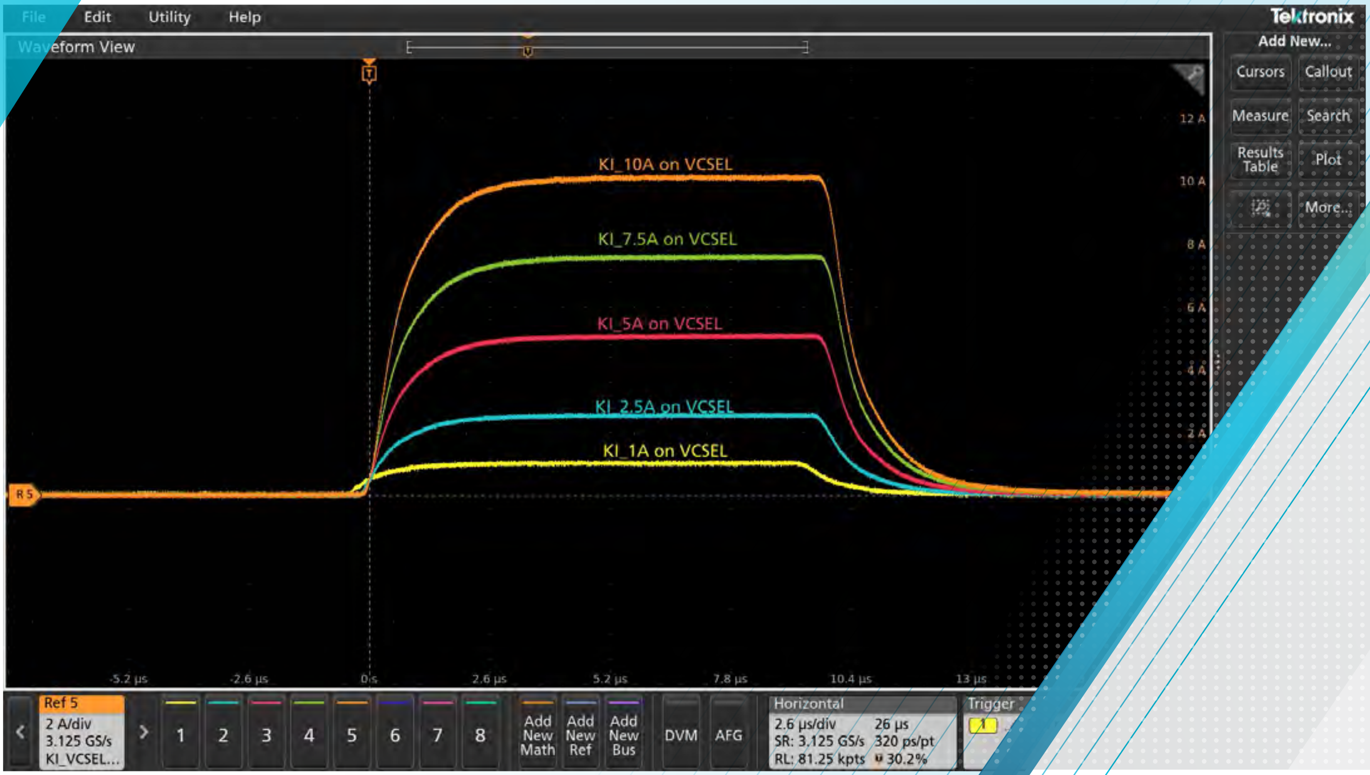
Generating Clean 10 μs Pulses with the 2601B-PULSE System SourceMeter® Instrument

APPLICATION NOTE



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A Tektronix Company

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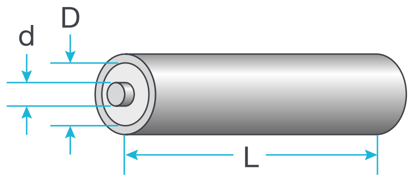
Introduction

The rapidly changing optical device industry demands equipment capable of responding quickly to test stimuli. Conventional Source Measure Units (SMUs) have typically been used for testing and measuring the response of most optical devices. As the demand for distance and velocity measurements in a 3D space has grown, Vertical Cavity Surface Emitting Lasers (VCSELs) have been widely used for depth information in 3D sensing. In many applications, VCSELs operate with pulse widths of a few nanoseconds and rise times of less than 1 ns. However, for wafer level or package level testing, pulses of tens of microseconds have been used because it is difficult to produce nanosecond pulses in test systems that have cables that are several meters in length. Some high-power illuminator VCSEL arrays require up to 10 A. Generating short pulses with rise times of just a few microseconds can be challenging. Keithley Instruments has introduced PulseMeter™ technology that supports 10 µs pulsing capability with 10 A currents and 10 V voltages. This application note introduces techniques to optimize cable connectivity to generate clean 10 µs pulses.

Cable Inductance

Various types of cables are best suited to different applications. Coaxial cables are widely used to transmit fast signals to a device under test (DUT). Each cable has its own characteristics, such as cable impedance, which is the relationship between its capacitance and its inductance. Cable inductance is the most critical factor in delivering clean 10 µs current pulses. The variables involved in determining this inductance are the center conductor's diameter, the distance to the outer shield, and the length (**Figure 1**). The relative permeability of coaxial cables, which depends on the insulating material, is typically 1. For example, if there is a coaxial cable with an inner diameter of 1.0mm, an outer diameter of 3.5 mm, a length of 1 m, and a relative permeability of 1 applied, then the inductance should be 250 nH, which is a typical coaxial cable inductance. For a cable with no outer shield, the induction could be much higher than that of a typical coaxial cable.



$$L_{coax} \approx \frac{\mu_0 \mu_r}{2\pi} \cdot \ln\left(\frac{D}{d}\right) \cdot L$$

Figure 1. Coaxial cable inductance

L_{coax} = Inductance of the coaxial cable in units of henries (H)

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$

μ_r = Relative permeability (generally 1 for most insulators)

