Laser Diode Junction Temperature Measurement Alternatives:
An Overview

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Abstract

Junction temperature affects laser diode performance in many ways. Light output center wavelength, spectrum, and power magnitude, and diode reliability are all directly dependent on the junction temperature. Coupled with the very high power densities, ranging well upwards of 1,000 W/cm^2 in the junction area, the thermal design of laser diode itself and the packaging in which it is encased becomes crucial to the overall performance of the device. Key to the validation of any thermal design is the ability to measure junction temperature. This same ability is also applicable to and necessary for the high-yield manufacture of these devices. This paper describes and compares three different methods for laser diode junction temperature measurements.

Introduction

There are basically three different methods for making laser diode junction temperature measurements. All three methods have been in use for more than two decades by various manufacturers and research laboratories. Two of the methods use the device's light output for an indirect method of junction temperature measurement. The third method is more traditional, considering it application to other types of diodes, and uses one of the device's electrical characteristics for an indirect measurement of junction temperature. This paper provides an overview of the three measurement methods.

Terms and Symbols

POM - Power Output Method
WSM - Wavelength Shift Method
FVM - Forward Voltage Method
K - K Factor, FVM
K_P - K Factor, POM
K_λ - K Factor, WSM
P_O - Power Output
λ_O - Wavelength Output
T_A - Ambient Temperature
T_J - Junction Temperature
V_F - Forward Voltage across a diode
I_F - Forward Current through a diode
I_M - Measurement Current through a diode
I_S - Sense Current through a diode
P_H - Heating Power
t_H - Heating Time
θ_{JX} - Thermal Resistance, Junction to Reference
X - Reference point for Thermal Resistance
ETM - Electrical Test Method

Power Output Method

The light power output of a laser diode is linearly proportional to its junction temperature (T_J). This attribute can be used to determine T_J if the relationship between T_J and the power output is known in advance. Unfortunately, this relationship is dependent not only on the process-dependent characteristics of the laser diode chip but also on the ability to get rid of the heat generated at the diode junction. The latter is a function of the chip package and the combination of chip attachment technique and material. The variability's make empirical determination the best approach to deriving the P_O vs. T_J relationship.

The empirical determination (i.e., calibration) requires a setup like the one shown in Figure 1. The diode under calibration is placed in a temperature-controlled environment (TCE) and pulsed with applied power at a very low duty cycle. Typically the pulse width is on the order of 0.1 to 1 µs and the duty cycle is in the range of 0.01 to 0.1% to minimize junction heating and the resultant change in P_O. The pulse width is keep as small as possible to minimize laser diode junction heating. The repetition rate is usually determined by the light power measurement sensor and circuitry. The light power

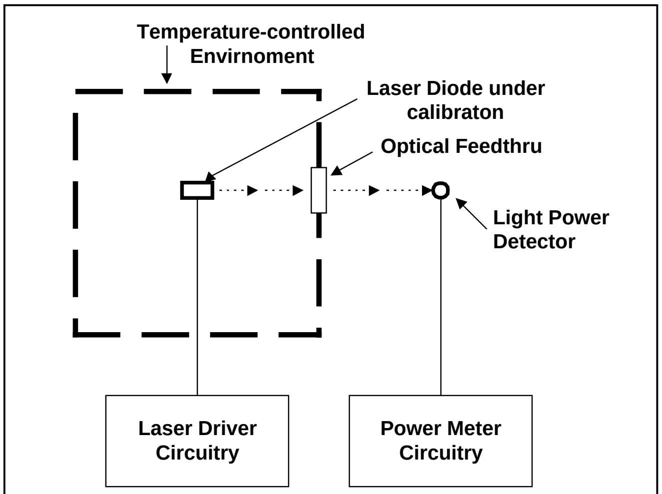

Figure 1. Power Output Calibration Setup

measurement apparatus is placed outside the temperature-controlled environment; its temperature is maintained relatively constant during the calibration process. The light passes through the environment wall using a window with temperature-independent transmission properties over the typical 25 to 100 °C calibration range. As the laser diode light output frequency will also shift as the diode is heated, the window must also have a flat frequency transmission band over the likely frequency shift range. Once the TCE has been stabilized at a fixed temperature, the diode is pulsed and the power output is recorded. The TCE temperature is then set to a higher temperature, usually 30 to 55 °C higher, and the process is repeated until the higher temperature limit is reached. When all the data has been collected, the graph shown in Figure 2 can be created and the slope reciprocal relating T_J to P_O determined; referred to as K_P in units or °C/mW. A typical value of K_P is in the range of 2.5 °C/mW in the 25 to 50 °C range for a 25 mW output device[1]; the exact value is specific to the laser diode construction and material.

