Using high-speed op amps for high-performance RF design, Part 1

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Why use op amps for RF design? Traditional RF design techniques using discrete transistors have been practiced successfully for decades. RF designers who are comfortable with things “as-is” will scrutinize introduction of a new design technique using op amps. The cost of high-speed op amps, in particular, will raise eyebrows. Why replace a transistor that costs a few cents with a component that may cost several dollars?

This is a valid question to ask for high-volume consumer goods; and, in almost every case, the answer will be to stay with traditional techniques. For high-performance RF equipment, however, high-speed op amps have some distinct advantages. Many other applications have migrated to op amps to take advantage of the superior performance they provide. It is reasonable to assume that high-speed applications such as RF will also make the move.

This article will be presented in two parts. Part 1 focuses on the actual topology of RF stages formed with op amps and the scattering parameters. Part 2 will focus on some fine points of RF design and more specifications unique to RF.

Advantages

The major advantage of using high-speed op amps is a high degree of flexibility over discrete transistor implementations. When discrete transistors are used, the bias and operating point of the transistor interact with the gain and tuning of the stage. In contrast, when op amps are used, the bias of the stage is accomplished simply by applying the appropriate power supplies to the op amp power pins. Gain of the stage is completely independent of the bias. Gain does not affect the tuning of the stage, which is accomplished through passive components.

Op amps also reduce transistor parameter drift over the system operating temperature range.

Disadvantages

As attractive as op amps are for RF design, there are some barriers hindering their use. The first is, of course, cost.

The RF designer must learn how to set the op amp’s operating point, but the process is considerably easier than biasing a transistor stage.

The RF designer is used to describing RF performance in certain ways. Op amp ac performance is described in terms of ac performance. The RF designer must learn how to translate op amp ac performance parameters into an RF context. That is one of the main purposes of this article.

Voltage feedback or current feedback?

The RF designer considering op amps is presented with a dilemma. Are voltage-feedback amplifiers or current-feedback amplifiers better for the design?

The bandwidth specification given in op amp data sheets refers only to the point where the unity gain bandwidth of the device has been reduced by 3 dB by internal compensation and/or parasitics—not very useful for determining the actual operating frequency range of the device.

Internally compensated, voltage-feedback amplifier bandwidth is dominated by an internal “dominant pole” compensation capacitor, resulting in a constant gain/bandwidth limitation. Current-feedback amplifiers, in contrast, have no dominant pole capacitor and therefore can operate much more closely to their maximum frequency at higher gain. Stated another way, the gain/bandwidth dependence has been broken.

Comparing a voltage-feedback and current-feedback op amp illustrates this:

- THS4001, a voltage-feedback amplifier with a 270-MHz (–3-dB) open-loop bandwidth, is usable to only about 10 MHz at a gain of 100 (20 dB).
- THS3001, a current-feedback amplifier with a 420-MHz (–3-dB) open-loop bandwidth, is usable to about 150 MHz at a gain of 100 (20 dB).

The choice is still up to the designer. At unity and low gains there may not be much advantage to using a current-feedback amplifier, but at higher gains the choice is clearly a current-feedback amplifier. Many RF designers would be extremely happy if they could obtain a gain of 10 (20 dB) in a single stage with a transistor—difficult to do. With an op amp, it is almost trivial.

The RF designer must be aware of some issues with current-feedback amplifiers:

- Conventional circuit topologies are unchanged for current-feedback amplifiers.
- Current-feedback amplifier data sheets recommend values for R_F, the feedback resistor. These recommendations should be taken seriously. Gain adjustment should be made with R_G.
- Keep capacitors out of the feedback loop.

Other than these restrictions, no additional care is needed with the current-feedback amplifier except the normal care in layout and meeting bypass requirements of high-speed RF circuitry.

For both voltage- and current-feedback amplifiers, capacitance on the inverting op amp input should be limited, as this is a major cause of instability. It is very easy to accumulate stray capacitance on a sloppy PCB layout. To reduce this stray capacitance, Texas Instruments recommends a hole in the ground and power planes under the inverting input of an op amp on a multilayer board.