D = Coaxial cable outer diameter

d = Coaxial cable inner diameter

L = Length of the coaxial cable

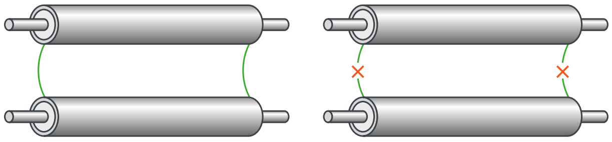
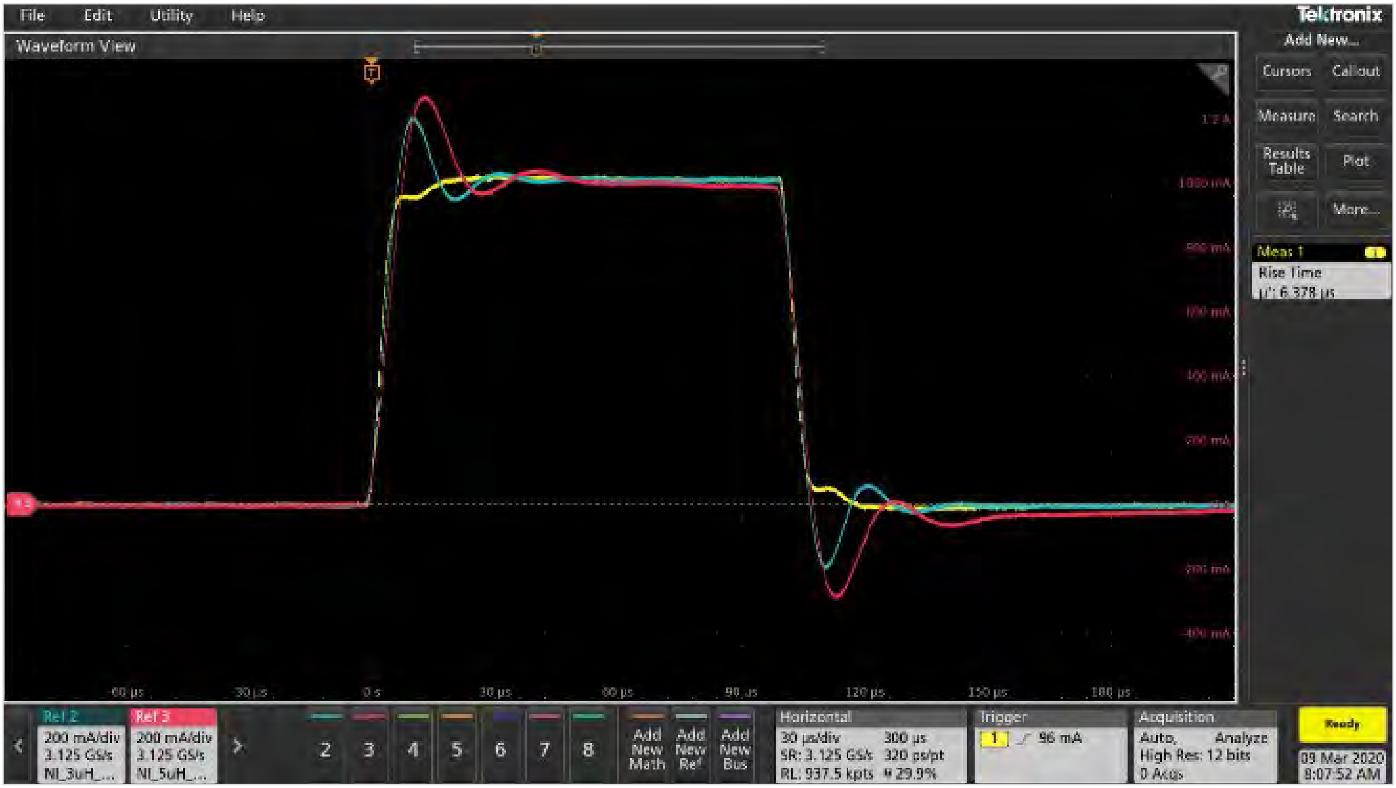


Figure 2. Coaxial cables, with shields connected (left) and shields disconnected (right).

In most cases, two coaxial cables are used in parallel to a DUT for high and low, as shown in **Figure 2**. The cable inductance of two cables must be higher than of a single cable. The problem is that the inductance of two cables is not simply twice the inductance of the single cable; it could be ~3–6 times higher than the inductance of the single cable. For example, a 1 m cable with 250 nH inductance can be 1.5 µH, not 500 nH, in two paralleled cables. The inductance can also vary at each cable placement. If the cables are placed far away from each other, this can create an extra inductance loop. Tying the shields of the two cables together at both ends of the cables is an effective way to fix this problem, reducing the inductance in the left-hand configuration in **Figure 2** to about 500 nH.

Oscillation, i.e., ringing, is the most significant challenge associated with highly inductive cabling for current pulses. Just as the capacitive loads can cause oscillation in voltage pulses, the inductive load has a negative impact on output current stability. **Figure 3** illustrates a 100 µs wide pulse on three different inductive loads: 1 µH, 3 µH, and 5 µH. This shows how more inductance produces greater instability on the pulse shape. This oscillation makes it hard to perform accurate measurements because the pulse cannot stabilize in a short period of time. Some instruments are designed to slow the rise time to provide a better pulse shape, but they require a longer settling time.



Meas 1
Rise Time
µ: 6.378 µs

Ref 2
200 mA/div
3.125 GS/s
NI_3uH_...

Ref 3
200 mA/div
3.125 GS/s
NI_5uH_...

Horizontal
30 µs/div 300 µs
SR: 3.125 GS/s 320 ps/pt
RL: 937.5 kpts 29.9%

Trigger
1 96 mA

Acquisition
Auto, Analyze
High Res: 12 bits
0 Acqs

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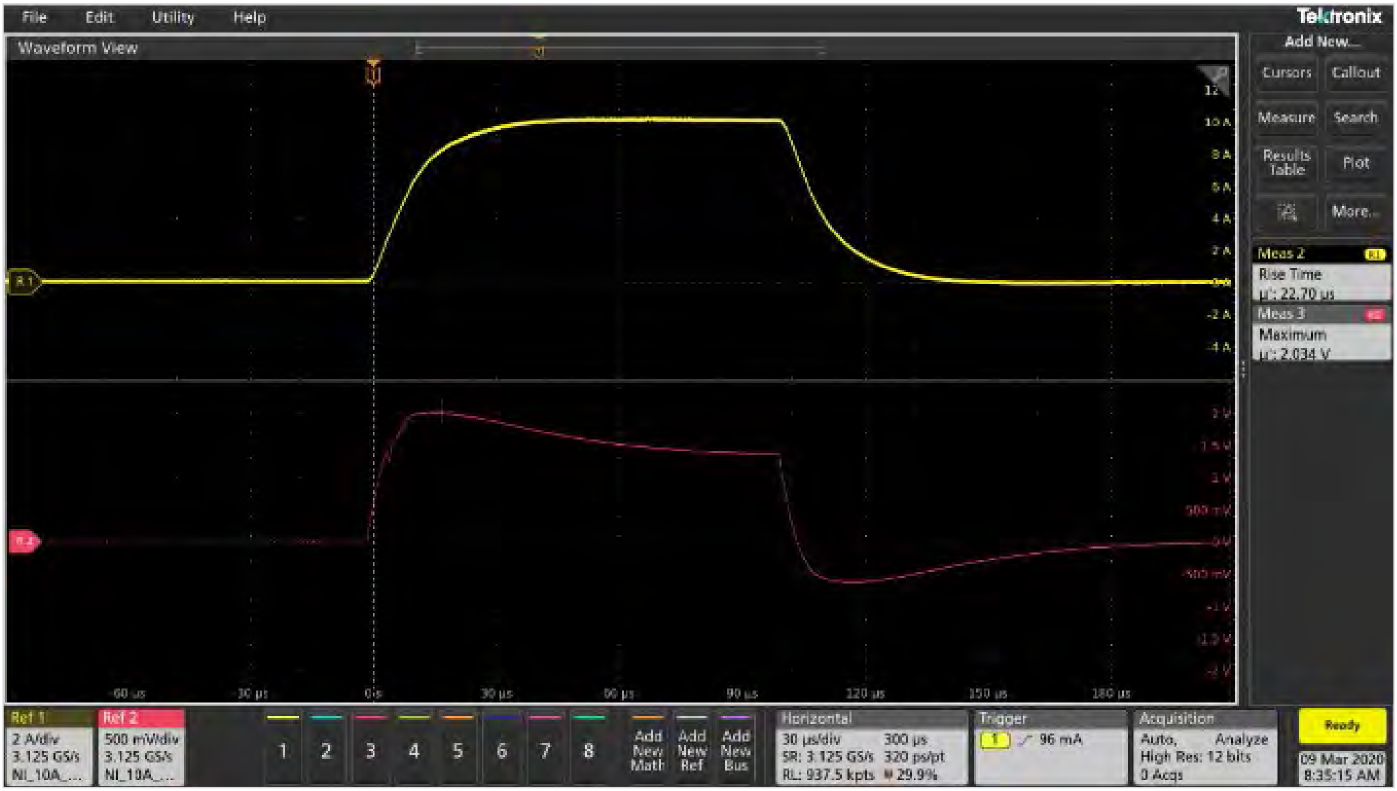
Figure 3. 1 A 100 µs pulses on 1 µH (yellow), 3 µH (blue), and 5 µH (red) inductors

