ENGINEERING TRIPOS PART IIA & E.I.S.T. PART I

ELECTRICAL AND INFORMATION ENGINEERING TEACHING LABORATORY

EXPERIMENT 3B6

SEMICONDUCTOR LASERS

OBJECTIVES

1. To gain experience of using a semiconductor laser, including electrical drive requirements and detection of the optical output signal.

2. To generate light-current and voltage-current curves for the laser, and hence understand how these relate to each other, and the laser threshold current.

3. To measure optical spectrum output from the laser, and understand how this relates to the properties of the laser.

Caution! Misuse may easily damage semiconductor lasers, and just possibly your eyes. Read the instructions in this handout and apply them carefully.

1. Introduction

Semiconductor lasers are now manufactured and used in millions per year in a wide variety of applications. For instance every telephone call you make in excess of about 30 km will be routed via optical fibre and a laser operating at either 1.3 µm or 1.5 µm wavelength; in this case the wavelengths are those at which fibres transmit best. Numerically, even more lasers go into CD players, and in this case the wavelength of 0.78 µm is the shortest where lasers may be cheaply manufactured. A shorter wavelength, 0.65 µm is incorporated in DVD players as one of a number of measures to increase the data density. The next generation of data storage devices use blue/violet lasers (Blu-ray) with wavelengths as short as 0.4 µm.. Hundreds of millions lasers per year are made for the 1.34 µm and 1.55 µm fibre communications bands (tele-communication links), and for the 0.85 µm fibre band (data-communication links), and smaller numbers for gas analysis, metrology etc. with wavelengths in the 1 µm to 6 µm range.

Semiconductor lasers may have output powers from milliwatts to watts, spectral widths from 10 nm to 0.001 nm and a wide range of other characteristics as well as package styles. However, a few general points may be made:

• Lasers are very bright: up to about 100 times brighter than the sun.

• Semiconductor lasers are efficient: up to 90% or so compared with 1% for a bulb and 0.1% for a HeNe laser.

• Semiconductor lasers are small.- max dimension around 0.5 mm - salt grain size.

• Semiconductor lasers don't emit narrow beams: typical cone angles are 5^{o} to 40^{o}.

• Laser beams are usually polarised, as opposed to LEDs or filament bulbs etc.

• Lasers are fast: typically 1 GHz or faster as opposed to around 10 MHz for an LED.

• Laser beams are coherent: they can give high contrast interference patterns.

The lasers provided are a typical CD player devices operating at 780 nm, and a telecommunication packaged laser. They are generally similar to those operating at all other wavelengths.

If you have not studied semiconductor lasers previously, you should read the related lecture notes and Appendices A and B, which give some background information on semiconductor devices and error analysis. [Preparatory mark]

2. Outline of Experiments

2.1 Set up the laser driver and oscilloscope.

2.2 Measure the laser's light-current and voltage-current characteristics.

2.3 Calculate the laser's wavelength.

2.4 Measure the output spectrum.

2.5 Calculate the effective refractive index of the semiconductor material.

Note: Section 2.4 requires the use of an optical spectrum analyser, which is shared. It is not necessary to have completed the other sections before making these observations although you should have completed reading through the notes.

3. Apparatus

3.1 Laser diode.

This is a standard CD laser mounted on the perspex front of a die cast box. The box contains a few components to protect the laser as well as giving access to its terminals during operation. The laser may also be rotated through 90^{o} about its own axis, so that the junction plane may be either horizontal or vertical.

