LNMIIT

The LNM Institute of
Information Technology

PHYSICS LABORATORY MANUAL

For Undergraduates
2013-14

The LNM Institute of Information Technology
Rupa ki Nangal, Post-Sumel, Via-Jamdoli,
Jaipur - 302031, Rajasthan, India

Laboratory Regulations

1. You should arrive punctually.

2. Mobiles must be switched off.

3. Experiments will be performed in pairs. Stay with the same person throughout the semester, otherwise problem will arise in allocating you experiments.

4. Attendance is compulsory. Absence for some reasons should be notified in advance to the instructor.

5. You are required to record your observations in a hardback laboratory notebook. Each student will maintain his/her laboratory notebook. You must get at least one observation of each kind checked and signed by your instructor.

6. You must complete all experimental work during the three hours session. Every observation made must be recorded directly on the laboratory notebook. No rough record is allowed.

7. You are required to submit the complete report in your next laboratory session.

Contents

A. Measurement & Instruments

This section of the manual describes the basic measurements and allied instruments that you will encounter in the laboratory.

Physical Measurements

In the grouping of physical measurements the quantities to be measured are length, mass, angle and time.

Length

There are three basic instruments for the measurement of length, (i) the meter ruler, (ii) the micrometer screw gauge and (iii) the vernier calipers. The table below details the range and accuracy of these three instruments.

Name	Range	Accuracy
Meter Ruler	0–100cm	1mm
Micrometer Screw Gauge	0–25mm	0.01mm
Vernier Calipers	0–150mm	0.02mm

Clearly, there is a wide variation in the range of the instruments and the first lesson is that the choice of instrument is determined by the length that is to be measured. If the length is $50cm$, then it clearly should be the Metre Ruler. The second lesson concerns the accuracy. In principle, you can measure a length of $2cm$ with all three instruments but the accuracy of your measurement will vary from $1mm$ to $0.01mm$. The choice, then, is also determined by the accuracy required. The accuracy of an instrument depends on its construction & operation and this is now described for each instrument

Meter ruler: The principle of the metre ruler is very simple. A known length (1 metre) is divided into 100 unit lengths of $1cm$. and these are further subdivided into 10 unit lengths of $1mm$. The accuracy of the instrument is the smallest division, namely $1mm$.

  Operation: Place one end of the ruler (or an appropriate 'zero') at one end of the length to be measured and read off the nearest value at the other end of the length to be measured.

Micrometer screw gauge: The principle of the micrometer is the screw thread. The pitch of the screw is $0.5mm$. that is one complete rotation of the screw advances or retracts the screw by $0.5mm$. Underneath the rotating barrel of the gauge is a ruler with $0.5mm$ divisions (actually two sets of $1mm$ divisions offset by $0.5mm$). The rotating barrel is itself subdivided into 50 units, such that rotation of the barrel through one unit advances or retracts the screw by $0.5/50 = 0.01mm$; the accuracy of the instrument is therefore $0.01mm$.

Operation: Place the object between the fixed and moving end faces and rotate the barrel until the object is in contact with both end faces. **Always rotate using the small slip knob at the end of the barrel.** This will ensure contact without damage to the object or the micrometer. The measured length is the reading on the ruler to the nearest full $0.5mm$ unit **plus** the portion of this unit shown on the rotating barrel. *Always check the visible zero setting and all for any offset from zero.*

Vernier calipers: The principle of the Vernier calipers is two-fold. First, the sliding piece allows the jaws to contact the sides of the object to be measured, in much the same way as the micrometer. The distance moved by the sliding jaw is then read off the fixed ruler on the main body of the instrument. The accuracy of that ruler as such, however, is only $1mm$. The much improved accuracy is provided by the 'Vernier' scale. This scale is marked on the sliding jaw; it has 10 divisions, each subdivided into 5, ie a total of 50 subdivisions. These subdivisions look like $1mm$ in length. But if you compare the fixed and Vernier scales, you will see that the 50 subdivisions on the Vernier scale correspond to 49 subdivisions (each of $1mm$) on the fixed scale! This is not a mistake but rather it is deliberately designed so that a subdivision on the Vernier scale is smaller than that on the fixed scale by $1/50 = 0.02mm$; this is the accuracy of the instrument. How a reading with this accuracy is achieved in practice is detailed below:

Operation: With **no** object between the jaws, the zeros of the Vernier and fixed scales are coincident. There is an increasing mismatch between the marks of these two scales until at the end of the Vernier scale there is again coincidence between the end mark on the Vernier and the $49mm$ mark on the fixed scale. Clearly, to obtain coincidence between the first subdivisions of the Vernier and of the fixed scales it would be necessary to move the sliding jaw by the deficit of $0.02mm$; coincidence between the second subdivisions would require 2 x $0.02 = 0.04mm$, and so on. A total of 50 x $0.02 = 1mm$ is required to achieve coincidence between the end mark of the Vernier scale and the $50mm$ mark of the fixed scale. Conversely, a measurement of the length of an object in contact with the jaws is the reading to the nearest full mm on the fixed scale at the Vernier zero PLUS the reading (in units of $0.02mm$) on the Vernier scale **where there is coincidence between the vernier and fixed scales.**

Other vernier instruments: There are three other instruments in the laboratory which incorporate Vernier scales. These are the travelling microscope, the weighing scales and the spectrometer. The travelling microscope combines magnified optical positioning with a ruler accuracy of $0.01mm$.

For the other two instruments some other parameter has been equated with a length scale.

In the case of the weighing scales, mass can be equated with the length of the balance arm that is divided into 10 units of $10g$. The rotating scale adds up to a further $10g$ with an accuracy of $0.1g$ and the Vernier scale accuracy is $0.01g$.

In the case of the spectrometer, angle can be equated with the length of a circular scale that has an accuracy of 0.5 degree. The Vernier scale is in the natural sub-unit of *minutes of arc* (60 minutes of arc = 1 degree) and the accuracy is one minute of arc (1').

Time

The stop-clock has a start/stop/reset push-button device with a digital display. In principle, the accuracy is the smallest digit, ie $0.01s$, but the response time of the button is of the order of $0.1s$ and that of the user may be significantly longer, say, of the order of $1s$. Timing accuracy is further discussed later in the section Accuracy & Uncertainty.

Electrical Measurements

In the grouping of electrical measurements, the principal instruments are the multimeter, oscilloscope, function generator and the power supply.

Multimeter

The multimeter provides conveniently in a single instrument a number of ranges of measurement of voltage (DC/AC), current and resistance. It is necessary to select the appropriate quantity and range as well as the proper connections for the two input leads. *The AC ranges are distinguished from the DC ranges by the symbol ($\sim$).*

Voltage: The voltage ranges are marked V. The two input sockets are marked COM and V, Ω.

Voltage is measured *across* a component, that is, the meter is connected *in parallel* with the component. *The meter displays the polarity of the voltage relative to the COM connection.*

Current: The current ranges are marked A. The two input sockets are marked COM and either A or $10A$, depending on the magnitude to be measured; the A connection is protected by a $2amp$ fuse and is only to be used for currents less than this limit. The $10A$ connection is protected by a $10amp$ fuse, and is only to be used for currents up to this limit. *This latter connection only works with the current range marked 10.*

Current is measured *through* a component, that is the meter is connected *in series* with the component. *The meter displays the polarity of the current entering the A (or 10A) socket.*

Resistance: The resistance ranges are marked Ω. The two input sockets are marked COM and V, Ω.

Resistance is measured *across* a component, that is, the meter is connected *in parallel* with the component. There is no polarity associated with this measurement.

It is important to realize that resistance measurement is really the measurement of the voltage resulting from a current supplied by the meter. *Therefore, this mode of resistance measurement cannot be carried out on components while they are in circuit.*

Range & display: The maximum display of 1999 corresponds to the end of the range selected. For example, selecting the voltage range marked 2 allows a measurement of voltage up to 1.999 volts. The next voltage range is marked 20. This range is appropriate for voltage between 2 and 20 volts.

The accuracy of the measurement is the least significant digit (note how this digit may arbitrarily change up or down by one unit during the reading). *The best practice is to use the range which is one setting above that at which the full 1999 shows.*

Oscilloscope, function generator & power supply

The oscilloscope is probably the most important of all electronic measuring equipment. Its main use is to display on a screen the variation or a potential difference (or voltage) as, a function of time. The result is a graph with voltage on the vertical (or y) axis and time along the horizontal (or x) axis. This is achieved by electrostatic deflection of an electron beam striking the front face phosphor in the cathode ray tube in the oscilloscope.

You will learn about oscilloscope, function generator and power supply in your electronics laboratory.

Plotting graphs

A graph is useful way of displaying the results of an experiment in which one parameter (call it x) is varied in well defined steps and another parameter (call it y) is measured in response. In this general case each (x, y) pair of values is represented by a point which is a distance x along the horizontal axis and a distance y along the vertical axis. For example, if the following data were obtained for the resistance of varying lengths of wire:

L (m)	1	2	3	4
R (Ω)	10	20	30	40

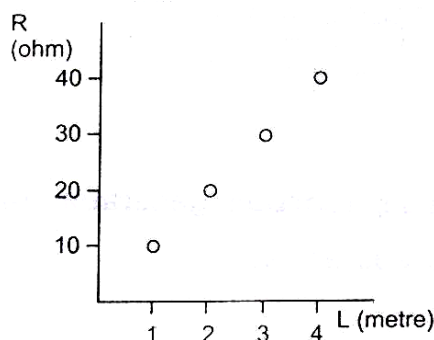The data would be graphed as shown below:

Figure 1: Resistance (R) vs Length (L)

Note the title, the labeled axes (with units!). These elements are essential for any graph! The usefulness of this particular graph is that it is clear at a glance that the resistance of the wire is proportional to its length. This is formally shown in the graph below where the data fall on a straight line through the origin.

Mathematically, this linear relation is expressed by the equation $y = mx$, where m is the slope. The slope of the straight line is obtained by constructing a right-angle triangle containing the straight line and lines parallel to the vertical and horizontal axes; the slope is the ratio of the lengths of the vertical and horizontal sides (shown dashed below). Note that for good accuracy the complete range of plotted data should be used.
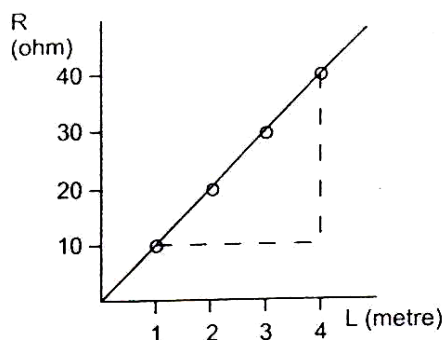
Figure 2: Resistance (R) vs Length (L) showing slope

In this particular example the slope is $(40\text{-}10)/(4\text{-}1) = 30/3 = 10$.
The resistance per unit length of the wire is 10 ohm per metre or simply $10\Omega m^{-1}$. (In shorthand R$(\Omega)=10\Omega m^{-1}$L(m).

This trivial example has been used to introduce you to the basics of graph plotting. Only rarely will your experimental data be in this ready-to-graph form. For example,

consider the following measurements of the resistance versus the temperature of a fixed length of the wire:

T (^oC)	100	200	300	400
R (Ω)	34	36	38	40

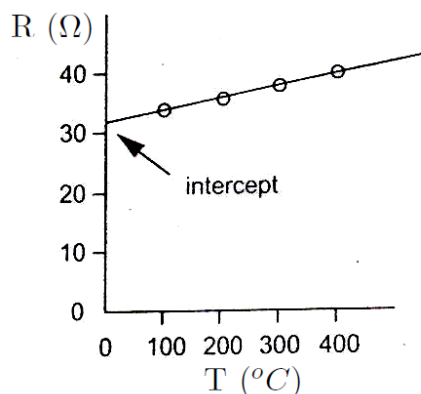The data could be plotted as shown in Fig. 3. This time, the straight line does not

Figure 3: Resistance (R) vs Temperature (T)

go through the origin and the mathematical expression is $y = mx + C$, where C is the intercept on the y axis. In this case the intercept, C is 32Ω and the slope, m is $2\Omega^oC^{-1}$. We can therefore write $R(\Omega) = 2(\Omega^oC^{-1})T(^oC) + 32\Omega$.

This example also illustrates an important value judgment about the axes of a graph. As drawn above most of the graph page is wasted. A better graph (and a more accurate one) is shown in figure on next page. The origin is now the point (30, 0) rather than (0,
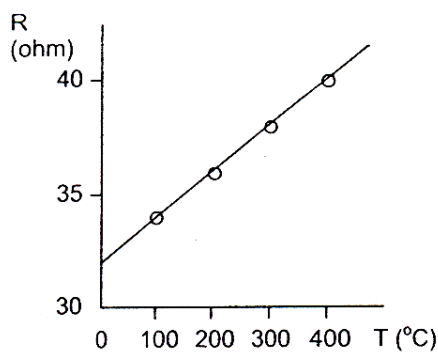

Figure 4: Resistance (R) vs Temperature (T)

0) and the labeling must show that clearly! Clearly the choice is dictated by whether the intercept is to be determined. Also, the intercept of interest may be on the horizontal (or x) axis. These considerations apart, you should always aim to use the full size of the available graph page.

What to do with a system which is not in linear form? A good example is the relation between period (T) of a simple pendulum and its length (L). These are related by the expression . When we plot a graph of T vs L we get a curve. But if we plot a graph of T^2 vs L, we should get a straight line of the form $y = mx$. That is, we re-write the expression in the form of a straight line as $T^2 = (4\pi^2/g)L$. In this way it is clear if our data matches the theory. Moreover, from the measurement of the slope m we obtain a value of $g = 4\pi^2/m$.

Finally, it is useful to start thinking of a graph as a way of *averaging* your data and this concept will be fully discussed in the next section on Accuracy and Uncertainty.

Accuracy and uncertainty (and errors!)

A physical measurement is never exact. Its accuracy is always limited by the nature of the apparatus used, the skill of the person using it and other factors. The best we can do is report a range of values, so there remains some uncertainty. So typically we may write: *The velocity of the ball was found to be* $5.13 \pm 0.02 ms^{-1}$. *This defines the range 5.11 to 5.15.*

The end points of the range can rarely be assigned with much precision (in this laboratory, at least), so if a calculated estimate of the uncertainty were to give us 0.018732 in the above, we would make it 0.02, retaining just a single significant figure. We must also trim the digits of the main (central) value to the same point so that 5.128765 become 5.13 in the stated result.

The three rules for a measured (or calculated) value are:

- Include the uncertainty estimate to one significant figure.

- Trim the digits of the value to the same significant figure.

- Don't forget the units.

How do we estimate uncertainty? In the case of most* individual measurements it arises naturally from the fact that the instrument has a printed scale (*special cases are discussed later!). A reasonable estimate of the uncertainty is plus-or-minus half the interval of the scale, if you use it straightforwardly. In the case of modern instruments with an electronic display, there may be a stated limit to the accuracy. In some such cases, if you try to read out more digits the ones at the end will fluctuate, telling you they are unreliable.

To keep things simple it is recommended that you use plus-or-minus the smallest interval of the scale.

But this is the start of a long story of statistics, to which we will pay little attention now. We will use our common sense and some very elementary mathematics. The mathematical rules follow in a separate section. Remember they are intended for rough-and-ready estimates–don't labour over enormous calculations – use short cuts and mental arithmetic whenever you can. If the person on the next bench gets ± 0.2 and you get ± 0.3, it's unlikely to matter at all. Do it quickly.

FAQ on uncertainty and errors

1. ***Isn't uncertainty called error?***
   Yes, it often is, alas. In fact it's quite traditional. The unfortunate thing is that it makes uncertainty sound like a mistake.

2. ***But don't we make mistakes?***
   We all do. These will give rise to data points that don't fit into the overall pattern, and can be checked and replaced. That's one reason why we take sets of measurements and fit them to some sort of theory.

3. ***But suppose I keep making the same error, such as using an instrument whose zero has not been set properly, or the wrong units?***
   Yes, we are all human. That would be called s systematic error. We've been talking about random errors or uncertainty here. A systematic error is something you usually don't know about, so you cannot state it! If you can, you should be able to eliminate it.

4. ***How can I detect a systematic error?***
   If experiment does not conform to theoretical expectations, one or the other needs to be improved. In the case of the experiment, search for systematic errors. This dialogue between theory and experiment is how both progress and reliable measurement techniques are developed.

5. ***How do I combine the errors from individual measurements?***
   There are basic rules for this as outlined below.

Combining errors of indivual measurements

If the measured values of A and B have certain uncertainties, what are the consequent uncertainties of AB, $A + B$ and $\sin(A + B)$?

For many, this is the hard part of the subject, but it boils down to a few simple rules and procedures. It is much less painful if you remember precise calculations with rough estimates make little or no sense. Feel free to take short cuts by making rough-and-ready approximations as you go along, in order to arrive quickly at an estimate of the final error.

Rules: Here we shall indicate the uncertainty of A by ΔA. That is, the measured range is $A + \Delta A$.

Rule 1: For addition (or subtraction) **add** the uncertainties.

> If $C = A + B$, or $C = A - B$, then $\Delta C = \Delta A + \Delta B$.
> Example: $A = 50 \pm 1, B = 20 \pm 2$, then $A + B = 70 \pm 3$ and $A - B = 30 \pm 3$

Rule 2: For multiplication (or division) **add** the relative uncertainties to get the relative uncertainty of the final quantity.

> If $C = A \times B$, or $C = A/B$, then $\Delta C/C = \Delta A/A + \Delta B/B$. Having found this fraction, simply multiply by C to get ΔC!
> Example: $A = 50 \pm 1, B = 20 \pm 2$. For $C = AB, C = 1000 \pm 120$. for $C = A/B, C = 2.5 \pm 0.3$

Note that, in particular, If $C = 1/A$, then $\Delta C/C = \Delta A/A$.

Rule 3: Dealing with functions.

There are two ways of dealing with functions, such as $C = \sin(A)$ or $C = \exp(A)$. One can express the uncertainty in terms of the derivative of the function. Perhaps you can see the logic of this. But a more straight forward approach, which should almost always work, is as follows.

Work out the values of the function for $A + \Delta A$ and $A - \Delta A$, and take these to define the range of values of the function C.

All of these rules can easily be justified by elementary mathematics, *provided that the relative uncertainties are small.*

Four special cases:

1. ***Judgement errors***
   These arise in cases where the experimenter has to make a judgement about when some condition is fulfilled in location or in time. Once the location or time is fixed it can be measured to a certain accuracy or error. However, this error may be much

less than the error associated with the judgement. A good example is the location of the viewing screen in the experiment on the convex lens. The experimenter has to make the judgement when the image on the screen is *in focus* and the error in position associated with this judgement may be much larger than the measurement error of the emphfinal position. The real error has to be estimated by gauging the range of position over which the image appears to be still *in focus.*

2. ***Improving the timing error in a periodic system***
   The error associated with a single measurement can be dramatically reduced by measuring the combination of many identical units. A good example of this is the measurement of the period of a pendulum. Suppose the measurement of a single swing is $20 \pm 1s$ (where the error of 1 includes the judgement error of when the swing starts and ends). The total time for 10 swings of the pendulum might be $195s$ but the error in this measurement would still be $1s$. The period would be $(195 \pm 1)/10$ or $19.5 \pm 0.1s$. The latter is a more accurate result.

3. ***Improving the count rate error in a "random emission" system***
   Radioactive emission is random in time. This means that repeated measurement of the emission, usually called *the count* in fixed periods of time shows a range of values (or error) which is related to the size of the count. The mathematics behind this is quite complex but the result is very simple: *The error in the count is the square root of the count!* For example, if the count is 100, the error is $\sqrt{100} = 10$, answer 100 ± 10. Now, suppose this count is taken in a time of $1s$. Ignoring any error in the time, the count rate (as opposed to the count) is clearly $100 \pm 10s^{-1}$. However, counting for the longer time of 10 s might yield a total count of 1020; the associated error is $\sqrt{1020} = 32$, i.e. the total count is 1020 ± 32. The count rate is $(1020 \pm 32)/10 = 102 \pm 3$. The latter is a more accurate result!