Another issue with the inductance of the cable is the level of voltage required on the rising and falling edges of the pulse to energize and de-energize the inductance. In **Figures 4 and 5**, a pulse with a 22 µs rise time produces just 2 V at the rising edge, but a 1.6 µs rise time creates about a 10 V drop. The inductance forces a voltage burden on the instrument during pulse edges. The instrument must support these peak voltages or produce slower rise and fall rates. The more serious challenge of the high voltage peak for fast pulses is settling in time to make a precise voltage measurement.

Keithley provides SC-182 low inductance cables, which have less than 150 nH of inductance per meter for better performance in fast pulse testing. With the outer shields of two 1 m cables shorted at both ends, the inductance would be less than 300 nH. Keithley also provides regular 50 Ω coaxial cables, which have about 350 nH of inductance per meter. Just as with low inductance cables, shorting the shields of these 50 Ω cables together at both ends reduces the inductance and improves pulse performance.



Meas 2
Rise Time
μ': 22.70 μs

Meas 3
Maximum
μ': 2.034 V

Ref 1
2 A/div
3.125 GS/s
NI_10A_...

Ref 2
500 mV/div
3.125 GS/s
NI_10A_...

Horizontal
30 μs/div 300 μs
SR: 3.125 GS/s 320 ps/pt
RL: 937.5 kpts 29.9%

Trigger
1 96 mA

Acquisition
Auto, Analyze
High Res: 12 bits
0 Acqs

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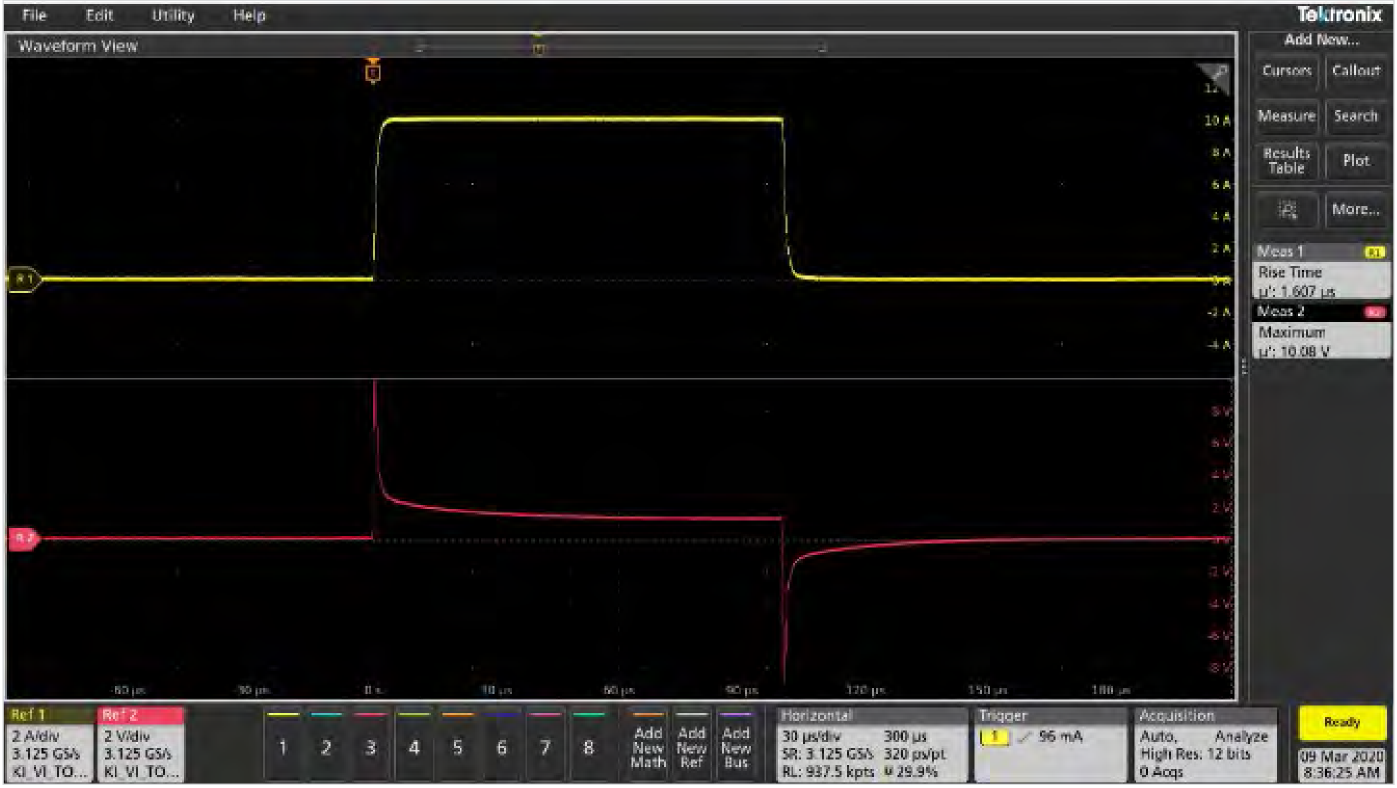
Figure 4. 22 μs rise time 10 A pulse on 1 μH inductor



Meas 1
Rise Time
μ': 1.607 μs

Meas 2
Maximum
μ': 10.08 V

Ref 1
2 A/div
3.125 GS/s
KI_VI_TO...

