Testing Laser Diode Modules and VCSELs with the 2601B-PULSE System SourceMeter® Instrument and KickStart Instrument Control Software

APPLICATION NOTE

KEITHLEY
A Tektronix Company

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Introduction

Laser diodes (LDs) and VCSELs (Vertical Cavity Surface Emitting Lasers) are the primary components used in optical communications, spectroscopy, 3D sensing and imaging, and a host of other important applications. As the demand for these applications grows, so does the need for the basic components themselves. This demand requires greater emphasis on developing accurate, cost-effective test strategies.

A typical LD module consists of a laser diode and a back facet monitor photodiode. Temperature-controlled LD modules also include a thermoelectric controller (TEC) and a thermistor to facilitate precise regulation of the LD's operating temperature, as illustrated in **Figure 1**. (High speed LD modules may also carry an integrated modulator chip that's not shown in **Figure 1**.)

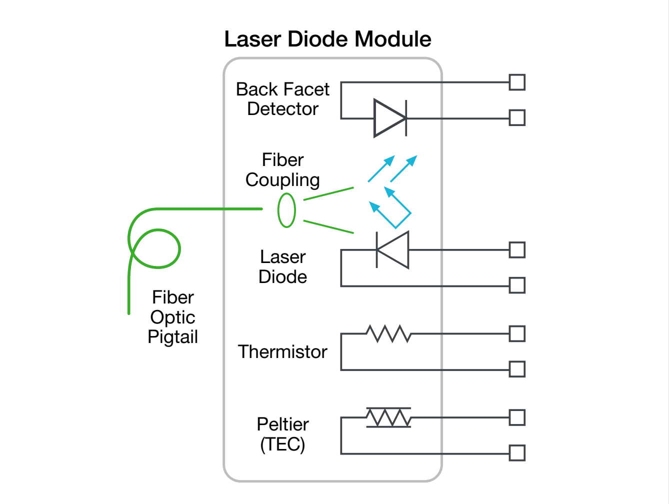


Figure 1: Typical laser diode module.

A VCSEL has a more complicated semiconductor structure than a standard laser diode, but typically a less complicated package. A classic cross-section of a VCSEL is shown in **Figure 2**. Unlike edge-emitting laser diodes, the VCSEL can be tested on wafer. This presents new opportunities and challenges in testing that will be addressed later in this application note.

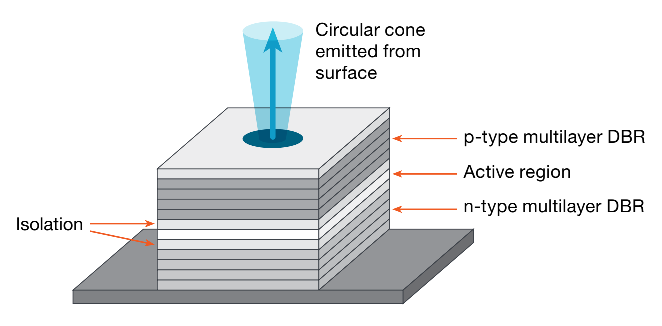


Figure 2: A Simplified VCSEL Structure.

It's important to remember that, with either device type, there are many testing steps taken in the value stream from R&D to manufacturing process. R&D involves lots of testing and measuring to achieve a breakthrough or the development of new intellectual property. The tools used in R&D are designed for flexibility—allowing you to adjust testing requirements and explore "what if" scenarios. The nature of manufacturing requires testing each component prior to the next step in assembly. For example, the cost of scrapping a complete laser module due to a failed back facet monitor photodiode is much greater than the cost of providing 100% testing of the photodiode component prior to the assembly step. High speed, flexible test solutions are essential to minimize the cost of the test.

This app note looks at both hardware and software tools that provide the results required in today's R&D labs.

Test Descriptions

During DC testing, the characteristics of interest for the LD or VCSEL module include:

- Laser forward voltage
- Kink test or slope efficiency (dL/dI)
- Threshold current
- Monitor (back facet) reverse-bias voltage
- Monitor (back facet) current
- Monitor (back facet) dark current
- Optical output power

The most common subset of the characteristics can be measured in a test known as the LIV test sweep. In R&D, this test helps the researcher and engineer identify key characteristics of their designs which may have the potential for commercialization. In manufacturing, this test identifies failed assemblies early in the test process, so expensive non-DC domain test systems are more cost-effective when testing the remaining higher yield components. **Figure 3** shows a common instrument configuration used to perform the LIV test sweep.

