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Cost Effective Methods for Characterizing Laser Transfer Curves

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When designing an optical transmitter, data sheet performance curves may not be enough—accurate characterization of the individual laser diodes may be required for design of the laser driver

Manufacturers of laser diodes use dedicated equipment to characterize these devices, which is expensive and, in most cases, unavailable to engineers who intend to use the laser diodes in the design of optical transmitters. This article is intended to provide cost effective and reliable methods that allow quick and accurate measurements of critical laser diode parameters.

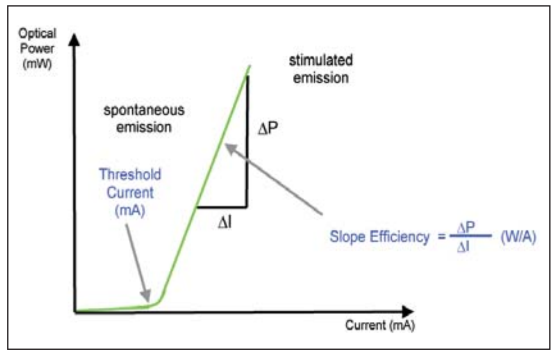

Figure 1 · Typical laser diode transfer function curve.

Laser Diode Fundamentals

Laser diodes, which are used in optical communications typically, come in a package that includes a pigtail pre-aligned with the laser, and a back facet monitor photo diode.

For digital transmission the laser light intensity is modulated so that each digital level has a distinct optical power. The optical digital levels must be kept constant over time and temperature to ensure network integrity. Figure 1 shows a typical laser diode transfer curve. There are two regions of operation that characterize the laser transfer function. To the left is the sub-threshold region, sometimes called the LED region. In this region spontaneous emission of light occurs. To the right, above laser threshold is the laser active region, above which stimulated emission of light occurs. In this linear region the intensity of the light is proportional to the current through the device. It is this region of the laser transfer curve that is used for digital transmission. The key characteristics of the laser transfer function are the threshold current, I_{th}, and the slope in the linear region beyond the threshold current, referred to as the slope efficiency, LI.

Assuming an equal probability of ones and zeros in the data stream, the average optical power is, P_{av}, is defined as:

$$P_{av} = \frac{P_1 - P_0}{2}$$

where P_1 is the optical power corresponding to a logic one and P_0 is the optical power corresponding to a logic zero.

The extinction ratio, ER, is defined as:

$$ER = \frac{P_1}{P_0}$$

A laser is basically a current-to-light converter and the slope efficiency, LI, is the conversion factor. The efficiency of the laser is given by the ratio of current to optical intensity or power, and the greater the LI the more efficient, thus providing higher optical power

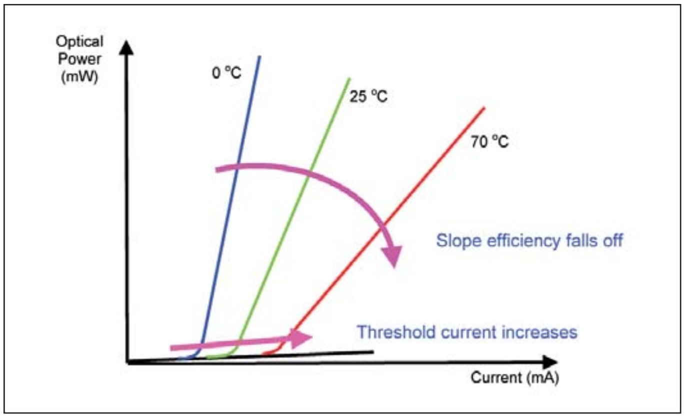

Figure 2 · Laser diode transfer curve variation over temperature.

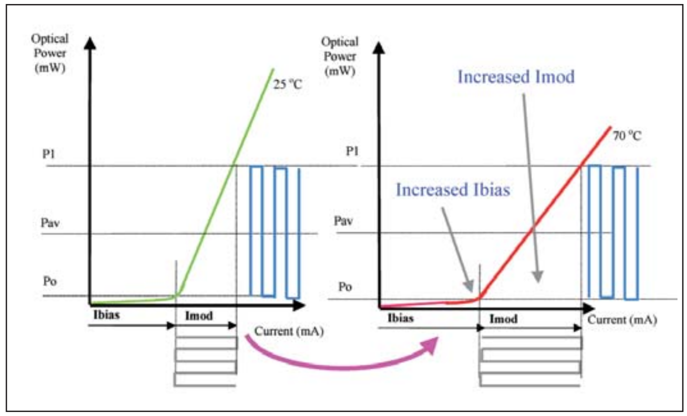

Figure 3 · Laser diode with increased bias and modulation current at higher temperature.

for a given current through the laser diode.

