Chapter 2

Development of Characterization Facilities for the High-Power Laser Diode

2. Development of Characterization Facilities for the High-Power Laser Diode

The consistent measurement of the laser diode performance characteristics is an essential tool during development and qualification of the laser diode. It is also necessary to test the laser diode performance frequently over the different stages of its production viz. from the structure-growth to packaging. The characterization measurement mainly includes the performance test namely optical, electrical, spectral, thermal parameters and the reliability test such as lifetime measurement of the device. In order to preserve the uniformity of measurement conditions with higher precision, we have developed and established an automated laser diode characterization facility using LabVIEW. This chapter discusses the characterization setup along with interfacing and programming technology used for the automation.

2.1 Laser Diode Characteristics

The laser diodes have a variety of applications including communications systems and solid-state laser pumping. When using a laser diode it is essential to know its performance characteristics. This can be done by carrying out series of experiments and obtaining certain significant parameters from which we can determine how well the laser diode is performing. There are number of laser diode characteristics that are essential to the overall device performance. The following is a brief description of the most common parameters that can be experimentally determined and the techniques involved in the analysis of the data.

2.1.1 Light–Current (L–I) Characteristics

One of the most commonly used and important laser diode characteristics is the Light – Current (L–I) characteristic curve, referred to as L–I curve (shown in Fig. 2.1). It is a plot of light output power as a function of drive/operating current for a specific laser diode at a certain temperature.

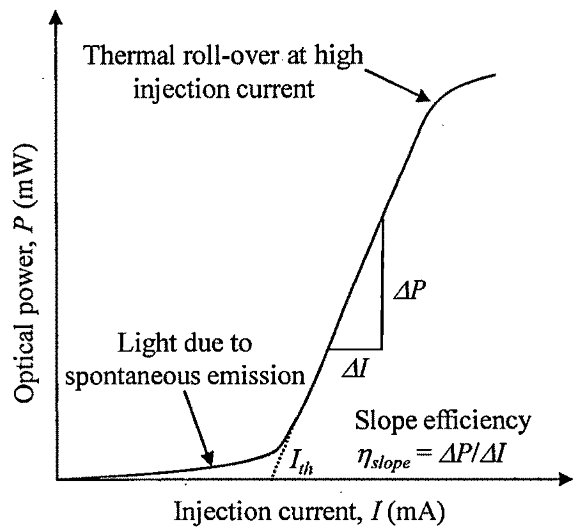


Figure 2.1: A typical Light vs. Current (L–I) characteristic curve of a high-power laser diode. I_{th} represents the threshold current at which the device begins to lase. The efficiency of the laser in converting electrical power to light power is determined by the slope of the L–I curve, denoted by the change in output power over the change in current (ΔP/ΔI).

As shown in Fig. 2.1, as the operating current is increased, initially the laser shows spontaneous emission which increases gradually until net gain through the cavity overcome the losses and stimulated emission dominates. From this characteristic, it can be seen that there is a threshold current (I_{th}) below which the laser action does not take place. Analyzing the L-I curve can yield some important information about the laser diode. The evidence of undesirable "kinks" or non-linearity's in the L–I curve indicate the intrinsic problems that lead to rejection of the device. For example a kink can be indicative of filamentary emission due to defects in laser structure or mode-hopping in the optical spectrum [44], which is very undesirable, particularly in applications like optical pumping and optical communication [45]. The L–I curve analysis provides us three fundamental laser characteristic of the laser – light output power, threshold current, and device efficiency. Furthermore, by varying the measurement conditions for L–I characteristics, more important parameters like characteristic temperature T_0 and thermal impedance R_{th} of laser diode can be extracted.

❖ Threshold Current

The first parameter of interest is the exact operating current value at which laser diode begins to lase. In other words, the current must supply enough carriers to overcome other internal losses, such as leakage current – The current going around the active region, not contributing any carriers for useful recombination and nonradiative recombination process, so that it can provide the necessary threshold gain [46]. At a low current level, spontaneous recombination dominates and the L–I curve (output power) remains low [47]. Once the current level passes threshold current, the stimulated emission causes sudden increase in curve and hence change in the slope of the curve [3].

It is generally desirable that the threshold current (I_{th}) be as low as possible, resulting in a more efficient device. A high threshold current can significantly heat up the device and cause its degradation. Also, a low threshold current minimizes the input power requirement of a laser and hence reduces the operating expenses of the laser based systems. As a result, threshold current is one measure used to quantify the performance of a laser diode.

Threshold current depends upon the laser diode structure design and the quality of the semiconductor material from which the device is fabricated. Nevertheless, the threshold current is more influenced by the physical dimensions of laser diode stripe, i.e., stripe width and cavity length. Hence, the threshold current is higher for a laser diode with larger stripe-area. In consequence to that it is better to evaluate the laser diode structures by means of threshold current density rather than by the threshold current. The threshold current density is the ratio of threshold current to stripe-area of the laser diode and is denoted by the symbol J_{th}. It is always desirable for a laser diode to have as low threshold current density as possible.

Since the lasing process is a steady-state phenomenon, gain should clamp at the threshold gain even as current is increased [47]. Therefore, ideally, the graph should exhibit linear behavior after lasing has begun. Using this fact one can plot a straight line on a linear part of the graph that extended down to the current axis, i.e. abscissa in L–I curve (as shown in Fig. 2.1). The intercept on the abscissa of this straight line is taken as threshold current, I_{th}. There are four different algorithms available to calculate the threshold current of a laser diode viz. linear fit, two segment fit, 1st derivative of L–I, and 2nd derivative of L–I [48]. We have combined the Linear Fit method with the Second derivative method to find the threshold current programmatically from experimental L–I curve.

❖ Device Efficiency

➢ Slope Efficiency (η_{slope})

Since it is necessary to get lasing at low threshold current, I_{th}, it is also desirable to get more and more extraction of the light from the laser diode with the expense of as little current as possible. In other words, with very little increase in operating current we want to have rapid increase in the output light emission. A laser diode, which has good electrical to optical conversion efficiency, is obviously a device that performs well. Hence, the laser diode efficiency is another essential parameter that is deduced from slope of the L–I characteristic curve above the I_{th} of the laser. It is very useful and practical parameter let us to know that how much more output power can be estimated from the laser at given ascertain amount of increasing in current above I_{th}. The laser diode slope efficiency is generally defined as the slope of the straight line, i.e. dP/dI, used to estimate I_{th} and measured in terms of watt/ampere (W/A), as shown in Fig. 2.1.

$$\eta_{slope} = \frac{dp}{dI} \tag{2.1}$$

➢ External Quantum Efficiency (η_d)

This is a figure of merit which indicates the efficiency of a laser device in converting the injected current carriers (electron–hole pairs) to photons emitted from the device (output light). It can be determined by measuring the slope efficiency of the device. In an ideal laser diode, the recombination of each electron–hole pair results in the generation of one photon, which is emitted from the device as well. Whereas in case of real laser diode, not all injected electron–hole pairs are results in the generation of the photons, some often recombine non-radiatively and cause device heating. In addition to that, some photons generated inside the laser cavity do not contribute to the light emission as they are getting absorbed into the laser material [3].

Thus, on increasing the operating current I by an amount dI, i.e. by injecting dI/q numbers of charge carriers in time dt, where q is the fundamental electronic charge, if the optical power increases by an amount dP, then we get $dP/(hc/\lambda)$ number of photons emitted out, where (hc/λ) is the energy of single photon with wavelength λ. Thus, according to the definition of external differential quantum efficiency (as per Eq. 2.2),

$$\eta_D = \frac{dP/(hc/\lambda)}{dI/q} = \frac{q\lambda}{hc}\frac{dP}{dI} \tag{2.2}$$

where, h is the Planck's constant, c is the velocity of light in vacuum and dP/dI is the slope efficiency of the laser diode.

- **Internal Quantum Efficiency (η_i)**

This is one of the main laser diode parameter that should be used to evaluate the quality of the semiconductor material from which the laser diode is manufactured. This parameter is a measure of the efficiency of a laser in converting injected current carriers (electron–hole pairs) into photons (light) within the laser diode structure. The net internal optical loss, on the other hand, is a coefficient that relates the number of existing photons to the number of photons that will remain inside the cavity after having traveled a certain distance. Hence, the internal quantum efficiency (Eq. 2.3) (η_i) is defined as the radiative recombination rate divided by the total (radiative + nonradiative) recombination rate [3]:

$$\eta_i = \frac{R_{rr}}{R_{rr} + R_{nr}} \tag{2.3}$$

The laser diode having longer cavities have a lower facet loss as the photons tends to remain inside the cavity for a longer period of time, rather than being emitted from the laser. This does not mean that laser with shorter cavities are preferred; lasers of longer cavities can reach a higher power although they have lower efficiencies [49]. Unlike the external differential quantum efficiency, the internal quantum efficiency is independent of the geometrical properties of the laser device, such as the cavity length or the stripe width. Consequently, it is the proper parameter for comparison of the material quality of various lasers made from various semiconductor wafers. Thus, the internal quantum efficiency can be derived by experimentally measuring external differential quantum efficiency of the devices having different cavity lengths and fitting the measured data into the following Eq. 2.4.

$$\frac{1}{\eta_d} = \frac{1}{\eta_i}\left[\frac{\alpha}{ln\left(\frac{1}{R}\right)}L + 1\right] \tag{2.4}$$

where, η_d is the device external quantum efficiency, α is the net internal optical loss, η_i is the internal quantum efficiency, R is the mean mirror reflectivity, and L is the cavity length.

As the equation suggests, a straight line can be obtained by plotting the reciprocal of the measured external efficiency versus cavity length. The intercept on the ordinate, i.e. Y axis, of the straight line gives the inverse of the internal quantum efficiency and that can be used in the Eq. 2.4 to obtain the net optical loss [47].

Note that there is a difference between internal quantum efficiency, η_i and external differential quantum efficiency, η_d. The internal quantum efficiency is a direct indication of the efficiency of a laser in converting electron-hole pairs (injected current) into photons (light) within the laser diode structure. But not all of the photons that are generated find their way out of the device; some of them are reabsorbed due to various internal loss mechanisms. As a result, the external differential quantum efficiency is an indication of the efficiency of a laser in converting electron-hole pairs (injected current) into photons emitted from the laser device (output light). The value of the external differential quantum efficiency is always smaller than the internal quantum efficiency. $(\eta_d) / (\eta_i)$ is the ratio of number of photons emitted from the laser to number of photons generated within the laser.

2.1.2 Voltage–Current (V–I) Characteristics

The Voltage – Current (V–I) characteristic is also an important measure of the laser diode like any other electronic or optoelectronic components. The laser diode specification for the forward voltage across the diode is essential in number of areas of its application. The forward voltage specification will vary according to the materials used in the diode, current, etc. Although the forward voltage does vary with temperature, this is not normally a major consideration. The typical laser diode V–I characteristic curve is shown in the Fig. 2.2.

