

## EXPERIMENT 8: Semiconductor Diode Lasers

### DESCRIPTION

#### PURPOSE

Learn the unique characteristics of semiconductor diode lasers.

#### INTRODUCTION

The semiconductor diode laser was predicted in 1959, one year after Schallow & Townes developed the general theory of the laser. The first Laser Diode (LD) was independently demonstrated in 1962 by groups at the corporate research laboratories of General Electric and IBM and the MIT Lincoln Laboratory two years after the first laser was built. The early semiconductor lasers operated only at cryogenic temperatures, and therefore were not of much practical use. By the early 1970s, efficient room-temperature LDs were developed and incorporated into the first major commercial applications, long distance fiber-optic telecommunications. Laser Diodes continue to enhance and transform the telecommunications industry; most long-distance telephone calls are now carried by diode-laser-generated light signals delivered over optical fibers and you will soon have telephone, television, and computer services delivered to your home by diode laser light over optical fibers. Beginning in the late 1970s, LDs found widespread use in consumer products such as laser video disk and audio compact disk players. LDs are also used in some laser printers (not all laser printers have lasers inside), magneto-optical computer disks, CD and DVD players and recorders, and bar-code scanners. The true “laser revolution” does not involve large killer-lasers (à la Buck Rogers, Luke Skywalker, and Ronald Reagan), but it involves the ever-shrinking LDs, which can now be made by the thousands on a single semiconductor wafer.

A semiconductor laser incorporates the three essential components of a working laser described in Experiment 3: **amplification** by stimulated emission, **feedback** by mirrors, and **delay** through the propagation time of light.

#### Amplification: Energy Levels in a Semiconductor

Recall that the “energy levels” of atoms describe the quantum-mechanical requirement that microscopic particles have discrete energy values, as shown in Fig. 8-1a. As two (or more) atoms come very close together (within approximately one atomic radius), their electrons can rearrange themselves to form new energy levels characteristic of a molecule (a few atoms) or solid (many, many atoms).

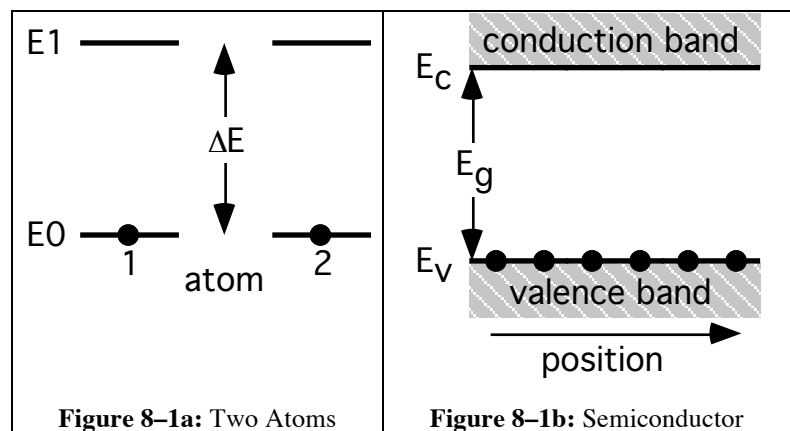
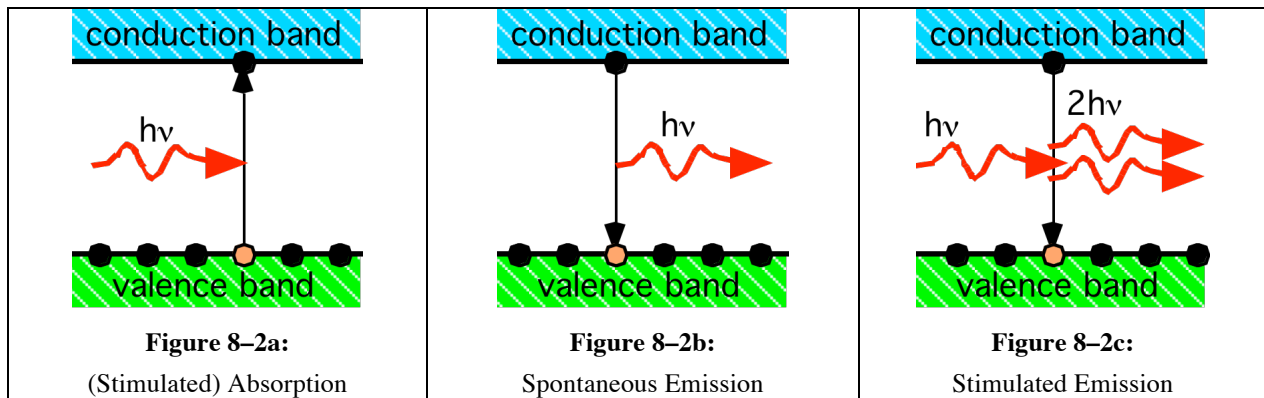