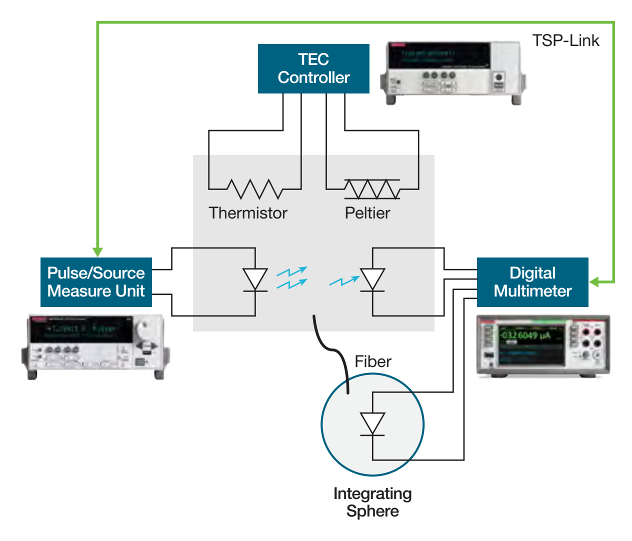


Figure 3: Typical block diagram of LIV instrumentation.

LIV Test Sweep

Forward Voltage Test

The forward voltage (V_F) test verifies the forward DC characteristics of the LD. Current (I_F) is swept and voltage drop across the LD is measured.

Some high powered LDs may require current (I_F) sweeps up to 2–3 A, usually in increments of 1 mA. Most need sweeps up to 1 A with 0.5 mA or 0.25 mA steps. Time per test sweep should be in the range of a few milliseconds for DC sweeps. The typical measurement range is 0–10 V and microvolt-level resolution is often required.

VCSELs have typically been lower powered devices requiring current (I_F) sweeps up 30 mA, with current steps of 1 µA. But that has changed as higher power VCSELs and arrays are being used in applications like LIDAR – light detection and ranging, for automotive and ADAS vehicle systems. Unfortunately, higher current runs the risk of device self-heating that could damage if not destroy the device. Thus, short pulse width sweeps, as short as 10 µs are used to test the VCSELs to minimize device heating and enable accurate measurements.

For the pulse test, we can use the 2601B-PULSE System SourceMeter 10 µs Pulser/SMU instrument to source pulsed current to the laser and measure the corresponding voltage drop.

Light Intensity Measurement

Light intensity (L) measurements verify the light output of the LD. Light output power increases as drive current is increased and the output of this test is usually displayed in milliwatts.

For light measurements, photodiode or photodetector is exposed to the output of the laser diode. This radiation is absorbed, and a current is produced by the detector. This resulting current is measured with a picoammeter, electrometer (a highly refined DC multimeter), or a precision digital multimeter. Typically, a measurement range of 100 nA is more than adequate for many lasers.

The returned photocurrent can then be used to determine the optical power of the device under test. Optical power measurements require a calibrated detector or integrating sphere. The calibration information, or responsivity (R), is a wavelength-dependent value determined during the calibration process. To calculate the optical power from a photocurrent, use the following equation:

$$L = I_p/R$$

where:

L = Optical power of the light source (watts)

I_p = Current from the detector. Commonly called photo-current (amps)

R = Responsivity of the detector at the wavelength of choice (amps/watt)*.

* The responsivity curve is provided when the detector or sphere/detector assembly has been calibrated.

The current measured by the detector is divided by the responsivity of the detector at the wavelength of interest. The result is the optical power impinging on the detector.

Lasing Threshold Current Test

The threshold current is the current at which the LD starts lasing. One technique for threshold determination is the second derivative technique. The threshold for this method is defined as the first maxima of the second derivative of the light output and is a calculation based on the light measurement (L). This is highlighted in **Figure 4**.

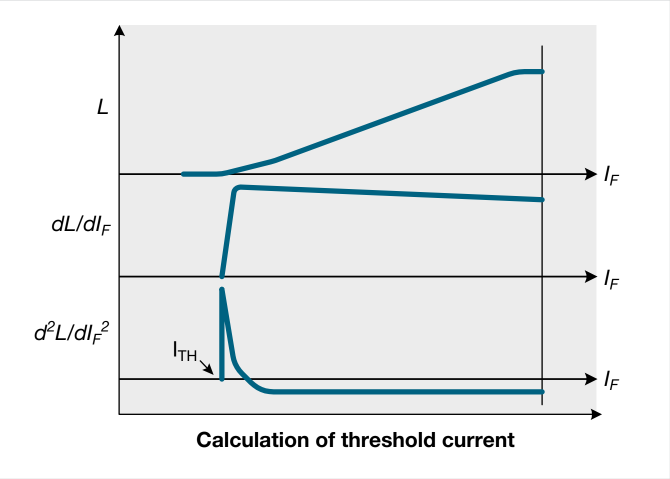


Figure 4: Graphical Calculation of Threshold Current.

Back Facet Monitor Diode (BFMD) Test

This test verifies the response of the back facet detector photodiode (also reverse-biased) to increase light output of the LD as the drive current is increased. Typical current measurement range is 0–100 mA and the required resolution is 0.1 mA. This measurement is typically performed with a picoammeter, electrometer or precision digital multimeter as long as it offers an acceptable low current measurement range. Typically, a measurement range of 100 nA is more than adequate for low powered optical devices.

Kink Test/Slope Efficiency

This test verifies the proportionality of the relationship between the drive current (I_F) and the light output (L) as depicted in **Figure 5**.

