KEITHLEY

Application Note Series

Number 2273

VCSEL Testing with the Model 2400 SourceMeter® Instrument

Introduction

The recent commercialization of vertical-cavity surface-emitting lasers (VCSELs, pronounced “vixsels”) into areas such as data communication, optical interconnections and memory, sensors, printers, etc. has led to explosive growth in production capacity. For many applications, VCSELs are slowly replacing traditional edge-emitting lasers, most notably in low-bandwidth and short-haul communication systems in which cost is a driving factor.

VCSEL manufacturers have the opportunity to test their devices at the wafer level. This is in contrast with Fabry-Perot, Bragg, and distributed feedback (DFB) lasers. Edge-emitting lasers like these must be cut from the wafer and the edges polished before testing is possible. This increases production costs significantly because the money spent in preparing the device for testing has been wasted if the device ultimately turns out to be defective. The ability to test VCSELs before they are cut from the wafer eliminates the need to continue to expend resources on bad devices.

Other advantages of VCSELs include their high reliability and the fact that they require much less current to operate than edge-emitting lasers. The light pattern emitted from the surface of the VCSEL is circular, rather than the elliptical pattern produced by edge-emitting lasers. This subtle difference in output allows for more efficient coupling of VCSELs to round fiber-optic cables. As shown in ***Figure 1***, VCSELs are formed with many layers of indium-gallium arsenide (InGaAs) to emit at the red, near IR, and IR wavelength regions. They are compatible with low-cost silicon, germanium, and InGaAs photodetectors (PD). The basic structure of a VCSEL consists of a thin active region sandwiched between two highly reflective distributed Bragg reflectors (DBR).

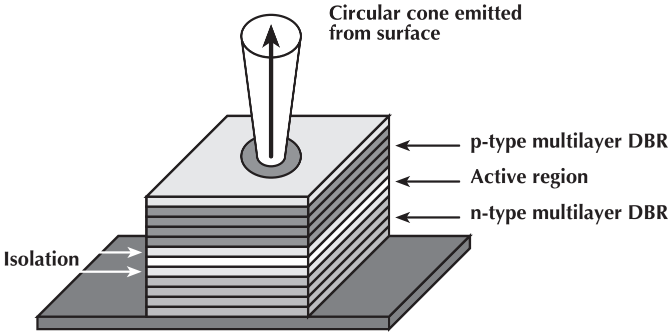

Figure 1. A Simplified VCSEL Structure (Source: Kartalopoulos).

Test Descriptions

The light intensity (L) - current (I) - voltage (V) sweep is a series of measurements performed on VCSELs to determine their operating characteristics. The L-I-V test identifies failed devices early in the production process, so expensive non-DC domain tests can be performed more cost-effectively on the remaining higher-yield components. The L-I-V test involves ramping current through the VCSEL and measuring the resulting light output via a photodetector (PD).

L-I-V Test Sweep

Forward Voltage Test

The Forward Voltage Test (V_F) test verifies the forward operating voltage of the VCSEL. Current (I_F) is swept (typically from 0 to 50mA) and the voltage drop across the VCSEL is measured. Most VCSELs are tested at levels less than 50mA, usually in increments of 0.25mA or 0.5mA.

Lasing Threshold Current Test

The threshold current is the current level at which the VCSEL begins lasing. The current threshold can be found by detecting the first maxima of the second derivative of the light output. ***Figure 2*** illustrates the graphical calculation of the threshold current of a VCSEL. The top line is the light output of the VCSEL as the current is swept from zero to several tenths of an ampere. The middle line is the first derivative of the light output and shows a steep slope as the light output begins to intensify. The bottom line is the second derivative of the light output. Note

