

# Using high-speed op amps for high-performance RF design, Part 2

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Advanced Linear Products, Op Amp Applications

This is Part 2 in a two-part series devoted to the topic of using op amps for RF design. Part 1 focused on how to form an RF stage from op amps and the scattering parameters. Part 2 focuses on other RF specifications and some of the finer points of RF design.

## Frequency-response peaking

Current-feedback amplifiers allow an easy resistive trim for frequency peaking that has no impact on the forward gain. This frequency-response flatness trim has the same effect in non-inverting and inverting configurations.

Figure 1 shows this adjustment added to an inverting circuit. This resistive trim inside the feedback loop has the effect of adjusting the loop gain and, hence, the frequency response without adjusting the signal gain, which is still set by  $R_F$  and  $R_G$ .

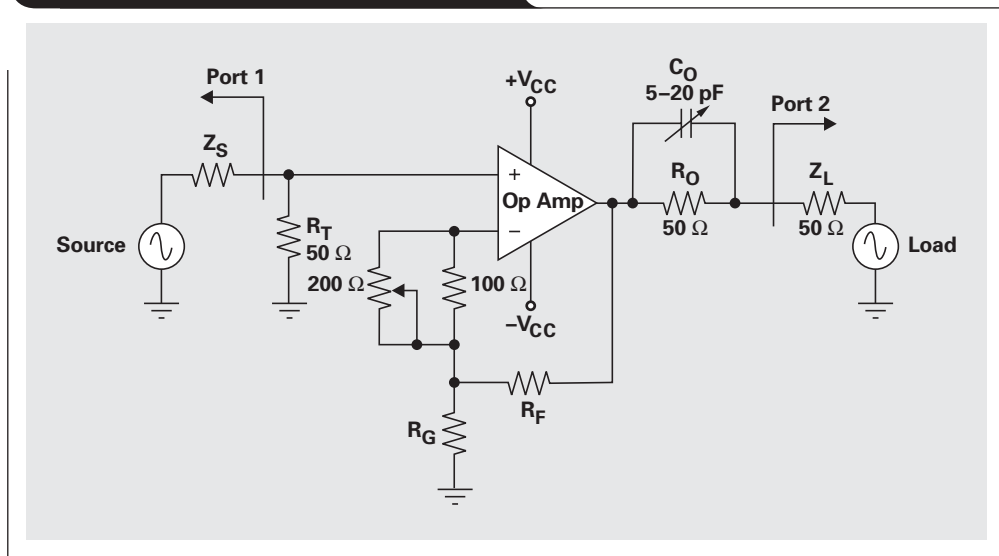
Values for  $R_F$  and  $R_G$  must be reduced to compensate for the addition of the trim potentiometer, although their ratio and, hence, the gain should remain the same. The adjustment range of the pot, combined with the lower  $R_F$  value, ensures that the frequency response can be peaked for slight variations in the current-feedback amplifier parameters.

## -1-dB compression point

The -1-dB compression point is defined as the output power, at a fixed input frequency, where the amplifier's actual output power is 1 dBm less than expected. Stated another way, it is the output power at which the actual amplifier gain has been reduced by 1 dB from its value at lower output powers. The -1-dB compression point is the way RF designers talk about voltage rails.

Op amp designers and RF designers have very different ways of thinking about voltage rails, which are related to the requirements of the systems they design. An op amp designer—interfacing op amps to data converters, for example—takes great pains not to hit the voltage rail of the op amp, thus losing precious codes. An RF designer, on the other hand, is often concerned with squeezing the last half decibel out of an RF circuit. In broadcasting, for example, a very slight increase in decibels means a lot more coverage. More coverage means more audience and more

Figure 1. Frequency-response peaking



advertising dollars. Therefore, slight clipping is acceptable, as long as resulting spurs are within FCC regulations.

Standard ac-coupled RF amplifiers show a relatively constant -1-dB compression power over their operating frequency range. For an operational amplifier, the maximum output power depends strongly on the input frequency. The two op amp specifications that serve a similar purpose to -1-dB compression are  $V_{OM}$  and slew rate.