Unfortunately, the laser transfer curve changes over time and temperature. With increasing temperature, the threshold current increases and the slope efficiency falls off exponentially. Aging effects cause the threshold current to increase and the slope efficiency to fall off exponentially over the life of the laser. Figure 2 shows typical laser transfer curves at three temperatures.

In operation, a DC bias current overcomes the threshold current and ensures that the laser is operating in its linear region. The modulation current then converts the data signal into the optical domain. To keep the average power and extinction ratio constant over time and temperature, the bias and modulation currents must be continuously adjusted to compensate for variations in the laser slope efficiency. Figure 3 illustrates how the bias and modulation currents have to change to compensate for variations in slope efficiency from 25ºC to 75ºC.

For feedback control purposes, communications lasers are manufactured with a back facet monitor photo diode (MPD) mounted adjacent to the laser. The MPD is a reverse-biased diode that conducts in proportion to the laser light intensity. Therefore, the MPD may be used to provide a direct measurement of the optical power emitted by the laser diode. Figure 4 shows a simplified drawing of a typical laser, MPD and pre-aligned fiber pigtail.

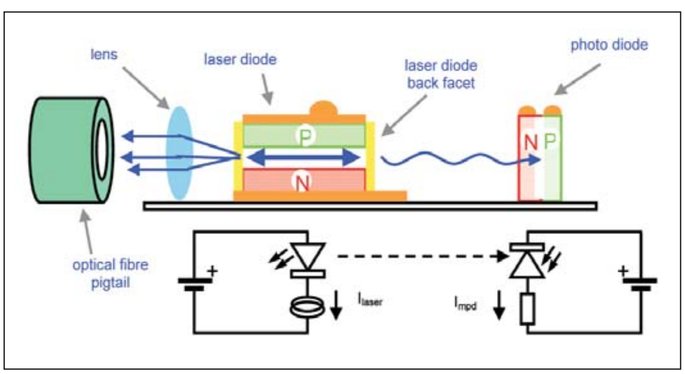

Figure 4 · Simplified drawing of a laser diode with fiber and back facet monitor photo diode

A laser diode driver (LDD) translates logic signals from the electrical domain to the optical domain, delivering current to the laser diode and monitoring its output with the MPD.

In industry, laser diode drivers employ several methods to establish and maintain average optical power and extinction ratio. There are open loop, single loop and dual loop schemes employed to control these parameters. The most popular are the single and dual loop schemes. The single loop LDD controls average power in a closed loop fashion using the MPD current as the feedback mechanism. The ER is then controlled as a function of modulation current in an open loop manner. Dual loop schemes use circuits that control P_{av} and ER based on measurements taken directly from the laser diode. Figure 5 shows a typical a dual loop laser diode driver application.

Figure 5 illustrates that the laser and MPD are used to provide feedback and close the control loops. To ensure accurate control, it is essential to keep the errors introduced by the feedback circuitry as low as possible over temperature and time. The MPD has to provide accurate conversions of the optical power into a proportional current over the lifetime of the circuits.

One of the main contributors in the feedback accuracy is Tracking Error. The laser diode and monitor photo diodes are physically separate components mounted adjacent to one another on a common substrate as shown in Figure 4. The various mounting materials used will expand at different rates and the mechanical misalignment causes coupling from the laser to the MPD to change with temperature—known as the Tracking Error. It may even be possible to obtain the same MPD current for two different levels of optical power. Laser data sheets specify the tracking error as a maximum deviation from a

