Application Note 122
January 2009

Diode Turn-On Time Induced Failures in Switching Regulators

Never Has so Much Trouble Been Had By so Many with so Few Terminals

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Introduction

Most circuit designers are familiar with diode dynamic characteristics such as charge storage, voltage dependent capacitance and reverse recovery time. Less commonly acknowledged and manufacturer specified is diode forward turn-on time. This parameter describes the time required for a diode to turn on and clamp at its forward voltage drop. Historically, this extremely short time, units of nanoseconds, has been so small that user and vendor alike have essentially ignored it. It is rarely discussed and almost never specified. Recently, switching regulator clock rate and transition time have become faster, making diode turn-on time a critical issue. Increased clock rates are mandated to achieve smaller magnetics size; decreased transition times somewhat aid overall efficiency but are principally needed to minimize IC heat rise. At clock speeds beyond about 1MHz, transition time losses are the primary source of die heating.

A potential difficulty due to diode turn-on time is that the resultant transitory "overshoot" voltage across the diode, even when restricted to nanoseconds, can induce overvoltage stress, causing switching regulator IC failure. As such, careful testing is required to qualify a given diode for a particular application to insure reliability. This testing, *which assumes low loss surrounding components and layout in the final application*, measures turn-on overshoot voltage due to diode parasitics only. Improper associated component selection and layout will contribute additional overstress terms.

Diode Turn-On Time Perspectives

Figure 1 shows typical step-up and step-down voltage converters. In both cases, the assumption is that the diode clamps switch pin voltage excursions to safe limits. In the step-up case, this limit is defined by the switch pins maximum allowable forward voltage. The step-down case limit is set by the switch pins maximum allowable reverse voltage.

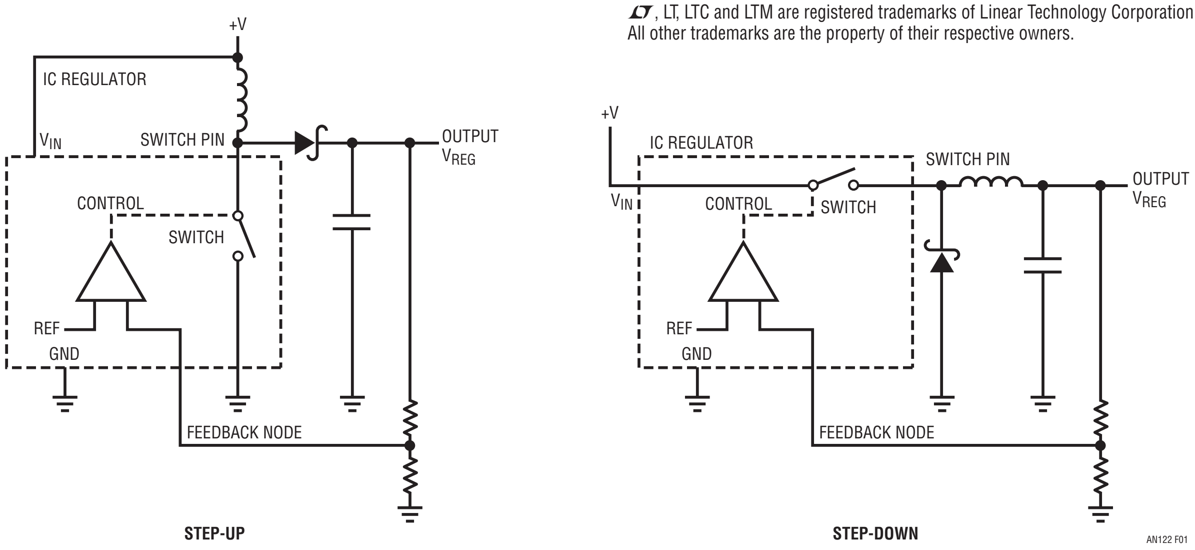

Figure 1. Typical Voltage Step-Up/Step-Down Converters. Assumption is Diode Clamps Switch Pin Voltage Excursion to Safe Limits

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Figure 2 indicates the diode requires a finite length of time to clamp at its forward voltage. This *forward turn-on time* permits transient excursions above the nominal diode clamp voltage, potentially exceeding the IC's breakdown limit. The turn-on time is typically measured in nanoseconds, making observation difficult. A further complication is that the turn-on overshoot occurs at the amplitude extreme of a pulse waveform, precluding high resolution amplitude measurement. These factors must be considered when designing a diode turn-on test method.

Figure 3 shows a conceptual method for testing diode turn-on time. Here, the test is performed at 1A although other currents could be used. A pulse steps 1A into the diode under test via the 5Ω resistor. Turn-on time voltage excursion is measured directly at the diode under test. The figure is deceptively simple in appearance. In particular, the current step must have an exceptionally fast, high-fidelity transition and faithful turn-on time determination requires substantial measurement bandwidth.

Detailed Measurement Scheme

A more detailed measurement scheme appears in Figure 4. Necessary performance parameters for various elements are called out. A sub-nanosecond rise time pulse generator, 1A, 2ns rise time amplifier and a 1GHz oscilloscope are required. These specifications represent realistic operating conditions; other currents and rise times can be selected by altering appropriate parameters.

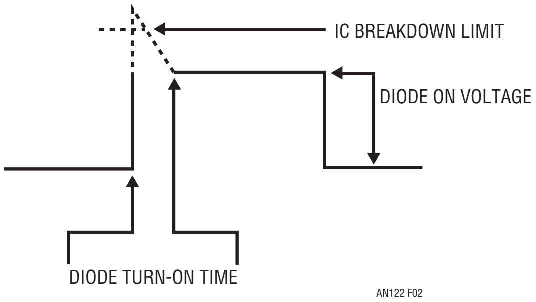


Figure 2. Diode Forward Turn-On Time Permits Transient Excursion Above Nominal Diode Clamp Voltage, Potentially Exceeding IC Breakdown Limit

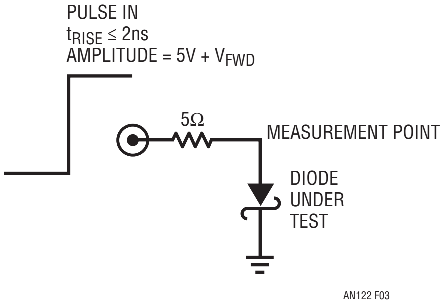


Figure 3. Conceptual Method Tests Diode Turn-On Time at 1A. Input Step Must Have Exceptionally Fast, High Fidelity Transition

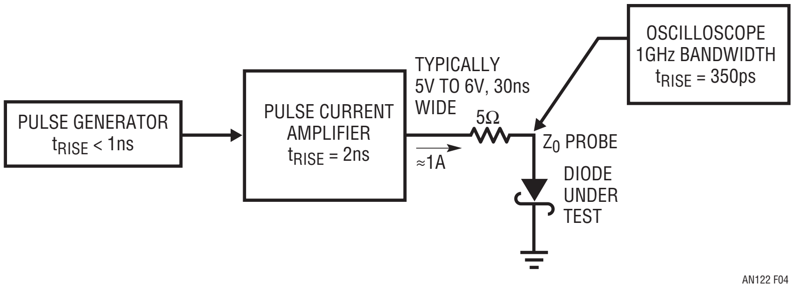


Figure 4. Detailed Measurement Scheme Indicates Necessary Performance Parameters for Various Elements. Sub-Nanosecond Rise Time Pulse Generator, 1A, 2ns Rise Time Amplifier and 1GHz Oscilloscope are Required

The pulse amplifier necessitates careful attention to circuit configuration and layout. Figure 5 shows the amplifier includes a paralleled, Darlington driven RF transistor output stage. The collector voltage adjustment ("rise time trim") peaks Q4 to Q6 F_T; an input RC network optimizes output pulse purity by slightly retarding input pulse rise time to within amplifier passband. Paralleling allows Q4 to Q6 to operate at favorable individual currents, maintaining bandwidth. When the (mildly interactive) edge purity and rise time trims are optimized, Figure 6 indicates the amplifier produces a transcendently clean 2ns rise time output pulse devoid of ringing, alien components or post-transition excursions. Such performance makes diode turn-on time testing practical.[1]

Note 1. An alternate pulse generation approach appears in Appendix F, "Another Way to Do It."