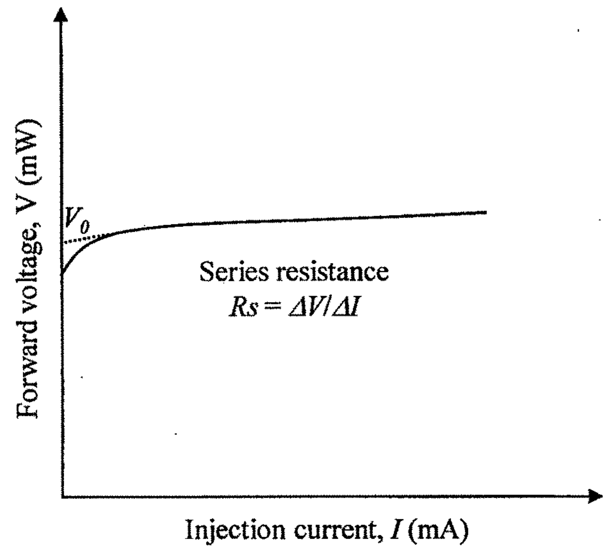
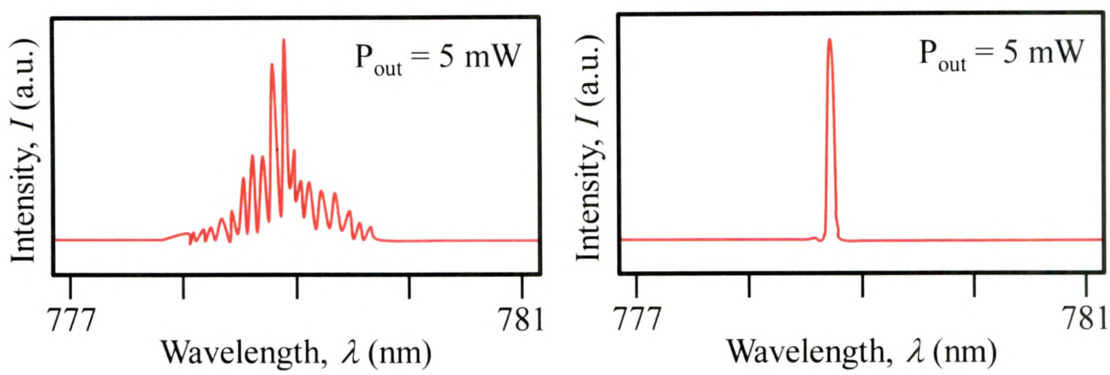


Figure 2.2: The typical laser diode V–I characteristic curve. The intercept on the Y-axis gives the value of the turn-on voltage, V_0, and the series resistance, R_S, can be determined from the slope of the linear part above the turn-on voltage of the V–I curve.

From the laser diode V–I characteristic curve we can extract two parameter viz. turn-on voltage, V_0, and series resistance, R_S. The intercept on the ordinate i.e. Y-axis of the V–I curve gives the value of the V_0. The turn-on voltage, V_0, indicates the lasing wavelength of the laser diode, which is ideally almost equal to the bandgap voltage i.e. $h\nu/q$ [1] of the device. The series resistance, R_S, of the laser diode is determined through calculating the derivative of the V–I characteristic curve above the turn-on voltage of the device [50]. From the values of the V_0 and R_S the total voltage, $V = V_0 + R_S I$, can be determined. The high series resistance values could be the result of low quality metal ohmic contacts of the device, leading to the degradation of laser diode. Thus, measurement of the series resistance value can be a means of assessing the quality of the metallic contacts deposited on the laser.

2.1.3 Spectral Response Measurement

The laser diode specification for wavelength will determine many of the applications for which it can be utilized. The capability of the laser diode to support number of spectral lines is a function of the cavity structure and the operating current as well. The laser diode may be specified as being either single or multimode following to their geometry. The photon generated into the laser diode structure is confined in a very thin waveguide layer viz. quantum well; such structure allows only a single mode operation in the direction perpendicular to the layers. However, the laser structure with wide waveguide compared to the wavelength of the light in the lateral direction can support multiple lateral optical modes, and the laser is known as a "multimode" laser diode. The number of spectral lines supported by a laser diode depends upon the cavity structure [51].



(a) **(b)**

Figure 2.3: Typical spectral response of (a) multimode laser diode exhibits spectral output having many peaks around their center wavelength and (b) single mode laser diode shows a well defined spectral peak.

The optical wave propagating through the laser cavity forms a standing wave between the two mirror facets of the laser diode. The period of oscillation of this curve is determined by the distance L between the two mirrors. This standing optical wave resonates only when the cavity length L is an integer number m of half wavelengths existing between the two mirrors, i.e., for $L = m\lambda/2$, where λ is the wavelength of light in the semiconductor material and is related to the wavelength of light in free space λ_0 through the index of refraction n by the relationship $\lambda = \lambda_0/n$. As a result of this situation, there can exist many longitudinal modes in the cavity of the laser diode each resonating at its distinct wavelength of $\lambda_m = 2L/m$. Thus, a multimode laser diode exhibits spectral output having many peaks around their center wavelength. The two adjacent longitudinal laser modes are separated by a wavelength of $\Delta\lambda = (\lambda_0)^2/2nL$. Unlike the multi-mode laser diodes, single frequency laser diodes such as Distributed Feed-Back (DFB) and Distributed Bragg Reflector (DBR) type of devices display a single well defined spectral peak [52,53]. Figure 2.3 shows these two spectral behaviors.

One of the measures of the spectral response quality is the linewidth. It is defined as the full width at half maxima (FWHM) of the main laser mode. The spectral linewidh is a measure of the phase noise under continuous wave (CW) operation. For distributed feed-back (DFB) lasers linewidths should be less than 5 nm. The spectrum of the main lasing mode can be approximated by a Lorentzian with a FWHM given by [54]:

$$\Delta v = \frac{R_{SP}}{4\pi} \frac{(1+\alpha^2)}{P_0} \tag{2.5}$$

where, R_{SP} is the spontaneous emission rate. One interesting fact about Eq. 2.5 is that the linewidth decreases as the output power increases. This is only true for low power levels as it has been shown experimentally that the linewidth saturates above 10 mW for 1.55 μm DFB lasers [55]. The linewidth enhancement factor is a material parameter influenced by the doping and geometry of the active region. From (11), it is clear that smaller enhancement factors are more desirable. Strained MQWs offer the smallest linewidth because such lasers have enhancement factors near unity [56].

Unlike other laser devices the laser diodes are unfavorably poor to provide a stable output in terms of the wavelength. They are affected by both the operating current and the temperature. Changes in temperature affect the bandgap, and hence the gain frequency profile of the junction. The lasing wavelength strongly depends on the operating temperature of laser diode [57]. As the temperature increases, the center wavelength shows the red-shift. This property of laser diode is useful in optical communication [58,59], spectroscopic applications [60,61], and pumping of solid state lasers [62] where the emission-wavelength of the laser diode can be accurately temperature-tuned.

2.1.4 Lifetime Measurement

Reliability and lifetime are concern in every laser diode application. In general, laser diode reliability may be defined as the ability to operate the device satisfactorily in a defined environment for a specified period of time, also known as *lifetime*. The laser diode life testing is used for part qualification during product development as well as for lot testing during the production life of the laser. Life tests generally consist of monitoring the operation of a sample group of lasers under carefully controlled conditions. Degradation is observed and recorded throughout the test by precise measurement of changes in the laser's operating characteristics.

There are several methods of extrapolating laser diode lifetime. Depending on the type and application of the laser diode, life test studies involve the periodic measurement of a variety of device parameters including operating current, optical output power, threshold current, and forward voltage. Aging studies are conducted in one of the following modes of operation:

❖ Constant Current Aging

Constant current aging mode is often referred to as ACC (automatic current control) mode [63]. In this mode laser current is held constant for the duration of the test and the optical output power is monitored continuously. The optical power shows exponential decay with time at constant current, following Eq. 2.6, due to the device degradation [64].

$$P_{out}(t) = P_0 \, exp\left(-\frac{t}{\tau}\right) \tag{2.6}$$

Here, P_0 is the initial power output of the device at time $t = 0$ and τ is the lifetime. The lifetime of the device can be determined by plotting the optical power data as function of time t and fitting the curve with exponential decay curve. We have estimated the device lifetime using ACC mode. The detail description of experimental and results are discussed in Ch. 6.

❖ Constant Power Aging

Constant power aging mode is also referred to as APC (automatic power control) mode [63]. In this mode, laser output power is held constant by continuously adjusting the current. The operating current has to be increased to maintain the constant optical power from the laser diode due to the device degradation. Conventionally, the laser diode lifetime is defined at the 50 % increase of operating current (*Iop*) [65]. Thus, by plotting operating current as a function of time, we can extrapolate the time necessary to increase the current by 50 % of initial current for constant optical power and can determine the life time of the device. Constant power aging is used most frequently in life- test studies because it closely resembles the typical mode of operation of laser diodes in use.

To reduce the testing time, the accelerated aging test could be performed to measure the device lifetime at precisely controlled high temperature. Aging is empirically related to temperature through the Arrhenius equation [66]:

$$t = c\, exp\left(\frac{E_a}{kT}\right) \tag{2.7}$$

where, c is a device constant in units of time, E_a is the activation energy, and k and T are Boltzmann's constant and absolute temperature respectively. Depending on the type of laser, typical activation energies range from 0.2 eV to 0.7 eV [63]. Thus, to measure the life time τ_1 of the laser diode at room temperature T_1, the experiment is performed at high temperature T_2 and the life time at that temperature τ_2 is obtained. Then by using Eq. 2.7, one can get the life time at room temperature as,

$$\tau_1 = \tau_2\, exp\left[\frac{E_a}{kT}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{2.8}$$

2.2 Why Automation?

In recent technological advancement there is a huge demand of the laser diodes in many applications. Hence, it is necessary to fabricate most reliable devices having good operation lifetime. The laser diode characterization is the most crucial part of the device manufacturing process. One has to check and assort a device/s for its different characteristics performance either good or bad. It is very time consuming and impractical practice to characterize each and every device manually. The handling of the instruments manually lead to the operator dependent output, and also one cannot fulfill the demands of good devices in time. Above all the manual testing can't assure the repeatability of the acquired data with quite accuracy. Hence an economic fabrication of the laser diode in volume has in turn necessitated development of automated production test.

2.2.1 Virtual Instrumentation

An instrument is a device designed to collect data from any system under the test and to display the information to a user based on the collected data. Such instrument consists of a transducer for data acquisition, a physical or software device that performs analysis on acquired data and finally gives an output via a display device or in form of memory/record. Now the question arises that from where the word *Virtual Instrumentation* (VI) comes from? So, when a large variety of data collection instruments were developed and designed specifically for computerized control operation, a new field has been created called VI. In general VI is the use of customizable software and standard measurement hardware to create user defined measurement systems, called VIs [67]. Conventional instrumentation systems are made up of pre-defined hardware components, such as digital multimeters and oscilloscopes that are completely specific to their measurement or analysis function. Because of their hard-coded functionalities, these systems are more limited in their versatility than virtual instrumentation systems.

The primary difference between conventional instrumentation and virtual instrumentation is the software component of a VI. The software enables complex and expensive equipment to be replaced by simpler and less expensive hardware and by means of simulation, of course. Thus, a VI is a user defined instrument that brings all the essential equipments for an experiment on a single workbench. The VI provides great functional flexibility to the user. Moreover, since VI is a PC based instrument, the data acquisition, analysis, and presentation of results are all done together on a single platform. The VI involves three technologies and, in general, allows the user to use the PC as a flexible instrument for measurements and characterization. These are: (1) Data Acquisition System, (2) Communication protocols, i.e. hardware interfacing, and (3) Programming.

2.2.2 Instruments for Laser Diode Characterization

The laser diode characterization requires various sophisticated equipments viz. current driver, photodetector, integrating sphere, spectrometer etc. The sophisticated laser current driver drives the laser diode in either pulse mode or continuous wave (CW) mode. The optical power is measured using a photodetector, accompanied by an integrated sphere and a lock-in amplifier. The spectral response measurement of the laser is carried out by means of a monochromator. And, finally, the laser diode mount attached with thermo electric cooler (TEC) heat sink arrangement. The technical specification and particulars of all the instruments used are discussed below.