Figure 8-1b shows the important characteristic energy levels of a semiconductor, the *valence band* and the *conduction band*, which are shared by all the

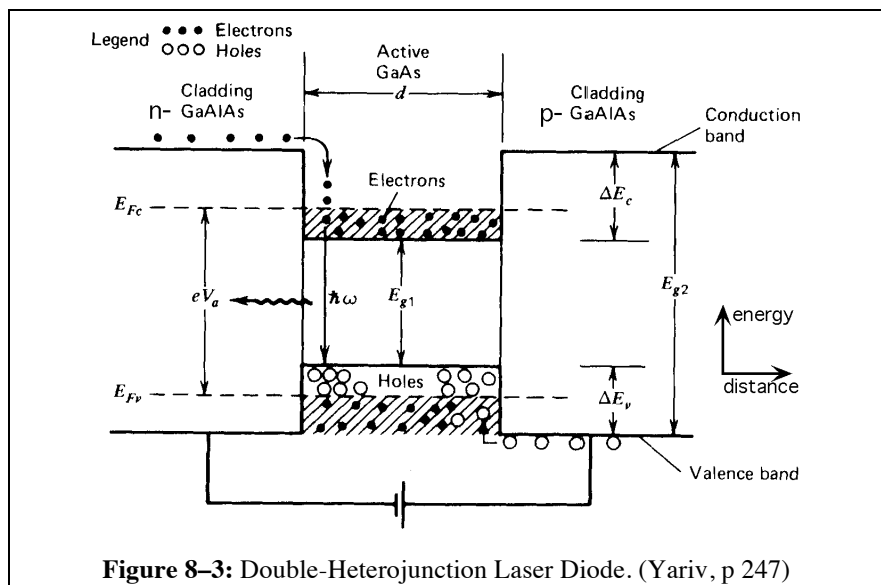
atoms in a semiconductor. In the semiconductor ground state, all of the available valence electrons share the valence band and none occupy the conduction band. The valence and conduction bands are separated by an “energy gap”  $E_g$ , analogous to the energy level separation  $\Delta E$  of individual atoms (Fig. 8-1a). Initially, most or all of the electrons may occupy the lower energy valence band. If a photon of energy  $h\nu = E_g$  (or slightly larger, for reasons we will not go into here) enters the semiconductor, it will excite an electron from the valence band into the conduction band, leaving behind a ‘hole’ in the valence band, as shown in Fig. 8–2a, equivalent to (stimulated) absorption in a single atom (see Fig. 3-2a). Recall that the PhotoDiode detector (PD, Exp. 2) operates by stimulated absorption in semiconductors. A semiconductor with an electron already in the conduction band can emit a photon by spontaneous emission (Fig. 8–2b) to operate as a Light Emitting Diode (LED) or by stimulated emission (Fig. 8-2c). The semiconductor is capable of providing light **amplification** if sufficient free electrons and holes can be generated in the semiconductor to produce population inversion; the result is a Laser Diode (LD).



**Recap:** A photodiode (PD) works by (stimulated) absorption, a light emitting diode (LED) works by spontaneous emission, and a laser diode (LD) works by stimulated emission.

**Population Inversion**

Population inversion in an LD is achieved electronically by injecting current, electrons and holes, into the active region from n- and p-doped semiconductor cladding layers as shown in Fig. 8–3. The cladding layers serve two functions. First, the cladding layers must have a larger energy gap  $E_{g2} > E_{g1}$  than the active region so that they can inject charge carriers.