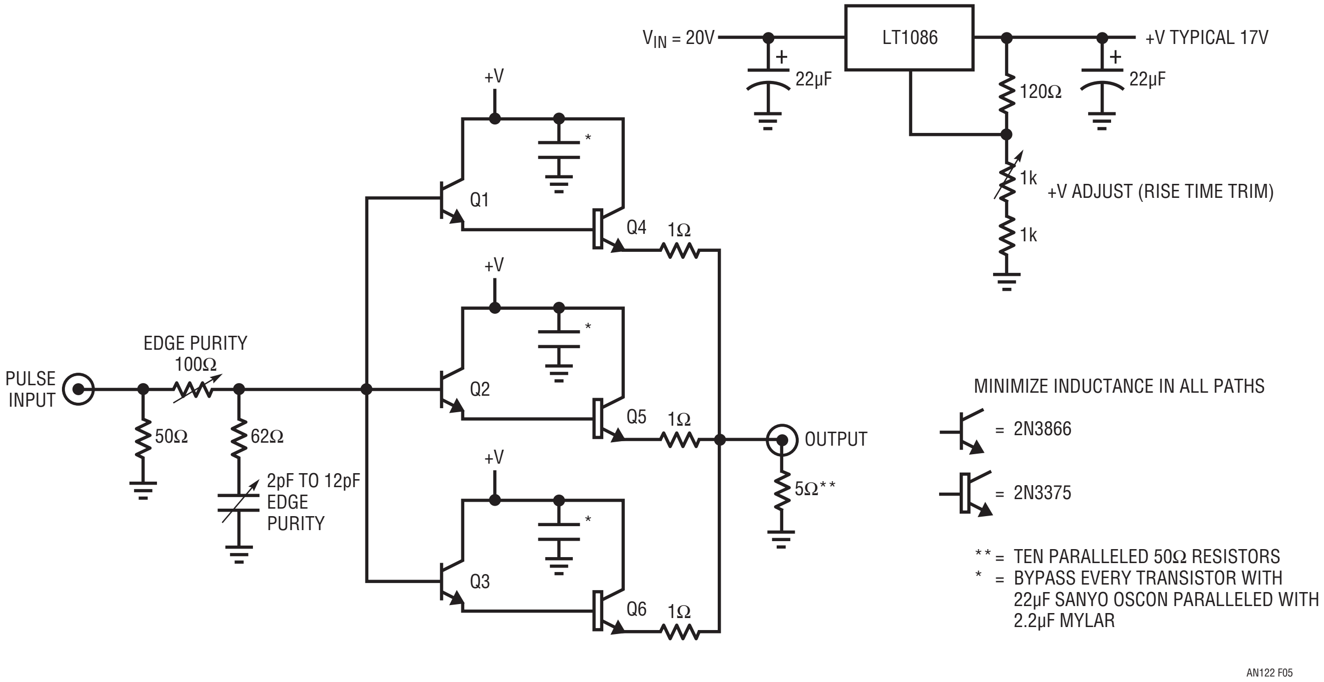


Figure 5. Pulse Amplifier Includes Paralleled, Darlington Driven RF Transistor Output Stage. Collector Voltage Adjustment ("Rise Time Trim") Peaks Q4 to Q6 F_T, Input RC Network Optimizes Output Pulse Purity. Low Inductance Layout is Mandatory

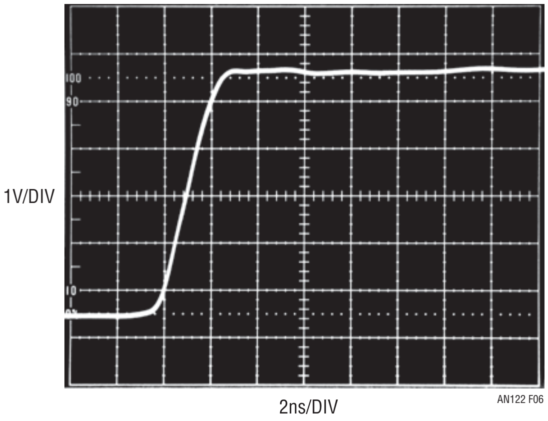
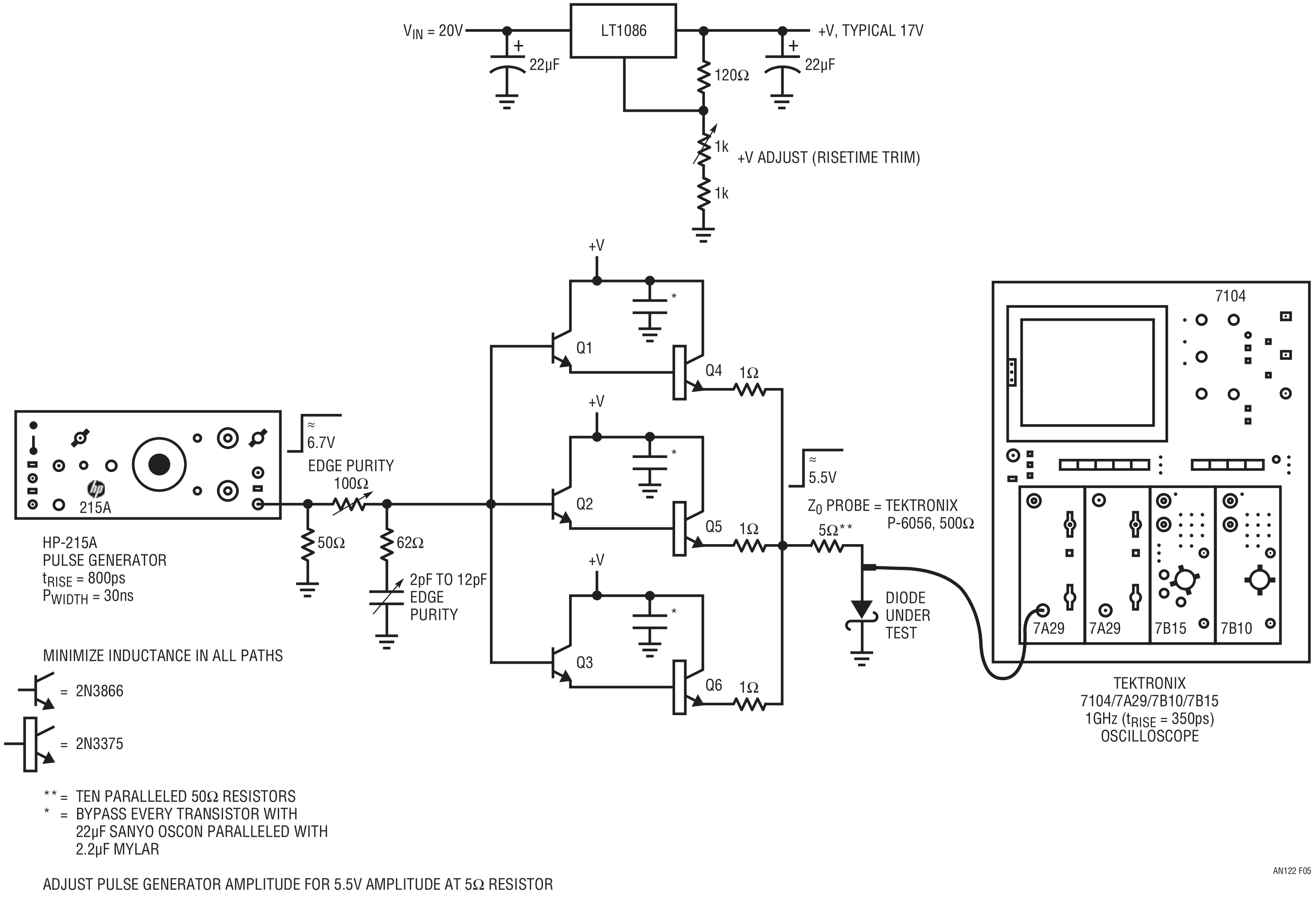


Figure 6. Pulse Amplifier Output into 5Ω. Rise Time is 2ns with Minimal Pulse-Top Aberrations



MINIMIZE INDUCTANCE IN ALL PATHS

** = TEN PARALLELED 50Ω RESISTORS
* = BYPASS EVERY TRANSISTOR WITH 22µF SANYO OSCON PARALLELED WITH 2.2µF MYLAR

ADJUST PULSE GENERATOR AMPLITUDE FOR 5.5V AMPLITUDE AT 5Ω RESISTOR

Figure 7. Complete Diode Forward Turn-On Time Measurement Arrangement Includes Sub-Nanosecond Rise Time Pulse Generator, Pulse Amplifier, Z_0 Probe and 1GHz Oscilloscope

Figure 7 depicts the complete diode forward turn-on time measurement arrangement. The pulse amplifier, driven by a sub-nanosecond pulse generator, drives the diode under test. A Z_0 probe monitors the measurement point and feeds a 1GHz oscilloscope.[2, 3, 4]

Diode Testing and Interpreting Results

The measurement test fixture, properly equipped and constructed, permits diode turn-on time testing with excellent time and amplitude resolution.[5] Figures 8 through 12 show results for five different diodes from various manufacturers. Figure 8 (Diode Number 1) overshoots steady state forward voltage for 3.6ns, peaking 200mV. This is the best performance of the five. Figures 9 through 12 show increasing turn-on amplitude and time which are detailed in the figure captions. In the worst cases, turn-on amplitudes exceed nominal clamp voltage by more than 1V while turn-on times extend for tens of nanoseconds. Figure 12 culminates this unfortunate parade with huge time and amplitude errors. Such errant excursions can and will cause IC regulator breakdown and failure. The lesson here is clear. Diode turn-on time must be characterized and measured in any given application to insure reliability.

