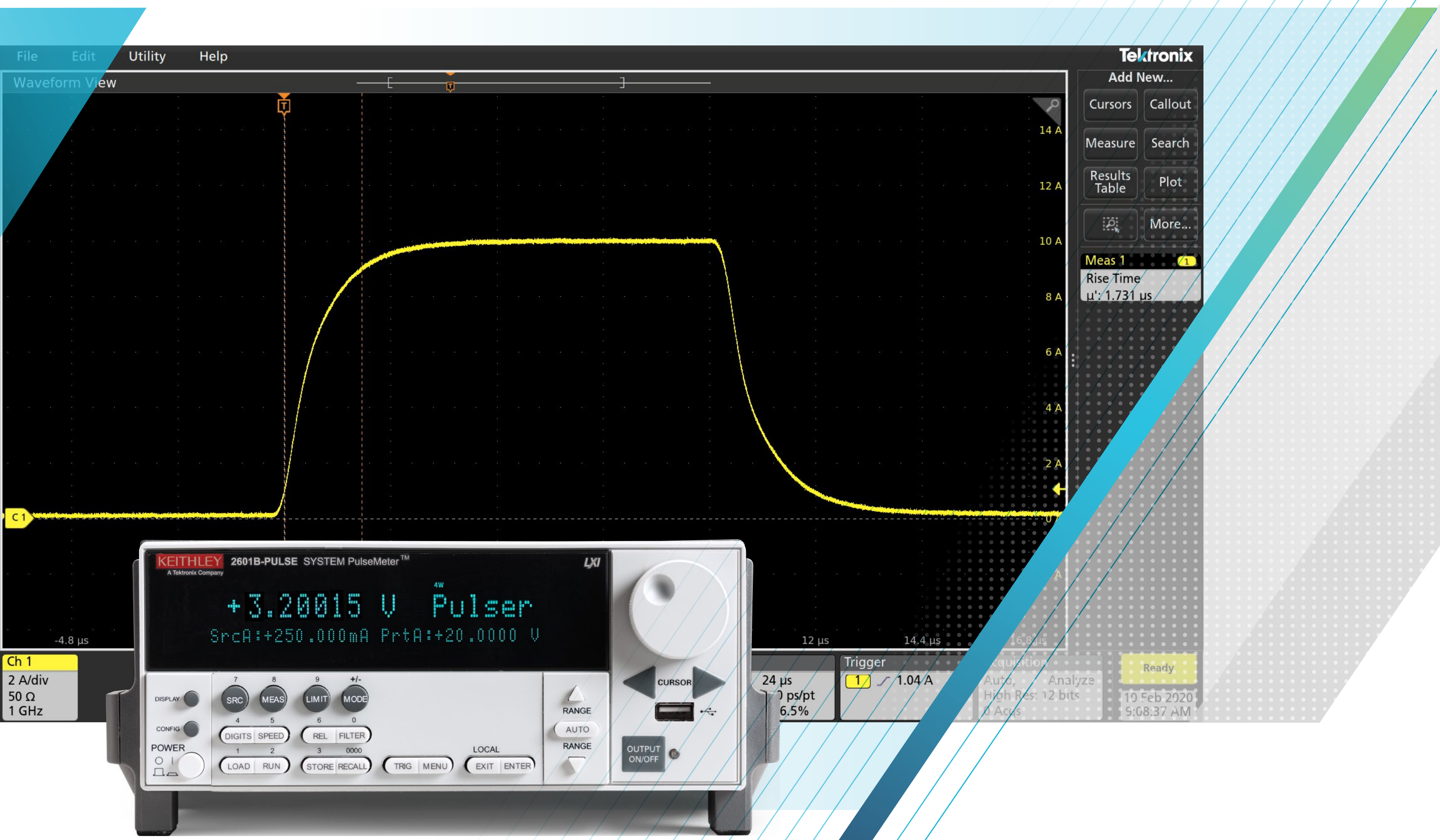
Pulse Testing of Laser Diodes and Vertical Cavity Surface Emitting Lasers

WHITE PAPER



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Thermal management is critical when testing vertical cavity surface emitting lasers (VCSELs) at the semiconductor wafer, bar, and chip-on-carrier production stages. As a result, pulsed testing is commonly used to minimize power dissipation. However, several sources of error remain when pulse testing VCSELs or laser diodes, including problems with coupling high current pulses to the DUT, optical detector coupling, and both slow response and inaccuracy in the detector itself. This paper explores solutions to each of these problems that can deliver shorter test times, more accurate results, and lower reject rates.