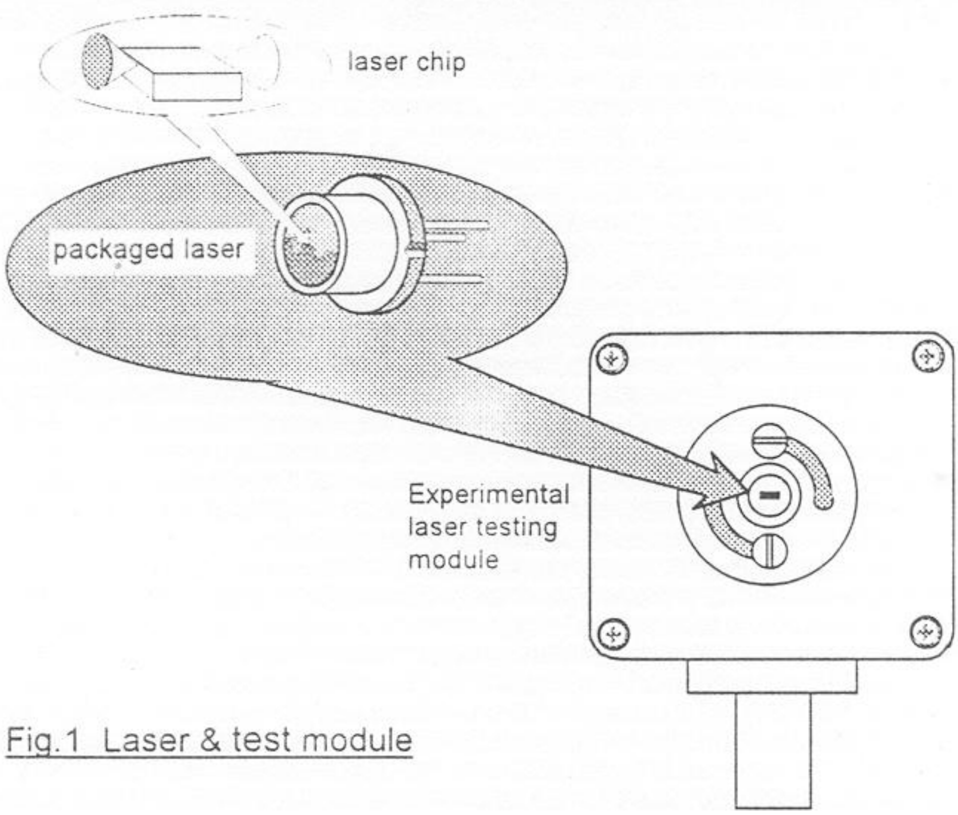


Fig.1 Laser & test module

3.2 Experimental Driver Box

A driver unit has been constructed specially for this experiment, which will provide appropriate (and safe) drive pulses for the laser, as well as 12 V DC. to drive the detector module.

3.3 Detector module

A silicon PIN photodiode is connected to a fast transimpedance amplifier (TIA) in this module, which needs to be connected to the 12 V supply from the driver box. The combination will "saturate" with modest signal levels, and the slit in front of the photodiode may be employed to bring the signal level into a linear regime.

Shared equipment

3.4 Telecommunications packaged laser

For measuring the output spectrum a different laser has been provided. This laser is contained in a standard telecommunication package. The light from the laser is coupled into an optical fibre inside the package and is guided down the fibre, which can then be connected to other equipment such as the optical spectrum analyser. A driver is also supplied for this laser. Your demonstrator will assist you in setting up the driver.

3.5 Optical Spectrum Analyser

The optical spectrum analyser is a complicated piece of equipment but works on a simple principle. It uses diffraction gratings to split the light into its different wavelength components and then detects how much light there is at each wavelength. This type of optical spectrum analyser is very versatile allowing a range of parameters to be set, such as resolution and sensitivity. Ask the demonstrator if you are unsure of any of the settings you are using.

4. Experimental Procedures

4.1 Set-up of Measurement Equipment.

Connect the laser and detector modules as shown in Figure 2, noting:

a) The output from the detector is via a terminal pin and a 'scope probe.

b) Power must be supplied to the detector module from the driver unit.

c) Laser current is monitored by the voltage across a resistor to ground: (think about the resistor value and its accuracy)

d) The laser voltage monitoring point is affected by (c); how can the true voltage be obtained?

e) The third (uncalibrated) 'scope input can be used for the photodetector module output, because the signal from this is uncalibrated anyway.

Set the driver output amplitude to minimum, pulse length to about 5 µs, and the duty cycle to 1% or less. No significant current should pass through the laser until the voltage reaches about 1.5 V. Is there really no current, or is it just too small to see? Increase the laser current to 60 mA, at which point the laser should be operating above its threshold current and an optical output signal should be observable.

4.2 Measurement of Light-Current Characteristics

The relationship between light out of the laser and drive current through it is by far the most important single laser characteristic, and the threshold current is the most important single parameter.

If the laser drive is increased from zero to the region of 40 to 55 mA, at some point the light output will start to increase rapidly; this is the threshold current of the laser. (Threshold is not the point at which the laser current starts to rise rapidly). Note the value of threshold current for your laser. (They vary somewhat.) Set the laser to (threshold + 20 mA) which will be referred to from now on as I_{max}, and adjust the detector position and slit so that the optical signal fills the oscilloscope screen, but no saturation is observable. If you don't understand what saturation means in this context, ask your demonstrator to explain. Measure optical output signal and laser voltage at a range of currents between zero and I_{max} and plot light-current and voltage-current curves. (Remember to correct for the effect of laser current on the circuit for each measured value of laser voltage.) If you start at I_{max} and work downwards, plotting as you go, it will ensure that your graph fits the paper, and will help you notice any wrongly taken points.

Please include a table of readings from the voltage monitor, current monitor and the photodiode output in your write-up.

