KEITHLEY A GREATER MEASURE OF CONFIDENCE

Photodetectors—Choose and Use Wisely for Best Results in Pulsed Laser Diode Test Systems

Helga Alexander, Keithley Instruments, Inc.

Testing laser diodes for fiberoptic communication systems requires a photodetector with a fast response. However, a 10–90% rise time is not the only important characteristic of a photodiode, particularly when it is used for absolute optical power measurements in pulsed mode.

Photodetectors for Laser Diode Production Testing

Given that 80% or more of a laser diode module's production costs are added during packaging, it is imperative to start with only known-good laser diode chips for communication modules. This requires laser diode testing at the bar or chip stage, using pulse techniques that prevent destructive self-heating of uncooled devices. A pulsed current source with a fast rise time is needed to drive the laser diode, and a photodetector with a fast response time is needed to measure laser output accurately.

Generally, PIN detectors are used, which can be based on silicon, germanium, or III-V compound technology, depending on application requirements. For pulsed light-current-voltage (LIV) testing, selection and use of these photodetectors involves a number of compromises, but a fast response time often is the dominant concern. Nevertheless, the relationships between a photodetector's response time and other characteristics, such as device structure, external circuitry, and bias voltage, must be considered.

Photodetector Construction and Performance

Photodiodes are the most commonly used detectors due to their low cost and generally good performance. Like all semiconductor detectors, they make use of their internal photoelectric effect. When a photon is absorbed, it causes an electron to be raised from the valence band to the conduction band, creating a charge-carrier pair (a hole in the valence band, electron in the conduction band). When the device is connected to an external circuit, the resulting charge flow is referred to as a photocurrent.

The most basic photodiode has a simple p-n junction structure. At the junction, diffusion of electrons into the p-type material and holes into the n-type material cause an opposing electric potential (sometimes called built-in potential or equilibrium potential) across an area called the depletion region (or layer). Reverse biasing the photodiode causes this potential to increase, and the depletion region to expand. Photons of sufficient energy impinging on this region will create electron-hole pairs, which will separate due to the combined equilibrium potential and externally applied reverse bias. These charges will quickly drift away from the junction and be collected by the electrodes. Drift current generated by photon absorption in the depletion region is the main component of photocurrent. It also is the component with the fastest response time.

Another component of photocurrent is called diffusion current. This component originates from charge carriers created by absorption of photons outside the depletion layer. While the majority of these charge carriers will recombine in the neutral region, some of them may manage to diffuse slowly to the junction and make a contribution to the photocurrent. This contribution is not welcome when a fast photodiode response is desired.

Designing for Fast Response. For fast response time, a photodiode has to be designed such that most of the photon absorption takes place in the depletion layer. Since photons must penetrate the p-region to reach the depletion layer, one way to achieve fast response is to make the p-region extremely thin and to expand the depletion layer by applying as large a reverse bias as possible. Unfortunately, this method also increases the dark current and its associated noise contribution. Dark current is the small amount of charge flow that results when electron-

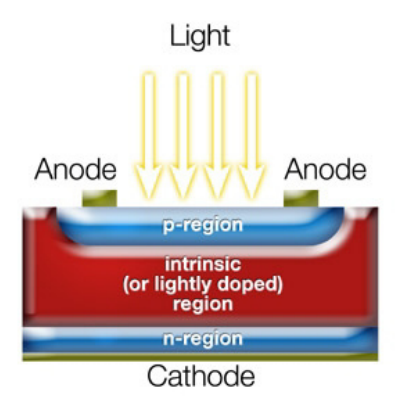

Figure. 1. Representation of a PIN photodiode structure.

hole pairs are generated with the detector not exposed to light. Generation of dark current charge carriers is more likely to occur with the introduction of impurities in doped semiconductor materials, such as those in a p-n junction photodiode. The dark current contribution increases as the depletion layer widens due to increases in reverse bias.