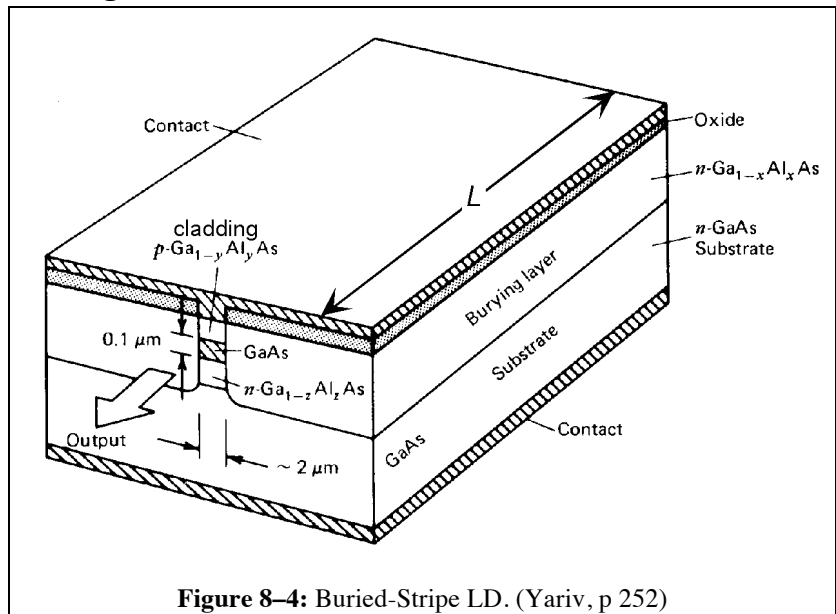


Second, the cladding layers must have a lower refractive index than the active layer so that the laser output is confined to the active layer by total internal reflection, just as light is con-

fined in an optical fiber. A common LD is the GaAs (“ga-as”) LD made of layers of different alloys, GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As (“al-gas”), as shown in Fig. 8-4. The active layer has an energy gap  $E_{g1} = 1.424 \text{ eV}$  so that the nominal emission wavelength is  $\lambda = hc/E_{g1} = 871 \text{ nm}$  (the actual operation wavelengths range from 750-880 nm due to the effects of dopants, the size of the active region, and the compositions of the active and cladding layers). The GaAs refractive index at these wavelengths is  $n = 3.5$  while the refractive index of the Al<sub>x</sub>Ga<sub>1-x</sub>As cladding layers is slightly smaller. Other semiconductors used in LDs include InP, GaN, and PbS.

**LD Construction: Transverse and Longitudinal Modes**

Fig. 8-4 shows the construction of a typical LD with cladding layers, electrodes, and GaAs active ‘stripe’. The laser cavity mirrors are the end facets of the semiconductor crystal, which has been cleaved (“broken neatly”). The end facets have reflectivity  $R = [(n-1)/(n+1)]^2 = 32\%$ , because of the high refractive index of GaAs. The dimensions of the stripe determine the pattern of the output emission (the “transverse mode” pattern) and also the possible laser emission

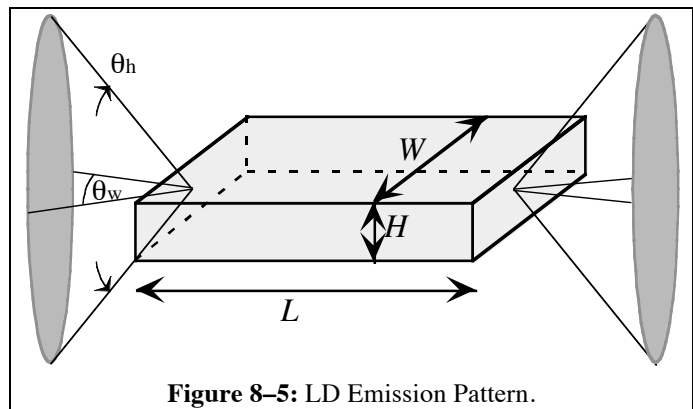


**Figure 8-4:** Buried-Stripe LD. (Yariv, p 252)

frequencies (the “longitudinal mode” pattern). The output pattern is dominated by diffraction because the width  $W \approx 10 \mu\text{m}$  and height  $H \approx 2 \mu\text{m}$  of typical LDs are comparable to the emission wavelength. The divergence angle of the emission along these two directions is inversely proportional to the dimensions as shown in Fig. 8-5. The angular width  $\theta$  of the emission pattern from a slit or rectangular opening of width  $d$  is