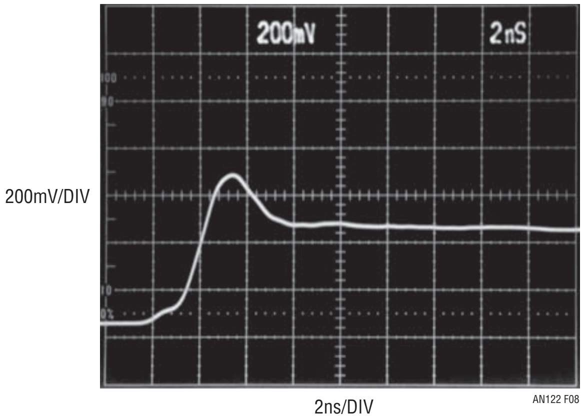


Figure 8. "Diode Number 1" Overshoots Steady State Forward Voltage for ≈3.6ns, Peaking 200mV

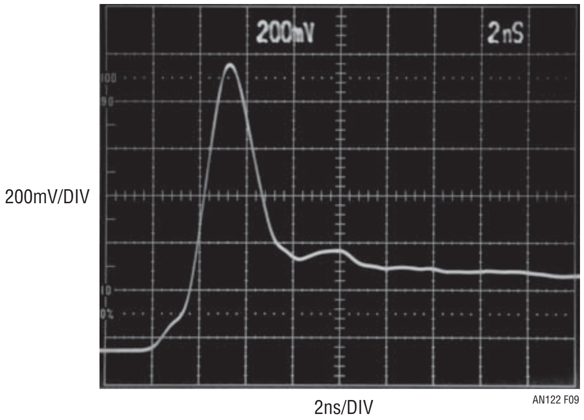


Figure 9. "Diode Number 2" Peaks ≈750mV Before Settling in 6ns… > 2x Steady State Forward Voltage

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Note 2. Z_0 probes are described in Appendix C, "About Z_0 Probes". See also References 27 thru 34.

Note 3. The sub-nanosecond pulse generator requirement is not trivial. See Appendix B, "Subnanosecond Rise Time Pulse Generators For The Rich and Poor."

Note 4. See Appendix E, "Connections, Cables, Adapters, Attenuators, Probes and Picoseconds" for relevant commentary.

Note 5. See Appendix A, "How Much Bandwidth is Enough?" for discussion on determining necessary measurement bandwidth.

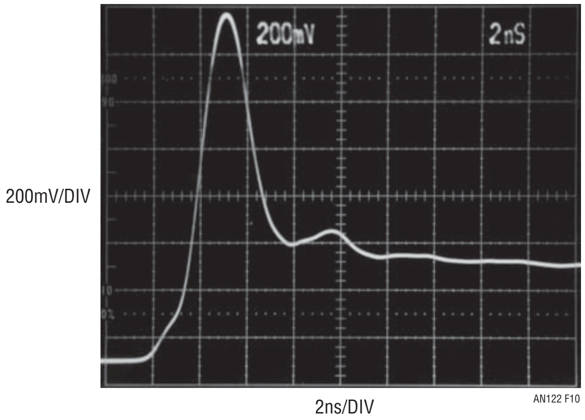

Figure 10. "Diode Number 3" Peaks 1V Above Nominal 400mV V_{FWD}, a 2.5x Error

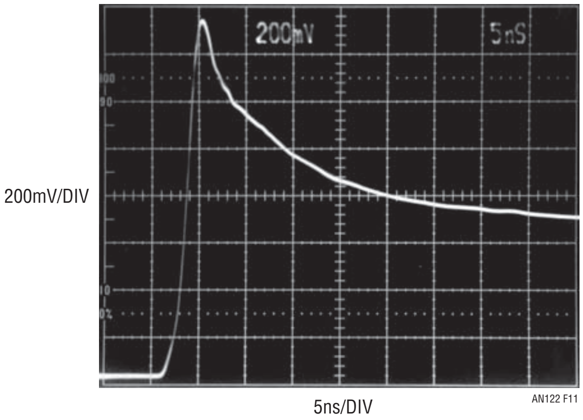

Figure 11. "Diode Number 4" Peaks ≈750mV with Lengthy (Note Horizontal 2.5x Scale Change) Tailing Towards V_{FWD} Value

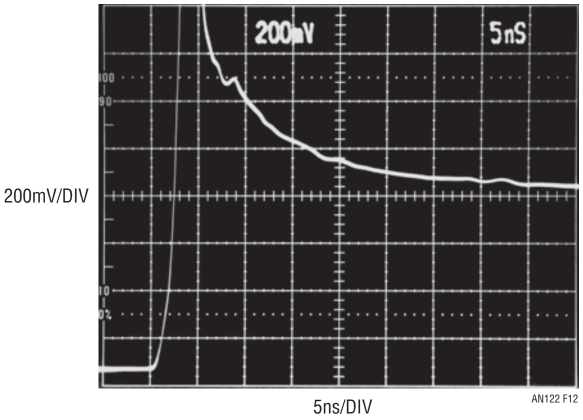

Figure 12. "Diode Number 5" Peaks Offscale with Extended Tailing (Note Horizontal Slower Scale Compared to Figures 8 thru 10)

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APPENDIX A

HOW MUCH BANDWIDTH IS ENOUGH?

Accurate wideband oscilloscope measurements require bandwidth. A good question is just how much is needed. A classic guideline is that “end-to-end” measurement system rise time is equal to the root-sum-square of the system’s individual components’ rise times. The simplest case is two components; a signal source and an oscilloscope.

Figure A1’s plot of $\sqrt{\text{Signal}^2 + \text{Oscilloscope}^2}$ rise time versus error is illuminating. The figure plots signal-to-oscilloscope rise time ratio versus observed rise time (rise time is bandwidth restated in the time domain, where:

$$\text{Rise Time (ns)} = \frac{350}{\text{Bandwidth(MHz)}})$$

The curve shows that an oscilloscope 3 to 4 times faster than the input signal rise time is required for measurement accuracy inside about 5%. This is why trying to measure a 1ns rise time pulse with a 350MHz oscilloscope (t_{RISE} = 1ns) leads to erroneous conclusions. The curve indicates a monstrous 41% error. Note that this curve does not include the effects of passive probes or cables connecting the signal to the oscilloscope. Probes do not necessarily follow root-sum-square law and must be carefully chosen

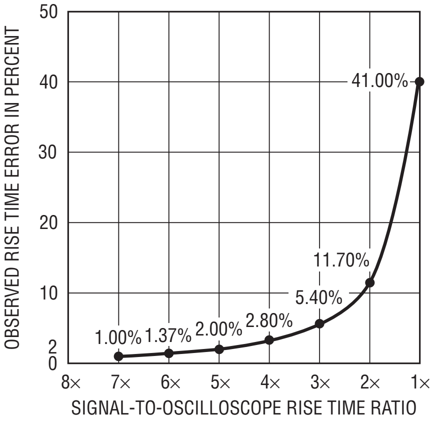


Figure A1. Oscilloscope Rise Time Effect on Rise Time Measurement Accuracy. Measurement Error Rises Rapidly as Signal-to-Oscilloscope Rise Time Ratio Approaches Unity. Data, Based on Root-Sum-Square Relationship, Does Not Include Probe, Which May Not Follow Root-Sum-Square Law

and applied for a given measurement. Figure A2, included for reference, gives 10 cardinal points of rise time/bandwidth equivalency between 1MHz and 5GHz.

Figures A3 through A10 illustrate pertinent effects of these considerations by viewing the text's diode turn-on time measurement at various bandwidths.[1] Figure A3 displays a typical diode turn-on in a 2.5GHz sampled bandpass, showing 500mV turn-on amplitude.[2] Figure A4's 1GHz bandwidth measurement has nearly identical characteristics, indicating adequate oscilloscope bandwidth. The dramatic error in observed turn-on overshoot amplitude as bandwidth decreases in succeeding figures is readily apparent and should not be lost to the experimenter.

Note 1. Prudent investigation requires verifying bandwidth of all elements in the signal path. See Appendix D, "Verifying Rise Time Measurement Integrity."

Note 2. 3.9GHz oscilloscope + 3.5GHz probe = 2.5GHz probe tip bandwidth.