4. ***Average values of non-uniform parameter***
   Suppose you need to measure the diameter of a ball. A single measurement will yield a value and associated error. However, a physical ball is not a perfect sphere and a measurement of diameter at another orientation may yield a different result. The more useful value of diameter is the average value estimated from a number of measurements. Suppose the following measurements are taken of the diameter:

25 ± 1	23 ± 1	28 ± 1	22 ± 1	24 ± 1	23 ± 1

   The average value is clearly $(25 + 23 + 28 + 22 + 24 + 23)/6 = 145/6 = 24.17$ but what is the error? This question brings us into the area of statistics and there is no easy answer to this other than a full statistical analysis. *One thing is certain: the error in the average is NOT the average of the errors!*

We recommend the following approximate method:

First, examine which is greater, the range of values or the error in any individual, value. In the unlikely event that it is the latter then this is the error in the average! More likely, the range of values is greater, as is the case here; the values range from 22 to 28, a range of 6. A crude estimate of the error is therefore ± 3. However, if you think about it, increasing the number of measurements will only increase this estimate of error, whereas the reverse would be the case in a proper statistical analysis. Visual inception of the data above shows that 5 out of the 6 values lie within the range 24 ± 2 and this is a more reasonable answer. ***When you encounter this type of error in an average, it is sufficient to make a rough estimate along these lines!***

B. Error bars on graphs

Whenever you enter data as a data point on a graph, the uncertainty in one or other of the x and y values can be indicated by error bars, which show the range of values for that parameter at each data point. This is helpful in judging by eye whether the data is consistent with some theory, or whether some particular measurement should be repeated.

This applies to graphs drawn by hand or by computer. In practice, it may be simplified in many cases. For example, if the relative uncertainty in x is much less that that in y– or vice-versa – it is not worth representing the smaller error bar on the graph or it might be that the uncertainty is too small to be visible, in that case there should be a statement on the graph to that effect.

Consider the following modified data set for the resistance versus the temperature of a fixed length of the wire:

T(^{o}C)	100 ± 1	200 ± 1	300 ± 1	400 ± 1
R (Ω)	34 ± 1	37 ± 1	38 ± 1	41 ± 1

When the bare data is graphed as shown in Fig 5(a) it is not possible to link the points with a straight line. However, when error bars are included for the R values (the error in T is much smaller) then it is possible to put a straight line through the error bars, as shown in Fig 5(b). These data now verify the linear relation. The remaining question is

(a)   (b)
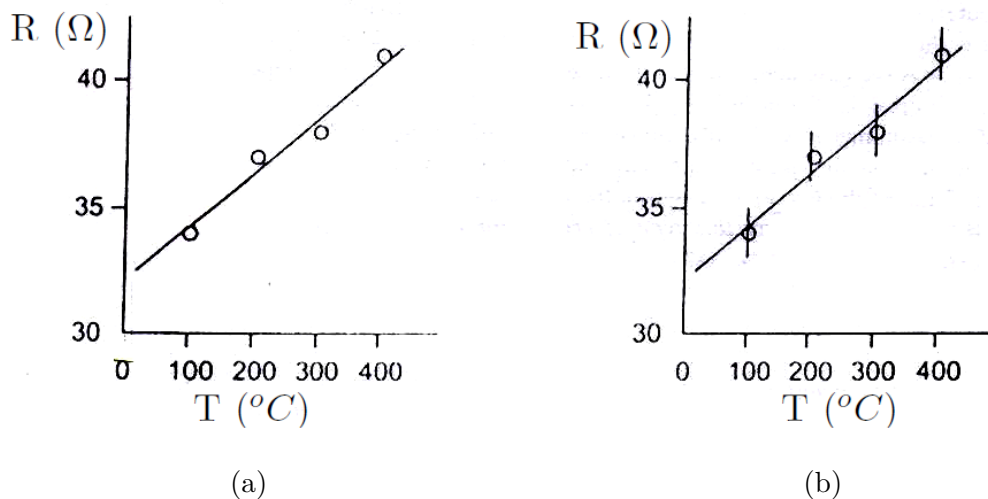
Figure 5: Resistance (R) vs Temperature (T) (a) without error bars and (b) with error bars

which straight line? It is clear that there is a smaller but finite range of lines of different slope which pass through the error bars. This is important if the slope is used to derive some parameter, e. g. a value of g in the pendulum experiment.

The slope then becomes $m \pm \Delta m$. Again, this is another example of the error associated with an average, as discussed above. Again too, it is difficult to be exact about this.

C. A comment of significant digits

In many cases the uncertainty of a number is not stated explicitly. Instead, the uncertainty is indicated by the number of meaningful digits, or significant figures, in the measured value. If we give the thickness of the cover of this booklet as $3.94mm$ which has three significant figures. By this we mean that the first two digits are known to be correct, while the third digit is in the hundredths place, so the uncertainty is about $0.01mm$. Two values with the same number of significant figures may have different uncertainty, a distance given as 253km also has three significant figures, but the uncertainty is about $1km$. When you use the numbers having uncertainties to compute other numbers, the computed numbers are also uncertain.

Suppose you measured the mass of a rock to be 8.2 grams and its volume to be 2.3 cm^3. How accurately can you determine its density?

Mass measured to 2 significant digits

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{8.2 \text{ gm}}{2.3 \text{ cm}^3} = 3.56521739 \frac{\text{gm}}{\text{cm}^3}$$

Volume measured to 2 significant digits

What's wrong with this calculation?

Not science, but fiction!

Maybe this doesn't look as impressive, but it is a better answer.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{8.2 \text{ gm}}{2.3 \text{ cm}^3} = 3.57 \frac{\text{gm}}{\text{cm}^3}$$

No fictional digits - - well, maybe the 7 is stretching it. It is reasonable to carry an extra digit or two in intermediate calculations.

$$\text{Density} = 3.6 \frac{\text{gm}}{\text{cm}^3}$$

It is better to keep only the number of digits of your weakest measurement for your final answer.

When we add and subtract numbers, it is the location of the decimal point that matters, not the number of significant figures. For example $123.62 + 8.9 = 132.5$.

Although 123.62 has an uncertainty of about 0.01 and 8.9 has an uncertainty of about 0.1, so their sum has an uncertainty of about 0.1 and should be written as 132.5 and not 132.52.

Exercise:

1. State the number of significant figures:

   (a) 0.43
   (b) 2.42×10^2
   (c) 6.467×10^{-3}
   (d) 0.029

(e) 0.0003

2. A rectangular piece of iron is $(3.70\pm0.01)cm$ long and $(2.30\pm0.01)cm$ wide. Calculate the area.

3. Mass of the planet Saturn is $5.69 \times 10^{26}kg$ and its radius is $6.6 \times 10^{7}m$. Calculate its density.

4. Estimate the percent error in measuring

   (a) A distance of about $56cm$ with a meter stick.

   (b) mass of about $16g$ with a chemical balance.

   (c) A time interval of about 4 min with a stop watch.

5. $3.1416 \times 2.34 \times 0.58 =$

6. $2.56 + 16.4329 =$

7. $16.4329 - 2.56 =$

Experiment 1

Introduction to Error Analysis and Graph Drawing

1.1 Mass Spring System

A spring (of mass $50\,g$) is suspended vertically. It is pulled slightly downward and time for 20 free oscillations is observed. Repeat the observations for three times. Calculate the average time period of this spring system. Now, using the equation, given below, calculate the force constant k of the spring, to two decimal places.

$$T = 2\pi \sqrt{\frac{m_o + (m_s/3)}{k}} \tag{1.1}$$

where m_o is mass of weight hanged and m_s is the mass of the spring.

Observation table

Sl.	T_{20} (sec)	Mean T_{20} (sec)	T (sec)	k (N/m)
1				
2				
3				

Table 1.1: Table to calculate the spring constant of a spring.

From the Eq. (1.1) the error in calculating k is obtained as follows. If $m_0 = 0$, then squaring Eq. (1.1) and re-arranging the terms we have,

$$k = \frac{4\pi^2}{3}\left(\frac{m_s}{T^2}\right)$$

Taking log on both sides,

$$\log k = \log\left(\frac{4\pi^2}{3}\right) + \log m_s - 2\log T$$

Taking derivative on both sides,

$$\frac{\Delta k}{k} = \frac{\Delta m_s}{m_s} + 2\left(\frac{\Delta T}{T}\right) \tag{1.2}$$

where we have changed the sign of in front of ΔT to calculate the maximum error.

1.2 Resistivity of a of nichrome wire

A homogeneous nichrome wire along with a digitial multimeter and a screw gauge is given to you.

1. Measure the resistance of the nichrome wire for three different lengths of the wire.

2. Use the screw gauge to determine the diameter of the wire.

3. Determine resistivity of the nichrome wire from your measurements using the formula

$$\rho = \frac{R\pi d^2/4}{L}, \tag{1.3}$$

$$\text{where,} \quad R = \text{resistance of the nichrome wire,}$$
$$d = \text{diameter of the nichrome wire,}$$
$$L = \text{length of the nichrome wire.} \tag{1.4}$$

4. From Eq. (1.3) derive an equation for $\Delta\rho/\rho$ and finally obtain $\Delta\rho$ for this experiment.

Observation table

Total number of circular scale (CS) divisions of the screw gauge = ...
One main scale division (MSD) = ... cm
Number of rotations required on the CS to cover 1 MSD = ...
Zero error on the CS = ...
Least count (l.c) of the screw gauge

$$l.c = \frac{\text{One main scale division (1MSD)}}{\text{No. of rotations on the CS} \times \text{Total number of CS divisions}} \, cm \tag{1.5}$$

Sl. No.	MSR (a)	CSR (b)	Total $(a + b \times l.c)$ (cm)
1			
2			
3			

Table 1.2: Table to calculate the diameter of the nichrome wire

Sl.	$L\,(cm)$	Resistance (Ω)	$\rho\,(\Omega.m)$
1			
2			
3			

Table 1.3: Table to calculate the resistivity of the wire

1.3   Finding τ and initial voltage across capacitor

You are given below the voltage decay as function of time across a capacitor in a *RC* circuit.

1. Obtain the value of characteristic decay time constant by plotting the data in a semi–logarithmic paper.

2. Obtain the initial value of the voltage across the capacitor.

Time (s)	Voltage (V)
6.2	5.53
8.7	4.89
10.0	4.58
12.5	4.04
16.3	3.35
18.4	3.05
22.5	2.45
25.0	2.16
28.5	1.85
32.9	1.44
38.8	1.09
42.0	0.92
47.8	0.70
52.0	0.56
55.4	0.47
62.5	0.33
67.2	0.26

Table 1.4: Data of voltage decay in a capacitor as a function of time.

The equation governing the relation between voltage and time for the capacitor is as given below.

$$v = v_o e^{-t/\tau} \tag{1.6}$$

$$\log v = \log v_o - \log e^{t/\tau} \tag{1.7}$$

$$\log v = \log v_o - \frac{t}{\tau} \log e \tag{1.8}$$

From $\log_{10} v$ vs t plot, the value of τ can be obtained.

1.4   Resonant Rings

In an experiment, paper rings of different diameter are mounted on a vibrating table to study their resonant frequencies. Depending on the diameter, the rings show resonant vibration for different frequencies of the vibrating table. The data from this experiment is given in Table 1.5. Use the formula $F = CD^n$.

Diameter of the ring (cm)	3.4	4.6	6.4	8.7	10.9	13.2
Resonant frequency (Hz)	63.48	30.77	13.38	6.24	3.58	2.19

Table 1.5: Data of resonant frequencies as a function of diameter of the rings

1. Plot resonant frequency vs diameter of the ring in a log-log graph to obtain the mathematical relationship between the two variables.

2. From your graph predict the resonant frequency for a ring of diameter $16\,cm$.

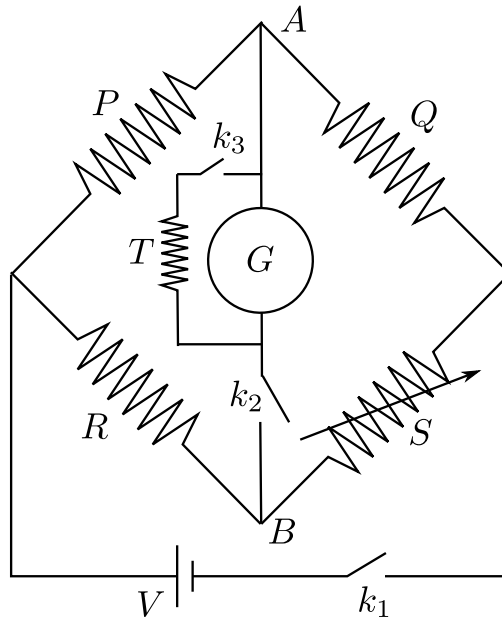## 1.5   To measure the electrical resistance of a given material

Figure 1.1: A wheatstone bridge.

The resistance of the wire is measured with the help of a wheatstone bridge up to the accuracy of three significant figures. By using the relation.

$$\frac{P}{Q} = \frac{R}{S} \tag{1.9}$$

where S is a variable resistor and R is an unknown resistor. If the ratio of the two known resistances P/Q is equal to the ratio of the two unknown resistances R/S, then the voltage difference between the points A and B will be zero and no current would flow through the galvanometer G. In case there is a voltage difference between points A and B, direction of the current in the galvanometer indicates the direction of flow of current through the bridge. In this manager an unknown resistance R can be calculated to an accuracy of high degree.

Fig. 1.2 shows the experimental setup of a wheatstone bridge.

Figure 1.2: A wheatstone bridge setup.

Observation table

Sl. No.	1000 (Ω) (a)	100 (Ω) (b)	10 (Ω) (c)	1 (Ω) (d)	Multiplier (m)	R (Ω)
1					1	
2					0.1	
3					0.01	
4					0.001	

where $R = m \times (a \times 1000 + b \times 100 + c \times 10 + d \times 1)\,\Omega$.

Experiment 2

Gyroscope and Moment of Inertia of a Wheel

A. <u>Gyroscope</u>

Purpose

To find the moment of inertia of gyroscope by measuring the precession frequency as a function of spin frequency of gyroscope.

Apparatus

Gyroscope, tachometer, stopwatch, weights.

Theory

Gyroscopes are used in compasses, in the steering mechanism of torpedoes and in inertial guidance systems. The objective is to find the moment of inertia of the gyroscope by measuring the precession frequency, as a function of the spin frequency of the gyroscope. The gyroscope that is free to rotate about all the three axes is balanced in horizontal position with the help of a counter weight C as shown in Fig. 2.1. As soon as a small weight is added on the left hand side of counter weight C, the gyroscope rotates counterclockwise and destabilizes (falls down). Remove the extra small weight, balance it again as before and spin the disk of the gyroscope with some angular velocity. Now hang the small weight again on the left hand side as before. The gyroscope now shows a completely new behavior and starts rotating in a direction perpendicular to the previous plane. This movement is known as precession. That is how a gyroscope increases the stability of a system. Try to explain this behavior using laws of mechanics. Can you cite some example from our everyday life where you see actual demonstration of this gyroscopic phenomenon?

If I is the moment of inertia of the gyroscope about its symmetric axis, the angular momentum $\vec{L}$ is given by,

$$\vec{L} = I\vec{\omega}_g \tag{2.1}$$

where $\vec{\omega}_g$ is the angular velocity of the spinning gyroscope. Now, the addition of an additional weight m, at a distance r from the support point O, introduces a supplementary torque $\vec{\tau}$

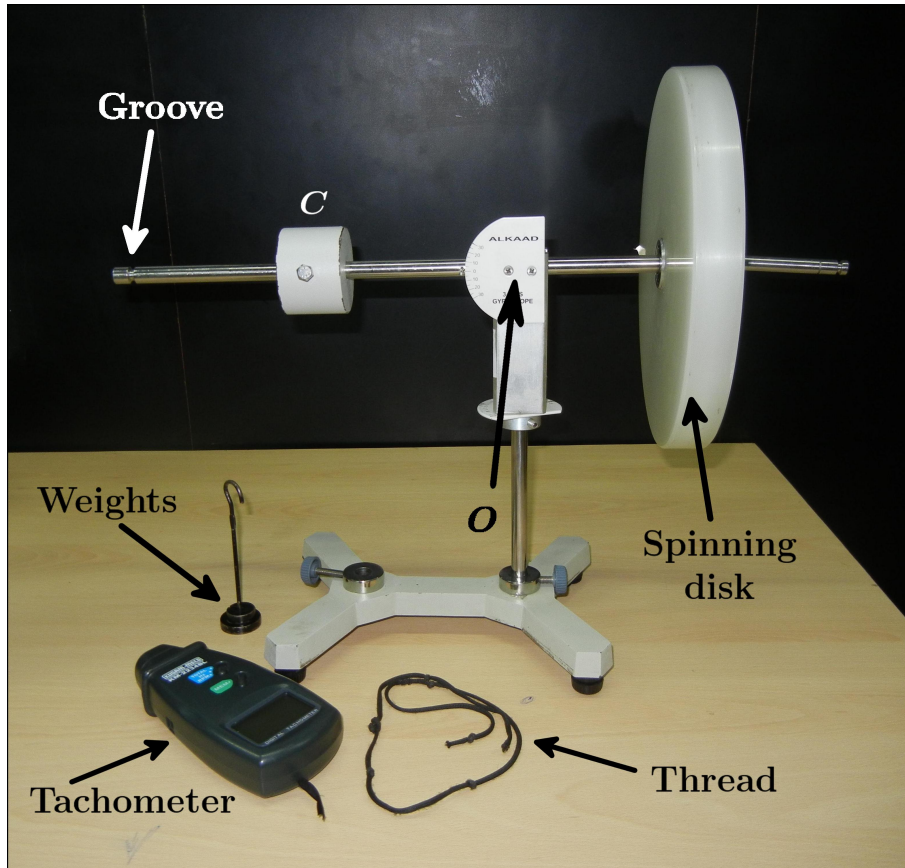$$|\vec{\tau}| = mgr = \left|\frac{d\vec{L}}{dt}\right| \tag{2.2}$$

Figure 2.1: Gyroscope setup

The gyroscope now starts précising with frequency ω_p under the influence of $\vec{\tau}$. Since $\vec{\tau}$ is perpendicular to $\vec{L}$ its effect is to change the direction of $\vec{L}$. In a time dt, $\vec{L}$ will rotate by $d\phi$, given by

$$\left| d\vec{L} \right| = |\vec{L}| d\phi \tag{2.3}$$

$$\omega_p = \frac{d\phi}{dt} = \frac{1}{|\vec{L}|} \left| \frac{d\vec{L}}{dt} \right| = \frac{1}{I\omega_g} \left| \frac{d\vec{L}}{dt} \right| = \frac{mgr}{I\omega_g} \tag{2.4}$$

where we have used Eqns. 2.1, 2.2 and 2.3. If T_p is the time for one precession revolution and T is the time taken by the gyroscope to spin about its axis (one rotation) then

$$\omega_g = \frac{2\pi}{T_g} , \tag{2.5}$$

$$\omega_p = \frac{2\pi}{T_p} , \tag{2.6}$$

Therefore from Eqn. 2.4,

$$\frac{1}{T_g} = \left(\frac{mgr}{4\pi^2 I} \right) T_p . \tag{2.7}$$

Thus a plot of $1/T_g$ vs T_p should yield a straight line for a fixed m, from which the moment of inertia I of the gyroscope, can be obtained.

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Procedure

Balance the gyroscope horizontally, using the counterweight C, without any weight m.

1. Give a spin to the horizontal balanced gyroscope and measure the time (T_g) required to complete one revolution using the given light barrier counter.

2. Immediately after this, hand a mass m into the groove at the longer end of the gyroscope. This is at a distance $r = 27cm$. The gyroscope will precess. Using the stop watch, measure the duration of half the rotation $T_p/2$.

3. Without any delay, remove the mass m, so that gyroscope stops processing, and measure T_g again, using the light barrier counter.

4. The average of T_g measured in steps (1) and (3) above is to be used in Eq. (2.7).

5. Repeat for several different initial spins of the gyroscope and fixed m and plot $1/T_g$ vs T_p and find the slope. Find I using Eq. (2.7).

6. Find I for another value of m.

Observation

For mass $m = \ldots\ldots$ gm.

Sl. No.	ω_{g1} (rpm)	ω_{g2} (rpm)	Mean ω_{gr} (rpm)	ω_g (rad/ sec)	T_g (sec)	$1/T_g$ (sec^{-1})	$T_p/2$ (sec)	T_p (sec)
1								
2								
3								
4								
5								

$$\text{where,} \qquad \omega_{gr} = \frac{(\omega_{g1} + \omega_{g2})}{2} \tag{2.8}$$

$$\omega_g = 2\pi \left(\frac{\omega_{gr}}{60} \right) \tag{2.9}$$

$$T_g = \frac{2\pi}{\omega_g} \tag{2.10}$$

Repeat your observations for another mass.