LIV Curves

The fundamental test of a laser diode and the VCSEL is a Light-Current-Voltage (LIV) curve, which simultaneously measures the electrical and optical output power characteristics of the device. This test is primarily used to sort or weed out bad devices before they can be built into an assembly. The device under test (DUT) is subjected to a current sweep while the forward voltage drop is recorded for each step in the sweep. Simultaneously, instrumentation monitors the optical power output. The resulting data is then analyzed to determine laser characteristics, including lasing threshold current, quantum efficiency, and "kink" detection (localized negative slope in the first derivative optical power output vs. injection current curve).

Thermal Management and Temperature Effect

Pulsed LIV testing is best done early in production, before the VCSEL is assembled into a module. For VCSELs and laser diodes still on the wafer, pulsed testing is essential because the devices have no temperature control circuitry at that point. Testing with DC would, either change their characteristics, or at worst, destroy them. In a later stage of production, when they've been assembled into modules with temperature controls, the devices can be DC tested and the results compared to those from the pulsed test. Some devices will pass a DC test and fail a pulsed test due to device characteristic changes resulting from temperature shift.

VCSELs are perfect for testing at the wafer stage prior to dicing because they radiate optical power perpendicular to the wafer plane. Although many VCSELs can be tested in non-pulsed mode due to their high efficiency, higher power devices require pulsed testing in the early stages of production. This avoids high thermal gradients that would induce mechanical stresses if non-pulsed DC testing were performed.

LIV characteristics are a function of laser temperature, which must be tightly controlled during the test, just as in normal operation. The principal reasons for performing low-duty-cycle pulsed LIV testing are thermal management, thermal response, and transient response. Typically, these issues arise because of the need to perform DC testing of laser diodes and VCSELs prior to mounting on a thermal management device, such as a heat sink or thermoelectric cooler (TEC), which is sometimes called a Peltier device.

When a laser diode or VCSEL is properly mounted on a TEC and operated in a module system or package, its temperature can be maintained within ±0.005°C. During a typical uncooled, non-pulsed LIV test, self-heating affects the electrical and optical performance of the laser. An internal temperature shift changes the forward voltage drop, dynamic resistance, quantum efficiency, and other characteristics. With short duration pulses, the laser diode's average power dissipation has minimal thermal effects.

Nevertheless, it has been found that VCSELs or laser diodes with poor pulsed LIV performance may pass non-pulsed DC testing. These faulty devices often cause high bit error rates in laser diode modules used for fiber optic data communication systems or detection faults in VCSEL-based LIDAR systems for automotive vehicles.

Another class of failures is characterized by good pulsed LIV characteristics while failing non-pulsed tests. Typically, these devices become optically unstable a few microseconds after lasing is initiated, accompanied by optical output dropping to a fraction of the expected power level. Therefore, comparing pulsed and non-pulsed LIV sweeps at appropriate production stages provides a better indication of DUT performance and the effectiveness of thermal management devices built into modules and packages.