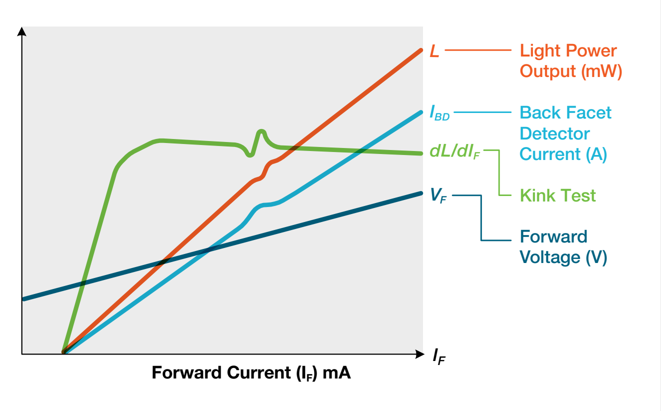


Figure 5. Typical Suite of LIV Curves.

The relationship between the drive current (I_F) and the light output power (L) should be linear about the nominal operating range. If the relationship is truly linear over the tested range, the first derivative of the curve will be a nearly horizontal line. This is graphed as dL/dI_F. The first derivative will tend to amplify any bumps or kinks in the light/current (L-I) curve. If this curve has any significant "kinks" or, in other words, is not smooth, the laser is considered defective. If operated at the I_F value corresponding to the "kink," the light output will not be proportional. The maximum value of the second derivative of the L vs. I_F curve can be used to calculate the threshold current, which is the value of the drive current at which the LD starts "lasing" or outputting significant light.

The kink and slope efficiency of a particular device are also calculations based on the analysis of the light measurement (L).

Temperature Testing

The LIV test is often performed at more than one laser diode temperature. In some cases, the LD is tested at both the nominal temperature and the extremes of the device specification, such as –40°C, 25°C and 85°C. Another common strategy is to perform the LIV test at several temperatures, such as 5°C, 10°C, 15°C, 20°C, 25°C, 30°C and 35°C. Then, these families of LIV curves are analyzed to ensure the device meets the specification.

Test System Configuration

As shown in **Figure 6**, a DC and Pulsed LIV test system includes a 2601B-PULSE Pulser/SMU, a 2510-AT Autotuning TEC SourceMeter instrument, a DMM7510 Digital Multimeter and a PC equipped with a GPIB interface card.

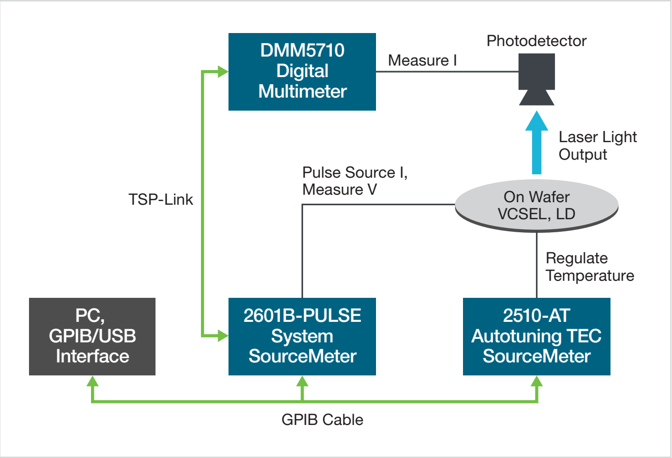


Figure 6: Typical LIV Test Setup for an LD Module. The 2601B-PULSE is used to characterize the laser diode or VCSEL. The DMM7510 monitor's the light output while the 2510-AT is controlling the LD module temperature. Can also be used to test VCSELs without the TEC controller.

VCSELs are the only type of lasers that lend themselves to testing at the wafer level. For production testing, a wafer prober makes the electrical connection to each device through a probe card. The prober station also positions the optical detector directly over the devices. The characterization can then be performed using a single 2601B-PULSE SourceMeter instrument.

If the probe card can connect to many devices simultaneously, then a system designed for multi-point testing should be constructed to test all of the devices each time the probe card makes contacts to the wafer. Due to the high number of devices on a wafer, a scanning approach to testing multiple devices may be too time consuming. Using many pairs of instruments to test multiple devices in parallel is often the optimum solution for applications that require high throughput.

The 2601B-PULSE System SourceMeter is an industry-leading high current/high speed pulser with measure plus the full functionality of a traditional SMU. The instrument offers leading 10 A current pulse output at 10 V with a pulse width minimum of 10 µs, perfect for testing vertical cavity surface emitting lasers (VCSEL) used in LIDAR and facial recognition, LEDs for lighting and displays, semiconductor device characterization, surge protection testing, and so much more. An example output pulse is shown in **Figure 7**.