Calculation

Plot a graph of $1/T_g$ vs T_p for both masses on the same graph paper using the same axes. The graphs should be a straight line passing through origin. Find the slope (s) and calculate the moment of inertia of the gyroscope from the obtained slope values.

$$I = \frac{mgr}{4\pi^2 s} \tag{2.11}$$

Result

Moment of inertia of the gyroscope

1. For mass $m_1 = \ldots\ldots\ldots$ kg m^2.

2. For mass $m_2 = \ldots\ldots\ldots$ kg m^2.

B. <u>Moment of inertia of a wheel</u>

Purpose

To determine the moment of inertia a wheel about its axis of rotation.

Apparatus

Wheel, mass, meter scale, slide calipers, stop watch, thread, tachometer.

Theory

The purpose of this experiment is to study angular motion and to determine moment of inertia experimentally. A bicycle wheel is mounted in a bracket fixed to a stand. A small mass m, is attached to a string the other end of which is wound around the pin (P), protruding from collar attached to the axle, as shown in Fig. 2.2 thus enabling the string to be wound uniformly around the collar. As the mass descends under the action of gravity it imparts an angular acceleration to the wheel. The velocity of the mass (v), and the angular velocity of the wheel (ω), are at any instant during the descent related to each other as $v = \omega r$, where r is the radius of the collar. Suppose that the loop in the pin falls off when the mass has just reached a distance h below the point from where the mass started descending; after this the wheel goes on rotating by virtue of its rotational inertia but comes to rest after some time because of frictional losses of energy. At the instant when the mass falls off

Loss in potential energy of m = Gain in kinetic energy of translation of m

+ Gain in kinetic energy of rotation of the wheel

+ Energy lost in overcoming friction at bearing

$$mgh = \frac{mv^2}{2} + \frac{I\omega^2}{2} + n_1 f$$
$$= \frac{mr^2\omega^2}{2} + \frac{I\omega^2}{2} + n_1 f \tag{2.12}$$

where I is moment of inertia of the wheel with its axle etc., f is the (unknown) amount of average energy lost per revolution and n_1 is the number of revolutions made by the wheel while m traveled through the height h. After this, the angular velocity goes on diminishing and the wheel comes to rest when the energy $I\omega^2/2$ has been used up in overcoming friction. If the wheel has by then made n_2 number of rotations after the mass has fallen

$$\frac{I\omega^2}{2} = n_2 f$$
$$\text{or} \qquad f = \frac{I\omega^2}{2n_2} \tag{2.13}$$

Substituting this in Eq.(2.12) we get

$$mgh = \frac{mr^2\omega^2}{2} + \frac{I\omega^2}{2} + \frac{I\omega^2 n_1}{2n_2} \tag{2.14}$$

$$I = \frac{2mgh - mr^2\omega^2}{\omega^2 \left(1 + n_1/n_2\right)} \tag{2.15}$$

A measurement of the various quantities enables I to be determined. You will probably find that the first term in Eqs. (2.12) or (2.14) is negligible. In that case you may neglect it.

Before beginning to take observations check if the wheel rotates freely. Hang a weight from the pin and let it descend from a suitable point. The height h can be chosen such that it is an integral multiple of $2\pi r$. This will ensure that n_1 is an exact integer.
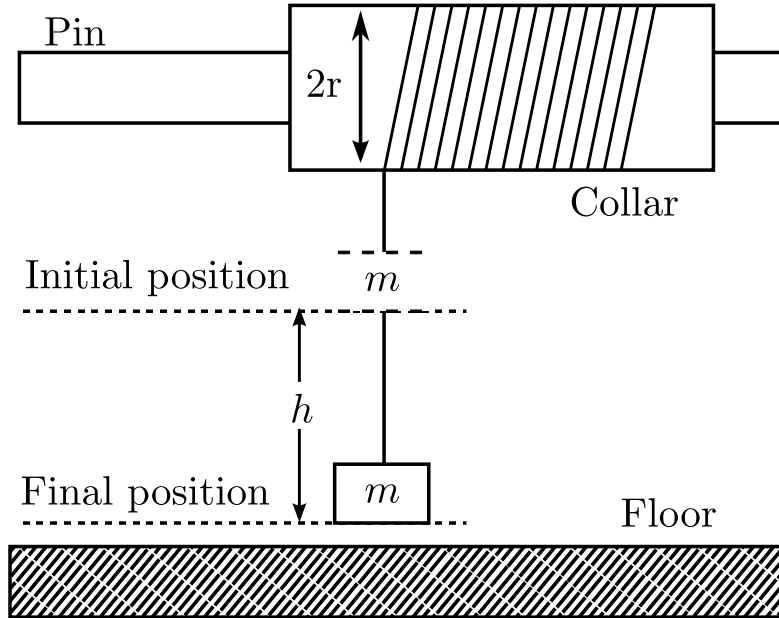

Figure 2.2: Setup (not to scale) to find the moment of inertia of a wheel. (Figure not to scale.)

Measurement of the angular velocity

There are three ways to measure ω.

1. Time the descent of the mass to fall from intial to final position. If this time is t_1, the velocity of the mass at the end of the descent is $v = 2h/t_1$. (Can you explain the factor 2 in this equation?) From this we have

$$\omega_1 = \frac{v}{r} = \frac{2h}{rt_1} \tag{2.16}$$

2. Wind up the string and let the mass descend again, this time to count n_2 (number of turns wheel takes to stop after the mass has fallen) and to measure the time interval t_2 from the moment the mass falls off till the moment the wheel comes to rest. Then

$$\omega_2 = \frac{4\pi n_2}{t_2} \tag{2.17}$$

n_1 was arranged to be a whole number but it may not be possible to make n_2 a whole number. So you must devise some way of measuring fractional revolutions. Repeat the measurement of n_2 and t_2 (with the same mass) at least once more.

3. Use the tachometer to measure ω_3. This is the most accurate of all the three. (Can you explain why this is so?). Using this value calculate the final value of moment of inertia.

In order to estimate the effect of friction, compute moment of inertia also from

$$mgh = \frac{mr^2\omega^2}{2} + \frac{I\omega^2}{2} \tag{2.18}$$

$$I = \frac{2mgh - mr^2\omega^2}{\omega^2} \tag{2.19}$$

which is same as Eq. 2.15 except for the friction term.

Procedure

- Hang a weight from the pin and let it descend from a suitable point. Ensure that the height h through which the weight falls just before getting detached from the wheel is an integral multiple of $2\pi r$. This assures n_1 to be an exact integer. Also measure the corresponding time of descend t_1. Take three readings and find the average. One can calculate the value of ω_1 by the first method using the value of t_1 and h.

- After the weight falls count the number of rotations n_2 and time t_2 it takes for the wheel to stop. Again take three values and find the average. Calculate the value of ω_2 by the second method.

- Now use the tachometer to calculate the value of ω_3 when the body just detaches from the wheel. Again take three readings and find the average.

- The quantities $\omega_1, \omega_2, \omega_3$ are measured by three different methods. However, they represent the same angular velocity.

Compare all the three values. It should be consistent. Now use that value of ω which you think is most accurate (why?) to calculate the value of moment of inertia.

Observation

Table for measurement of radius of collar

Mass $m = \ldots\ldots$ mg.
Least count of the vernier $(l.c.) = \ldots\ldots$ mm.

Sl.	MSR (m)	VSR (v)	Diamter $(t = m + v \times l.c)$	Mean diameter (d)	Radius (r)
	(mm)	—	(mm)	(mm)	(cm)
1					
2					
3					

Table for measurement of angular velocity (ω)

	h (cm)	n_1	t_1 (sec)	$\omega_1 = 2h/(rt_1)$ (rad/ sec)
1st Method	1.			
	2.			
	3.			
Average			———	———
		n_2	t_2 (sec)	$\omega_2 = 4\pi n_2/t_2$ (rad/ sec)
2nd Method		1.		
		2.		
		3.		
Average			———	———
			RPM	$\omega_3 = 2\pi(\text{RPM}/60)$ (rad/ sec)
3rd Method			1.	
			2.	
			3.	
Average			———	

Results

1. The moment of inertia I determined is $I = \ldots\ldots\ldots$ kg m^2.

2. Moment of inertia without considering friction is $I = \ldots\ldots\ldots$ kg m^2.

Precautions

1. Uncertainty in the measurement of the height from the measuring scale is the most probable source of error since this distance varies with the starting point of the mass.

2. Suggest a way to decrease this error.

3. Possible errors in taking measurements with the help of a tachometer.

Appendix

Explanation of factor 2 in Eqn. (2.16)

When using the formula $v = $ distance / time, either the velocity should be uniform or an average velocity. Since in this case the velocity keeps on changing, (because of uniform

accleration g), one has to consider average velocity.

$$v_{\text{avg}} = \frac{h}{t_1} \tag{2.20}$$

$$v_{\text{avg}} = \frac{v_{\text{in}} + v_{\text{max}}}{2} = \frac{0 + v}{2} = \frac{v}{2} \tag{2.21}$$

Combining the above two equations we get Eqn. (2.16).

Explanation of factor 2 in Eqn. (2.17)

Explanation is same as above. The only difference is that here the initial angular velocity is maximum, and final angular velocity is zero.

$$\omega_{\text{avg}} = \frac{\theta}{t_2} = \frac{2\pi n_2}{t_2} \tag{2.22}$$

$$\omega_{\text{avg}} = \frac{\omega_{\text{max}} + \omega_{\text{final}}}{2} = \frac{\omega + 0}{2} = \frac{\omega}{2} \tag{2.23}$$

Combining the above two equations we get Eqn. (2.17).

Experiment 3

Damped and Forced Oscillators: Bar Pendulum and LCR Circuit

A. <u>Bar Pendulum</u>

Purpose

To determine the value of acceleration due to gravity using angular oscillations of a long bar.

Apparatus

Stop watch, long bar, meter scale, knife edge.

Theory

The purpose of this experiment is to use angular oscillations of rigid body in the form of a long bar for determining the acceleration due to gravity. The particular form of the body is chosen for the sake of simplicity in performing the experiment. The bar is hung from a knife-edge through one of the many holes along the length. It is free to oscillate about the knife-edge as axis. Any displacement θ, from the vertical position of equilibrium would give rise to an oscillatory motion just as in the case of a simple pendulum. The difference is that since this is rotating rigid body here we consider the torque of the gravitational force giving rise to the angular acceleration.

The restoring torque τ for an angular displacement θ is

$$\tau = -Mgd\sin\theta \tag{3.1}$$

where M is the mass of the compound pendulum and d the distance between the point of suspension O and the centre of mass of the bar C.

Since τ is proportional to $\sin\theta$, rather than θ, the condition for simple angular harmonic motion does not, in general, hold here. For small angular displacements, however, the relation $\sin\theta \approx \theta$ is a good approximation, so that for small amplitudes in turn for small values of θ.

$$\tau = -Mgd\theta = I\frac{d^2\theta}{dt^2} \tag{3.2}$$

where I is the moment of inertia of the bar about the point of suspension O. The solution

of the above equation is given by

$$\theta(t) = A\sin(\omega t + \phi) \tag{3.3}$$

$$\text{where,} \quad \omega = \frac{2\pi}{T} = \sqrt{\frac{Mgd}{I}} \tag{3.4}$$

is the angular velocity of the compound pendulum. Thus, the period of oscillation is given by

$$T = 2\pi\sqrt{\frac{I}{Mgd}} \tag{3.5}$$

Due to the parallel axis theorem we have

$$I = I_0 + Md^2, \tag{3.6}$$

where, I_0 is the moment of inertia of the pendulum about it's center of gravity (C.G).

Inserting Eq. (3.6) in Eq. (3.5), we get the complete d dependence of the time period T as

$$T = 2\pi\sqrt{\frac{I_0 + Md^2}{Mgd}} \tag{3.7}$$

Since I_0 can be expressed as Mk^2, where k is the radius of gyration, Eq. (3.7) can be rewritten as

$$T = 2\pi\sqrt{\frac{Mk^2 + Md^2}{Mgd}} = 2\pi\sqrt{\frac{k^2 + d^2}{gd}}. \tag{3.8}$$

A simple pendulum consists of a mass m hanging at the end of a string of length L. The time period of a simple pendulum is given by

$$T = 2\pi\sqrt{L/g}. \tag{3.9}$$

So, the time period of a simple pendulum equals the time period of a compound pendulum when

$$L = \frac{d^2 + k^2}{d} \tag{3.10}$$

Re-arranging the above equation

$$d^2 - Ld + k^2 = 0 \tag{3.11}$$

gives us a quadratic equation in d. If d_1 and d_2 are the two solutions of the above equation, then we find

$$d_1 + d_2 = L \tag{3.12}$$
$$d_1 d_2 = k \tag{3.13}$$

Since both d_1 and d_2 are positive, we conclude that there are two point of suspensions on one side of the C.G. of the compound pendulum where the time periods are equal. Similarly, there are two points of suspension on the other side of the C.G where the time periods are same. Thus, for a compound pendulum, there are four points of suspension, two on either side of the C.G. where the time periods are equal. The simple equivalent length L is sum of two of these point of suspension located asymmetrically on two sides of the C.G.

To facilitate further analysis it is useful to square Eq. (3.7) to get

$$T^2 = 4\pi^2 \left(\frac{I_0 + Md^2}{Mgd} \right) \qquad (3.14)$$

In order to gain insight in the dependence of T on d let us first look at the dependence for (i) small d and (ii) large d. For small d (specifically for $Md^2 \ll I_0$) we have

$$T^2 \sim 4\pi^2 \frac{I_0}{Mgd} \qquad (3.15)$$

$$T \sim \frac{1}{\sqrt{d}} . \qquad (3.16)$$

Thus T decreases as d increases. In the opposite limit i.e. for large d (specifically for $Md^2 \gg I_0$) we have

$$T^2 \sim 4\pi^2 \frac{Md^2}{Mgd} \qquad (3.17)$$

$$T \sim \sqrt{d} \qquad (3.18)$$

Thus T increases as d increases in this case. Physically the origins of d^2 in the numerator is coming from the expression for the moment of inertia $I \sim d^2$.

It is then just a question of which effect dominates for a given values of d. To understand this better (or more quantitatively) let us looks at the turning point. The minimum of the expression for T^2 as a function of d can be determined by taking the taking derivative of T^2 with respect to d and setting it equal to zero (and ensuring the sign of the second derivative term corresponds to a minimum). Following this procedure gives

$$d = \sqrt{\frac{I_0}{M}} \qquad (3.19)$$

Eq. (3.19) can be written as $I_0 = Md^2$. This relation is satisfied at the minimum or at the turning point. Using this in Eq. (3.7) we find that the turning point occurs when the magnitude of the two terms of the numerator are equal. For $Md^2 \ll I_0$ the I_0 term dominates in the numerator and d dependence is given by the denominator. In the region $Md^2 \gg I_0$ the Md^2 term dominates in the numerator and so the d dependence is dominated by the numerator.

History of the experiment

Galileo was the first person to show that at any given place, all bodies fall freely when dropped, with the same (uniform) acceleration, if the resistance due to air is negligible. The gravitational attraction of a body towards the center of the earth results in the same acceleration for all bodies at a particular location, irrespective of their mass, shape or material, and this acceleration is called the acceleration due to gravity, g. The value of g varies from place to place, being greatest at the poles and the least at the equator. However, direct measurement of the acceleration due to gravity is very difficult.

Therefore, the acceleration due to gravity is often determined by indirect methods, for example, using a simple pendulum or a compound pendulum. If we determine g using a simple pendulum, the result is not very accurate because an ideal simple pendulum cannot be realized under laboratory conditions. Hence, a compound pendulum is used to determine the acceleration due to gravity in the laboratory.
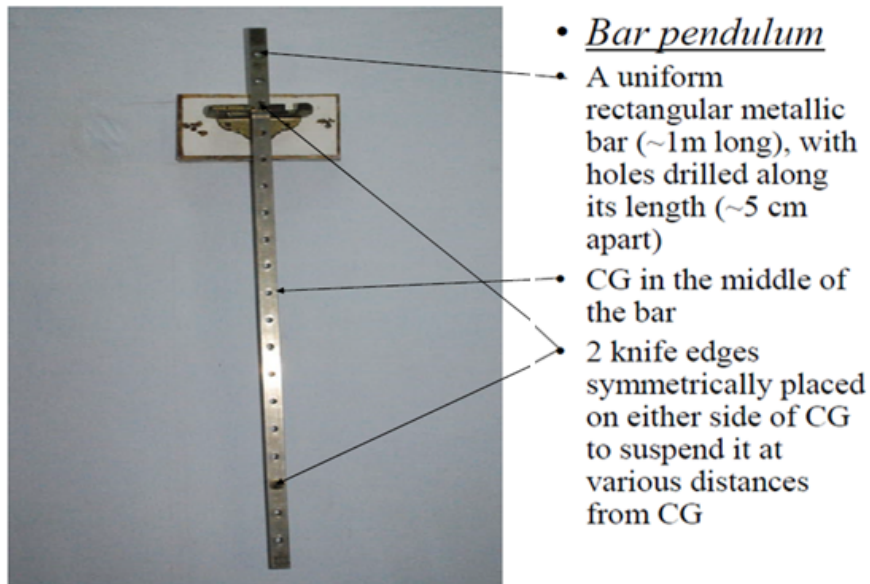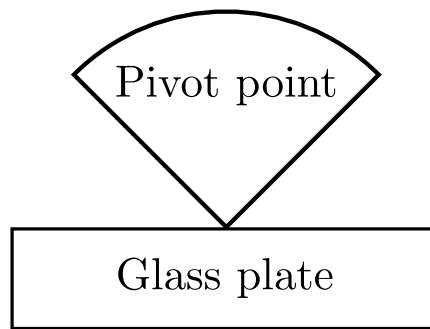
Figure 3.1: Image of a bar pendulum

Figure 3.2: Pivot or knife edge of the bar pendulum

Procedure

- Balance the bar on sharp wedge and mark the position of its center of gravity (C.G.).

- Ensure that the frame on which movable knife edge / pivot is to be rested is horizontal.

- Suspend the pendulum in the first hole. The knife edge or pivot should be placed on the glass plate as shown in Fig. 3.2.

- The distance d is the distance between point of suspension (bottom of the hole) and the C.G.

- Start the oscillation of the pendulum.

- Use the stop watch to measure the time for 20 oscillations. The time should be measured after the pendulum has had a few oscillations and the oscillations have become regular.

- Repeat the process by suspending the pendulum in the consecutive holes.

Sl.	d (cm)	No. of oscillations (sec)			Time for 20 osc (T_{20}) (sec)	Mean (T_{20}) (sec)	T (sec)
		1	2	3			

Table 3.1: Table to measure acceleration due to gravity via a compound pendulum.

- Draw a graph by taking distance along X-axis and time period along Y-axis as shown in Fig. 3.3. Shift the axes to draw a full page graph.
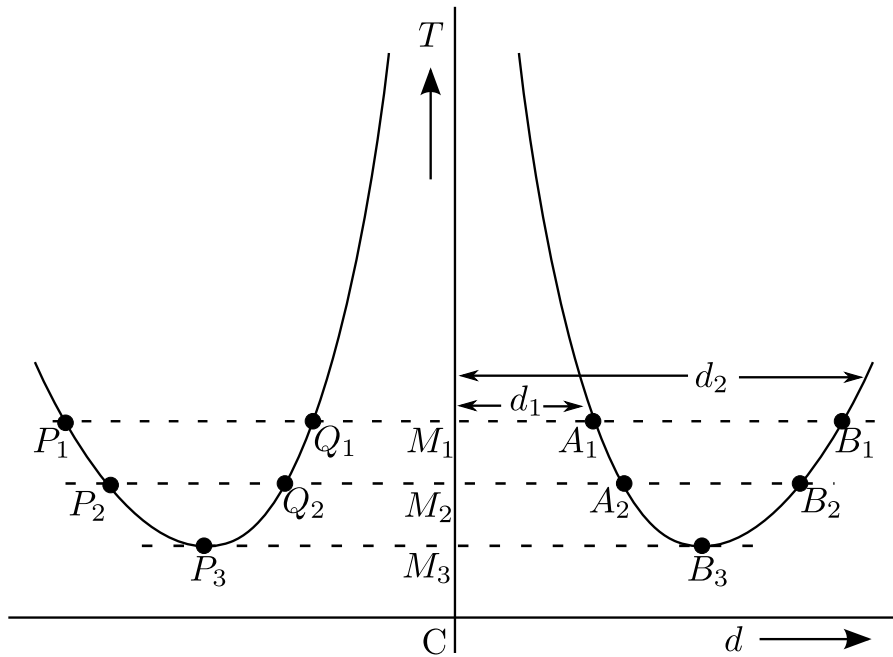

Figure 3.3: Plot of time vs distance from center of gravity of bar

Calculation

1. With the help of the graph, distance d_1 and d_2 can be measured from which the value of g can be calculated by using formulas

$$d_1 + d_2 = L \tag{3.20}$$

$$g = \frac{4\pi^2 L}{T^2} \tag{3.21}$$

where d_1 and d_2 the distances M_1A_1, M_1B_1 respectively and T is the time CM_1 as shown in Fig. 3.3. As there are two branches one could take the mean of Q_1M_1 and M_1A_1 for the distance d_1 and mean of P_1M_1 and M_1B_1 for the distance d_2 for substitution in this formula.