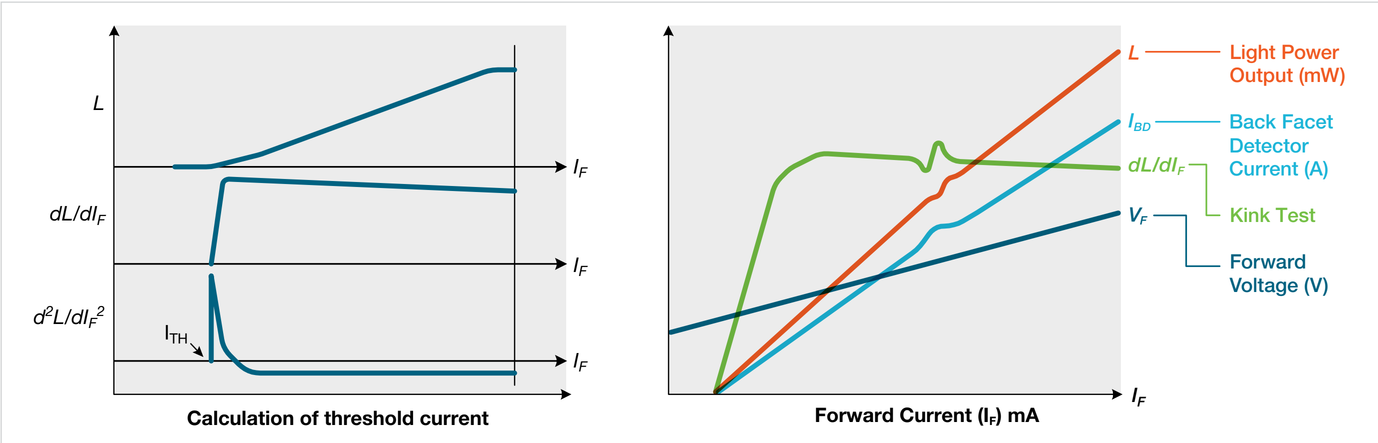


Figure 1: LIV curves

Pulse Parameters

Testing a laser diode or VCSEL properly requires a current pulse of the right shape. It should reach full current fairly quickly (but not so fast that it causes overshoot and ringing), then stay flat long enough to ensure that the result accurately represents the laser diode's true output. The first challenge in a pulsed LIV test is delivering constant current pulses with suitable magnitude, duration, duty cycle, and rise and fall times, like as shown in **Figure 2**.

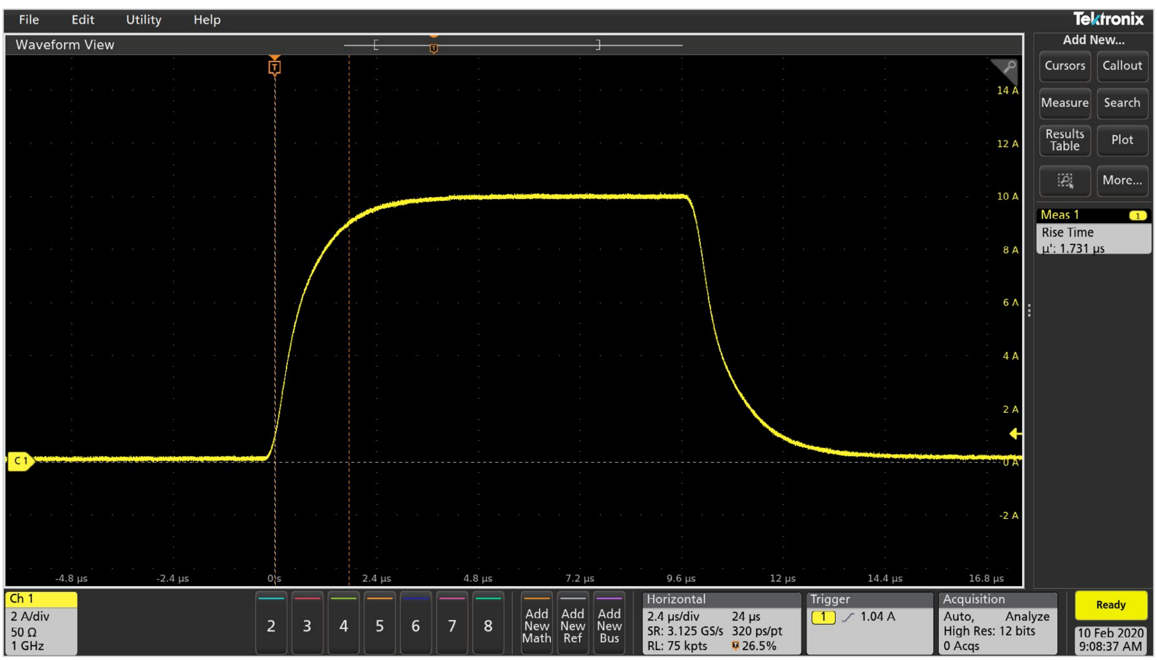


Figure 2: 10 A, 10 μs current pulse with 1.7 μs rise time

To optimize kink detection, the difference in pulse characteristics between adjacent current steps in the LIV sweep must be as deterministic as possible. An example is shown in **Figure 3**.