Ref 2
2 V/div
3.125 GS/s
KI_VI_TO...

Horizontal
30 μs/div 300 μs
SR: 3.125 GS/s 320 ps/pt
RL: 937.5 kpts 29.9%

Trigger
1 96 mA

Acquisition
Auto, Analyze
High Res: 12 bits
0 Acqs

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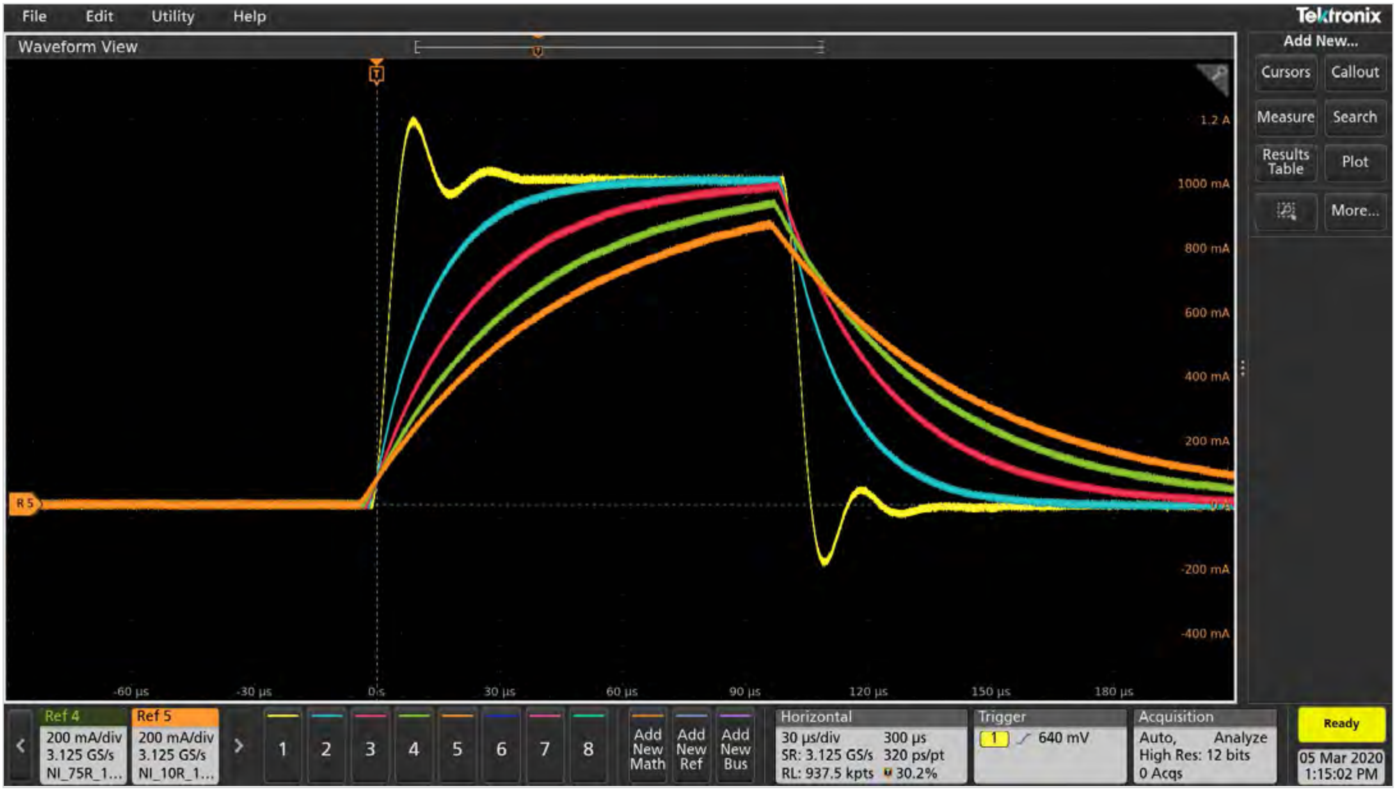
Figure 5. 1.6 μs rise time 10 A pulse on 1 μH inductor

No Tuning

Several instruments support addressing the negative impact that load and cable resistance and inductance have on pulse edges by providing the ability to “tune” the instrument’s behavior to account for the impact. Changing the gain-versus-frequency behavior of the control loop or changing the pulse edge rates are two ways to tune the pulse shape. Any change to the load-cable resistance-inductance requires re-tuning the instrument.

The design of the 2601B-PULSE System SourceMeter® instrument supports load-cable resistances of up to 20 Ω and inductances of up to 3 µH. The pulse edges remain virtually unchanged for all resistances of 20 Ω or less and all inductances of 3 µH or less. If the load-cable resistance changes. the pulse shape remains fast and clean.

Figure 6 demonstrates how the resistance of the DUT influences the pulse shape. As the resistance goes higher, the rise time gets slower. This is the natural and typical behavior of a regular source measure unit. The high impedance load puts voltage burden on the current source. This high impedance increases closed loop gain, which is low bandwidth, resulting in slow pulse edges. The pulse current level sweep test is commonly used in Light-Current-Voltage (LIV) measurements of optical devices. Though a pulse is once tuned at a specific current level, it doesn’t follow that the tuning characteristic is applicable to every other current level. The regular SMU current amplitude sweep shown in **Figure 7** illustrates that not all the waveforms have a flat and stable pulse top with a single tuned factor. This instability of the sweep current waveform is reflected in an inaccurate LIV measurement. This sets a limitation to use some narrow current range or requires tuning the pulse for every other current level.



