BY JEFFREY LIES, TAMARA PAPALIAS, AND MIKE WONG • INTERSIL CORP

Choosing high-speed amplifiers for noise-sensitive applications

VOLTAGE FEEDBACK, CURRENT FEEDBACK, BIPOLAR, CMOS–ALL HAVE ADVANTAGES AND DRAWBACKS. HERE'S A ROAD MAP FOR PICKING THE BEST TYPE FOR YOUR APPLICATION.

High-speed amplifiers have broken the gigahertz barrier, making them an attractive choice in many applications. Fundamental differences exist in the types of amplifiers on the market. The two most critical characteristics involve process (bipolar or CMOS) and feedback (current or voltage). Both current- and voltage-feedback amplifiers are popular for high-speed applications. This article focuses on noise characteristics, as well as the strengths and limitations of each type. An understanding of the differences in circuit topology, along with basic noise and distortion characteristics, is crucial for optimal product selection.

VFAs (voltage-feedback amplifiers) are the most common op-amp topology. This topology has three stages: a differential-input stage, a gain/level-shift stage, and an output stage. **Figure 1** presents a simplified schematic of the EL5157, a popular VFA.

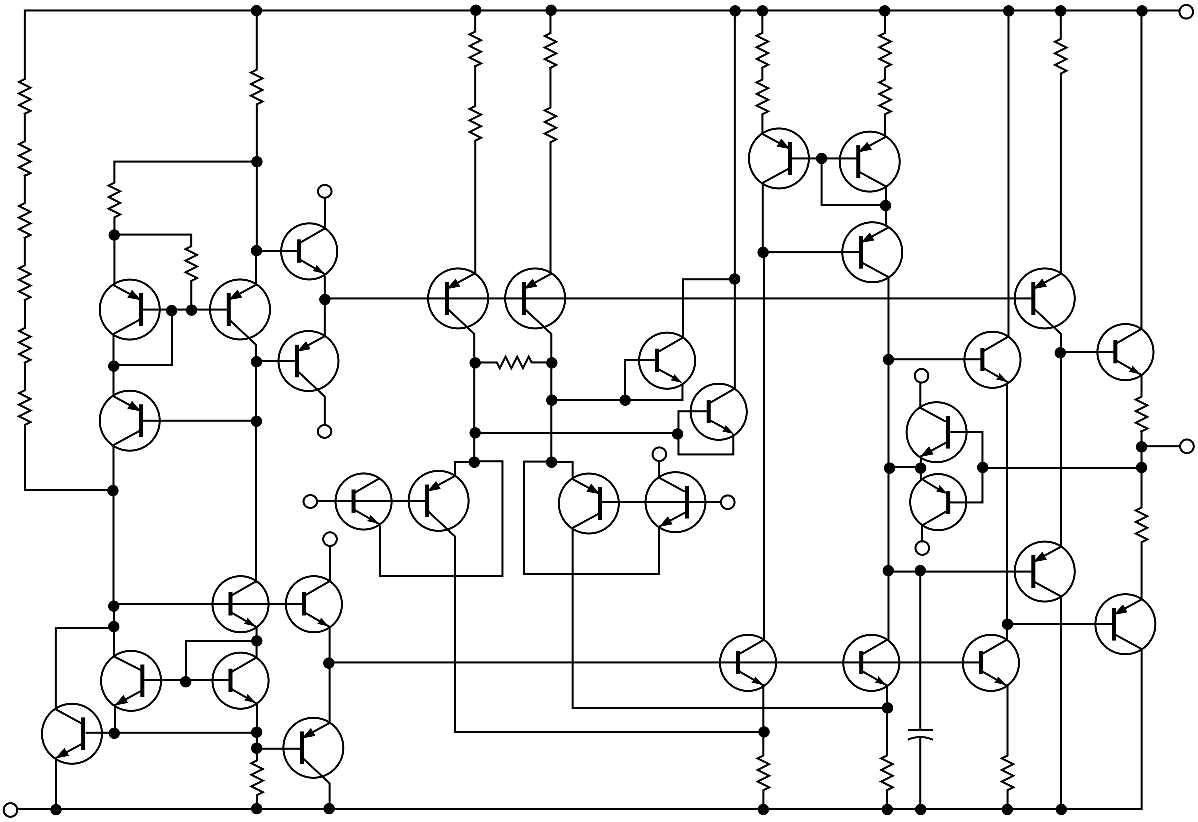

Figure 1 The EL5157 is an example of a voltage-feedback-amplifier topology.

