Keysight Technologies
State of the Art in Sub-10 ps Pulse Generators: Technology, Performance, and Applications

White Paper

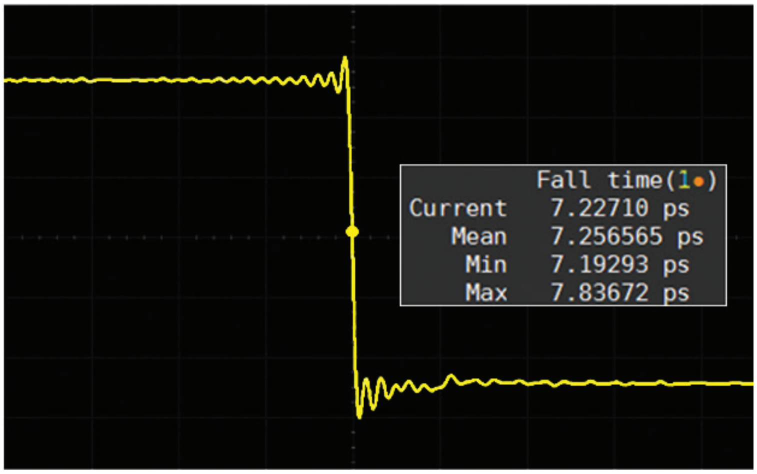
Introduction

Until very recently, the need for pulses with sub-10 ps rise times consisted of small niche applications at the periphery of worldwide technology research and development. However, the never ending march toward faster processing and communications technologies has pushed data rates ever higher and the corresponding signal frequencies into the 10s of GHz. To keep up, measurement systems such as the real time oscilloscope have rapidly pushed into record acquisition bandwidths of greater than 60 GHz (for example the Keysight Technologies, Inc. 90000 Q-Series 63 GHz real time oscilloscope). A whole host of important applications now demand pulse generation of sub-10 ps edge speeds. From calibration and metrology standards, to step response measurements, to characterization of devices using time domain reflectometry and transmissometry (TDR and TDT), engineering at today's data rates and bandwidths requires ultra-fast pulses with rise times below 10 ps and frequency content well beyond 60 GHz.

There are two very different architectures used to produce sub-10 ps pulses. The first, and perhaps most intuitive, is the ubiquitous differential amplifier. Simply fabricate an amplifier that can switch fast enough to generate the desired rise time and we're finished. The challenge is many applications demand edge speeds that push the limits of even the fastest amplifier designs and semiconductor processes in the world. We will return to the differential amplifier, but first our discussion focuses on the second pulse generator architecture, the shock line. Only recently have semiconductor processes enabled differential amplifiers to match, and even surpass, the edge speeds produced by shock lines. For this reason, the shock line has historically been the dominant architecture for applications that demand the absolute fastest edge speeds.

Abstract

Pulse generators boasting rise times in the sub-10 ps regime have a wide range of important applications in electronics and semiconductor design, manufacturing, and test. While shortest possible rise (or fall) times remain the banner specification, there are many other factors that contribute to the performance of a sub-10 ps pulse generator. Two architectures are commonly employed for these high performance devices. The choice of architecture has a strong impact on the speed, quality, and flexibility of the edge produced. This article will present an overview of sub-10 ps pulse generator architectures, important performance considerations, and conclude with a discussion of key applications.



```
         Fall time(1●)
Current   7.22710 ps
   Mean   7.256565 ps
    Min   7.19293 ps
    Max   7.83672 ps
```

Figure 1. 7.2 ps fall time (90%-10%) generated using the Keysight N2806A calibration pulse generator and measured at 63 GHz on the Keysight Infiniium 90000 Q-Series real time oscilloscope

The Shock Line

The shock line is simply a nonlinear transmission line, and has been studied for its ability to sharpen electromagnetic pulses since the 1960s [1], and perhaps even earlier. The shock line was so named because it was discovered that an electromagnetic shock wave is produced when charges in the transmission line are accelerated faster than the phase velocity of the corresponding electromagnetic wave [2,3]. The motion of charges necessary to support an extremely sharp pulse in the nonlinear transmission line proved fast enough to reveal this phenomenon long before the shock line architecture was integrated into a semiconductor process for pulse generation [4,5]. However, all physics and history aside, the shock line has proven to be an elegant and effective architecture for the generation of ultra-fast pulses. The best example of a modern shock line based pulse generator is the Picosecond Pulse Labs 4005.