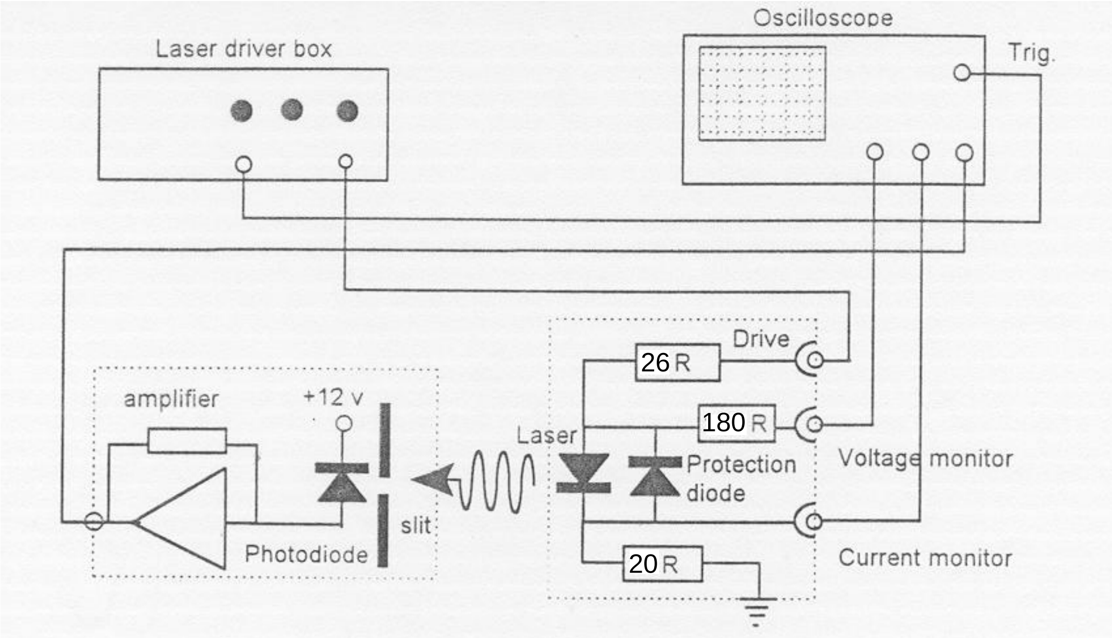


Fig. 2 Circuit for Laser driving & monitoring

The laser above threshold can be regarded as a constant voltage drop with some unwanted but inevitable series resistance. Determine the value of this series resistance from the voltage-current curve you have plotted, and note it in your write-up, together with an estimate of its accuracy. (Hint. It won't be very accurate at all.)

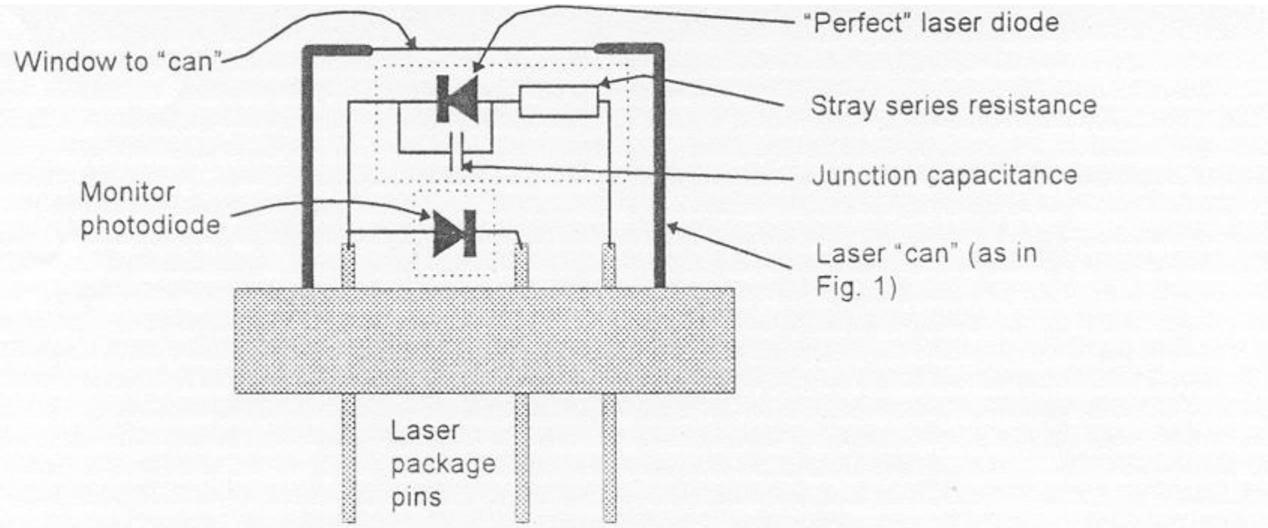


Fig.3 Equivalent circuit of laser diode.