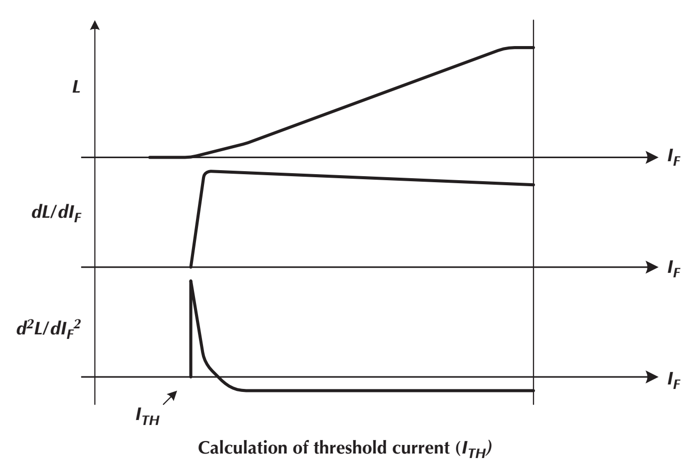

Figure 2. Graphical Calculation of Threshold Current

the sharp peak of the second derivative line at the knee of the light intensity output. This peak indicates the location of the threshold current.

Light Intensity Measurement

Light intensity (L) measurements verify the light output of the VCSEL. Light output power increases as drive current is increased. The output of this test usually falls in the range of milliwatts. The measurement may be AC- or DC-based. For AC-based measurements, an optical power meter is used. For DC-based measurements, a reverse biased photodiode is exposed to the output of the VCSEL and the resulting photodiode DC current is measured with a picoammeter or electrometer (a highly refined DC multimeter). Then, the software embedded in the system uses the current value and the PD calibration data to calculate the output power of the module. The typical range for photodiode current is 0 to 3mA, while the typical required resolution is 0.1nA. The DC approach is reportedly faster than the AC approach.

Kink Test/Slope Efficiency

The kink test verifies the proportionality of the relationship between the drive current (I_F) and the light output (L), as depicted in ***Figure 3***. In non-defective lasers, the relationship between the drive current (I_F) and the light output power (L) is linear near 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, graphed as dL/dI_F. The first derivative will amplify any bumps or “kinks” in the L-I_F curve. If the curve has any significant “kinks” in it (i.e., is not smooth), the laser is considered defective. In other words, if the VCSEL is 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. Threshold current is the minimum current required by a laser to begin “lasing” or outputting significant light.

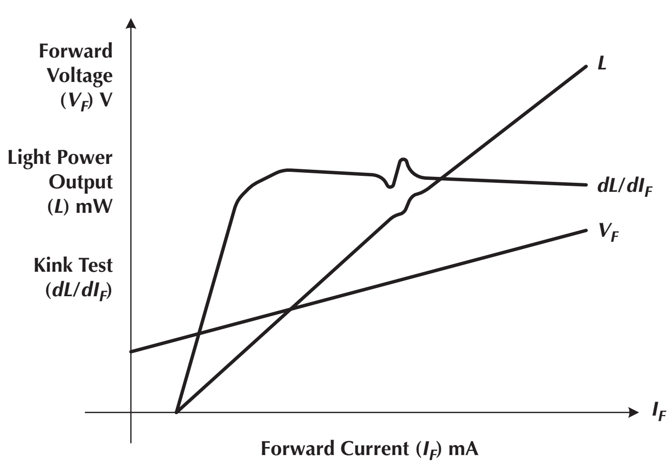

Figure 3. Typical Suite of L-I-V Curves of a Defective Laser Diode

Test System Description

Single Device Test System

Figure 4 illustrates a typical DC characterization system for testing a single VCSEL. In this configuration, the Model 2400 SourceMeter® instrument is connected to the VCSEL. The light output from the device shines through the input port of an integrating sphere. A photodetector (PD), combined with an integrating sphere, is used to determine the amount of optical power the VCSEL is generating. The test fixture is typically kept in the dark to avoid corrupting the results with errors due to ambient light.