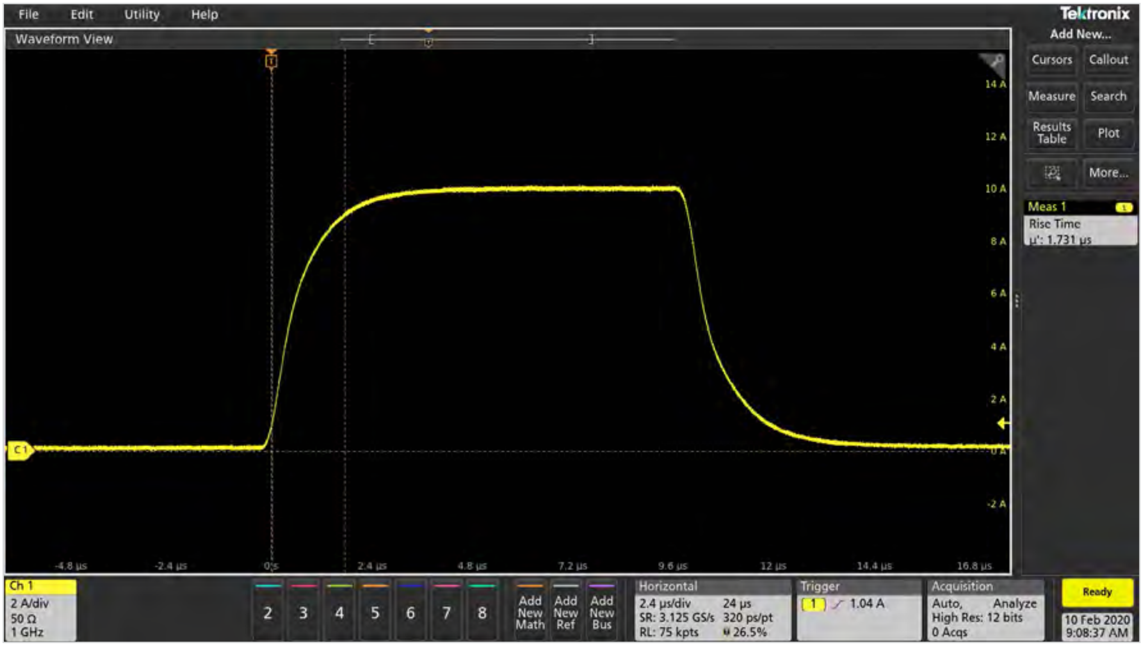


Figure 7: 10 A @ 10 V at 10 µs pulse width with 1.7 µs rise time.

The pulser's built-in dual 1 Megasample/second (MS/s), 18-bit digitizers make it possible to acquire both pulse current and voltage waveforms simultaneously without the need to use a separate instrument. For automated system applications, the 2601B-PULSE's Test Script Processor (TSP®) runs complete test programs from inside the instrument for industry-best throughput. In larger, multi-channel applications, the Keithley TSP-Link® technology works together with TSP technology to enable high-speed, pulser/SMU-per-pin parallel testing.

The 2510-AT Autotuning TEC SourceMeter controls the TEC element and maintains stable module temperature while the DMM7510 Digital Multimeter measures the output current from the photodetector. The DMM7510 also offers Keithley's TSP technology, allowing it to be connected to the 2601B-PULSE for test script control and triggering.

The PC programs the controls of the 2510-AT and can be used to upload test scripts to the 2601B-PULSE and the DMM7510, enabling complete coordination of test execution, data collection and later analysis of the measurement results using popular software tools or Keithley's KickStart Instrument Control software.

Utilizing Test Script Processor

With many instruments, the PC controls all aspects of the test. In each element of a test sequence, the instruments must be configured for each test, perform the desired action, and then return the data to the controlling PC (**Figure 8**).

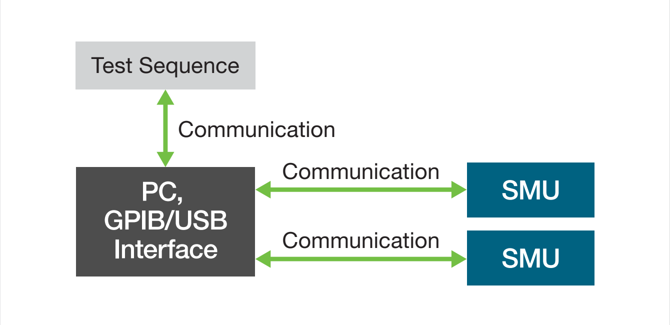


Figure 8: PC control of standard instruments.

The controlling PC then must collect the data, provide the appropriate analysis information, and for production tests, evaluate the pass/fail criteria and perform the appropriate action for binning the device under test. Each command sent and executed consumes precious production time and lowers throughput.

Obviously, a large percentage of this test sequence is consumed by communicating information to and from the PC. Series 2600B instruments, like the 2601B-PULSE and even the DMM7510 offer the unique ability to increase the throughput of complicated test sequences dramatically by decreasing the amount of traffic over the communications bus. In these instruments, the majority of the test sequence is embedded in instrument. The Test Script Processor (TSP) is a full-featured test sequence engine that allows control of the test sequence, with internal pass/fail criteria, math, calculations, and control of digital I/O (see **Figure 9**). TSP can store a user-defined test sequence in memory and execute it on command. This limits the "set-up" and configuration time for each step in the test sequence and increases throughput by lessening the amount of communications to and from the instrument and PC.