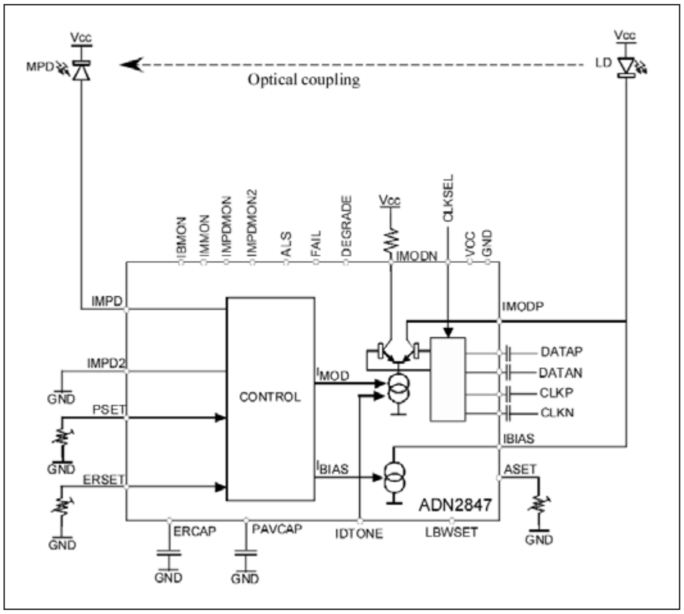

Figure 5 · Laser diode driver with laser module.

given optical power over the operating temperature range, usually expressed in dB. This gives an estimation of the maximum possible error in the P_{av} control loop caused by the laser module itself, which can be used for average power error budget calculations. When more accurate estimations of the average power errors are needed, the tracking error must be measured for each individual laser module.

Headroom is another issue when using the laser module in conjunction with laser drivers. The trend in laser diode drivers is to reduce power consumption and supply voltages are accordingly reduced. The high-speed circuitry within the laser diode driver is usually an open collector or open drain differential pair. For proper operation of the laser diode driver output stage, the forward voltage drop, combined with any voltage drop on the interfacing circuitry, must maintain an adequate voltage to ensure the voltage at the output pin of the LDD will not fall below the minimum specified in the laser diode driver data sheet.

In the laser data sheet, the forward voltage drop is specified in continuous wave (CW) mode. This number is generated using a DC current and does not take account of any parasitic impedances which may increase the forward voltage drop when switching data.

When designing an optical transmitter it is important to determine the actual forward voltage drop across the laser when it is switching at the highest data rate. Based on the results of headroom calculations using this voltage drop, the designer will choose between DC or AC coupled laser configurations.

The slope efficiency when it is quoted on the laser data sheet is given at a single temperature and in continuous wave mode. However, because slope efficiency can change dramatically over temperature it is important to determine its behavior at temperature extremes. Once the slope efficiency performance is completely determined over the operating conditions, the applications engineer may then derive the laser diode driver current requirements.

One can see from the above discussion that it may be necessary to elaborate on the specifications provided in the typical laser diode data sheet in order to design a driver for a particular application. To characterize the laser diodes, there are two practical schemes: the DC method and the AC method.

The DC Method

The DC method appears to be the simplest way to characterize a laser. One simply uses a current sink to pull current through the laser and the resultant optical power is measured using a Digital Communications Analyzer. The resulting MPD current may also be measured as a voltage drop across a resistor. Figure 6 shows a very simple schematic for the DC scheme.

The results are taken on a point-by-point basis, with smaller increments in current achieving better measurement resolution. Then, one simply joins up the dots to draw the LI curve. The threshold current can be identified as the point where optical power level begins to increase in a linear fashion that is proportional to the current applied. This DC scheme can also be used over temperature to predict changes in threshold current and to once again draw the LI curve on a point-by-point basis. The resulting MPD currents can also be noted.

The forward voltage drop can be measured by simply putting a digital voltmeter across the laser diode.