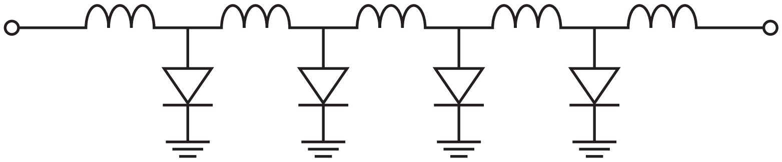


Figure 2. Oversimplified shock line diagram, produce a nonlinear transmission line by replacing capacitors with reverse biased diodes. Thus, capacitance varies with instantaneous voltage on the line.

Understanding the performance of shock line based pulse generators requires a basic understanding of how they work. Figure 2 shows an oversimplified diagram of a shock line. As mentioned earlier, a shock line is simply a nonlinear transmission line. There are a variety of ways to achieve the desired nonlinearity, however one of the most common is to replace the capacitors with reverse biased diodes in the semiconductor process. The transmission line becomes nonlinear as the capacitance at any point on the line depends on the instantaneous voltage at that point. Basic transmission line theory states that propagation delay through a transmission line is given by:

$$\tau = \sqrt{LC}$$

The Shock Line (continued)

Thus, an increase in capacitance also increases the delay of the signal through the line. Returning to our shock line circuit model, the capacitance of a reverse bias diode increases as the reverse bias across the diode decreases. Figure 3 depicts an over-simplified example of how the shape of the slow falling edge evolves as it propagates through the line. A falling edge, plotted in voltage versus time, appears as a rising edge in voltage versus position shown here. It is common that the falling edge in a pulse generator has negative polarity and we adhere to that convention here. Notice that the leading edge of the pulse, in space, applies a much smaller reverse bias than the more negative trailing voltage and therefore experiences a higher capacitance on the line. The result is the leading edge of the pulse is delayed with respect to the rest of the pulse and the pulse sharpens considerably. With proper engineering, the pulse produced by a shock line can be shaped to reliably output the desired edge speed.

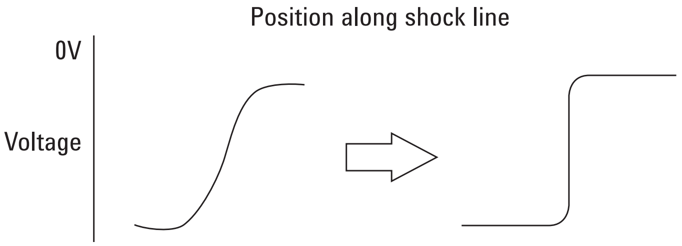


Figure 3. Oversimplified and idealized cartoon of how an edge transforms propagating through a shock line.

Unfortunately, the shock line architecture has inherent drawbacks. These will become more clear in the next section on performance considerations. However, it should be apparent that this architecture is polarity dependent. For a given shock line, depending on the voltage polarity and orientation of the diodes, you can output either a fast rising edge or a fast falling edge, but not both (it should be noted that the negative polarity fast falling edge is by far the most common). Successful attempts have been made in research literature to accelerate both rising and falling edges using a MOS varacter shock line in Silicon [6], however achieving close agreement between the rising and falling edge speeds continues to prove challenging. Afshari, et al. demonstrated an 8 ps rise time and 23 ps fall time [6]. Further, the shock line also struggles in applications where greater flexibility in waveform generation is desired. A shock line can output fast edge speeds, one pulse at a time. However, due to limitations accelerating both rising and falling edges, the architecture struggles with square waves greater than hundreds of megahertz and cannot hold a DC bias following the trailing edge of the pulse. Finally, shock line architectures commonly exhibit very poor source matching. This becomes increasingly problematic for fast pulses with significant high frequency content.