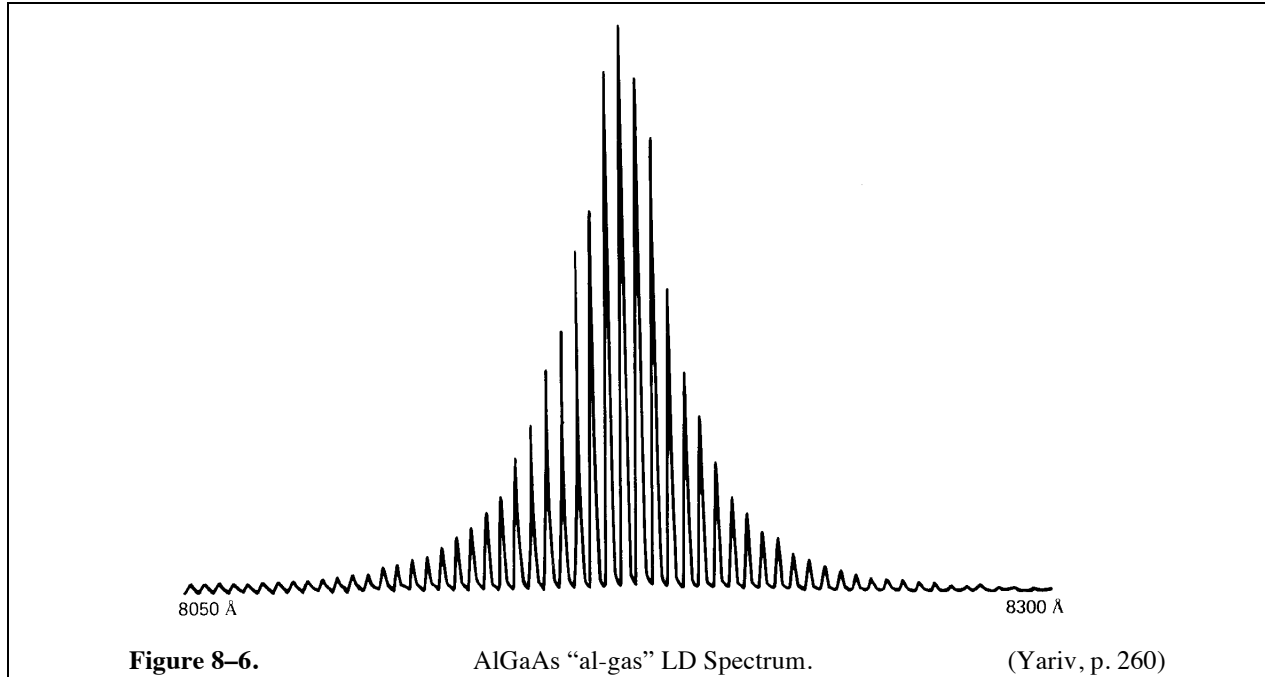
$$\theta = 2 \arcsin(\lambda/d). \tag{8-1}$$

For example, a laser wavelength of 850 nm and strip width  $W = 10 \mu\text{m}$  has a divergence angle  $\theta_w = 10^\circ$ . Similarly if the strip height  $H = 2 \mu\text{m}$ , the divergence angle  $\theta_h \approx 50^\circ$ . Note that the smaller dimension produces the larger divergence angle, as shown in Fig. 8-5. The dimensions  $W$  and  $H$  of the active region of a LD can be determined by measuring the output emission cone angles and using Eq. 8-1.



**Figure 8-5:** LD Emission Pattern.

The longitudinal modes, or optical resonances of the Fabry-Perot optical resonator formed by the cleaved facet end mirrors, are determined by the length  $L$  of the stripe and the refractive index  $n$  of refraction of the semiconductor. The resonant frequencies from Eq. 8-2 are multiples of the free spectral range  $f_{\text{FSR}} = c/2nL$ . Fig. 8-6 show the output spectrum of a typical LD. The center wavelength  $\lambda = 817.5 \text{ nm}$  and the peak separation  $\Delta\lambda = 0.45 \text{ nm}$ , are used to calculate the *free spectral range*  $f_{\text{FSR}} = c\Delta\lambda/\lambda^2 = 200 \text{ GHz}$  so that the length of this LD used in Fig. 8-6 LD is  $L = c/2nf_{\text{FSR}} = 215 \text{ }\mu\text{m}$ . (Compare to a typical HeNe laser with  $L = 30 \text{ cm}$  and  $f_{\text{FSR}} = 500 \text{ MHz}$ .)