Ref 4: 200 mA/div, 3.125 GS/s, NI_75R_1...
Ref 5: 200 mA/div, 3.125 GS/s, NI_10R_1...
Horizontal: 30 µs/div 300 µs, SR: 3.125 GS/s 320 ps/pt, RL: 937.5 kpts 30.2%
Trigger: 1 640 mV
Acquisition: Auto, Analyze, High Res: 12 bits, 0 Acqs
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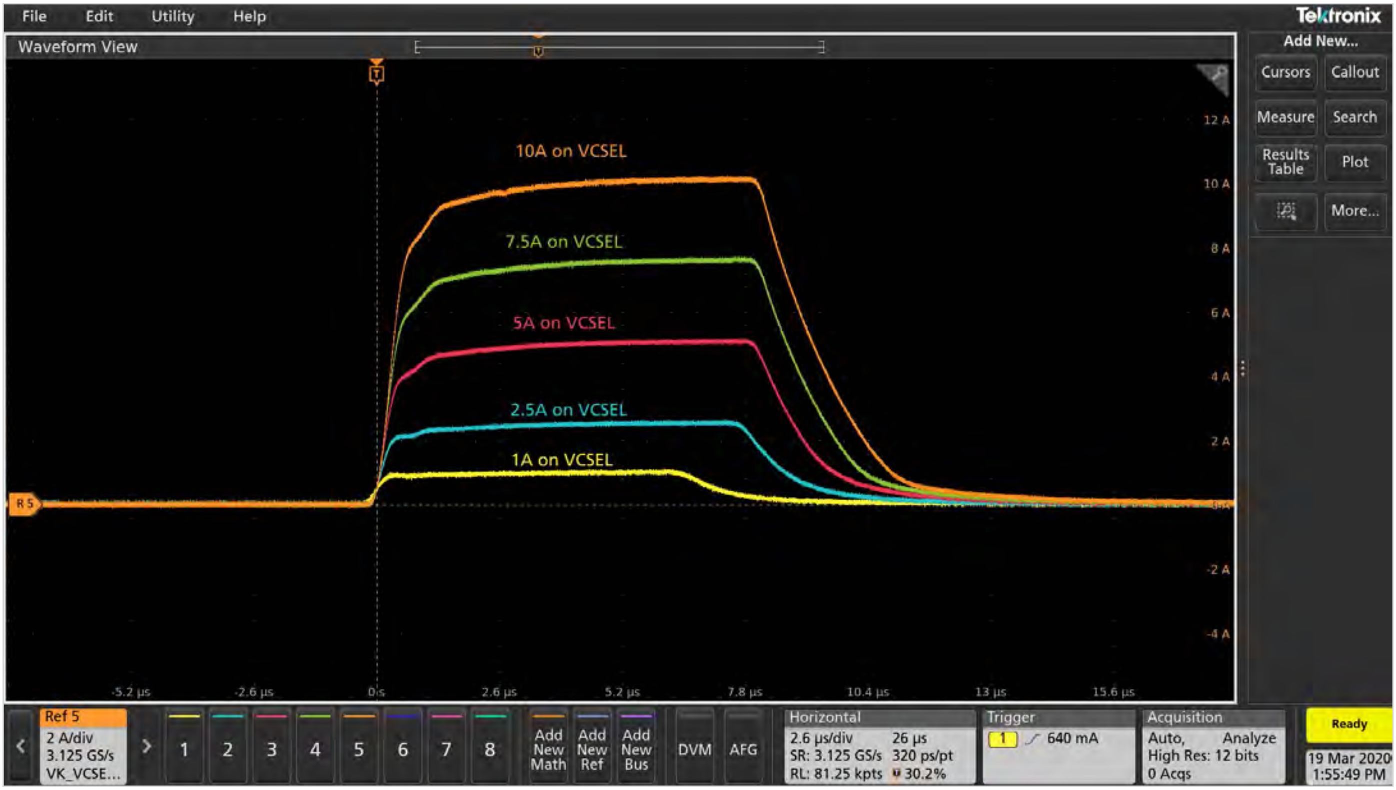
Figure 6. Regular SMU 1 A 100 µs pulse on 1 Ω (yellow), 2.5 Ω, 5 Ω, 7.5 Ω, and 10 Ω (amber) resistors



Ref 5
2 A/div
3.125 GS/s
VK_VCSE...

Horizontal
2.6 µs/div 26 µs
SR: 3.125 GS/s 320 ps/pt
RL: 81.25 kpts 30.2%

Trigger
1 640 mA

Acquisition
Auto, Analyze
High Res: 12 bits
0 Acqs

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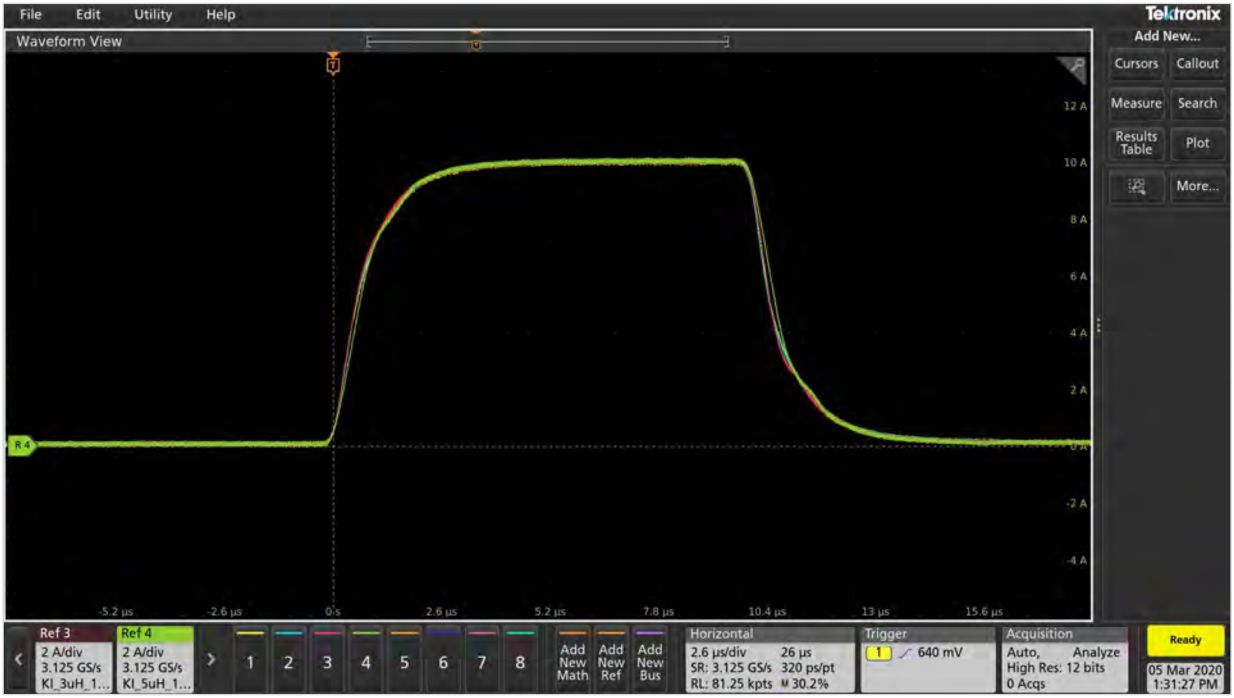
Figure 7. Regular SMU amplitude sweep at 1 A (yellow), 2.5 A (blue), 5 A (pink), 7.5 A (green), and 10 A (amber) on a VCSEL

The 2601B-PULSE combines all the functionality of a standard source measure unit with fast pulsing capability. It can produce a maximum current of 10 A and a maximum voltage of 10 V, and pulse widths as short as 10 µs, and it requires no tuning. As long as the unit is operating within its operating range and has 3 µH total inductance, including cables and the DUT, the unit will generate clean 10 µs pulses. Based on Keithley's patent-pending PulseMeter technology, this design allows for fast edges with no overshoot for a wide range of load impedances.

