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Testing Bond Quality by Measuring Thermal Resistance of Laser Diodes

APPLICATION NOTE

ILX Lightwave®
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Testing Bond Quality by Measuring Thermal Resistance of Laser Diodes

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INTRODUCTION

The invention of the laser has revolutionized science and industry. The first lasers, made of solids (ruby lasers), liquids (dye lasers) and gasses (HeNe lasers), tended to be large devices. The introduction of the semiconductor laser, or laser diode (LD), opened the way for new technologies such as CD players, laser printers, and most recently optical telecommunications.

After determining the proper way to manufacture the laser chip itself, one of the most important steps in the manufacture of LDs is bonding the chip onto some sort of sub-mount that allows the laser to be handled, durable electrical connections to be made, and heat to be conducted away from the laser itself. The ability to conduct heat away from the laser is critical in keeping operating temperatures low, thus improving the laser's performance and its lifetime.

There are several methods of testing the quality of the bond, ranging from the destructive, such as a sheer test where the chip is physically broken off its sub-mount, to non-destructive, such as sonogram measurements where void spaces in the bond can be identified using sound. In addition, electrical and optical measurements can also give insight into bond quality.

In the drive towards automation, the electrical and optical measurements are a more natural choice. These measurement techniques fit smoothly into a production line because they only require delivering current to the laser chip in the same way it would be delivered in normal operation or testing, and then measuring power, voltage, or spectral content using instrumentation that is frequently already a part of the production process.

This ILX Lightwave Application Note will summarize the methods that historically have been used to measure bond quality and will recommend two favored methods that offer the easiest implementation and interpretation, and the best accuracy and repeatability.

MEASUREMENT METHODS

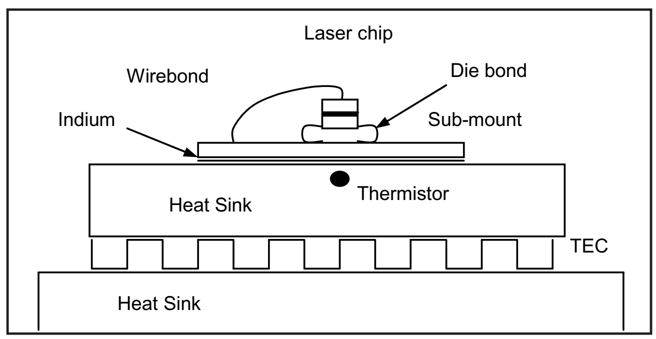

Figure 1.

Experimental Setup

Lasers are tested at several different stages in the manufacturing process, with measurements at each stage focused on confirming functionality and quality and eliminating flawed product before more money is spent testing a defective product. Three general stages are bare chip, chip-on-carrier, and packaged device.

The details of testing at each stage vary, but the typical set-up is shown in Figure 1. The LD is bonded to a sub-mount, which is then placed onto a heat sink. A highly conductive material, such as indium, thermal grease or sil pad is placed between the sub-mount and the heat sink. A thermistor, either in the heat sink or bonded to the sub-mount is used to regulate the temperature of the laser using a TEC that lies underneath the heat sink and is attached to a much larger heat sink for power dissipation. The current through the laser, the forward voltage across the laser, and the thermistor temperature are manipulated in various ways and data are collected. Thermal resistance is calculated in a variety of ways as described below.

Measurable Parameters

In general, when current is driven through a LD its temperature increases. If the bond between the chip and the carrier is good, the temperature rise will be smaller because heat is conducted away from the chip; if the bond is poor, the temperature rise will be larger because the heat builds up in the chip. Therefore, one way to evaluate bond quality is to measure parameters of the laser that depend on its temperature.

There are four parameters of LD operation that are readily measured: threshold current, output power, longitudinal mode (wavelength), and forward voltage. While measurements of threshold current and output power are easily understood, measuring the wavelength and forward voltage of the LD offer more straightforward interpretation for determining thermal resistance.

In all the cases discussed in this application note, the technique of choice is to measure parameters during pulsed operation of the LD (typically 1μs pulse width with 0.1% duty cycle) and compare the values with those measured during continuous wave (cw) operation. The assumptions here are that the heat injected into the LD during pulsed operation is negligible and that the effect of other processes on the values of the interesting parameters is negligible. That is to say that the difference in the measured parameters between pulsed and cw operation is due only to the change in the junction temperature of the LD.

Threshold Current

One of the fundamental parameters of LD operation is the threshold current. Typically, the lower the threshold current, the “better” the laser is. The quality of the laser is not important for these experiments, however. It is the change in threshold current that occurs with changing temperature that is critical.