RISE TIME	BANDWIDTH
70ps	5GHz
350ps	1GHz
700ps	500MHz
1ns	350MHz
2.33ns	150MHz
3.5ns	100MHz
7ns	50MHz
35ns	10MHz
70ns	5MHz
350ns	1MHz

Figure A2. Some Cardinal Points of Rise Time/Bandwidth Equivalency. Data is Based on Rise Time/Bandwidth Formula in Text

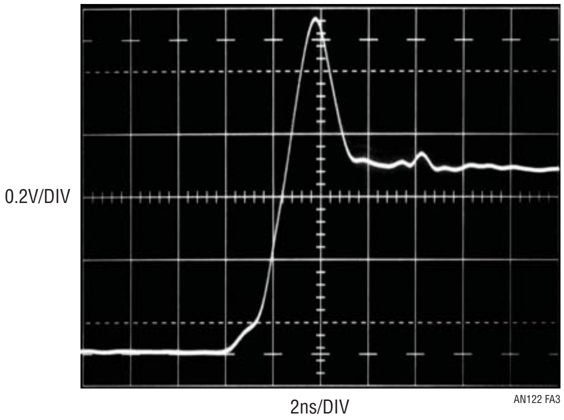


Figure A3. Typical Diode Turn-On Viewed in 2.5GHz Sampled Bandpass Displays 500mV Turn-On Peak

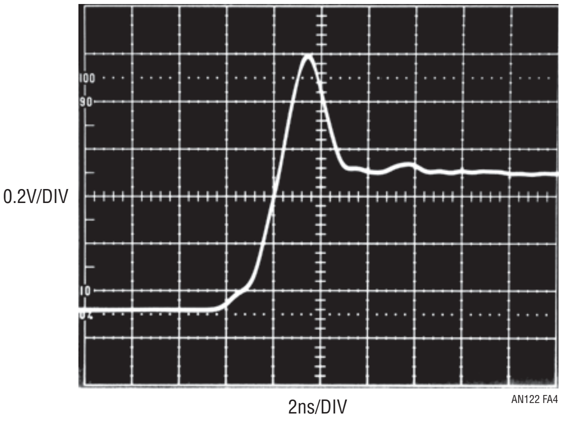


Figure A4. Figure A3's Diode Turn-On Observed in 1GHz Real Time Bandwidth Has Nearly Identical Characteristics, Indicating Adequate Oscilloscope Bandwidth

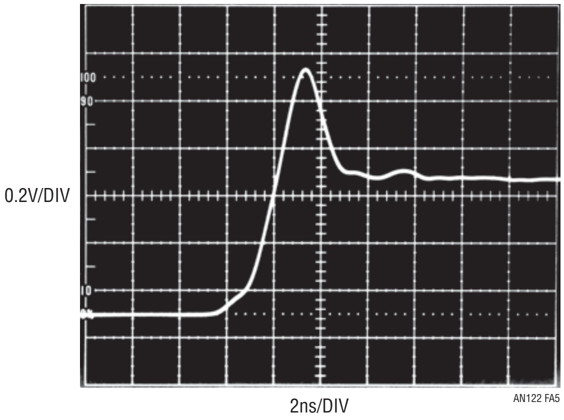


Figure A5. 600MHz Oscilloscope Bandwidth Results in ≈440mV Observed Peak, an 12% Amplitude Error

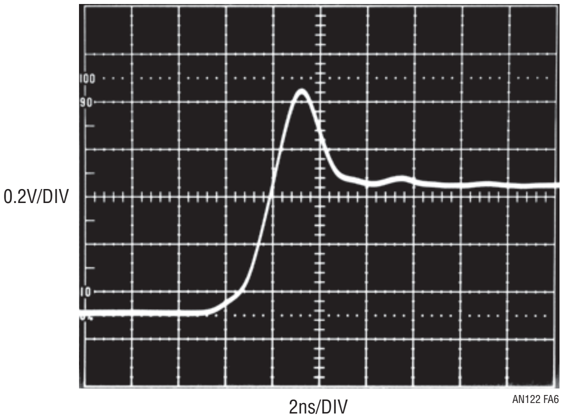


Figure A6. 400MHz Measurement Bandwidth Causes 20% Error

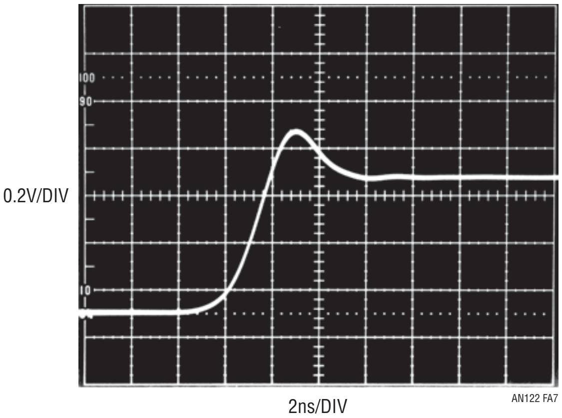


Figure A7. 60% Error Occurs with 200MHz Oscilloscope Bandwidth

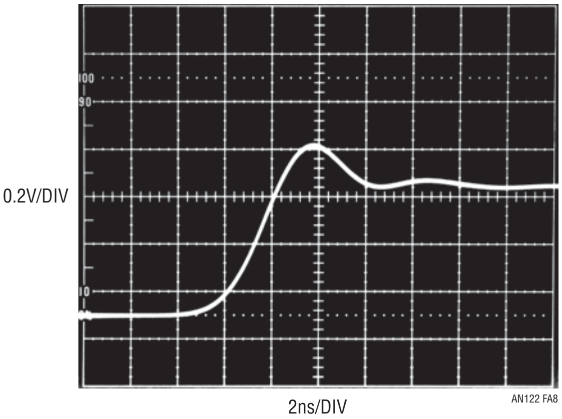


Figure A8. 65% Error (!) in 75MHz Bandwidth

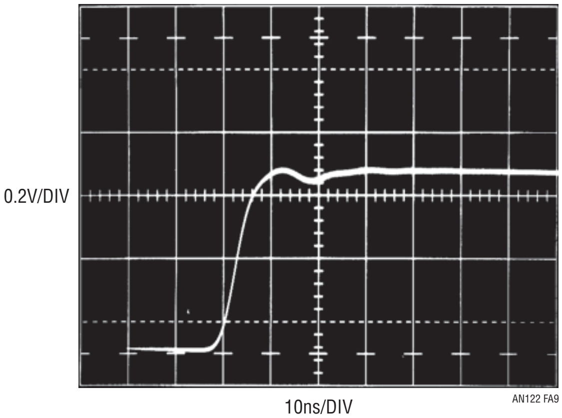


Figure A9. 50MHz Oscilloscope Just Hints at Peaking. Note 5x Horizontal Scale Change vs Figures A3 through A8

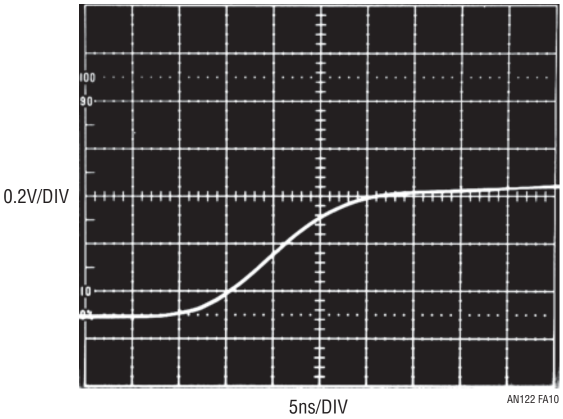


Figure A10. 20MHz Oscilloscope Bandwidth Presentation is Smooth…and Worthless. Note 2.5x Horizontal Scale Change vs Figures A3 through A8

APPENDIX B

SUBNANOSECOND RISE TIME PULSE GENERATORS FOR THE RICH AND POOR

The pulse amplifier requires a sub-nanosecond input rise time pulse to cleanly switch current to the diode under test. The majority of general purpose pulse generators have rise times in the 2.5ns to 10ns range. Instrument rise times below 2.5ns are relatively rare, with only a select few types getting down to 1ns. The ranks of sub-nanosecond rise time generators are even thinner, and costs are, in this author's view, excessive. Sub-nanosecond rise time generation, particularly if relatively large swings (e.g. 5V to 10V) are desired, employs arcane technologies and exotic construction techniques. Available instruments in this class work well, but can easily cost $10,000 with prices rising towards $30,000 depending on features. For bench work, or even production testing, there are substantially less expensive approaches.