❖ Current Driver

A precise laser diode current source is critical for L-I and I-V characteristics measurements. Any good laser diode current source must both drive and protect the laser diode under test. Protection means that external current and voltage spikes must not reach the laser diode. The ability to pulse a laser diode at low-duty-cycles is very useful in diode evaluation since a laser diode will not generate significant heat in a pulse mode and the characterization can be accomplished with minimal thermal effects.

(a) **(b)**

Figure 2.4: Front panel of (a) ILX Lightwave's LDP–3840 laser diode precision pulse current source and (b) Newport – 5600 high-power laser diode driver.

We have used ILX Lightwave's LDP-3840 Precision Pulse Current Source, shown in Fig. 2.4 (a) for low power pulse measurements of laser diodes. LDP-3840 is a microprocessor controlled instrument ideal for providing clean, reliable current pulses to laser diodes. The driver provides 0 to 3 A maximum peak pulse current, with pulse widths adjustment from 100 ns to 10 μs. The advanced pulse network of the LDP-3840 provides fast rise times while maintaining overshoots less than 5 %, and offers selectable polarity pulse modes.

For high-power and CW operation, we have used Newport-5600 high-power laser diode driver, shown in Fig. 2.4 (b). The driver is capable to source current up to 65 A CW current with high precision. It can also be operated in quasi-CW (QCW) mode with 0.25 % to 20 % duty cycle variation. The pulse width can be varied from 100 μs to 1 s. The driver also has the facility to measure the forward voltage across the diode as well as the optical power through photodetectors or thermopile detectors directly.

Beside these current drivers we have also used the voltage–current source meter (Keithley 2420C, Keithley Instruments Inc.) to source the laser diode with constant CW current. The source meter provides measurement of voltage from ±5 μV (source) and ±1 μV (measure) to ±60 V and current from ±100 pA to ±3 A with 0.012 % basic measure accuracy with 5½-digit resolution. Also the source meter features Standard SCPI GPIB, RS-232, and Keithley Trigger Link interfaces useful for device interfacing with PC.

❖ Photodetectors

The photodetector senses the optical power of the light falling upon it and converts the variation of this optical power into a correspondingly varying photo-current. A good photodetector must fulfill these requirements i.e. high sensitivity to the specific wavelength, minimum noise and a fast response such that it can handle the desired data rate. The photodetector should also be insensitive to the temperature variations and have a long operation life. Figure 2.5 shows the photograph of two photodetectors used for the experiments.

(a) (b)

Figure 2.5: Photograph of photodetectors, (a) silicon detector (818-SL) and (b) germanium detector (818-IR), used for the experiment.

The choice of the detector depends on the wavelength of emission of the laser diode. A variety of semiconductor detectors are available to cover the spectral range from 200 – 1800 nm. The spectral response of a photodetector is principally determined by the construction of the detector and the type of material used. We have used the 818 Series low power semiconductor detectors for laser diode characterization setups. For wavelength range from 400 nm to 1100 nm, Model 818-SL silicon detector is used while for 1100 nm to 1800 nm wavelength range; 818-IR germanium detector is used for the experiments in combination with the integrated sphere. For high-power laser diodes, optical attenuators are used in front of photodetectors.

❖ Integrating Sphere

Integrating spheres are designed to collect the power of highly divergent laser beams from laser diode or other light sources, since these beams can overfill the input of a photodetector and cause considerable measurement error. The hollow spherical cavity has a diffusive internal wall and two or more ports. The photodetector placed on one port measures the light intensity and depending on the integrating sphere's attenuation and calibration data, the optical power can be measured. The optical power measurement with integrated sphere is insensitive to errors caused by the detector positioning or problems associated with overfilling or saturation of the active area of detector.

Typically the laser diode is positioned very close to the internal port of the sphere as shown in the Fig 2.6 (a) and light emitted from the front facet of the device is collected by the internal cavity of the integrating sphere which is coated with a highly reflective material. A baffle positioned between the input port and the detector port prevents the detector from directly viewing the emitting aperture of the laser. What the detector sees is a uniformly illuminated environment within the cavity of the sphere.

In an integrating sphere, the detected radiation flux is always a small fraction of the incident flux. This attenuation is caused by light reflecting many times before reaching the detector, which makes the integrating sphere an ideal tool for measurement of optical output power of high-power laser diodes. We have used Newport's 819-IS-2 inch integrating sphere which is suitable for laser diode measurements because of their relatively thin walls, only a few millimeters thick, making it possible to position the laser diode very close to the internal cavity of the sphere. Figure 2.6 (b) shows the actual photograph of the integrating sphere used for the experiments with a photodetector fixed on one of its ports. The assembly consists of a Model 819-IS integrating sphere with one of the 818 Series low-power semiconductor detectors, and is calibrated to NIST traceable standards.

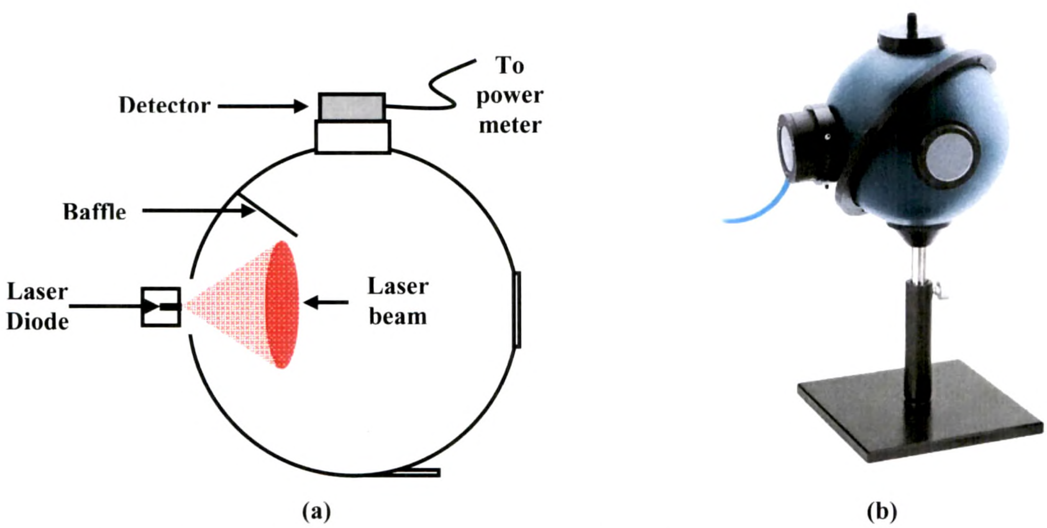


Figure 2.6: (a) Schematic representation and (b) photograph of integrating sphere.

❖ Lock-in Amplifier

Operation and significance of a lock-in amplifier can be visualized in a number of ways. The lock-in amplifier relies on the concept of phase sensitive detection [68]. The phase sensitive detection refers to the demodulation or rectification of an ac signal by a circuit which is controlled by a reference waveform. The phase sensitive detector effectively responds to signals which are coherent (same frequency and phase) with the reference waveform and rejects all others. In a light measurement system the device which causes the signal to be modulated is usually a chopper or pulse current driver. The reference waveform is an output coherent with the chopping action provided by the chopper or trigger pulses from current driver and the ac signal is the signal from the photo detector.

An approach to visualizing the phase sensitive detector is to consider the switch as a multiplier as shown in Fig 2.7. The output of a multiplier switch includes component at two frequencies, $f_s + f_r$ and $f_s - f_r$, where, f_s – signal frequency, f_r – reference frequency. If $f_s = f_r$, as is the case where the reference waveform is derived from the device which is modulating the signal, then there will be an output at 0 Hz i.e. dc. Any other component in the signal e.g. a noise component at a frequency of f_n will give rise to an ac output at frequencies of $f_n + f_r$ and $f_n - f_r$ which will be smoothed or averaged to the mean value of noise, i.e. zero, by the filter.

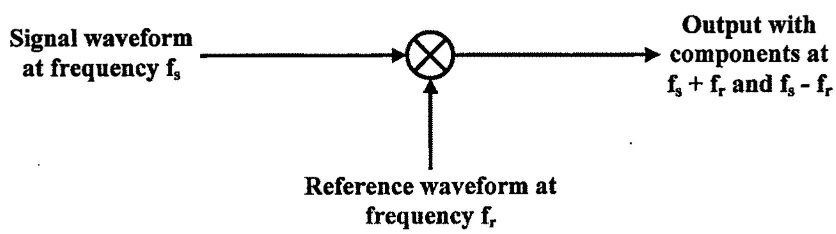


Figure 2.7: Simplified view of lock-in operation.

Lock-in amplifiers are used to detect and measure very small AC signals – all the way down to a few nano-volts. Accurate measurements may be made even when the small signal is obscured by noise sources thousands of times larger. The device behaves as a band pass filter and performs the same function as a tuned amplifier followed by a rectifier but with some advantages like a very precise bandwidth and very high noise rejecting capability. We have used SR-530 analog lock-in amplifier supplied by Stanford Research Systems, Inc.

❖ Monochromator

The monochromator is a very useful instrument in spectroscopic characterizations. It passes only a certain desired wavelength of light with a small band-pass window from a polychromatic input light. It is based on diffraction of light by a grating. One or more diffraction gratings are mounted on a stepper motor and can be rotated to get desired wavelength diffracted at the output slit. The band pass is determined by the slit width. We have used CVI's CM-110 1/8 m monochromator for spectral response measurement of laser diodes. The monochromator contains two gratings, one with 600 groves/mm and the other with 1200 groves/mm. The two gratings cover a wide spectral range from 0 to 3000 nm with the resolution of 0.2 nm.

❖ Spectrometer

Measurement of the spectral response of the laser diode by a monochromator provides quite appreciable data. However, the minimum scanning step for spectral response is limited by the resolution of monochromator i.e. 0.2 nm only. Due to this limitation we have used the spectrometer HR2000 (High-resolution Miniature Fiber Optic Spectrometer, Ocean Optics), shown in Fig. 2.8. It is a small-footprint, modular spectrometer that provides wavelength scanning starting from 200 nm to 1100 nm with optical resolution to 0.035 nm (FWHM). However the specific range and resolution depends on the grating and entrance slit selections. The HR2000 is especially suited for applications such as wavelength characterization of lasers and LEDs. A simplistic interfacing approach to PC via USB makes this instrument handy and versatile, as it doesn't required any external power supply - it draws its power from the computer.

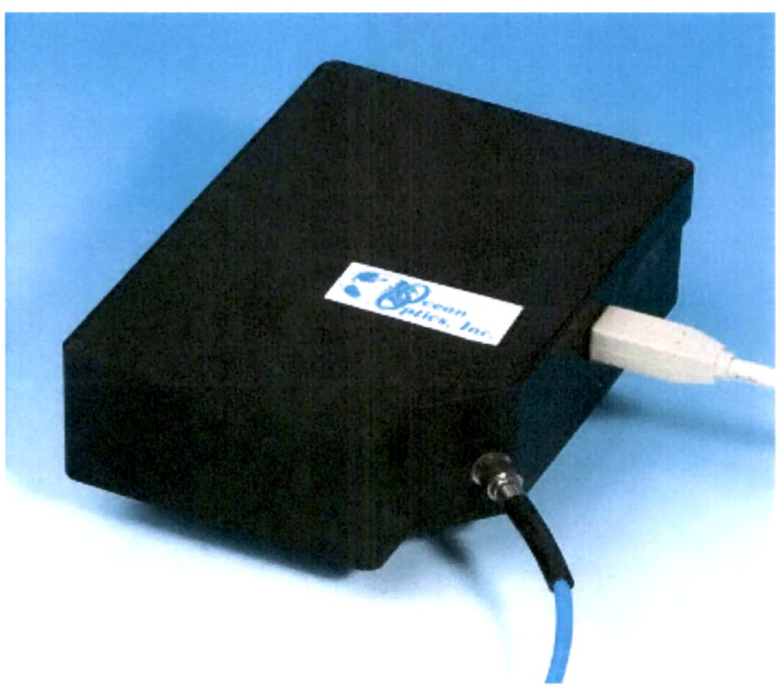


Figure 2.8: Ocean Optics HR2000 High-Resolution Fiber Optic Spectrometer.