Figure 8 shows the results for a 10 A, 10 µs pulse with three different load inductances. The pulse shape holds at 5 µH load inductance without tuning, even though the maximum specified load inductance is 3 µH. **Figure 9** shows the results of another experiment made with various load resistances from 1 Ω to 10 Ω with a 1 A, 10 µs pulse. Given that a resistance of 10 Ω is quite a high impedance, it would normally slow the rise time, much as is shown in Figure 6; here, however, all the waveforms are most likely identical, like a single waveform.



Ref 3: 2 A/div, 3.125 GS/s, KI_3uH_1...

Ref 4: 2 A/div, 3.125 GS/s, KI_5uH_1...

Horizontal: 2.6 µs/div, 26 µs, SR: 3.125 GS/s, 320 ps/pt, RL: 81.25 kpts, 30.2%

Trigger: 1, 640 mV

Acquisition: Auto, Analyze, High Res: 12 bits, 0 Acqs

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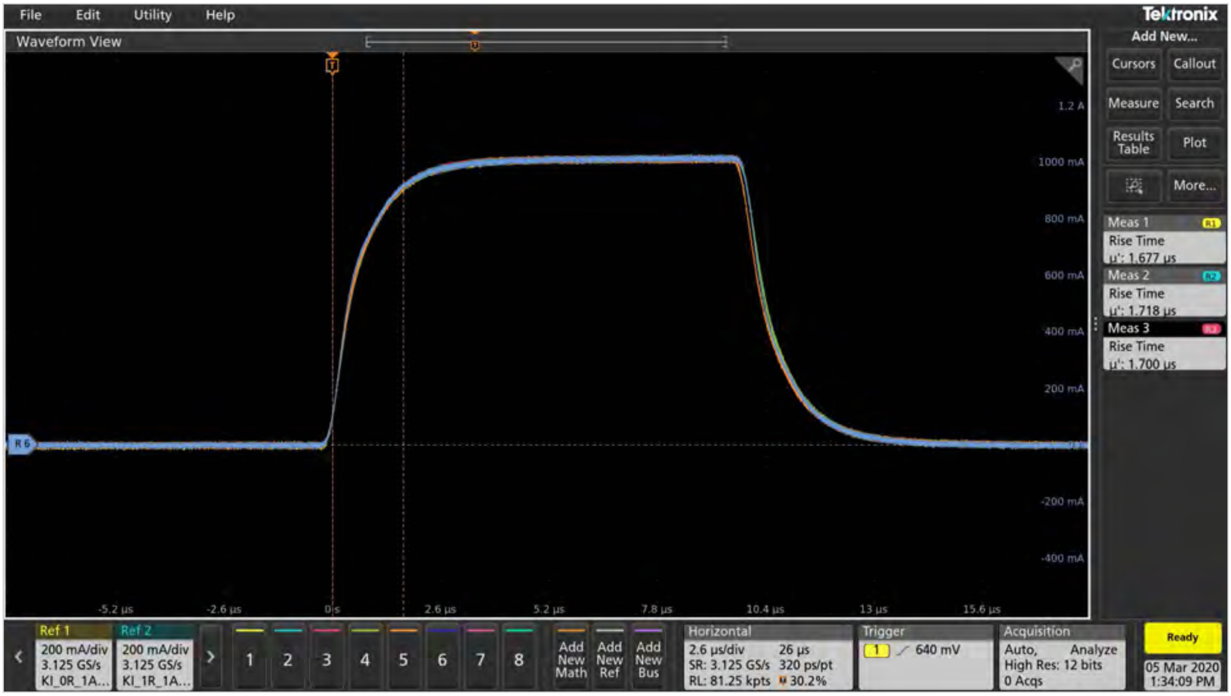
Figure 8. 2601B-PULSE 10 A pulse on 1 µH, 3 µH, and 5 µH inductors



Meas 1 (R1): Rise Time µ': 1.677 µs

Meas 2 (R2): Rise Time µ': 1.718 µs

Meas 3 (R3): Rise Time µ': 1.700 µs

Ref 1: 200 mA/div, 3.125 GS/s, KI_0R_1A...

Ref 2: 200 mA/div, 3.125 GS/s, KI_1R_1A...

Horizontal: 2.6 µs/div, 26 µs, SR: 3.125 GS/s, 320 ps/pt, RL: 81.25 kpts, 30.2%

Trigger: 1, 640 mV

Acquisition: Auto, Analyze, High Res: 12 bits, 0 Acqs

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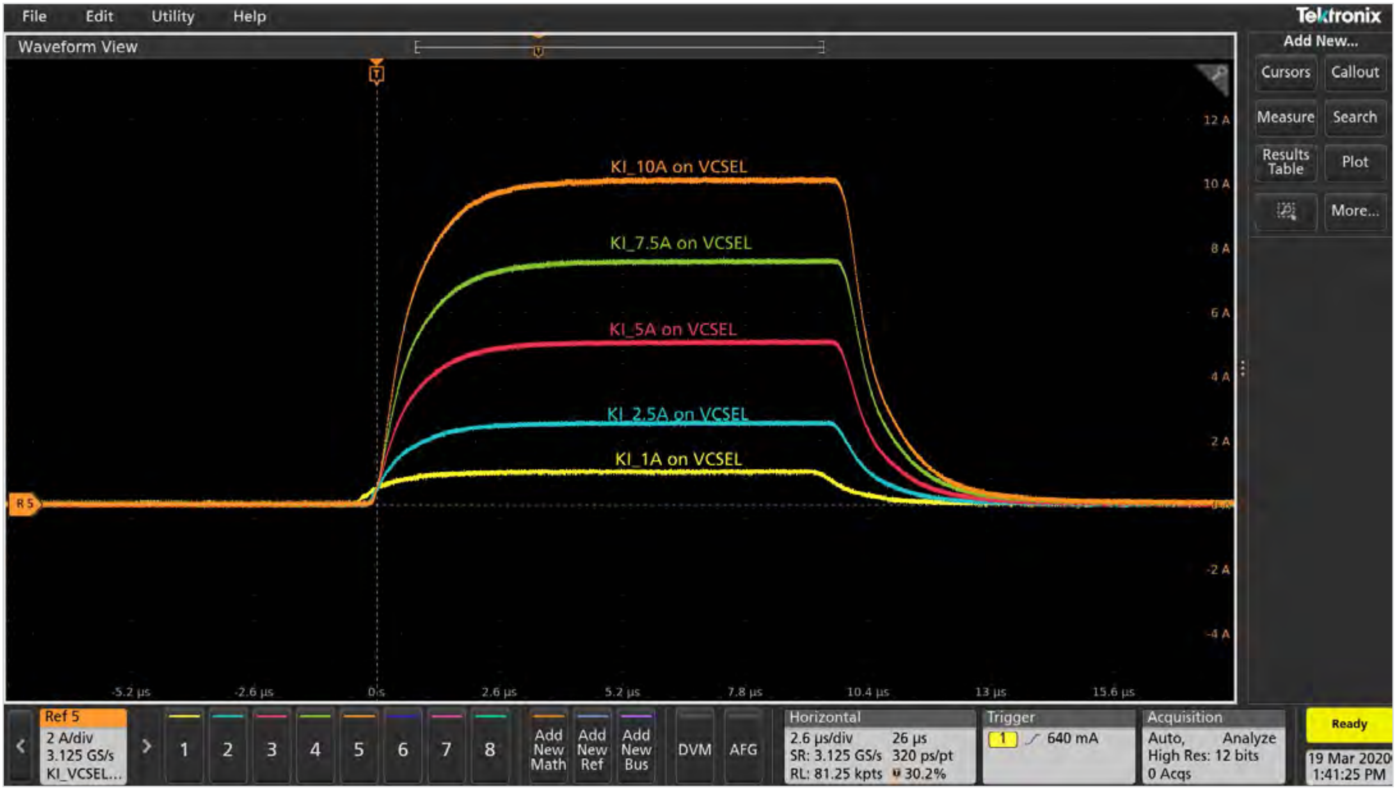
Figure 9. 2601B-PULSE 1 A pulse on 1 Ω, 2.5 Ω, 5 Ω, 7.5 Ω, and 10 Ω resistors