The secondary market offers sub-nanosecond rise time pulse generators at attractive cost. The Hewlett-Packard HP-8082A transitions in under 1ns, has a full complement of controls and costs about $500. The Tektronix type 111 has edge times of 500ps, with fully variable repetition rate and external trigger capabilities. Pulse width is set by external charge line length. Price is usually about $25. The HP-215A, long out of manufacture, has 800ps edge times and is a clear bargain, with typical price below $50.[1] This instrument also has a very versatile trigger output, permitting continuous trigger time phase adjustment from before to after the main output. External trigger impedance, polarity and sensitivity are also variable. The output, controlled by a stepped attenuator, will put a clean ±10V pulse into 50Ω in 800ps.[2]

400ps Rise Time Avalanche Pulse Generator

A potential problem with older instruments is availability.[3] As such, Figure B1 shows a circuit for producing sub-nanosecond rise time pulses. Rise time is 400ps, with adjustable pulse amplitude. Output pulse occurrence is settable from before-to-after a trigger output. This circuit uses an avalanche pulse generator to create extremely fast rise time pulses.[4]

Q1 and Q2 form a current source that charges the 1000pF capacitor. When the LTC1799 clock is high (trace A, Figure B2) both Q3 and Q4 are on. The current source is off and Q2's collector (trace B) is at ground. C1's latch input prevents it from responding and its output remains high. When the clock goes low, C1's latch input is disabled and its output drops low. The Q3 and Q4 collectors lift and Q2 comes on, delivering constant current to the 1000pF capacitor (trace B). The resulting linear ramp is applied to C1 and C2's positive inputs. C2, biased from a potential derived from the 5V supply, goes high 30ns after the ramp begins, providing the "trigger output" (trace C) via its output network. C1 goes high when the ramp crosses the potentiometer programmed delay at its negative input, in this case about 170ns. C1 going high triggers the avalanche-based output pulse (trace D), which will be described. This arrangement permits the delay programming control to vary output pulse occurrence from 30ns before to 300ns after the trigger output. Figure B3 shows the output pulse (trace D) occurring 25ns before the trigger output. All other waveforms are identical to Figure B2.

When C1's output pulse is applied to Q5's base, it avalanches. The result is a quickly rising pulse across Q5's emitter termination resistor. The collector capacitors and the charge line discharge, Q5 collector voltage falls and breakdown ceases. The collector capacitors and the charge line then recharge. At C1's next pulse, this action repeats. The capacitors supply initial pulse response, with the charge lines prolonged discharge contributing the pulse body. The 40" charge line length forms an output pulse width about 12ns in duration.

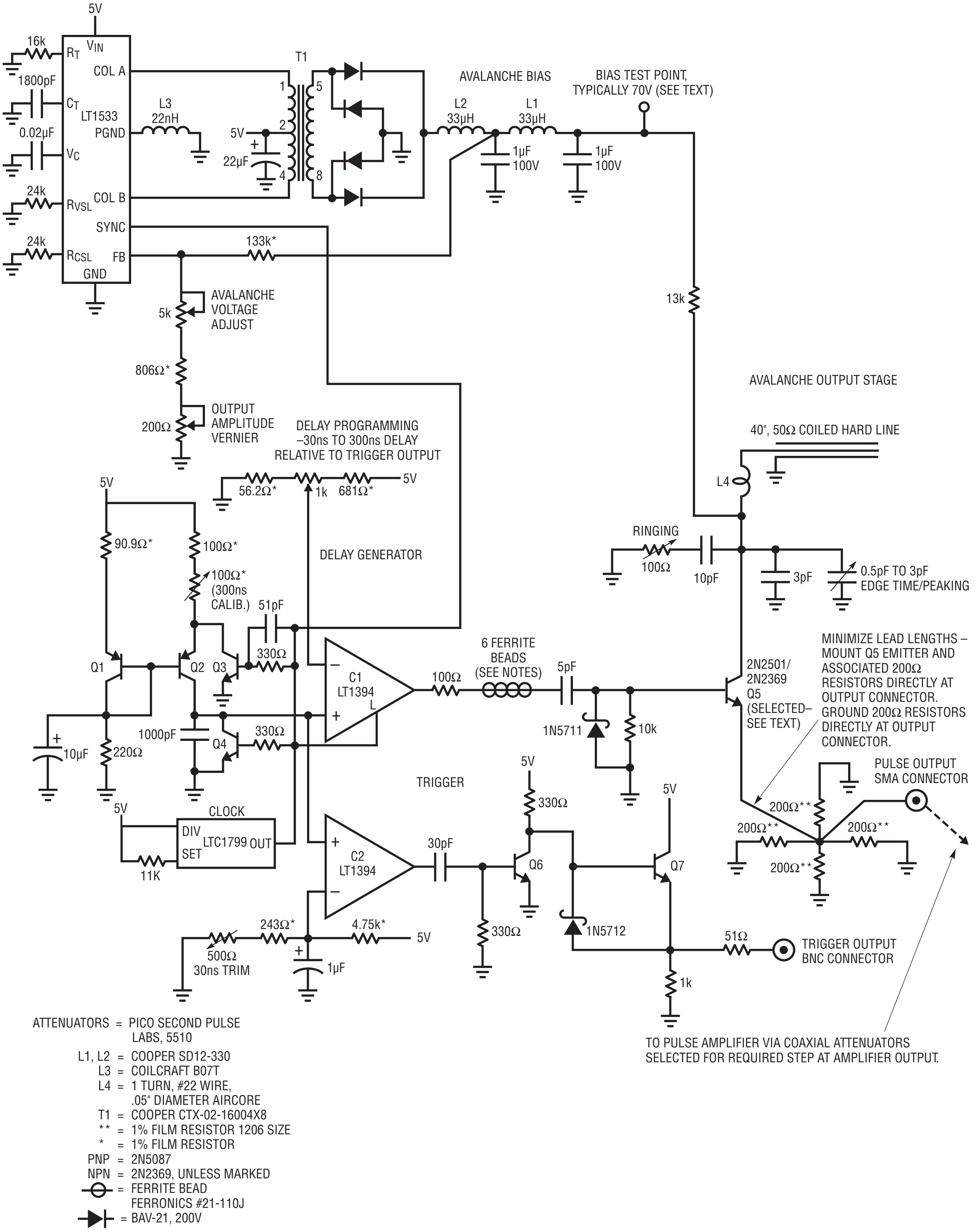
Avalanche operation requires high voltage bias. The LT1533 low noise switching regulator and associated components supply this high voltage. The LT1533 is a "push-pull" output switching regulator with controllable transition times.

Note 1. The absurdly low valuation may be due to the instrument's front panel controls and markings, which only subtly hint at its capabilities.

Note 2. Instrument afficionados would do well to study this instrument's elegant step-recovery diode based output stage, a thing of exotic beauty. See Reference 35.

Note 3. Residents of Silicon Valley tend towards inbred techno-provincialism. Citizens of other locales cannot simply go to a flea market, junk store or garage sale and buy a sub-nanosecond pulse generator.

Note 4. The circuits operation essentially duplicates the aforementioned Tektronix type 111 pulse generator (see Reference 11). Information on avalanche operation appears in References 7 through 25.



ATTENUATORS = PICO SECOND PULSE LABS, 5510
L1, L2 = COOPER SD12-330
L3 = COILCRAFT B07T
L4 = 1 TURN, #22 WIRE, .05" DIAMETER AIRCORE
T1 = COOPER CTX-02-16004X8
** = 1% FILM RESISTOR 1206 SIZE
* = 1% FILM RESISTOR
PNP = 2N5087
NPN = 2N2369, UNLESS MARKED
= FERRITE BEAD FERRONICS #21-110J
= BAV-21, 200V

Figure B1. Variable Delay Triggers a Sub-Nanosecond Rise Time Pulse Generator. Charge Line at Q5's Collector Determines ≈10ns Output Width. Output Pulse Occurrence is Settable from Before-to-After Trigger Output

Output harmonic content (“noise”) is notably reduced with slower switch transition times.[5] Switch current and voltage transition times are controlled by resistors at the R_{CSL} and R_{VSL} pins, respectively. In all other respects the circuit behaves as a classical push-pull, step-up converter.

Circuit Optimization

Circuit optimization begins by setting the “Output Amplitude Vernier” to maximum and grounding Q4’s collector. Next, set the “Avalanche Voltage Adjust” so free running pulses *just* appear at Q5’s emitter, noting the bias test points voltage. Readjust the “Avalanche Voltage Adjust” 5V below this voltage and unground Q4’s collector. Set the “30ns Trim” so the trigger output goes low 30ns after the clock goes low. Adjust the delay programming control to maximum and set the “300ns Calib.” so C1 goes high 300ns after the clock goes low. Slight interaction between the 30ns and 300ns trims may require repeating their adjustments until both points are calibrated.

