Proper Design Techniques Solve High-Speed Op-Amp Stability Problems

Successful high-speed circuit designs need the right combination of grounding, power-supply bypassing, and decoupling.

Richard Gawel
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Modern op amps have much higher operating bandwidths than their predecessors. These new devices are excellent building blocks that can greatly simplify the design and construction of high-bandwidth video and RF systems. However, these high-bandwidth, fast-settling op amps can easily become unstable if designers don't observe some special precautions. So, designers must understand common instability issues and how to avoid them.

Effective grounding, bypassing, and decoupling are all essential to preserving high-frequency circuit stability. All three have closely related applications. "Grounding" effectively creates a common signal "sink" by providing a low-inductance signal-return path. Also, using a "ground plane" can help isolate the different sections of an RF circuit from each other. Sometimes an entire side of a pc board will be metal to provide a ground plane for the best conduction of RF signals. Or, it may be a series of thick traces that run around different portions of the pc board, providing a common low-impedance ground reference.

Power-supply bypassing transfers most of the RF energy present on the power-supply lines to ground. This minimizes signal transfers between amplifier stages via the common power-supply line. Finally, power-supply decoupling, normally an RC low-pass filter in the power-supply line, is even more effective in preventing RF energy from flowing between amplifier stages that share a common supply line.

Grounding basics: "Ground" or "earth ground" is a common engineering term that has been used for over a hundred years. Yet the generality of this term and its widespread use has led to much confusion.

The IEEE Dictionary defines an earth ground as: "A conducting connection, whether intentional or accidental, by which an electrical circuit or equipment is connected to the Earth, or to some conducting body of relatively large extent that serves in place of the Earth."

Generally, the purpose of "grounding" a piece of equipment, or an individual component, is to provide a low-impedance return path to the power supply. There are many good reasons to do this, including hum and noise reduction, preserving circuit stability (by preventing high-level signals from feeding back into low-level circuitry), and avoiding multiple dc return paths that can lead to offset errors.

Problems arise when designers fail to pay attention to some important details that may, at first, seem trivial. A very typical problem occurs when the same grounding point is used for both high- and low-level signals. An extreme example of this is where a low-level signal component is tied to the same grounding point as a power-supply filter capacitor. The high currents flowing in the capacitor modulate the low-level signal and introduce power-supply hum into the signal path. Similar problems occur when high- and low-level signals share a common ground-return line, especially a thin (high-Z) run on a pc board. The high-level signal mixes with and modulates the weaker signal, often causing crosstalk or oscillation.

Another common problem occurs when high-level digital circuitry shares a common ground-return line with analog circuitry. The digital signal, with its large switching currents, modulates the analog signal and introduces digital noise and interference.

With any high-frequency circuit, it's always good practice to keep all connections as short as possible, and to directly ground all components to the pc-board ground using separate, very short ground wires, or a common ground plane. Avoid daisy-chain grounds, where a ground wire connects to one component and then directly off to another, then another, forming a "chain" of grounds. Because these components are all grounded at different points along the wire, each component's "grounding point" will be at a slightly different potential. This can introduce some very strange effects, including "motor boating" (low-frequency audio oscillations) and other forms of instability. It can also cause dc circuit errors. Even though these may only be a few millivolts, if they occur at the input of a high-gain amplifier, they can add up to a large dc error at the output.

Power-supply bypassing: Adequate power-supply bypassing can also be critical when optimizing the performance of a high-frequency circuit. Although the modern op amp has excellent power-supply rejection in the audio range, this drops off rapidly at video and RF frequencies. Driving high-frequency signal currents, or transient switching currents, into low-impedance loads often creates very high signal levels on the power-supply line.

Usually, an op amp's power-supply bypassing consists of one or more capacitors connected between each power-supply pin and ground. This ensures a low-impedance ac path to ground over a wide frequency range-typically much wider than the amplifier's 3-dB bandwidth.