❖ Data Acquisition Systems

The data acquisition (DAQ) system consists of the computer (PC i.e. personal computer) and other hardware/s to make the physical component of the VI. The elements of the

DAQ system include the PC, transducers, signal conditioning, DAQ hardware and software as shown in Fig. 2.9. The detail of the complete DAQ system is discussed below.

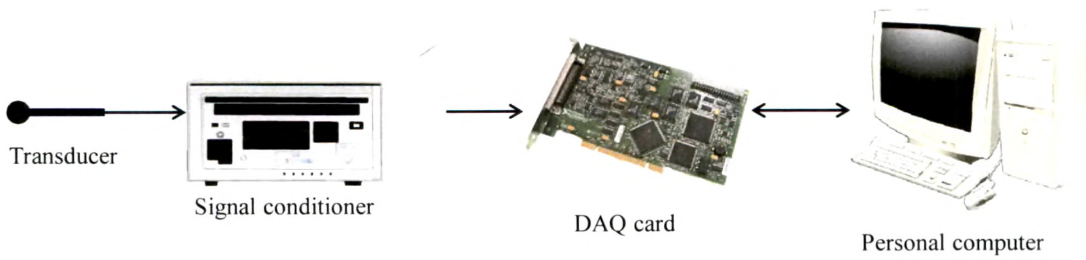


Figure 2.9: A typical data acquisition system comprise a transducer, signal conditioner, a data acquisition card, and a computer of course having specific software to acquire, store and analyzed the data.

A transducer senses changes in a physical parameter, such as temperature, and converts into an electrical signals, such as voltage variations. The electrical signals generated by the transducer must be optimized for the input range of the DAQ card. Signal conditioning accessories can amplify low-level signals, and then isolate and filter them for more accurate measurements. In addition, some transducers require voltage or current excitation to generate a voltage output which can be provided by the signal conditioning circuit. Following to the signal conditioning the DAQ system consist of DAQ hardware, which converts the analog signal into the digital data format. In other words we can say that it enables the user to communicate with computer in a simple way. We have used National Instrument's PCI-6024E DAQ card (Fig. 2.10) for our data acquisition purpose, discussed in detail below.

DAQ hardware (PCI-6024 DAQ Card): The DAQ hardwares, which are usually special kind of circuit boards, are generally installed in the PC. We have used PCI-6024E DAQ card from National Instruments, shown in Fig. 2.10.

The National Instruments PCI-6024E is a low-cost data acquisition board that delivers high-performance, reliable data-acquisition capabilities in a wide range of applications. It provides 12-bit resolution on 16 single-ended analog inputs with sampling rate up to 200 kS/s and two 12-bit analog outputs with sampling rate of 10 kS/s. It also contains 8 digital I/O lines and two 24-bit counters. The input and output voltage range is from -10 V to +10 V.

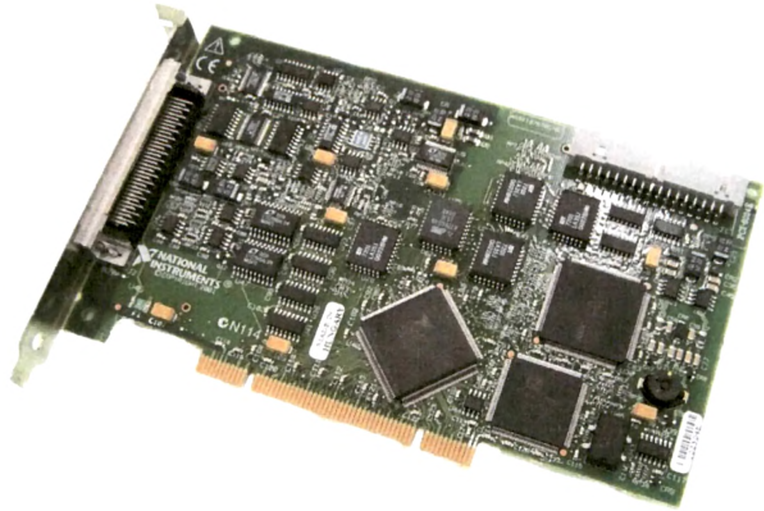


Figure 2.10: PCI-6024E data acquisition card from National Instruments having analog input and output sampling rate 200kS/s and 10 kS/s, respectively. It also contains 8 digital I/O lines and two 24-bit counters.

Finally, the signals in the form of digital data are processed in the PC with the help of appropriate software and are analyzed to give meaningful information about the device under test (DUT). The PC used for the data acquisition system decides the maximum speeds at which one can continuously acquire the data. We have used LabVIEW (ver. 8.2) as a software tool to build our VIs. Details about the LabVIEW software are given in section 2.2.4

2.2.3 Hardware Interfacing

A typical automated measurement setup will use multiple instruments to conduct an experiment. For a virtual instrumentation, any of these aforementioned instruments need to be connected to the PC. There are various communication protocols to connect different hardware/s and instruments with PC. These protocols include serial communication, parallel communication, general purpose interface bus (GPIB) etc.

❖ Serial Communication

Serial communication is a popular means of transmitting data between a computer and a peripheral device such as a programmable instrument or even another computer. The data transfer takes place one bit at a time over a single communication line in serial communication. It can be utilized when data transfer rate is low or over a long distance communication.

For serial communication, four parameters have to be specified: (1) baud rate of the transmission, (2) number of data bits encoding a character, (3) parity-bit (optional), and (4) number of stop-bits. Each transmitted character is packaged in a character frame, which consists of a single start bit followed by the data bits, the optional parity bit, and the stop bit or bits. The Fig. 2.11 shows a typical character frame encoding of the data.

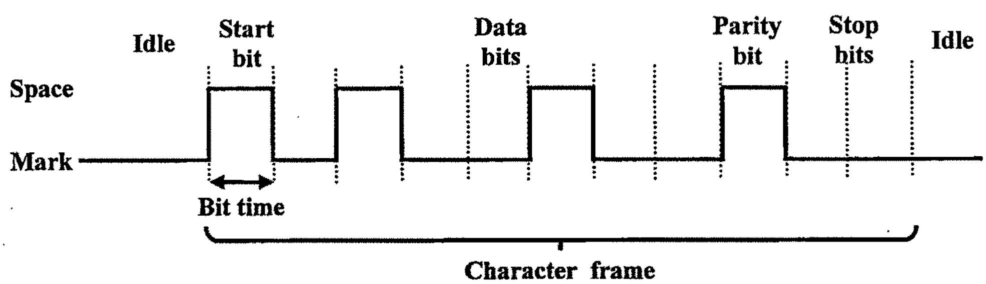


Figure 2.11: A package of a single byte containing data and framing bits i.e. start bit and stop bit comprise with one parity bit.

Serial Ports can be of two types, D-Type 25 pin connector and D-Type 9 pin connector. There are different standards of serial port communication, including RS-232, RS-449, RS-422, and RS-423. RS-232 is the most widely used serial communication standard.

❖ Universal Serial Bus (USB)

Universal serial bus (USB) is a high-speed serial bus which allows a user to connect electronic device and computer peripherals to a computer. The USB interface is not only providing communication but also an electric power supply to the device connected to the computer. It has effectively replaced a standard interfaces viz. serial and parallel ports, and separate power chargers for portable devices, as well. It also supports plug-and-play installation of the devices and hot plugging, where device can be connected or disconnected while power is on. The computer does not need to restart every time to use the device having USB interface. USB can transfer data starting from 1.5 MBit/s to 5GBit/s depending on its standard, i.e. USB 2.0, USB 3.0 etc.

❖ Parallel Port Communication

The Parallel Port allows the input of up to 9 bits or the output of 12 bits at any given time, thus requiring minimal external circuitry to implement many simpler tasks. The port is composed of 4 control lines, 5 status lines and 8 data lines. It uses mostly a D-Type 25 Pin female connector. Newer Parallel Port's are standardized under the IEEE 1284 standard first released in 1992.

❖ General Purpose Interface Bus (GPIB)

The GPIB, also referred to as IEEE 488 or HPIB (Hewlett-Packard Interface Bus), was invented by Hewlett-Packard Corporation in 1974 to simplify the interconnection of test instruments with computers [69]. It is a digital, 8-bit parallel communications interface with data transfer rates of 1 Mbyte/s and higher, using a three-wire handshake. A standard GPIB setup has one controller, one or more instruments and GPIB cables.

The controller usually refers to a PCI-GPIB card connected to a PC. The picture of GPIB board used for the experiment is shown in Fig. 2.12. This controller allows the user to interact with the instruments. The instrument can be anything that has a GPIB connection such as current driver, lock-in amplifier, etc. The GPIB cable simply connects the instrument and the controller. These instruments can either be arranged in a star or in a linear configuration as shown in Figs. 2.13 (a) and (b), respectively.

The GPIB uses a 24-conductor parallel bus that consists of eight data lines, five bus management lines (ATN, EOI, IFC, REN, and SRQ), three handshake lines, and eight ground lines. GPIB uses a byte-serial, asynchronous data transfer scheme. This means that whole bytes are sequentially handshake across the bus at a speed that the slowest participant in the transfer determines. Because the unit of data on the GPIB is a byte (eight bits), the messages transferred are frequently encoded as ASCII character strings. All GPIB devices and interfaces must have a unique GPIB address between 0 and 30.

Address 0 is normally assigned to the GPIB interface. The instruments on the GPIB can use addresses 1 to 30.

