By Jim Williams, Linear Technology

DERIVING A SLEW-RATE-MEASUREMENT APPROACH REQUIRES UNDERSTANDING SLEW RATE'S RELATIONSHIP TO AMPLIFIER DYNAMICS.

The taming of the slew

Slew rate defines an amplifier's maximum rate of output excursion. This specification sets limits on undistorted bandwidth, an important capability in ADC-driver applications. Slew rate also influences achievable performance in DAC-output stages, filters, video amplification, and data acquisition. You must verify an amplifier's slew rate by measurement if your application's performance depends on that parameter.

AMPLIFIER DYNAMIC RESPONSE

Amplifier-dynamic-response components include delay, slew, and ring times (**Figure 1**). The delay time is small and is almost entirely due to amplifier propagation delay. During this interval, no output movement occurs. During *slew time*, the amplifier moves at its greatest possible speed toward the final value. *Ring time* defines the region during which the amplifier recovers from slewing and ceases movement within some defined error band. *Settling time* is the total elapsed time from input application until the output arrives at and remains within a specified error band around the final value (**references 1**, **2**, and **3**).

You measure slew rate during the middle two-thirds of output movement at unity gain and express the result in volts per microsecond. By discounting the initial and final movement intervals, you ensure that amplifier-gain-bandwidth limitations during partial input overdrive do not influence the measurement.

Historically, slew-rate measurement has been relatively simple. Early amplifiers had typical slew rates of 1V/μsec, and later versions sometimes reached hundreds of volts per microsecond. Standard laboratory pulse generators easily supplied rise times well beyond amplifier speeds. As slew rates have reached 1000V/μsec, the pulse generator's finite rise time has become a concern. At least one recent device, the LT1818, has a 2500V/μsec slew rate, or 2.5V/nsec, comparable with a Schottky TTL gate's transition time. Such speed eliminates almost all pulse generators as candidates for putting the amplifier into slew-rate limiting.

PULSE-GENERATOR RISE TIME AFFECTS MEASUREMENT

Pulse-generator-rise-time limitations are a significant concern when attempting to accurately determine slew rate, as a unity gain amplifier's response to progressively faster pulse-generator rise times demonstrates (**Figure 2**). The data shows a nonlinear slew-rate increase as pulse-generator rise time decreases. The continuous slew-rate increase with decreasing generator rise time, although approaching a zero-rise-time-enforced boundary, hints that the source has not yet driven the amplifier to its slew-rate limit. Determining whether this condition is satisfied requires a faster pulse generator than one with a 1-nsec rise time.

Most general-purpose pulse generators have rise times in the region of 2.5 to 10 nsec. Instrument rise times of less than 2.5 nsec are relatively rare, and only a select few can reach 1 nsec (**Reference 2**). The ranks of generators that offer rise times of less than 1 nsec

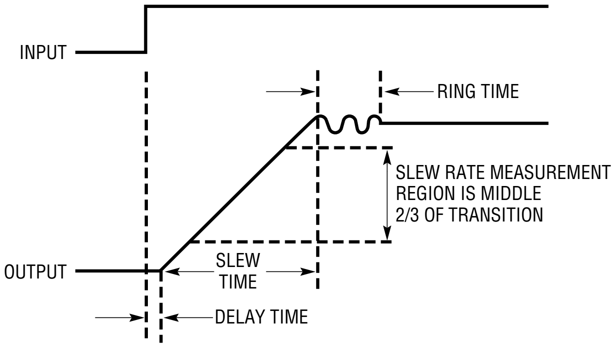


Figure 1 Amplifier-response components include delay, slew, and ring times. You typically measure slew rate during the middle two-thirds of the slew time.