The Differential Amplifier

In this section, we will not discuss how a differential amplifier works. Rather, we will briefly review the technology that has enabled differential amplifiers fast enough to generate sub-10 ps rise and fall times. The best example of this technology can be found in Keysight's N2806A calibration pulse generator. Inside the remote head is a gold plated block of machined aluminum that guides the signal to two custom ASICs; a pre and post amplifier fabricated using Keysight's proprietary InP HBT technology. Figure 4 shows a picture of this machined aluminum packaging and InP integrated circuits. This semiconductor process is one of just a handful in the world capable of generating sub-10 ps rise and fall times. The benefit of this architecture, switching speed aside, is the flexibility of a differential amplifier; rising and falling edge speeds are closely matched, square waves can be output up to the bandwidth limitations of the device (tens of GHz), devices can be engineered with excellent source matching, and if desired the amplifier can hold a DC bias indefinitely following a pulse.

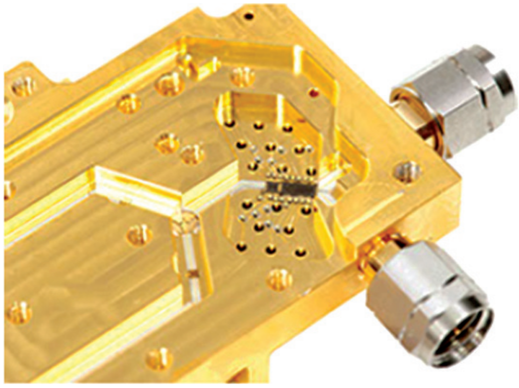


Figure 4. Inside the remote head of the Keysight N2806A pulse generator. The packaging is gold plated, machined aluminum. The InP pre and post amplifiers are visible in the corner nearest the two differential RF outputs.

Performance Considerations

When evaluating sub-10 ps pulse generators, how do these differences in architecture translate into performance metrics that can be found on a data sheet? While the fall time remains the banner specification, many other metrics are significant factors in the ultimate performance of the pulse generator.

Fall time

The specification that gets the headlines, the fall time is typically faster than the rise time and thus more prominently displayed. The number itself has significant nuances to be aware of. First, be sure to know whether the spec is for a 90%-10% or 80%-20% measurement. Second, because these edge speeds are so fast, measurement systems such as oscilloscopes do not have enough bandwidth to directly measure the true edge speed accurately. Therefore, some math is required to convolve out the bandwidth limits of the scope to get a more accurate fall time produced by the generator. Unfortunately vendors estimate the fall time of their pulse generators differently leaving considerable room for ambiguity in this critical performance metric.

Rise time

You may have to dig a little to find specified rise times as they can be orders of magnitude slower than the fall time specification. However, comparing this spec will help you determine the polarity dependence of the generator.

Differential outputs

This may not be explicitly specified, especially if the generator is not differential. However, a differential generator will have two RF outputs that enable many differential measurements and applications not accessible to a single-ended device. Typically only generators with closely matched rise and fall times will be differential. This is a critical advantage of using a differential amplifier architecture for pulse generation.

Maximum rep rate

This spec is also closely tied to the matching of rise and fall times. A generator that can output sub-10 ps rising and falling edges can generally handle extremely high rep rate signals. This enables the generator to output square waves and PRBS signals into the many tens of gigahertz with ultra-fast edge speeds.

Step duration

Some generators have both minimum and maximum hold times for a step typically on the order of tens of nanoseconds. Others have the flexibility to follow the input signal and hold a step indefinitely.

RF output impedance

Most commonly you will find generators are designed to output the step into a 50 ohm load, and have output impedances to match. However, the quality of the output impedance matching can vary widely. A good way to test this is ask the pulse generator vendor for a plot of S22 return loss for the RF output. A large return loss indicates poor output impedance matching and will produce significant reflections, detrimental to signal integrity and measurement quality.

Performance Considerations (continued)

Other specifications

There are many other specifications important to consider, however they are all relatively straightforward and do not need further explanation, such as output voltage, input trigger threshold, etc.