Use the value of series resistance you have obtained to help you calculate the voltage across the "perfect diode" part of the laser equivalent circuit at the lasing threshold circuit. Should this value change if the laser is driven above threshold?

4.3 Calculation of laser wavelength

All light exists in the form of wave packets or photons where the energy of each of these is given by:

$$E_{ph}=hc/\lambda$$

where: E_{ph}=photon energy, h = Plank's constant, c = velocity of light (in free space), and λ = wavelength of light.

Since nothing else is involved, the energy of each photon emitted must be equal to the energy change of an electron as it moves from the conduction band to the valence band in the semiconductor of which the laser is made. (Another way of putting this is that a hole and electron "recombine".) Given that the average potential difference between electrons in the conduction & valence bands equals the voltage across the perfect diode, calculated in section 4.2 above, you should now calculate the mean wavelength of the laser. Sources of inaccuracy in this calculation are important, and you should identify them, and hence estimate the accuracy of the wavelength that you calculate.

4.4 Measurement of laser output spectrum

For this section a different laser has been provided along with an optical spectrum analyser. It is not necessary to have completed the previous sections before making these the following measurements; you may wish to use the shared equipment when it is available. Care should be taken when handling optical fibre, it will snap if bent to sharply.

The threshold current is indicated on the laser driver (15.5 mA) along with the maximum drive current. Exceeding this current may damage the laser, or increase the output to a hazardous level both for yourself and for the optical spectrum analyser.

You can locate the output from the laser using a broad sweep at a course resolution. (Hint: this laser has a telecommunications application.) Having located the output, centre the sweep at this wavelength and reduce the measurement span. Reduce the resolution so that it is set to the smallest possible value, ensuring that all the features of the spectrum can be resolved. The sensitivity of the optical spectrum analyser should be set lower than the observable features. Ask the demonstrator if you are unsure of any of the settings you are using.

Use the optical spectrum analyser to measure the output of the laser at drive currents above (17 mA) and below (14 mA) threshold. Sketch the spectra including all the main features such as centre wavelength λ_0 and 3 dB width. Measure the spacing of the longitudinal cavity modes – these are the ripples that you see in the spectrum. Read the following section about the spacing of the modes and decide the best way of best way of making this measurement.

4.5 Calculation of the effective refractive index of the semiconductor material

When the cavity resonates, i.e. standing waves exist within it, there must be an integer number m of wavelengths in the round trip that the light makes. Therefore:

$$m\lambda_g = 2\,L$$

where L is the length of the cavity (remembering the light travels twice the length of the cavity in a round trip) and λ_g is the wavelength inside the cavity ($\lambda_g = \lambda / n$, where λ is the wavelength in free space and n is the refractive index of the material in the cavity). Converting to frequency (with the speed of light in free space, $c = f\,\lambda$)

$$f = mc \,/\, 2nL$$

This shows there are an infinite number of possible longitudinal cavity modes each with a distinctive frequency f_m. Consecutive modes are separated by a constant difference:

$$\Delta f = f_{m+1} - f_m = c \,/\, 2nL$$

and in terms of wavelength (as $\Delta f = c\, \Delta\lambda / \lambda^2$)

$$\Delta\lambda = \lambda^2 \,/\, 2nL$$

Only the modes that have sufficient gain are seen in the output spectrum of the laser. As explained in the appendix the gain is determined by the material composition. The expressions above allow either effective refractive index to be calculated from the output spectrum if the length of the device is known, or vice versa. The length of the laser is indicated on box containing the laser. Calculate the effective refractive index from your observations of the output spectrum.

5. Conclusions and write-up

You should have now met the most important measurements associated with laser diodes. Explain all these measurements in your write-up to show that you understand them (this will also help you remember them in the future). Optical measurements tend to be inaccurate compared with electrical ones, so you should pay particular attention to sources of error and their implications.

One important source of variability in these measurements has been ignored: lasers are temperature sensitive, and the temperature in the laboratory could vary at extremes from less than 15^{o}C to over 25^{o}C. It is therefore important to record the temperature and significant fluctuations during your experiment.

Expected outcomes:

Part I:

(i) obtained data and L-I and V-I plots of the CD laser with related errors,

(ii) explanation of the different regimes of operation of the device and how these are related with the fundamental light emission processes in semiconductor devices, along with answers to the theoretical questions in handout,

(iii) estimation of the stray series resistance R_s and lasing wavelength λ_0 of the device and estimation of the related errors,

(iv) comment on temperature effects on obtained measurements.