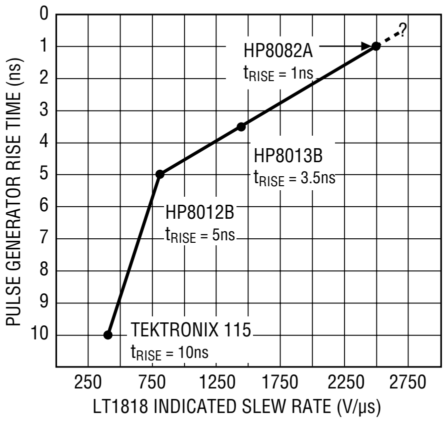


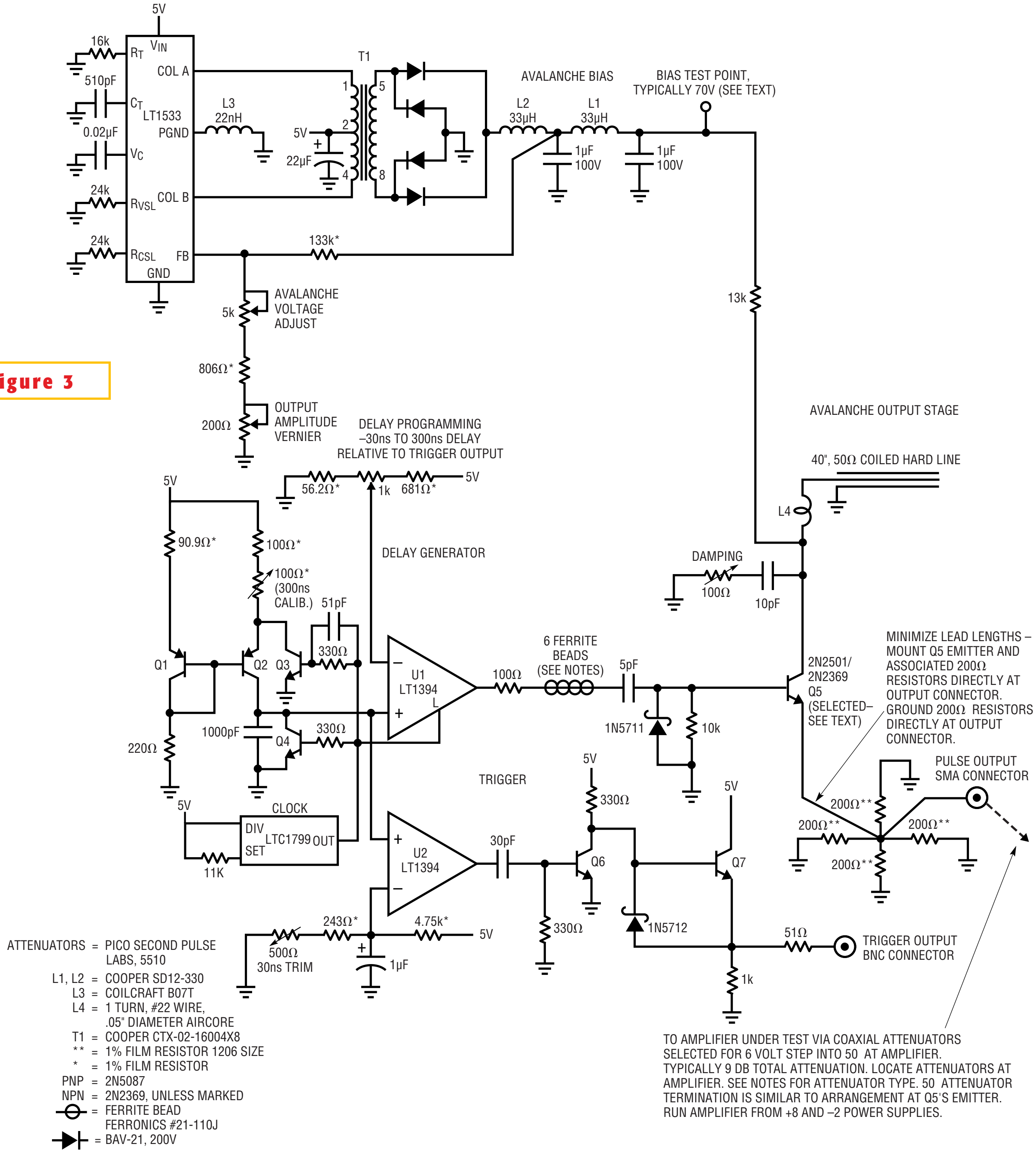
Figure 2 Summarized data for the pulse generators demonstrates that decreasing rise time promotes higher observed slew rate. Verifying slew-rate-limiting occurrence requires a pulse generator with a rise time of less than 1 nsec.

are even thinner. They employ arcane technologies and exotic construction techniques, particularly in situations that require relatively large swings of 5 to 10V (**references 4 to 16**). Available instruments in this class work well but can easily cost $10,000; prices rise toward $30,000, depending on features. For slew-rate testing in a laboratory or production environment, there is a substantially less expensive alternative.

