Characteristics of a heterojunction semiconductor-laser

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Abstract: *Laser diodes are devices that when electrically pumped, produces laser light. The device is made of layers of semiconductor junctions, thus sometimes called a semiconductor-laser. This technology currently has varyity of practical applications e.g. laser printing & pointing, fiber-optical communication technology, CD/DVD/Blu-ray reading & recording and barcode reading.*

1 Heterostructural laser diode

A heterostructural laser diode is one of many types of semiconductor-lasers. It consist of a P-N junction with some energy gap, sandwiched in-between a pair of P-N junctions with relatively larger energy gaps. The device is driven by injecting electric current in metalic contacts placed on both sides of it. Light is formed in the devices optical cavity, where photons can stimulate the de-excitation of charge carriers, creating more identical photons. If a wall of the cavity is made semi-transparent, some photons escape as laser-light.

2 Threshold current and internal quantum efficiency

The fundamental nature of a laser diode, and thus its primary area of investigation is its tendency to transform input current into emitted light, and, more deeply, its efficiency in doing so.
There are several parameters that concern the practical value of a particular laser diode, and their comparative evaluation establishes the verdict over the diode's practical use.
A laser diode exhibit a growing onset of emittance as the current increases from zero, reaching a point, whose corresponding current is refered to as threshold current, where the light-to-current (LI) relationship is linear. In reality, as the area where current must stimulate varies, the threshold current density is what governs the onset of linear LI relationship. This can be measured by investigating both a LI-plot and the area of the diode. Next, the slope of the linear LI curve is of interest; a steep curve corresponds to a higher LI ratio. Direct measurement of this slope yields the unitless External differential quantum efficiency, η_d, as the slope divided by the hypothetical ideal slope; $hc/\lambda q$, where h is the Planck's constant, c the speed of light, λ the wavelength and q a (positive) electron charge:

$$\eta_D \equiv \frac{\frac{\Delta P}{\Delta I}}{\frac{hc}{q\lambda}}. \quad (1)$$

For several temperatures T we inject current to the

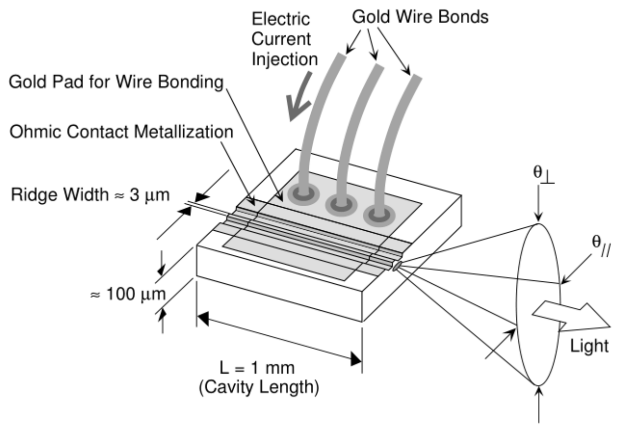

Figure 1: A schematic representation of a heterostructure laser-diode

laser-diode at regular intervals, starting from 0 mA up to roughly 150 mA. For each value of current the laser-diodes optical power P, is also measured by a spectrometer. By plotting the current against the optical power for each measurement, we are able to estimate the laser-diodes threshold current I_{th} and its external quantum efficiency η_D at each temperature. The slope of the line that best fits the points above the threshold current, where stimulated emission governs behaviour, seen in figure 2, tells us how many watts of optical power is gained for every unit charge increased. We're interested in taking the ratio of the plot in figure 2's numerical slope to $hc/q\lambda$, as in eq. (1):

T [°C]	I_{th} [mA]	η_D
-10.0	138.0	0.59
0.2	145.0	0.57
10.2	157.0	0.57
19.9	169.0	0.53

According to these results, η_D seems to drop somewhat as the temperature is increased. We believe the intervals between measured points of I is to large, especially near the threshold current.