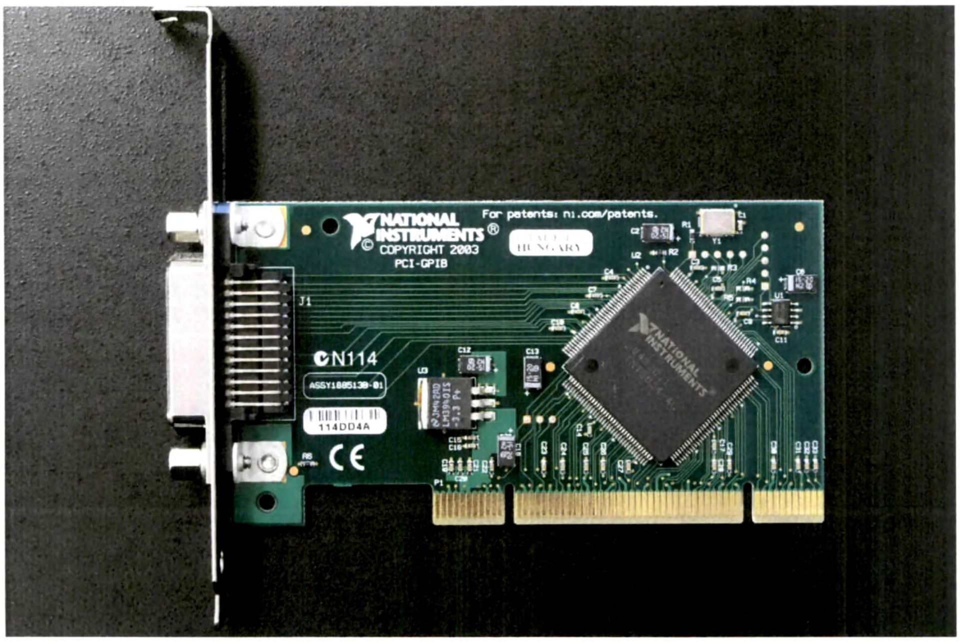
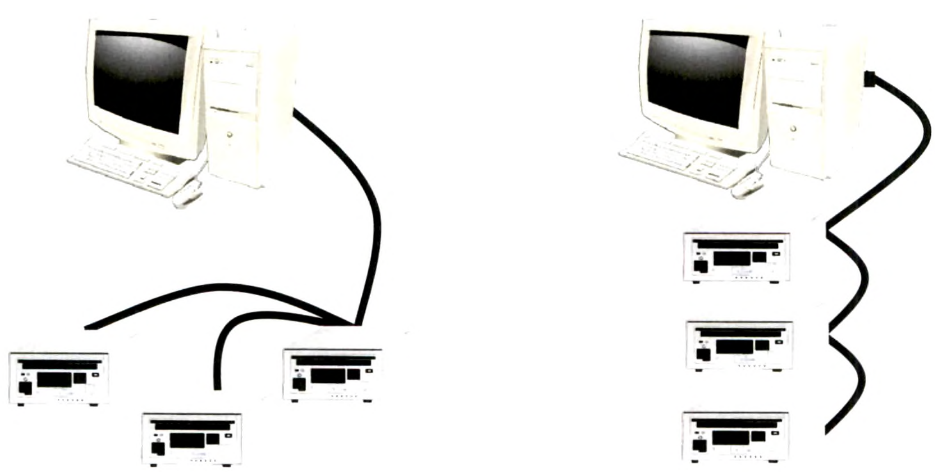


Figure 2.12: National Instruments' PCI-GPIB card with GPIB cable.



(a) (b)

Figure 2.13: Interfacing of the PC with instruments via GPIB in (a) Star configuration and (b) linear configuration.

The GPIB exists due to the need for a standard to control and communicate with multiple bench-top instruments. It also provides fast data transfer rates. GPIB is also relatively easy to program, enabling the communication to be readily established.

2.2.4 LabVIEW Programming

We have used LabVIEW developed by National Instruments as a programming tool to build VIs for laser diode characterization. A term LabVIEW stands for '***Lab**oratory* ***V**irtual* ***I**nstrument* ***E**ngineering* ***W**orkbench*'. Instead of using text-based programming code the LabVIEW is a graphical programming language utilizes the icon to create an application. The main difference between LabVIEW and the other text based programming language is the program execution. In text based programming language the instruction determines the program execution where as in case of LabVIEW the flow of the data determines the program execution. The LabVIEW is a powerful software tool for designing test, measurement and control systems as it provides complete integrated environment to interface with real-world signals and analyze data for meaningful information and display results in flexible manner. LabVIEW programs are called virtual-instruments (VIs), because their appearance and operation reproduce the physical instruments. A VI in another LabVIEW program is called a sub-VI which corresponds to a subroutine in text-based programming languages. A VI consists of three components: (1) Front panel, (2) Block diagram and (3) Icon and connector pane.

The front panel is a set of controls and displays for the user to operate the system while it is running. As their name suggests, controls are the inputs and indicators are the outputs to the system. Furthermore, graphical displays, lights, analog meter displays, switches, and other controls and indicators like in oscilloscope, can be utilized on the front panel of the VI and make the system interactive and easy to use. One can easily customize the front panel to operate the system in a convenient manner.

The block diagram is a collection of actions bound together like a flowchart and can be manipulated to clearly show the flow of data. The block diagram is where the user can link all the controls and indicators together with various logics and operations. To build a VI for any system application user has to select significant icons from the ***icon and connector pane*** corresponding to the particular action and place it on the block diagram. Later the icons placed on the block diagram need to be *wired* together by means of connectors in an order to produce a coherent path through the system. LabVIEW follows a dataflow model for running VIs. A block diagram node executes when all its inputs are available. When a node completes execution, it supplies data to its output terminals and passes the output data to the next node in the dataflow path.

Although the original use of LabVIEW was graphical measurement and data acquisition, it can also be used for general purpose programming. All of the basic functions of a traditional text-based language such as file input and output, data structures, and program flow are available in LabVIEW.

2.3 Automation of the Experimental Setup

In order to carry out laser diode characterization in less amount of time with better accuracy and uniformity, we have automated the whole laser diode characterization facility. The automated characterization facility allows very fast data acquisition with more precision and reliability. Since the test and measurements are done in a very less time, there is a reduced chance of device failure even for bad devices. Moreover, it eliminates the human errors in measurements. Since the data are fed directly to the PC, quick mathematical calculations, easy data processing and analysis are possible. We have followed the virtual instrumentation approach for the automation of laser diode characterization facility.

2.3.1 L–I–V Characteristics Measurement

Figure 2.14 shows a schematic diagram of experimental setup for laser diode characterization [70]. A high-power (65 A) laser diode current-driver (Newport-5600) and a low-power (3 A) precision pulse current-driver (ILX-Lightwave LDP-3840) have been used to drive current in the laser diodes depending on the types of the laser diode i.e. either high-power or low power. We have used the 818-SL silicon detector and 818-IR germanium detector with specific attenuator in case of high intensity light, to detect the light output. The optical power is measured using Newport's integrating sphere and Lock-in amplifier (SR-530). The detector used to detect the light output is 818-SL silicon photodetector. The current driver and Lock-in amplifier have been interfaced with PC using PCI-GPIB (IEEE-488.2). These instruments are controlled by a VI made in LabVIEW-8.2. The actual photograph of L–I and I–V measurements setup is shown in

Fig. 2.15. The laser diode chip/bar was mounted on a probing stage attached with thermo electric cooler (TEC) module and an individual laser diode stripe was probed using gold coated Tungsten Carbide tip as shown in Fig. 2.16. TEC module is arranged on a heat sink with a cooling fan. The probing arm is assisted by an XYZ mount as shown in Fig. 2.16.

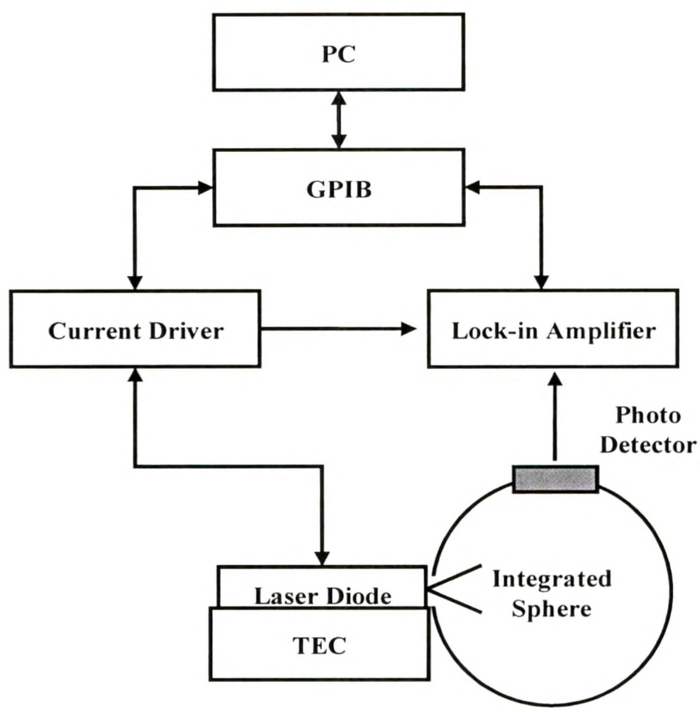


Figure 2.14: A schematic diagram of experimental setup for laser diode L–I and I–V characterization. Photo-detector attached to the integrated sphere detects the light output of the laser. The electrical signal corresponds to the light power form the detector fed in to the lock-in amplifier and hence to the computer by means of GPIB.

A LabVIEW program (VI) measures L–I and I–V characteristics simultaneously. The VI features input current control with desired step increase, time delay, lock-in amplifier sensitivity, current driver mode selection viz. constant output current (I_O), constant monitor photodiode current (I_m) and constant optical power (P_O), and data storage. One can also choose to operate the current driver in either pulse mode or continuous wave (CW) mode. While measuring the L–I–V characteristics the VI initializes instruments and checks for their status and controls the current output using PCI-GPIB IEEE 488.2 commands.

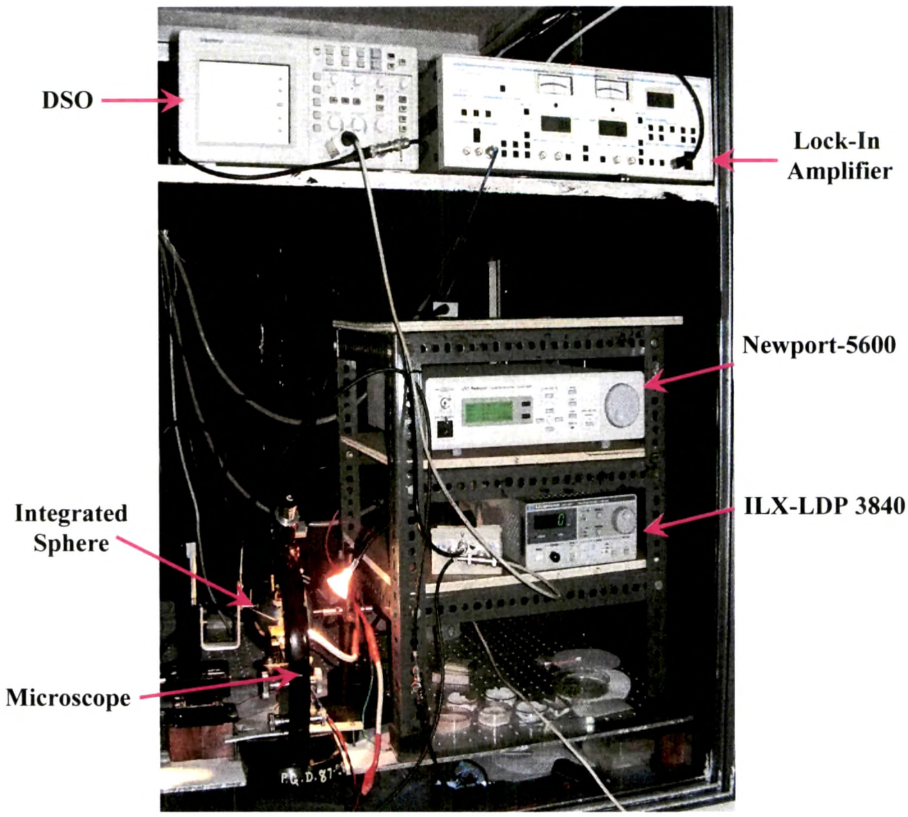


Figure 2.15: L–I and I–V characteristics measurement setup photograph.