However, there are some disadvantages in using the DC characterization method. Because it is so simple the measurement is usually performed manually, which means that it takes a relatively long time to perform the test. There are also the associated resolution problems because it is a point-by-point representation of the slope efficiency. There are also thermal issues associated with this method—the laser itself has a thermal time constant. When the laser current is switched at a frequency that is greater than this time constant, it not an issue. However, in the DC case, the current is not switched and, therefore, at high currents there are I^2R errors which will actually alter the slope efficiency, and the measurement will be different than the actual behavior of the laser. When the laser is switching current the I^2R effect is a function of the average current, but in the DC method the power dissipated is a function of the total current, which can be much larger than the average. Because laser slope efficiency falls off exponentially with temperature one can gather

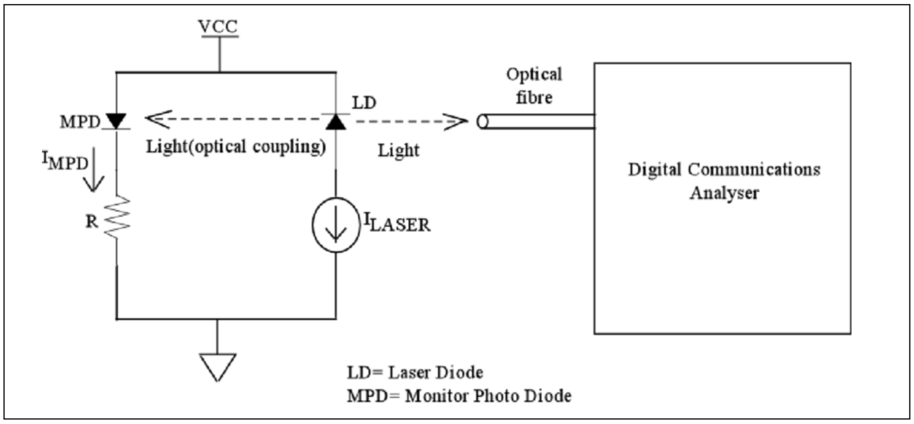

Figure 6 · Simplified schematic of a DC characterization scheme.

data that does not represent the laser's performance in the intended application.

The AC Method

AC characterization of a laser will provide a continuous and accurate representation of the laser, and will exercise the laser in a fashion similar to the intended application. There are several ways to achieve dynamic characterization of the laser. The most intuitive way is to apply a ramp or, preferably, a sawtooth current. When using a sawtooth current, with the Digital Communications Analyzer properly triggered, one can observe the actual LI curve on the screen. As long as the frequency of the sawtooth waveform is greater than the thermal time constant of the laser, the effects of excessive self-heating at high currents are avoided. Any self heating effects are due to the average power dissipated in the device.

Figure 7 show a block diagram that illustrates the AC characterization principle. The function generator provides the sawtooth waveform. The signal is applied to a voltage to current converter which provides the necessary current to drive the laser. The offset and the amplitude of the saw tooth waveform has to be set in a manner which will provides the intended current range over which the laser will operate.

Figure 8 shows the schematic for an AC characterization scheme. It is uses a voltage-controlled current source with a sawtooth waveform is applied to the non-inverting input of the operational amplifier to generate

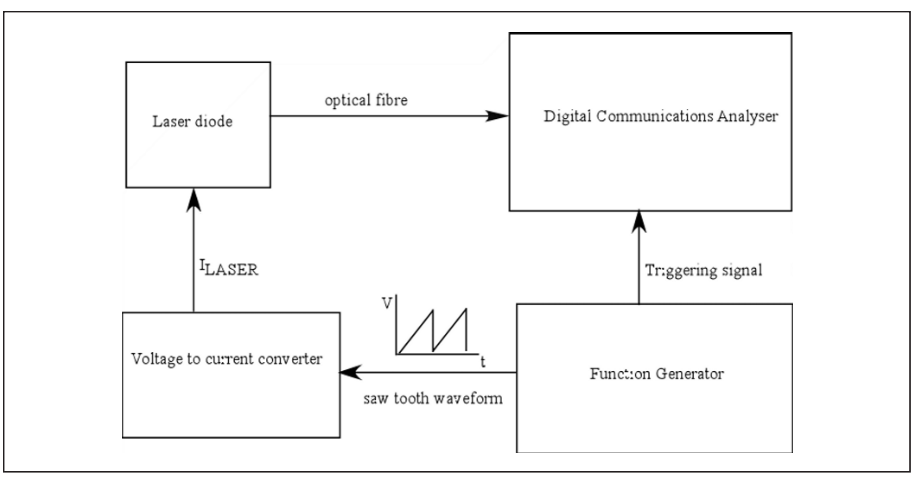

Figure 7 · Block diagram of an AC characterization scheme.