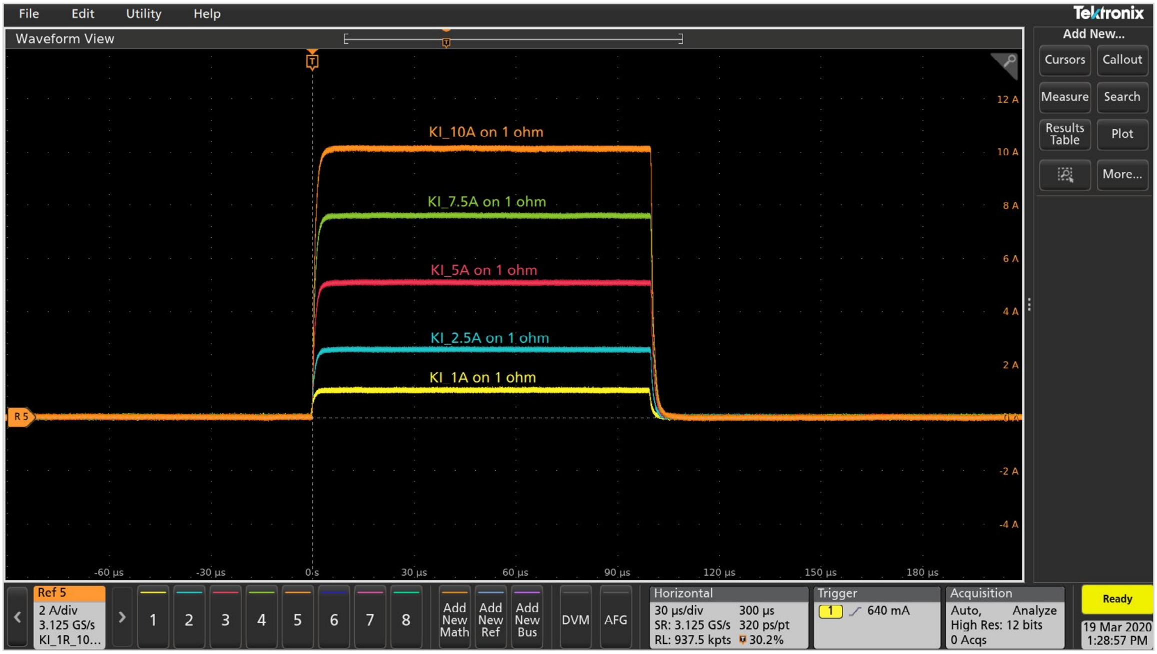


Figure 3: Amplitude sweep at 1 A, 2.5 A, 5 A, 7.5 A, and 10 A on a VCSEL

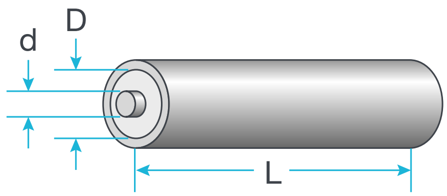
Two common methods of delivering current pulses are a pulsed constant current source coupled directly to the laser diode, and the use of a pulsed constant voltage source driving a known resistance. The pulsed current source is the more deterministic of these two methods.

The maximum source signal amplitude for a pulsed LIV test can typically exceed the nominal operating current of the laser diode or VCSEL by a factor of two. For early stage testing. It is common to use pulse widths of 500 ns to 50 µs, with a duty cycle typically ≤3%. Currents can range from a few tens of milliamps to several amperes. These test conditions are driven by the desire to minimize the average power dissipation while keeping test duration as short as possible. This can put great demands on the system, especially with respect to impedance matching.

The rise and fall times of the high current pulses should be short enough to preserve the flat time at the top of the current pulse. The sum of the rise time and the fall time should be less than 30% of the total pulse width to allow for signal settling time and flat time at the top. On the other hand, keeping the slew rate as low as possible reduces the high frequency spectral content, which helps reduce pulse transmission problems and settling time.

Pulse Delivery and Cable Inductance

Coax cable is widely used to transmit fast signals to a device under test. Each cable has its own characteristic cable impedance which is a relationship of the capacitance and the inductance. The most critical factor between the two is the cable inductance in order to deliver a clean 10 µs pulse. The variables needed in calculating this inductance are center conductor diameter, distance to outer shield, and length shown in **Figure 4**. The relative permeability of coax cables, which depends on the material of the insulator, is usually 1. For example, the calculated inductance of a coaxial cable with 1 mm inner diameter, 3.5 mm outer diameter, 1m length, and relative permeability of 1 is applied, is 250 nH which is a somewhat typical value for coaxial cable inductance. Unshielded cable can have much higher inductance.



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

Figure 4. Coaxial cable inductance

where:

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

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

μ_r = relative permeability

D = coaxial cable outer diameter

d = coaxial cable inner diameter

L = length of the coax cable

In most cases, two coaxial cables are used in parallel from the test instrument to the DUT connected to the high terminal and the other to the low terminal. The problem is that the inductance of the two cables is not double the inductance of just a single cable. It could be as much as 3 to 6 times higher depending on how the cables are routed from the instrument to the DUT. For example, a 1 meter cable with 250 nH inductance is not 500 nH in two paralleled cables but can be as high as 1.5 µH. Extra loop inductance can be created depending on how far apart the cables are. To eliminate the loop inductance, the shields of the two cables should be tied together at both ends of the cable.