The usual arrangement for a pc board is to have a relatively large bypass capacitor for each supply line at a point close to where dc power enters the board. Practical values between 1 and 100 µF may be used. As a rule, larger capacitors are needed in circuits that must deliver large transient currents into the load. In these applications, the power-supply bypass capacitor stores the necessary transient energy, which otherwise wouldn't be available directly from the supply itself due to lead inductance.

If the pc board holds several op amps, relatively small (0.1-µF) local-bypass capacitors can be used at each op amp's power-supply pins. A much larger capacitor, located where the supply line enters the pc board, can serve as a common bypass for each supply. The effectiveness of a common bypass depends on several factors, including the length and width of the wire runs between this bypass and each op amp, the value of the bypass, and most importantly, the transient current required to drive the load. In many cases, the power supply will have a very low output impedance, and the pc wire runs will be very short. Therefore, the power supply itself will be able to provide the transient energy needed to drive the load. If so, only a small local bypass is needed at each op amp-just enough to supply short-duration energy to the op amp.

It's possible to make a rough estimate of the minimum capacitance required to supply a transient current into a particular load impedance. The maximum transient current needed will equal the peak signal voltage divided by the load impedance. Another issue is the amount of ripple that can be tolerated at the op amp's supply pins. Strong signal currents being driven into a load must be provided by the power supply. Less-than-ideal bypassing will introduce a signal-frequency ripple (modulation) in one or both of the op amp's supply pins.

In applications where the op amp will be driving a relatively high-impedance load, such as the input (s) of many popular ADCs, smaller, less-expensive capacitance values may often be used. This also saves space on crowded pc boards.

The table provides "cookbook" minimum values of bypass capacitance to keep the ripple on the op amp's power-supply pins at 25% or less. Fortunately, many times in an actual circuit, the power supply itself greatly reduces the ripple level. For the purposes of this article, use of this table is sufficient-rather than a detailed equation.

RECOMMENDED MINIMUM BYPASS CAPACITANCE VERSUS SIGNAL FREQUENCY*

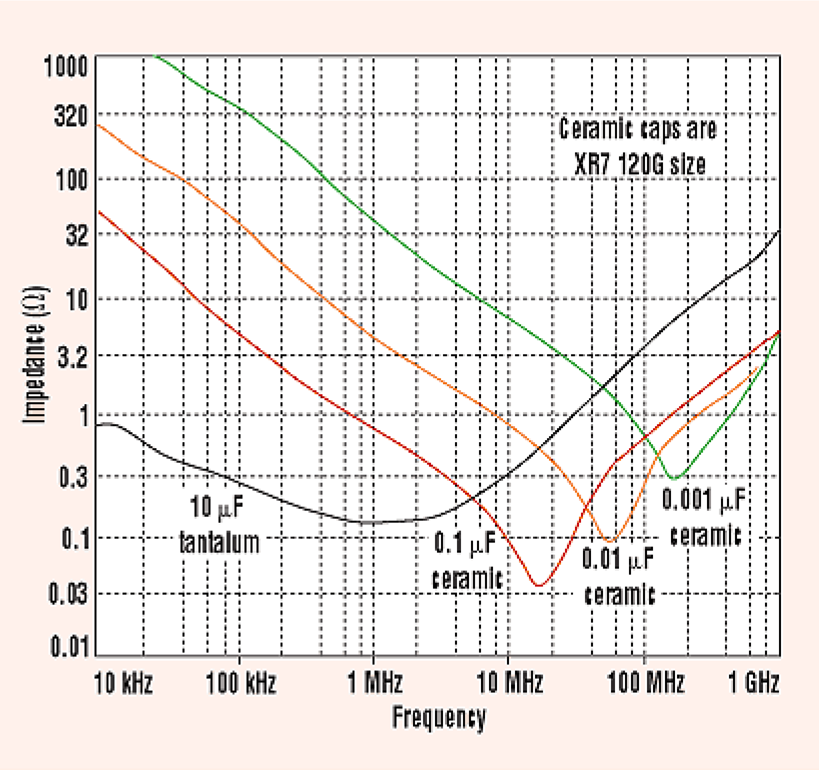
Frequency	Capacitance
10 kHz	0.1 µF
100 kHz	0.01 µF
1 MHz	0.001 µF
10 MHz	100 pF