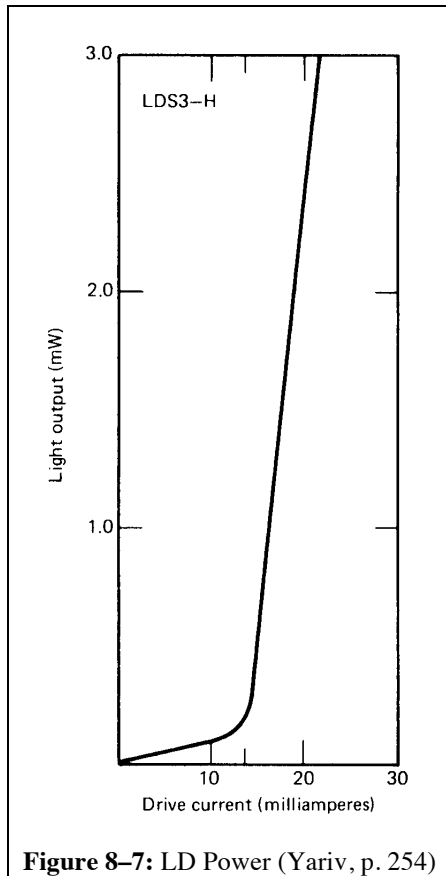
### Output Power

Each electron injected into the active layer can produce a photon by spontaneous or stimulated emission. The optical power inside the laser should be equal to the rate of electron injection ( $J/e$ ) times the overall internal efficiency  $\eta = QR_{\text{eff}}$  (the emission quantum efficiency  $Q$  times the round-trip feedback reflectivity  $R_{\text{eff}}$  of the laser cavity) times the photon energy  $hc/\lambda$ . Then the internal laser power should be  $P_i = (J/e)(\eta hc/\lambda)$ . But stimulated emission is competing with stimulated absorption and other losses in the laser cavity. Therefore amplification occurs only when the current is above a threshold injection current  $J_{\text{th}}$ , which must make up for internal losses such as absorption and incomplete internal reflectance  $R_{\text{eff}}$ . In the laser cavity, the power is

$$P_i = \frac{(J - J_{\text{th}})hc}{e\lambda} \eta_{\text{ext}}. \quad (8-2)$$

The emitted power, taking the output mirror transmission ( $T_o \approx 69\%$  for the GaAs laser) into account, is

$$P_o = P_i T_o. \quad (8-3)$$



**Figure 8–7:** LD Power (Yariv, p. 254)

Figure 8–7 shows emission both above *and* below the threshold current  $J_{th} \approx 14$  mA. Below  $J_{th}$ , the LD is generating only spontaneous emission (like the glow of the He-Ne tube when it isn't lasing) and is, effectively, only an LED! The LED emission has a lower external efficiency than the LD emission because spontaneous emission is in all directions and only a small fraction escapes at the ends of the laser. This results in a much smaller slope below  $J_{th}$  as on Fig. 8-7. Note: Each LD has a different threshold current and the best LDs usually have the lowest thresholds.

#### **ADDITIONAL READING**

*Fundamentals of Photonics*, by B. A. Saleh and M. C. Teich (Wiley, New York 1991), 542-640.

*Laser Electronics*, by Joseph T. Verdeyen, (Prentice-Hall, New York, 1981), pp. 287-303.

*Quantum Electronics, third ed.*, by A. Yariv (Wiley, New York, 1989), pp. 232-263.

## PROCEDURE

**NOTE:** The laser diode and LED are very sensitive to static electricity or to excess drive currents. Be careful not to exceed the stated operating conditions.