Part II:

(i) sketches of obtained optical spectra below and above threshold using a large (~100 nm) and narrow wavelength span (~5-10 nm),

(ii) recorded data on centre wavelength λ_0, peak output power P_0 and 3 dB spectral width for the two operating conditions,

(iii) explanation of the observed differences in recorded spectra and how these are related to the fundamental light emission processes in semiconductor devices,

(iv) measured mode spacing above and below threshold and comment on its values,

(v) calculation of the refractive index of the semiconductor device and comment on its value,

Appendix A: A brief introduction to the semiconductor laser

- Optical Absorption and Emission Processes in Materials

There are three major types of electron/photon interactions in materials:

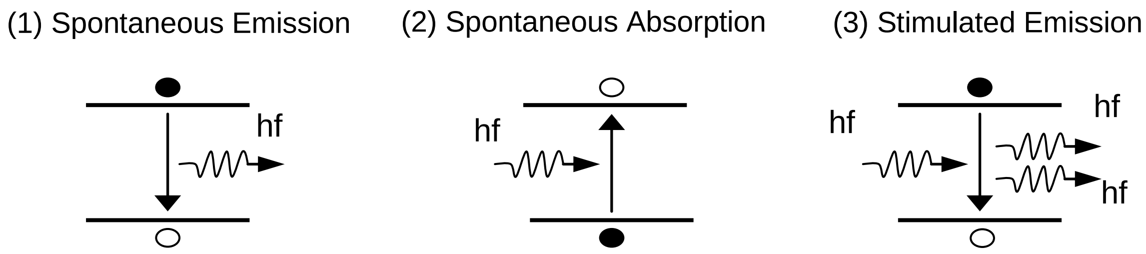


Fig. 1

(1) Spontaneous Emission:

An electron in a high energy level falls to the valence band, losing energy which is emitted as a photon – the basis of operation of a light emitting diode.

(2) Spontaneous Absorption:

An incident photon is absorbed in a material causing the excitation of an electron to a higher energy level – the basis of operation of a photodiode.

(3) Stimulated Emission:

A photon, incident upon an electron in a higher energy level causes the electron to fall to a lower level thus generating a second photon. This is therefore an amplifying action. Two photons are generated from one and in turn they can cause the generation of two further photons. Using this process, high optical powers can be generated and this operation is the basis of lasing action. The generated photon has the same frequency and phase as the incident photon and therefore very pure monochromatic and coherent light is generated.

- **Conditions for Laser Operation**

In order for a system to lase, two main conditions must be achieved, (i) stimulated amplification must be stronger than absorption so that any optical signal is rapidly amplified in power, and (ii) some form of optical feedback must be provided so that lasing light generated can in part be fed back so that stimulated amplification can continue to occur, thus causing sustained stimulated emission and hence lasing output.

As a result of these requirements, in a typical laser system, much more care must be taken to ensure that the light does not scatter or “leak” out of the lasing region. It is also important to ensure that an optical cavity is bounded by reflectors, so that a lasing filament is formed which oscillates back and forth within the cavity, and that the generated light is confined to cause further stimulated emission. By using partial reflectors, some of the light is emitted from the cavity as the output from the laser.

The formation of such a cavity however has a major effect on the form of optical spectrum generated. This can be understood by considering Fig. 2. If the laser cavity is formed by two mirrors with power reflection set a distance L apart, the optical filament will oscillate at such a wavelength so that nodes occur at both reflectors. As a result, only a series of different wavelengths λ_m can be supported by such a cavity, when $L = m\frac{\lambda_m}{2}$, where m is an integer.

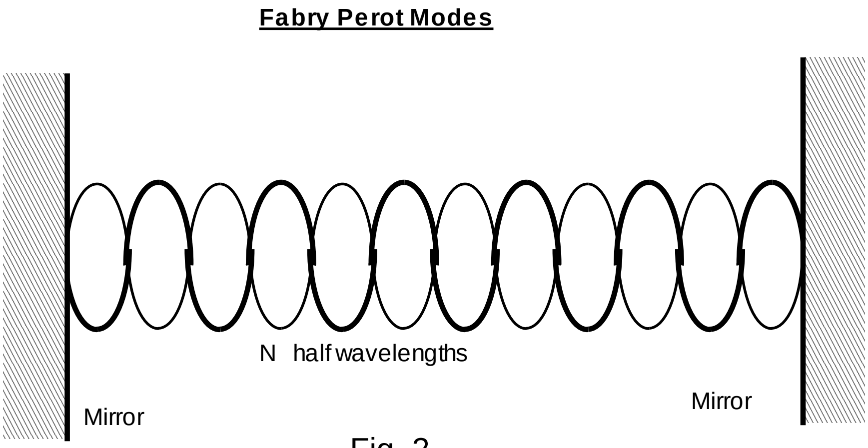
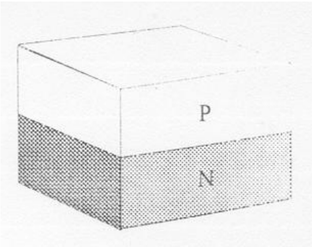