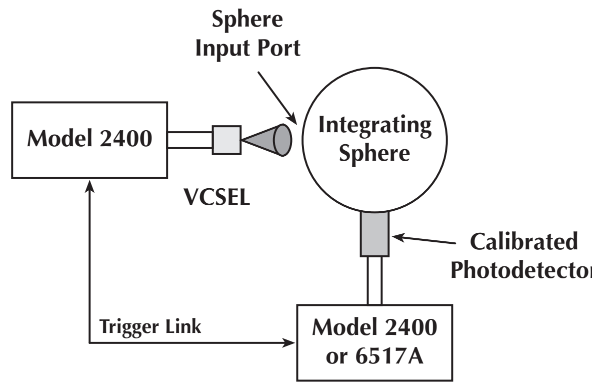

Figure 4. Typical SourceMeter/Electrometer-based Test System for VCSEL Testing.

One SourceMeter instrument performs a series of DC tests on the VCSEL. The SourceMeter instrument is capable of sourcing current or voltage of either polarity, so the entire DC characterization of the VCSEL can be performed without the need to flip or move the VCSEL from its initial test position. A second SourceMeter instrument or an electrometer is connected to a photodetector. These two instruments are used together to capture light intensity data on the VCSEL. In order to characterize the light intensity of a laser diode, the first SourceMeter instrument performs a multi-point current sweep on the VCSEL that spans its operating range (see ***Figure 5a***). The resulting light output is measured via the PD with either the second SourceMeter instrument or the Model 6517A Electrometer (see ***Figure 5b***).

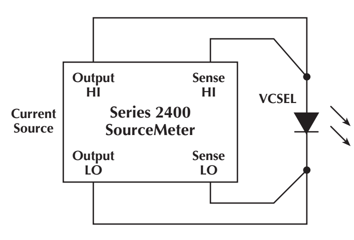

Figure 5a. VCSEL Source Circuit.

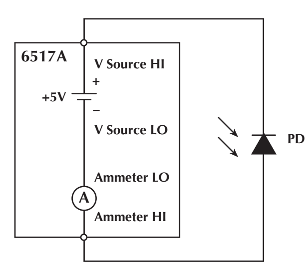

Figure 5b. Photodetector Measurement Circuit.

Multiple/Array VCSEL System

For wafer testing, multi-die packages, or burn-in applications, it is often necessary to test many VCSELs at once. The most cost-effective way to test many devices at one time is to include switching in the test system configuration. Burn-in applications often require that each VCSEL be powered for extended periods of time, which requires dedicated source capabilities without switching. The measurements of the PDs in a burn-in system are generally multiplexed to monitor the VCSEL performance over time. ***Figure 6*** is an example of a VCSEL switching test system configuration. Actual systems can be configured for any number of laser elements and for various electrical specifications.

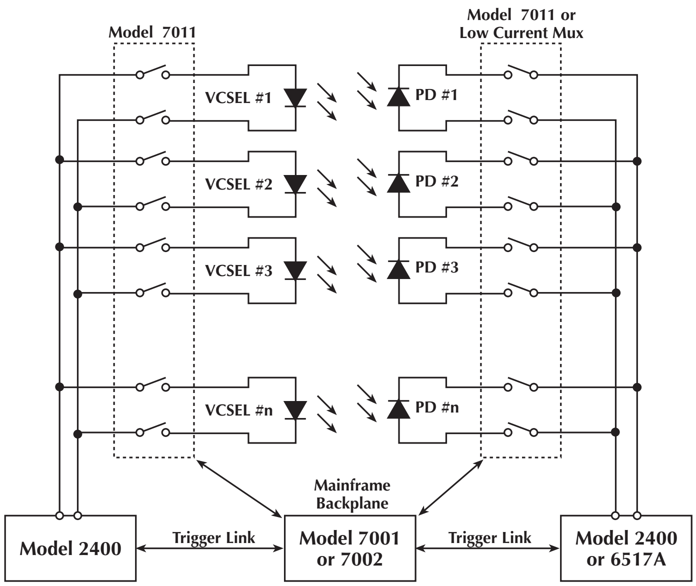

Figure 6. Testing Multiple VCSELs with the Series 7000 Switching Family.