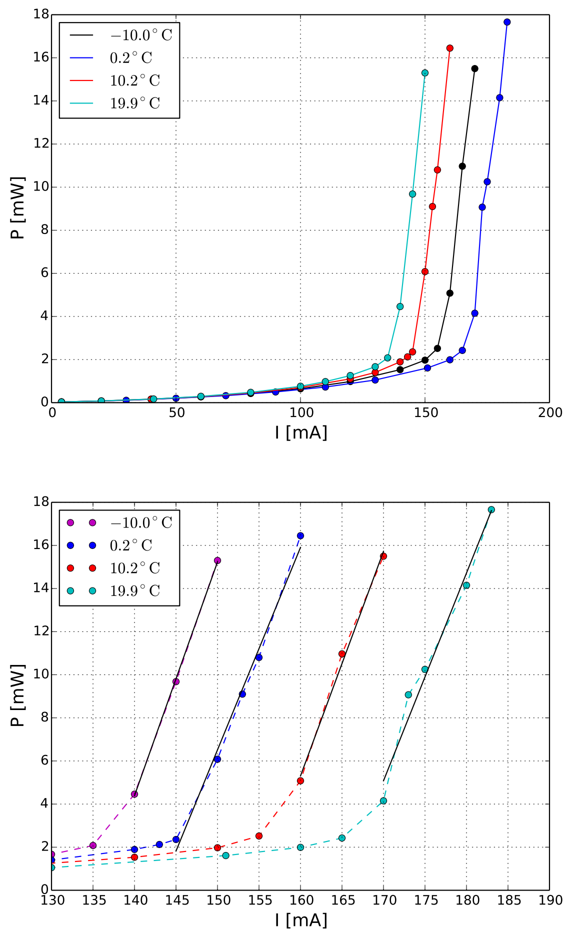

Figure 2: Injected current I plotted vs. the optical power P for different axis-limits of I. From this graph the threshold current and external quantum efficency can be read.

3 The laser-diodes characteristic temperature

The characteristic temperature T_0 is a measure of the temperature sensitivity and the thermal stability in general of the device. At higher values of T_0, the device's threshold current and external quantum efficiency increases less rapidly as functions of temperature. Again, the LI curve is measured for different temperatures, and from the data, the logarithm of the determined threshold current is plotted against temperature, from which a best fit line's linear slope is calculated. In figure 3, we plot the temperature values we measured at, versus their corresponding threshold current as determined from figure 2. We have the relation

$$I_{th} = I_0 \exp\left(\frac{T}{T_0}\right),$$

from which, after dividing by I_0, taking the natural logarithm of both sides and adding $\ln I_0$, we obtain,

$$\ln I_{th} = \ln I_0 + \frac{T}{T_0}. \qquad (2)$$

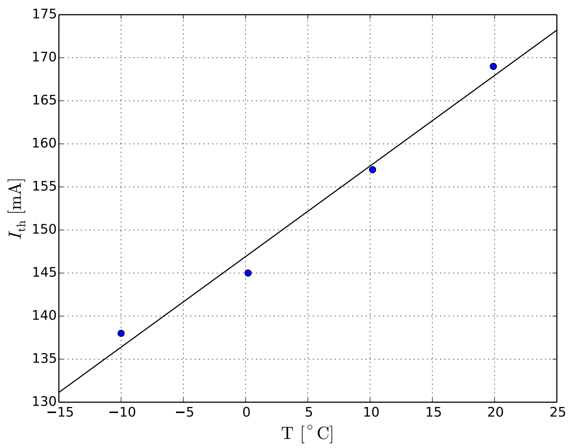

Figure 3: Operating temperature plotted vs. corresponding threshold current

We try plotting equation (2) against T, as seen in figure 4, primarly in order to obtain the characteristic temperature T_0, but also the characteristic current I_0. The slope of line in figure 4 is $1/T_0$ and the line intersects the vertical axis at $\ln(I_{th}(T=0))$. From this we obtain the values

$$I_0 \simeq 22.3 \text{ mA},$$

and

$$T_0 \simeq 145^\circ \text{ C}.$$

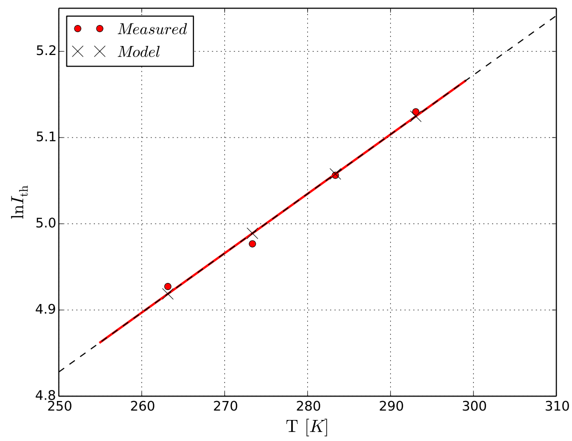

Figure 4: The operating temperatures plotted versus the logarithm of the determined threhold current I_{th}. The red dots and line represent the measurement points and its best fitted line, respectively. The black ones represent I_{th} given from equation (2) after having obtained I_0 and T_0 from the measurements.