2. Choose another line P_2B_2 and find g_2 using Eqns. (3.20) and (3.21), where d_1 is the mean of Q_2M_2 and M_2A_2, d_2 is the mean of P_2M_2 and M_2B_2 and $T = CM_2$.

3. At the minima, ensure that P_3M_3 is equal to M_3B_3. Then calculate g_3 via the formula

$$g = 4\pi^2 \frac{P_3B_3}{CM_3^2} \tag{3.22}$$

4. Find the average value of g.

Theoretical error

Acceleration due to gravity (g) is given by the formula

$$g = \frac{4\pi^2 L}{T^2} \tag{3.23}$$

Taking log and differentiating

$$\frac{\partial g}{g} = \frac{\partial L}{L} + 2\frac{\partial T}{T} \tag{3.24}$$

Thus, maximum possible error $= \dots\dots\dots\%$.

Results

- The standard value of $g = \dots\dots\dots m/sec^2$.

- Percentage error $= \dots\dots\dots\%$.

Precaution

1. The Knife edge is made horizontal. If it is not perfectly horizontal the bar may be twisted while swinging.

2. The motion of a bar should be strictly in a vertical plane.

3. The amplitude of the swing should be small.

4. The time period of oscillations should be determined by measuring time by large number of oscillations with an accurate stop watch.

5. All distances should be measured and plotted from one end of the rod.

B. <u>LCR circuit</u>

Purpose

To study the behaviour of oscillating circuits and the resonance effect in series connected LCR circuit. This experiment also enables study of forced damped oscillation.

Apparatus

Function generator, inductance coil ($1mH$), capacitors (0.01μF), three resistances, Cathode Ray Oscilloscope (CRO), breadboard etc..

Theory

There is in general an analogy between resonating mechanical systems (like a driven spring mass system) and electrical systems involving inductors, resistor and capacitors. In the electrical case it is the charge $q(t)$ on the capacitor (or the current $I = dq/dt$) that satisfies a differential equation analogous to the displacement of the mass in the familiar spring mass system. Consider the circuit given in Fig. 3.4 consisting of an inductor (L), capacitor (C) and a resistance (R) connected in series with a source of sinusoidally varying emf $V = V_o \cos \omega t$. Equating the voltage drops across the resistor, capacitor and the inductor to the total emf, we get

$$V_o \cos \omega t = RI + \frac{q}{C} + V_L \tag{3.25}$$

$$V_o \cos \omega t = RI + \frac{q}{C} + L\frac{dI}{dt} \tag{3.26}$$

Differentiating the equation with respect to time and rearranging, we get

$$L\frac{d^2I}{dt} + R\frac{dI}{dt} + \frac{I}{C} = -\omega V_o \sin \omega t \tag{3.27}$$

which is analogous to the equation of motion for a damped oscillator given by

$$m\frac{d^2x}{dt} + b\frac{dx}{dt} + kx = F_o \cos \omega t \tag{3.28}$$

where kx is the spring force and $b(dx/dt)$ is the damping force acting on the mass.

The current of $I(t)$ has the solution

$$I(t) = I_0 \cos(\omega t - \phi) \tag{3.29}$$

where I_0 exhibits resonance behavior. The amplitude I_0 and the phase ϕ are given by

$$I_0 = \frac{V_0}{\left(R^2 + \left(\omega L - \frac{1}{\omega C} \right)^2 \right)^{1/2}} \tag{3.30}$$

$$\tan \phi = \left(\omega L - \frac{1}{\omega C} \right) / R \tag{3.31}$$

We can write $I_0 = V_0/Z$, where

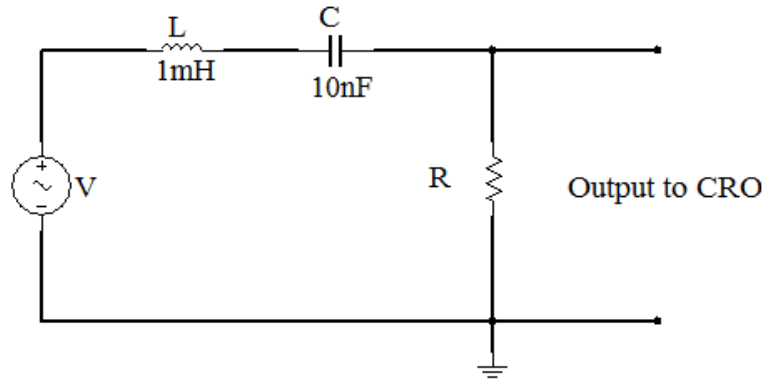$$Z = \left[R^2 + \left(\omega L - \frac{1}{\omega C} \right)^2 \right]^{1/2} \tag{3.32}$$

Figure 3.4: LCR resonant circuit and setup

Define X as

$$X = \left(\omega L - \frac{1}{\omega C}\right) = X_L - X_C \qquad (3.33)$$

so that Z is given by

$$Z = (R^2 + X^2)^{1/2} \qquad (3.34)$$

At resonance i.e. $\omega L = 1/\omega C$, I_o will be maximum. The corresponding angular frequency is known as the resonance frequency given by

$$\omega_o = \frac{1}{\sqrt{LC}}$$

$$\text{or,} \quad f_o = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \qquad (3.35)$$

where f_0 is the corresponding ordinary frequency also called the natural frequency of electromagnetic oscillations in LCR circuit without an external source of emf.

Procedure

1. The series LCR circuit is to be connected as shown in Fig. 3.4.

2. Set the inductance and the capacitance to low values ($L \sim 1mH, C \sim 0.01\mu F$), such that the resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

is the order of few kHz.

3. Vary the frequency of the oscillator and record the voltage across the resistance R.

4. Repeat it for three values of the resistors (say $R = 56\Omega, 100\Omega$ and 470Ω).

5. Take data of about 25 points for each resistance and plot the current amplitude as a function of frequency f.

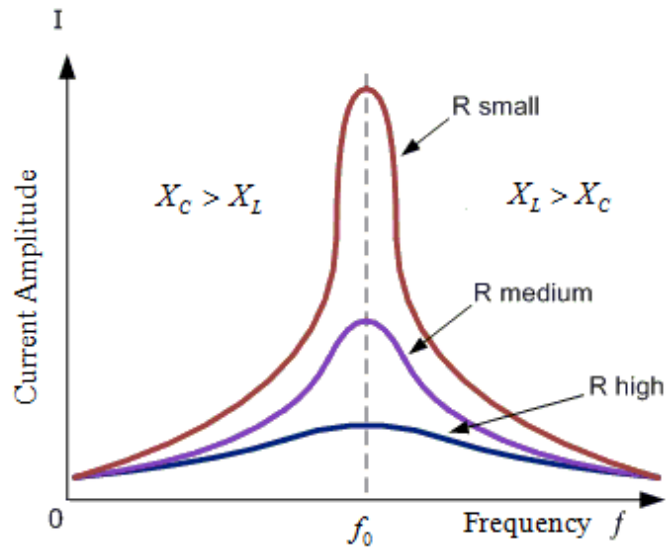6. Find the experimental resonance frequency f_0' from plot.

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Figure 3.5: Bandwidth of series LCR resonance circuit

Observation

Table 1: Variation of current with frequency f

Sl.	Frequency (Hz)	$I = V/R$		
		$R = 56\,\Omega$	$R = 100\,\Omega$	$R = 470\,\Omega$

Result

1.

2.

Precautions

1. The connecting wires should be straight and short.

2. If the amplitude of the output voltage of the oscillator changes with frequency, it must be adjusted.

3. The values of inductance and capacitance are so selected that the natural frequency of the circuit lies almost in the middle of the available frequency range.

Appendix

Resistance color coding

The electronic color code is used to indicate the values or ratings of electronic components, very commonly for resistors, but also for capacitors, inductors, and others. To distinguish left from right there is a gap between the C and D bands. See Fig. 3.6.

- Band A is first significant figure of component value (left side).

- Band B is the second significant figure (Some precision resistors have a third significant figure, and thus five bands.)

- Band C is the decimal multiplier.

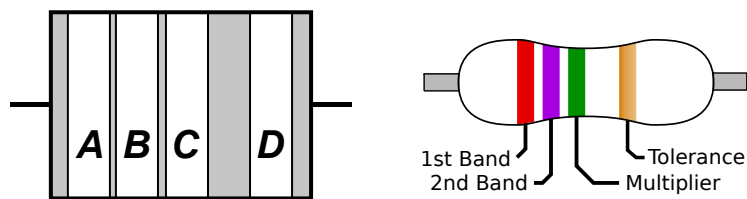- Band D if present, indicates tolerance of value in percent (no band means 20%).

Figure 3.6: Color coding of resistor bands

The standard color code is shown in Table 3.2.

Sl.	Color	Significant figures	Multiplier	Tolerance
1	Black	0	$\times 10^0$	––
2	Brown	1	$\times 10^1$	$\pm 1\%$
3	Red	2	$\times 10^2$	$\pm 2\%$
4	Orange	3	$\times 10^3$	––
5	Yellow	4	$\times 10^4$	$\pm 5\%$
6	Green	5	$\times 10^5$	$\pm 0.5\%$
7	Blue	6	$\times 10^6$	$\pm 0.25\%$
8	Violet	7	$\times 10^7$	$\pm 0.1\%$
9	Gray	8	$\times 10^8$	$\pm 0.05\%$
10	White	9	$\times 10^9$	––
11	Gold	––	$\times 10^{-1}$	$\pm 5\%$
12	Silver	––	$\times 10^{-2}$	$\pm 10\%$
13	None	––	––	$\pm 20\%$

Table 3.2: Resistor color coding. A mnemonics to remember the color codes of electronic components in resistors is: **B**etter **B**e **R**ight **O**r **Y**our **G**reat **B**ig **V**enture **G**oes **W**est.

Capacitor color coding

Sl.	Color	Significant figures	Multiplier	Capacitance tolerance	DC working voltage	Operating tempera-ture
1	Black	0	$\times 10^0$	$\pm 20\%$	$--$	$-55°C$ to $+70°C$
2	Brown	1	$\times 10^1$	$\pm 1\%$	100	$--$
3	Red	2	$\times 10^2$	$\pm 2\%$	$--$	$-55°C$ to $+85°C$
4	Orange	3	$\times 10^3$	$--$	300	$--$
5	Yellow	4	$\times 10^4$	$--$	$--$	$-55°C$ to $+125°C$
6	Green	5	$\times 10^5$	$\pm 0.5\%$	500	$--$
7	Blue	6	$\times 10^6$	$--$	$--$	$-55°C$ to $+150°C$
8	Violet	7	$\times 10^7$	$--$	$--$	$--$
9	Gray	8	$--$	$--$	$--$	$--$
10	White	9	$--$	$--$	$--$	$--$
11	Gold	$--$	$--$	$\pm 5\%$	1000	$--$
12	Silver	$--$	$--$	$\pm 10\%$	$--$	$--$

Table 3.3: Capacitor color coding.

Experiment 4

Fraunhoffer Diffraction

Purpose

- To understand what is meant by Fraunhoffer diffraction.

- To observe single slit diffraction patterns and plot the intensity profile of the pattern.

- Determine slit width from the diffraction formula.

Apparatus

Digital Multi-meter (DMM), He-Ne laser source, sliding detector (photocell), optical rail and mounts.

Theory

Diffraction is the wave phenomenon which describes the deviation from straight line propagation of a wave when it encounters an obstruction. In the case of light waves both opaque and transparent obstacles cause this effect which results in *shadow patterns* on a screen which are quite different from those expected if light travelled only in straight lines.

There are basically two categories of diffraction effects. The first is Fraunhoffer diffraction, which occurs when the waves incident on the slit and the screen (detector) are plane waves. This diffraction is produced when both the light source and screen are effectively at an infinite distance from the given obstacle. Fresnel diffraction is the second type and refers to diffraction produced when either the source or screen or both are at finite distances from the obstacle.

We can observe Fraunhoffer diffraction experimentally by using a collimated light source and (i) placing the viewing screen at the focal plane of a convex lens located behind the obstacle or (ii) by placing the screen at a large distance from the obstacle. The schematic of a single slit diffraction apparatus is shown in Fig. 4.1.

In this experiment we concentrate on Fraunhoffer diffraction patterns although you can observe the different patterns produced by Fresnel diffraction by placing the viewing screen close to the diffraction slit used.

Fig. 4.1 shows a plane wave of wavelength λ incident on a slit width a. The diffraction pattern, intensity versus y is plotted in the figure. Wave theory predicts that the Fraunhoffer diffraction pattern intensity due to a rectangular slit will be of the form

$$I = I_o \frac{\sin^2 \beta}{\beta^2} \qquad (4.1)$$

where $\beta = (ka \sin \theta)/2$, $k = 2\pi/\lambda$, a = slit width and θ = angle formed by the light ray with respect to the system central axis. The minima in the diffraction pattern occurs when $I(\theta) = 0$. This condition requires that

$$a \sin \theta_m = m\lambda \qquad (4.2)$$

where, m is the order number in diffraction pattern and θ_m is angle measured with respect to system central axis to the mth order minima. The shape of this pattern is shown in
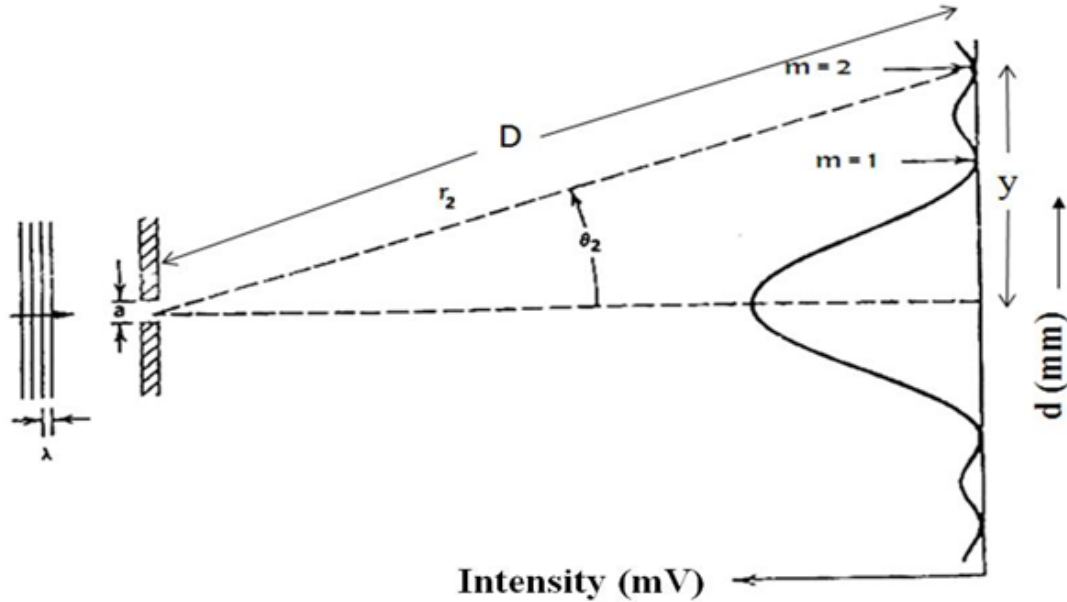

Figure 4.1: The Fraunhoffer diffraction pattern of a single slit.

Fig. 4.1. If θ_m is small, then

$$\sin \theta_m \approx \theta_m = \frac{m\lambda}{a} . \qquad (4.3)$$

Further from geometry we have

$$\sin \theta_m \approx \theta_m = \frac{y}{D} . \qquad (4.4)$$

where y = the distance between central maxima to the mth order minima point and D = distance between slit and photo diode (observed form instrument). Combining Eqs. 4.3 and 4.4, the slit width can be calculated as

$$a = \frac{m\lambda D}{y} \qquad (4.5)$$

Experimental procedure

1. Let the laser warm up for at least fifteen minutes before starting the experiment.

2. Position the laser at one end of the bench and align the beam so that it travels parallel to and along the central axis of the bench all along its length.

3. Let the beam pass through a beam expander. Adjust the slit position until the laser beam is incident on the full width of the slit.
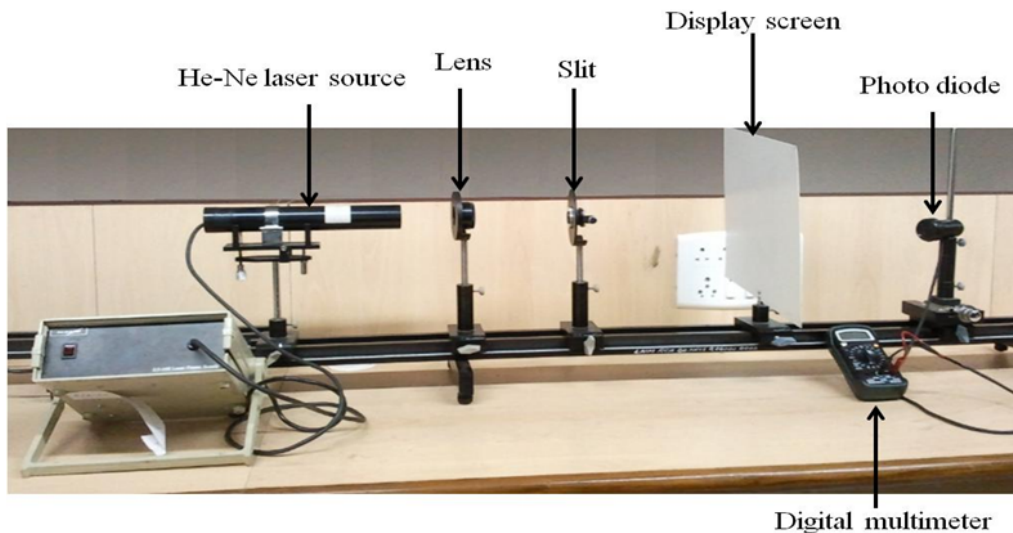
Figure 4.2: Experimental setup for single slit diffraction pattern

4. Attach the viewing screen to a component carrier and position it at the end of the bench furthest from the laser.

5. Observe the diffraction pattern on the screen. Adjust the screen position if necessary to obtain image clarity. Sketch the pattern observed for two different slit widths. What is the effect of varying the slit width?

6. Now replace the screen with the sliding detector. Beware that the smallest division on the sliding detector is 0.01 cm, and the detector can be moved over a distance of 4 cm. Check that the un-obstructed laser beam is at the proper level to be incident on the detector central slit-adjust if necessary.

7. Adjust the position of the slit along the optical bench until the central (principal) maximum and the first subsidiary maxima of the single slit diffraction pattern are fully extended along the direction of travel of the detector–obviously the pattern gets wider as the slit is moved closer to the laser and hence further away from the detector.

8. Form a clear diffraction pattern and SLOWLY scan the pattern from second maxima on one side to second maxima on the other side with the sliding detector .

9. Plot intensity versus position. How do your results agree with theoretical predictions?

10. Calculate the slit width using the diffraction Eq 4.5.

Observation

Sl. No.	Distance			Intensity (mV)
	MSR (mm)	VSR	Total reading (mm)	
1.				
2.				
3.				
⋮				

Result

The calculated slit width from the diffraction pattern $a = $ .... mm.