*For 25% power-supply ripple while driving a 2-k Ω load

Although there may be power-supply bypassing somewhere on a pc board, it's essential that additional bypassing be provided right at the op amp's power-supply pins. A bypass capacitor located even 2 in. away from the op amp might be ineffective, as it's isolated from the op amp by the inductance of the amplifier's power-supply lines. In fact, a 2-in. pc-board trace has approximately 50 nH of inductance at 100 Mhz, which equals about 30Ω.

Aside from the issue of inductance, even fairly short line lengths in the supply or signal paths can be long enough to amount to a significant portion of a wavelength at UHF frequencies. These lines can act as antennas, radiating the signal into other portions of the pc board, causing instability and crosstalk. For example, at 1 GHz, a 2.8-in. (71-mm) pc trace is very close to one-quarter wavelength, and it can radiate very effectively into other circuitry on the pc board. Therefore, it's always good practice to keep all line lengths on a high-speed pc board as short as possible.

Every "real world" capacitor also contains inductance and resistance. Figure 1 graphs the impedance versus frequency curves of four common surface-mount (chip) bypass capacitors. Note that an ideal capacitor will have a decreasing impedance as frequency increases with a slope of -6 dB/octave, equal to -20 dB (-10X)/decade. Yet in the real world, this continues until the capacitor's resonant frequency is reached.



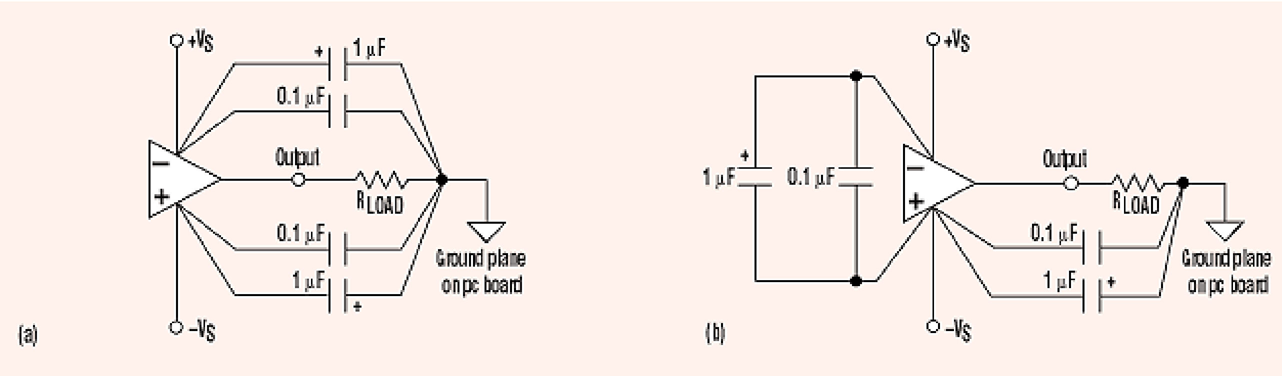
1. A capacitor's impedance decreases with frequency until its self-resonant frequency is reached. Above resonance, the impedance becomes inductive and increases with frequency.

At frequencies below a capacitor's point of resonance, its impedance is capacitive, and it functions as a real capacitor. At resonance, though, the capacitor's inductive and capacitive reactances are equal, and the capacitor's impedance is purely resistive. The value of this resistance is the capacitor's equivalent series resistance (ESR). An ideal capacitor would have a resistance of 0 Ω at resonance. But this is never achieved with real components. Above the resonant frequency, the capacitor's impedance becomes inductive.