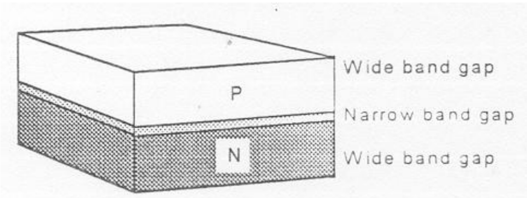
Fig. 2

-Semiconductor lasers

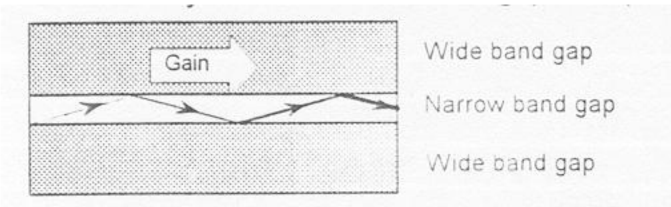
Semiconductor lasers are extremely bright light sources very similar to LEDs, but with the extra features of optical gain and feedback. The simplest LED is just a block of a direct band gap semiconductor such as GaAs, with a PN junction formed in it.



When connected to an external electrical supply, and forward biased, current flows through the device. The current flows as electrons travelling towards the junction in the n-type material, and holes travelling to the junction in p-type material. The electrons and holes don't accumulate but recombine close to the junction plane, and in direct band-gap material a photon is emitted for each hole-electron pair. Crystalline silicon is an indirect semiconductor, and will not emit light in this way: the energy associated with recombination is converted into phonons, which are packets of acoustic waves (analogous to photons as packets of electromagnetic waves). This process leads to heating of the material.

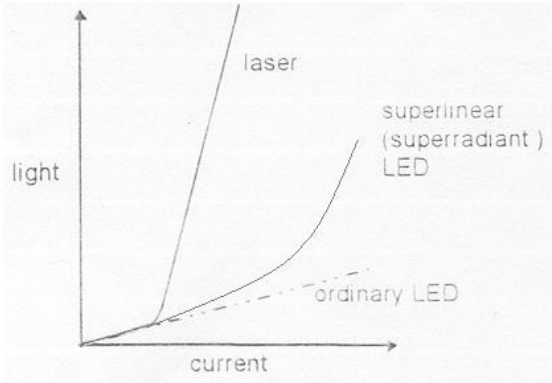


LEDs work better if the holes and electrons are concentrated near the junction in a thin layer of material with a narrow band gap. E.g. a thin layer of GaAs may be sandwiched between layers of wider band gap $Ga_{1-X}Al_XAs$, (with "x" typically 0.4). Very high densities of holes and electrons per unit volume are then possible, and the LED emits very high densities of photons per unit volume, and incidentally develops a very fast response if its drive current is modulated. Such a sandwich structure of different semiconductors is known as a double heterostructure; the wavelength of emission is determined by narrow gap material in the middle of the sandwich.



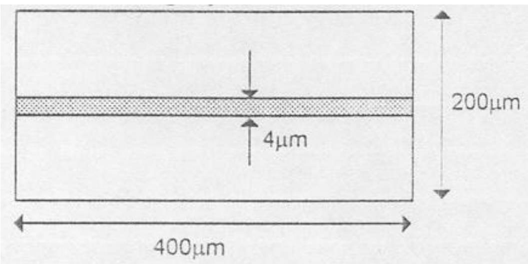
The central layer with a narrow bandgap also (most conveniently) has a larger refractive index than the surrounding wider gap layers and so rays travelling at a shallow angle in the middle layer are totally internally reflected at its boundaries: the structure forms a slab waveguide. The high density of holes and electrons within the waveguide also cause it to give optical gain to the emitted photons travelling within it: photons cause stimulated emission of further identical photons, hence multiplying up the numbers travelling there. This gain process only takes place with high carrier densities, and indeed with low carrier densities the travelling photons suffer net absorption. This increasing gain with carrier density (and hence drive current) causes the characteristics of edge emitting LEDs to become superlinear.

If the ends of an edge emitting LED are smooth, they will reflect some of the light incident on them (about 40% at normal incidence for most semiconductors) while the rest is emitted.

