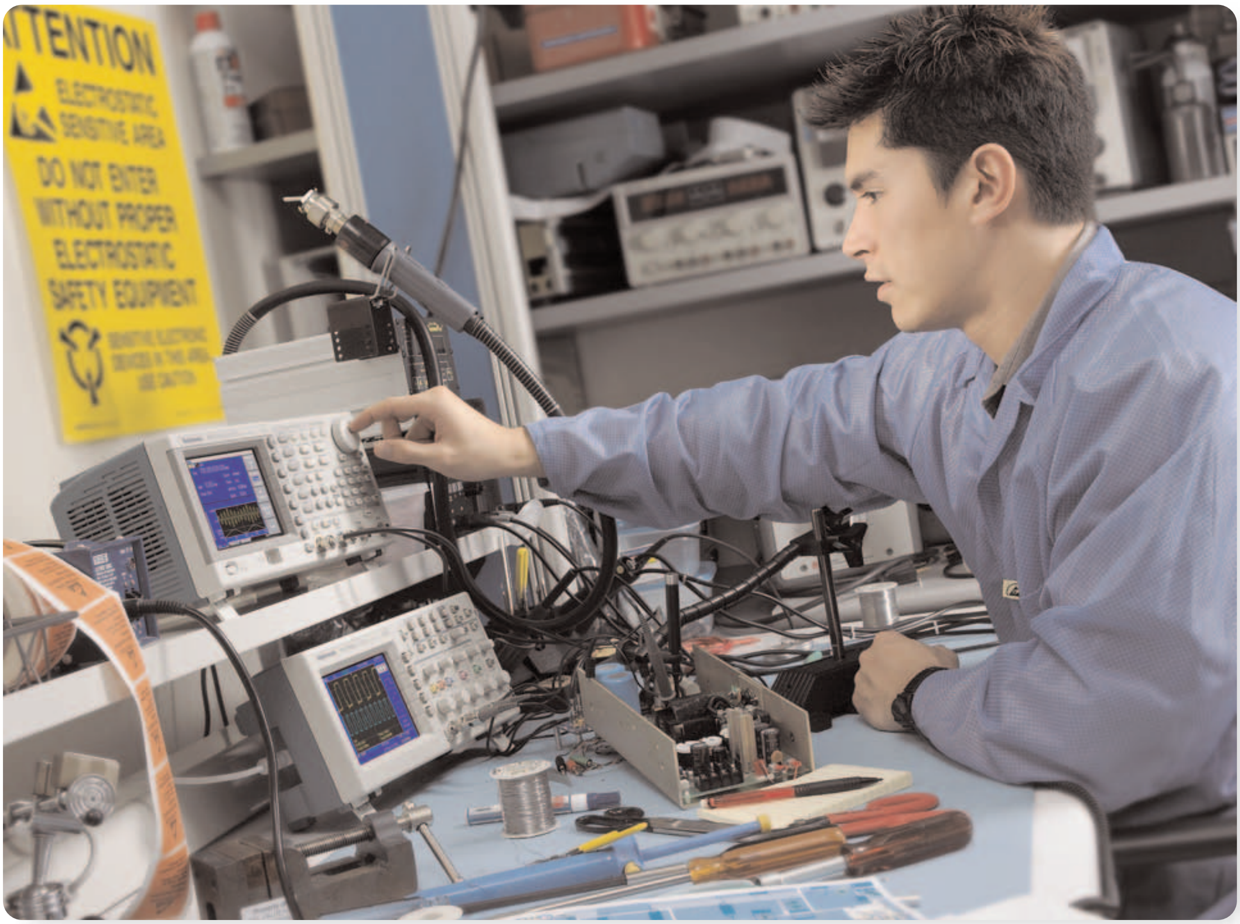
Semiconductor Characterization Counts on Flexible Stimulus Signals



Semiconductors are everywhere. They are the basic building blocks of today's communication and computing systems. They are the foundation for consumer electronic products and aerospace technologies. They support industrial systems, environmental controls, and more. In this application note we will see how a class of measurement instruments known as signal sources can help you accurately evaluate the behavior of some basic semiconductor devices. The topics herein will be of interest to designers developing new semiconductor devices, as well as engineers designing those devices into end-user products.

What Is Semiconductor Characterization?

After a series of exhaustive layout and modeling processes, the "first silicon" prototype of a new semiconductor component emerges from fabrication. Will it perform as expected? Cumulative internal tolerances and unforeseen interactions among circuit elements can still detract from the device's intended performance. Consequently the device must be tested to establish that it meets the basic design specifications. This step is called design validation or verification, and it proves that the design is functionally workable.

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A second, more comprehensive set of characterization tests determines the device's "headroom" and operating margins. Characterization is the main subject of this application note: measuring the device's actual performance limits. Once these limits are known to be satisfactory, manufacturing tolerances can be specified, yield goals set, and data sheets printed. Conversely, poor characterization results can send a device back to the design department for another turn. Characterization plays an important role in the semiconductor design process.