Figure 10 shows the type of current amplitude sweep typically used for LIV measurements, offering a consistent rise time and pulse width for each current level. When compared with **Figure 7**, **Figure 10** shows a flat, consistent pulse width for each level and a consistent rise time, which allows for a stable, more consistent optical measurement because current change is directly related to changes in optical power and light intensity.



Ref 5
2 A/div
3.125 GS/s
KI_VCSEL...

Horizontal
2.6 µs/div 26 µs
SR: 3.125 GS/s 320 ps/pt
RL: 81.25 kpts 30.2%

Trigger
1 640 mA

Acquisition
Auto, Analyze
High Res: 12 bits
0 Acqs

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Figure 10. 2601B-PULSE amplitude sweep at 1 A, 2.5 A, 5 A, 7.5 A and 10 A on a VCSEL

2601B-P-INT Replacement BNC Connector Box

The 2601B-PULSE is provided with the 2601B-P-INT Replacement BNC Connector Box. When mounted on the rear of the 2601B-PULSE, this box provides the interconnections needed for switching the coaxial connectors between SMU mode and fast pulse mode. It enables switching automatically between pulse measurements and DC measurements. That means both a device's on-state and off-state characteristics can be measured without an external switching system.

The 2601-P-INT also provides an optical safety interlock function. The 2601B-PULSE's output voltages are not a safety shock hazard; however, this model is widely used in testing laser diodes and VCSELs, which can produce an eye safety hazard. **Figure 11** illustrates the 2601B-P-INT's optical interlock function. Activating this function requires placing a jumper on the 2601B-P-INT in the interlock enable position, providing an external 5 VDC power source, and setting the 2601B-PULSE to report the state of the interlock. When interlocked, the HI and LO are shorted to each other so the 2601B-PULSE cannot energize an optical device.

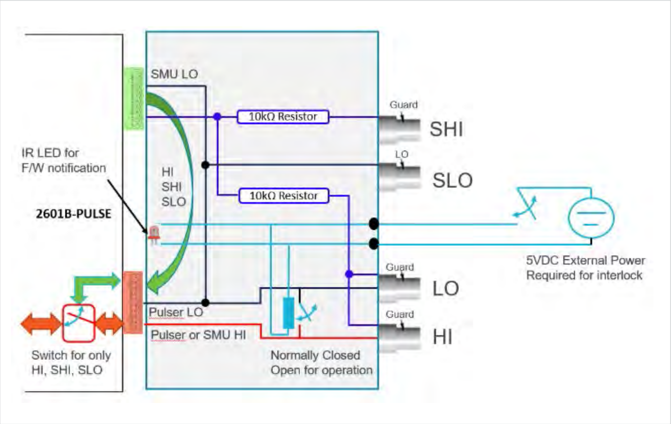

Figure 11a. Block diagram of the 2601B-P-INT Replacement BNC Connector Box

Figure 11b. 2601B-P-INT connections

Another consideration when using coaxial cable is that the guards of HI and LO must be shorted at the end of the DUT side to minimize the cable inductance. Guard shorting allows forming a closed loop at the shield side of the cables. If a 10 A current flows over the high to the low, the current will induce some amount of current on the shields flowing backward from the low side to the high side at the pulse rising edge. This current induction is a natural phenomenon that cannot be prevented. Be careful to avoid affecting this current to the voltage sensing cables by placing the sensing cables as far as possible away from the high and the low.

The interlock box also supports BNC connectors that allow the output to be easily connected to the DUT. However, great performance in low current measurements shouldn't be expected because of the coaxial connection without guards. The 2601B-P-INT has guard on the shields of the coaxial connection. Exercise caution when working with the shields of the connecters, but these guards carry a maximum of 40 V with the 2601B-PULSE, so they don't represent a safety issue. Guards should not be connected to any ground or any low. Guard connections not only support good performance in low current measurement but also in short current settling during off-state current measurement. For most optical device tests, low current sourcing and measurement are required in the reversed current or reversed voltage measurement.

Pulse Operation

The 2601B-PULSE does not support manual operation for the fast pulse mode through the front panel controls because the pulses are too short to be handled manually. The SMU mode can be controlled through the front panel. Two methods of operation can be used to control the instrument in the fast pulse mode. The first of these methods, KickStart software (versions later than V2.3.0), supports the 2601B-PULSE, providing basic operations like complete waveform measurement and pulse top measurement. **Figure 12** shows the complete waveform measurement of an optical device with a 3 A, 10 μs pulse. The I-V curve measurement shown as **Figure 13** is the basic measurement for the optical device characteristics. KickStart also supports setting the test conditions, obtaining results data, and plotting the data with ease.