Precautions

1. Never look directly into the laser beam and take care to avoid reflections entering your eyes.

2. Do not disturb the setup once the diffraction pattern has been obtained.

3. Do not use the backlight of the multimeter. This would drain the battery of the multimeter.

4. Avoid stray light falling on the photo detector while measuring the instensity of light.

Experiment 5

Refractive index of glass with the help of a prism

Purpose

- To understand the accurate leveling and focusing of a spectrometer.

- Investigation of the variation in the refractive index, μ of a prism with wavelength λ.

- Determination of the constants a and b of the Cauchy equation which defines the relationship of μ as a function of λ.

Apparatus

Spectrometer, prism, mercury light source, high voltage power supply, magnifying lens, spirit level, torch light etc.

Theory

The fact that a prism is capable of dispersing light is due to the variation of its refractive index with wavelength. In this experiment the refractive index is obtained for a variety of wavelengths by measuring the *minimum deviation* angle of the prism for each wavelength.

To understand what is meant by the term *angle of minimum deviation*, consider Fig. 5.1. The incident parallel light beam is refracted by the prism in such a way that it is deviated by the angle θ_d from the undeviated direction. The angle is known as the angle of deviation and varies with both the wavelength and the angle at which the incident light intersects the prism.

If the prism is rotated about the axis it is found that the angle of deviation changes but never becomes less than a certain minimum value, δ_{min} known as the angle of minimum deviation i.e. no matter what the orientation of the prism, as long as it is in the path of the incident light beam, the light beam will be deviated through at least this angle. When the prism is oriented in such a way that the exit beam is deviated through the least possible angle δ_{min}, then further rotation of the prism in either direction will cause the exit beam to move further away from the least deviated direction. Thus for each wavelength in a spectral light source, there is a variation of the angle of deviation, θ_d with the angle of incidence, θ_i and at some value of the angle of incidence, the angle of deviation reaches a minimum as seen in Fig. (5.3).
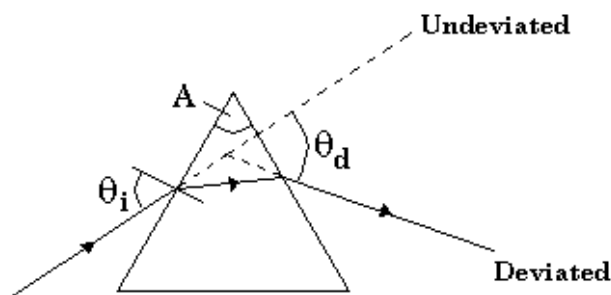
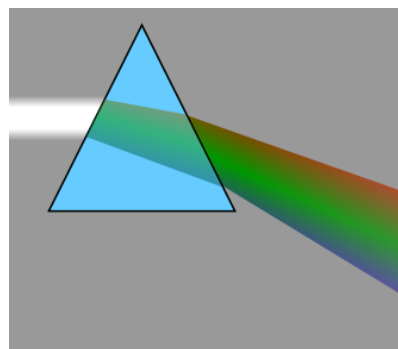Figure 5.1: Deviation of monochromatic light ray due to prism.

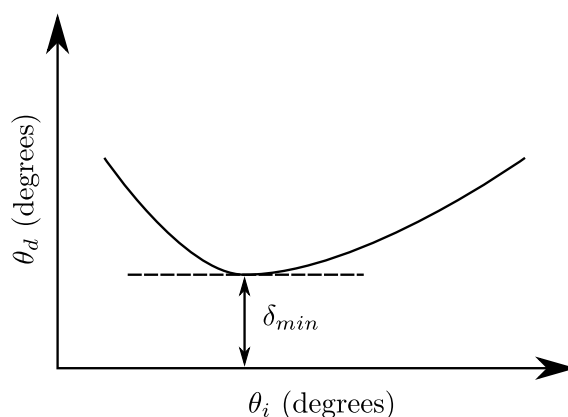Figure 5.2: Spectrum due to a prism.

Figure 5.3: Variation of the angle of deviation (θ_d) with the angle of incidence (θ_i) for a particular wavelength.

Relation between μ and λ

The refractive index of the prism material, μ is a function of the angle of minimum deviation (δ_{min}), the incident wavelength (λ) and the prism refracting angle (A). Thus, by measuring δ_{min} for a variety of wavelengths, the variation of μ with wavelength may be determined.

To derive the exact relationship, consider the prism as seen in Fig. (5.4). It can be shown that the minimum value of the angle of deviation, δ_{min} occurs when the ray passes through the prism symmetrically i.e. when the angle at which the light emerges is equal to the angle of incidence such that the ray passes parallel to the base of the prism as in Fig. (5.4). At each face the ray changes direction by $\theta_i - \theta_r$ and so the total minimum deviation is

$$\delta_{min} = 2(\theta_i - \theta_r) \tag{5.1}$$

From Fig. 5.4, it is shown that the angle $\angle MNO$ is the same as that of the refracting angle of the prism. Referring to the triangle LMN it is obvious, using trigonometry, that $A = 2\theta_r$. Snell's Law is of course $\mu = \sin\theta_i / \sin\theta_r$ but $\theta_i = \delta_{min}/2 + \theta_r$, where $\theta_r = A/2$ and hence we have

$$\mu = \frac{\sin\left((A + \delta_{min})/2\right)}{\sin(A/2)}. \tag{5.2}$$

An empirical equation of the form

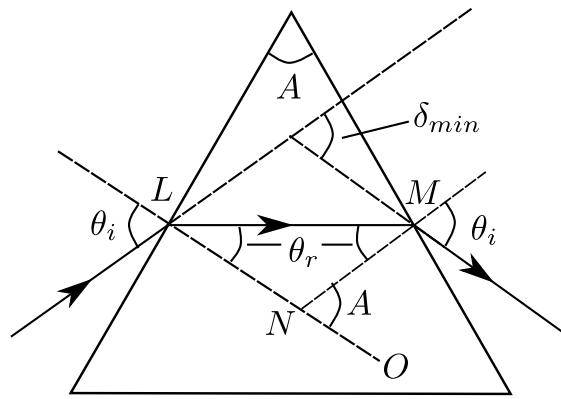$$\mu = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} \tag{5.3}$$

45

Figure 5.4: Condition for minimum deviation

was developed by Cauchy to describe the variation of μ with wavelength. Where a, b and c are constants and it is the purpose of this experiment to verify this equation (neglecting terms of higher order than the second) and to derive the constants a and b for the prism material.

Note: As the variation in refractive index over the whole of the visible is only of the order of 3% this means that δ_{min} varies only very slowly with wavelength. Both a fair degree of experimental skill and great care in making the various measurements are necessary if reasonable results are to be attained.

Experimental procedure

Initially make sure you understand what each component of the spectrometer as detailed in Fig. (5.5) does. The experimental setup consists of following parts. To obtain satisfactory
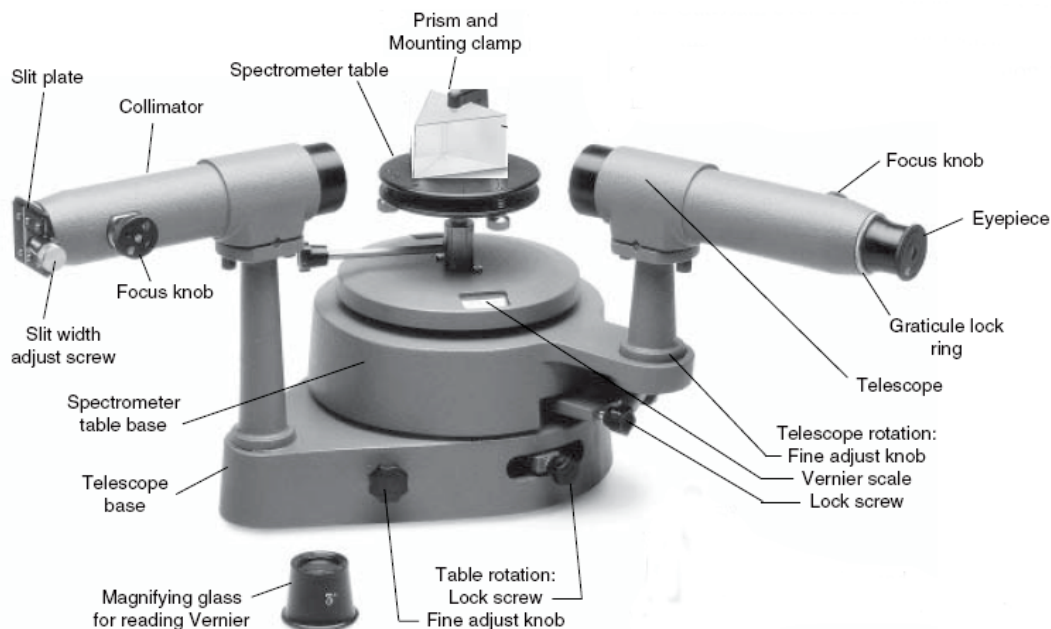

Figure 5.5: Spectrometer with its components

results the spectroscope requires some initial adjustments before the desired measurements can be performed. For this experiment great care must be taken in adjusting the

spectrometer so that the telescope is focused at infinity and the collimator set to give an accurately parallel beam. It is particularly important to ensure that the cross-hairs of the telescope are sharply visible and that no parallax exists between them and the spectral line images. The following steps should ensure this:

1. *Focusing the telescope:* Focus the telescope for the parallel rays from the distance object by sliding the eyepiece looking through telescope in and out, until a sharp image of object is seen. Due to the location of the laboratory this may not be possible so the building opposite may be used for this purpose.

2. *Levelling the collimator:* Place the spirit level on the collimator tube with its axis parallel to the axis of the tube. If the position of the collimator, the bubble is found to be displace from its central position, turn the levelling screws provided with the collimator tube, in the same direction to bring the bubble back to its central position. This make the axis of the collimator tube horizontal.

3. *Levelling of the prism table:* There are three levelling screws A, B, C just below the prism table for levelling the table. There are parallel lines drawn on the prism table parallel to the line joining the screws B and C. Place the spirit level parallel to these lines and bring the bubble to the central position by turning the screws B and C equally in opposite directions. Now place the spirit level perpendicular to the line BC. If the bubble is not in the central position, then turn the A screw alone to bring the bubble in the center. Continue this for a couple of times until the bubble is in the center in both the positions. This makes the table vertical to the axis of rotation.

4. *Focusing the slit:* Place a discharge lamp (Mercury lamp as a visible light source) in front of the spectroscope and turn the telescope until it is in line with and pointing directly at the collimator. Looking through the telescope and adjusting the position of the focusing screw on the collimeter until a sharp image of the slit is observed in the telescope. The collimeter now gives parallel rays which will fall on the prism.

Finding the least count for the spectrometer

It should be noted by the student that 30 vernier scale divisions (VSD) coincides with 29 circular scale divisions (CSD). So,

$$30 \text{ VSD} = 29 \text{ CSD} \tag{5.4}$$

$$1 \text{ VSD} = \frac{29}{30} \text{ CSD} \tag{5.5}$$

Therefore, the least count

$$\text{LC} = 1 \text{ CSD} - 1 \text{ VSD} \tag{5.6}$$

$$= \left(1 - \frac{29}{30}\right) \text{ CSD} = \frac{1}{30} \text{ CSD} \tag{5.7}$$

Since $1 \text{ CSD} = (1/2)° = 30'$, we have

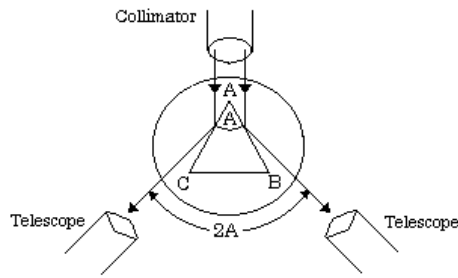$$\text{LC} = \frac{1}{30} \times 30' = 1' \tag{5.8}$$

Figure 5.6: Measurement of the reflecting angle of prism.

Measurement of the angle of prism (A)

- Set up the prism and spectrometer as in Fig. (5.6). Lock the prism table.

- Place the telescope cross-hairs in turn on the image of the slit reflected from surface AB and then surface AC.

- At each position record the angular position of the telescope on the vernier scale- the angle between the two positions of the telescope is $2A$, twice the apex angle of the prism and hence A can be found.

- Repeat above step 2 and 3 to get an average value for $A(\approx 60^o)$.

Viewing the spectrum due to refraction

The telescope and prism are rotated until the spectrum formed by refraction is found. The approximate prism position is shown in Fig. 5.7.

Further rotation of the prism while viewing the spectrum through the telescope will result in reaching the angle of minimum deviation. This is where the spectral lines "turn back" on themselves i.e. move opposite to their initial direction of travel while the prism is still being rotated in the same direction.

Position the prism and telescope so that the spectral lines are at the angle of minimum deviation i.e. at the point where the spectral lines "turn back" on themselves.
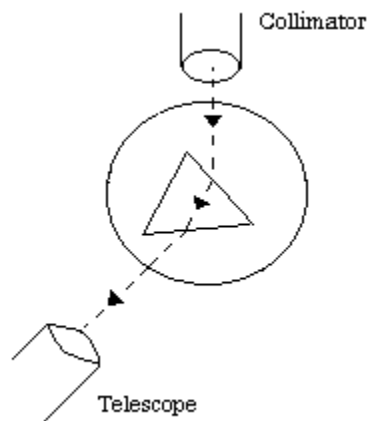

Figure 5.7: Prism position for viewing the spectrum due to refraction.

Turning the prism towards the telescope, increases the angle of incidence, thus moving to the right hand side of δ_{min} in the curve of Fig. (5.3). Conversely turning the prism

Lamp	Colour	Wavelength (nm)
Mercury	Violet	400
	Blue	475
	Green	510
	Yellow	570
	Orange	590
	Red	650
Sodium	Yellow (D_1)	589.6
	Yellow (D_2)	589.0

Table 5.1: Discharge lamp wavelengths

towards the collimator, decreases the angle of incidence, hence moving through the angle of minimum deviation to the left hand side of the curve of Fig. 5.3.

Measurement of the angle of minimum deviation, δ_{min} for each wavelength

1. Using the Hg spectral lamp, observe the first order field of view of refracted spectrum. Find the point of minimum deviation for the Hg spectrum. The approximate prism position is as shown in Fig. 5.7.

   (Remember minimum deviation corresponds to the point at which movement of the lines of the Hg spectrum over the field of view of the telescope is reversed, although direction of rotation of the telescope continues in the same sense.)

2. Several spectral lines should be in the field of view of the telescope. Position the telescope on the highest wavelength spectral line and lock the prism table and telescope. It is essential that the prism and prism table remain in this position for the remainder of the experiment.

3. Using the telescope fine adjustment screw, position the crosshairs of the telescope accurately on the spectral line of interest and read the vernier to the nearest minute of arc.

4. The above step can be repeated for the other lines in the field of view of the telescope there should be enough movement in the telescope fine adjustment screw to allow positioning of the cross-hairs on all of the Hg spectral lines of Table 5.1 without unlocking the telescope again. If this is not the case, just unlock the telescope and reposition it such that the crosshairs of the eyepiece are on the spectral line of interest. It is imperative that the prism and prism table remain in their original fixed position.

5. Rotate the telescope anticlockwise until the undeviated image of the slit through the prism is in the field of view. Again position the crosshairs on the centre of the clit image and record the angular reading of the telescope on the vernier scale.

6. The actual value for δ_{min} for each wavelength is the difference between the appropriate angular reading of the telescope position for minimum deviation and for the undeviated (straight through) position as seen in Fig. (5.1)

Observation

Measurement of angle of prism (A)

Least count of the spectrometer (L.C.) = ...

Sl. No.	Position I			Position II			$2A = \theta_1 - \theta_2$	Prism angle (A)
	CSR	VSR	Total reading (θ_1)	CSR	VSR	Total reading (θ_2)		
–	(deg)		(deg)	(deg)		(deg)	(deg)	(deg)
1								
2								
3								

Table 5.2: Table for measuring angle of prism (A). CSR - Circular scale reading, VSR - Vernier scale reading.

Measurement of angle of minimum deviation (δ_{min})

Angle made by undeviated ray (θ') =

Sl. No.	Colour	Angle of minimum deviation			$\delta_{min} = \theta' - \theta$	$\mu = \dfrac{\sin((A+\delta_{min})/2)}{\sin(A/2)}$	λ	$1/\lambda^2$
		CSR	VSR	Total reading (θ)				
–	–	(deg)		(deg)	(deg)		(nm)	(m^{-2})
1	Violet							
2	Indigo							
3	Blue							
4	Green							
5	Yellow							
6	Orange							
7	Red							

Table 5.3: Table for measuring angle of minimum deviation. CSR - Circular scale reading, VSR - Vernier scale reading.

Calculation

1. Calculate the refractive index μ, of the prism material for each wavelength using Eq. 5.2. Tabulate also a corresponding set of values for $1/\lambda^2$.

2. Draw a graph of μ vs $1/\lambda^2$.

3. Extract values for the Cauchy constants, a (intercept) and b (slope), of Eq. 5.3 from your graph. The least squares fitting routine can be used to get a more accurate value for a and b.

Results

1. Values of Cauchy constants reported from your plot?

2. Calculate the value of refractive index at an intermediate value of wavelength = 520 nm from your graph?

3. What is the significance of Cauchy plot? Mention your special comments.

Appendix

Subtraction of angles (Geometrical)

While considering the difference between two angles, always consider the angle which is less than $180°$.

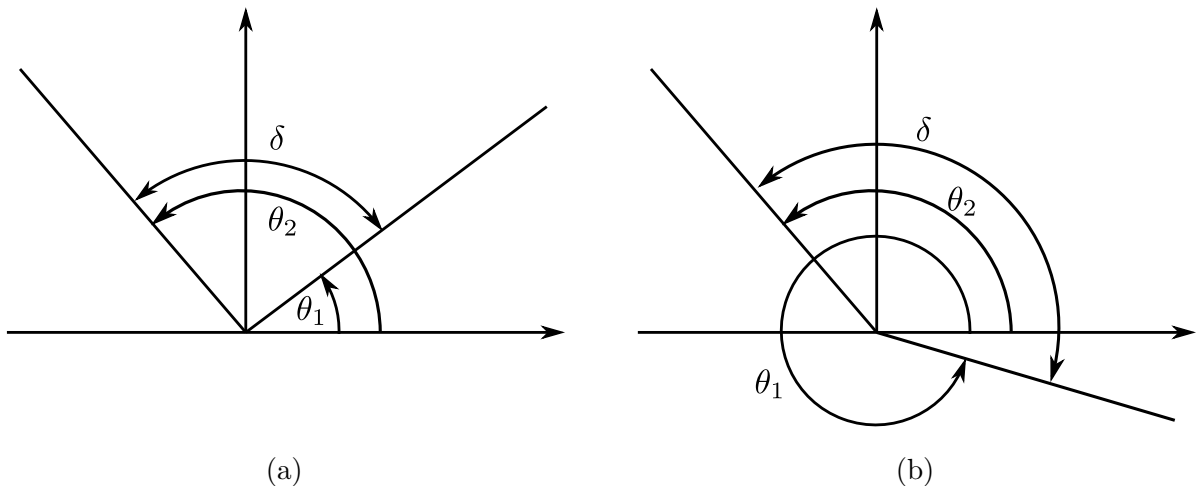(a)   (b)

Figure 5.8: Difference of angles in the two cases should be as follows: (a) $\delta = |\theta_2 - \theta_1|$ and (b) $\delta = (360 - \theta_1) + \theta_2 = 360 - (\theta_1 - \theta_2)$.

Subtraction of angles (Mathematical)

Try to substract $45°25'$ from $90°15'$. (Hint: Remember that $1° = 60'$).

Experiment 6

Helmholtz coil and eddy currents

A. <u>Helmholtz coil</u>

Purpose

To study the magnetic field produced by current carrying coils.