Because of these potential problems, most high-speed circuits built today use surface-mount chip capacitors, which are small, essentially leadless, and have very low internal inductance. The resonant frequency of these devices is typically much higher than that of through-hole capacitors. Therefore, their useful frequency range is much higher. In addition, multilayer pc boards are commonly used. These frequently employ four or more layers: a ground plane, two or more signal planes, and one or two power planes. The lines in each power plane are made wide enough to reduce supply-line series inductance to extremely low values. Running the positive supply line directly over the negative supply line further reduces inductance. It's still advisable to keep the lines of the op amp's feedback loop as short as possible.

Occasionally, power-supply bypassing can actually contribute to instability in high-frequency op-amp circuits. When using a single bypass capacitor, the power-supply line inductance, together with the bypass capacitor's capacitance, form a resonance. The inductance and capacitance of the bypass capacitor itself create a second resonance.

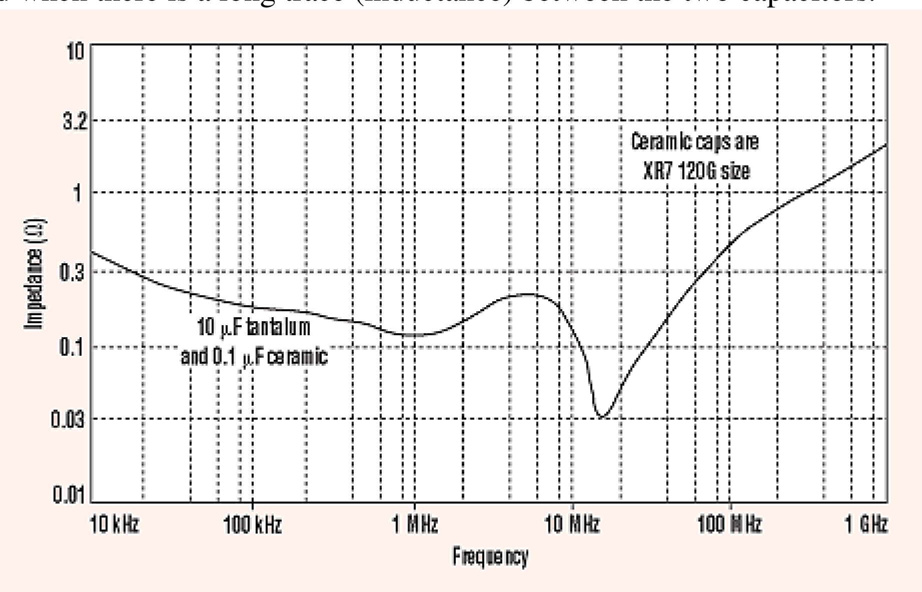
In high-speed op-amp circuits, a parallel combination of two chip capacitors is recommended (Fig. 2a). A 1-µF tantalum and a 0.1-µF ceramic capacitor are typical. Multiple bypass capacitors can provide a low ac impedance between the supplies and ground, over a much wider frequency range than with a single capacitor.



2. Bypassing in fast op-amp circuits is typically accomplished by a parallel combination of two chip capacitors (a). Some applications may benefit from connecting one of the capacitor pairs between the supply pins (b). This improves the op amp's high-frequency power-supply rejection ratio.

A second method of power-supply bypassing connects one of the capacitor pairs between the supply pins, rather than having each supply bypassed to ground (Fig. 2b). This method helps to compensate for any lack of high-frequency power-supply rejection ratio (PSRR) in the op amp, while providing only half as much bypass capacitance on the positive supply rail. Both methods have their advantages. When in doubt, it's always safer to bypass both supplies.