Deviation from an ideal step

This performance metric is very unlikely to be found on a data sheet as it is difficult to quantify with a single number. However, the measurement and corresponding plot versus frequency is a critical parameter in evaluating the quality of the step generated, not just the raw speed. Many generators have a lot of sharp transitions in their spectral content. Keysight's InP differential amplifier architecture produces a smooth roll off in the frequency domain and the closest to ideal step response available. Figure 5 shows a plot comparing the Keysight N2806A generator, dark blue (magnitude) and dark red (phase), versus a popular shock line based generator, bright blue (magnitude) and bright pink (phase). Regardless of your application, a higher quality edge will give you better, more accurate, and more repeatable results.

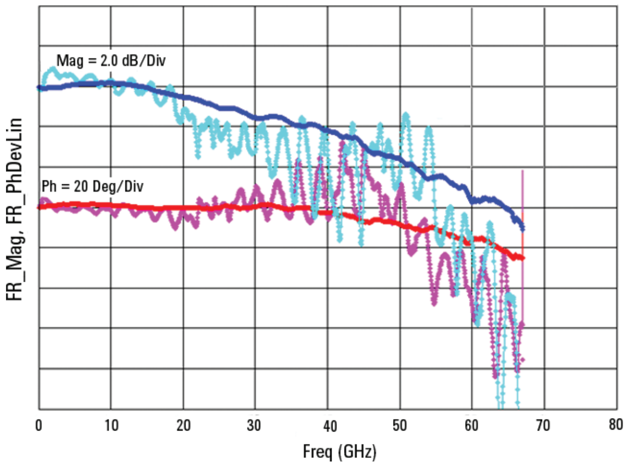


Figure 5. Plot of deviation from the ideal step for Keysight N2806A, dark blue (magnitude) and dark red (phase), versus popular shock line based generator, bright blue (magnitude) and bright pink (phase). Notice the lack of resonances in the spectral content of the Keysight generator, much more closely approximating the ideal step for more accurate and repeatable measurements.

Example Applications

There are many important uses for sub-10 ps pulse generators as technologies push into uncharted bandwidths and data rates. Below, we highlight just a couple of these applications.

Time domain reflectometry and transmissometry

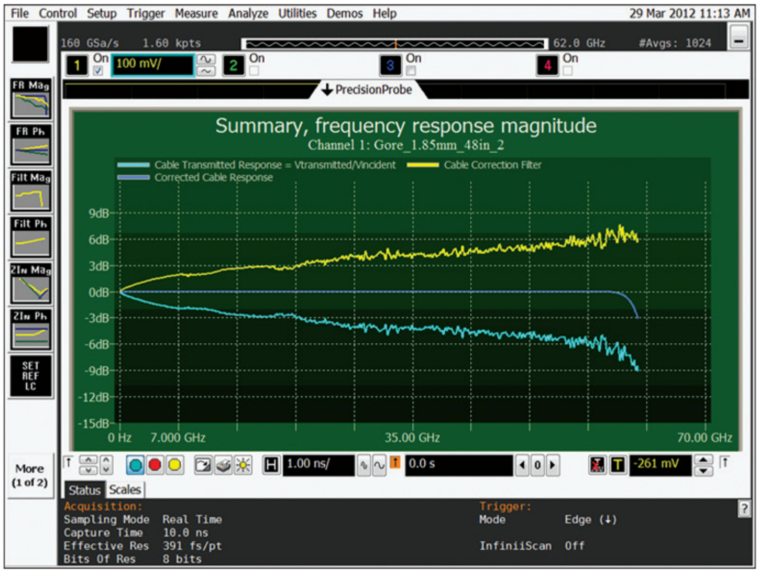
The interaction of a fast edge with a circuit element can be used to characterize the behavior of that element. Observing the signal that is reflected back by the circuit element is called time domain reflectometry (TDR). Similarly, observing the signal that is transmitted through the element is called time domain transmissometry (TDT). The combination of these techniques, both of which fall under the umbrella of network analysis, can fully characterize an element in a circuit so that its effects can be removed, modeled, or otherwise accounted for.