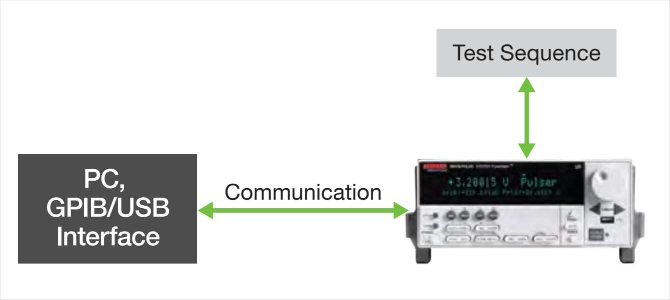


Figure 9: Use of the embedded Test Script Processor (TSP) to store the test sequence. Note decreased communications traffic.

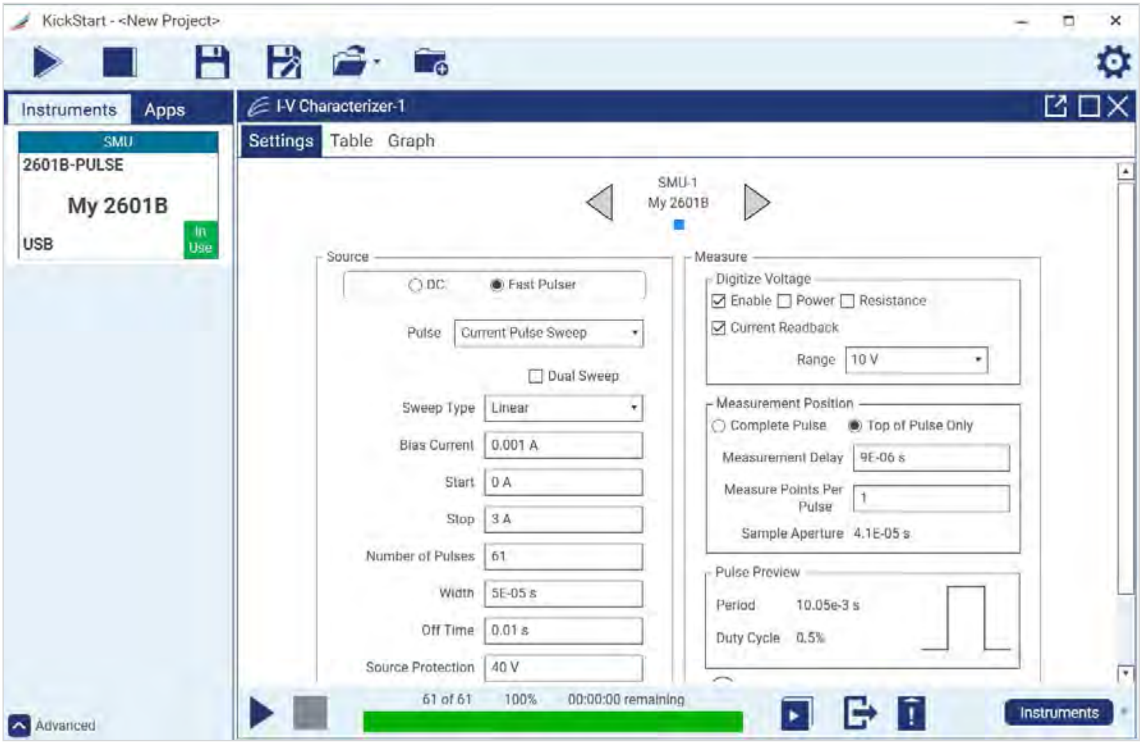
For example, here is a simple step-by-step process for programming the 2601B-PULSE:

1. Create the script.
2. Download the script to the instrument.
3. Call the script to run.

The 2601B-PULSE script can be written/downloaded using Keithley's Test Script Builder Software or downloaded to the instrument using another program such as Visual Studio or LabVIEW. See the 2601B-PULSE's User's Manual for more information on programming the 2601B-PULSE.

Using KickStart Software to Prototype Tests

A fast and convenient way to perform R&D tests on VCSELs or LDs is to use Keithley's KickStart software. KickStart simplifies what you need to know about the instrument so that in just minutes you can take the instrument out of the box and get real data on your device. By plotting data immediately and offering quick statistical summaries of the data in the reading table, KickStart allows you to gather insights faster and make the decisions you need to move on to the next stage of device development. The software saves you time by facilitating quick replication of tests and comparison of results using convenient export features. KickStart enables you to focus your time on interpreting the test results so that your team can meet its innovation goals.