Characterization measurements are required for just about every type of emerging semiconductor design, from a simple analog op amp to a high-speed digital telecom switch or a CPU. A full measurement regime encompasses both analog and digital parameters. These may include maximum frequency (Fmax), threshold voltage, sensitivity, gain, slew rate, and settling time on the analog side; Setup/Hold time, tolerance for aberrations, and jitter and skew in the digital domain.

A third tier of measurements known as stress tests may be included in the characterization routine, or it may be a separate step. Stress tests subject the device to signal aberrations, timing conflicts, amplitude errors, thermal changes, and other challenging abnormal conditions. The goal is to detect problems waiting to happen, such as an input buffer that meets specifications but fails when it encounters a transient amplitude peak. If these conditions are understood in advance, solutions can be found and costly recalls prevented.

The well-known increases in complexity and operating frequency are a constant factor in semiconductor technology evolution. This is a great benefit for the end user, but a challenge for the designer or test engineer trying to characterize new components.

Most importantly, the growing complexity and speed requirements have engineers looking for measurement solutions that are well-matched to the demands of the device under test, yet cost-effective.

The balance of this document will be devoted to the use of signal sources in semiconductor measurement applications. Where appropriate, the oscilloscope's role in the tests will be summarized. For more information about oscilloscope applications, go to www.tektronix.com, select "Oscilloscopes" from the Product Portfolio menu, and click on "Find By Application" under the main headline.

The Signal Source: a Cornerstone of Characterization

What is a Signal Source and Why is it Necessary?

The term "signal source" encompasses function generators, pulse generators, RF sources, arbitrary waveform generators, and more. The signal source is commonly used in measurement applications of all kinds. Typically it provides a controlled signal with known attributes. The signal exercises newly-designed circuit elements, often acting as a surrogate for components yet to be integrated into the design. The response to the "stimulus" signal, as it is known, is a measure of the circuit's performance.

For the purposes of semiconductor characterization, a signal source must be capable of producing a variety of waveforms, both analog and digital. Consequently, function generators have become a mainstay of the characterization lab. These cost-effective instruments can select from a range of functions (waveforms based on mathematical algorithms) including sine, square, pulse, triangle, and more.

Even more flexible is the arbitrary waveform generator, known as the "arb" or AWG. This full-featured tool can replicate any imaginable waveform, or even mimic a signal acquired by an oscilloscope. Digital sampling is the underlying architecture for the AWG.

A third signal source architecture bridges the function generator and AWG platforms. This is the Arbitrary/Function Generator (AFG), whose name denotes a function generator with arbitrary waveform capabilities. The AFG delivers the essential features and versatility needed for semiconductor characterization. Less costly but also less performance than an AWG, the AFG relies on both sampling technology and Direct Digital Synthesis (DDS; see sidebar) to generate an endless variety of waveforms, transients, and intentional distortions.

Choosing a Signal Source

Every engineer understands the importance of signal source "banner" specifications like bandwidth, accuracy, amplitude resolution, and memory depth.

But "secondary" features matter, too. Does your DUT require extensive characterization of its response to pulse edge variations? If so, it would be wise to select an instrument that allows independent rise/fall time programming. Are you testing communication devices? A built-in modulator can expedite measurements requiring AM, FM, PM, FSK, or PWM. Similarly, an integrated noise generator is useful for many tests including signal-to-noise, frequency response, and more.

User interface features, too, are an essential consideration. The emerging class of AFGs offers a large, color display that summarizes all of the settings currently in effect, and even displays a graphical representation of the waveform being produced. Coupled with this highly readable display is a system of shortcut keys and high-level menus that simplifies and speeds instrument operation. Novice users can learn the instrument quickly, and seasoned test engineers will get more work done, faster.

Software waveform development tools can speed up complex tasks and assist with documentation and process control. With PC connectivity to benchtop instruments becoming the rule rather than the exception, a robust waveform creation software package is indispensable.

Application Examples

Note: in the following application examples, Tektronix AFG3000 Series instruments will provide all necessary stimulus signals. The abbreviated term "AFG" will be used to denote appropriate models in the AFG3000 Series.

Characterizing Comparator Performance

The analog comparator is an essential gateway between the analog and digital environments. When it detects an analog voltage on its "+" (non-inverting) input greater than the threshold voltage on its "-" (non-inverting) input, the comparator's output switches to a predetermined binary value. The comparator's simplicity has made it one of the most common components in today's electronic systems.

Several factors impact the comparator's effectiveness:

– Does it detect the threshold accurately and respond correctly?

– How does it react as the input voltage nears the switching threshold?

– How does it handle duty cycle variations, slow risetimes, and other signal flaws?

These are just some of the questions that characterization measurements must answer. In the following description we will utilize an AFG and an oscilloscope from the Tektronix TDS5000 Series plus two 10X oscilloscope probes.