In the frequency domain, the total bandwidth over which the characterization is accurate depends on the frequency range of the spectral content of the fast edge. In order to characterize circuit elements beyond 40 GHz, a sub-10 ps edge is necessary to provide sufficient high frequency content. In these instances a pulse generator can be employed to accelerate the calibration edge to the speeds necessary to achieve the desired characterization bandwidth. In 2011 Keysight introduced its award winning PrecisionProbe software, which enables rapid TDT measurements to automatically remove the insertion loss of cables, probes, and fixtures in real time oscilloscope measurements. Now, in 2012 Keysight is introducing the N2807A PrecisionProbe advanced kit, demonstrated in Figure 6, which includes the N2806A Calibration pulse generator to enable insertion loss removal beyond 60 GHz. Using Keysight's DCA86100D sampling oscilloscope, the 54754A TDR module, and Keysight's N2806A Calibration pulse generator TDR/TDT measurements can be made beyond 40 GHz, as shown in Figure 7.

Step response and calibration

Having a known step with an extremely fast edge and a nearly ideal step response in the frequency domain is an invaluable tool in demanding step response and calibration measurements. Many test and measurement systems, as well as custom electrical and optical systems in research and industry, require calibration to very high frequencies using a fast, nearly ideal step. For example, a sub-10 ps pulse generator is an ideal piece of equipment to measure the rise time capabilities and calibrate the response of an oscilloscope.

Example Applications (continued)



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Acquisition:                                          Trigger:
Sampling Mode  Real Time                              Mode         Edge (↓)
Capture Time   10.0 ns
Effective Res  391 fs/pt                              InfiniiScan  Off
Bits Of Res    8 bits
```

Figure 6. Frequency response magnitude plot showing insertion loss correction of 1.85 mm cable using Keysight's PrecisionProbe advanced and 90000 Q-Series real time oscilloscope. The light blue is the uncorrected response of the cable, the yellow is the correcting filter applied by the scope. The dark blue is the corrected response of the cable, flat out to 62 GHz. This high bandwidth TDT is enabled by the 63 GHz of bandwidth on the oscilloscope and the sub-7 ps edge speeds generated by the Keysight N2806A calibration pulse generator.

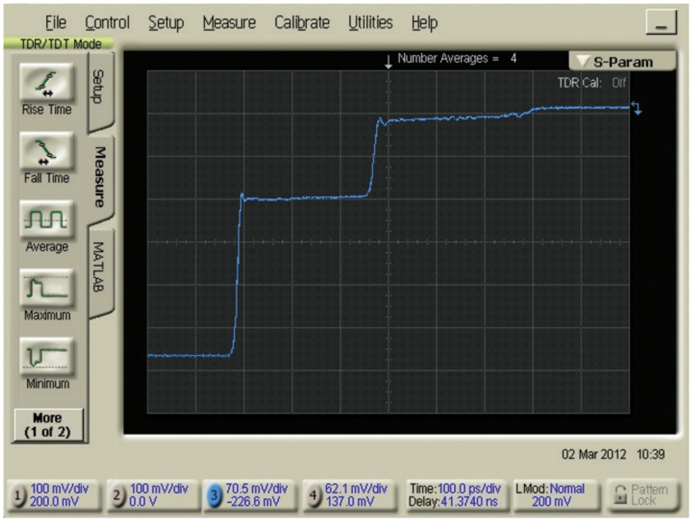

Figure 7. Incident and reflected step from high bandwidth TDR measurement on a broadband open circuit. The measurement was made using a Keysight DCA86100C sampling oscilloscope with two modules, 86118A 70 GHz electrical module and 54754A TDR module. The edge out of the TDR module was accelerated using the Keysight N2806A calibration pulse generator.

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Author Bio

Daniel Ruebusch manages strategic marketing of high performance oscilloscopes at Keysight Technologies. Daniel joined Keysight in 2011. He has past experience in semiconductor device physics and processing and consumer sales and marketing. Daniel holds a B.S. from Cornell University in both Electrical Engineering and Materials Science and an M.S. in Electrical Engineering from U.C. Berkeley. He is a published technical author.

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