The input stage is an NPN differential pair in parallel with a PNP pair. The second stage consists of a pullup current source. Any difference (signal or error) in the currents of the signal-path transistors appears across the output impedance of the current source at the high-impedance node. The output stage buffers the high-impedance node to the output.

CFA TOPOLOGY

CFAs (current-feedback amplifiers) have a different input structure. The input stage has a unity-gain buffer between its inverting and noninverting inputs that gives the CFA topology some distinct advantages. CFAs' popularity lagged voltage-feedback designs until the emergence of fully complementary bipolar processes. Fortunately, these processes are widely available today, so CFAs can exploit the current switching, which is faster than bipolar circuits' voltage switching.

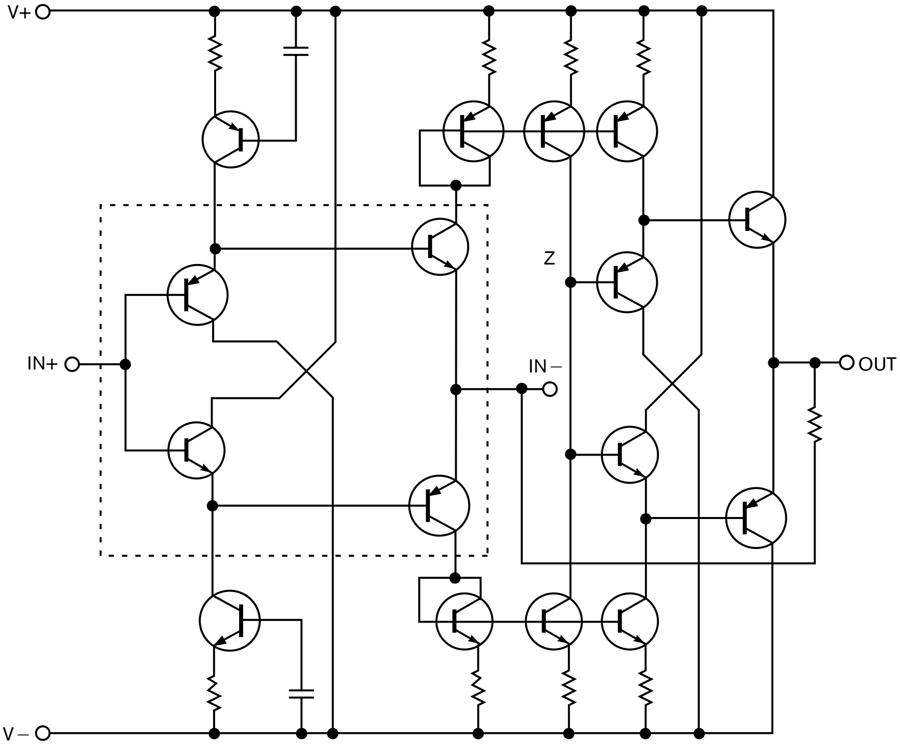

Figure 2 In this current-feedback amplifier, the noninverting input has high impedance and is buffered to the inverting input.

In **Figure 2**, the noninverting input has high impedance and is buffered to the inverting input (see dashed box). The input impedance of the inverting input is very low, and its signal reaches the high-impedance node through current mirrors. The high-impedance node, Z, is buffered to the output.

A higher level look at the CFA structure highlights its advantages (**Figure 3**). Any voltage difference across feedback resistor R_F creates an error current into the inverting input. Because the impedance at the inverting input is low, this feedback is a current. Another name for a CFA is a transimpedance amplifier, because any change in the inverting-input current causes an output-voltage change. The inverting input can source and sink high transient currents, which bias current does not limit. The current mirrors supply current on demand from the power supply to the high-impedance node, giving CFAs high slew rates. A unity-gain buffer completes the circuit, driving the output to the voltage necessary to minimize the feedback error current.