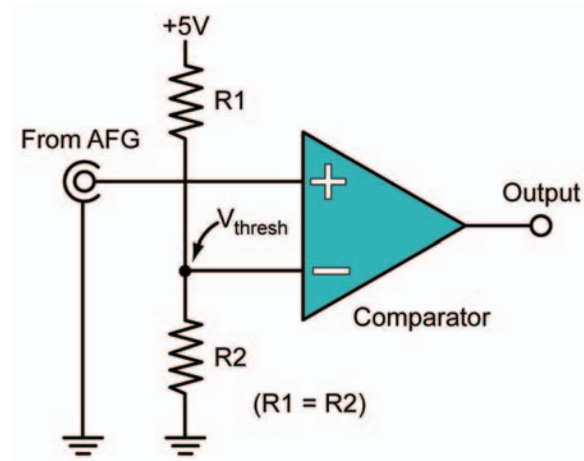
The Device Under Test

The Device Under Test (DUT) in this example is a "generic" analog comparator with relatively low bandwidth, but the tests described here are applicable to any similar device irrespective of its bandwidth. Figure 1 shows a simplified schematic of the device test fixture.

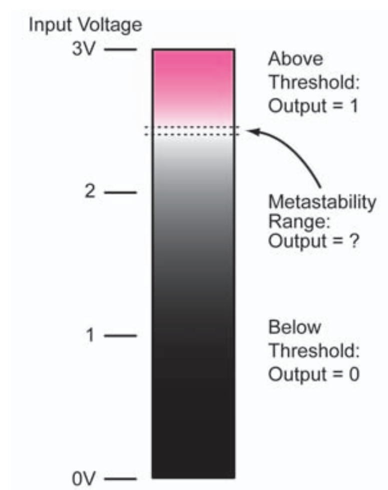
Testing for Metastability and Threshold Characteristics

The first characterization test will determine the voltage level at which the device output switches under a dynamically changing stimulus signal. The comparator's non-inverting input looks for a voltage greater than the Vthresh value set by the voltage divider made up of R1 and R2. Since the two resistors in Figure 1 have the same value and the power supply is +5V, the threshold voltage in this case will be +2.5 volts. Therefore the comparator output should switch when the input voltage exceeds that value, within some specified tolerance. It is common practice to use a variable DC power source to measure this parameter initially, but AC conditions can produce dramatically different results. Therefore it is the job of the characterization procedure to confirm the comparator's dynamic switching performance and determine tolerances.

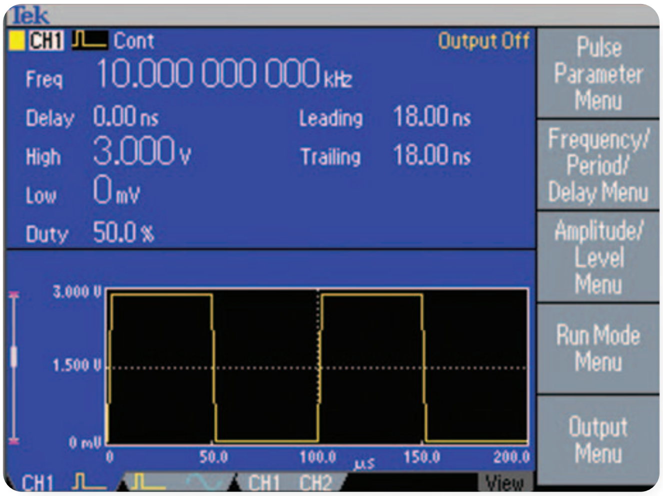
The test consists of applying a 10 kHz pulse to the comparator's non-inverting input and varying the amplitude until the output becomes metastable. Metastability denotes a condition of threshold "uncertainty" in which the output is unpredictable. The output may switch at, say, 2.48V in one cycle, yet it fails to switch at the same level during the next cycle. The object is to develop a guardband specification that helps designers stay well clear of the metastability range. Figure 2 shows how metastability relates to a tiny slice of the input voltage range.



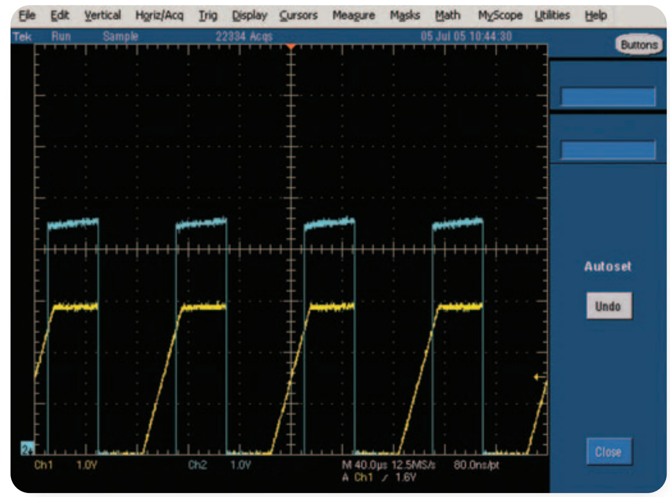
▶ **Figure 1.** *The comparator test fixture.*