Source
○ DC ● Fast Pulser
Pulse: Current Pulse Sweep
☐ Dual Sweep
Sweep Type: Linear
Bias Current: 0.001 A
Start: 0 A
Stop: 3 A
Number of Pulses: 61
Width: 5E-05 s
Off Time: 0.01 s
Source Protection: 40 V

Measure
Digitize Voltage
☑ Enable ☐ Power ☐ Resistance
☑ Current Readback
Range: 10 V
Measurement Position
○ Complete Pulse ● Top of Pulse Only
Measurement Delay: 9E-06 s
Measure Points Per Pulse: 1
Sample Aperture: 4.1E-05 s
Pulse Preview
Period: 10.05e-3 s
Duty Cycle: 0.5%

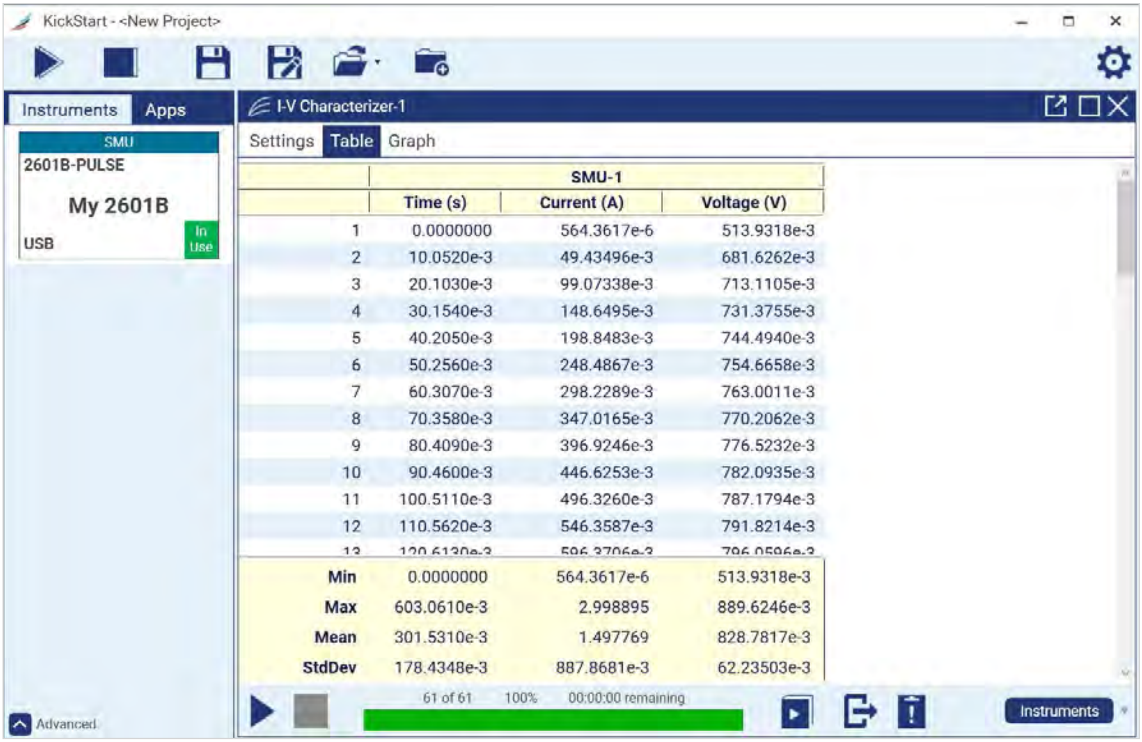
61 of 61 100% 00:00:00 remaining

Figure 10: KickStart Instrument Control Software.

To create a simple current sweep pulse train to test on a VCSEL, for example, the following settings can be applied:

- Source:
  - Fast Pulser
  - Pulse: Current Pulse Sweep
  - Sweep Type: Linear
  - Bias Current: 0.001 A
  - Start: 0 A
  - Stop: 3 A
  - Number of Pulses: 61
  - Width: 5E-05 s (50 µs)
  - Off Time: 0.01 s
  - Source Protection: 40 V
  - Measure / Digitize
- Measure:
  - Digitize Voltage:
    - Enable
    - Current Readback
    - Range: 10 V
  - Measurement Position:
    - Top of Pulse Only
    - Measurement Delay: 9E-06 s (9 µs)
    - Measure Points Per Pulse: 1

After running the test on a VCSEL, you can review the results in KickStart either in tabular form or in a graph as shown in **Figures 11 and 12**.



	SMU-1		
	Time (s)	Current (A)	Voltage (V)
1	0.0000000	564.3617e-6	513.9318e-3
2	10.0520e-3	49.43496e-3	681.6262e-3
3	20.1030e-3	99.07338e-3	713.1105e-3
4	30.1540e-3	148.6495e-3	731.3755e-3
5	40.2050e-3	198.8483e-3	744.4940e-3
6	50.2560e-3	248.4867e-3	754.6658e-3
7	60.3070e-3	298.2289e-3	763.0011e-3
8	70.3580e-3	347.0165e-3	770.2062e-3
9	80.4090e-3	396.9246e-3	776.5232e-3
10	90.4600e-3	446.6253e-3	782.0935e-3
11	100.5110e-3	496.3260e-3	787.1794e-3
12	110.5620e-3	546.3587e-3	791.8214e-3
13	120.6130e-3	596.3706e-3	796.0596e-3
Min	0.0000000	564.3617e-6	513.9318e-3
Max	603.0610e-3	2.998895	889.6246e-3
Mean	301.5310e-3	1.497769	828.7817e-3
StdDev	178.4348e-3	887.8681e-3	62.23503e-3

61 of 61 100% 00:00:00 remaining

Figure 11: Tabular view of results in KickStart.