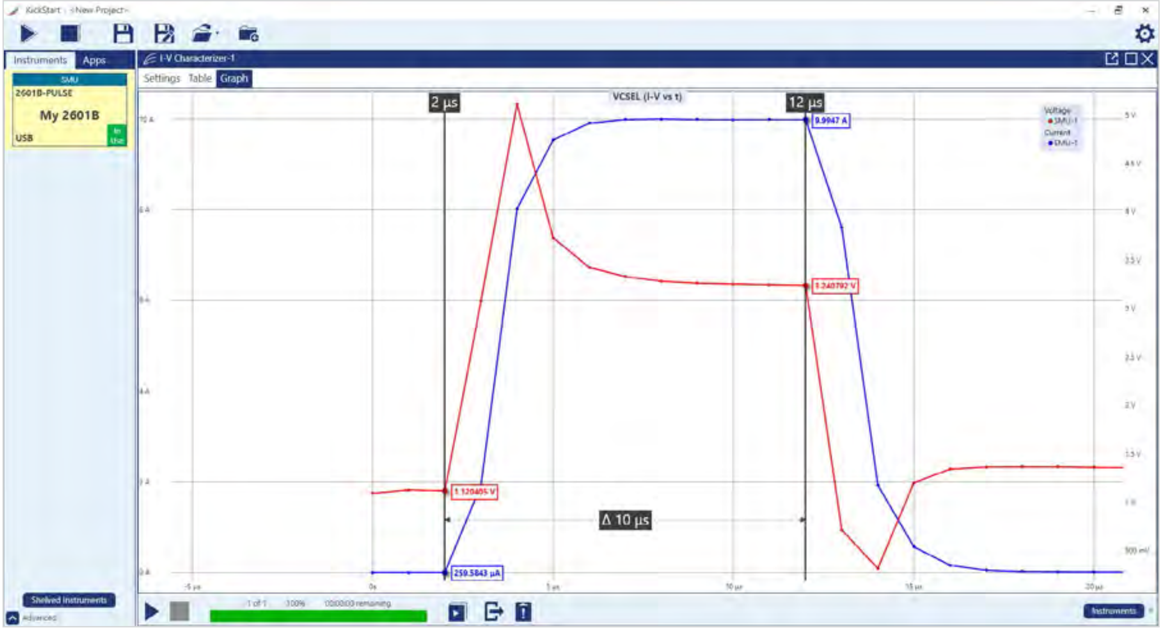

Figure 12. 3 A, 10 μs complete waveform measurement

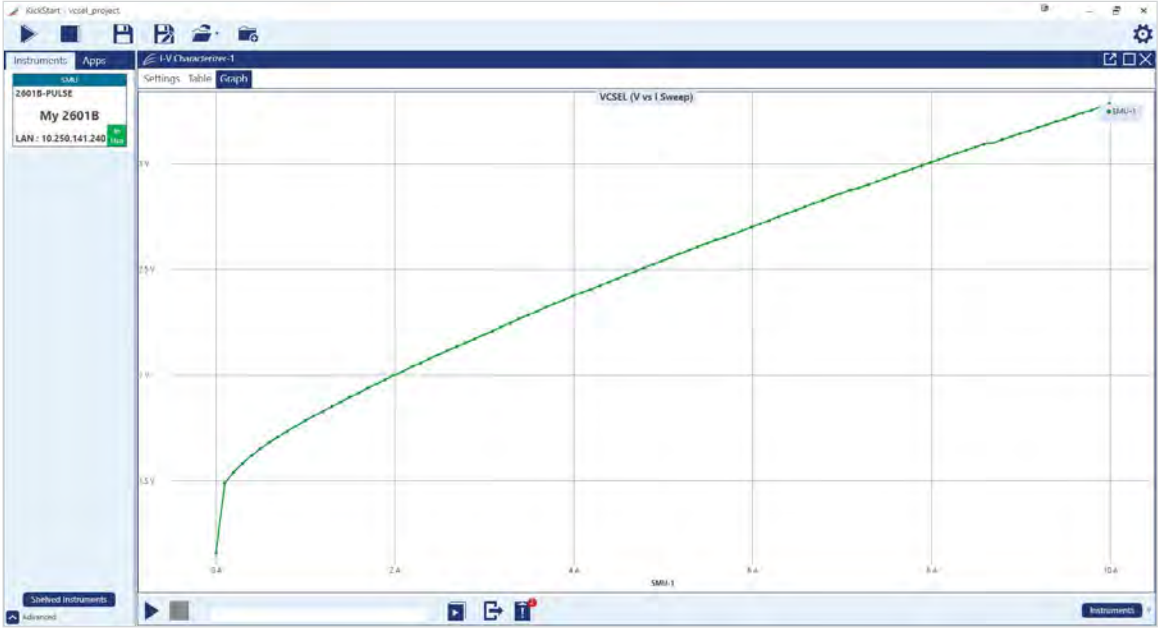

Figure 13. Pulse top sweep measurement 0 A to 10 A

Figure 14 is a simple example of a TSP script to perform a 10-pulse current sweep in a trigger model. There are some difference from a regular 2600 SMU trigger model. A minimum of three timers are required for this kind of measurement in the regular trigger model to control pulse period, pulse width, and measurement start. But in the new pulse trigger model, a single trigger is enough for pulse period, and there are separate commands for pulse width (smua.trigger.source.pulsewidth), and measurement start (smua.trigger.measure.delay). The reference manual for the 2601B-PULSE describes all the details of using scripts and how to build the trigger model to generate the short pulse.

```
reset()                                                  -- Restore default settings
smua.nvbuffer1.clear()                                   -- Clear the measure buffer
smua.trigger.count = 10                                  -- Set the number of pulses to 10.
trigger.timer[1].count = 9                               -- Generate additional trigger events for the pulse sweep
trigger.timer[1].delay = 1e-3                            -- Pulse period.
trigger.timer[1].passthrough = true                      -- First trigger passes through immediately
trigger.timer[1].stimulus = smua.trigger.ARMED_EVENT_ID  -- Specify which event starts the timer.
smua.trigger.source.action = smua.ENABLE                 -- Enable source level changes during the sweep.
smua.trigger.source.lineari(1, 10, 10)                   -- Specify a 10-point linear pulse sweep from 1 A to 10 A.
smua.trigger.source.pulsewidth = 10e-6                   -- Set the source pulse width to 10 microseconds.
smua.trigger.source.stimulus = trigger.timer[1].EVENT_ID -- Pulse start when the trigger timer event occurs
smua.trigger.measure.action = smua.ENABLE                -- Pulse Mode Enable
smua.pulser.measure.delay = 9e-6                         -- 9 microseconds measure delay after pulse start
smua.trigger.measure.v(smua.nvbuffer1)                   -- Measure voltage and save in nvbffer1
smua.pulser.enable = smua.ENABLE                         -- Enable pulse mode.
smua.source.output = smua.OUTPUT_ON                      -- Turn the source output on.
smua.trigger.initiate()                                  -- Initiate the trigger model.
waitcomplete()                                           -- Wait for pulse commands to complete.
```

Figure 14. TSP script example for a 10-pulse sweep measurement

Conclusion

Every cable has its own characteristics, which can affect short pulse performance. If any coaxial cable is used for this application, it is highly recommended that the shields of the HI and LO cables be shorted at both ends to reduce the cable inductance. Even with minimum cable inductance, generating 10 µs, 10 A clean pulses can still be challenging in various devices. Keithley Instruments introduced the 2601B-PULSE using new PulseMeter technology that requires no tuning for any kind of device as long as the unit is operated within its specification. The 2601B-P-INT provides an interlock for optical safety and a convenient solution for using high current pulse measurement and low current DC measurement together without changing connections.

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