occur. As in the non-inverting case, using 200 Ω shows a large narrow peak that will most likely result in stability issues and/or oscillations.

However, notice that above 10 MHz the same general shape occurs for both the CFB and VFB amplifiers. This is caused by the amplifiers' input and output impedances becoming very high above their bandwidth limit. When this occurs, there is a path for the input signal to flow through R_G , through C_F , and then to feed forward to the load. Of course, the amplifiers' own input and output capacitances also affect the amount of feed-through in the circuit; but it is important to remember that this occurs above the amplifiers' usable bandwidths.

Just as for the noninverting configuration, using ferrite chips has several advantages for the inverting configuration.

Figure 10. Frequency responses with resistors (gain = -5)

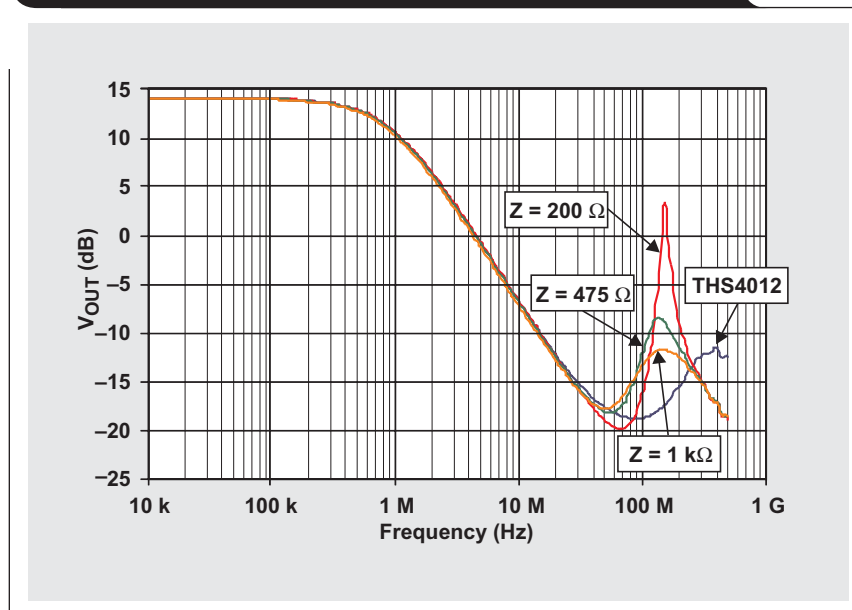


Figure 11 shows the frequency responses of several of these chips. Figure 12 shows the results of using various ferrite chips from the same AG family.

As expected, all of these graphs show the same type of results obtained with the noninverting configuration. Using a low-Q ferrite chip with high impedance will result in a stable system. Although the noise plots for this configuration are not presented here, they will show the same type of results as the noninverting configuration; using ferrite chips will have the lowest output noise of any configuration.

Conclusion

Although this article shows only two configurations with capacitors in the feedback path, it shows the fundamental feasibility of this compensation technique. While resistors do work very well, producing the most stable responses, the drawbacks of the output noise coupled with the dc and ac errors may limit some of the applications.

Using ferrite chips helps alleviate many of these issues, producing the lowest noise of all with no dc errors or in-band ac signal errors; and stability is almost as good as when utilizing resistors. It is important to choose the proper ferrite chip with the amplifier; but this is considered normal procedure for any circuit design and is no more difficult than selecting the right amplifier for the system.

This simple technique helps eliminate one of the major drawbacks of using the CFB amplifier while allowing any system to enjoy many of its benefits. Designers of multiple feedback filters, for example, once limited to the use of VFB amplifiers, can now take advantage of the superior slew rates and lack of gain-bandwidth product characteristics found in the CFB amplifier.

References

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Document Title

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2. "The Current-Feedback Op Amp: A High-Speed Building Block," Application Bulletin . . .sboa076
3. "Current Feedback Amplifiers: Review, Stability Analysis, and Applications," Application Bulletinsboa081
4. "Low-Noise, High-Speed Current Feedback Amplifiers," Data Sheetslos385
5. "Effect of Parasitic Capacitance in Op Amp Circuits," Application Reportsloa013

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Figure 11. Frequency responses above 10 MHz with ferrite chips (gain = -5)

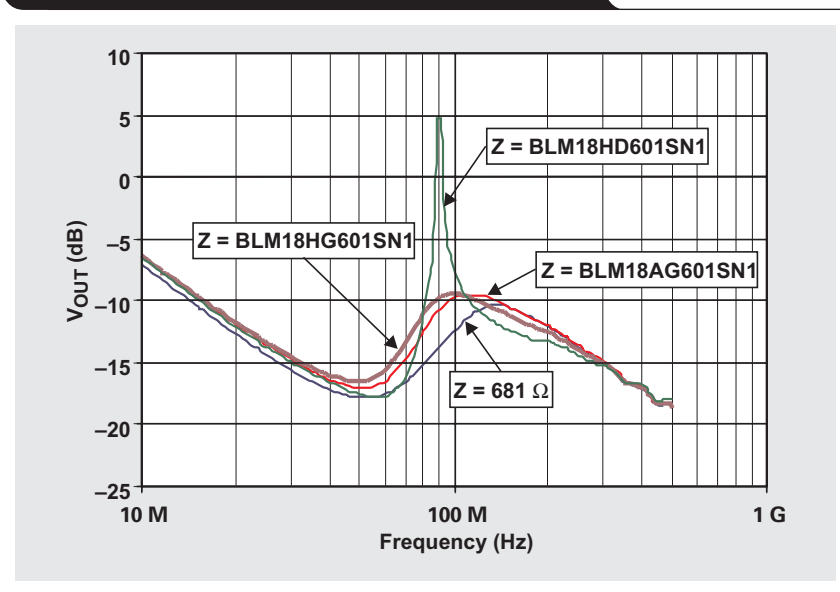
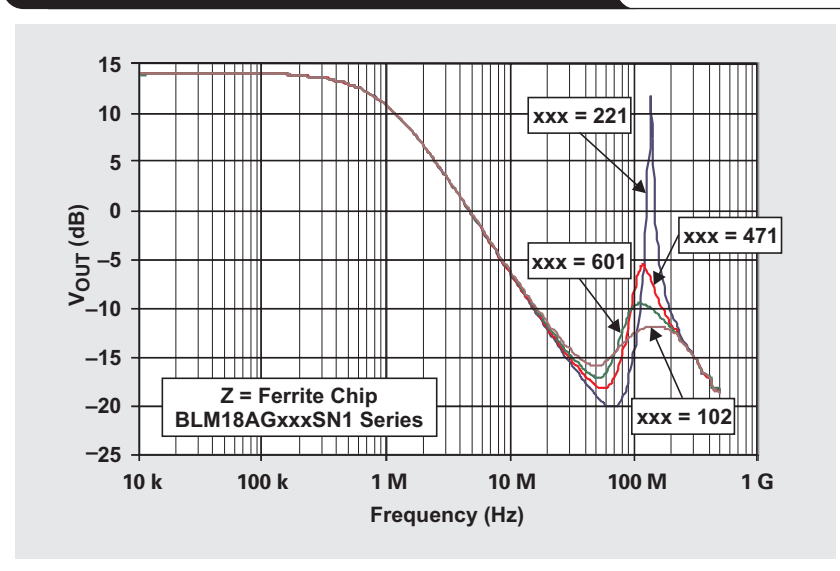


Figure 12. Frequency responses with AG series ferrite chips (gain = -5)



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