The value of R_F determines the amount of current fed back to the inverting input. Therefore, when you vary the gain of a

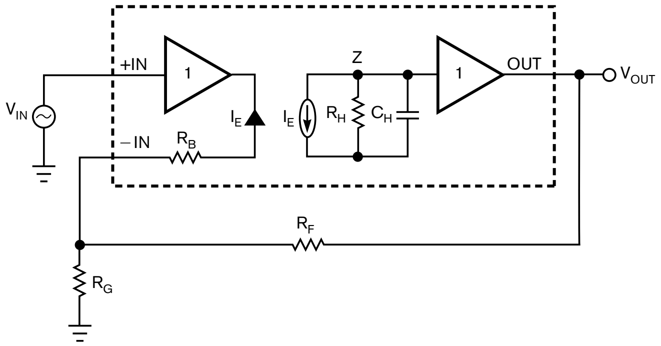

Figure 3 A current-feedback amplifier is also called a transimpedance amplifier because any change in the inverting-input current causes an output-voltage change.

TABLE 1 DOMINANT TYPES OF NOISE IN AN OPERATIONAL AMPLIFIER

Type of noise	Calculation
Thermal (Johnson) noise	$V_{JN}=\sqrt{(4KTR\Delta f)}$
Shot noise	$I_{SN}=\sqrt{(2qI_{DC}\Delta f)}$
Flicker (1/f) noise	$I_{FN}=\sqrt{(k_d I_{DC}^{a} f^{-b}\Delta f)}$

Notes:
K = Boltzmann's constant (1.38×10^{-23} J/K).
T = absolute temperature in Kelvin (0°C = 273 Kelvin).
R = resistance of component/device.
I_{DC} = dc current.
q = charge on an electron (1.6×10^{-19} C).
Δf = system bandwidth.
f = center frequency of operation.
k_d = device constant (varies by orders of magnitude; even on one wafer, MOS tends to be higher than a bipolar-junction transistor).
a = fabrication constant (ranges from 0.5 to 2).
b = constant (approximately = 1).

CFA, you should adjust the value of R_G. Also, although VFAs exhibit a gain-bandwidth trade-off, CFA bandwidth is inversely proportional to the value of R_F.

OP-AMP-NOISE CALCULATIONS

Figure 4 presents a classic noise model of an operational amplifier with feedback. The **figure** shows all of the possible noise sources, including thermal (Johnson) noise voltages for the external feedback and gain resistors. Whereas the resistor-noise sources do not change versus frequency, the voltage- and current-noise sources in association with the op amp are frequency-dependent. Therefore, op-amp data sheets provide plots of input voltage and current noise.

The two main components of noise within op amps are flicker and white noise. Flicker noise, also called 1/f noise because its contribution is inversely proportional to frequency, dominates at low frequencies (less than a few megahertz for CMOS and less than a few kilohertz for bipolar designs). White noise includes contributions of shot noise from bias currents and thermal noise from resistances in devices and other circuit structures. With its flat amplitude characteristic with respect to frequency, white noise dominates at medium and high frequencies. **Table 1** lists the types of noise and their mathematical equivalents.

By convention, noise quantities are input-referred. That is, the presented value is the amount that would appear at the input to cause the resultant noise at the circuit output. For example, if a noise source exists at an amplifier's output, you divide it by the closed-loop gain to refer it to the input. Referring all of the noise to the same node simplifies comparing and combining the influence of various noise contributions.