The most significant challenge of high inductance in cables is overcoming oscillations, overshoots, and undershoots in the current pulse. Where capacitance can result in oscillation in a voltage pulse, inductance will have a negative impact on output current stability. For example, **Figure 5** illustrates the impact of several inductive loads on a 100 µs pulse.

The results of the test show that increasing inductance increases the level of overshoot and instability of pulse shape. The instability can make it hard to make accurate measurements because the pulse settling time may be too long.

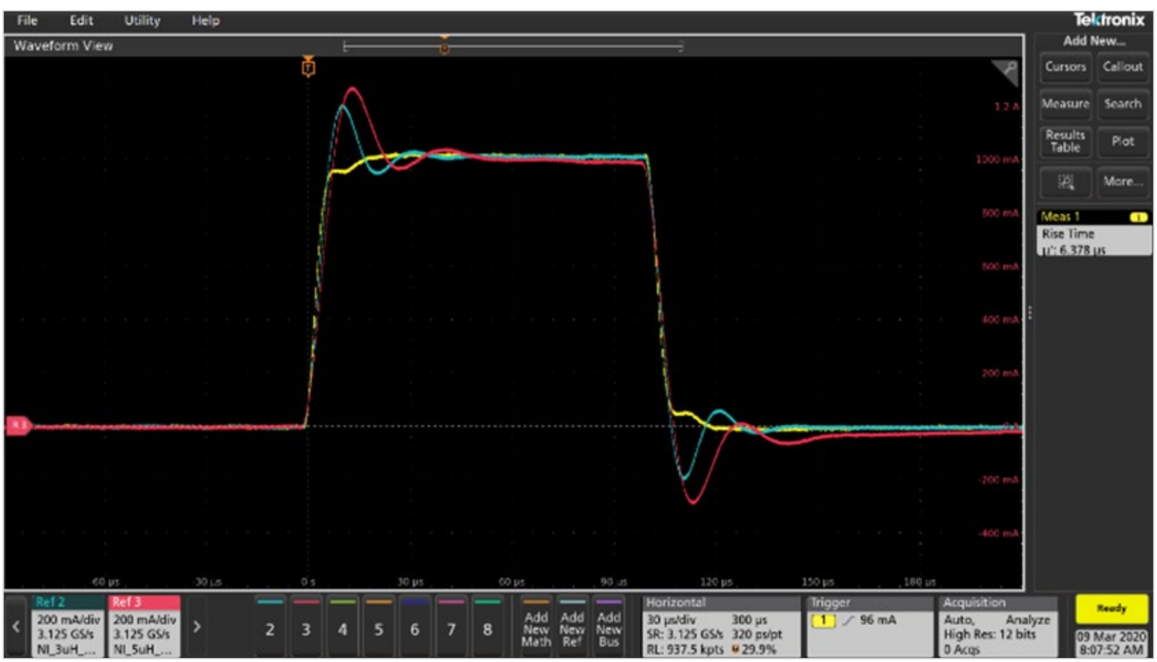


Figure 5. 1 A 100 µs Pulses on inductors , 1 µH (yellow), 3 µH (blue), and 5 µH (red).

Another issue with respect to the inductance of the cable is the amount of voltage that develops at the rising and falling edges of the pulse. The instantaneous voltage across an inductor is given by L×di/dt, where L is the inductance and di/dt is the rate of change of the current with respect to time. As you might guess, the shorter the rise and fall times, the larger the voltage that develops at the edges. In **Figures 6 and 7**, a 22 µs rise time in the pulse results in a 2 V voltage at the rising edge, but a 1.6 µs rise time creates about a 10 V voltage spike. This voltage spike can give the instrument some burden in voltage at the edge. The instrument must support the voltage peak. If it is limited in voltage, it could be slow at the rising edge. The more serious problem of the high voltage peak in fast pulsing is the requirement of an additional settling time to make precise voltage measurements.