▶ **Figure 2.** *The metastable range is a narrow band of voltages at which the comparator's output may be unpredictable.*



▶ **Figure 3.** *Setting up the AFG for the comparator threshold accuracy measurement.*



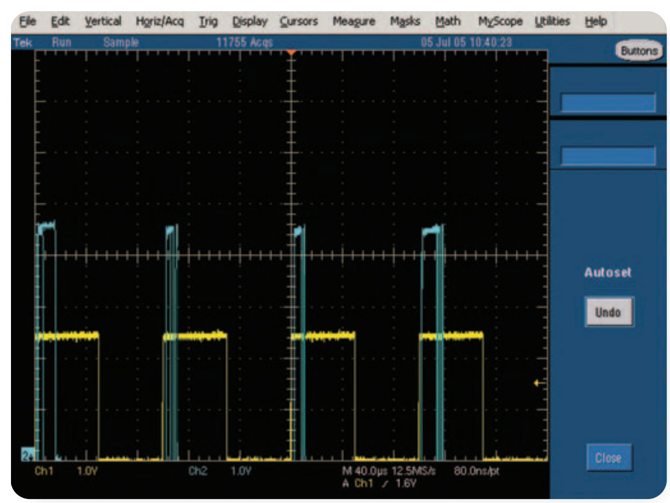
▶ **Figure 4a.** *The blue output trace confirms that the comparator is switching in step with the input (yellow trace), as expected.*

Figure 3 is a screen showing the waveform setup for the threshold accuracy characterization.

The signal source is a Tektronix AFG3000 Series arbitrary/function generator. The instrument's large color screen simplifies the setup procedure by displaying all of the relevant numerical settings as well as a representation of the waveform and its amplitude levels. The frequency of the pulse cycle is 10 kHz. When each positive-going pulse edge crosses the 2.5 V threshold, the comparator will switch to a logic "1," while the negative-going edges should cause the output to switch to a logic "0" at the same threshold voltage.

Figure 4a verifies this basic functionality. Here, two channels of the oscilloscope are monitoring the comparator's input and output, respectively. The input trace is yellow, while the output trace is blue. The comparator's output is in step with its input signal.

To determine the metastability point, simply reduce the amplitude of the input signal until the comparator output begins to switch erratically, as in Figure 4b.



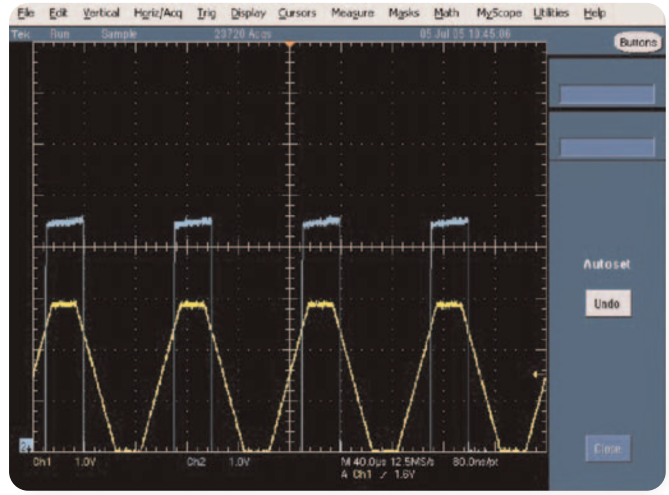
▶ **Figure 4b.** *The amplitude of the input (yellow trace) has been reduced to determine the point at which the output begins to switch erratically.*

Duty Cycle Variations

The duty cycle of the incoming signal is often a factor in the comparator's metastability behavior in the area of the threshold. This phenomenon is easy to characterize using the AFG's "Duty/Width" function. Once the basic threshold level is confirmed using the preceding steps, set the threshold to that level and reduce the duty cycle until the metastability condition reappears. Problems may not set in until the duty cycle approaches 99%. At that point, increase the input voltage until the output stabilizes, and measure that voltage with the oscilloscope. This is the true threshold value.

Edge Transition Time Variations

Adjusting the slope (rise and fall time) of the input signal provides further insight into the comparator's threshold behavior. The AFG's pulse mode permits independent setting of the rise and fall times. Set the duty cycle back to 50% and increase the edge transition times to 25 microseconds. Note the effect on the pulse width at the output of the comparator: it becomes much narrower than that of Figure 5.



▶ **Figure 5.** *Increasing the input transition time causes changes in the comparator output.*

Characterizing Amplifier or Filter Performance

Every new semiconductor amplifier and filter design has bandpass characteristics that must be measured to ensure the product's compliance with design goals. Most amplifiers are designed to deliver a linear response over a range of frequencies appropriate to their application (whether that application is subsonic or RF). Similarly, filters are designed to admit predetermined bands of frequencies and reduce or reject all others.