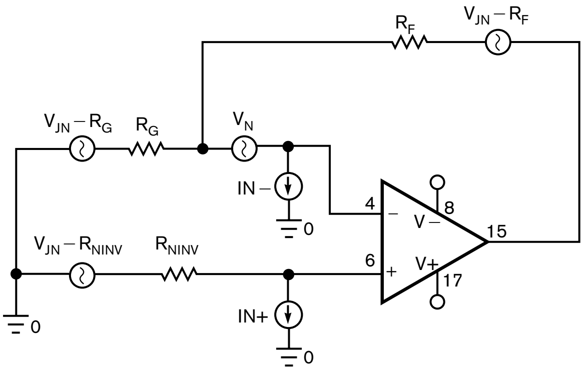

Figure 4 This classic noise model of an op amp with feedback shows all of the possible noise sources, including thermal (Johnson) noise voltages for the external feedback and gain resistors.

For **Figure 4**'s amplifier example, you can calculate the noise sources, as **Table 2** shows. To facilitate comparison, all noise sources appear as voltages. The third column identifies the voltage gain that each noise source experiences.

Noise is a random quantity. A noise source's average voltage

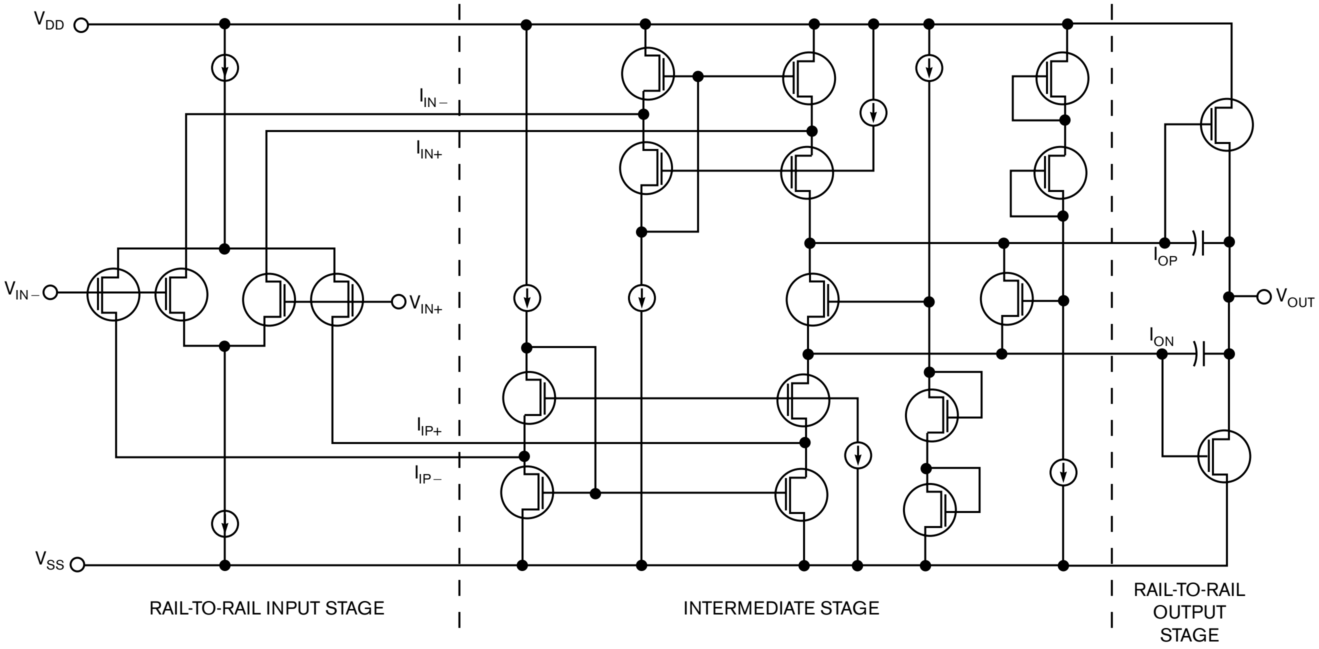

Figure 5 In this simplified CMOS op amp, both inputs connect to MOSFET gates, which allow virtually zero current flow. Thus, only voltage determines the output signal, explaining the amplifier's low level of input-current noise.

is zero, as is a sine wave's. However, the average power is *not* zero. Therefore, when summing the contributions of different noise sources, you add the power of each source to get the total power. Power, P, is proportional to voltage, V, squared and inversely proportional to the resistance, R, at the node:

$P=I\cdot V=(V/R)\cdot V=V^2/R$.