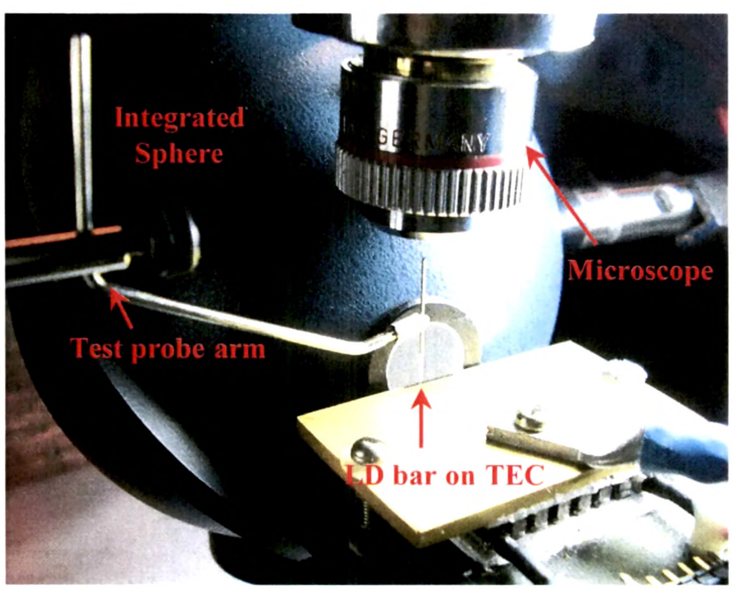
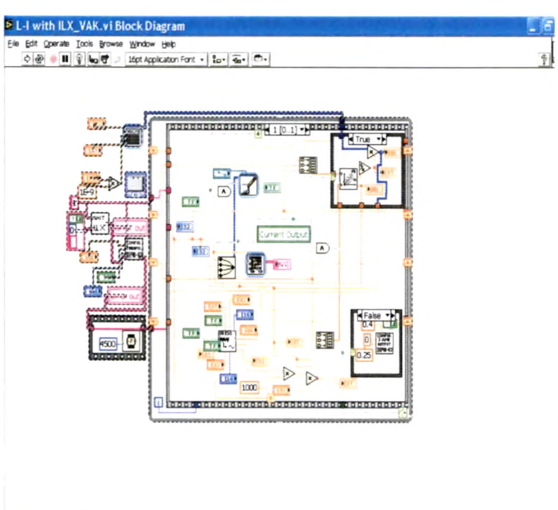


Figure 2.16: Laser diode chip/bar mounted on the probing stage attached with TEC probed for L–I and I–V characteristics measurements [70].

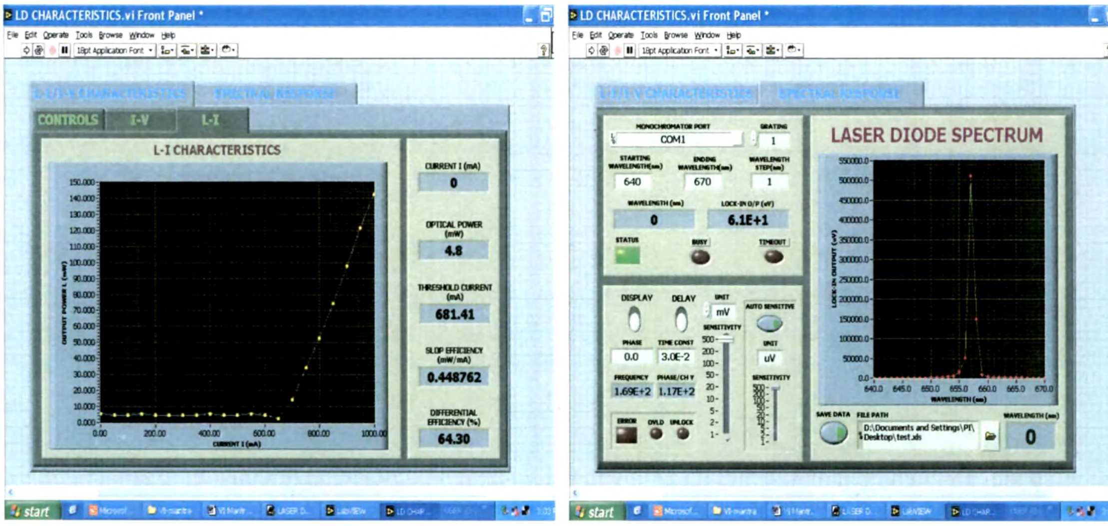
The light emitted by Laser Diode is collected by the integrated sphere and corresponding photocurrent, generated by photodiode is measured using a Lock-in amplifier whose output is read by the VI. The optical power and laser voltage are dynamically plotted against the input current. The linear portion of L-I and I-V curves are separated using the double differentiation of L-I and I-V curves. The post threshold portion is then fitted using "Linear Curve Fit" to get the slope and intercept. The Differential Quantum Efficiency of laser diode is obtained from the slope of linear portion of the L-I curve. However, the optical power obtained from L-I curve is the power emitted by the front facet. To calculate the differential efficiency, the total power generated inside the cavity is used, which is calculated from front facet output using known values of front and back facet reflectivities. The slop of the I–V curve gives the series resistance of laser diode.

In addition to the dynamic data acquisition and display the program also analyzes the data and computes essential parameters like threshold current, turn-on voltage and differential quantum efficiency for the laser diode. The results are displayed graphically as well as numerically. The programming code of the VI for laser diode characterization is shown in Fig. 2.17 (a). Figure 2.17 (b) shows controls and indicators of graphical user interface (GUI) for the L-I and I-V characteristic measurement. The L-I curve plot on the GUI is shown in Fig. 2.17 (c). Figure 2.17 (d) illustrates GUI for laser diode spectral response measurement.



(a)

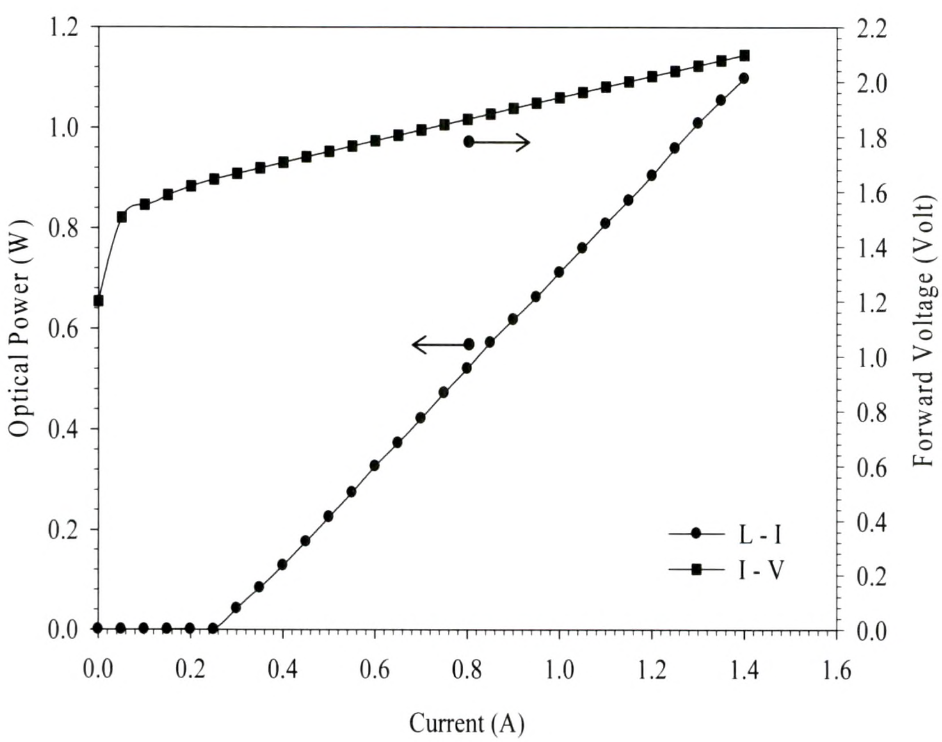
(b)



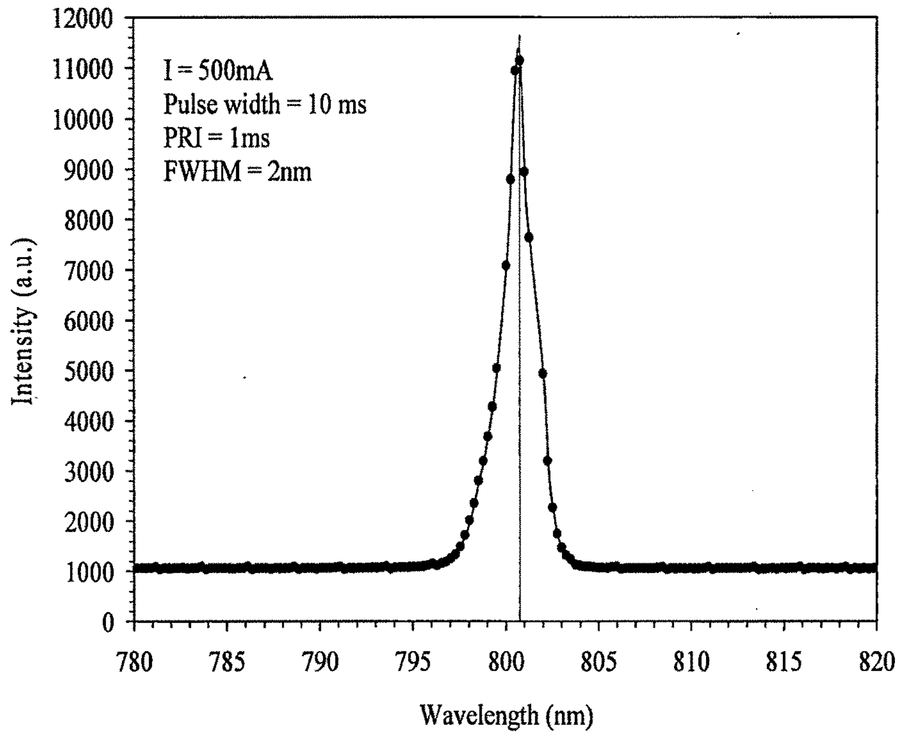
(c) (d)

Figure 2.17: (a) Block diagram of VI and GUI screen shot for (b) controls of L–I and I–V characteristics (c) L–I characteristics plot and (d) Spectral response measurement.

Figures 2.18 (a) and (b) show the experimental L–I–V Characteristics and the spectral response of the 808 nm TO (transistor outlook) package high-power laser diode. The diode emission, in this case, was recorded from 640 nm to 670 nm with 1 nm step size and 2 nm band-pass of the monochromator.



(a)



(b)

Figure 2.18: (a) L–I–V characteristics and (b) spectral response of 808 nm TO package high-power laser diode.

The VI allows the user to carry out two main characterization of laser diode in a same program viz. L–I–V characteristics. Thus, it is very useful in the field of research and other areas where frequent characterization of laser diode is required. Beside its obvious advantages over manual measurements like less time and effort consumption, the automated setup has many beneficial features including precision, consistency and uniformity in data acquisition, especially because these measurements have to be carried out in the dark room. Accuracy of L–I measurements is better than ± 2 % mainly decided by the photodiode whereas the wavelength accuracy is ± 0.2 nm.

The limitation of this setup lies in the hardware side. As Newport's 5600 current driver is typically a high-power laser diode driver, it cannot measure the voltage for low power laser diode below 1.5 V. Moreover, in the pulse mode, the duty cycle and frequency cannot be controlled by the program. Similarly the minimum scanning step for spectral response is limited by the resolution of Monochromator.

Further, slight modification in the VI with required change in measurement conditions of experimental setup allows determination of more laser diode parameters as discussed earlier. Experimental setups and necessary modifications in VIs for measurements of parameters like Characteristic temperature (T_0), Thermal Impedance (R_{th}), degradation rate and life time of laser diodes are described here.