Apparatus

Helmholtz coils, connecting wires, gaussmeter, regulated power supply, measuring scale, etc.
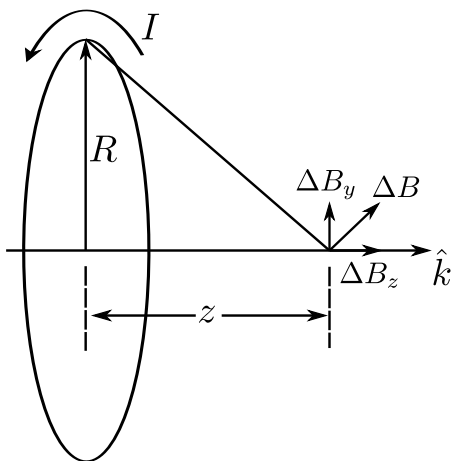
Theory

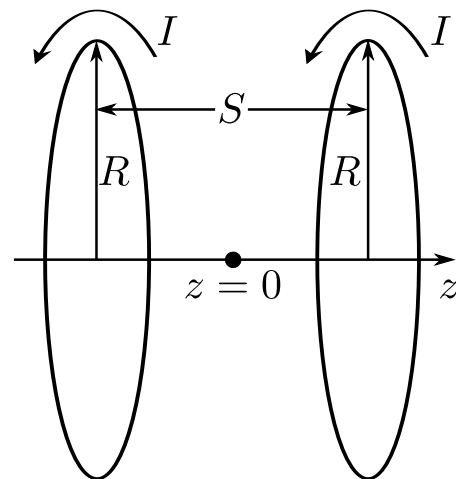Figure 6.1: Magnetic field perpendicular to a current carrying coil.

Figure 6.2: Helmholtz coil.

The magnetic induction of a circular coil of radius R, carrying a current I, at a distance z from the center of the loop along the axis (see Fig. 6.1) is given by

$$\vec{B}(z) = \frac{\mu_o I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \, \hat{k} \tag{6.1}$$

If there are two such parallel coils at a distance S such that the current flows in the same direction in both the coils (see Fig. 6.2), then magnetic field adds in the space between

them. Then we have

$$\vec{B}(z) = \frac{\mu_o I R^2}{2} \left[\frac{1}{\left[\left(R^2 + \left(\frac{S}{2} + z \right)^2 \right) \right]^{3/2}} + \frac{1}{\left[\left(R^2 + \left(\frac{S}{2} - z \right)^2 \right) \right]^{3/2}} \right] \quad (6.2)$$

At the midpoint $\partial \vec{B}/\partial z$ is zero. Further $\partial^2 \vec{B}/\partial z^2$ is also equal to zero at $z = 0$ if $S = R$. Because of these properties, the axial magnetic field is fairly constant over certain region in the middle of the pair of coils. This arrangement is very popular in producing uniform axial fields in regions easily accessible to experimental situations needing such uniformity.

In this experiment we will study the magnetic field variations for such a pair of Helmholtz coils. The magnetic field is measured using a Hall probe connected to a gauss-meter.

Construction of Helmholtz coils

The two coils are made of copper wire windings in 14 layers, each of 11 turns, such that the total number of turns $(n) = 154$. The sockets of the coil winding are cast into the plastic foot of the coil and the connecting leads can be used to connect the coils in parallel or series as required. The sockets are numbered $(1, 2)$ to make it easier to wire the coils. See Fig. 6.3. In the Helmholtz arrangement, the coils are positioned by three spacer rails so
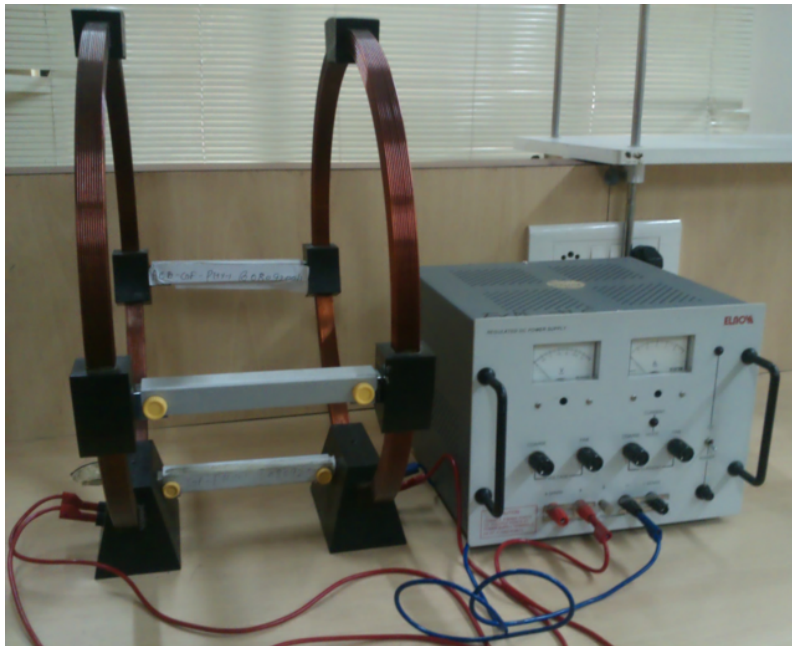

Figure 6.3: Experimental setup of Helmholtz coil.

that their axial spacing is equal to the average coil radius. The rails can be removed after undoing knurled screws, allowing coils to be used individually or with variable spacing.

The coil of the diameter	400 mm
No of turns per coil	154
Coil resistance	$2.1\,\Omega$

Procedure

- Calibrate the Hall probe attached to the gaussmeter.

- Connect the coils with the power supply in such a way that both the coils have the same current in proper direction. *In no case the current should exceed* $3A$.

- Place the hall probe perpendicular to the magnetic field and measure the readings at regular intervals.

Observation

We study the magnetic field in current carrying coil (Helmholtz coil) in three different scenarios:

(A) Magnetic field along the axis of the coils when current is flowing in the same direction in both the coils

Sl.	Distance (cm)	Magnetic field (Gauss)		
		$I_1 = \ldots$ A	$I_2 = \ldots$ A	$I_3 = \ldots$ A

(B) Magnetic field along the axis in a single coil

Sl.	Distance (cm)	Magnetic field (Gauss)		
		$I_1 = \ldots$ A	$I_2 = \ldots$ A	$I_3 = \ldots$ A

(C) Magnetic field along the diameter in a single coil

Sl.	Distance (cm)	Magnetic field (Gauss)		
		$I_1 = \ldots$ A	$I_2 = \ldots$ A	$I_3 = \ldots$ A

Plot the intensity of magnetic field with distance along the coil for different current value for above describe three case.

Results

1.

2.

B. <u>Eddy currents</u>

Purpose

Understand some qualitative and quantitative aspects of eddy currents.

Apparatus

Electromagnet (iron core), DC power source of coil, one disc made of copper fitted on a motor, Digital Tachometer, electronic stopwatch, Gauss Digital Meter, mettalic plate, magnetic and non-magnetic masses etc.
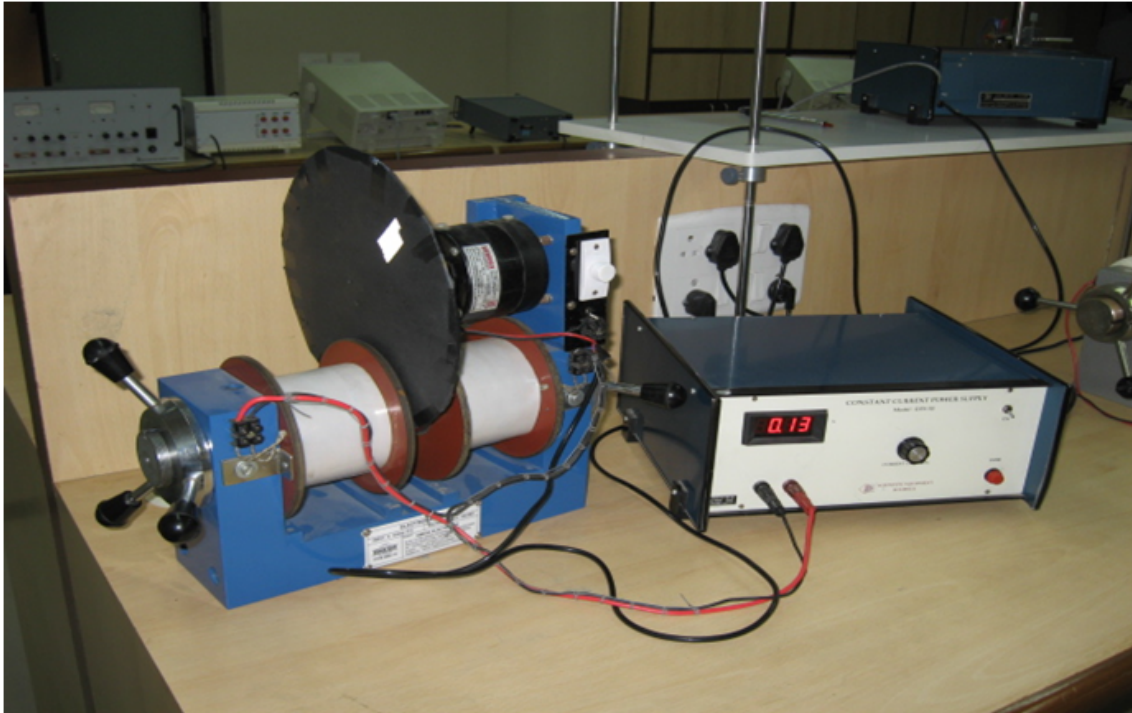

Figure 6.4: Experimental setup to study the effect of eddy current.

Theory

According to the law of electromagnetic induction when the flux through coil changes then emf is induced in the coil. This is formulated in Lenz's law which states that

> When magnetic flux through a coil changes with time, a current is induced in the coil in such a way so as to oppose the cause of change. (Explained in Fig. 6.5).

Eddy currents

When magnetic flux in a solid conductor changes, electrons experiencing a Lorentz force set a swirling currents in the conductor perpendicular to their motion. These circulating eddies of current create tiny electromagnets with magnetic field that oppose the effect of applied magnetic field.

Concept of DC motor and magnetic levitation will also be explained in this section.
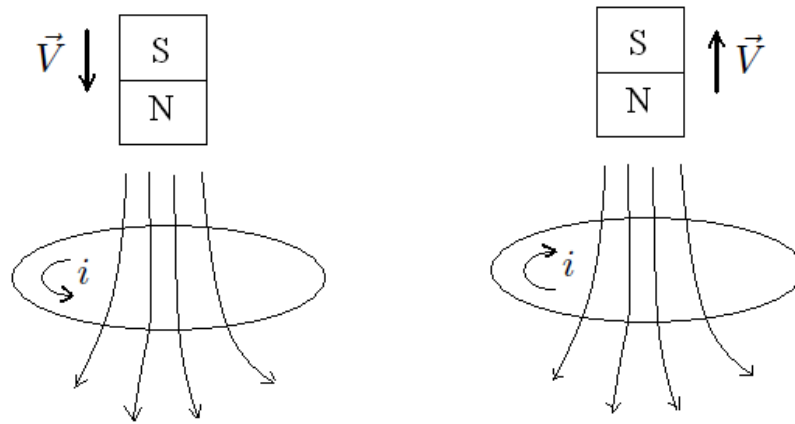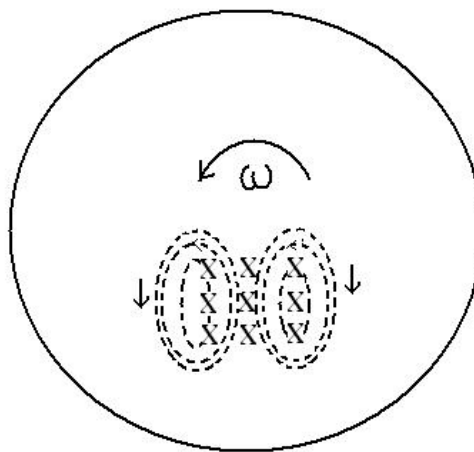
Figure 6.5: Lenz's law

Figure 6.6: A sketch of the eddy currents in a rotating disc. The crosses represent a steady magnetic field perpendicular to the plane of disc.

Experiment 7

Mechanical waves and Climate simulation

A. <u>Mechanical waves</u>

Purpose

- Creating harmonic standing waves.

- Study wavelength (λ) as function of frequency (ν) and to find out the phase velocity v_p.

- To measure linear mass density μ of the string.

Apparatus

Function generator, amplifier, mechanical oscillator, rubber rope, measuring tape, support rod, support base, and weights.

Theory

A wave is an oscillation which propagates itself in space and time and usually periodically through matter and space. One can differentiate between transverse and longitudinal waves. In the case of transverse waves, the oscillation is perpendicular to the direction of the propagation of the wave. In the case of longitudinal waves, the oscillation and the propagation are in the same direction. A simple example of a wave is a harmonic wave given as

$$y = A\sin(kx - \omega t) \tag{7.1}$$

where, A is the amplitude of the oscilation.

         k is called the wave number and is related to the

           wavelength λ by the relation $k = 2\pi/\lambda$.

         ω is called the angular frequency (measuered in

           radians per meter) and is 2π times the frequency.

Now consider two transverse waves having same amplitude, frequency, and wavelength but travelling in opposite directions in the same medium

$$y_1 = A\sin(kx - \omega t)$$
$$\text{and} \quad y_2 = A\sin(kx + \omega t) \tag{7.2}$$

where y_1 represents a wave traveling in the $+x$ direction and y_2 represents a wave traveling in $-x$ direction. Adding these two functions gives the resultant wave function y

$$y = y_1 + y_2 \tag{7.3}$$
$$= A\sin(kx - \omega t) + A\sin(kx + \omega t)$$
$$y = 2A\sin(kx)\cos(\omega t) \tag{7.4}$$

This represents a wave function of standing waves. The speed of a wave on a string which is under tension T and having a mass per unit length μ is given by

$$v_p = \frac{\omega}{k} = f\lambda = \sqrt{\frac{T}{\mu}} \tag{7.5}$$

and is called the phase velocity.

Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 7.1 while Fig. 7.2 shows the various intruments of the experiment.
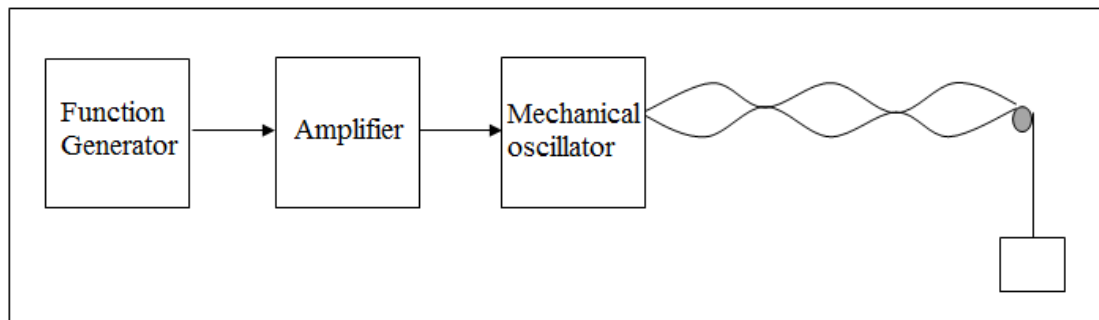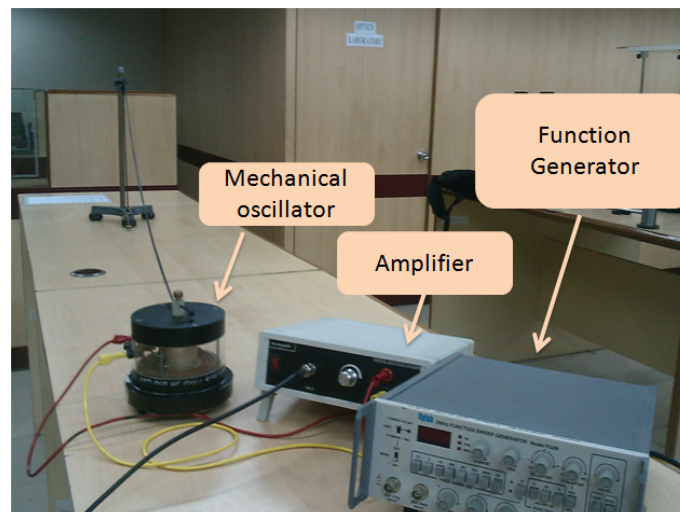

Figure 7.1: Schematic of standing wave generation

Figure 7.2: Experimental setup

Observation

For a given setup, record

1. Frequency from the function generator $(10\,Hz - 25\,Hz)$.

2. Tension from the weight attached to the rope through the pulley.

3. Wavelength from the position of the nodes.

For constant mass $m = \dots\dots\dots$ kg

Sl.	Frequency (f) (Hz)	Number of loops (n)	Length (L) (cm)	$\lambda = 2L/n$ (cm)	$1/\lambda$ (cm^{-1})
1					
2					
3					
4					
5					

For constant frequency $f = \dots\dots\dots$ Hz

Sl.	Mass (m) (Kg)	$T = mg$ (N)	Number of loops (n)	Length (L) (cm)	$\lambda = 2L/n$ (cm)	$v_p = f\lambda$ (cm/s)	v_p^2 (cm/s)^2
1							
2							
3							
4							
5							

Calculation

1. Plot the frequency as a function of $1/\lambda$. From this graph, the phase velocity v_p is determined. Keep the tension in the string constant i.e. mass is constant.

2. The phase velocity v_p of the rope waves, which depends on the tensile stress (T) on the rope, is to be measured when frequency is constant. The phase velocity is plotted as a function of tensile stress. Plot v_p^2 vs T and hence find the mass/unit length of the string using Eq. (7.5).

Results

1. Phase velocity (for constant mass) $v_p = \dots\dots\dots$

2. Mass per unit length (for constant frequency) $\mu = \dots\dots\dots$

B. <u>Climate simulation</u>

Purpose

To study the effect of changing the albedo (α) and solar constant (S) on the temperature of the earth's surface.

Theory

The earth's climate system is an elaborate type of energy flow system (Fig. 7.3) in which solar energy enters the system, is absorbed, reflected, stored, transformed, put to work, and released back into outer space. The balance between the incoming energy and the outgoing energy determines whether the planet becomes cooler, warmer, or stays the same. The earth reflects about 31% of the solar energy (α) received; the remainder is used to operate the climate and maintain the temperature of our planet. Since the amount of energy received approximately equals the amount given back to space, the earth is approximately in a steady state in terms of energy. In the figure, the present amount of
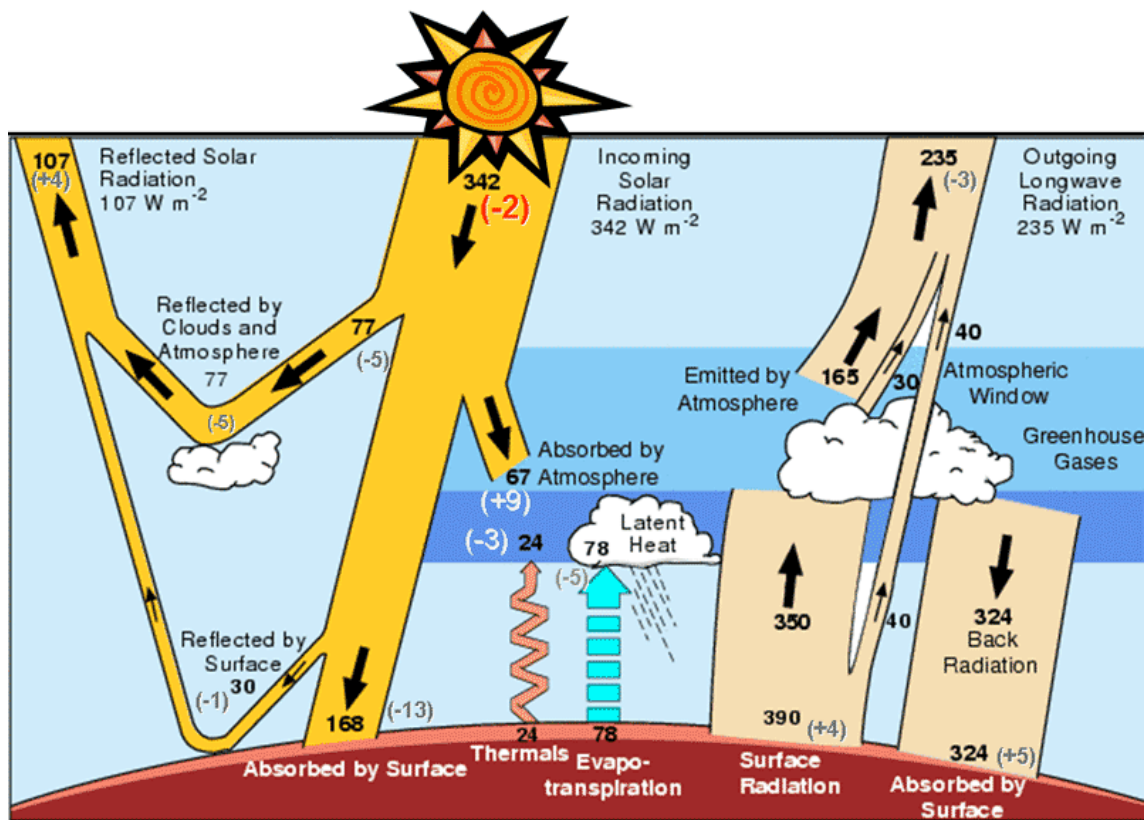

Figure 7.3: Earth's climate system

energy from the sun radiation's received by the Earth system is $342\,W/m^2$ ($= S/4$ where S is the solar constant) and due to reflectance of $107\,W/m^2$ the albedo α is $107/342 = 0.31$. We study the values of solar constant S and albedo α on the temperature of the surface of the earth at various latitudes.