With all of the noise sources referred to the same node, they will be across the same impedance. Therefore, you can calculate the total noise power at that point. If you want the related total voltage, reverse the equation; that is, enter P and either I or R and solve for V.

The noise sources in **Table 2** are uncorrelated, and you can sum them as the preceding paragraphs describe. Correlated noise results from a single source or from dependent sources that relate the behavior of one source to another. Because the noise behavior of correlated sources is related, you can't simply add the source powers.

TABLE 2 AMOUNT OF NOISE PER NOISE SOURCE

Noise source	Noise (as a voltage)	Noise gain
Input-voltage noise	Vn	$1+R_F/R_G$
Inverting-input current noise	$In-\times R_F$	1
Noninverting-input current noise	$In+\times R3$	$1+R_F/R_G$
Johnson noise of R_F	$\sqrt{(4KT\times R_F)}$	1
Johnson noise of R_G	$\sqrt{(4KT\times R_G)}$	$-R_F/R_G$ (inverting)
Johnson noise of R_{NINV}	$\sqrt{(4KT\times R_{NINV})}$	$1+R_F/R_G$

TABLE 3 TYPICAL VALUES FOR NOISE QUANTITIES IN VFA, CFA AND CMOS TOPOLOGIES

	VFA	CFA	CMOS
V_N	0.86 nV/$\sqrt{\text{Hz}}$	4 nV/$\sqrt{\text{Hz}}$	20 nV/$\sqrt{\text{Hz}}$
IN−	1.4 pA/$\sqrt{\text{Hz}}$	20 pA/$\sqrt{\text{Hz}}$	2 fA/$\sqrt{\text{Hz}}$
IN+	1.4 pA/$\sqrt{\text{Hz}}$	8 pA/$\sqrt{\text{Hz}}$	2 fA/$\sqrt{\text{Hz}}$

VFA AND CFA NOISE ANALYSIS

To understand the noise differences between VFAs and CFAs, you need only compare the architectural differences between their input stages (**figures 1** and **2**). The VFA input structure is a differential pair. Therefore, in bipolar technologies, the inputs connect to bases of PNP or NPN transistor pairs or to both. The currents through these nodes are small base currents; because the noise current is proportional to the base current, low-input-noise current results.

The CFA, on the other hand, has two inputs connecting to very different structures. The noninverting op-amp input connects to the base of bipolar transistors, so the noise current is comparable with that at the inputs of VFAs. Conversely, the inverting op-amp input is the buffer's output, typically NPN and PNP emitters. Because emitter current is much larger than base current (by a factor of the current gain, β), the noise is proportionally higher, as well. CFA inverting-input noise currents typically are in the 20- to 30-pA/$\sqrt{\text{Hz}}$ range, compared with the VFA's 1- to 5-pA/$\sqrt{\text{Hz}}$ typical range.

The feedback resistor, R_F, transforms this larger noise current into a voltage. Input-referred noise voltage is a more complicated parameter, being a function of not only the input transistors (primarily transistor base resistance and collector current), but also the type of load the input stage drives. It is generally sufficient to say that CFAs typically deliver an input-noise voltage that is at least as low as that of VFAs that haven't been optimized for low noise. **Table 3** shows typical noise currents and voltages for a VFA, a CFA, and, for comparison, a CMOS amplifier.

VFA circuits are optimized for sensitivity to the input-voltage difference. Therefore, the voltage-noise contribution is the lowest of the three. The current noise at both inputs is low because the base current into each terminal is small. For the CFA, the feedback node has emitter current flowing instead of a base current. This larger current naturally has a larger current noise associated with it.