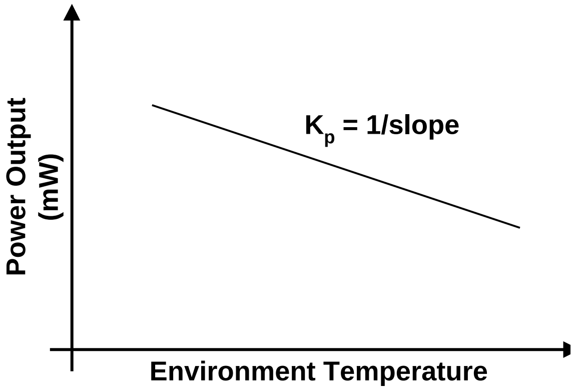

Figure 2. Power output calibration results

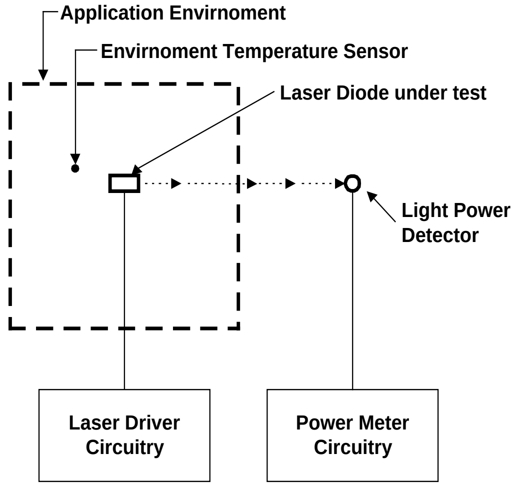

Figure 3. Temperature shift measurement in actual application

Once K_P is known, the laser diode junction temperature in an actual application environment can be determined in the following manner. Place the laser diode in the application environment as shown in Figure 3. and allow thermal equilibrium to occur before applying power to the laser diode. Monitor ambient temperature (T_A) at the diode base or package to determine when equilibrium has occurred. Then apply a very short duration pulse, on the order of 1 µs or less, and measure the initial light power output (P_{Oi}). This establishes a light power output corresponding to T_A. Then apply normal application power to the laser diode and again measure the light power output (P_O). Measure T_A again; it will probably increase due to power dissipation in the laser diode. Then the junction temperature is:

$$\boldsymbol{T_J = T_A + \Delta T_J} \qquad \textbf{(1)}$$

where

$$\boldsymbol{\Delta T_J = (P_O - P_{Oi})(K_P)} \qquad \textbf{(2)}$$

$\therefore$

$$\boldsymbol{T_J = T_A + (P_O - P_{Oi})(K_P)} \qquad \textbf{(3)}$$

Wavelength Shift Method

The Wavelength Shift Method (WSM) is very similar to the Power Output Method (POM), differing only in the temperature sensitive parameter (TSP). The shift in light output center wavelength (λ_O) is a good TSP because it behaves linearly with device junction temperature with a positive slope, as shown in Figure 4.

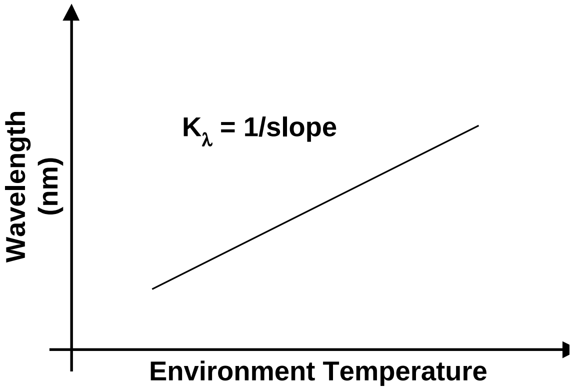

Figure 4. Wavelength Shift Calibration Results

The calibration procedure to obtain the reciprocal of the slope, refereed to as K_λ, is very similar to that for the POM. Instead of measuring light power output, the equipment setup measures λ_O, as shown in Figure 5. The calibration procedure is basically the same: apply a very short duration power pulse to the diode being calibrated, long enough for the measurement equipment to determine λ_O but short enough not to cause any significant junction heating - pulse duration of 1 µs or less is sufficient. The value of K_λ is typically in the 3 °C/nm range[2] but the specific value is heavily dependent on the laser diode construction.