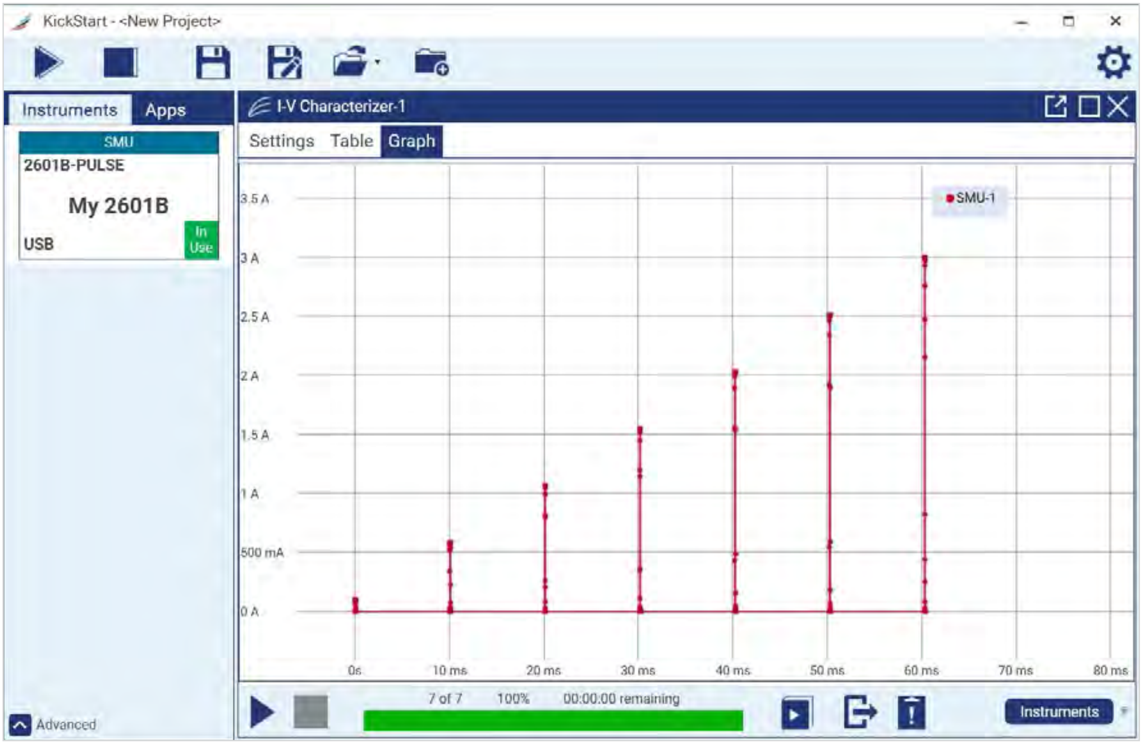


Figure 12: Graph view of results from a VCSEL current pulse sweep.

KickStart offers the ability to zoom into a particular pulse so you can review the current source as well as the measured voltage using the built-in dual 1 Megasample/second (MS/s), 18-bit digitizers. An example is shown in **Figure 13** from the test ran on the VCSEL.

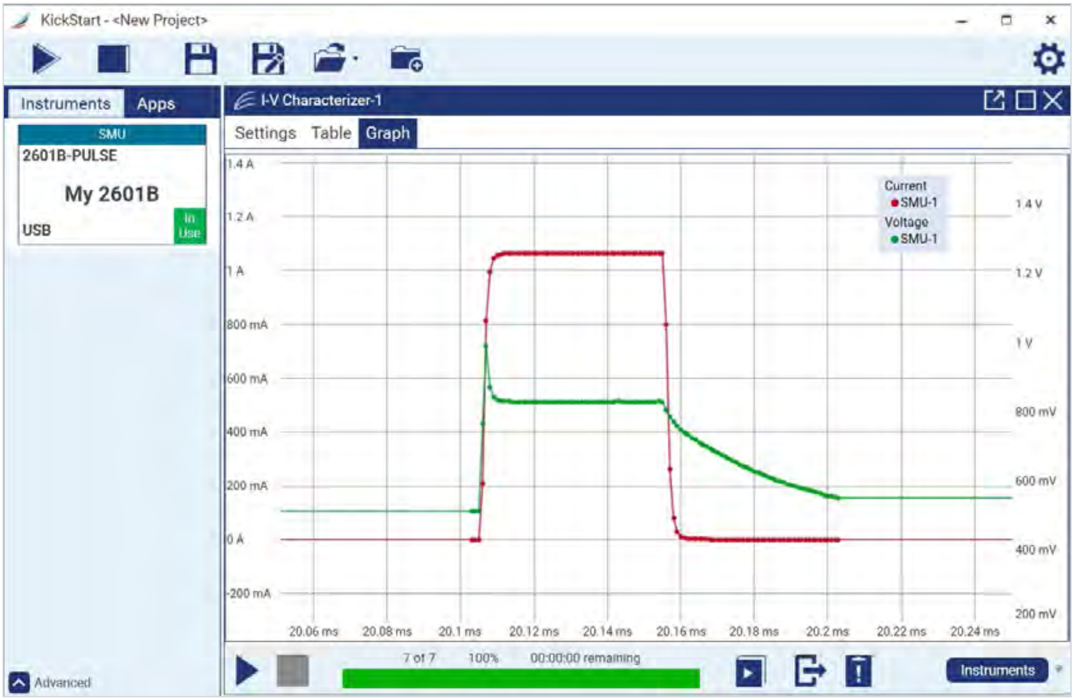


Figure 13: Graph zoomed on a particular pulse output.