In the CMOS case, the input is purely capacitive (**Figure 5**). The input is again a differential pair. Because both inputs connect to MOSFET gates, which allow virtually zero current flow, only the voltage determines the output signal, explaining the

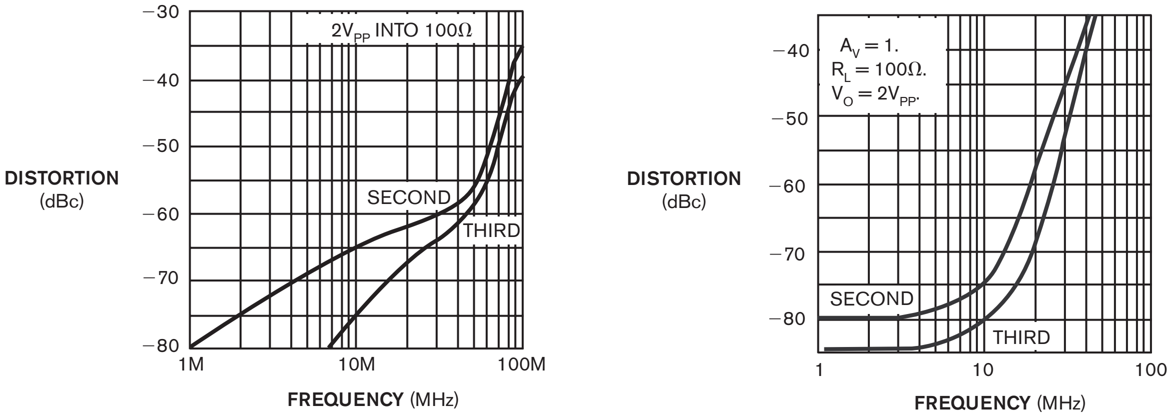

Figure 6 These data-sheet curves show typical second- and third-harmonic-distortion values for CFAs (a) and VFAs (b).

CMOS amplifier's low level of input-current noise. The input-voltage noise, though higher in the CMOS case, is still within an order of magnitude of the other two examples. So, if the voltage gain is low, as in transimpedance amplifiers, the higher noise is inconsequential. A drawback of CMOS amplifiers is that the 1/f-knee frequency is inversely proportional to the device channel lengths, so the more advanced the process, the higher the frequency of the 1/f knee.

TABLE 4 SUMMARY OF OP-AMP TOPOLOGIES, STRENGTHS, AND APPLICATIONS

Topology	Strengths	Example use
VFA	Input symmetry Low input voltage and current noise Low distortion at low frequency	Communications systems
CFA	Slew rate Bandwidth Low distortion at high frequency	ADC driver
CMOS	Dynamic range Rail-to-rail operation Lowest input current noise	Transimpedance amplifier/photodetector

VFA AND CFA DISTORTION CHARACTERISTICS

At low frequencies, VFAs provide the lowest distortion. The differential-pair input stage acts much like an electronic seesaw. When the op amp encounters a negative feedback, it attempts to level the seesaw. **Figure 6** provides distortion values from the data sheets of a typical CFA and VFA. Of course, there are products on the market that do not follow these curves. Check the data sheet before choosing an amplifier for your application.

The CFA accepts a voltage at its noninverting input and a current at its inverting input. The seesaw effect is still there, but only after $V_{IN}+$ translates into a current. This translation is imperfect, introducing errors that appear in the second-harmonic distortion. At higher frequencies, most of the loss comes from slew-rate limitations. Because CFAs have higher slew rates than VFAs, they exhibit lower distortion characteristics at high frequencies. CFAs also maintain relatively constant distortion at different gain settings.

In xDSL systems, communications signals travel through telephone lines whose lengths can reach 20,000 feet. The receive signal can be as small as 30 mV with a 4-MHz bandwidth. Amplifying this signal requires a low-noise amplifier. Filtering is also necessary to remove high-frequency noise from the lower frequency transmit signal.

The line receiver's closed-loop gain must be at least 30V/V, and the driver front end's ADC has 14-bit resolution. To use the full range of the 14-bit ADC, the input SNR (signal-to-noise ratio) must exceed 84.3 dB. For example, a 20-mV input signal would require a noise level of less than 1.2 µV. The limit of the amplifier's input-voltage noise is 0.9 nV/$\sqrt{\text{Hz}}$ with a 4-MHz bandwidth. You should use a VFA—not only for its low input-voltage noise, but also because VFAs are more flexible in active-filter configurations.