When two or more bypass capacitors are used, several points of resonance may occur instead of just one. In theory, if two capacitors are used in parallel, at some frequency, one may be capacitive while the other is inductive, thus forming an LC resonance. Fortunately, the Q of most electrolytic, tantalum, and ceramic capacitors is low enough that these resonances are well damped, so those that occur are minor and don't usually affect system performance. Figure 3 shows a measured curve of impedance versus frequency for two parallel connected capacitors. In this parallel capacitance arrangement, only one significant resonance point remains, at 15 MHz. This potential problem can be exacerbated when there is a long trace (inductance) between the two capacitors.



3. Two chip capacitors connected in parallel produce the impedance versus frequency curve shown here. A 10-mF tantalum and a 0.1-mF ceramic capacitor were used.

In many applications, it's vitally important that all power-supply bypass capacitors, and any external compensation capacitors, be grounded at a common point on the ground plane, centrally located close to the IC. This provides a "star ground" connection, which keeps the inductance of each capacitor's ground line closely matched to that of the others. With chip capacitors, a true "star" connection isn't always possible. But a "quasi star" may be created by having all of the amplifier's chip caps share a pad, which is connected to the ground plane at a single point.

Modern ADSL op amps, such as the AD8016 and AD8017, that must often deliver high transient currents into the load need fairly large electrolytic or tantalum bypass capacitors. These should be in the 4.7- to 22-µF range, connected in parallel with a smaller capacitor, such as 0.1 µF. The longer RC decoupling time constant achieved by using the larger capacitors will provide faster settling time and lower distortion in high-speed switching applications. Some brands of electrolytic capacitors require a small series resistor. This resistor dampens any resonance effects caused by the power-supply line inductance and the bypass capacitance by lowering the Q of the bypass capacitor.

As mentioned earlier, high-frequency op-amp pc boards should use a metal ground plane on at least one side-with all grounds being returned to the ground plane. Basically, a ground plane provides a common, very low-impedance connection through which all ground currents can flow.

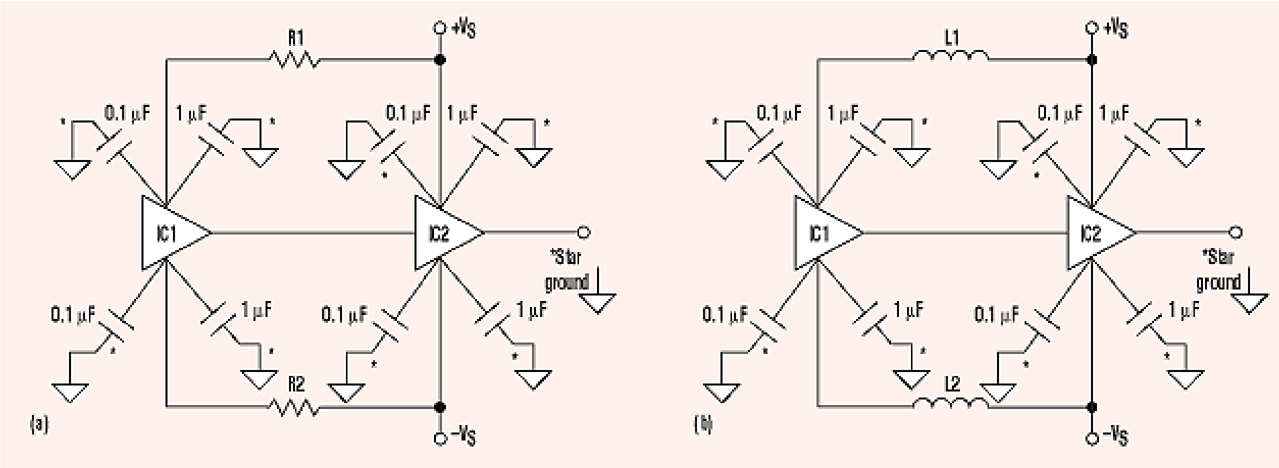
Sometimes, though, using a pc board with a ground plane isn't enough. High-speed op amps that are externally compensated, such as the AD8021, or those that have a gain-bandwidth product in the gigahertz range, often need special layout considerations.