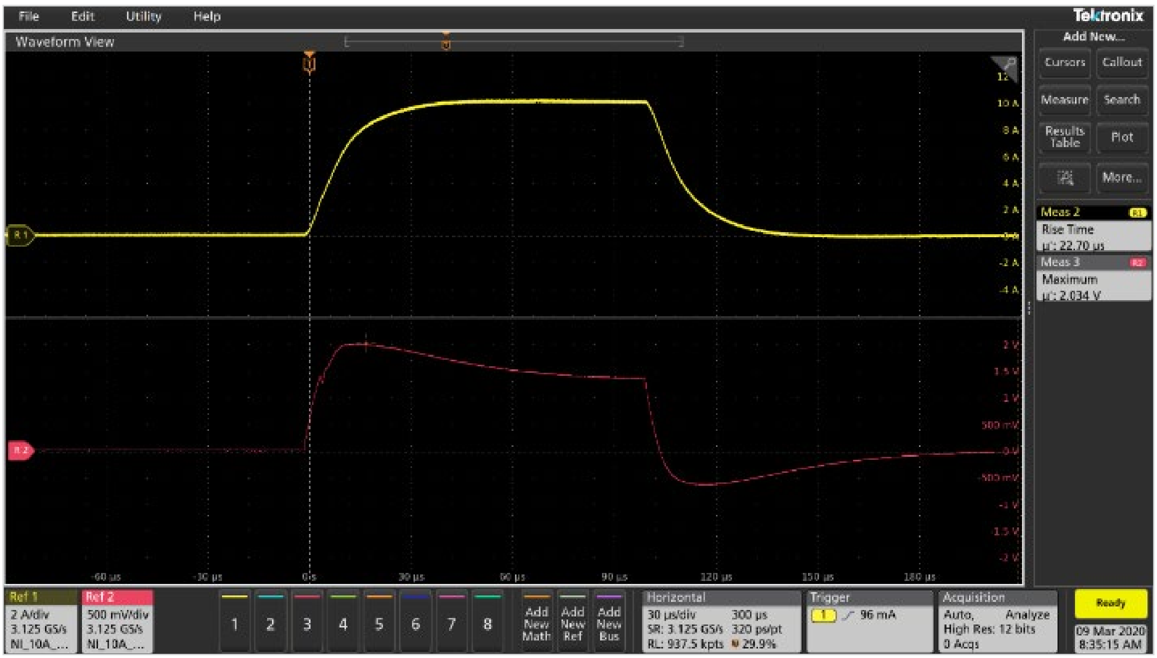


Figure 6. 22 µs rise time 10 A Pulse on inductor 1 µH

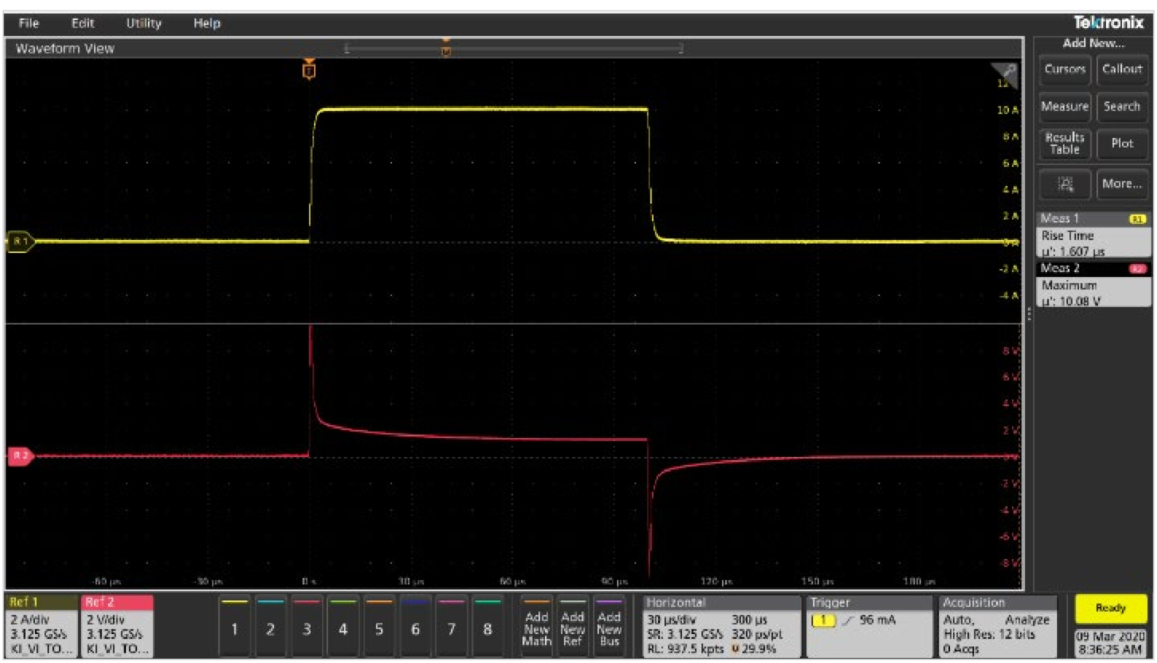


Figure 7. 1.6 µs rise time 10 A Pulse on inductor 1 µH

The challenge comes down to how to provide a usable current pulse to the device that results in no oscillations, overshoot, and undershoot so you can properly test the device and make accurate voltage measurements even with varying cable inductances and device to device inductance variability.

Coupling to the Detector

Capturing the pulsed optical output of the laser diode is not an easy task. Three detector materials are commonly used: silicon (Si), germanium (Ge), and indium gallium arsenide (InGaAs). Each has its advantages and disadvantages. As **Figure 3** shows, the choice of detector depends largely on the wavelength of light involved. At wavelengths less than about 800nm, silicon is the only choice. But much telecommunications work is done between 1300 nm and 1700 nm, where it would appear that InGaAs would be best because its response is fairly uniform, and it holds up well to about 1700 nm.

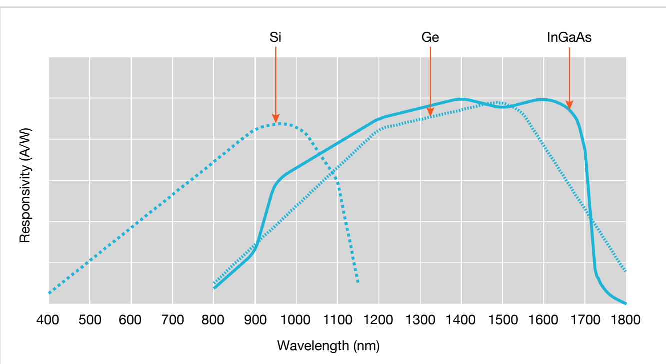


Figure 8. The choice of detector depends largely on the wavelength of light involved.