### Operate the Laser Diode Current Source as follows:

- i) Connect the LED directly to pin 8 (negative) and pin 4 (positive) on the back of the current source *or* connect the LD to the special adapter cable, which plugs into the back of the current source.
- ii) Turn on the AC power and enable the key switch if so equipped.
- iii) Push the “MODE” button until the “CURRENT” mode indicator is lit.
- iv) Push the “DISPLAY” button until the “LIMIT” display indicator is lit.
- v) Adjust the current limit to the desired value with a small screwdriver.
- vi) Push the “DISPLAY” button until the “CURRENT” display indicator is lit.
- vii) Turn the control knob fully counter-clockwise.
- viii) Push the “OUTPUT” button and wait for the “OUTPUT ON” indicator to light.
- ix) Turn the control knob clockwise to the desired current.
- x) The current may be turned off by pushing the “OUTPUT” button again and waiting until the “OUTPUT ON” indicator turns off.

### ACTIVITY 1: MEASURE LED OUTPUT

**Equipment:** LED, current source, volt meter, optical power meter.

Connect the LED to the current source. Adjust the current limit to 40.2 mA and the initial current to 0.0 mA (knob fully counter-clockwise). Place the power meter as close as possible to the LED and cover with a black cloth. Reset the zero of the power meter. Turn on the current source and measure the current, voltage, and output power of the LED in 2 mA steps from 0 to 40 mA. Plot the voltage vs. current and the power output vs. current before continuing. Record the emission wavelength center and range with the handheld spectrometer.

Questions:

- 1) What is the resistance of the LED at 10 mA current? At 20 mA current?
- 2) Why connect the LED with forward voltage bias but the PD with reverse bias?
- 3) Write down an expression for the power output of the LED in terms of the current, optical frequency, and emission efficiency  $\eta_{\text{ex}}$ . (Hint: LEDs have no threshold.)
- 4) Calculate  $\eta_{\text{ex}}$  from your results. What factors make  $\eta_{\text{ex}}$  less than unity?

### ACTIVITY 2: MEASURE LD OUTPUT: THRESHOLD AND SLOPE EFFICIENCY

**Equipment:** Laser diode, current source, optical power meter.

**NOTE:** Do not let the output power exceed 5 mW; excess power will damage the laser.

Record the LD specifications from the label. Connect the temperature controller and operate at 20°C. Connect the LD to the current source and voltmeter. Adjust the current limit to 45.2 mA and the initial current to 0.0 mA (knob fully counter-clockwise). Place the power meter as close as possible to the LD and cover with a black cloth. Reset the zero of the power meter. Turn on the current source and measure the current, voltage, photodiode monitor current, and output

power of the LD from 0 mA in 2 mA steps up to 25 mA current and then in 1 mA steps up to 5 mW output power. Plot the voltage and power output vs. current before continuing.

Questions:

- 1) Determine the threshold current from your graph of power vs. current.
- 2) Determine the slope efficiency ( $\Delta P/\Delta I$ ) and the quantum efficiency from your graph.
- 3) Calculate  $\eta_{\text{ex}}$  from your results.

### ACTIVITY 3: RECORD THE LASER DIODE SPECTRUM

**Equipment:** Laser diode, collimating lens, current source, spectrometer.

Operate the laser diode at 4 mW output power and direct the laser output into the spectrometer entrance slits. Set up the spectrometer with 20  $\mu\text{m}$  slits and 0.2  $\text{\AA}/\text{s}$  scan rate, the PMT at  $-765\text{ V}$ , the picoammeter at 20  $\mu\text{A}$  full scale, and the chart recorder at 1 V full scale and 2 cm/min paper advance rate. Change these settings as necessary. Record the emission spectrum over a range  $\pm 10\text{ nm}$  from the nominal emission wavelength. Set the LD current 5-10 mA below threshold and the spectrometer slits to 200  $\mu\text{m}$  and repeat the scan.

Questions:

- 1) Why are the two spectra different?
- 2) Calculate the free spectral range of the laser from your first spectrum.
- 3) Calculate the laser stripe length assuming an index of refraction of 3.5.
- 4) Calculate Planck's Constant  $h$  from Einstein's relation  $eV = hc/\lambda$  using your results in Activities 2 and 3;  $\lambda$  is the peak emission wavelength and  $V$  is the threshold voltage.

### ACTIVITY 4: MEASURE THE LASER OUTPUT PATTERN

**Equipment:** Laser diode (without collimating lens), strong converging lens, current source, lens, PD detector, optical chopper, oscilloscope.