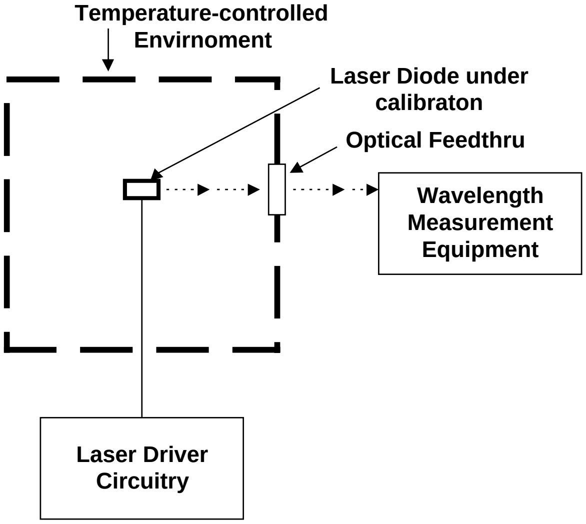

Figure 5. Wavelength Shift Calibration Setup

To determine T_J in an actual application, the Temperature-Controlled Environment of Figure 5 is replaced with the actual application environment. A temperature sensor is used to monitor the temperature at the laser diode mounting surface or package to determine when temperature equilibrium has occurred with the environment. Then a short-duration power pulse (about 1 µs or less) is applied to the laser diode to establish the initial wavelength (λ_{Oi}) of the laser diode output. Next, the application power is applied and both λ_O and T_A are monitored until a steady-state condition occurs. Then the junction temperature is:

$$T_J = T_A + \Delta T_J \tag{4}$$

where

$$\Delta T_J = (\lambda_O - \lambda_{Oi})(K_\lambda) \tag{5}$$

$\therefore$

$$T_J = T_A + (\lambda_O - \lambda_{Oi})(K_\lambda) \tag{6}$$

Forward Voltage Method

Laser diodes, like most other semiconductor junction diodes, have a forward voltage characteristic that can be used for temperature sensing. The key requirement in using this characteristic is that the Measurement Current (I_M), sometimes referred to as the Sense Current (I_S), must be large enough to turn the junction on but not so large as to cause significant self-heating of the junction. Typically the best value is right around the knee of the diode forward characteristic as shown in Figure 6. One milliamp is sufficient for most laser diodes, although high power output units may require up to 50 mA.

Calibration of the V_F temperature characteristic requires a setup like the one shown in Figure 7. The low value of I_M insures that the environment and junction temperatures are the same. Note that because calibration requires only a constant current and a voltage measurement capability, multiple units can be calibrated at the same time in a batch mode. The Temperature Calibration System shown contains the current source, voltmeter, a thermocouple meter and a multi-channel electronic switch.