Figure 3 shows a circuit for producing rise-time pulses of less than 1 nsec. The circuit's rise time is 360 psec, and its pulse amplitude is adjustable. You can set the output pulse to occur either before or after a trigger output. This circuit uses an avalanche pulse generator to create extremely fast rise-time pulses.

Q1 and Q2 form a current source that charges the 1000-pF capacitor. When the LTC1799 clock is high both Q3 and Q4 are on (**Trace A, Figure 4**). Under the same conditions, the current source is off and Q2's collector (**Trace B**) is at ground. U1's latch input prevents it from responding, and its output remains high. When the clock goes low, comparator U1's latch input is disabled, and its output drops low. The Q3 and Q4 collectors lift, and Q2 turns on, delivering constant current to the 1000-pF capacitor (**Trace B**). The resulting linear ramp appears on

Figure 3



A variable delay triggers a pulse generator with a rise time of less than 1 nsec. The charge line at Q5's collector determines the output width: about 10 nsec. You can set the output pulse occurrence before, during, or after the trigger output.

U1 and U2's positive inputs. U2, biased from a potential derived from the 5V supply, goes high 30 nsec after the ramp begins, providing the "trigger output" (**Trace C**) via its output network. U1 goes high when the ramp crosses the potentiometer-programmed delay at its negative input—in this case, about 170 nsec. U1's going high triggers the avalanche-based output pulse (**Trace D**). This arrangement permits the delay programming control to vary output-pulse occurrence from 30 nsec before to 300 nsec after the trigger output.

When U1 applies its output pulse to Q5's base, the NPN transistor avalanches. The result is a quickly rising pulse across Q5's emitter-termination resistor. The 10-pF collector capacitor and the charge line discharge, Q5's collector voltage falls, and breakdown ceases. The 10-pF collector capacitor and the charge line then recharge. At U1's next pulse, this action repeats. The 10-pF capacitor supplies the initial pulse response, and the charge lines prolonged discharge contributes the pulse body. The 40-in. charge line forms an output pulse width of about 12 nsec.

Avalanche operation requires high voltage bias. The low-noise LT1533 switching regulator and associated components supply this high voltage. The LT1533 is a push-pull output switching regulator with controllable transition times.

Slower switch transitions notably reduce noise in the form of output harmonic content (**Reference 4**). Resistors at the RCSL and RVSL pins control the switch current and voltage transition times, respectively. In all other respects, the circuit behaves as a classical push-pull, step-up converter.

You begin optimizing the circuit by setting the output-amplitude vernier to its maximum and grounding Q4's collector. Next, set the avalanche-voltage adjust so that free-running pulses begin to appear at Q5's emitter, noting the bias test points voltage. Readjust the avalanche-voltage 5V below this voltage, and unground Q4's collector. Set the 30-nsec trim so that the trigger output goes low 30 nsec after the clock goes low. Adjust the delay programming control to maximum and set the 300-nsec calibration so that U1 goes high 300 nsec after the clock goes low. You may have to repeat the adjustments for the 30- and 300-nsec trims until you've calibrated both points, due to a slight interaction.

Select Q5 from a population for optimal avalanche behavior. Such behavior, although characteristic of the device specified, is not guaranteed by the manufacturer. During one recent selection experiment, a sample of 30 Semelab 2N2501s spread over a 17-year date-code span produced a yield of about 90%. All "good" devices switched in less than 475 psec, and some switched in less than 300 psec. You may substitute a 2N2369, available from a number of suppliers, including Philips Semiconductors and Central Semiconductor, though their switching times are rarely less than 450 psec. In practice, you should select Q5 for an in-circuit rise time of less than 400 psec and then optimize the output-pulse shape for slew-rate testing by adjusting Q5's collector damping trim. The optimization procedure takes full advantage of the freedom that slew-rate testing does not require pulse purity.