Procedure

1. On the left hand side of Fig. 7.4, we see the default value for FS, which is a way to change the solar constant by a given percentage. We also see the default values for albedo, ice albedo, constants A, B and K as well as the critical temperature (Tcrit) and solar constant (SC). The last is a number of iterations needed (steps), before calculating each zonal temperature.

2. By moving mouse over each parameter, a pop up text box appears. This box explains what the parameter is and contains its default value as well as the range of values that can be selected in the program.

3. In the boxes next to the default values, we can choose the values to undertake climate simulation experiments and pass them into the program by pressing the set button. Finally, by selecting the calculate button, the program calculates and presents the value of each zonal temperature on a temperature latitude chart.
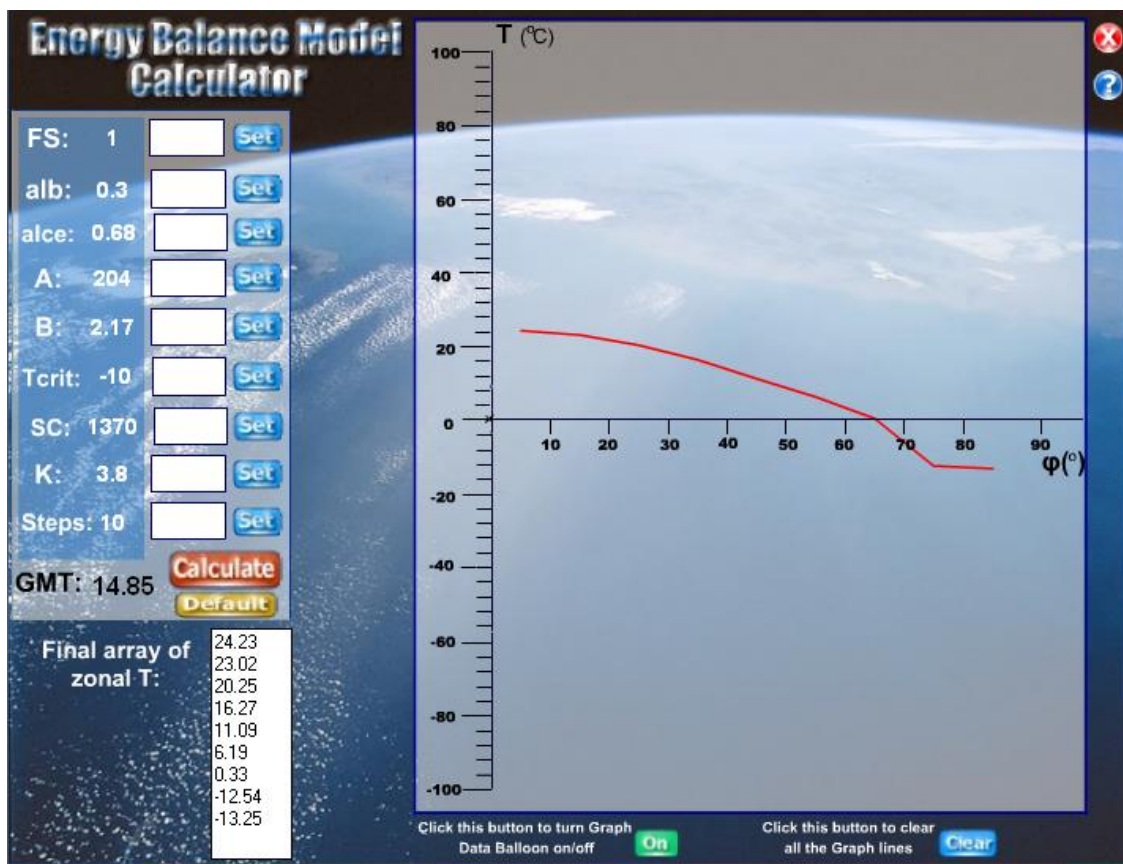

Figure 7.4: Energy balance output on the computer screen

Observation

From the graph, note the values of the surface temperature at latitude 30° north.

1. By varying solar constant from 1300 W/m^2 to 1450 W/m^2 keeping albedo at default value of 0.3.

2. By varying albedo from 0.25 to 0.35 keeping solar constant at default value of 1370 W/m^2.

Table 1: For varying solar constant at constant albedo = ...

Sl.	Solar constant	Temperature
1		
2		
3		
4		

Table 2: For varying albedo at constant solar constant = ... 1370 W/m^2.

Sl.	Albedo	Temperature
1		
2		
3		
4		

Result

1. On increasing solar constant and keeping albedo constant, increase in the temperature at 30° latitude.

2. On increasing albedo and keeping solar constant, decrease in temperature at 30° latitude.

Experiment 8

Electromagnetic induction and Van de Graff generator

A. <u>Electromagnetic induction</u>

Purpose

- To study the flux and emf in the coil as a function of time

- To study the maximum emf and total flux as a function of the velocity of the magnet.

- To demonstrate damping due to induced current.

Apparatus

Faraday setup, diode, capacitor, breadboard, connecting wire, CRO etc.

Theory

Faraday's law of electromagnetic induction tells us that a change in magnetic flux gives rise to an induced emf ε given by

$$\varepsilon = -\frac{d\phi}{dt} \,, \tag{8.1}$$

where ϕ is the magnetic flux. A simple apparatus has been designed, whose schematic diagram is shown in Fig. (8.1), enables us to change θ at different rates through a coil of suitable area of cross-section. A rigid semicircular frame of aluminium is pivoted at the centre of the semicircle. The whole frame can oscillate freely in its own plane, about a horizontal axis passing through its centre. A bar magnet can be mounted at the centre of the arc and the arc passes through a coil C.

It is very instructive to study the emf, induced in the coil as the magnet passes through the coil while oscillating. In this experiment we will use a computer to monitor emf induced as a function of time.

The rate of change of flux through the coil is essentially proportional to the velocity of the magnet, as it passes through the coil. Choosing different amplitudes of oscillations can vary the velocity.

If I is the moment of inertia of the oscillatory system and ω is the angular velocity of the magnet, then the kinetic energy of the system is $I\omega^2/2$ and potential energy can be represented by $MgL(1 - \cos\theta)$ at any instant of time, where L is the effective length of
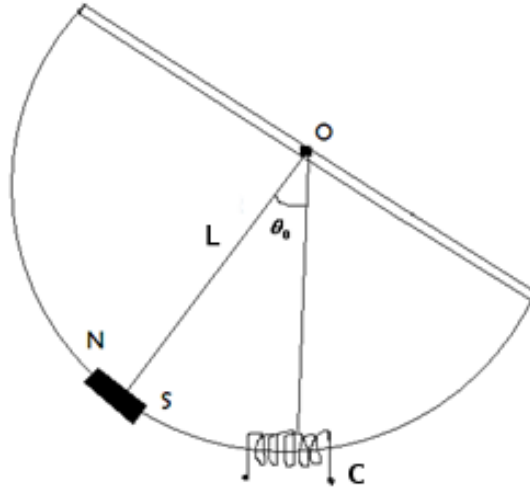
Figure 8.1: Schematic of the coil moving in and out of the magnetic field.

the corresponding simple pendulum. If θ_o is the maximum angular amplitude and ω_{max} is the maximum value of angular velocity, then

$$\frac{1}{2}I\omega_{max}^2 = MgL(1 - \cos\theta_o)$$

$$\text{or,} \quad \omega_{max}^2 = \frac{2MgL}{I}(1 - \cos\theta_o) \tag{8.2}$$

The motion can be regarded approximately as simple harmonic and its time period is given by

$$T = 2\pi\sqrt{\frac{I}{MgL}} \tag{8.3}$$

From Eq. (8.2) and (8.3), we get

$$\omega_{max} = \frac{4\pi}{T}\sin(\theta_o/2) \tag{8.4}$$

$$v_{max} = \frac{4\pi}{T}L\sin(\theta_o/2) \tag{8.5}$$

where v_{max} is the maximum linear velocity associated with ω_{max}. Angular amplitude θ_o is directly measured from the instrument. Velocity is computed by measuring T and θ_o.

Procedure

1. **Charging of capacitor to obtain** ε_{max}
   The induced emf can be measured by using a simple circuit as shown in Fig. 8.2. The induced emf in the coil charges a capacitor C, through a resistance R and a diode D and the voltage developed across C is measured by voltmeter V. The diode current can flow only if the voltage at A is greater than B. Thus once a capacitor attains a voltage ε, current can flow through the capacitor only if the induced emf is greater than ε. If the time constant RC is not small compared to the time taken for the magnet to cross the coil, the capacitor does not get fully charged in AC signal oscillation. It may take several oscillations to do so.

   Connect a resistor, diode and a capacitor given to you in series with the coil. Observe the signal across resistor, diode and the capacitor as a function of time.
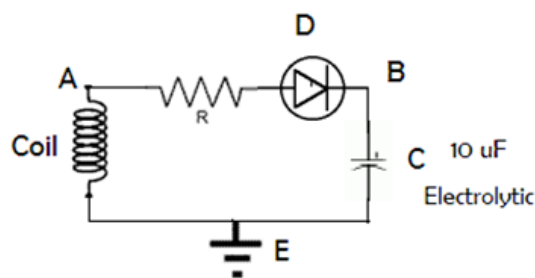
Figure 8.2: Circuit diagram for charging of a capacitor

Calculate v_{max} using Eq. (8.5) and plot a graph between ε_{max} vs v_{max}. ε_{max} is the maximum potential obtained in the CRO.

2. **Induced emf as a function of velocity**
   You can use the computer interface provided to measure the voltage as a function of time. The instructor will explain you how to use the software.

   - Ensure that the support for the apparatus is vertical by adjusting levelling screws. Adjust the weights W_1 and W_2 mounted on the horizontal bar to make zero of the scale as the mean position. Centre of the magnet must be inside the coil.

   - **Measure time period T:** First find out the time period of the oscillation T for the apparatus. Connect the terminals of the coil to interface (COBRA 3), and record couple of oscillations by releasing the magnet from small initial amplitudes. Measure the time period from the plots on your computer screen. Make sure you account for a whole one cycle while measuring the T.

   - **Plot of t vs $\phi(t)$:** Record one or two oscillations. Focus on only one of them by using magnification button. Use the integration feature of the software to obtain flux ϕ as a function of time. You can integrate only half of the pulse, since the pulse is highly symmetric. Plot this on a graph paper for the complete pulse.

   - v_{max} **dependence of slope of $\varepsilon(t)$ at mean position and ϕ:** The emf induced in the coil can be written as

   $$\varepsilon = -\left(\frac{d\phi}{d\theta}\right)\frac{d\theta}{dt} = -\omega\frac{d\phi}{d\theta} \tag{8.6}$$

   Note that when the magnet is at its mean position, then $\omega = \omega_{max}$ or velocity is at its maximum since $V_{max} = \omega_{max} R$. However, $d\phi/d\theta = 0$ at that point. Hence emf will go through a zero corresponding to the mean position. Also note that

   $$\left(\frac{d\varepsilon}{dt}\right)_{V_{max}} = -\left(\frac{d^2\phi}{d\theta^2}\right)_{v_{max}}\omega^2_{max} \tag{8.7}$$

   Hence a plot of the slope of $\varepsilon(t)$ at the zero, corresponding to the mean position against v^2_{max} would be linear. The proportionality constant depends only on the geometry of the coil and the magnet.
   For calculating Φ use "Show integral" mode as before.

3. **Electromagnetic damping in an oscillating system**
   We observe that the successive oscillations are not of the same amplitude. This is

due to damping. Possible sources are: (i) air resistance, (ii) friction at the point of suspension, and (iii) induced emf (Lenz's law).

The system (for small θ) and for damping proportional to velocity would satisfy the equation

$$I\frac{d}{dt}\left(\frac{d\theta}{dt}\right) + k\frac{d\theta}{dt} + \lambda\theta = 0 \tag{8.8}$$

where I is moment of inertia about origin, k is damping coefficient and $\lambda\theta$ is restoring couple $(Mgl\theta)$, if treated as a simple pendulum of length 1.

The amplitude would exponentially decay only if k is a constant and damping term depends linearly in velocity. Record a large number of oscillations starting from initial amplitude of 300 to study the damping behaviour in the absence of induced current in the coil. The plot seen on the screen may not be correct representation of data since the number of points to be plotted is too large. Therefore divide the time axis to approximately 8 to 10 zones and take data after magnifying 1 pulse from each zone. Plot ε_{max} and $(d\varepsilon/dt)_{(v_max)}$ as a function of time or number of oscillations. From your data calculate Q of this oscillator using $A = A_o e^{rt/2}$ and $Q = \omega_o/r$.

Now, connect a resistor of about $220\,\Omega$ (the coil resistance is around $900\,\Omega$) in series with the coil and record voltage dropped across the resistor as a function of time (for large number of oscillations as in the previous case). Repeat analysis of data as above.

4. **Useful features of the software measure:**
   It is easy to use the software given to you. Take a few minutes to summarize yourself with it before going to the detailed experiments. All you have to do is to click the required icon given at the top. Some of the important ones are as follows:

   ARROW: In this mode simply point the cursor at the required point to obtain values of the coordinates.

   MARK: Use this mark a portion of the curve. The x-coordinate of the mark portion are shown on the bottom. The marked portion is highlighted in a different colour.

   SURVEY: You can adjust the left bottom and right top coordinates of the cursor box to obtain coordinates and their differences in this mode. You can use this to calculate slopes around a point.

   SHOW INTEGRAL: Mark the portion of the curve for which you need to calculate the integral and then click this icon to obtain the value. If you need to start from the origin, each time, take the cursor out of the plotting area and drag it across the origin to ensure that starting point is the same.

   SLOPE: Mark the required portion of the curve for which you need the slope and then click this icon to get slope. However, we recommend use of survey mode to get slope more accurate.

Observations

Sl.	θ_0	1		2		3		Avg T_{20}	T	ϵ_{max}	v_{max}
	(deg)	T_{20} (sec)	ϵ_{max} (V)	T_{20} (sec)	ϵ_{max} (V)	T_{20} (sec)	ϵ_{max} (V)	(sec)	(sec)	(V)	(m/s)
1											
2											
3											
4											
5											

Sl.	Angle θ_o (degree)	Slope $= d\varepsilon/dt$	v_{max}^2	$\Phi(v_{max})$
1				
2				
3				
4				
5				

Plots

1. ε_{max} vs v_{max}

2. $\left(\frac{d\varepsilon}{dt}\right)_{max}$ vs v_{max}^2 and report $\Phi(v_{max})$.

3. ε_{max} vs $\left(\frac{d\varepsilon}{dt}\right)_{max}$

Result

Write down the conclusion in your own words by analysing the graphs.

B. Van de Graaff generator

Purpose

To learn how a Van de Graaff generator works and what it is used for and explain demonstration/experiments that involve the Van de Graaff generator.

Theory

In 1930, an American physicist, Robert J. Van de Graaff, designed a type of electrostatic generator capable of providing very high voltages. Such machines were originally used with high voltage X-ray tubes and also for atom-splitting experiments. Much valuable information about the structure of atoms and nuclei was obtained from these experiments.

The Van de Graaff generator uses a Teflon pulley at the lower end of the machine, attached to an electric motor. A rubber belt passes over the pulley. As the pulley turns, the pulley acquires a negative charge while the inside surface of the belt near the pulley acquires an equal amount of positive charge. The outside surface of the belt acquires an equal amount of negative charge by induction. An electrode in the form a wire screen (called the lower brush) drains away these negative charges to the ground. A similar screen electrode (called the upper brush) at the top of the belt removes the positive charges and deposits them on the collector dome. The Teflon pulley retains the negative charges that it acquires.

Positive charges stay on the inside surface of the belt and travel upwards as the belt moves. At the top, it runs over an aluminium pulley that conducts the positive charges and retains them. Free electrons from the mettalic pulley flow on to the belt and are carried down to the lower plastic pulley. As the belt keeps running, more charges are deposited on both pulleys. The positive charges are transferred to the collector dome and negative charges are drained into the ground. The belt plays an important role in transporting negative charges from the upper comb to the lower comb and positive charges from the lower comb to upper comb. There is no transfer of charge from the electrical lines. The device would work exactly the same if it were powered by a hand crank.

On the metallic collector dome, the positive charges spread out due to electrostatic repulsion and become uniformly distributed due to the dome's spherical shape. The buildup of positive charges on the dome continues until ionization intensity is reached. At equlibrium, the potential difference between the collector dome and generator housing can reach one-half million volts. The air between the collector experinces dielectric breakdown and the generator discharges the accumulated static charge in the form of a spark. This discharge causes the potential difference to drop below the ionzation threshold but it is brought up again in a matter of seconds. This process continues as long as the generator is running.

Experimental setup

Discharge sphere The apparatus is ready to use as soon as the appropriate supply is connected. If the belt does not rotate provide assistance by moving the belt by hand. To obtain spark discharge in the air adjust the distance between the dome and the discharging sphere to about 50mm. Sparks in excess of 50 mm are easily obtained under normal, dry conditions.

Faraday's pail This is used to show that the charge always resides on the outside surface of a conducting container. Plug the calorimeter into the top of the dome. The Perspex rod plugs on to the stem inside the pail so that the thread and metallised

Figure 8.3: A Van de Graaff generator

particle may be hung either inside or outside the pail. Run the generator until charged and stop the generator for this experiment. When the particle is hanging inside the pail, its behaviour proves that no charge resides on the inside surface of the pail. When the particle is hanging outside, it is obvious that the charge resides on the outer surface of a conductor.

Lighting neon lamp One end of the neon lamp holder may be brought close to the dome whilst holding the other end in the hand. Be sure the hand is touching the metal plug at the end of the holder. The current flowing from the dome to the lamp holder, through your body and then to earth is sufficient to make the neon lamp glow.

Bouncing ball This can be used as a model to demostrate ions in motion. Plug in the unit at the top of the dome. When the dome is charged, the spheres lying on the base of the cylinder are charged and repelled upwards. They carry the charge to the top of the cylinder, and discharge when they touch the metal cap. They then fall back under gravity to the bottom, where they are recharged and process repeats. Eventually, the top will become charged also, and the spheres will repelled by both ends of the cylinder. If the top is grounded, which you can do by touching it, the spheres will move rapidly as they continuously transfer charge from the bottom to the top.

Repulsion This can be used as a simple pith ball. Hold the insulating rod in hand and bring it near to the charged dome. It will first be attracted to the dome, but when it touches, it will share some of the charge and be repelled stongly, showing that similarly charged bodies repel. When the unit is plugged on the top of the dome, its degree of repulsion will roughly indicate the amount of charge on the dome.

Thread brush This is also demonstrates repulsion of like charges. Plug it in position at the top of the pillar (and hence at the top of the dome) and layout of the threads, spacing them evenly around the dome. When the dome is charged, the threads rise nearly vertically with approximately even spacing between them.

69

Pointed wheel This is a model of an electrostatic motor. Place the wheel in the pivot which is supported at the top of the dome. When it is continuously charged the wheel begins to rotate quite rapidly due to the reaction caused by discharge taking place at the points at the end of the arms of the wheel.