2.3.2 Spectral Response Measurement

In case of spectral response measurement, the light from laser diode is made to focus at the input of the monochromator. A monochromator (CVI-CM110) has been interfaced using serial port (RS232) with PC. The monochromator wavelength is controlled by the VI. Again the output of monochromator is fed to the photo detector through an optical chopper. This chopper provides the triggering to the Lock-in amplifier. A picture of this setup is shown in the Fig. 2.19.

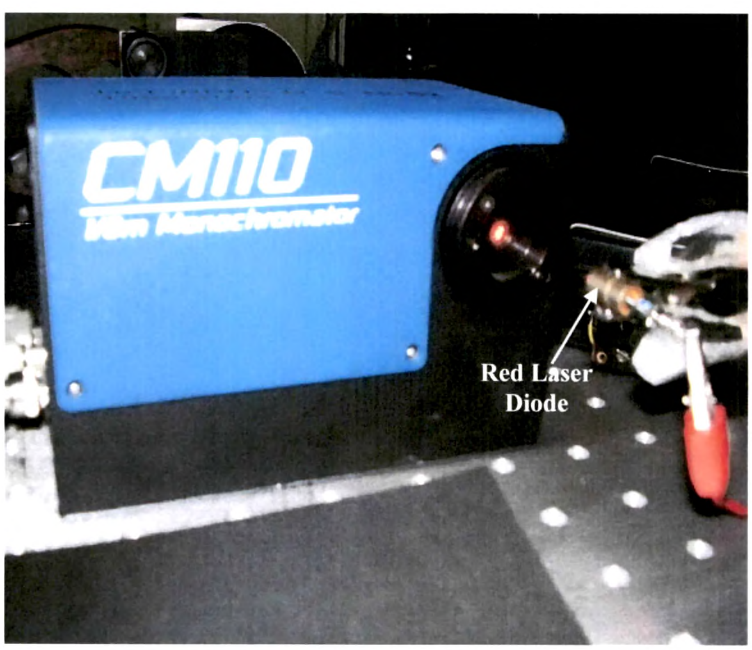


Figure 2.19: Spectral response measurement setup.

The VI corresponding to the spectral measurement provides control over monochromator grating selection, wavelength range, scanning steps and delay. GUI controls and plot of spectral response measurement of laser diode is shown in Fig. 2.17 (d).

Though the monochromator gives the laser spectral response with quite good accuracy, the time consuming data acquisition process to scan the entire spectrum restrict the utilization of this experimental setup. Because one has to run the laser diode for longer time until the whole spectral scan is over. The continuous device operation causes device heating and hence the shift in the output spectral mode, as the wavelength of the laser diode strongly depends on the temperature. To overcome this restriction we have used the high resolution miniature fiber optic spectrometer (HR2000, Ocean Optics).

2.3.3 Junction Temperature Measurement

High-power laser diodes are finding extensive application due to their small size, low threshold current and high electrical to optical efficiency. Low value of junction temperature is required for high-power operation of laser diode. The operating characteristic and lifetime of semiconductor laser are also strongly affected by junction temperature. It affects the laser diode performance in many ways. Light output, center wavelength, spectrum, power magnitude, and diode reliability are, all directly dependent on junction temperature.

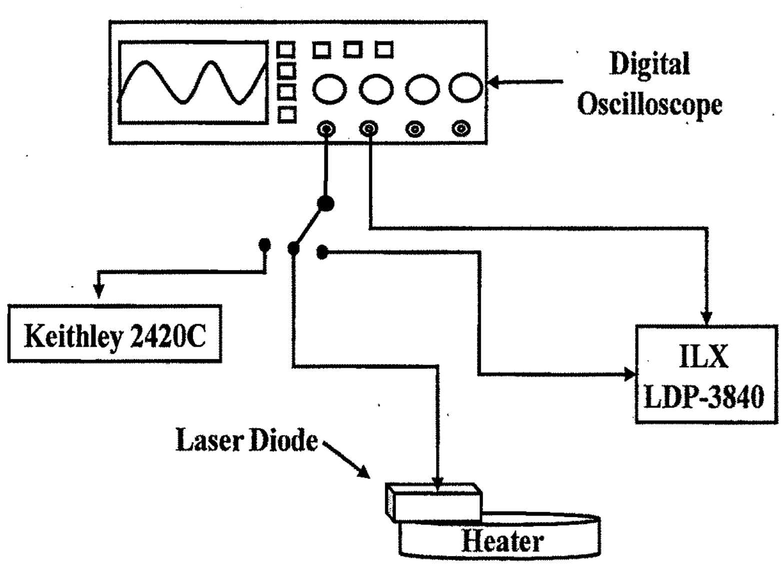
Junction temperature can be deduced from the laser threshold and the stimulated emission. However, these techniques are weakly accurate and of low sensitivity. The thermo reflectance techniques provides high sensitivity and high spatial resolution but it works excellently only for low power laser diodes where the temperature distribution in the laser is weak. Other methods like Electroluminescence (EL), Photoluminescence (PL), and Non-contact method are also reported [71]. The Raman scattering spectroscopy provides temperature profile with high resolution of 1 μm. However, Raman spectroscopy needs a sophisticated experimental setup and the precision of temperature is as low as 10 K. Nematic liquid crystal with infrared (IR) laser illumination has also been reported, however, the experimental setup is quite difficult and expensive [71].

In this study, forward voltage is employed in the measurement of the junction temperature of laser diode. Because it is quite easy, simple instrumentation is used and the results are very precise with the accuracy of ±3 °C. The experimental setup to determine the junction temperature of laser diode was optimized. The current–voltage characteristic measurement of laser diode at different temperature gives voltage–temperature relation. Using this relation one can directly get the junction temperature at a particular operating current. The relation between temperature (T) and forward voltage (V_f) of device is linear with negative slope.

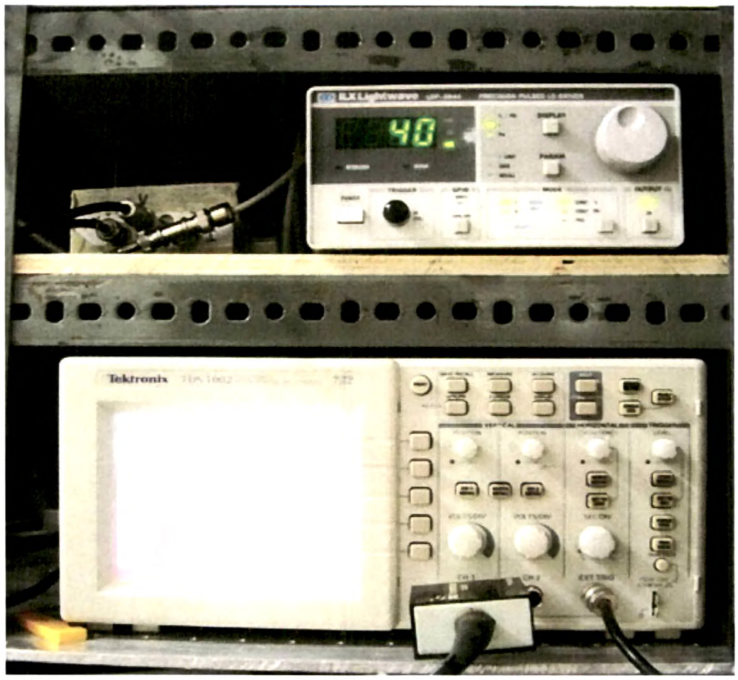
$$\Delta V_f = \alpha\, \Delta T_j \tag{2.9}$$

where, α is correlation factor [72].

The 650 nm InGaP quantum well laser diode chip was used for the measurement of junction temperature. Figure 2.20 shows the schematic and experimental set up for measurement of the laser diode junction temperature. We have used Precision Pulse Current Source (ILX Lightwave LDP-3840) for low power pulse measurements of laser diodes. The laser diode was operated in pulse mode with in the current range of 0-80 mA with 1μs wide pulse width and 0.25 % duty cycle. Lower valued pulse width and duty cycle prevents the self-heating of the diode. Laser diode was kept on a heater for voltage measurement at different temperatures. A digital oscilloscope (Tektronix TDS 2002) measures the voltage across the diode. Entire measurement is done at ambient temperature. For I-V measurement in CW mode the constant operating current is supplied to the laser diode through source meter (Keithley 2420C).



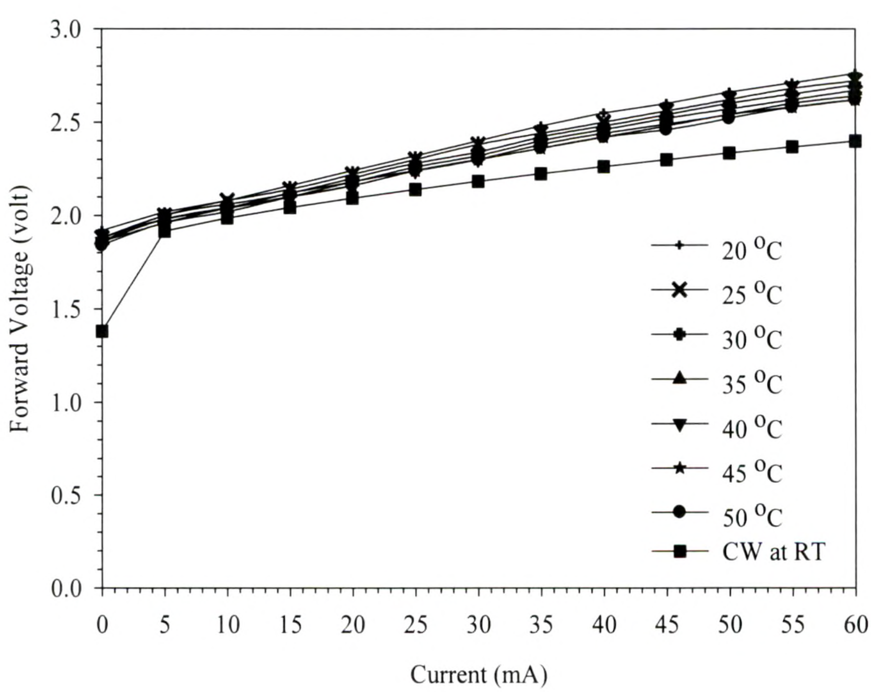
(a)



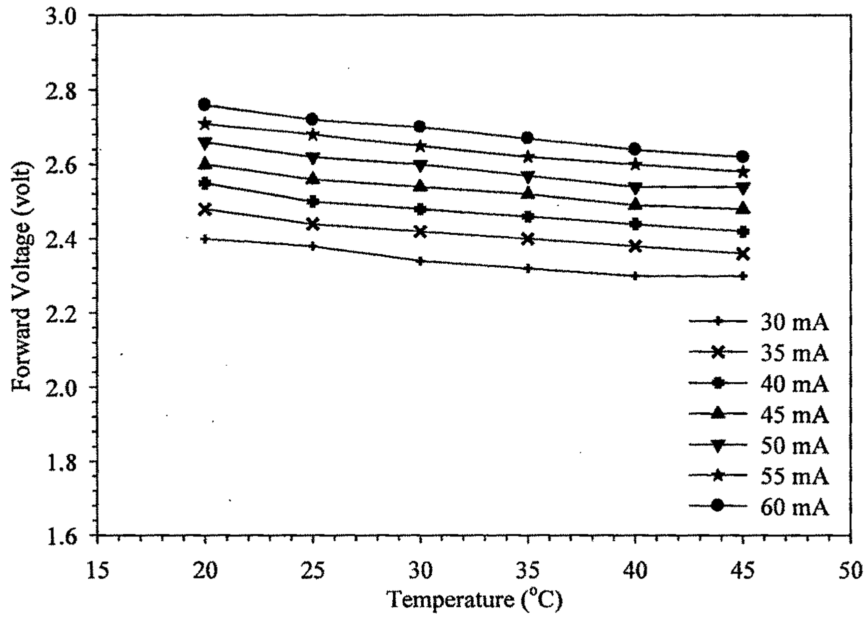
(b)

Figure 2.20: (a) Schematic and (b) measurement set up to find laser diode junction temperature.