Power-supply decoupling: Issues of power-supply decoupling are similar to those of power-supply bypassing, except that the emphasis is on minimizing any signal transfer between ICs, or discrete amplifier stages, via the power-supply lines. Signal transfer between stages is very undesirable as it may lead to intermodulation distortion, crosstalk, and instability. All op amps will have some supply-current variation due to signal changes. But this is greatly minimized by the amplifier's PSRR. As the op amp's operating frequency increases, though, PSRR decreases and eventually becomes very low at RF frequencies.

Therefore, at RF signal frequencies, significant signal currents may flow in the power-supply lines unless special precautions are taken. Power-supply bypassing right at the chip is normally very effective. But sometimes, more isolation between individual ICs or stages is needed.

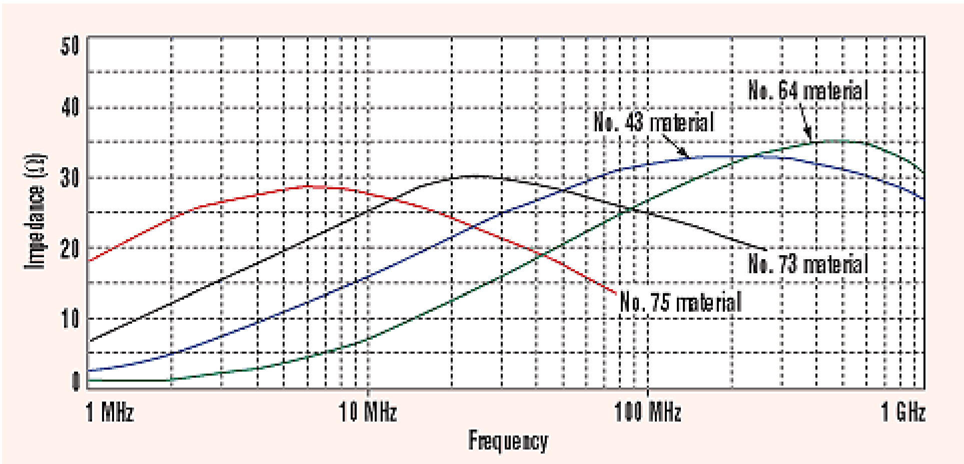
One solution is to add a small resistance in series with each IC's power-supply line(s) (Fig. 4a). This provides a simple low-pass RC filter. A typical value for this resistor is 10 Ω or less. In some applications, this simple RC filter's gradual rolloff characteristic of 6 dB/octave may not be enough to stabilize the circuit. An even more serious problem with this decoupling method is that the series resistor deregulates the IC's power supply, because the voltage at the op amp's power-supply pins varies with supply current. This, in effect, reduces the op amp's PSRR and introduces dc offset errors. If the resistor is increased to make the RC filter more effective, the voltage drop could become severe enough to shut down the op amp during large-signal periods when it must deliver high output currents.

Replacing the resistor with a small inductor of low internal resistance creates a more effective decoupling filter (Fig. 4b). Small ferrite beads are commonly used for this purpose as they're very low cost and have no significant series resistance to degrade the op amp's PSRR. Ferrite beads can be attached to a short length of bus wire and soldered into the board as a through-hole component.



4. Adding a small resistance in series with each IC's power-supply line improves decoupling (a). A more effective decoupling filter replaces the resistor with a small inductor that has low-series resistance (b). Small ferrite beads are often used for the inductor.

Figure 5 shows typical impedance versus frequency values for several common types of ferrite beads. Note that their impedance characteristics are similar to that of a low-Q inductance, and that different ferrite materials are effective over different frequency ranges. For example, the number 43 ferrite material is effective over most of the VHF/UHF range.



5. These curves show the impedance versus frequency characteristics of several common ferrite beads. The number 43 material is effective over most of the VHF and UHF range. (Reprinted with permission from the ARRL Handbook.)