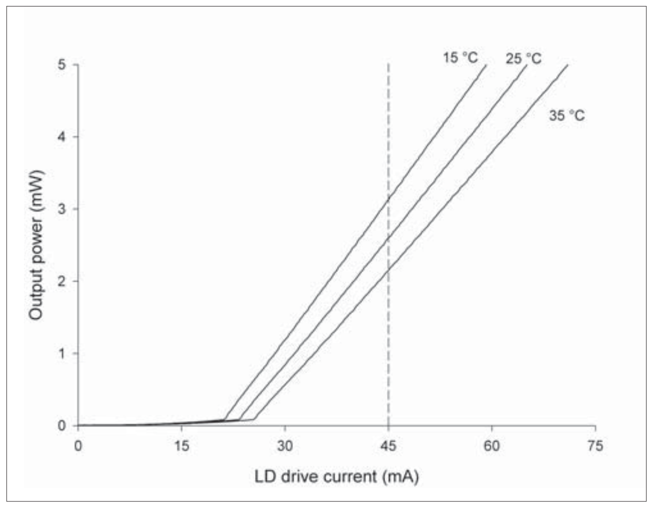

Figure 2.

A typical set of output power (light) versus current (LI) curves is shown in Figure 2. The threshold current is the point at which the LI curve has an elbow and the slope of the output power with respect to input current changes drastically.
Three LI curves are shown in the figure, with each curve being taken at a different temperature. It is clear that the behavior of the laser depends strongly on the operating temperature. The threshold current has a measurable change with temperature.

A relation commonly used to describe the temperature dependence of the threshold current is $I_{th} \propto \exp(T/T_0)$ [Pankove], where I_{th} is the threshold current at an active region temperature T, and T_0 is a constant called the characteristic temperature. The LI curves measured for pulsed and cw operation with constant thermistor temperature can be used to generate the temperature rise of the active region: $\Delta T = T_0 \, ln[I_{th}(cw)/I_{th}(pulsed)]$ [Laff] Then, using the known difference in power injected into the laser between the pulsed and cw operation, one can calculate the thermal resistance as $R_{th} = \Delta T/\Delta P$.

While this method appears to be straightforward, it is not the ideal measurement for production or even R&D environments. First, the threshold current may be calculated any number of different ways which result in varying values. This variation leads to error in the calculation. In addition, LI curves can take a significant amount of time to complete for both cw and pulsed operation. Finally, the calculation of R_{th} used an empirically determined formula and is not very enlightening.

Output Power

In addition to changing the threshold current, changes in laser temperature also change the output power of a LD at a fixed input current, as can be seen in Figure 2. The vertical dashed line shows three different levels of output power for a single drive current. The differential quantum efficiency of LDs is independent of temperature, so changes in output power are only due to changes in threshold current.

To illustrate this point, consider the following situation. At a certain temperature a laser produces 10 mW output power with a threshold current of 20 mA and a drive current of 120 mA. That means that 100 mA produced approximately 10 mW of power. If the temperature increases so the threshold becomes 25 mA, only 95 mA is left to produce output power. In this situation, the output power at a drive current of 120 mA will be approximately 9.5 mW.

This situation can be exploited to perform a null experiment as follows. First, the peak output power for pulsed operation of the laser at T_0 and a fixed drive current is measured. Second, the laser is operated cw and the output power is measured. This power will be lower than the original power because running the laser cw heats it more than running it pulsed. The temperature is then lowered to T_1 so that the peak power under cw operation equals the original peak power under pulsed operation. The difference in temperature $\Delta T = T_0 - T_1$ can be used along with ΔP, the difference in input power between pulsed and cw operation, to determine Rth as described above.

Again, this method is performed by taking several LI curves under several conditions, and can be too slow for production environments.

Longitudinal Mode

The physical size of a LD plays a critical role in determining the output wavelength of the device. For a Fabry-Perot type laser, the front and back facets of the chip determine the lasing wavelength. In a DFB laser, the facets, as well as the grating within the chip determine the preferred, forbidden, and suppressed wavelengths. As the temperature of the chip rises, the physical dimensions increase, and the wavelength becomes longer in response. The change in wavelength with junction temperature can be easily calibrated by recording the wavelength as the laser temperature is changed, and a typical value for the dependence is 0.09 nm/°C. The temperature dependence can be used to determine the temperature of the junction and to calculate the thermal impedance of the laser.

As before, the laser is first operated in a pulsed fashion. The mode structure of the laser is observed using an optical spectrum analyzer. For single mode lasers such as DFBs, the wavelength of the main mode is measured and recorded. For multi mode lasers such as Fabry-Perots, one strong mode is selected and its wavelength is measured and recorded. In the latter case, one must keep track of the chosen mode as the parameters of the laser (temperature and drive current) are changed.

Once the pulsed operation is documented, the laser is then run in cw mode. The wavelength is recorded, as well as the drive current through and forward voltage across the laser. Using the measured change in wavelength and the calibration of wavelength dependence on temperature, the change in junction temperature between pulsed and cw mode, $\Delta T = (\Delta T/\Delta\lambda) * \Delta\lambda$, can be calculated: the change in power is calculated using the current and voltage, and the final value of thermal impedance is calculated as shown above.