Another way to control the width of the depletion region is to construct a p-i-n photodiode, where an intrinsic semiconductor layer is created between the p and n regions of the device (***Figure 1***). The undoped (or lightly doped) intrinsic layer of fixed width serves the same function as the depleted region of a p-n junction. Since it lacks doping impurities that generate current carriers in the dark, photodiode sensitivity is improved [1]. More importantly, photon absorption is concentrated in this region, thereby keeping undesirable diffusion current to a minimum. The bias voltage, and thus the electric field, is concentrated and virtually constant across the absorption region. This greatly decreases the average drift time of the optically generated carriers [2]. Hence, p-i-n photodiodes are usually the detectors of choice when a fast response is required, as is the case in pulse testing of diode lasers.

Spectral Sensitivity. The bandgap of the detector material is the main factor that determines the optical wavelength response of a photodiode. Germanium (Ge) and indium gallium arsenide (InGaAs) photodiodes can detect radiation ranging from approximately 800nm to 1700nm, making them well suited for testing telecom transmitter lasers. Silicon (Si) is the detector material of choice for shorter wavelengths, being sensitive from 300nm to 1100nm. Although a particular photodiode can detect radiation over a range of wavelengths, its photocurrent output varies considerably with wavelength for a given optical input power. This is known as the spectral sensitivity (or responsivity) of the photodiode, and is dependent on detector composition and device structure. ***Figure 2*** shows typical responsivities for Si, Ge and InGaAs. Photodiodes based on all three types of materials are readily available.

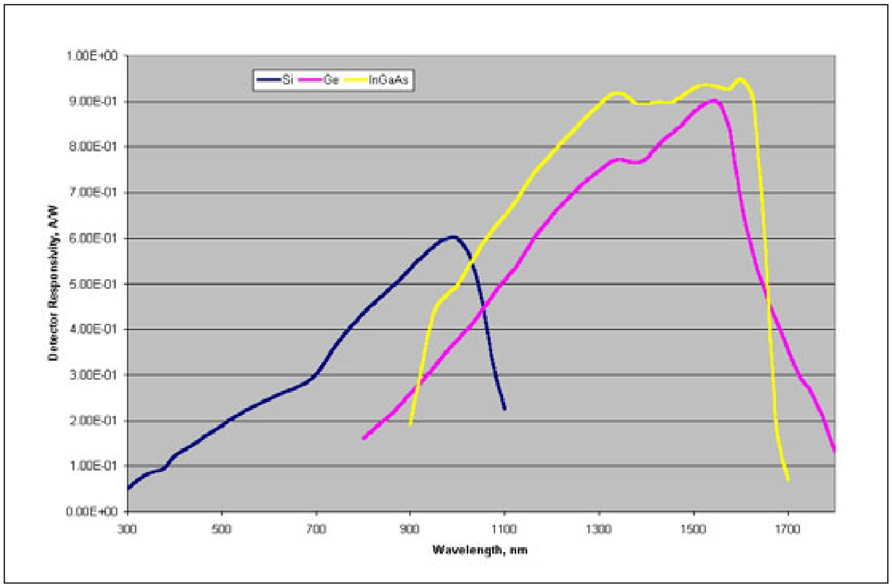

Figure. 2. Typical responsivity curve for Si, Ge, InGaAs

Different Characteristics for Different Applications

Detectors used as fiberoptic receivers in the telecom industry must have extremely fast rise times to detect optical signals modulated at several gigahertz. Despite their speed, detectors of this type may lack the characteristics needed for other applications, such as pulsed LIV testing. For LIV applications, the detector usually is expected to make an absolute power measurement at various laser drive currents. Therefore, all the light emitted by the laser must be captured, either directly by the detector or by an integrating sphere that incorporates the detector in the inner sphere wall. Since the beam emitted by a laser diode is highly divergent, intercepting all the light for absolute power measurements requires a large area detector, with a diameter of several millimeters. This makes a fast fiberoptic receiver with a typical diameter of 50µm unsuitable for use in LIV testing.