A review of traditional RF amplifiers

A traditional RF amplifier (Figure 1) uses a transistor (or, in the early days, a tube) as the gain element. The dc bias ($+V_{BB}$) is injected into the gain element at the load through a bias resistor, R_B. RF is blocked from being shorted to the supply by an inductor, L_C, and dc is blocked from the load by a coupling capacitor.

Both the input impedance and the load are 50 Ω, which ensures matching between stages.

When an op amp is substituted as the active circuit element, several changes are made to accommodate it.

By themselves, op amps are differential-input, open-loop devices. They are intended for a closed-loop operation (different from a receiver's AGC loop). The feedback loop for each op amp must be closed locally, within the individual RF stage.

There are two ways of accomplishing this—"inverting" and "non-inverting." These terms refer to whether or not the output of the op amp circuit is inverted from the input. From the standpoint of RF design, this is seldom of any concern. For all practical purposes, either configuration will work and give equivalent results. The non-inverting configuration is probably the easiest to use.

Figure 2 shows a non-inverting RF amplifier. The input impedance of the non-inverting input is high, so the input is terminated with a 50-Ω resistor. Gain is set by the ratio of R_F and R_G. For log gain,

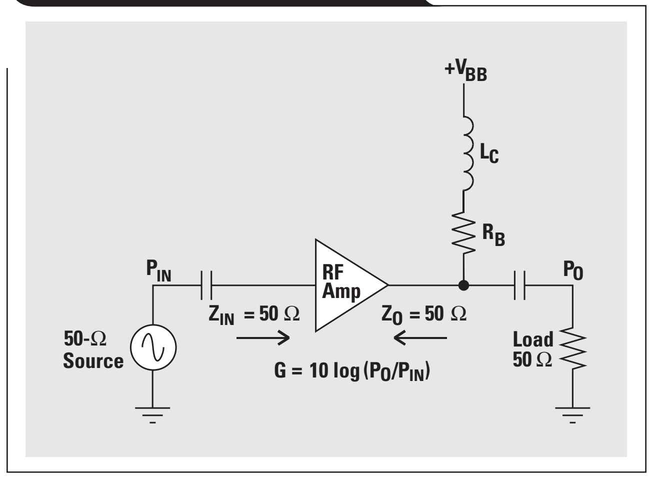
$$G = 20\log\frac{1}{2}\left(1+\frac{R_F}{R_G}\right)\text{ dB.}$$

For a desired gain,

$$1+\frac{R_F}{R_G} = 2(10^{G/20}).$$

The output of the stage is converted to 50 Ω by placing a 50-Ω resistor in series with the output. This, combined with a 50-Ω load, means that the gain is divided by 2 (–6 dB) in a voltage divider; so a unity-gain (0-dB) gain stage would become a gain of 0.5, or –6 dB.

Figure 1. Traditional RF stage



The RF designer may notice that the power-supply requirements have been complicated by the addition of a second negative supply. The stage can be modified easily for single-supply operation.

Amplifier gain, revisited

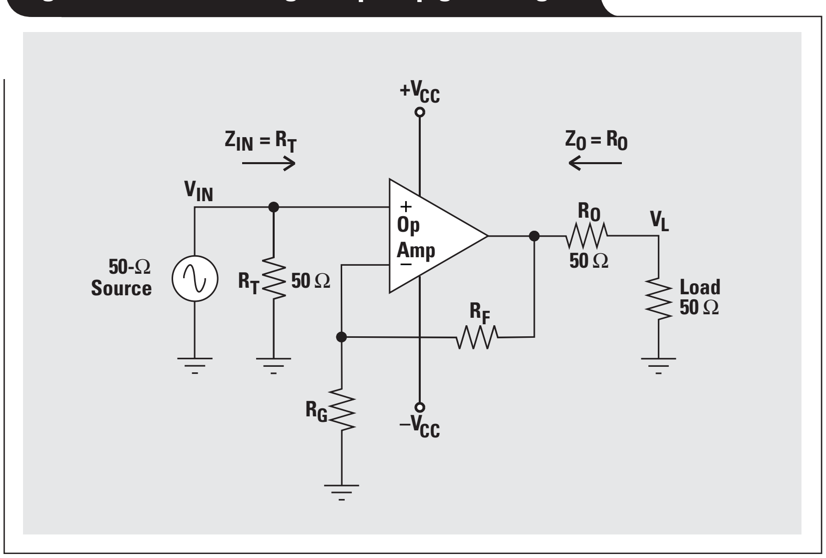
Op amp designers think of the gain of an op amp stage in terms of voltage gain. RF designers, however, are used to thinking of RF stage gain in terms of power:

$$\text{Absolute power (W)} = \frac{V_{rms}^{\;2}}{50\,\Omega}.$$

$$P_O(\text{dBm}) = 10\log\left(\frac{\text{Absolute power}}{0.001\text{ W}}\right).$$

$$\text{dBm} = \text{dBV} + 13 \text{ in a 50-}\Omega\text{ system.}$$

Figure 2. Non-inverting RF op amp gain stage



Scattering parameters

RF stage performance is often characterized by four "scattering" parameters, which are defined in Table 1. (VSWR, or voltage standing-wave ratio, is just another term for input or output reflection.)

The term "scattering" has a certain implication of loss, and that is indeed true in three cases. Reflections, as in the VSWR scattering parameters S_{11} and S_{22}, can cancel useful signals. Reverse transmission, S_{12}, steals output power from the load. The only desirable scattering parameter is S_{21}, the forward transmission. Design of an RF stage involves maximizing S_{21} and minimizing S_{11}, S_{22}, and S_{12}.

Small-signal ac parameters specified for RF amplifiers are derived from S-parameters. These specifications are frequency-dependent. They are measured with a network analyzer and an S-parameter test set. The test circuit is shown in Figure 3.

Table 1. Scattering parameters

	SCATTERING PARAMETER	RF AMPLIFIER SPECIFICATION
S_{11}	Input reflection	Input VSWR
S_{22}	Output reflection	Output VSWR
S_{21}	Forward transmission	Amplifier gain and bandwidth
S_{12}	Reverse transmission	Reverse isolation

Input and output VSWR S_{11} and S_{22}

VSWR is a ratio and therefore a unitless quantity. It is a measure of how well the input and output impedances are matched to the source and load impedances. They should be as closely matched as possible to avoid reflections.

VSWR is defined as:

$$\text{VSWR} = \frac{Z_{I/O}}{Z_S} \text{ or } \frac{Z_S}{Z_{I/O}}, \text{ whichever} > 1,$$

where $Z_{I/O}$ is the amplifier input or output impedance; and Z_S is the test system source impedance. The ideal VSWR is equal to 1:1, but typical VSWRs will be no better than 1.5:1 for RF amps over their operating frequency range.

Measuring the input VSWR is a matter of measuring the ratio of the reflected power versus incident power on Port 1 (S_{11}) in Figure 3. A perfect match will reflect no power. Output VSWR is measured the same way at Port 2 (S_{22}).

An op amp's input and output impedances are determined by external components selected by the designer. For this reason, VSWR cannot be specified on an op amp's data sheet.

Return loss

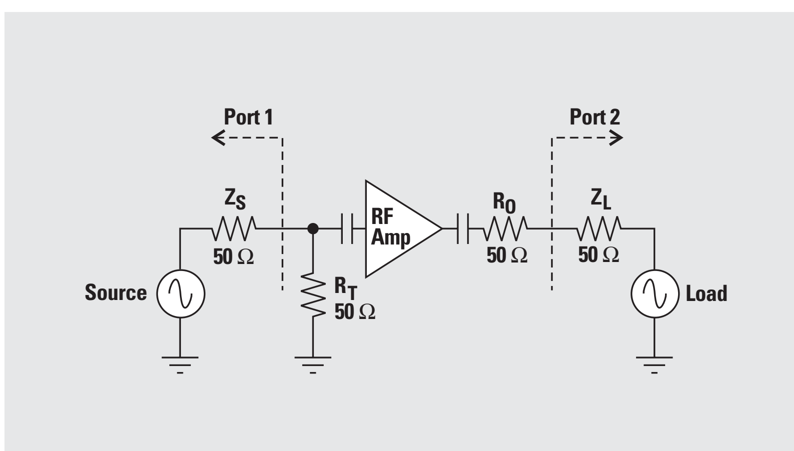
Return loss is related to VSWR in the following way:

$$\text{Return loss} = 20\log\left(\frac{\text{VSWR}+1}{\text{VSWR}-1}\right) = 10\log(S_{11})^2 \text{ input}$$

$$\text{or} = 10\log(S_{22})^2 \text{ output.}$$

R_O is not a perfect match for Z_L at high frequencies. The output impedance of the amplifier will increase as the loop