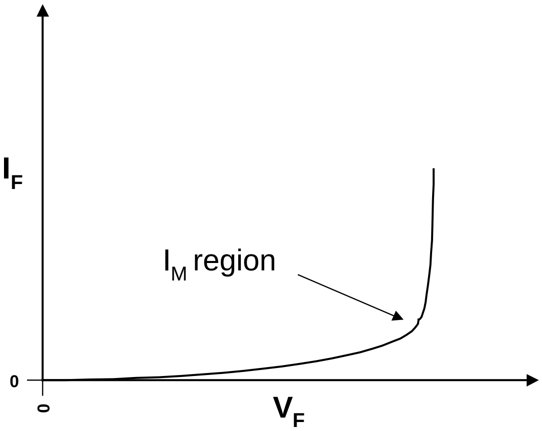

Figure 6. Typical Diode Forward Current-Voltage Characteristic

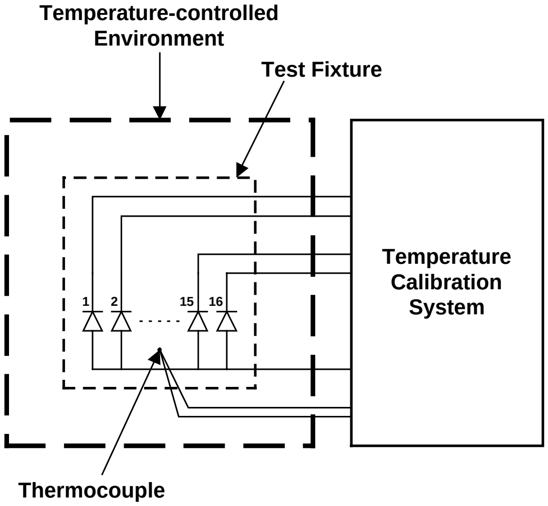

Figure 7. VF - Temperature Calibration Setup

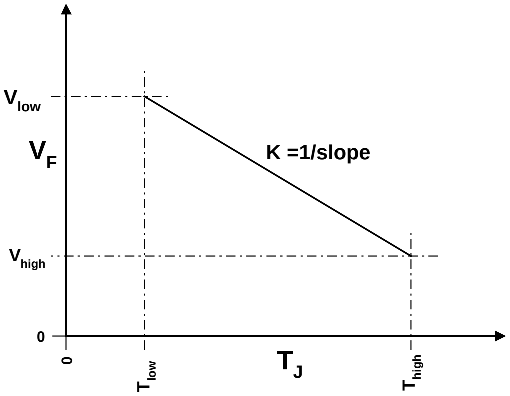

Figure 8. V_F - T_J Calibration Results

The relationship between VF and Temperature is, for most practical purposes, very linear and produces the curve shown in Figure 8. The calibration constant is K Factor, or just K, is typically in the range of 0.5 °C/mV for silicon-based PN-junctions but can vary greatly depending on the specific laser diode construction and materials, typically being in the 1 to 3 °C/mV range. Although the slope is negative, K is always stated as a positive number:

$$K = \left| \frac{T_{high} - T_{low}}{V_{low} - V_{high}} \right| \qquad (7)$$

Typical practice is to calibrate five or more devices at a single time. Batch calibration serves two purposes. First, it reduces the time necessary to calibrate all the devices individually. The initial temperature and the final temperature stabilization periods, which can take 30 minutes or more depending on the temperature environment used for the calibration, only has to be done once instead of for each diode. Second, making measurements in batch form helps to reduce potential errors if the data is averaged. Further, to save thermal testing time, the results of calibration batch are usually averaged (K_{avg}) and the standard deviation (σ_K) determined. If the ratio of σ_K/ K_{avg+} is less than 1.03, then thermal testing on the batch units can proceed using the K_{avg} for all units without causing a significant error in the thermal test results. A ratio of greater than 1.03 requires using the individual values of K for thermal testing. The higher ratio also indicates potential process control problems in the fabrication of the diodes.

The Forward Voltage Method (FVM), also referred to as the Electrical Test Method (ETM)[3,4,5], for laser diode junction temperature measurements uses a three-step sequence of applied current levels to determine a change in junction voltage (ΔV_F) under Measurement Current (I_M) conditions. The setup for the measurement is shown in Figure 9. First, I_M is applied and the diode-under-test junction voltage is measured - the measurement value is referred to as V_{Fi}. Second, I_M is replaced with a desired amount of Heating Current (I_H) for a time duration (t_H) consistent with the steady-state or transient data required. During this time the diode voltage (V_H) is measured for determining the amount of power (P_H) being dissipated in the diode. Third, I_H is removed and quickly replaced with I_M and a final junction voltage measurement is be made - this voltage is referred to as $V_{Ff.}$ The three-step operation shown graphically in Figure 10.