There is another important difference in detector requirements for telecom and LIV applications. A telecom photodiode detector receives an optical pulse train and must determine when the digital bits are on and off. A fast response time helps ensure a low bit error rate (BER). For absolute power measurements in LIV testing, the detector must also be calibrated so that the photocurrent generated by an individual optical pulse is related to the power input from the laser.

LIV Testing

In laser diode production, LIV tests are used to sort lasers for various applications and to weed out defective devices as early as possible in the production process. LIV tests also determine some of the optical and electrical characteristics of the final packaged product.

An LIV curve is generated by applying a range of drive currents to the laser diode and plotting voltage drop and light output as a function of current (***Figure 3***). The test instrument is configured for a drive current sweep with small step increments and a simultaneous measurement of the laser diode's forward voltage drop for each current step. The optical power output from the laser's rear and back facets are also measured at each step, which requires calibrated photodetectors [3].

An important characteristic obtained from an LIV curve is the laser's threshold current. This is the injection current value at which light output increases dramatically, signaling the onset of stimulated emission (lasing action), as indicated by the knee of the dL/dI_F curve in ***Figure 3***. The laser's slope efficiency ($\Delta L/\Delta I$) is another important piece of information. It is desirable for the laser to produce a large increase in light output for a small increase in injection current. Ensuring the laser's output is linear and kink-free is another purpose of LIV testing. Kinks are small bumps and abrupt, discontinuous changes in the slope of the LI curve, which are more easily seen on the dL/dI curve. Manufacturers base a laser's maximum output power rating on the linearity and absence of kinks in the LI curve.

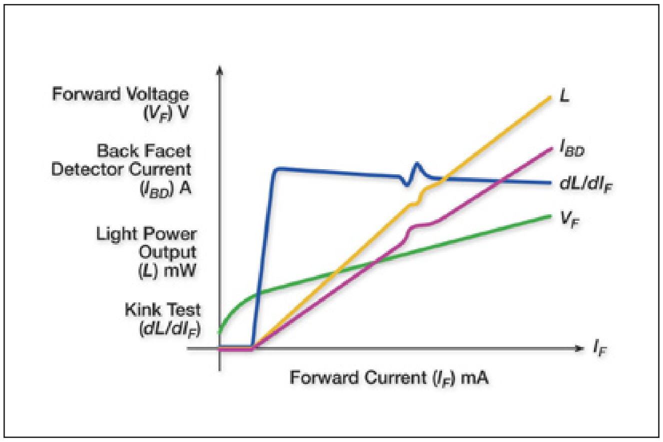

Figure. 3. "Smoothed" LIV curves, from originals obtained with a Keithley Model 2520 Pulsed Laser Diode Test System.

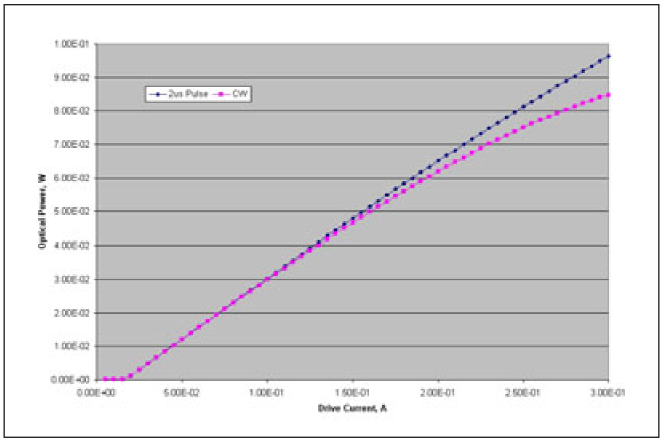

Figure. 4. Optical power output from a diode laser as a function of drive current for pulsed and CW mode.

Unfortunately, both the threshold current and slope efficiency are influenced by temperature changes caused by self-heating of the device. Both quantities decrease with an increase in temperature. This makes thermal control a necessity during diode laser testing in continuous wave (CW) mode. However, early testing at the laser diode bar or chip stage usually precludes the use of active cooling.