Q5 requires selection for optimal avalanche behavior. Such behavior, while characteristic of the device specified, is not guaranteed by the manufacturer. A sample of 30 2N2501s, spread over a 17-year date code span, yielded ≈90%. All “good” devices switched in less than 475ps with some below 300ps.[6] In practice, Q5 should be selected for “in-circuit” rise time under 400ps. Once this is done, output pulse shape is optimized by adjusting Q5’s collector damping trims (“edge time/peaking” and “ringing”). The trims are somewhat interactive, but not unduly so, and optimal adjustment converges nicely. The pulse edge is carefully adjusted so that maximum transition speed is attained with minimal sacrifice of pulse purity.[7] Figures B4 through B6 detail the optimization procedure. In Figure B4, the trims are set for significant effect, resulting in a reasonably clean pulse but sacrificing rise time.[8] Figure B5 represents the opposite extreme. Minimal trim effect accentuates rise time, but promotes post-transition ring. Figure B6’s compromise trimming is more desirable. Edge rate is only slightly reduced, but post-transition ring is significantly retarded, resulting in a 400ps rise time with high pulse purity.[9, 10]

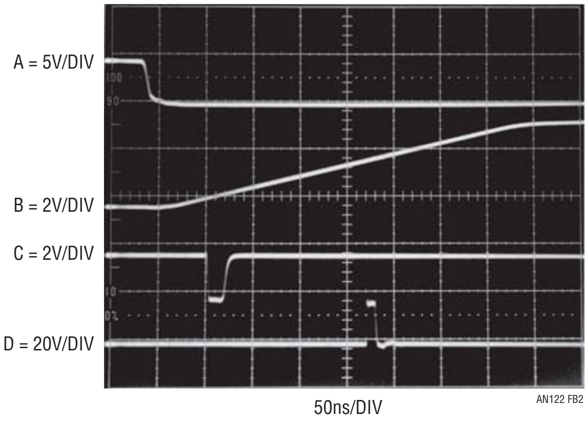


Figure B2. Pulse Generator’s Waveforms Include Clock (Trace A), Q2’s Collector Ramp (Trace B), Trigger Output (Trace C) and Pulse Output (Trace D). Delay Sets Output Pulse ≈170ns After Trigger Output

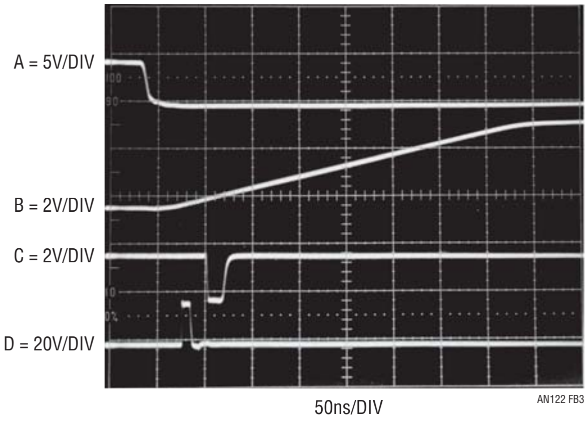


Figure B3. Pulse Generator’s Waveforms with Delay Adjusted for Output Pulse Occurrence (Trace D) 25ns Before Trigger Output (Trace C). All Other Activity is Identical to Previous Figure

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Note 5. The LT1533’s low noise performance and its measurement are discussed in Reference 25.

Note 6. 2N2501s are available from Semelab plc. Sales@semelab.co.uk; Tel. 44-0-1455-556565. A more common transistor, the 2N2369, may also be used but switching times are rarely less than 450ps.

Note 7. Optimization procedures for obtaining high degrees of pulse purity while preserving rise time appear in Reference 11.

Note 8. The strata is becoming rarefied when a sub-nanosecond rise time is described as “sacrificed”.

Note 9. Faster rise times are possible, although considerable finesse is required in Q5’s selection, layout, mounting, terminal impedance choice and triggering. The 400ps rise time quoted represents readily reproducible results. Rise times below 300ps have been achieved, but require tedious effort.

Note 10. Accurate rise time determination at these speeds mandates verifying measurement signal path (cables, attenuators, probes, oscilloscope) integrity. See Appendix D, “Verifying Rise Time Measurement Integrity” and Appendix E, “Connections, Cables, Adapters, Attenuators, Probes and Picoseconds.”

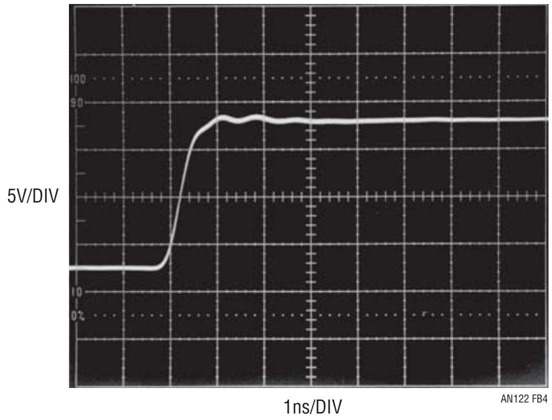


Figure B4. Excessive Damping is Characterized by Front Corner Rounding and Minimal Pulse-Top Aberrations. Trade Off is Relatively Slow Rise Time

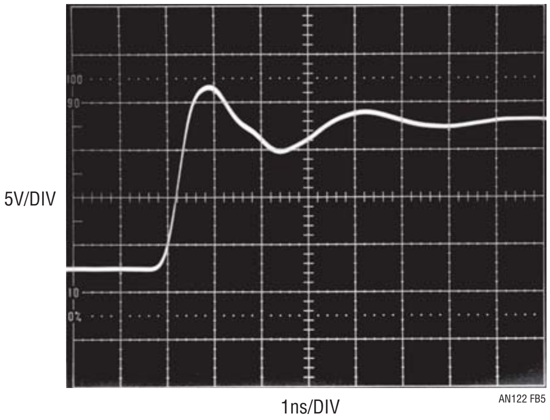


Figure B5. Minimal Damping Accentuates Rise Time, Although Pulse-Top Ringing is Excessive

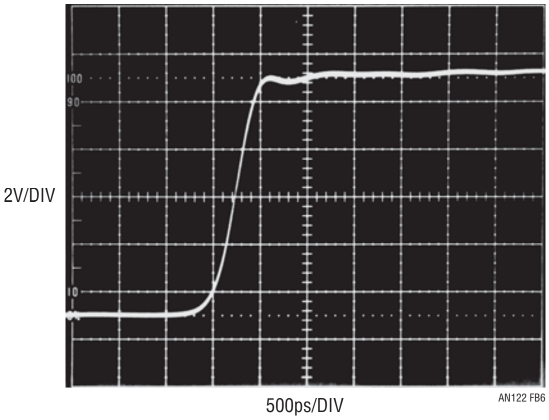


Figure B6. Optimal Damping Retards Pulse-Top Ringing While Preserving Rise Time

APPENDIX C

ABOUT Z_0 PROBES

When to Roll Your Own and When to Pay the Money

Z_0 (e.g. “low impedance”) probes provide the most faithful high speed probing mechanism available for low source impedances. Their sub-picofarad input capacitance and near ideal transmission characteristic make them the first choice for high bandwidth oscilloscope measurement. Their deceptively simple operation invites “do-it-yourself” construction but numerous subtleties mandate difficulty for prospective constructors. Arcane parasitic effects introduce errors as speed increases beyond about 100MHz (t_{RISE} 3.5ns). The selection and integration of probe materials and the probes physical incarnation require extreme care to obtain high fidelity at high speed. Additionally, the probe must include some form of adjustment to compensate small, residual parasitics. Finally, true coaxiality must be maintained when fixturing the probe at the measurement point, implying a high grade, readily disconnectable, coaxial connection capability.

Figure C1 shows that a Z_0 probe is basically a voltage divided input 50Ω transmission line. If R1 equals 450Ω, 10x attenuation and 500Ω input resistance result. R1 of 4950Ω causes a 100x attenuation with 5k input resistance. The 50Ω line theoretically constitutes a distortioness transmission environment. The apparent simplicity seemingly permits "do-it-yourself" construction but this section's remaining figures demonstrate a need for caution.

Figure C2 establishes a fidelity reference by measuring a clean 700ps rise time pulse using a 50Ω line terminated via a coaxial attenuator – no probe is employed. The waveform is singularly clean and crisp with minimal edge and post-transition aberrations. Figure C3 depicts the same pulse with a commercially produced 10x Z_0 probe in use. The probe is faithful and there is barely discernible error in the presentation. Photos C4 and C5, taken with two separately constructed "do-it-yourself" Z_0 probes, show errors. In C4, "Probe #1" introduces pulse front corner rounding; "Probe #2" in C5 causes pronounced corner peaking. In each case, some combination of resistor/cable parasitics and incomplete coaxiality are likely responsible for the errors. In general, "do-it-yourself" Z_0 probes cause these types of errors beyond about 100MHz (t_{RISE} 3.5ns). At higher speeds, if waveform fidelity is critical, it's best to pay the money.