At low frequencies, increasing the power of a fixed frequency input will eventually drive the output “into the rails”—the  $V_{OM}$  specification. At high frequencies, op amps will reach a limit on how fast the output can transition (respond to a step input)—the slew rate limitation. The op amp slew rate specification is divided by two, because of the matching resistor used at the output.

As is the case for op amps used in any other application, it is probably best to avoid operation near the rails, as the inevitable distortion will produce harmonics in the RF signal that are probably undesirable for FCC testing. That said, if harmonics are still at an acceptable level at the -1-dB compression point, it can be a very useful way to boost power to a maximum level out of the circuit.

## Two-tone, third-order intermodulation intercept

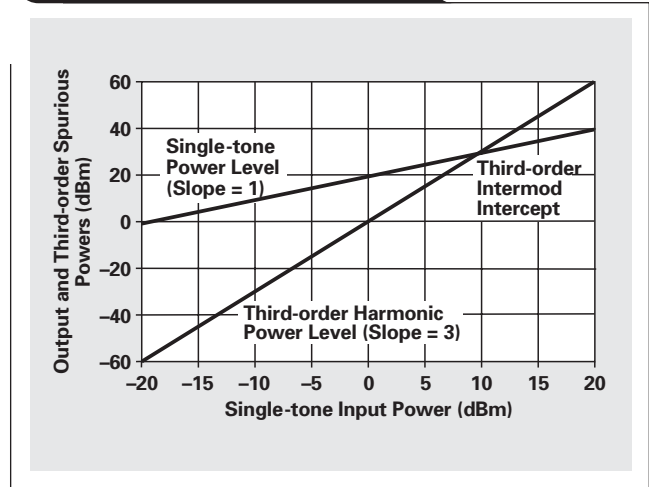
When two closely spaced signals are present in the RF bandwidth being amplified, sum and difference frequencies are created. These sum and difference frequencies are intermodulation harmonics. They are undesirable and may lead to problems with FCC testing of the system.

The problem with these harmonics is that they increase in amplitude three times as fast as the fundamentals. Figure 2 shows a theoretical system with a beginning fundamental signal level of 0 dBm, with intermodulation harmonics at -60 dBm. As the amplitude of the fundamentals is increased, the harmonics increase at three times the rate of the fundamentals, leading to an eventual intercept of the two lines at +30 dBm.