Without active cooling, self-heating of the laser chip can be avoided by performing LIV sweeps in pulsed mode. ***Figure 4*** illustrates the decrease in optical power during CW mode operation without active cooling, as compared to pulsed mode. Note the rapid decrease at higher CW drive currents. Pulse testing avoids this undesirable thermal effect, as long as the pulse duty cycle is kept low. Most pulse testing of laser diodes is performed with pulse widths of 500ns to 1µs at a 0.1% duty cycle or less. This not only minimizes average power dissipation in the device under test (DUT), it helps keep the test cycle as short as possible.

Detector Characteristics for Pulsed Optical Power Measurements

Laser diode light output measurements during LIV testing require a photodetector with the following characteristics:

- The photodiode must have adequate sensitivity over the desired wavelength range.
- The active area must be sufficiently large to fully intercept a laser diode's divergent beam.
- The rise time must be sufficiently short for a pulse width of 500ns.
- For any given optical power, the photocurrent produced by an optical pulse input must be equal to that produced by a CW input.

As can be seen from ***Figure 2***, each detector material is sensitive over a clearly defined wavelength range. If the operating wavelength of the laser under test is near the cutoff wavelength of a detector, a small shift in laser wavelength may cause a dramatic decrease in photocurrent. This can be avoided by using a detector with a flatter responsivity curve in the wavelength range of interest.

Another good rule of thumb is to choose the smallest detector that will work for a particular application. Using a detector that is larger than necessary has severe disadvantages. An increase in area leads to a decrease in detector speed, due to an increase in junction capacitance. It also increases dark current and cost.

Nonetheless, a smaller detector makes it more difficult to ensure that all the laser radiation is intercepted and measured. A laser diode's divergent beam requires detector placement within a few millimeters of the laser's light emitting facet, which can create problems. For example, the close proximity of laser facet and detector aperture makes it difficult to insert neutral density filters (often required to avoid detector saturation). A better solution is an integrating sphere with a built-in detector to capture diverging radiation. In this case, the size of the photodiode is determined by the size of the integrating sphere, detector location in the sphere wall, expected optical input power, and the ability of the instrumentation to measure low photocurrents.

Of course, the rise time of the detector is still an important consideration. This parameter is a measure of the time response of the photodiode to a light pulse input. It is defined as the time required for the detector output to change from 10% to 90% of its "steady" or "settled" output level. As discussed earlier, telecom photodetectors are readily available with response times in the nanosecond or even picosecond range. However, as a prerequisite for absolute optical power measurements, a detector's photocurrent must reach 100% of its peak value before the end of each pulse. In other words, its output current has to be "settled." If there is a slow diffusion current component contributing to the total photocurrent, a photodiode with a rise time of a few nanoseconds could take several microseconds to rise from 90% to its settled (100%) output value. For pulse widths of 500ns or less, this would cause an inaccurate optical power measurement.

Calibration Issues

Calibrating a photodetector or integrating sphere/detector system means determining the photocurrent the detector is expected to produce for a given optical input power at a particular wavelength. These calibration constants, given in amperes/watt, can then be used to convert photocurrent to optical power.

A calibration usually is performed over a wide range of wavelengths, so the radiation source has traditionally been a monochromator and a halogen lamp with a spectrum that contains wavelengths from the visible to

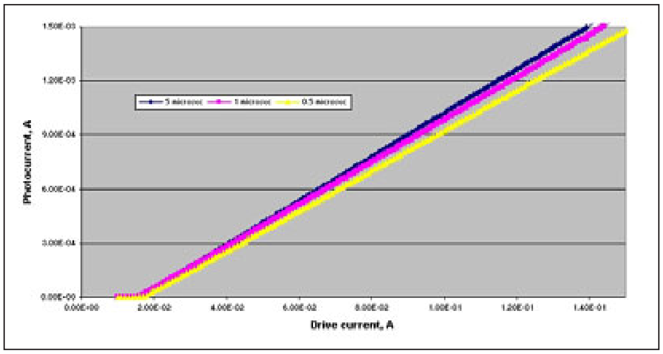

Figure. 5. LI curves using the same diode laser and detector under three different pulse width conditions. Note that, in this case, shorter pulses cause the slope of the LI curve to be less steep because the photocurrent of each pulse was not settled.