Figure 3. Scattering-parameter test circuit



gain falls off. This will change the output VSWR. A peaking capacitor, C_O, added in parallel with R_O, can compensate for this effect (Figure 4). Because op amp output impedance will be well defined, a fixed value usually can be substituted after experimentation determines the correct value.

Reducing the input impedance of the amplifier will extend the maximum usable frequency by swamping the effects of high-frequency parasitic components.

Forward transmission S_{21}

The forward transmission S_{21} is specified over the operating frequency range of interest. S_{21} is never specified on an op amp data sheet because it is a function of the gain, which is set by the input and feedback resistors R_F and R_G, respectively. The forward transmission of a non-inverting op amp stage is:

$$S_{21} = A_L = \frac{V_L}{V_{IN}} = \frac{1}{2}\left(1 + \frac{R_F}{R_G}\right).$$

The forward transmission of an inverting op amp stage is:

$$S_{21} = A_L = -\frac{V_L}{V_{IN}} = -\frac{1}{2}\left(\frac{R_F}{R_G}\right).$$

Op amp data sheets show open-loop gain and phase. It is the responsibility of the designer to know the closed-loop gain and phase. Fortunately, this is not difficult. The data sheets often include excellent graphs of open-loop bandwidth and sometimes include phase. Closing the loop produces a straight line across the graph at the desired gain, curving to meet the limit. The open-loop bandwidth plot should be used as an absolute maximum. The designer who approaches the limit does so at the expense of extensive compensation and complex PCB layout techniques.

Reverse transmission S_{12}

Op amp topologies, in particular current-feedback amplifiers, assume that both inputs are connected to low impedances. Therefore, the reverse isolation of op amp RF circuits is excellent.

Reverse isolation is somewhat better in non-inverting current-feedback amplifier configurations, because the output signal must also leak through the circuitry connecting the non-inverting and inverting inputs to get to the source.

Phase linearity

Often, a designer is concerned with the phase response of an RF circuit. This is particularly the case with video design, which is a specialized type of RF design. Current-feedback amplifiers tend to have better phase linearity than voltage-feedback amplifiers.

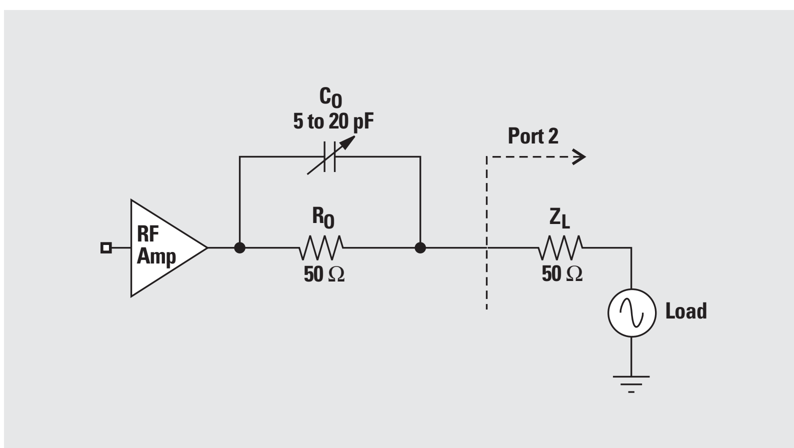
- Voltage-feedback THS4001: Differential phase = 0.15°.
- Current-feedback THS3001: Differential phase = 0.02°.

Look for Part 2 of this article and conclusions to be published in a future issue of *Analog Applications Journal*.

Related Web sites

www.ti.com/sc/device/THS3001
www.ti.com/sc/device/THS4001

Figure 4. Output peaking capacitor



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