Operate the laser diode at 4 mW output power. Place the chopper so that the outer set of teeth intercept the laser beam and place the converging lens after the chopper so that it collects all the light from the laser. Focus the laser beam on the photodiode. Connect output of the photodiode to one input of the oscilloscope and the sync output of the chopper controller to the oscilloscope trigger. Note that the detector signal is not perfectly square because it takes a finite time for the blade to cover the laser beam. Using the oscilloscope cursor controls, measure the time it takes the photodiode signal to rise from 20% to 80%. The distance traveled by the chopper blade during this time is equal to the blade velocity times the 20% to 80% time measured with the oscilloscope. Calculate the Gaussian beam diameter ( $W$  or  $H$ ), which is this distance between divided by 0.835. Do this twice, once with the blade crossing the beam horizontally and once crossing vertically. Repeat the horizontal and vertical beam width measurements with the LD operating 5 mA below threshold. Determine the polarization of the LD output relative to the output stripe orientation.

Questions:

- 1) Determine the horizontal ( $\theta_h$ ) and vertical ( $\theta_w$ ) angular widths from your 80%/20% values of  $W$  and  $H$ .

- 2) Determine the laser facet dimensions  $W$  and  $H$  using the relations  $\sin(\theta_h/2) = \lambda/H$  and  $\sin(\theta_w/2) \approx \lambda/W$  using the higher-current results.
- 3) Explain the different results with the different laser operating currents.

### ACTIVITY 5: MEASURING PLANCK'S CONSTANT WITH LEDs (OPTIONAL)

In 1900, German physicist Max Planck (1858-1947) was trying to model the spectrum of electromagnetic radiation emitted by a warm (or hot) body. This “Black Body Radiation” is what you see coming from the sun, the filament of an incandescent light, or a hot electric stove element. In order to make the observations agree with the theory, Planck had to assume that the electromagnetic radiation was grouped in equal discrete clumps of energy that we now call photons. The clumps at each frequency have a discrete energy  $E = hf$ , where  $E$  is the energy of the clump,  $f$  is the frequency, and  $h = 6.626 \times 10^{-34}$  J-s.

You will measure the spectrum emitted by LEDs of several different colors and also threshold voltage for them to turn on and emit light and use this data to calculate Planck's constant.

**NOTE:** LEDs usually have one short and one long lead; the long lead is the positive lead and should be connected to the positive terminal of the power supply or current source. The LEDs can be burned out by application too much current.

#### ACTIVITY 5A: MEASURE THE LED THRESHOLD VOLTAGE

**Equipment:** Several LEDs, power supply, X-Y recorder.

Connect one LED to the power supply, resistor, and X-Y recorder as shown in Fig. A. Place a clean piece of paper on the recorder and set the origin near the lower left corner of the paper. Adjust the X-axis scale to 0.2 V/in, or about 3 V full scale (The Y-axis scale is fixed at 0.05 V/in, or about 40 mA full scale). Engage the recorder servo and pen functions. Slowly increase the power supply voltage until the pen reaches the top of the paper, tracing out the current-voltage (I-V) curve for the LED. (Be sure to record some identifying characteristic of the LED for future reference.)

Repeat for all LEDs, determining the threshold voltage for each. One each I-V curve, draw a tangent line along the rising part, extrapolating to  $Y = 0$  (current = 0). Record the value of the X-intercept ( $V = 0$ ) for each curve. This is the threshold voltage of the LED.