Slew-rate testing permits overshoot and post-transition aberrations if they do not influence amplifier response in the measurement region. A simple procedure allows you to optimize the waveform (**Figure 5**). Set the damping trim for significant effect, resulting in a reasonably clean pulse but sacrificing rise time (**Figure**

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For more information on products such as those discussed in this article, contact any of the following manufacturers directly, and please let them know you read about their products in *EDN*.

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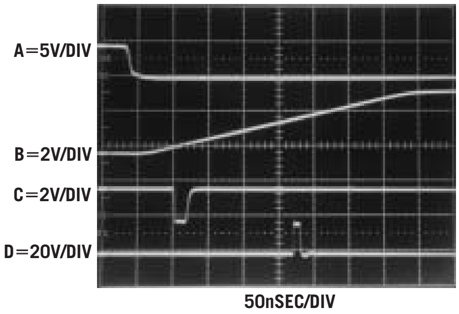

Figure 4 The pulse generator's waveforms include the clock (Trace A), Q2's collector ramp (Trace B), the trigger output (Trace C), and the pulse output (Trace D). A delay sets the output pulse to occur about 170 nsec after the trigger output.

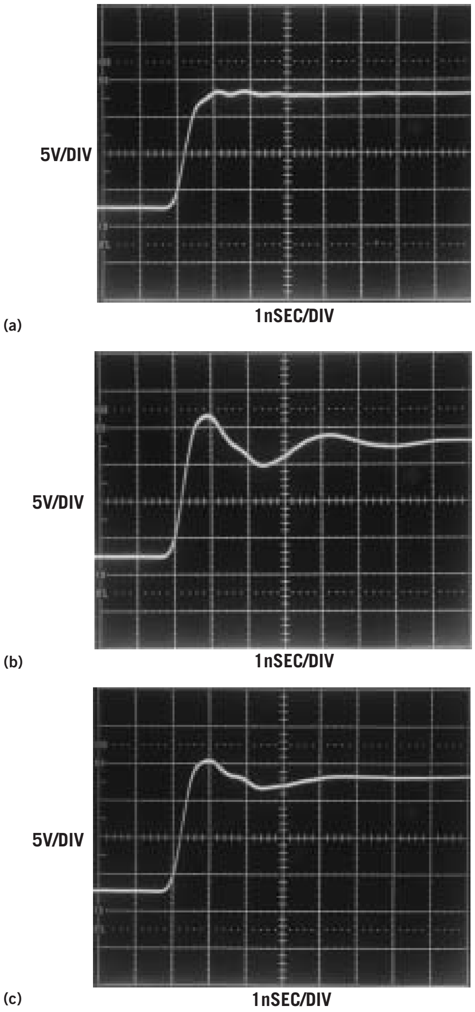

Figure 5 Excessive damping trades off the rise time and rounds the front corner but minimizes pulse-top aberrations (a). Minimal damping accentuates rise time, but pulse-top ringing is excessive (b). Optimal damping retards pulse-top ringing and preserves rise time in the slew-rate-measurement region (c).

5a). Notice the waveform with the control at the opposite extreme (**Figure 5b**). Minimal damping accentuates rise time, but pronounced post-transition ring may influence amplifier operation during slew testing. A damping point corresponding to a realistic compromise only slightly reduces the edge rate but significantly attenuates post-transition ring (**Figure 5c**). A 1-GHz- real-time-bandwidth oscilloscope (Tektronix 7104/7A29/7B15) with a 350-psec-rise-time limit produced the traces that the photographs depict. Accurately determining the rise time for the circuit in **Figure 5c** requires more bandwidth and verification of the measurement signal-path integrity, including cables, attenuators, probes, and the oscilloscope (see **sidebar** "Verifying rise-time-measurement integrity"). Subsequent photos (see the

VERIFYING RISE-TIME-MEASUREMENT INTEGRITY

Any measurement requires the experimenter to ensure measurement confidence. Some form of calibration check is always in order. High-speed time-domain measurement is particularly prone to error, and various techniques can promote measurement integrity.

A battery-powered, 200-MHz crystal oscillator produces 5-nsec markers, useful for verifying oscilloscope timebase accuracy (**Figure A**). A single 1.5V AA cell supplies the LTC3400 boost regulator, which produces 5V to run the oscillator. A peaked attenuation network delivers the oscillator output to the 50Ω load. This circuit provides well-defined 5-nsec markers and prevents overdriving low-level sampling oscilloscope inputs (**Figure B**).