Both types of components tend to have a linear frequency range that is relatively "flat" as seen on a frequency vs. amplitude plot. At either end of this range, there is a steadily decreasing amplitude response. The points at which the amplifier or filter's response is -3 dB down from the peak-to-peak amplitude defines the bandwidth boundaries. Most designers use a "swept" sine wave signal as the stimulus when determining the frequency boundaries. When viewed on an oscilloscope, the amplifier or filter output signal envelope will exhibit the highest output when the input signal sweeps through the component's passband, and will taper off at all other frequencies.

In this application example we will examine a filter and measure the upper frequency at which its output amplitude is 70.71% of the peak-to-peak value. The procedure is equally applicable to amplifier measurements. The tools required are once again an AFG and an oscilloscope with probes. Since there is no need to monitor the input signal to the DUT, only one oscilloscope channel will be used.

Sweeping Through The Frequency Band

Pressing the AFG's sweep mode button brings up a screen with all the essential waveform settings in view, including a representation of the waveform itself. Figure 6 depicts this screen. As before, the parameters are set with a combination of soft keys, front-panel numeric entries, and the scrolling wheel.

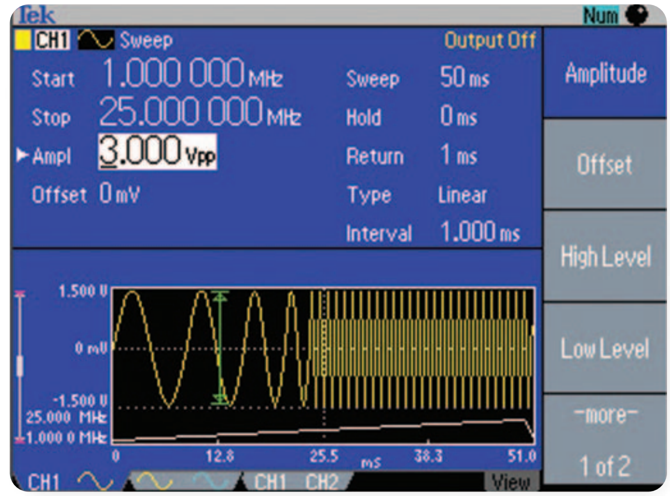
Take a close look at the waveform frame near the bottom of the screen. It summarizes all of the salient details about the generated signal: amplitude; the frequency endpoints; the slope of the "ramp" that steadily increases the frequency; and the total length (time) of the sweep. Note the return time (1 ms) at the end of the sweep; this is the point at which the signal resets to its start frequency and begins a new sweep.

Feeding the signal through the DUT yields the result shown in Figure 7. Here the oscilloscope trigger point is positioned exactly at the left edge of the graticule and the horizontal range is set to display one entire sweep. As the waveform reveals, the filter rejects the very lowest frequencies in the sweep range but its response rises rapidly as the sweep proceeds. A broad range of flat response follows, and then decays as the sweep frequency increases beyond a certain point. This region of decaying response is the area of interest, since at some point on the downward trend it crosses the -3 dB point.

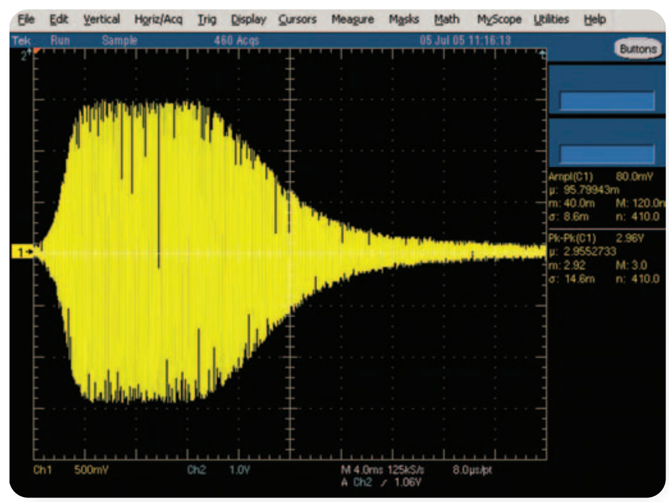
Homing In On The -3 dB Point

The signal source, working with some of the oscilloscope's automated measurement features, will help us find the -3 dB point:

– The first step in making the measurement is to ensure that the maximum peak-to-peak input voltage is precisely known. Most modern oscilloscopes have an automatic P-P measurement mode for waveforms displayed on the screen. Using this mode, adjust the AFG's signal amplitude until the amplitude measured at the filter output exactly matches the desired value; in this case it is 3.00 volts peak-to-peak.



▶ **Figure 6.** *Setting up for the filter/amplifier characterization. Note the frequency "sweep" in the waveform window.*



▶ **Figure 7.** *The frequency sweep causes the output signal amplitude of the device under test to change, revealing a characteristic frequency response envelope.*

– The -3 dB point of a 3 Vp-p sine signal is equivalent to 70.71% or 2.12 volts.

– Increase the start frequency of the AFG sweep until the measured amplitude is 2.12 volts. The resulting displayed frequency represents the -3 dB point.