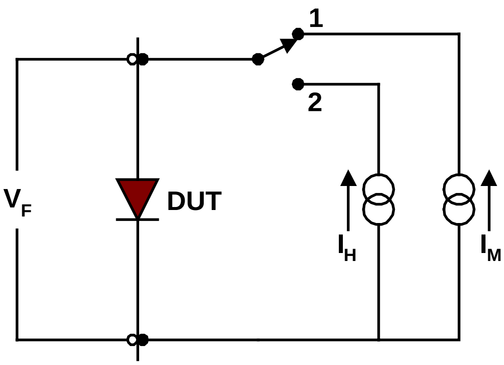

Figure 9. FVM Measurement Setup

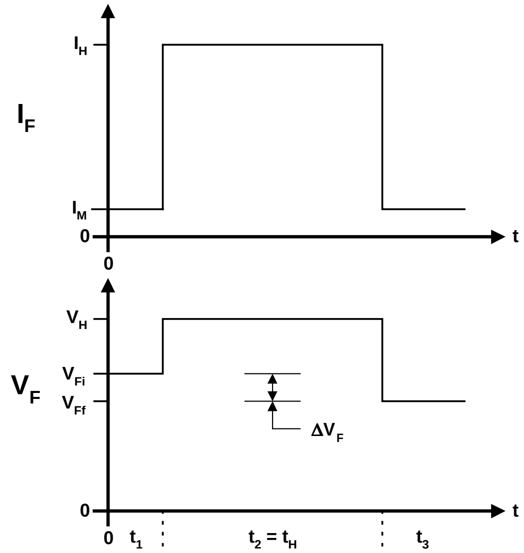

Figure 10. FVM Measurement Waveforms

As discussed with the two previous methods, the FVM also requires the use of a temperature sensor (T_A) placed on the laser diode mounting surface or package to determine T_J in absolute terms. This sensor, in conjunction with monitoring of V_F under I_M conditions before the start of the test, is also used to determine if temperature equilibrium conditions exist before the start of the test. Without power applied to the diode, the V_F reading will settle down to a value corresponding to the temperature of the external sensor. The value of T_J can then be calculated as follows:

$$T_J = T_A + \Delta T_J \qquad (7)$$

where

$$\Delta T_J = (V_{Fi} - V_{Ff})(K) \qquad (8)$$

$\therefore$

$$T_J = T_A + (V_{Fi} - V_{Ff})\left(\left| \frac{T_{high} - T_{low}}{V_{low} - V_{high}} \right| \right) \qquad (9)$$

Thermal Resistance

One of the applications for laser diode junction temperature measurements is to determine the device's thermal resistance. Thermal resistance is defined as the temperature difference across a heat flow path divided by the power dissipation that caused the temperature difference.[6] For most laser diodes, the heat is produced at the junction and heat flows through a single path to back side of the diode to the mounting surface. Thus, one end of the path is always the junction (J) and the other is the surface upon which the diode is mounted (M) or the bottom mounting surface of the package (referred to as C for case). The thermal resistance symbol is either θ_{JM} or θ_{JC}. Generically, thermal resistance is stated as θ_{JX}, where X is the reference point that must be defined.

The same data obtained from any of the methods discussed above, with the addition of P_H and the appropriate selection of Heating Time (t_H), can also be used to calculate the laser diode thermal resistance. For the FVM, the thermal resistance is calculated as follows:

$$\theta_{JX} = \frac{\Delta T_J}{P_H} = \left[\frac{K \times \Delta V_F}{I_H \times V_H}\right] \qquad \textbf{(10)}$$

The value of t_H and the environmental conditions determine the meaning of the thermal resistance X subscript. For greatest accuracy on high power conversion laser diodes, Equation (10) has to take into account the portion of applied electrical power (P_H) that is converted to optical output power (P_O). Hence, a more exact value of thermal resistance is:

$$\theta_{JX} = \frac{\Delta T_J}{P_H - P_O} = \left[\frac{K \times \Delta V_F}{(I_H \times V_H) - P_O}\right] \qquad \textbf{(11)}$$

Conclusion

No overview of laser diode junction temperature measurement methods would be complete without some comparison of the alternatives. The list below compares the different methods in relative terms of implementation ease, operational ease, production orientation and cost.

The comparison favors the FVM for most applications. Although all three methods can be used for thermal resistance measurements, only the FVM offers the most flexibility for measurements in a wide range of application environments. Additionally, the FVM is most suitable for thermal transient measurements for die attachment or assembly process control evaluation on a production line basis.

Comparison Item	POM	WSM	FVM
Measurement Type	Optical	Optical	Electrical
TSP	P_O	λ_O	V_F
Calibration Type	Individual	Individual	Batch
Calibration Setup	Difficult	Difficult	Easy
Calibration Cost	High	High	Low
Measurement Setup	Difficult	Difficult	Easy
Measurement Cost	Low	High	Moderate
Automation Potential	Moderate	Low to Moderate	High
Production orientation	Low	Low	High

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References

1. Product Catalog, Melles Griot, (2002), pp. 45.2-45.3
2. Ibid
3. Mil-Std 750, Method 3101, U.S. Dept. of Defense.
4. Hughes, J.J., Gilbert, D.B., and Hewrylo, F.Z., “Measurement of the Thermal Resistance of Packaged Laser Diodes”, *RCA Review*, Vol. 46, (June 1985), pp. 200-213.
5. Siegal, B., “Electrical Transients Simplify LED Junction-Temperature Measurements”, *Electro-Optical systems Design*, Kiver Publications, Inc., (November 1981), pp. 47-49.
6. “Integrated Circuit Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)”, *JESD51-1*, EIA JEDEC,.