DRIVING AN ADC

CFAs excel at driving high-speed, high-resolution ADCs, especially for pulsed inputs. A distinct CFA advantage for this application is that the CFA's output rise time remains nearly constant, regardless of the output step size. The slewing current is equivalent to the inverting-input current during transients, which is a function of the voltage difference across R_F. Therefore, the CFA's slew rate actually increases as the step size increases. Whereas a VFA may become slew-rate-limited for voltage swings of less than 1V, CFAs typically do not reach slew-rate limit for steps smaller than several volts.

In addition to its slew-rate advantage, the CFA offers exceptional bandwidth (be careful; excess bandwidth still contributes to total noise), distortion, settling time, and relatively low supply current, which make it a prime contender for ADC drivers. For example, the EL5166 is a good choice for driving 14-bit ADCs, because of its 1.4-GHz bandwidth, 6000V/µsec slew rate, and 70-dB second harmonic distortion at 20 MHz. With ADC drivers, the load that the CFA's feedback network presents is not usually a concern. This characteristic allows designers to use low-value feedback resistors to minimize noise and maximize the driver's performance.

TRANSIMPEDANCE AMPLIFIER

Wide bandwidth and low input-bias and noise currents make modern high-speed CMOS amplifiers ideal choices for photodiode transimpedance amplifiers. The key elements in a transimpedance design are capacitances at the inverting input (including diode, amplifier-input, and parasitic capacitance), the transimpedance gain set by R_F, low input-current noise to allow wide dynamic range, and sufficient gain-bandwidth product (**Figure 7**). With these four variables set, you often need a feedback capacitor in parallel with R_F to control the frequency response and ensure stability.

If the amplifier is a rail-to-rail, single-supply device, you can connect the noninverting input to ground, allowing the output to reach true zero when the photodiode is not exposed to any light. This setup allows the circuit to avoid the delay that the output would need to travel from the negative rail.

To achieve the best performance, select components according to the following guidelines:

- For lowest overall system noise, select R_F to provide all of the required transimpedance-stage gain. Because the CMOS amplifier has virtually no current noise, a lower R_F value (to lower the transimpedance-stage noise) would necessitate including additional gain stages, ultimately producing poorer overall noise performance. The noise that R_F produces increases as the square root of resistance, whereas the signal value increases linearly. Therefore, placing all of the required gain in the transimpedance stage improves the SNR.

- Minimize capacitance at the inverting input. This capacitance causes amplification of the op amp's voltage noise. A low-noise voltage source to reverse-bias a photodiode can significantly reduce its capacitance. Smaller photodiodes have lower capacitance. Use optics to concentrate light on a small photodiode.
- Because noise increases with increased bandwidth, limit the circuit bandwidth to only what is necessary. To limit bandwidth, parallel the feedback resistor with a capacitor, even if stability is not an issue.
- PC-board leakage can degrade the performance of an otherwise well-designed amplifier. Carefully clean the pc board. A pc-board guard trace that encircles the summing junction (inverting input) and drives at the same voltage as the summing junction can help control leakage.

Both CFA and VFA topologies are popular choices for high-speed applications. An understanding of the differences in circuit topology, along with basic noise and distortion characteristics, is crucial for optimal product selection. **Table 4** summarizes the aforementioned discussion and examples.

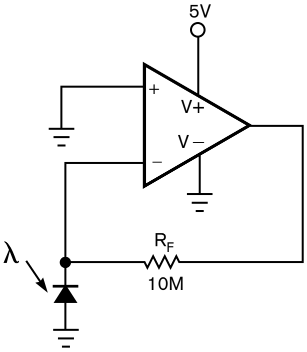

Figure 7 Among the key elements in a high-speed transimpedance amplifier for use with a photodiode are capacitances at the inverting input (including diode, amplifier-input, and parasitic capacitance).

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