In the multiple device test system, an individual VCSEL is selected for testing and the corresponding relay is closed both for the VCSEL and the PD used to verify light intensity. The SourceMeter instrument performs the necessary DC tests, then forces sufficient current to light the VCSEL. While the VCSEL is lit, a second Model 2400 (or a Model 6517A Electrometer) measures the increased leakage of the PD. Once this testing process is completed, the switching channels for the next device are selected.

The offset current specification for the Model 7011 Multiplexer Card is <100pA, which may exceed the error budget for the test system. Therefore, substituting a Model 7158 (or 7058) Low Current Scanner Card for the 7011 will lower the offset value to <1pA (<30fA typical). It is important to note that using a low current card will decrease the number of available channels in the system. The low current cards only have ten channels available for scanning, which implies that four times as many cards are required when they are substituted for the Model 7011.

Integrated Devices

Many sensors today integrate both VCSELs and PDs into the same package for applications such as reflective object sensors, optical switches, or other hybrid devices. An external PD or other light sensing device is used to monitor the output of the VCSEL independently. DC tests are performed using the SourceMeter instrument, but when the light intensity measurements are taken, both the internal and external PDs are measured. The VCSEL must pass all of the required DC and optical tests, and the internal PD data must correlate to the data taken on the "standard" external device. ***Figure 7*** illustrates an example of this type of test system using one Model 2400 SourceMeter and one Model 2500 Dual Photodiode Meter.

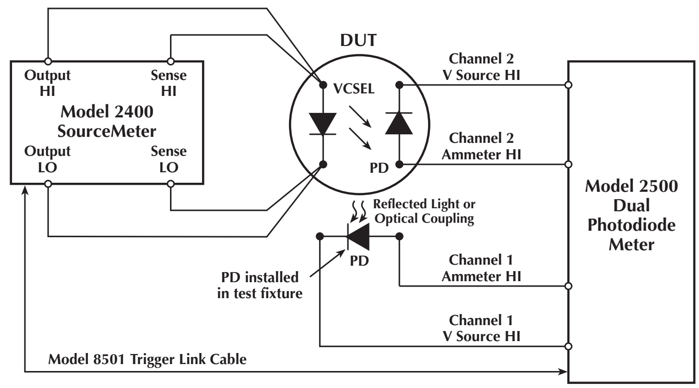

Figure 7. Measuring an Integrated VCSEL/PD Device with a Model 2400 and Model 2500.

Measuring the PDs can be done with either the Model 2500 or two Model 2400s, depending on the test specification's current sensitivity requirements. The Model 2400 measures currents down to ~10nA, while the Model 2500 reliably measures currents less than 1pA.

Wafer Testing

VCSELs are the only type of lasers that lend themselves to testing at the wafer level. ***Figure 8*** illustrates a simple test system for testing VCSELs on the wafer. Generally, two Model 2400 SourceMeter instruments are used for this type of 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.

If the probe card can connect to many devices simultaneously, then a system similar to ***Figure 6*** 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.

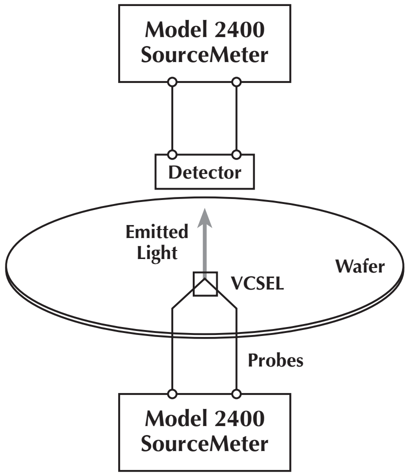

Figure 8. Wafer level testing of VCSELs.