Once you confirm timebase accuracy, you must check rise time. You should include the lumped signal-path rise time, including attenuators, connections, cables, oscilloscope, and anything else in the path in this measurement. Such end-to-end rise-time checking is an effective way to promote meaningful results. A guideline for ensuring accuracy is to have four-times-faster measurement- path rise time than the rise time of interest. Thus, a 360-psec rise-time measurement requires a verified 90-psec measurement-path rise time to support it. Verifying the 90-psec-measurement path rise time, in turn, necessitates a faster-than-22.5-psec rise-time test step. **Table A** lists some very fast edge generators for rise-time checking.

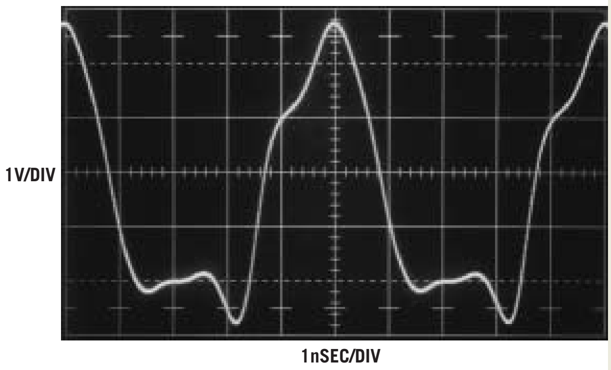

Figure B The time-mark generator output terminated into 50Ω produces a peaked waveform, which is optimal for verifying timebase calibration.

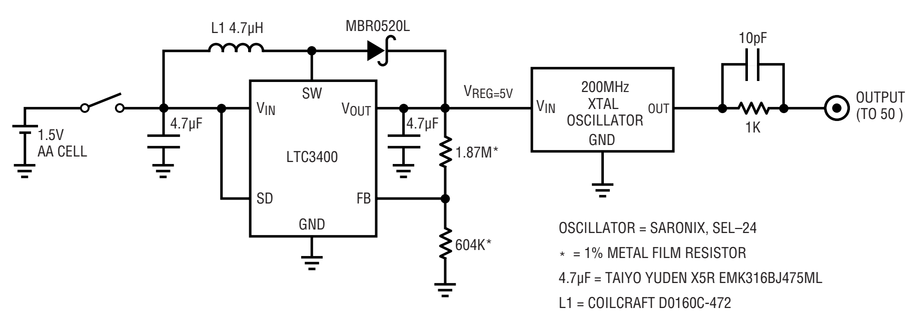

Figure A A 1.5V battery powers a 200-MHz crystal oscillator that provides 5-nsec time markers. A switching regulator converts the 1.5V source to 5V to power the oscillator.

TABLE A–FAST EDGE DETECTORS FOR RISE-TIME CHECKING

Manufacturer	Model	Rise time (psec)	Amplitude	Availability	Comments
Avtech	AVP2S	40	0V to 2V	Current production	Free-running or triggered operation, 0 to 1 MHz
Agilent	213B	100	≈175 mV	Secondary market	Free-running or triggered operation to 100 kHz
	1105A/1108A	60	≈200 mV	Secondary market	Free-running or triggered operation to 100 kHz
	1105A/1106A	20	≈200 mV	Secondary market	Free-running or triggered operation to 100 kHz
Picosecond Pulse Labs	TD1110C/TD1107C	20	≈230 mV	Current production	Similar to discontinued HP1105/1106/8A; see above
Stanford Research Systems	DG535 OPT 04A	100 psec	0.5V to 2V	Current production	Must be driven with stand-alone pulse generator
Tektronix	284	70 psec	≈200 mV	Secondary market	50-kHz repetition rate; pre-trigger 75 to 150 nsec before main output; calibrated 100-MHz and 1 GHz sine-wave auxiliary outputs
	111	500 psec	≈±10V	Secondary market	10- to 100-kHz repetition rate; positive or negative outputs; 30- to 250-nsec pretrigger output; external trigger input; pulse width set with charge Lines
	067-0513-00	30 psec	≈400 mV	Secondary market	60-nsec pretrigger output; 100-kHz repetition rate
	109	250 psec	0V to ± 55V	Secondary market	≈600-Hz repetition rate (high-pressure Hg Reed-relay based); positive or negative outputs; pulse width set by charge lines