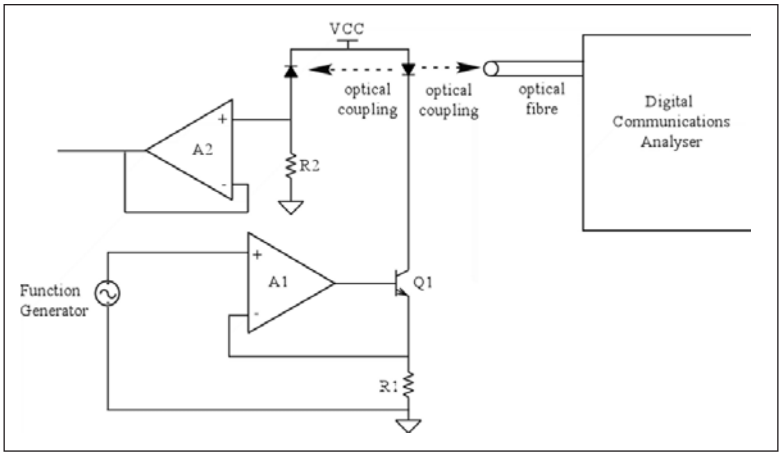

Figure 8 · An AC characterization scheme.

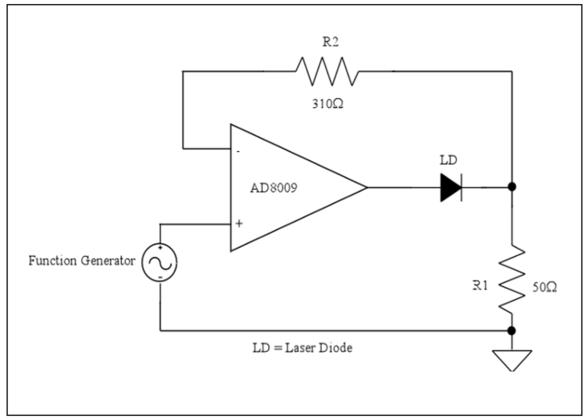

Figure 9. Schematic of the improved AC characterization scheme.

a ramp current. The amplitude and offset of the sawtooth waveform are chosen to ensure the current swing in the laser remains within the specified limits.

The input voltage appears across resistor R1, which has a value selected to ensure that the current through the laser is within the desired or specified limits of the laser. Note that the collector current of Q1 differs from the emitter current by the base current. This can be considered as an error and a Super beta transistor, or MOS transistor is required to ensure this error is negligible.

If the current generator (operational amplifier and transistor) is fast enough, one can apply a sine wave to determine the frequency response of the laser. The MPD response can also be examined by measuring the current flowing through it for different values of optical power in the laser. The current in the MPD is converted to a voltage by R2 and this may be measured at the output of operational amplifier, A2.

The tracking error may be determined by applying a current that gives an optical power equal to the desired average power at 25ºC. The resulting monitor photo diode current is then recorded. The temperature can then be changed and the optical power has to be changed by adjusting the current to re-establish the initial monitor photo diode current. The maximum variation of the optical power that produces the same monitor photo diode current gives the actual Tracking Error, which can be expressed in dB using the following formula:

Tracking Error =

$$\max\left[\left|10\log\left(\frac{P_{av}}{P_{av}@25°\mathrm{C}}\right)\right|\right]$$

where P_{av} is the desired average power.

The same scheme may be used to determine the Tracking Error in the DC method described earlier.

Using high impedance probes to capture the voltages at the anode and cathode of the laser diode and applying the necessary math to the signals at the two probes, the forward voltage across the laser can be determined. The math function is typically available on any Digital Communications Analyzer.

This method of characterization does not require a DC current pedestal to overcome the laser's threshold current. One can switch above and below threshold and once the threshold current is identified one can then apply the known DC portion of the current to overcome the laser threshold current, then on top of this apply a square wave current which will simulate the working conditions of the laser. The maximum frequency of the square wave is limited by the bandwidth of the operational amplifier and transistor.

An Improved AC Characterization Scheme

Figure 9 shows a schematic of an improved AC characterization scheme. This scheme employs a current feedback operational amplifier to provide the necessary bias and modulation current, and provides a much wider bandwidth than the circuit shown in Figure 8. Resistor R1 sets the current through the laser. The AD8009 is a high bandwidth current feedback amplifier capable of delivering 175 mA of load current, and has a large signal bandwidth of 440 MHz. It allows the user to overcome the bandwidth limitations of the voltage amplifier in Figure 8, and theoretically does not have the associated transistor beta error.