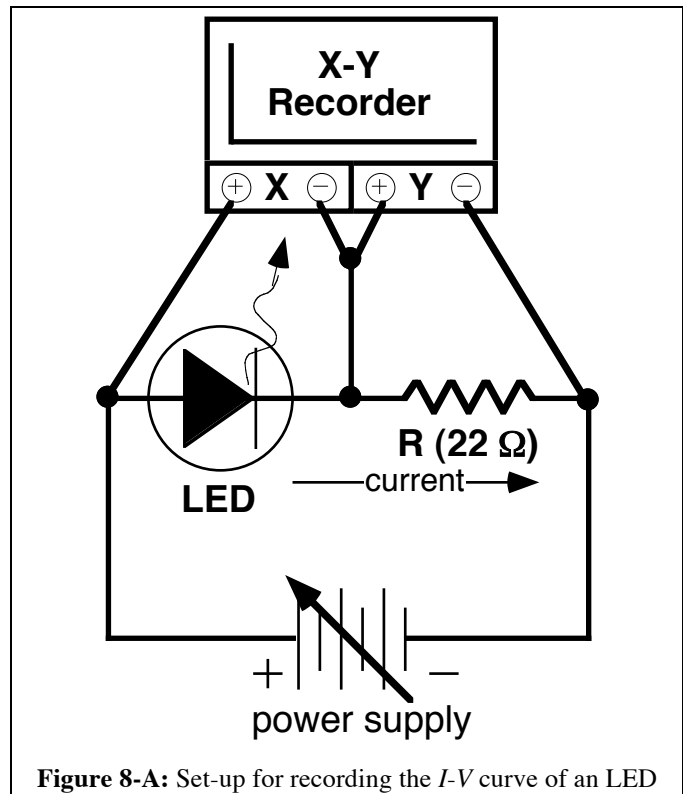
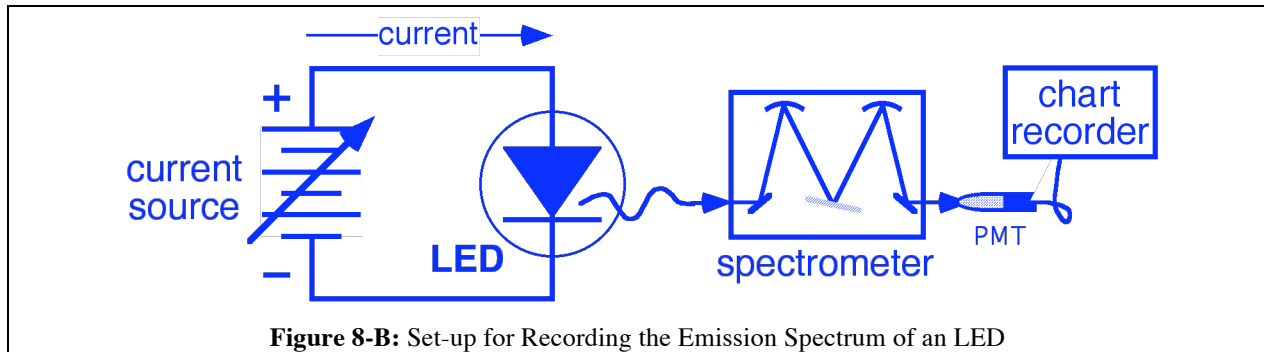


Figure 8-A: Set-up for recording the I-V curve of an LED



**ACTIVITY 5B: MEASURE THE LED EMISSION SPECTRUM**

**Equipment:** Several LEDs, current source, spectrometer, chart recorder.



**Figure 8-B:** Set-up for Recording the Emission Spectrum of an LED

Connect one LED to the current source and operate at 30 mA. Position the LED up against the entrance slit of the spectrometer. Set the spectrometer to operate with 200  $\mu\text{m}$  slits, 2  $\text{\AA}/\text{s}$  scan rate, and 1100 V PMT voltage. Set the chart recorder to operate at 1 cm/min and 2 V full scale. Slew the spectrometer to find the approximate center wavelength of the LED emission. Now perform a wavelength scan, with chart recording, from 500  $\text{\AA}$  below to 500  $\text{\AA}$  above the emission peak. Mark the chart every 100  $\text{\AA}$ . Repeat for each LED. (Note, you may need to change the chart recorder settings to for some of the LEDs to make a nice plot of 30-70% of full scale and 10-20 cm width.)

Calculate the frequency of the peak wavelength for each LED, noting that the measurement was made in air where the index of refraction is approximately  $n = 1.0003$ . The frequency is therefore  $f = c/n\lambda$ , where the speed of light in a vacuum is  $c = 299,792,458$  m/s. Now plot the threshold voltage  $V$  (from Activity A) vs. the frequency  $f$  of the peak wavelength (from activity B) and draw a best-fit straight line through the data. Calculate the slope of this line and Planck's constant  $h$  from the relation  $eV = hf$ , where  $e = 1.602 \times 10^{-19}$  C is the elementary charge.

Questions:

- 1) What was Albert Einstein awarded the Nobel Prize for?
- 2) Should you ever make up a formula to explain the data if the theoretical basis for that formula makes no sense to you (or anyone else you ask)?

My sincere thanks to the good folks at Kansas State University for developing a similar experiment and for Dr. Chuck Lang for pointing out calling my attention to it and thus inspiring today's exercise.