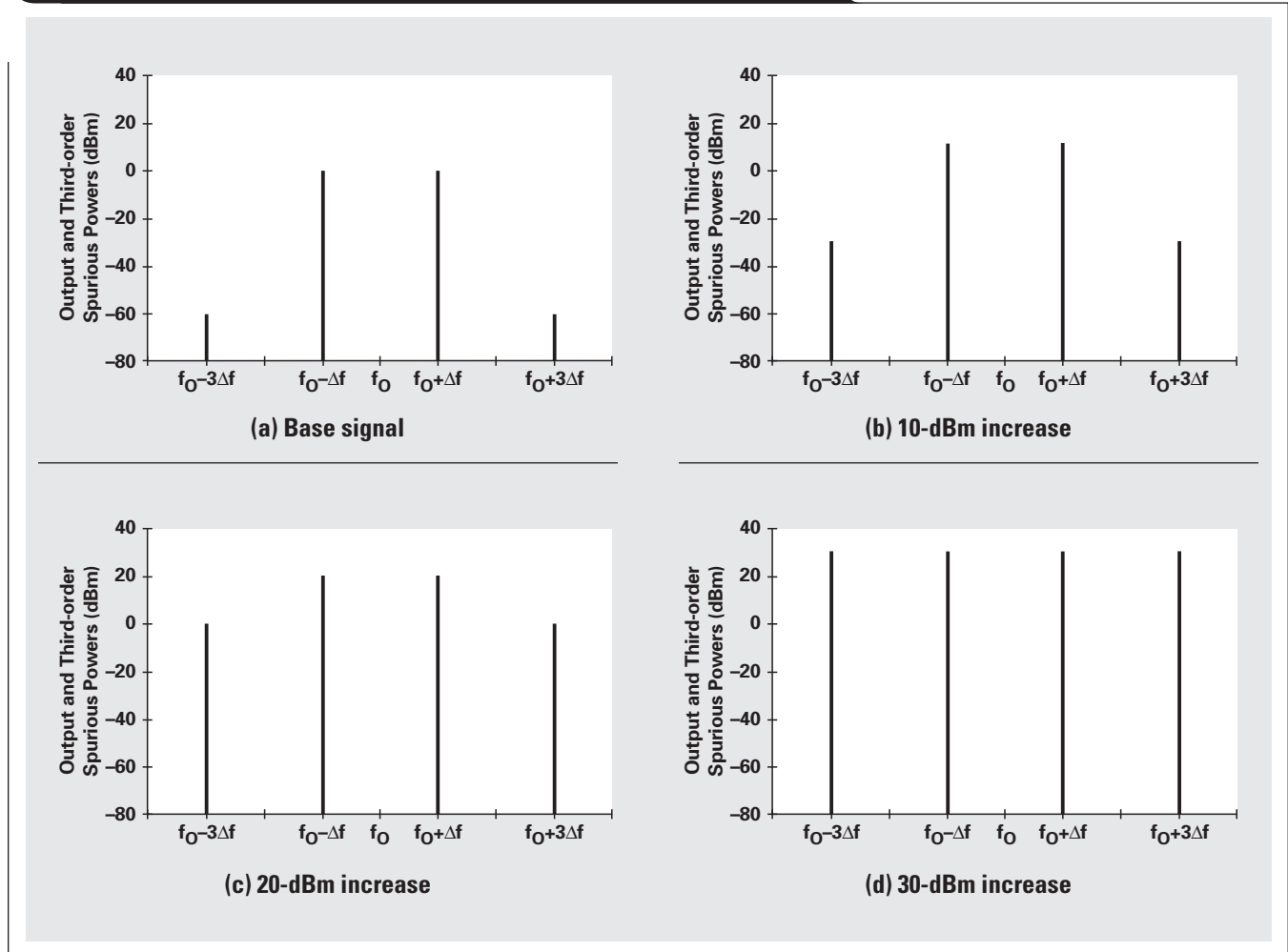
The typical RF circuit cannot be adjusted to +30 dBm, so the third-order intermodulation intercept is theoretical. The third-order intermodulation intercept should be as high as possible so that the intermodulation harmonics will be proportionally lower at any real-world fundamental level.

Figure 3 illustrates the two-tone intermodulation intercept in a different way. The fundamental frequencies at  $f_0 - \Delta f$  and  $f_0 + \Delta f$  are shown amplified in 10-dBm steps in Figures 3(b), 3(c), and 3(d). While the fundamentals are raised a total of 30 dBm, the third-order harmonics at  $f_0 - 3\Delta f$  and  $f_0 + 3\Delta f$  increase 90 dBm, eventually attaining the same amplitude as the fundamentals! Clearly, this must be avoided in a working RF system if spurs are to be rejected at all.

**Figure 2. Two-tone, third-order intermodulation intercept**



**Figure 3. Two-tone, third-order intermodulation intercept amplitudes**



## Noise figure

The RF noise figure is the same thing as op amp noise, when an op amp is the active element. There is some effect from thermal noise in resistors used in RF systems, but the resistor values in RF systems are usually so small that their noise can be ignored.

Noise for an op amp RF circuit is dependent on (1) the bandwidth being amplified and (2) gain.

This example uses the  $11.5 \text{ nV}/\sqrt{\text{Hz}}$  op amp. The application is a 10.7-MHz IF amplifier. The signal level is 0 dBV, and the gain is unity.