The output from the laser diode can be coupled to the detector in several ways. One is simply to put the laser right against the detector, but this method has several drawbacks. Not all the light may reach the detector.

Often for packaged parts, the best solution is an integrating sphere—a hollow ball coated on the inside with a diffuse reflecting material and equipped with a mounting for a detector and a port for feeding in the light to be measured (**Figure 9**). The integrating sphere accepts all the light from the source, randomizes its polarization, and distributes it evenly over its inside surface. A detector mounted through the side of the sphere then "sees" a measurable and repeatable fraction (about 1%) of the light fed into the sphere. There's plenty of light to measure but not enough to overpower the detector.

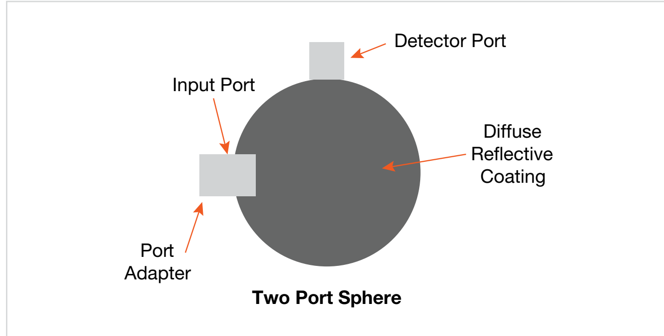


Figure 9. An integrating sphere solves the problem of coupling instrumentation to the output of the laser diode.

Unfortunately, an integrating sphere is not practical when testing VCSELs at the wafer level. Normally, 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. If the probe card can connect to many devices simultaneously, then a test system similar to the one illustrated in **Figure 10** can be constructed to test all of the devices each time the probe card makes contact with 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.