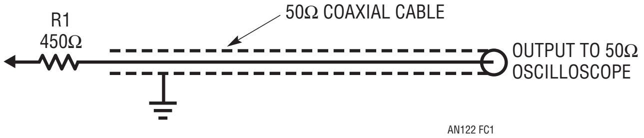


Figure C1. Conceptual 500Ω, "Z_0", 10x Oscilloscope Probe. If R1 = 4950Ω, 5k Input Resistance with 100x Signal Attenuation Results. Terminated Into 50Ω, Probe Theoretically Constitutes a Distortionless Transmission Line. "Do It Yourself" Probes Suffer Uncompensated Parasitics, Causing Unfaithful Response Above ≈100MHz (t_{RISE} = 3.5ns)

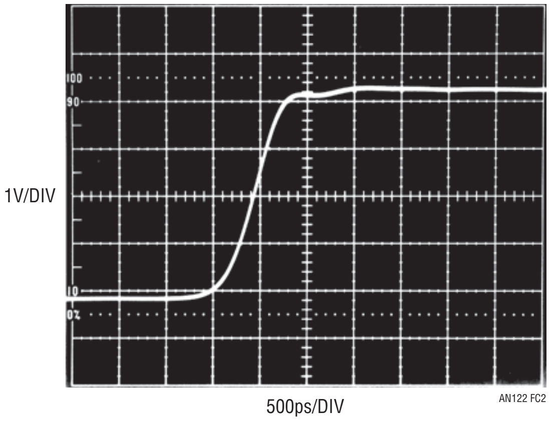


Figure C2. 700ps Rise Time Pulse Observed Via 50Ω Line and Coaxial Attenuator Has Good Pulse Edge Fidelity With Controlled Post-Transition Events

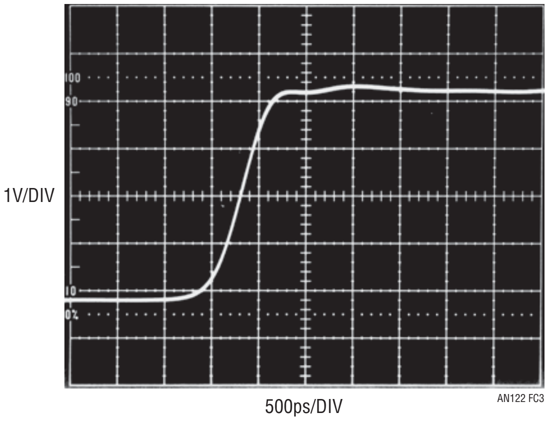


Figure C3. Figure C2's Pulse Viewed With Tektronix Z_0 500Ω Probe (P-6056) Introduces Barely Discernible Error

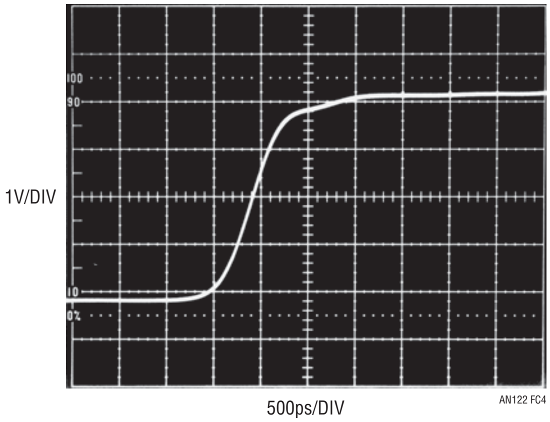


Figure C4. "Do It Yourself" Z_0 Probe #1 Introduces Pulse Corner Rounding, Likely Due to Resistor/Cable Parasitic Terms or Incomplete Coaxiality. "Do It Yourself" Z_0 Probes Typically Manifest This Type Error at Rise Times ≤ 2ns

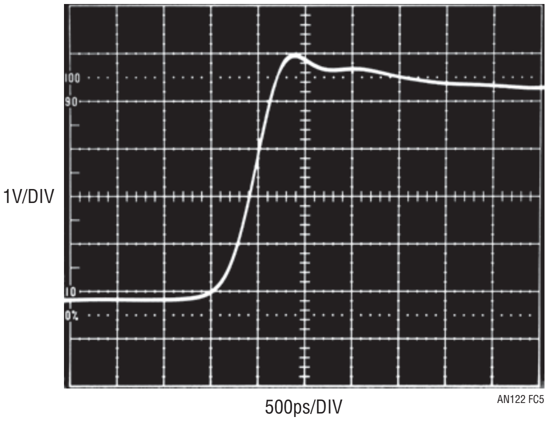


Figure C5. "Do It Yourself" Z_0 Probe #2 Has Overshoot, Again Likely Due to Resistor/Cable Parasitic Terms or Incomplete Coaxiality. Lesson: At These Speeds, Don't "Do It Yourself"

APPENDIX D

VERIFYING RISE TIME MEASUREMENT INTEGRITY

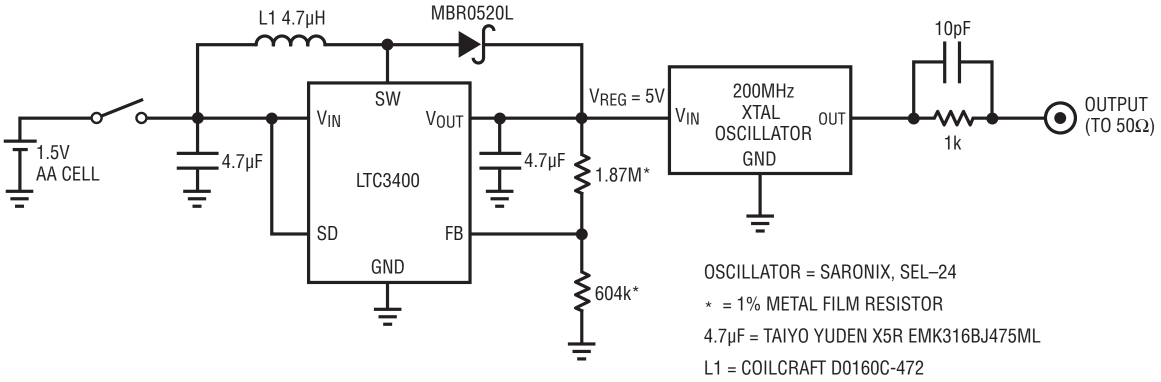
Any measurement requires the experimenter to insure measurement confidence. Some form of calibration check is always in order. High speed time domain measurement is particularly prone to error and various techniques can promote measurement integrity.

Figure D1's battery-powered 200MHz crystal oscillator produces 5ns markers, useful for verifying oscilloscope time base accuracy. A single 1.5 AA cell supplies the LTC3400 boost regulator, which produces 5V to run the oscillator. Oscillator output is delivered to the 50Ω load via a peaked attenuation network. This provides well defined 5ns markers (Figure D2) and prevents overdriving low level sampling oscilloscope inputs.

Once time base accuracy is confirmed it is necessary to check rise time. The lumped signal path rise time, including attenuators, connections, cables, probes, oscilloscope and anything else, should be included in this measurement. Such "end-to-end" rise time checking is an effective way to promote meaningful results. A guideline for insuring accuracy is to have 4x faster measurement path rise time than the rise time of interest. Thus, Appendix Figure B6's 400ps rise time measurement requires a verified 100ps measurement path rise time to support it. Verifying the 100ps measurement path rise time, in turn, necessitates a 25ps rise time test step. Figure D3 lists some very fast edge generators for rise time checking.[1]

The Hewlett-Packard 1105A/1106A, specified at 20ps rise time, was used to verify Appendix Figure A3's measurement signal path. Figure D4 indicates a 140ps rise time, promoting measurement confidence.

Note 1. This is a fairly exotic group, but equipment of this caliber really is necessary for rise time verification.



OSCILLATOR = SARONIX, SEL–24
* = 1% METAL FILM RESISTOR
4.7µF = TAIYO YUDEN X5R EMK316BJ475ML
L1 = COILCRAFT D0160C-472

Figure D1. 1.5V Powered, 200MHz Crystal Oscillator Provides 5ns Time Markers. Switching Regulator Converts 1.5V to 5V to Power Oscillator

MANUFACTURER	MODEL NUMBER	RISE TIME	AMPLITUDE	AVAILABILITY	COMMENTS
Avtech	AVP2S	40ps	0V to 2V	Current Production	Free Running or Triggered Operation, 0MHz to 1MHz
Hewlett-Packard	213B	100ps	≈175mV	Secondary Market	Free Running or Triggered Operation to 100kHz
Hewlett-Packard	1105A/1108A	60ps	≈200mV	Secondary Market	Free Running or Triggered Operation to 100kHz
Hewlett-Packard	1105A/1106A	20ps	≈200mV	Secondary Market	Free Running or Triggered Operation to 100kHz
Picosecond Pulse Labs	TD1110C/TD1107C	20ps	≈230mV	Current Production	Similar to Discontinued HP1105/1106/8A. See above.
Stanford Research Systems	DG535 OPT 04A	100ps	0.5V to 2V	Current Production	Must be Driven with Stand-alone Pulse Generator
Tektronix	284	70ps	≈200mV	Secondary Market	50kHz Repetition Rate. Pre-trigger 75ns to 150ns Before Main Output. Calibrated 100MHz and 1GHz Sine Wave Auxiliary Outputs.
Tektronix	111	500ps	≈±10V	Secondary Market	10kHz to 100kHz Repetition Rate. Positive or Negative Outputs. 30ns to 250ns Pre-trigger Output. External Trigger Input. Pulse Width Set with Charge Lines
Tektronix	067-0513-00	30ps	≈400mV	Secondary Market	60ns Pre-trigger Output. 100kHz Repetition Rate
Tektronix	109	250ps	0V to ±55V	Secondary Market	≈600Hz Repetition Rate (High Pressure Hg Reed Relay Based). Positive or Negative Outputs. Pulse Width Set by Charge Lines