4 Spectra and energy gap

The spectrum of a laser diode exhibits several peaks, centered around a primary wavelength, the center

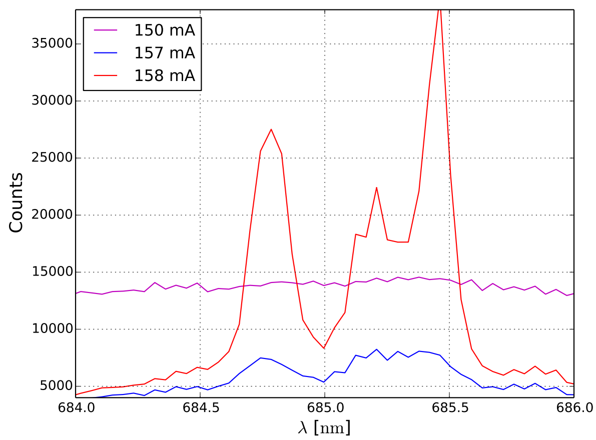

Figure 5: The laser-diodes spectra plotted for several current values at room temperature.

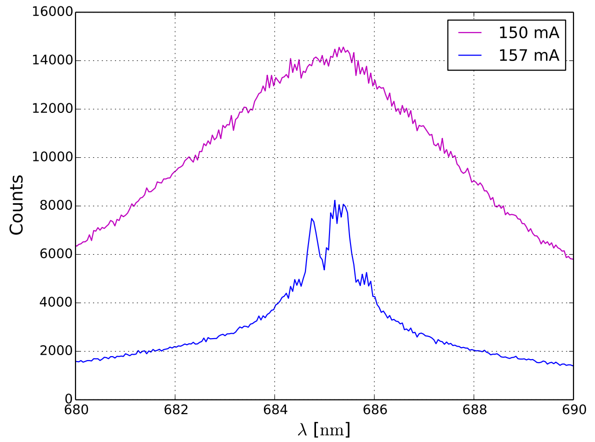

Figure 6: The laser-diodes spectra plotted for several current values at room temperature.

wavelength. Comparing the spectra below and above the threshold current, it is evident that the center wavelength is not nearly as sharp below I_{th}, meaning the light radiated is a more mixed combination of wavelengths. Same goes for operation at currents above I_{th}, but we see a much sharper peak in certain wavelengths due to stimulated emission.

Unfortunetaly the data on center wavelength for different temperatures was lost, therefore we cannot estimate how much the spectra shifts due to change in temperature, nor investigate if in fact the energy gap decreases ≈ 0.435 eV for each 10° C increased for temperatures close to room temperature. However, the energy gap can be investigated. As a conducting charge carrier's energy level drops down to that of the valence band, it emits a photon with energy corresponding to the difference in those energy levels. Knowing that, and the fundamental relationship between a photons energy E to its wavelength λ, which is $E = hc/\lambda$ we can determine the energy gap. We get,

$$E_g = \frac{hc}{\lambda} = 1.81 \text{ eV}$$

comparing this result to a graph where E_g has been plotted as a function of T for different direct-bandgap type $Al_xGa_{1-x}As$ lasers, it looks like we are dealing with $x = 0.3$ or a $Al_{0.3}Ga_{0.7}As$ type laser-diode.

5 Optical cavity

The optical cavity of the device has dimensionality affecting the standing wave of the propagating optical wave in a quantified manner; the cavity length L must have a numerical value that is an integer number m of half wavelengths:

$$L = m\frac{\lambda}{2}. \tag{3}$$

The spectral range Δf is,

$$\Delta f = f_2 - f_1 = c\left(\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2}\right) = \frac{c}{2nL}$$

so we can write

$$\Delta\lambda = \frac{\lambda_1\lambda_2}{2nL}$$

and we can express the cavity length L with,

$$L = \frac{\lambda_1\lambda_2}{2n\Delta\lambda} = \frac{c}{2n\Delta f} \tag{4}$$

where n is the semiconductors refractive index, which is approximated to be $n \approx 3.5$.

As figures 5 and 6 suggest, the laser-diode displays a series of peaks in light intensity at values not far from the center wavelength $\lambda_0 = 685.4$ nm. We measure the wavelength distance $\Delta\lambda$ between a few of them, who result in a few similar values of $\Delta\lambda$, the most common one corresponded to,

$$\Delta\lambda \simeq 0.085 \text{ nm}$$

which yields information about the cavity length L. For this particular semiconductor, we get

$$\Delta f \simeq 54.4 \text{ GHz},$$

and

$$L \simeq 787.3 \ \mu\text{m}.$$

Practical values of L are usually in the orders of hundreds of μm, so this value seems reasonable.

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