We had found that the decrease in forward voltage for given constant operating current with increasing junction temperature, as shown in Fig. 2.21 (a). These results are quite good in agreement to the Eq. 2.9.



(a)



(b)

Figure 2.21: (a) Voltage vs. Current at different ambient temperature, (b) Forward Voltage vs. Temperature at different operating current.

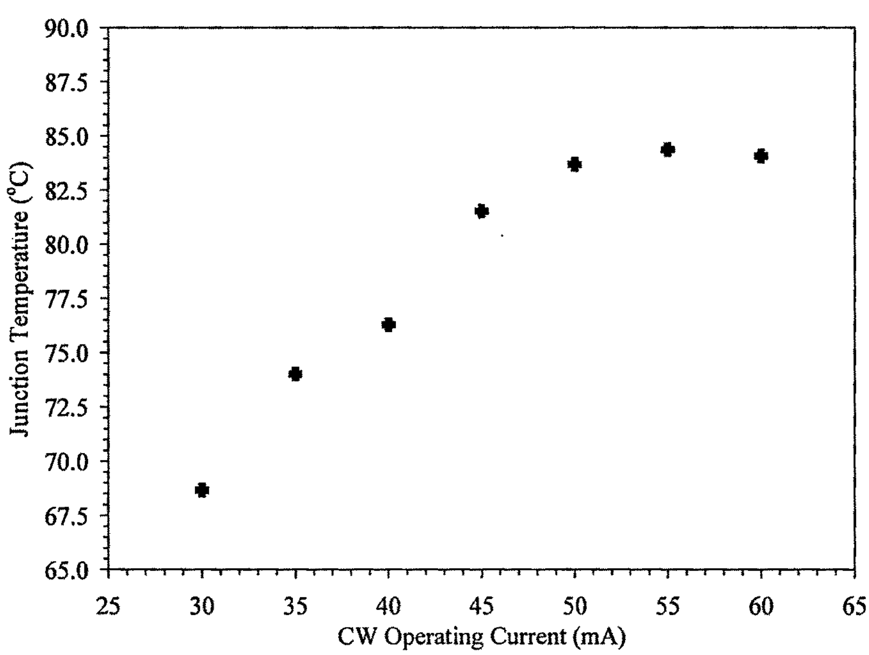


Figure 2.22: Junction temperature vs. operating current.

Fitting the experimental data of voltage – temperature relation, shown in Fig. 2.21(b), linearly to the type of, $Y = m X + c$, we get the value of junction temperature for constant operating current in CW mode. From this we can get the calibrated relation between junction temperature and operating current of laser diode, shown in Fig. 2.22.

2.3.4 Estimation of Maximum Power (P_{max}) for COMD

One of the major issues associated with the high-power operation of the laser diode is the mirror facet damage. We have optimized an experimental setup to measure the P_{max}, maximum optical output power, at catastrophic optical mirror damage (COMD). Generally COMD occurs at low operating temperature (< 40 °C). Figure 2.23 shows the schematic of P_{COMD}, power density at COMD.

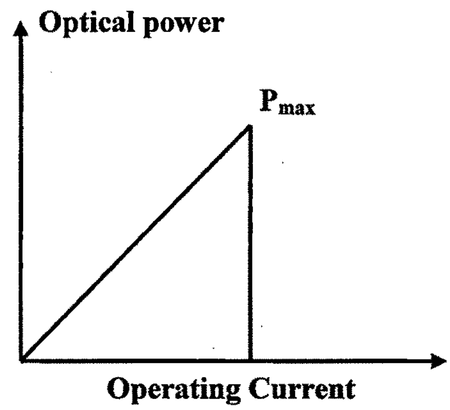


Figure 2.23: Schematic of L-I for P_{COMD}.

The L–I measurement at room temperature has been carried out in pulse, with essential higher repetition rate and duty cycle, or CW mode. Gradual increase in operating current leads non-radiative recombination and we could observe sharp decrease in optical output power. The P_{COMD} was calculated using equation.

$$P_{COMD} = \frac{P_{max}}{\left[w \times \left(d/\Gamma\right)\right]} \times \left(\frac{1+R}{1-R}\right) \tag{2.10}$$

Here, P_{max} is the maximum power just before COD, (in *Watt*), (d/Γ) is the equivalent/transverse spot size, (in μm), d is quantum well width, Γ is fraction of optical power residing in quantum well, R is front facet reflectivity, and P_{COD} is power density at COD.

The experimental was optimized to measure the P_{max}, the maximum power just before the COD occurs. The precision pulse laser diode driver (ILX Lightwave LDP – 3840) and Lock-in amplifier (SR 530) was connected to computer by GPIB. Whole operating and measurement system was automated using VI (Virtual Instrument) program of LabVIEW. For the temperature stability the device was mounted on TEC. The operating current was gradually increased up to the sharp decrease in the optical output power of the laser diode under the test. For the initial optimization we have used the commercially available class-2A laser pointer diode. An experimental setup and the VI user interface are shown in Fig. 2.24 and Fig. 2.25.

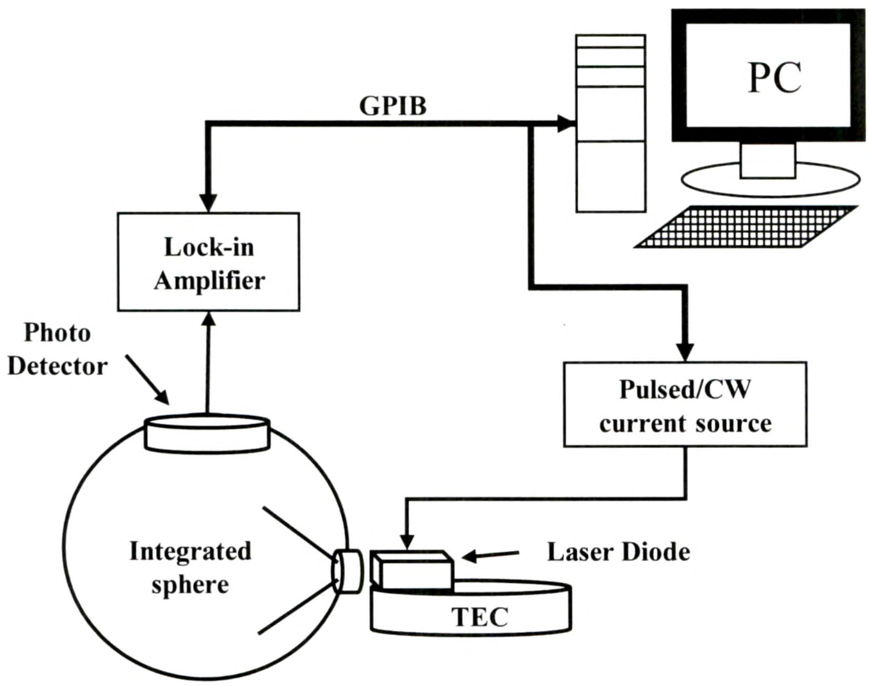
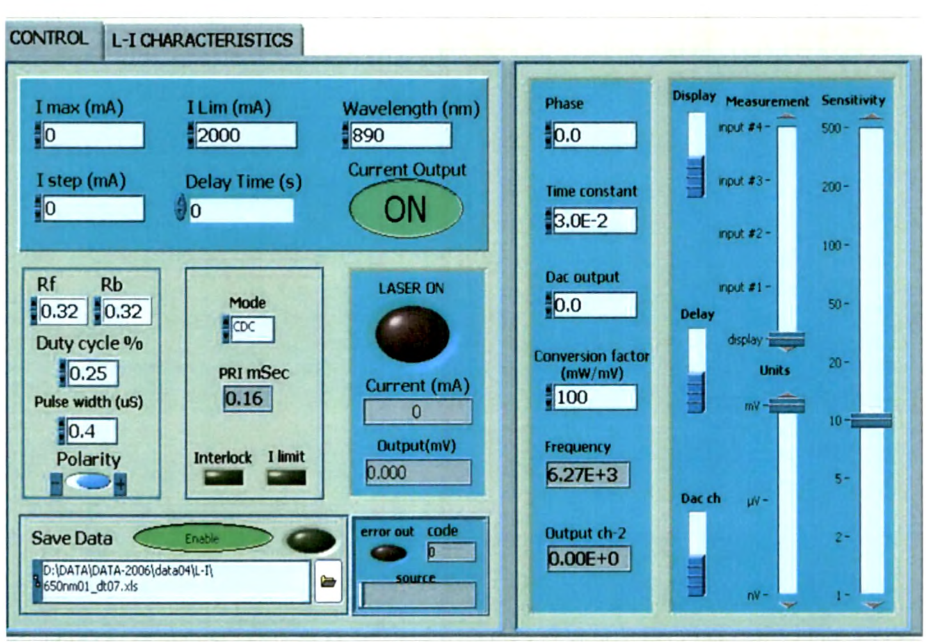
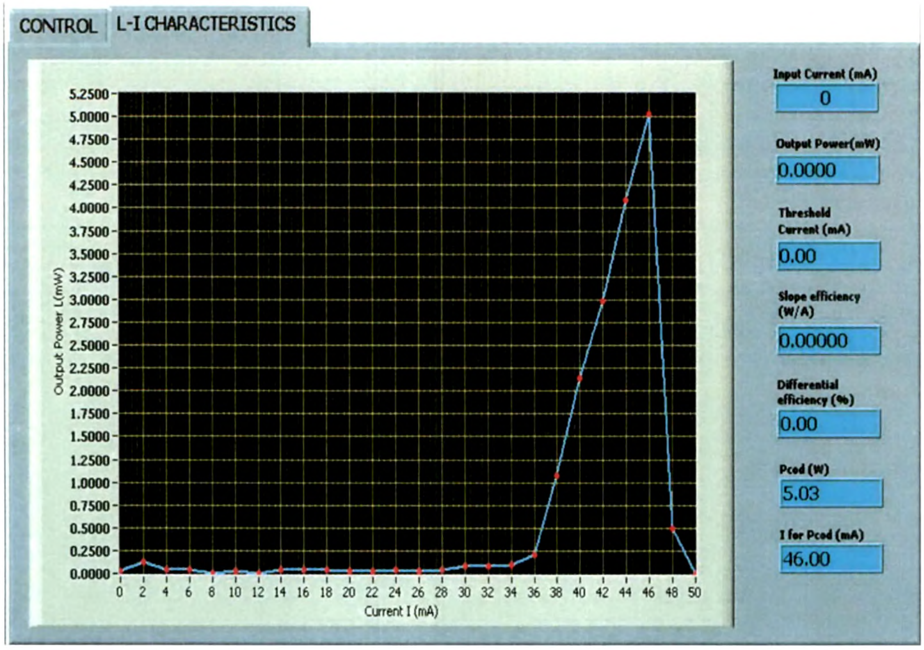


Figure 2.24: Experimental Schematic for P_{max} measurement.



(a)



(b)

Figure 2.25: (a) Front panel of Lab-VIEW VI user interface to control the diode operation of L-I measurement. (b) The graph shows the sudden drop in optical output power and we have P_{max} value.

* * *