Methods and Techniques

Synchronization with Trigger Link

The Trigger Link is a hardware handshake bus used by the instruments in the test system to ensure proper test sequencing. It is a standard feature on all newer Keithley instruments, including all the instruments mentioned in this application note. When the meter and switch mainframe are connected via a Trigger Link cable, they can trigger each other to allow faster test execution. This built-in bus eliminates the need for direct PC control of most system functions. When the Trigger Link function is used properly, the only functions the PC performs are initiating the test and retrieving data from the system.

For further details on configuring synchronized test systems with Trigger Link, refer to Keithley Application Note #2217 "Trigger Synchronization of Multiple SourceMeter Instruments."

Contact Check

The SourceMeter Contact Check function helps eliminate measurement errors and false product failures resulting from contact fatigue, breakage, or contamination, loose or broken connections, or relay failures. Before each automated test sequence begins, the contact to the DUT is verified, which can help minimize tooling and false failure costs.

The contact check function verifies that the resistance between the HI/LO test lead pairs is less then a specified threshold. Contact is verified between the Output HI/LO, Sense HI/LO, and Guard/Guard Sense pairs. By using pulse transformers and a reference resistance, the contact can be verified very quickly (typically within 350µs). The reference resistance can be set to three different values (5Ω, 15Ω, 50Ω). Contact check does not pass a signal through the DUT, only between the three HI/LO pairs mentioned. If a contact check failure is detected, the test will abort and give a failure indication over the front panel, the IEEE-488 interface bus, and the digital I/O port.

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 60Hz, a 1 NPLC measurement would require 1/60 seconds, or 16.667ms. 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 soak times for the V_F test range from 1 to 5ms, and 5 to 20ms for the I_L 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.

Lead Resistance

The series resistance from the test leads running from the instrument to the VCSEL is a common source of voltage measurement error. This series resistance is added into the measurement when making a 2-wire connection (***Figure 9a***). The effects of lead resistance are particularly detrimental when long connecting cables and high currents are used, because the voltage drop across the lead resistance becomes significant compared to the measured voltage.

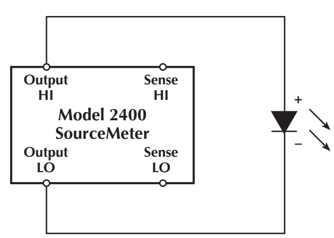

Figure 9a. Two-wire Connection.

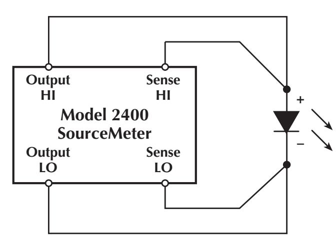

Figure 9b. Four-wire Connection.

Use the 4-wire remote sensing method rather than the 2-wire technique to eliminate this problem. With the 4-wire method (***Figure 9b***), a current is forced through the LED using the Output HI/LO test leads, then the voltage across the LED is measured using the Sense HI/LO set of leads. As a result, only the voltage drop across the LED is measured.

Leakage Current

Stray leakage in cables and fixtures can be a source of error in measurements involving very low current, such as PD dark current measurements or light levels near the laser output threshold. To minimize this problem, test fixturing should be constructed with high resistance materials.

Using the built-in guard of the SourceMeter instrument is another way to improve low current measurement performance. The guard is a low impedance point in the circuit that is at nearly the same potential as the high impedance point to be guarded. This concept is best illustrated by example (***Figure 10***).