Figure D3. Picosecond Edge Generators Suitable for Rise Time Verification. Considerations Include Speeds, Features and Availability

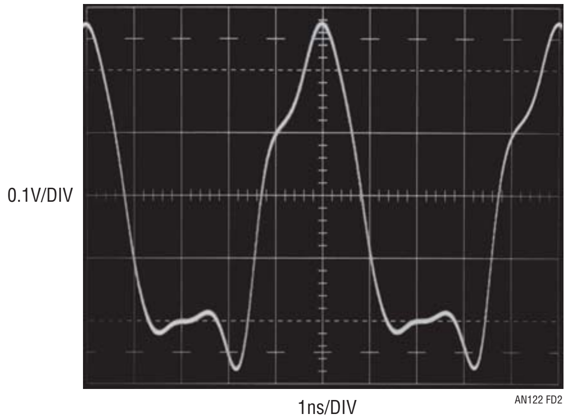


Figure D2. Time Mark Generator Output Terminated into 50Ω. Peaked Waveform is Optimal for Verifying Time Base Calibration

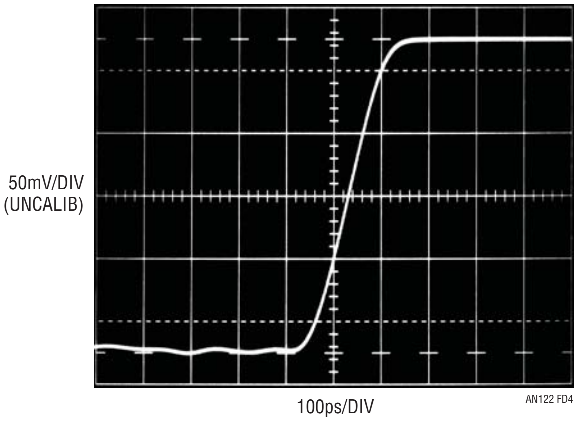


Figure D4. 20ps Step Produces ≈140ps Probe/Oscilloscope Rise Time, Verifying Appendix Figure A3's Signal Path Rise Time

APPENDIX E

CONNECTIONS, CABLES, ADAPTERS, ATTENUATORS, PROBES AND PICOSECONDS

Sub-nanosecond rise time signal paths must be considered as transmission lines. Connections, cables, adapters, attenuators and probes represent discontinuities in this transmission line, deleteriously affecting its ability to faithfully transmit desired signal. The degree of signal corruption contributed by a given element varies with its deviation from the transmission lines nominal impedance. The practical result of such introduced aberrations is degradation of pulse rise time, fidelity, or both. Accordingly, introduction of elements or connections to the signal path should be minimized and necessary connections and elements must be high grade components. Any form of connector, cable, attenuator or probe must be fully specified for high frequency use. Familiar BNC hardware becomes lossy at rise times much faster than 350ps. SMA components are preferred for the rise times described in the text. Additionally, to minimize inductance and cable induced mismatch and distortion, the text's pulse amplifier output should be connected *directly* (no cable) to the diode under test. Mixing signal path hardware types via adapters (e.g. BNC/SMA) should be avoided. Adapters introduce significant parasitics, resulting in reflections, rise time degradation, resonances and other degrading behavior.

Similarly, oscilloscope connections should be made directly to the instrument's 50Ω inputs, avoiding probes. If probes must be used, their introduction to the signal path mandates attention to their connection mechanism and high frequency compensation. Passive "Z_0" types, commercially available in 500Ω (10x) and 5kΩ (100x) impedances, have input capacitance below 1pF.[1] Any such probe must be carefully frequency compensated before use or misrepresented measurement will result. Inserting the probe into the signal path necessitates some form of signal pick-off which nominally does not influence signal transmission. In practice, some amount of disturbance must be tolerated and its effect on measurement results evaluated. High quality signal pick-offs always specify insertion loss, corruption factors and probe output scale factor.

The preceding emphasizes vigilance in designing and maintaining a signal path. Skepticism, tempered by enlightenment, is a useful tool when constructing a signal path and no amount of hope is as effective as preparation and directed experimentation.

Note 1. See Appendix C, "About Z_0 Probes"

APPENDIX F

ANOTHER WAY TO DO IT

If some restrictions are tolerable, an elegantly simple alternative method for generating the fast rise 1A pulse is available. The Tektronix type 109 mercury wetted reed relay based pulse generator will put a 50V pulse into 50Ω (1A) in 250ps.[1] Pulse width is set by an externally connected charge line with an approximate scale factor of 2ns/ft. Figure F1, a simplified schematic, shows type 109 operation. When the relay contacts close, the charge line discharges via the 50Ω-diode path. The pulse extends until the line depletes; depletion time depends on line length. The relay structure is very carefully arranged to assume wideband, 50Ω characteristics. Figure F2 shows the result. The 109 drives the monitoring 1GHz oscilloscope to its 350ps rise time limit with a 50V high fidelity pulse.

Operating restrictions include finite relay life (≈200 hours), obtaining the instrument (out of production for 20+ years), difficulty in observing its low frequency output on some oscilloscopes and test fixture layout sensitivity due to the 250ps rise time. Additionally, the faster rise time may not approximate actual circuit operating conditions as closely as the text's 2ns circuit.

Note 1. See Reference 36.

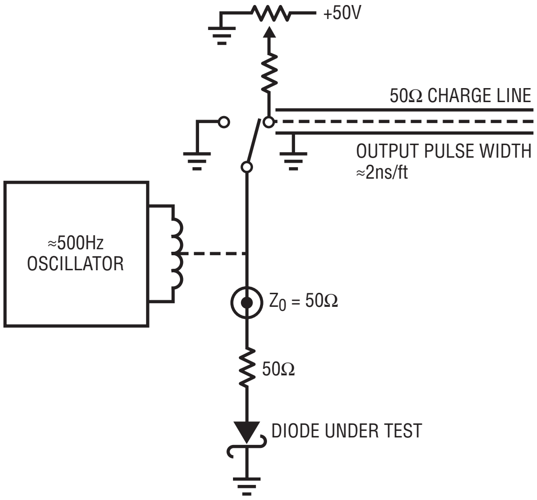


Figure F1. Simplified Operation of Tektronix Type 109 Mercury Wetted Reed Relay Based Pulse Generator. When Right Side Contacts Close, Charge Line Discharges Into 50Ω-Diode Load. Strict Attention to Construction Allows Wideband, 50Ω Characteristics, Permitting 250ps Rise Time, High Purity Output Pulse

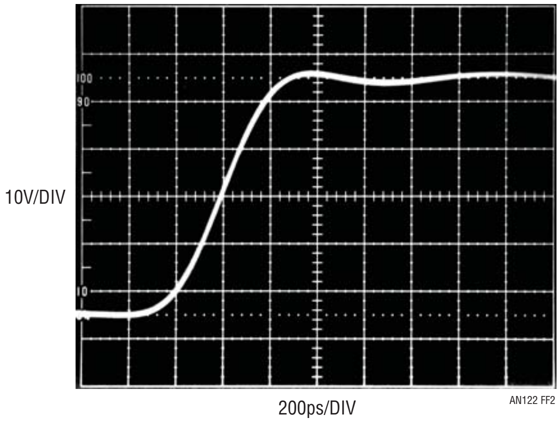
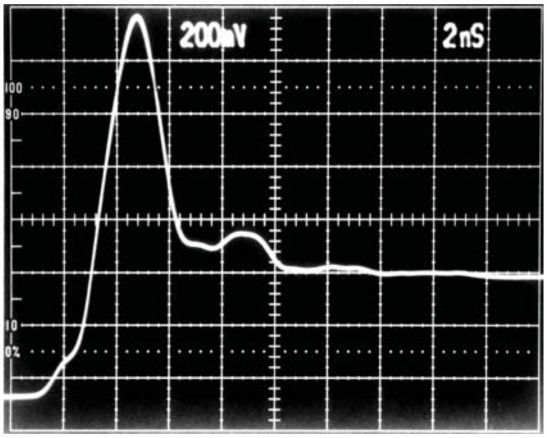


Figure F2. Tektronix Type 109 Produces High Purity, 50V, 1A Pulse, Driving Monitoring 1GHz Oscilloscope to its 350ps Rise Time Limit



"Now I am become Death, the destroyer of worlds."

Vishnu, to the Prince.

Bhagavad Gita

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