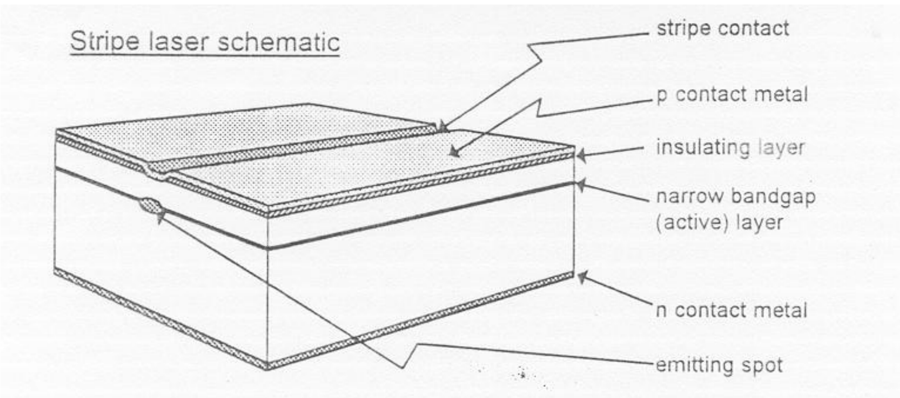


Some light will therefore travel along the waveguide, increasing in intensity due to the gain, be reflected back into the waveguide, and carrying on to make a round trip of the entire structure. Hence gain and feedback are both present, which are necessary conditions for oscillation. If the both are strong enough, optical oscillations occur, and we have a laser.

The LED above which was evolved into a laser started as a simple block with current being injected over the whole of its area. Superradiance and lasing gain require typical current densities in a double heterostructure of 1000 A/cm^2, so with the typical dimensions of a real laser shown to the left, the current needed would be around 1 A, driving the whole chip. In fact it is usual to drive only a narrow stripe, as shown, which typically might cover 1/50 of the chip area, and hence require a current of only about 20 mA, which is much more compatible with modern electronics. In fact with simple narrow stripes as in the schematic below, much of the current spreads out sideways, and a typical operating current is increased to perhaps 40 mA, which is similar to the current required for the CD laser supplied for the experiment. In such a laser, light is emitted from a single small spot at each end of the stripe.



The laser shown below is similar to that supplied for the experiment, with an active layer of $Ga_{1-x}Al_xAs$ (with "x" around 0.1), surrounded by $Ga_{1-y}Al_yAs$ layers (with "y" around 0.45). Lasers for optical communications are usually constructed so as to emit at 1.3 µm or 1.5 µm, in which case the active regions will be $Ga_{1-x}In_xAs_{1-y}P_y$ and the surrounding "cladding" layers will be InP. In this case the two ratios of elements in the active layer (i.e. "x" and "y") have to be carefully controlled so that the atomic spacing is the same as that of InP (This happens automatically with GaAlAs, because Ga and Al are of almost identical size).



Many lasers today are much more sophisticated, employing diffraction gratings for feedback, "quantum wells" as active regions, etc., etc., to give threshold currents less than 10 mA, modulations speeds over 10 GHz and so on. However the basic principles given above still apply.

Appendix B: Introduction to error analysis

B1. Types of error

Most errors can be classified as either *systematic* or *random*.

Random errors cause the spread of points around a straight line or the fact that taking the same reading again may not give the same result. They are often put down to ‘experimental error’, but when designing an experiment, or reporting a result, you should consider the possible sources of random error (and how they might be reduced). Because of their random nature, errors from uncorrelated sources are added in quadrature (it is unlikely that random errors would all be at maximum at the same time).

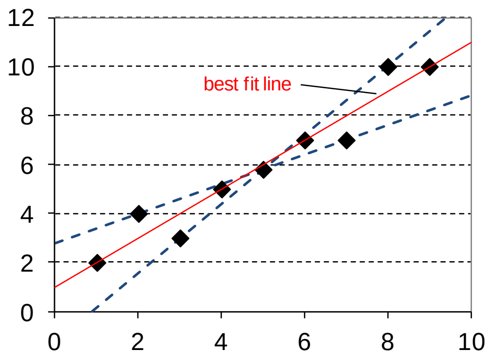
(total random error)^2 = (random error from cause **a**)^2 + (random error from cause **b**)^2 + …

Systematic errors are the same for all readings taken. Examples include the actual resistance of the 20 Ω resistor, which will be the same for all the readings but is unlikely to be exactly 20 Ω, how close it is depending on the manufacturing tolerances (how can you check these ?). You should think very carefully about sources of systematic error as they can be difficult to detect. There are ways of turning systematic errors into random errors which are easier to detect, in the example above using a different resistor of the same specification for each measurement would show up the variation in resistance. This is important if the systematic errors are large, fortunately resistors are typically manufactured to a tolerance of 1-10%. Because they are the same for all measurements systematic errors add linearly.