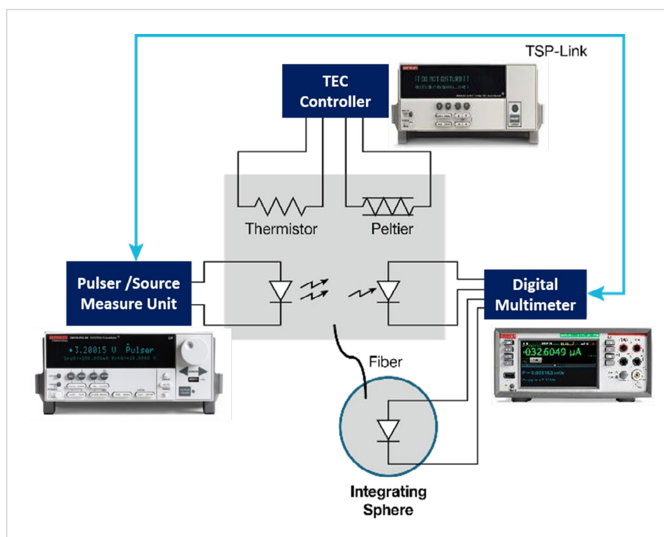


Figure 10. Typical LIV Test Setup for a Laser Diode Module. The same instrumentation can be applied for testing VCSELs. The 2601B-PULSE is used to source current pulses at 10 A @ 10 V at 10 µs to the device under test and monitor the light output with a digital multi-meter while the Thermal Electric Cooler (TEC) is controlling the module temperature.

Capturing Pulsed Laser Optical Output

One of the most difficult tasks in pulse LIV testing is capturing the pulsed optical output of the laser diode at its peak values. The short duration optical pulse is not a friendly signal for most commercial optical power meters. Typically, optical power meters are designed for high precision measurements that often require many seconds of integration time to complete one reading. Although it is possible to use these instruments, they require long integration periods to accumulate several thousand laser pulses. Then the firmware, or an external PC-based test program, must calculate peak optical power using the assumption that average power is a function of the duty cycle for the current pulse driving the laser. A further assumption is that the integral of the noise signal is zero.

Because of optical power meter deficiencies, test engineers have also devised faster, more accurate methods for pulsed LIV testing. Measuring voltage and current in the laser diode fed with high speed pulses isn't easy.

Historically, the most common method has employed a combination of rack-mounted instruments, along with fairly complex, custom-designed software running on a PC controller. In addition to the PC used for test sequencing and signal analysis, the equipment list for this system includes a current pulser/SMU instrument, optical measurement components (photodiode detectors, etc.), a Thermal Electric Cooler (TEC) instrument, and a digital multimeter for measuring the output signal from the integrating sphere or a photo detector.

The design approach to this type of system is to include both pulsed and non-pulsed operating modes. This dual functionality allows both types of LIV sweeps (pulsed and DC) to be performed on a single platform, using the same measurement channels. An example is the Keithley 2601B-PULSE System SourceMeter® 10 µs Pulser/SMU instrument as shown in **Figure 11**. The 2601B-PULSE's control loop system eliminates the need to tune for load changes up to 3 µH so that current pulse has no overshoot and ringing when outputting pulses from 10 µs up to 500 µs at a current up to 10 amps. This ensures a fast rise time, so devices are sourced with a current pulse to properly characterize the device or circuit. Comparing pulsed and non-pulsed test results provides more complete information on DUT performance.

Figure 11: Keithley 2601B-PULSE System SourceMeter

System Speed and Throughput

Today, efficiency and low cost are vital to surviving manufacturing production environment. Testing must be fast, accurate and inexpensive. This means using an optical power meter is not the best choice because it integrates light output over time, with a low duty cycle input that can make for an extended integration period. In addition, the accuracy of the measurement depends on how accurately the duty cycle of the pulses is known and how closely the duty cycle of the light output matches the duty cycle of the electrical input.

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. The controlling PC then must 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. Instruments like the 2601B-PULSE and Keithley's newest DMMs like the DMM7510 and DMM6510 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. The 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.

Conclusion

This paper has reviewed the impact of cable inductance, the need for thermal management, and the various components to create a pulsed and DC LIV test system. When production throughput matters, the 2601B-PULSE System SourceMeter is a desirable solution having both a pulser and SMU in one instrument. This instruments’ pulser function provides reliable, repeatable pulse waveforms, widths, rise times, and fall times as high as 10A @ 10V and as low as 10 µs. The instrument provides many benefits including:

- No manual tuning of pulse output to ensure high pulse fidelity, reduced testing time, and cost savings in production.
- Make DC/Pulse current and voltage measurements with a single instrument.
- Characterize VCSELs with confidence. Develop the next generation of materials, components, and modules.
- Minimize device self-heating; minimizes burned probe tips. Protect your VCSELs, VSCEL array, LEDs.
- Measure down to single-digit ms sampling rates while outputting 10 µs, 10 Amp current pulses at 10 volts.

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