All of the measurement capabilities as in the previous method can be realized using this improved scheme, but you get simplicity—you can use a 50 ohm scope probe to replace R1 and examine the electrical characteristics of the laser. Also, an optical eye can be generated at appreciable bit rates. Figure 10 shows a 100 Mbps optical eye.

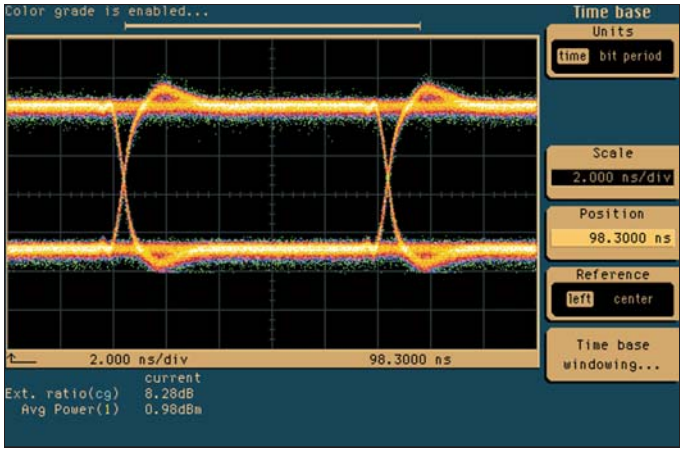

Figure 10 · Optical eye at 100 Mbps.

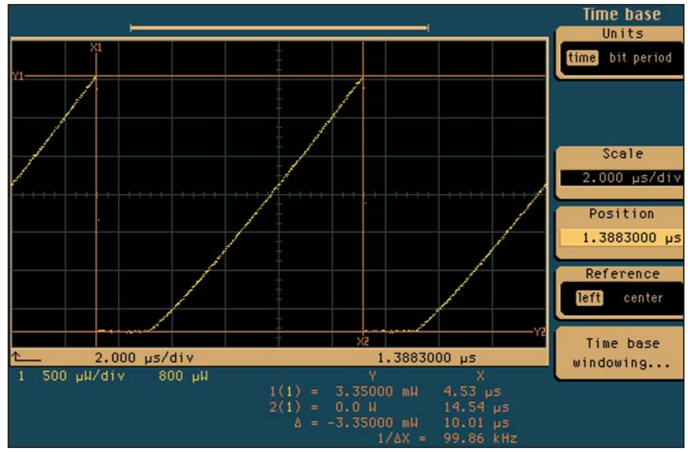

Figure 11 · Laser LI curve.

Figure 11 shows an actual laser diode transfer curve in real time, once again achieved by applying a ramp current to the laser and measuring the resultant optical signal on a Digital Communications Analyzer. By applying a sawtooth waveform one can see the LI current, with the scope trace showing the actual optical power versus time.

The scope trace provides a direct measurement of the laser power but not the current. To determine the current one simply uses a second scope channel to record the input signal against the optical one. The current is simply the input amplitude divided by the load resistor R1. The ramp frequency is orders of magnitude above the laser thermal time constant and, therefore, the self-heating errors associated with the DC scheme are removed.

The MPD current can be measured using the circuit shown in Figure 8 as a voltage drop across resistor R2. The frequency response of the MPD is measured by applying a sine wave current to the laser and measuring the resultant MPD current versus frequency.

This laser transfer curve is a true representation of the actual laser response. Applying a square wave to the circuit, one can examine the switching response of the laser. If the expected rise and fall times of the laser are expected to be greater than the slew rate of the AD8009 then these numbers may be recorded. Using a pseudo-random bit stream also allows the user to establish whether or not the intended average power and extinction ratio is achievable on a chosen laser. Finally, the Tracking Error and forward voltage may be measured in the same manner described in the first AC scheme.

Summary

As modern optical communication systems require increasingly higher bit rates combined with low power consumption, the concepts presented in this article offer a practical and cost effective aid in designing and implementing reliable high performance optical transmitters.

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