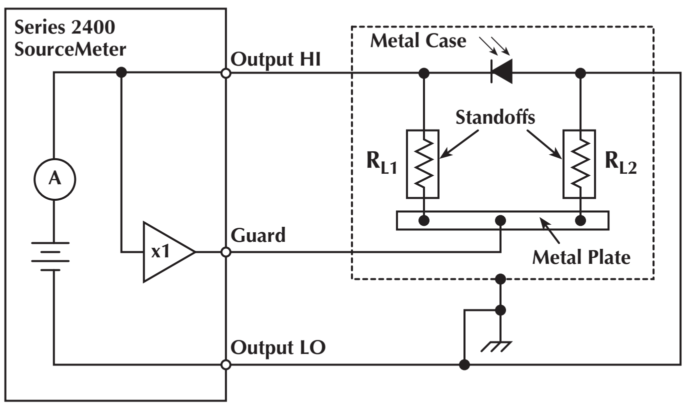

Figure 10. Series 2400 Guarding Technique.

In this example, the PD to be measured is mounted on two insulated standoffs (R_{L1} & R_{L2}). Guard is used in this circuit to ensure that all the current flows through the diode, not through the standoffs. In general, cable guard should be used when sourcing or measuring currents less than 1mA. Connecting the Guard terminal of the instrument to the metal plate guards this circuit. This puts the bottom of insulator R_{L1} and R_{L2} at almost the same potential as the top. Both ends of the insulator are at nearly the same potential, so no significant current can flow through it. All the current will then flow through the LED as desired. Similar connection schemes can be used with the Models 6517A and Model 2500 when measuring PD current.

WARNING: Guard is at the same potential as Output HI. Therefore, if hazardous voltages are present at output HI, they are also present at the Guard terminal.

Electrostatic Interference

High resistance measurements may be affected by electrostatic interference occurring when an electrically charged object is brought near an uncharged object. To reduce the effect of electrostatic fields, a shield can be built to enclose the circuit being measured. As shown in ***Figure 10***, a metal shield connected to ground surrounds the PD under test. The Output LO terminal of the SourceMeter must be connected to the metal shield to avoid noise due to common mode and other interference. Using this type of shield will also help operators avoid contacting the standoff metal plate because the plate is at guard potential.

Light Interference

Testing VCSELs involves detecting the amount and intensity of light produced by the VCSEL, so the test fixture must be shielded from light. Typically, the inside of the test fixture is also painted black in order to reduce reflection within the fixture.

Light interference can be problem when multiple devices are being tested simultaneously, such as in wafer testing. Light from testing adjacent lasers could strike a single photodetector and corrupt the test data. Therefore, ensure that either devices are tested sequentially or that devices being tested simultaneously are located far enough away from each other on the wafer surface.

Example Programs

Keithley has developed an example Microsoft Visual Basic program in order to perform the VCSEL/PD tests presented by the test system shown in ***Figure 4***. To obtain a copy of the program (VCSEL.zip), visit Keithley's World Wide Web site (http://www.keithley.com).

Note: The test programs that are provided are intended to illustrate the concepts presented in this note. The programs may need to be altered in order to accommodate desired test parameters and timing.

Equipment List

The following equipment is needed to configure the system shown in ***Figure 4***:

- Model 2400 SourceMeter instrument.
- Model 6517A Electrometer/High Resistance System.
- Model 8501 Trigger Link Cable.
- Two Model 7007 IEEE-488 Interface Cables.
- Model KPCI-488 IEEE-488 computer interface board with PC.
- Light shielded enclosure with integrating sphere and calibrated photodetector.
- Custom wiring harness for connecting the test equipment to the DUT and PD.

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present.

These high voltage and power levels make it essential to protect operators from any of these hazards at all times. Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris. For example, capacitors and semiconductor devices can explode if too much voltage or power is applied.
- 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.

References

S. V. Kartalopoulos, *Introduction to DWDM Technology: Data in a Rainbow,* IEEE Press, New York, 2000.

Robert A. Morgan, "VCSELs," *Honeywell Photonics,* July 20, 1999, <http://www.htc.honeywell.com/photonics/vcsels.html> (6 Oct. 2000).

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