B2. Estimating random errors from a graph

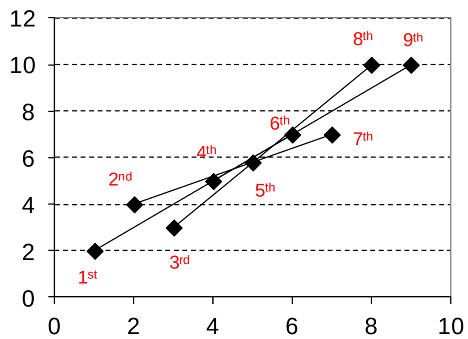
B2.1 Quick estimate

A quick estimate of the random errors can be obtained by drawing lines through the two extremes either side of the best fit. In a normal distribution we would expect 95% of the points to fall within 2 standard deviations either side of the mean. If we approximate the extremes to this 95% value we can get an estimate of the standard deviation by halving this range. This technique is for a quick indication only, and a more precise method should be used when reporting a result.



B2.2 Points in pairs

Pair roughly equally-spaced points as widely spaced as possible. Do not use any point twice as this would give it an unfair weighting. The example of 9 measurements uses the following pairings: 1st and 6th (highlighted), 2nd and 7th, 3rd and 8th, 4th and 9th. If an uneven number of points has been taken it is normal to ignore the middle point. For each pair obtain the gradient and intercept. This gives a series of numbers for the gradient and intercept, from which you can obtain the standard deviations as normal. This technique only works for a linear fit.



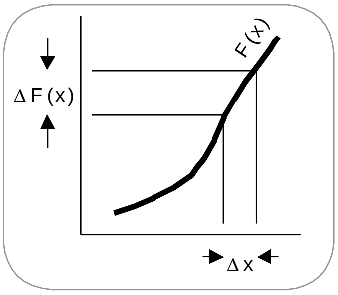
B2.3 Regression analysis

This is the most accurate method, but also the most computationally exhaustive. It is most efficient to use the built-in functions in software packages such as Matlab and Excel. However you should ensure you understand the definitions of these functions, for example the correlation is an indication of how good a fit it is to a straight line, this is not the same as the error in the gradient. Note that when using Excel you may have to install the 'Analysis ToolPak' Add-In to obtain these functions.

B3 Propagation of errors

Having obtained a result, and estimated the error on that result, you may want to use it in a calculation. How big is the error on the result of the calculation? Converting to a percentage will only work if you have a linear dependence. Calculating the result for the two extremes will give the correct result, but will only allow you to deal with the error in a single variable.

If we have a function $F(x)$, where x is the variable we have measured, then we can use the approximation:



$$\frac{\Delta F(x)}{\Delta x} \approx \frac{dF(x)}{dx} \quad \text{to give us} \quad \Delta F(x) = \frac{dF(x)}{dx}\Delta x$$

where Δx and $\Delta F(x)$ are the errors in the variable and function respectively.

If we have more than one variable we can use partial differentiation to give the error (σ_F) in the function $F(xy...z)$, remembering that random errors add in quadrature.

$$\sigma_F^2 = \left(\frac{\partial F}{\partial x}\right)^2 \delta x^2 + \left(\frac{\partial F}{\partial y}\right)^2 \delta y^2 + \ldots + \left(\frac{\partial F}{\partial z}\right)^2 \delta z^2$$

where δx, δy,…,δz are the errors in the respective variables.

For example, the laser current value *I* in the experiment is found using the measured voltage *V* and resistor value *R*: $I = f(V,R) \Rightarrow \Delta I = \sqrt{(\frac{df}{dV}\Delta V)^2 + (\frac{df}{dR}\Delta R)^2}$

B4. Quoting errors

When quoting a result you should not quote it beyond the level of the error e.g. 4.3±0.2 or 4.35±0.21 are correct but 4.356±0.2 is incorrect. In most simple cases the error itself should be quoted to one or at most two significant figures.

$$\Delta\sigma = \frac{\sigma}{\sqrt{2N-2}}$$

We can calculate the uncertainty in the error ($\Delta\sigma$) if we assume a normal distribution (see left), σ is the standard deviation and N is the number of samples or measurements. This means that taking 9 measurements gives an uncertainty in the error of 25%, and ~10% when taking 50 measurements. This is the reason errors are quoted to one or at most two sig. figs.

Figures you are given to work with will in fact rarely include estimates of the error. In such cases it is usually implicit that the error is smaller than the least significant digit. For example if the length table is specified as 1912 ± 1 mm. If the error were any greater the table should really have been specified as 1910 mm long, because specifying the length (or any value) to a greater precision than the error allows is not meaningful.