This method is a little slow because of the need to calibrate the dependence of the wavelength on temperature. An alternative method suggested by Paoli [Paoli] eliminates that step by performing a null experiment. Instead of calculating the change in temperature between pulsed and cw operation, the temperature change necessary to shift the cw wavelength to the pulsed wavelength is measured and recorded. This measured change in temperature is used to calculate thermal impedance as shown above.

Using the wavelength shift method is, perhaps, the most intuitive way to measure and understand thermal impedance. Again, however, for production environments, where speed is critical, this method may be too slow.

Another drawback of this method is that the location of the thermistor used to stabilize the LD temperature affects the final measurement. In the case of packaged diodes where the thermistor is mounted on the substrate very close to the location of the chip, the thermistor very closely tracks the temperature of the a the laser. This means that when the thermal impedance is measured, it is the impedance of the chip-to-sub-mount bond that is measured. In the case of a chip-on-carrier, or other arrangement where the therimistor is farther away from the chip (such as is shown in Fig. 1) it is the thermal impedance of all the material between the laser chip and the thermistor, which will be much larger than the impedance of the chip-to-sub-mount bond.

This method will still be useful if one is looking for variations in R_{th} in a batch of lasers to weed out flawed bonds, but if the variations are small, they may be difficult to distinguish because of the larger absolute value of R_{th} that is measured.

Forward Voltage

Threshold current, output power, and wavelength are three parameters of LD operation that are obvious options for probing the temperature behavior of a chip. Forward voltage at a fixed drive current is less obvious. This method may be more appealing because there is no need to gather any of the output light in this method because one need only measure voltage and current to determine thermal impedance.

It is the typical forward-voltage-versus-junction-temperature relationship that is critical here. The voltage drop across a LD decreases for a given current with increasing junction temperature because of the temperature dependence of the quasi-Fermi levels. This dependence for a Fabry-Perot laser is shown in Figure 3.

There are two methods that may be used in this circumstance. The first is similar to the wavelength null method, where the forward voltage necessary for a given fixed current is measured in both pulsed and cw mode. The temperature of the LD is then changed until the voltage required in the cw case equals the voltage required in the pulsed case. This change in temperature is combined with the change in power to calculate thermal impedance.

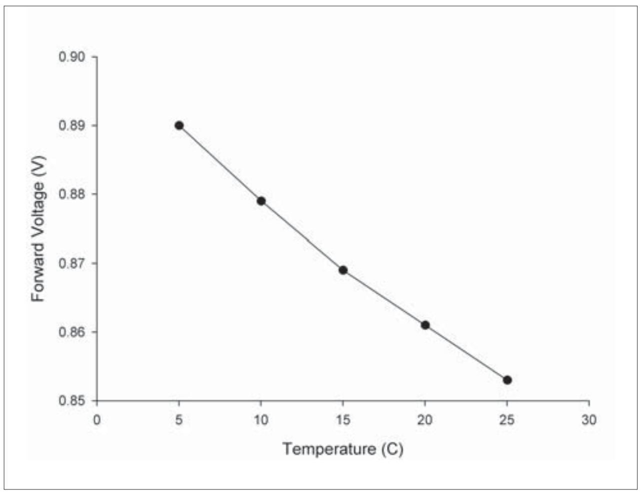

Figure 3.

The second method requires a calibration of the dependence on forward voltage required to drive 1 mA on junction temperature, $\Delta V/\Delta T$. Once the calibration is made, the procedure is as follows. The laser diode is run at a very low "probe" current of 1 mA. The forward voltage is measured. Then, a pulse of higher current, typically 50 mA or 100 mA, depending on the maximum allowable current of the laser, is run through the laser. A typical value for measuring R_{th} of the chip-to-sub-mount bond is 400 ms. (Varying the duration of the heating pulse can give more information on the structure of the laser diode and its mount. See Hughes for more details.) The current and voltage of the heating pulse are recorded and used to calculate the power injected into the laser. After the pulse, the probe current is again applied and the voltage required to achieve the previous level is recorded. Knowing the change in voltage, the calibration of change in voltage to change in temperature, and the input power, the thermal impedance can again be calculated.

This last method requires a calibration, but the calibration and the measurement of R_{th} itself are very fast measurements, so this method is well suited to use in production environments as well as research and development laboratories.

RECOMMENDATION

Of the several methods mentioned above, the wavelength null method offers the most straightforward and intuitive method for measuring thermal impedance. Viewing the spectrum on an OSA gives a good feel for the behavior of the laser with temperature changes, and most labs have the equipment needed to perform this simple measurement.

The fastest method of those discussed is the forward voltage method using the heating pulse. This method is fast, it does not require any optical measurement and thus does not force the user to couple light into a fiber, and by varying the duration of the heating pulse one can probe the construction of the laser and its mount.

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