These three simple steps produce one of the most important characterization results for any analog amplifier or filter. With this basic parameter defined, further details about the DUT's frequency response can be observed. Using the AFG's continuous mode (in which it outputs a single-frequency waveform), you can set the base frequency at the known -3 dB point and manually vary the frequency in very small increments while observing the effect on the oscilloscope (it will be necessary to speed up the oscilloscope's timebase setting to view just one or two cycles of the DUT output waveform).

In this example, the AFG's user interface and architectural advantages play a key role in getting the job done efficiently. The sweep setup procedure makes it easy to define the needed stimulus signal, The display confirms the waveform characteristics at a glance, while the numerical parameters on the same screen yield quick, precise answers about amplitude, frequency, and more. And the scrolling knob speeds up the search for the -3 dB frequency.

Characterizing the Slew Rate Performance of an Operational Amplifier

High-speed operational amplifiers (op amps) are among the most common analog components in use today. They can be found in television sets, set-top boxes, video broadcast equipment, wireless communications base stations, fiber-optic products, global positioning systems, radar systems, satellite receivers, point-of-sales terminals, card readers, bar code scanners, and many other areas.

The right op amp for a given application is selected based on bandwidth, noise and distortion characteristics, power consumption, gain variability, output power, settling time and slew rate performance. In order to determine these parameters, semiconductor manufacturers must thoroughly measure and characterize their devices.

Timing characteristics are critical in many applications, and slew rate plays a key role in an op amp's timing behavior. Op amps used in set-top boxes and security video applications need a high slew rate combined with ultra-low distortion. Slew rate and transient response are also an issue for op amps that drive piezo electric devices, and for those that drive extremely fine movement in applications such as commercial ink jet printers, ultrasonic cleaners, and other industrial and medical devices.

Settling time is relevant in data acquisition circuits when signals are changing rapidly. This occurs, for example, when a multiplexer switches channels. If the op amp is used as buffer between a multiplexer and an analog to digital converter, the op amp output must settle quickly before the A/D converter can sample the signal.

The op amp's transient response or slew rate performance is affected by a number of factors. These include op amp's own configuration, circuit board parasitics, and both internal current limitations and node capacitance. Slew rate performance may also depend on the supply voltage, because higher voltage means more current to charge internal capacitances.

In some cases, the op amp's transient response is different for the rising and falling edges of the input signal. The time required to charge internal capacitances may be different for the two edges. This is known as asymmetrical slew rate performance. This characteristic sometimes affects whether the op amp is used in an inverting or non-inverting configuration.

To optimize the circuit in which the op amp is used, you must thoroughly understand the component's slew rate performance. Knowing the physical boundaries, saturation points, overshoot, and settling time characteristics makes it possible to optimize gain and feedback resistors, slow down the input signal slew rate, or take other measures to achieve the desired circuit behavior.

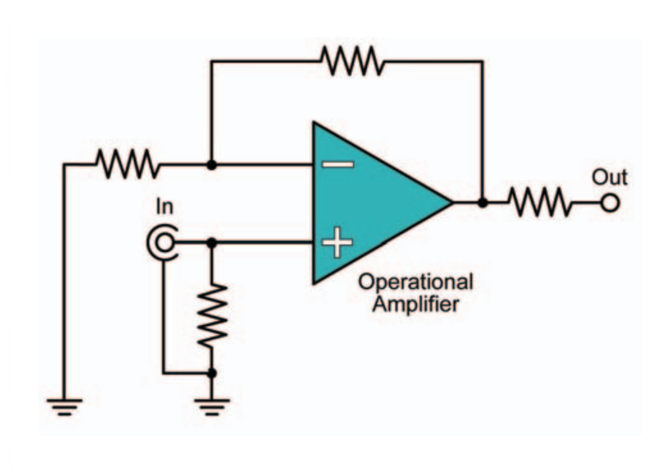
To characterize an op amp's slew rate performance, it is necessary to measure the transient response output with an oscilloscope while stimulating the input with a pulse signal having variable rise time, variable fall time, and variable amplitude. The signal source being used must provide full and independent control over all these parameters. The Tektronix AFG3000 Series signal sources deliver this flexibility, along with ample bandwidth and precision to ensure accurate results.

Stimulating and Characterizing an Op Amp

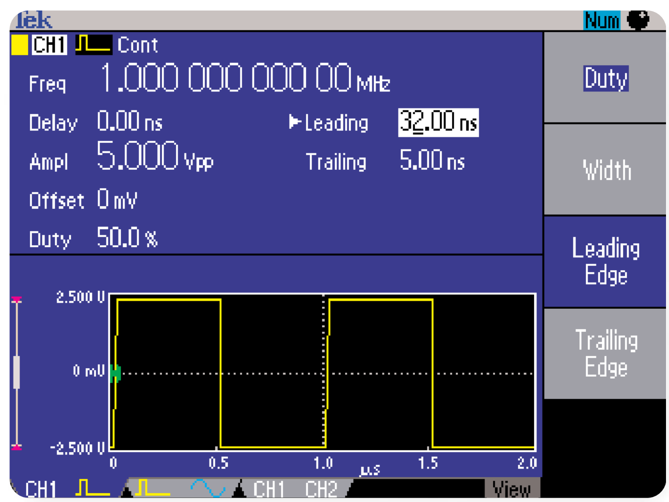
The following procedure explains the process of measuring op amp slew rate characteristics. Figure 8 shows a simplified schematic of the op amp under evaluation. It is a 220 MHz high-speed op amp intended for video line driver applications.