KickStart also provides analysis tools, such as cursors and statistics so you can review the results further as shown in **Figure 14**.

Min : 9.99247 A
Max : 9.996703 A
Mean : 9.994695 A
Std Dev : 1.256341 mA
Peak-to-peak : 4.23336 mA
Number of points : 10
Area Under Curve : 24.98677 nA-hr

Figure 14: Analysis example of a pulse within KickStart.

Methods and Techniques

Cabling

Cabling must be optimized for accuracy and test speed. High quality, low noise cable is required for all measurements. The cable characteristics for the LD and VCSEL drive signal are much different from those of the photodiode signals. Cable inductance can also be a factor and could result in pulse outputs that have overshoot and undershoots as shown in **Figure 15**.

Figure 15: Pulse outputs that have overshoots and undershoots due to cable inductances.

The photodiode signal is generated by sourcing several volts and measuring the current flow in the nanoampere range. At such low currents, it is critical to use a low noise shielded cable to optimize the signal-to-noise ratio. Using the shortest length of cable will also improve the signal-to-noise ratio by reducing leakage and induced currents, as well as minimizing capacitance.

The slew rate (dV/dt) of the LD drive signal, if testing LD's, is a function of the semiconductor junction. The junction voltage will change only a few millivolts for a current change of tens of milliamps. As a result of the low slew rate requirements, the capacitance of the LD drive signal cable is not as critical to the application as the voltage drop across the cable as it carries up to 3 A. A large gauge cable will help reduce the voltage drop over the length of the cable while having minimal impact on the speed of the test.

In all cases, the cabling must be shielded and as short as possible to reduce noise and capacitance. Lower noise means less integration time is required for each measurement and the test sweep will be faster.

Typical Sources of Error

Junction Self-Heating

As test times get longer, the semiconductor junction of the VCSEL will tend to get increasingly hot. The forward voltage test tends to be susceptible to junction self-heating. As the junction heats, the voltage will drop or, more importantly, the leakage current will increase during the constant voltage test.

Therefore, it is important to keep the test time as short as possible without sacrificing measurement accuracy or stability. The instruments in the SourceMeter® family allow users to configure the device soak time before the measurement, as well as the amount of time the input signal is acquired. The soak time allows any circuit capacitance to settle before the measurement begins. The measurement integration time is determined by the number of power line cycles (NPLC). If the input power is at 60 Hz, a 1 NPLC measurement would require 1/60 seconds, or 16.667 ms. The integration time defines how long the analog-to-digital converter (ADC) acquires the input signal. Usually, the integration time chosen represents a trade-off between speed and accuracy.

Typical DC soak times for the V_F test can range from 1 ms to 5 ms, and 5 ms to 20 ms for the light/current (L-I) test. These short test times help reduce errors due to junction self-heating. It's possible to characterize the junction heating characteristics by performing a series of tests and varying only the soak time with each repetition of the test. Pulse testing on the other hand further reduces junction heating while applying higher currents when the pulse widths are typically <50 µs.

Leakage Currents

In addition to the nominal leakage characteristics of the cabling and DUT fixturing, conductive contamination of the fixture will increase over time, producing leakage currents. Techniques to minimize leakage may be required when measuring low currents or when using low current photodiodes.

One technique for minimizing leakage current is to use a guarded fixture. In a guarded fixture, the region near the DUT is held at the same potential as the Output HI signal. This reduces the potential difference between the DUT and the leakage paths.

Electrostatic Interference

High resistance measurements, like those made using photodiodes, may be affected by electrostatic interference from charged objects. It may be necessary to use an electrostatic shield (Faraday cup) to eliminate electrostatic effects. For more information, see the section titled "Low Current Measurements" in the sixth edition of Keithley's *Low Level Measurements Handbook*.

- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.
- It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

Light Interference

Stray light entering the optical fibers, or the integrating sphere will skew the test results. Take care to ensure that all components are properly shielded at all wavelengths that could affect the conductance of the semiconductor junctions. This is especially critical for dark current measurements of the photodiode.

Conclusion

Not only does DC and Pulse testing of LD modules and VCSELs drive innovation in the R&D lab as well as reduce manufacturing cost by identifying failed components early in the manufacturing process, it can also play a critical role in accelerated lifecycle testing. Many LD and VCSEL manufacturers offer high reliability LD and VCSEL parts that have successfully endured days of LIV type testing at elevated operating temperature to identify unstable parts prior to incorporation in subsystems destined for unique environments including for undersea operations and automotive/ADAS vehicle LIDAR systems.

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