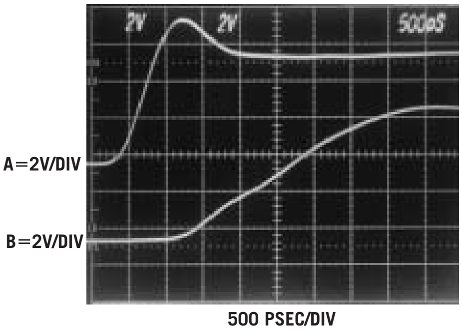

Figure 6 Trace A's 360-psec rise-time pulse completes its transition before the amplifier output (Trace B) begins moving. Trace A's rise time is actually about 150 psec faster than depicted due to the 1-GHz measurement bandwidth that limits the observed response.

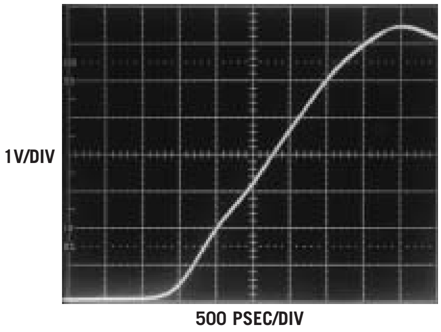

Figure 7 A close examination of the LT1818's response indicates an approximate 2800V/µsec slew rate, revealing an 11% error in the measurement with a 1-nsec rise-time pulse in Figure 2.

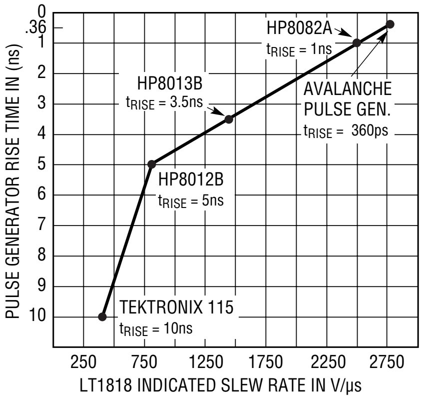

Figure 8 This restatement of the data from Figure 2 includes the avalanche pulse generator results. A further significant slew rate increase is unlikely as the required input step rise time approaches zero.

Web version of this article at www.edn.com), using a 3.9-GHz-bandwidth oscilloscope, the Tektronix 556 with 1S2 sampling plug-in capable of a 90-psec-rise-time, indicate a 360-psec output rise time. The other photo, using a 6-GHz-bandwidth oscilloscope, the Tektronix TDS 6604, which offers a 60-psec rise time, aids measurement confidence by verifying the 360-psec rise time. The 360-psec rise time is almost three times faster than the 1-nsec rise-time pulse generator, which is the fastest of those that generated the data in **Figure 2** and that promoted a 2500V/µsec slew rate. **Figure 6** puts this kind of speed into perspective. Trace A's 360-psec rise time completes its transition before Trace B's 400-MHz LT1818 amplifier begins to move. Trace A's rise time is actually faster than depicted, because the 1-GHz real-time-measurement bandwidth limits observed response. Applying this faster rise-time pulse should add useful information to **Figure 2**'s data.

REFINING SLEW-RATE MEASUREMENT

The unity gain amplifier's response to the 360-psec rise-time pulse in a 1-GHz real-time bandpass indicates a measurement-region slew rate of about 2800V/µsec (**Figure 7**). This measure reveals an 11% error in the earlier assessment (**Figure 8**). The new data suggests that, although slew-rate "hard" limiting may not be occurring, little practical improvement is possible, because rise time is approaching zero. A faster rise-time pulse generator could confirm this assessment, but any slew-rate improvement would likely be academic. Realistically, you rarely encounter the large-signal, 360-psec-rise-time input required to promote 2800V/µsec slew rate in practical circuitry.□

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You can find all the references for this article in its Web version at www.edn.com.

AUTHOR'S BIOGRAPHY

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