Pulse Signal Drives the Op Amp

The AFG drives the op amp's non-inverting input (symbolized schematically with a "+" character) with a pulse wave. An oscilloscope connected to the op amp output measures the transient response. When you select the pulse function on the AFG, its display shows the signal

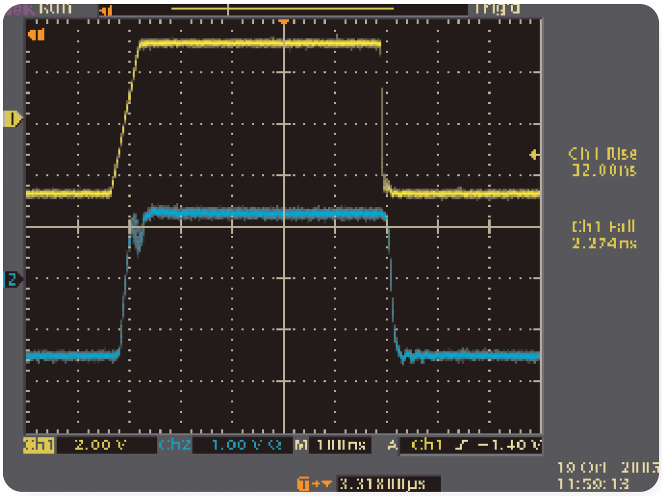


▶ **Figure 8.** *Operational amplifier (op amp) slew rate characterization fixture.*

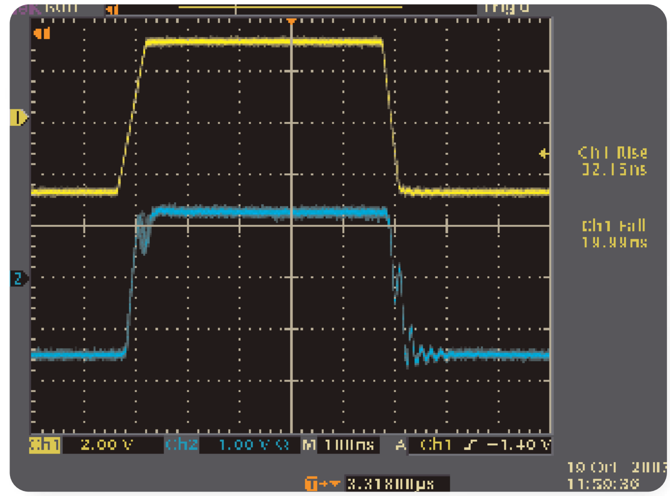


▶ **Figure 9.** *Setting up the AFG for a slew rate measurement.*

frequency, amplitude, and pulse duty cycle as well as leading and trailing edge times, as shown in Figure 9. A graphical depiction of the pulse waveform on the screen confirms the settings you have chosen.



▶ **Figure 10.** *When the risetime of the input signal (yellow) is increased, the op amp output's rising edge begins to oscillate.*



▶ **Figure 11.** *Increasing the fall time. The trailing edge of the output begins to oscillate at some point.*

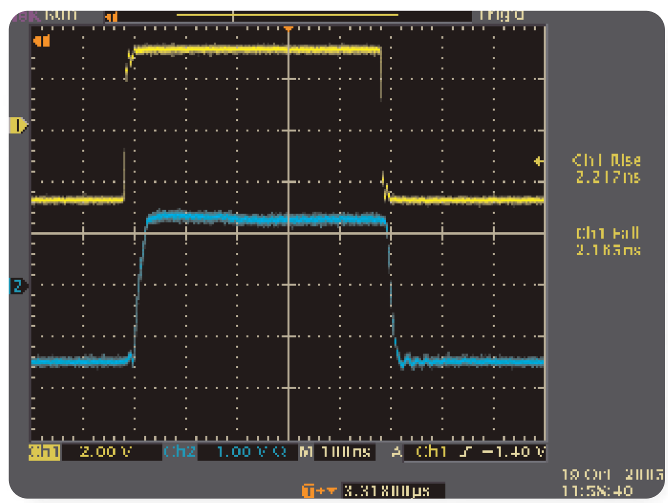
To characterize the op amp's slew rate performance, vary the leading and trailing edge time while observing the op amp's output signal on the oscilloscope screen (Figure 10). The AFG3000 allows both edges to be manipulated independently. In Figure 10 the input signal to the op amp is shown in yellow and the output trace is blue.

Start by holding the trailing (falling) edge constant at 2.5 ns. As the transition time of the leading (rising) edge is gradually increased, the output starts to oscillate when the risetime reaches 32 ns.