Figure 4 is extrapolated from real data. The  $1/f$  corner frequency, in this case, is much lower than the bandwidth of interest. Therefore, the  $1/f$  noise can be completely discounted (assuming that filtering removes any noise that would cause the amplifier or data converter to saturate).

For narrow bandwidths, noise may be quite low! The noise for various bandwidths is shown in Table 1.

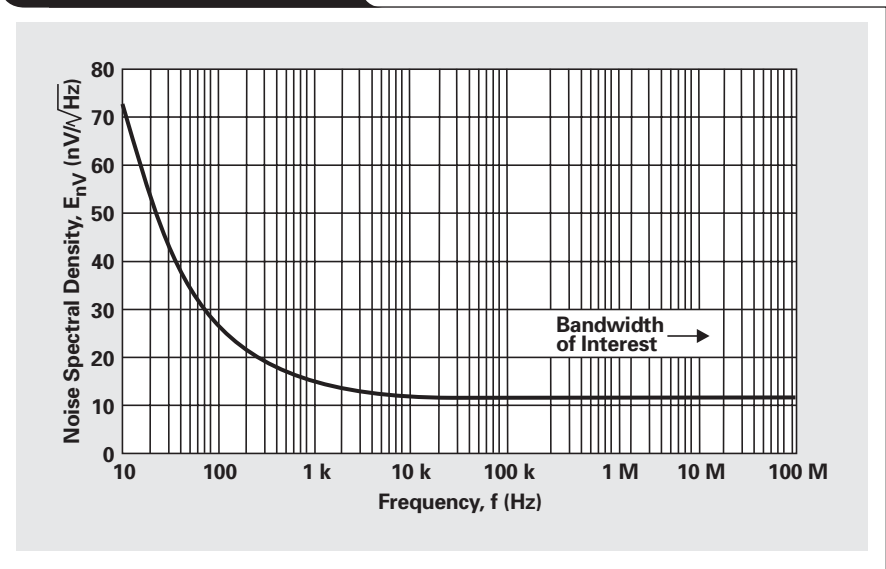
**Table 1. Noise for various bandwidths**

| BANDWIDTH (kHz) | EQUIVALENT INPUT NOISE ( $\mu\text{V}$ ) | SIGNAL-TO-NOISE RATIO (dB) |
|-----------------|--|----------------------------|
| 280             | 6.09                                     | -104.3                     |
| 230             | 5.52                                     | -105.2                     |
| 180             | 4.88                                     | -106.2                     |
| 150             | 4.45                                     | -107.0                     |
| 110             | 3.81                                     | -108.4                     |
| 90              | 3.45                                     | -109.2                     |

Obviously, there is a slight advantage in reducing the bandwidth. A lower-noise op amp, however, will provide the greatest benefit.

Noise is amplified by the gain of the stage. Therefore, if a stage has high gain, care must be taken to find a low-noise op amp. If the gain of a stage is low, the noise will not be amplified as much, and a less expensive op amp may be suitable.

**Figure 4. Noise bandwidth**



## Conclusion

Op amps are suitable for RF design, provided that the cost can be justified. They are more flexible to use than discrete transistors, because the biasing of the op amp is independent of the gain and termination. Current-feedback amplifiers are more suitable for high-frequency, high-gain RF design because they do not have the gain/bandwidth limitations of voltage-feedback op amps.

Scattering parameters for RF amplifiers constructed with op amps are very good. Input and output VSWRs are good because the effects of termination and matching resistors can be controlled independently of stage biasing. Reverse isolation is very good because the RF stage uses an op amp consisting of dozens or hundreds of transistors instead of a single transistor. Forward gain is very good with a current-feedback amplifier.

Special considerations apply to RF design that do not normally apply to op amp design—the phase linearity, the  $-1\text{-dB}$  compression point (as opposed to voltage rails), the two-tone, third-order intermodulation intercept, peaking, and noise bandwidth. In just about every case, the performance of an RF stage implemented with op amps is better than one implemented with a single transistor.

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