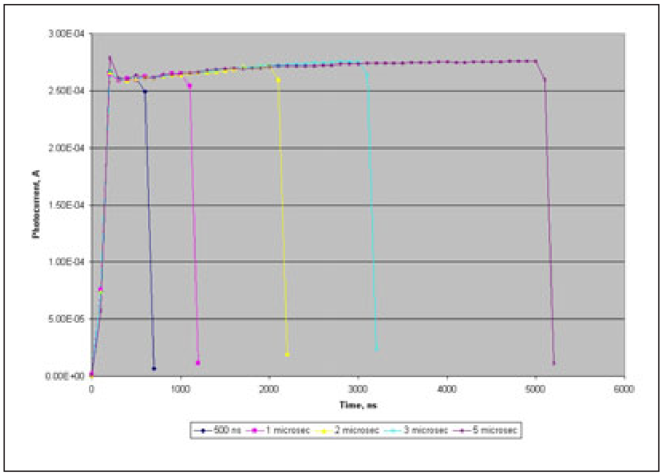

Figure. 6. Pulse shapes of the same laser at various pulse widths, showing that the photocurrent value reported can be lower for shorter pulses than for longer ones.

the infrared. The monochromator's diffraction grating acts as a filter and allows only certain narrow bands of wavelengths to pass through the output slit. The calibration is a comparison of the detector under test to an NIST (National Institute of Standards and Technology) traceable reference detector. Currently, calibration labs and NIST offer responsivity calibrations performed in CW mode only. NIST does not presently offer a detector responsivity calibration service performed with a pulsed source. Therefore, analyzing the pulse performance of the photodetector and test setup is usually required after CW calibration (discussed in the next section).

Pulse Shape Considerations

The shape of the photodetector's output current pulse is important for good LIV measurements. Ideally, the photocurrent pulse should have a perfectly flat top, representing a "settled" value equal to the photocurrent produced with an equivalent CW power input value. If the photocurrent is still rising at the end of the optical input pulse, then the measured power will be lower than the actual power. If the photocurrent output pulse has settled before the trailing edge of the optical input pulse occurs, the measured power will be representative of the actual optical power. ***Figure 5*** illustrates how a long settling time produces an incorrect slope in a laser diode's LI curve, i.e., an inaccurate power measurement.

If a photodetector is intended to provide absolute calibrated power measurements with a pulsed optical source, users should evaluate individual photocurrent pulse shapes with their own laser sources at different pulse widths. This will show whether the measured output power of each optical pulse is based on a "settled" photocurrent value or if the measured value would actually be higher if a longer pulse width were used (see ***Figure 6***). However, keep in mind that the photocurrent pulse is a result of both the detector response and the shape of the input pulse from the laser. If the laser has a slow response to a short drive current pulse, this could also be responsible for a longer rise time in the photocurrent output pulse.

In some cases, the pulse width required for an accurate power measurement from a particular detector, source, and test setup may be longer than desirable. If a shorter pulse width is necessary, the test engineer can use data plots obtained with longer pulses to make a few suppositions. For example, such plots can be used to infer the percentage by which the power displayed is lower than it would have been if the pulse width were long enough for the photocurrent to settle. However, this is not an ideal solution, and it underscores the need to choose a detector that gives the best possible results for a particular application.

References

1. Hecht, Jeff. *Understanding Fiber Optics.* Prentice-Hall, 1999.
2. Donati, Silvano. *Photodetectors: devices, circuits, and applications.* Prentice-Hall, 2000.
3. *DC Production Testing of Telecommunications Laser Diode Modules*, Keithley Application Note #2214.

Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) • www.keithley.com

No. 2517
0304