While maintaining the leading edge's 32 ns risetime, slowly increase the fall time of the trailing edge. As Figure 11 reveals, the op amp output starts to oscillate when the falling transition time reaches approximately 20 ns.

Clearly this op amp has asymmetrical characteristics. If you had simply assumed that the op amp would respond identically to both edges, you might mistakenly pass a device that would fail in its end use application due to its differing leading and trailing responses.

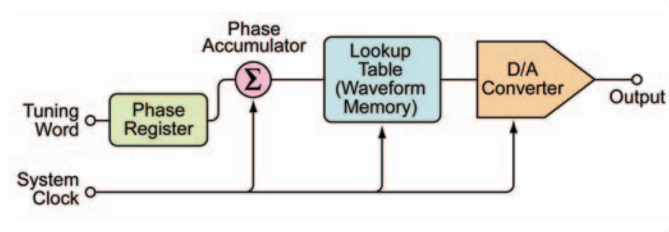
Now reduce both rise and fall times while observing the waveform. In this instance, the output gets steadily "cleaner" as the transition times get shorter. As Figure 12 demonstrates, the cleanest transient response is achieved when leading and trailing edge times are set to 2.5 ns. This is the shortest risetime the AFG3000 can produce.



▶ **Figure 12.** *Leading and trailing edges are both set to 2.5 ns transition time, achieving a stable, clean output.*

The conclusion of this characterization measurement is that the input signal on this op amp must have a risetime below 32 ns, and a fall time of less than 20 ns. If the intended system input to the op amp exceeds these values, then a different component must be selected for the job. Chances are, there is an op amp that is perfectly matched to the needs of your signal environment.

This example illustrates the importance of understanding an op amp's disparate slew rate behavior when dealing with leading and trailing edges. This in turn demonstrates the value of a signal source that is capable of varying its edge times independently.



▶ **Figure SB.** *Simplified block diagram of a DDS-based signal generation scheme.*

A Closer Look At Direct Digital Synthesis

Direct digital synthesis (DDS) is the enabling technology behind the latest generation of cost-effective high-performance signal source platforms. DDS is a true digital methodology designed to produce analog waveforms. It is "agile," with very fast switching from one output frequency to another and it delivers excellent frequency resolution at a cost lower than that of conventional arbitrary waveform generators.

A DDS device is architecturally simple, consisting of a phase accumulator, a lookup table (memory), and a digital-to-analog converter (DAC) plus some ancillary functions. Figure SB is a simplified block diagram of a typical DDS implementation.

The DDS output signal is formed by the incoming system clock (a fixed frequency), the binary value stored in the external frequency register, and the contents of the waveform memory.

The frequency register provides a binary number known as the "tuning word" in most industry references. The tuning word proceeds to the phase accumulator via a local buffer known as the phase register. To create a signal, the frequency register adds a constant phase increment value to the phase accumulator during each clock cycle. True to its name, this element accumulates the successive input values, with the current value acting as an index pointer to the lookup table.

The nature of the lookup table is the key to the overall capability of the instrument. A simplistic function generator will have a fixed selection of waveform types. An arbitrary/function generator (AFG) provides user-programmable memory space in addition to this, allowing custom waveforms to be stored and reproduced.

Once the appropriate sample has been read from the lookup table, The DAC converts the binary value to an analog voltage.

Although both the AWG with true arbitrary capability and the AFG based on DDS rely on a sample memory, they differ dramatically in the way they determine their output frequency. The AWG always reads linearly through the memory and simply speeds up the clock to produce higher output frequencies.

In contrast, the AFG maintains a fixed system clock frequency. The 360 degrees of a waveform cycle are spread across the full capacity of the waveform memory (up to 131,072 sample locations in some instruments). If the phase increments are large, the AFG skips ahead through the 360-degree cycle quickly, reading every nth sample and delivering a high-frequency signal. If the increments are small, the phase accumulator will take more steps and even repeat individual samples to complete the 360 degrees, producing a lower-frequency output waveform.

The DDS architecture provides a host of key performance benefits. It combines precise digitally-controlled frequency and phase tuning capabilities with unsurpassed frequency agility and phase coherency. Constant tuning resolution ensures predictable output signal characteristics over a wide range of frequencies. With these advantages, DDS-based signal generation tools are finding their way into myriad measurement applications, including semiconductor characterization.

Conclusion

The signal source is a core tool for today's semiconductor characterization process. To characterize the response of an emerging IC design, first there must be a stimulus. The signal source drives the device under test with signals that help define the boundaries of performance.

A new class of DDS-based signal sources offers higher performance, more productivity (ease of use), and better cost effectiveness than ever before. Features such as independently adjustable rise and fall times give engineers the tools to detect design flaws early in the process, when revisions are less costly. Amplitude and frequency accuracy ensure repeatable results, while an information-rich user interface makes it easy to interpret those results.

The application examples included in this document illustrate just a few of these capabilities. Today's DDS-based signal sources are the solution of choice for applications that call for uncompromised performance in an instrument suitable for the individual designer's bench.

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