Point discharge This demonstrates the continuous brush discharge from a point as opposed to the intermittent spark discharge between the dome and the sphere. Plug it in at the top of the dome. When the dome is charged an almost silent discharge (the brush and corona discharge) accompanied by a faint glow will be observed (in dark room) coming from the point of the discharger. The 'ion wind' produced from the point is strong enough to be felt on the back of the hand and will alter or sometimes extinguish a candle flame.

It is impossible to build any charge the dome with the point discharger connected. This can be demonstrated by connecting the head of hair, and watching the hair collapse when the point discharger is brought in contact with the dome.

Electrical chimes The electric chimes demonstrate the charging and discharging concept by which the chimes ringing.

Experiment 9

Hall Effect

Purpose

- Measurement of Hall coefficient of a semiconductor to determine the type of carrier which contributes more in the conduction mechanism.

- Determination of the concentration of these charge carriers at room temperature.

- To study the dependence of Hall coefficient on temperature.

Apparatus

Hall probe (Ge, p-type: Ge single crystal with four spring type pressure contact is mounted on glass-epoxy strips. Oven, temperature sensor, Hall effect set-up, electromagnet, constant current power supply, digital Gauss meter.

Theory

Semiconductor materials can have two types of carriers: electron and hole. Conductivity measurements of a particular semiconductor cannot reveal which kind of carrier mostly contributes in the conduction mechanism. However, this information can be obtained from Hall Effect measurements. This effect was discovered by E. H. Hall in 1879.

Consider a p-type semiconductor sample as shown in the Fig. 9.1, with a magnetic field B in z direction perpendicular to the plane of the paper. If current is flowing through the crystal in $-X$ direction (by application of voltage V_x between 1 and 2). A voltage will appear across contacts 3, 4 (along y axis) which is called Hall voltage and this effect is called Hall effect. For the p-type semiconductor the direction of current is same as the direction of flow of holes. Assuming velocity of hole as $\vec{v}_x = v_x(-i)$, the magnetic force acting on the holes is

$$
\begin{aligned}
F_m &= ev_x(-\hat{i})xB(\hat{k}) \\
F_m &= ev_xB\hat{j}
\end{aligned}
\tag{9.1}
$$

This magnetic force will lead to accumulation of holes on the bottom surface, since the semiconductor sample is as a whole neutral. Side 3 will become negatively charged. This will produce hall potential, V_H. In equilibrium, the electrostatic force F_e is equal and
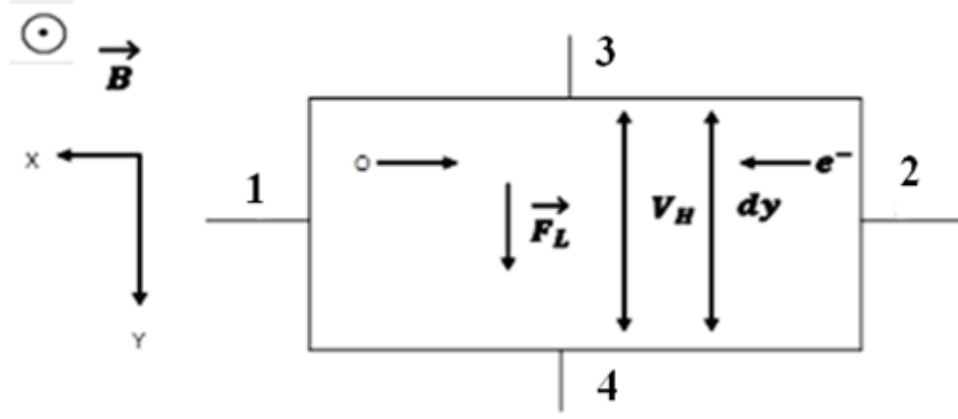
Figure 9.1: Schematic diagram of production of Hall Voltage in a semiconductor.

opposite to F_m.

$$\vec{F}_e = -\vec{F}_m,$$
$$F_e = \frac{V_h}{dy}e,$$
$$V_h = v_x B dy,$$
$$\text{or,} \quad v_x = \frac{V_h}{Bdy} \tag{9.2}$$

We also know that $J_x = nev_x$, where J_x is the current density, n is number of holes/volume. If dz is the thickness of sample then

$$J_x = \frac{I_x}{dydz} = nev_x = ne\frac{V_h}{Bdy}, \tag{9.3}$$

$$V_h = \frac{BI_x}{dz}\frac{1}{ne} \tag{9.4}$$

$$\text{and} \quad R_H = \frac{1}{ne} \tag{9.5}$$

where R_H is the Hall coefficient. Since n is always positive,

- When R_H is positive, it means holes contribute more in the conduction mechanism, since charge is positive.

- If R_H is negative, it means electron contribute more in the conduction mechanism, since charge is negative.

Misalignment of voltage probes shown in Fig. 9.2, gives rise to an extra potential V_R in each measurement. For p-type Ge sample V_R is independent of magnetic field. Therefore, Hall voltage is measured for two different magnetic fields to remove the V_R.

If R_H is measured at two different magnetic fields B_1 and B_2, the expression for R_H is given by

$$R_H = \frac{(V_2 - V_1)dz}{(B_2 - B_1)I} \tag{9.6}$$

The significance of R_H is that from the sign of R_H, the type of charge carrier that mostly take part in conduction mechanism can be identified. Secondly one can calculate the concentration of charge per unit volume at room temperature.

Effect of temperature: Increase of temperature of this p-type semiconductor sample causes electron to move to the conduction band, leaving behind a hole in the valence band. So, in the higher temperature, both of these carriers are needed to be considered for the study of Hall effect. When electrons and holes are present in the semiconductor sample, both charge carriers experience a Lorentz force in the same direction since they would be drifting in the opposite direction as shown in the Fig. 9.1. Thus, both holes and electrons
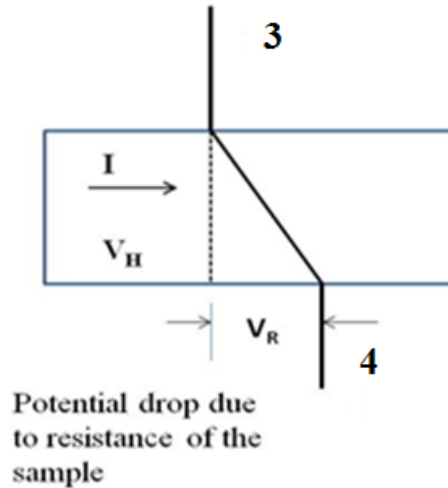

Figure 9.2: Misalignment of voltage probes.

tend to pile near the bottom surface. The magnitude of Lorentz force, however, will be different since the drift velocities (drift mobilities) will be different. Once equilibrium is reached there will be no current in the y-direction, but there will be an electric field in the y direction, produced by the unequal accumulation of electrons and holes.

Expression of Hall coefficient when two types of carriers are present is given below

$$R_H = \frac{p\mu_h^2 - n\mu_e^2}{e(p\mu_h + n\mu_e)^2} \tag{9.7}$$

Eq. (9.7) correctly reduces to Eq. (9.5) when only one type of carrier is present. Since the mobilities μ_h are not constants but function of T, the Hall coefficient given by Eq. (9.7) is also a function of T and it may become zero and even change sign. In general $\mu_e > \mu_h$ so that inversion may happen only if $p > n$; thus *Hall coefficient inversion* is characteristic of only *p-type* semiconductors.

Measurement of temperature using a thermocouple

A thermocouple is a device consisting of two different conductors (usually metal alloys) joined at one end, as shown in the figure, produce a voltage, proportional to a temperature difference, between either ends of the two conductors. This produced voltage is called thermo emf. In the present experiment, if the thermocouple junction end is placed close to the semiconductor sample and other end is kept at room temperature, the thermocouple will produce thermo emf, if there is a temperature difference between these two ends and that will be proportional to the difference of temperature. By the measurement of this thermo emf the temperature of the hot end can be found out using a calibration table. Note that a null voltage is measured if no temperature difference exists between the tail end and the junction end: a temperature difference is needed to operate the thermocouple.
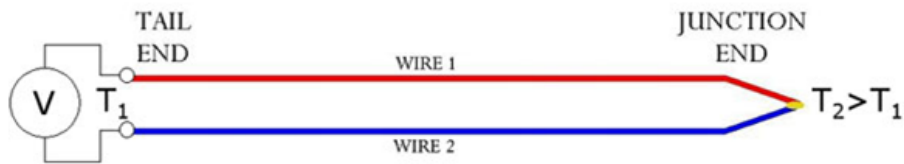
Figure 9.3: Temperature measurement by a thermocouple.

In this lab, k-type thermocouple is used which is made out of two different alloys: Chromel (Ni+ 10%Cr) and Alumel (Ni+2%Al, 2% Mn,+1%Si). The operating temperature ranges from 270 to $1372^o C$.

Experimental Setup

The sample is Ge (p-type) with medium doping and with a thickness of $0.50\,mm$. The instruments required for hall coefficient measurement is shown in Fig. 9.

(a) Hall Effect setup

(b) Electromagnet with constant power supply

(c) Digital gauss meter
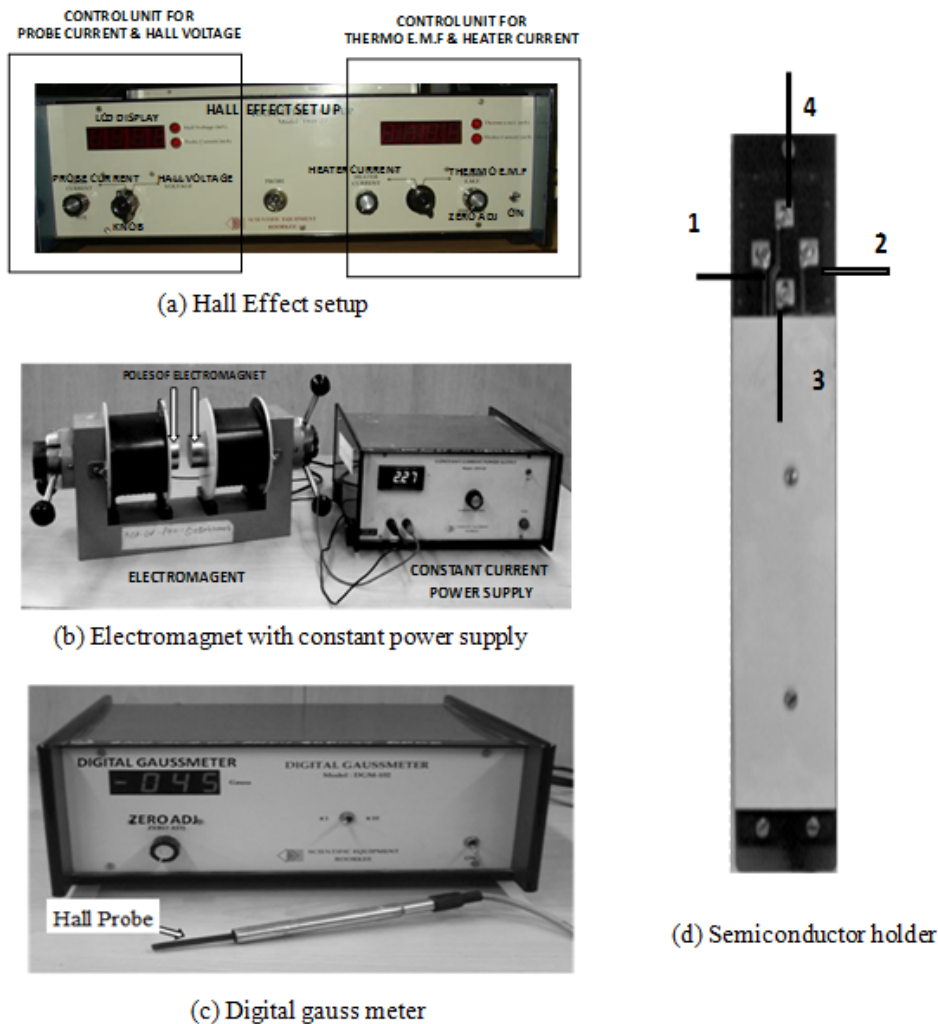
(d) Semiconductor holder

Figure 9.4: The instruments required for hall coefficient measurement.

Procedure

1. Connect the Current supply source to the electromagnet (EM).

2. Check the magnetic field of the EM by a Hall probe without supplying the current. This is the residual magnetic field.

3. The values of the Heater current and the thermo emf to be adjusted initially to zero.

4. Now apply a current to the EM such that the magnetic field produced is equal to 3K Gauss.

5. Connect the semiconductor holder to the Hall Effect measurement setup. Supply a current of $3.5\,mA - 4\,mA$ to the semiconductor and maintain it throughout the experiment.

6. For the measurement of Hall voltage, turn the knob to Hall voltage position in Hall effect setup.

7. The corrected Hall voltage can be obtained by subtracting the Hall Voltage at residual magnetic field from hall voltage measured for $3K\,gauss$.

8. Take the first measurement at room temperature with zero heater current value and zero thermo emf.

9. For different heater current values, measure the Hall voltage and thermo emf as shown in the sample data sheet. Repeat the measurement of Hall voltage for the following Heater current values: $400mA, 600mA, 700mA, 800mA$. Wait for at least $15-20$ min after changing the heater current value for the stabilization of the setup at that particular value.

10. Switch off the current supply source of the electromagnet while waiting.

11. From the measured values calculate the Hall coefficient and plot a graph between Hall coefficient and temperature.

Calibration table for chromel-alumel thermocouple

$°C$	0	1	2	3	4	5	6	7	8	9
0	0.00	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36
10	0.40	0.44	0.48	0.52	0.56	0.60	0.64	0.68	0.72	0.76
20	0.80	0.84	0.88	0.92	0.96	1.00	1.04	1.08	1.12	1.16
30	1.20	1.24	1.28	1.32	1.36	1.40	1.44	1.49	1.53	1.57
40	1.61	1.65	1.69	1.73	1.77	1.81	1.85	1.90	1.94	1.98
50	2.02	2.06	2.10	2.14	2.18	2.23	2.27	2.31	2.35	2.39
60	2.43	2.47	2.51	2.56	2.60	2.64	2.68	2.72	2.76	2.80
70	2.85	2.89	2.93	2.97	3.01	3.05	3.10	3.14	3.18	3.22
80	3.26	3.30	3.35	3.39	3.43	3.47	3.51	3.56	3.60	3.64
90	3.68	3.72	3.76	3.81	3.85	3.89	3.93	3.97	4.01	4.06
100	4.10	4.14	4.18	4.22	4.26	4.31	4.35	4.39	4.43	4.47
110	4.51	4.55	4.60	4.64	4.68	4.72	4.76	4.80	4.84	4.88

Sample data sheet

| Sl.	Heater Current	Thermo emf	Temp	Hall Voltage at $B_2 = $ 3000 G	Hall Voltage at residual filed B_1	Difference of Hall Voltage	Hall Coefficient
	(mA)	(mV)	$°C$	(mV)	(mV)	(mV)	cm^3/C
1.	0	0	18	56.5	1.4	55.1	22.96×10^3
2.	200	0.2	23	56.8	1.6	55.2	23.00×10^3
3.	300	0.48	30	56	1.2	54.8	22.83×10^3
4.	400	0.9	40.5	52.3	0.9	51.4	21.42×10^3
5.	500	1.37	52.3	41.8	0.6	41.2	17.17×10^3
6.	600	1.87	64.5	23.5	0.4	23.1	9.63×10^3
7.	650	2.25	73.5	8.7	-0.3	9	3.75×10^3
8.	700	2.54	80.8	0.7	-1	1.7	0.71×10^3
9.	750	2.83	87.8	-3.1	-1.5	-1.6	-0.67×10^3
10.	800	3.13	94.8	-4.8	-1.7	-3.1	-1.29×10^3
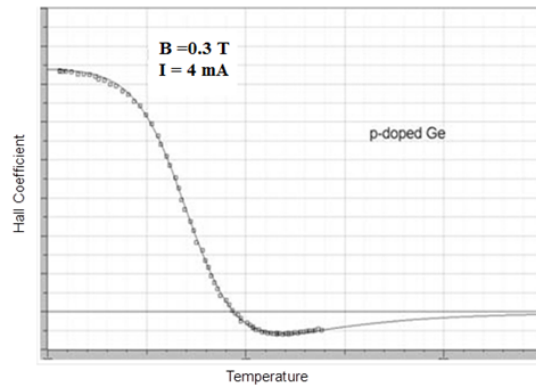
Figure 9.5: Graph showing variation of Hall Coefficient with temperature

Results

1.

2.

Experiment 10

Diffraction grating

Purpose

- To understand the diffraction, diffraction grating and how diffraction grating works with the help of basic diffraction grating equations and experimental studies.

- To measure the wavelength of the light source with the help of diffraction grating.

Apparatus

Spectrometer, diffraction grating, mercury light source, high voltage power supply, magnifying lens, spirit level, torch light, etc.

Theory

Preliminary discussion

Interference refers to the interaction of two or more wave trains of light having the same frequency and having a phase difference which remains constant with time (coherent sources), so that they may combine with the result that the energy is not distributed uniformly in space but is a maximum at certain points and a minimum (perhaps zero) at others.

Diffraction phenomenon is described as the apparent bending of waves around small obstacles and the spreading out of waves past small openings. Diffraction patterns are marked by a rapid decrease in intensity with increasing distance from the center of the pattern.

A diffraction grating is made by making many parallel scratches on the surface of a flat piece of transparent material. It is possible to put a large number of scratches per centimeter on the material, e.g., the grating to be used has 6000 lines/cm on it. The scratches are opaque but the areas between the scratches can transmit light. Thus, a diffraction grating becomes a multitude of parallel slit sources when light falls upon it.

Diffraction grating equation

When parallel bundle of rays falls on the grating. Rays and wave fronts form an orthogonal set so the wave fronts are perpendicular to the rays and parallel to the grating (as shown in Fig. 10.1) the diffraction of light occurs. According to Huygens' Principle, every point on a wave front acts like a new source, each transparent slit becomes a new source so cylindrical wave fronts spread out from each. These wave fronts interfere either constructively or destructively depending on how the peaks and valleys of the waves are related.

Whenever the difference in path length between the light passing through different slits is an integral number of wavelengths of the incident light, the light from each of these slits

will be in phase, and then it will form an image at the specified location. Mathematically, the relation is simple

$$m\lambda = d\sin\theta_m \qquad (10.1)$$

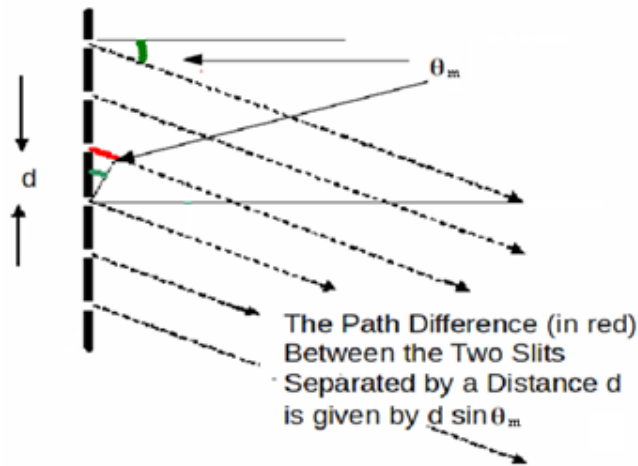Eq. (10.1) is known as *grating equation*. The light that corresponds to direct transmission

Figure 10.1: Geometrical conditions for the diffraction from multiline grating.

(or specular reflection in the case of a reflection grating) is called the zero order, and is denoted $m = 0$. The other maxima occur at angles which are represented by non-zero integers m. Note that m can be positive or negative, resulting in diffracted orders on both side of the zero order beam.

Diffraction gratings are often used in monochromators, spectrometers, lasers, wavelength division multiplexing devices, optical pulse compressing devices, and many other optical instruments.

Resolving power of grating

This equation then leads to the following expression for the resolving power of the diffraction grating

$$R = \frac{\lambda}{\Delta\lambda} = mN \qquad (10.2)$$

Here λ is the average of wavelength, $\Delta\lambda$ is the difference between wavelengths, m is the order and N is the total number of slits on the grating.

Thus, the distance between maxima depends on the distance between slits and the resolution, the relative sharpness of the maxima, depends on the total number of slits. (Often a grating is characterized by the number of slits per unit length. From this information one can, of course, deduce the distance between the slits.

Procedure

As with many optical instruments, the spectroscope requires some initial adjustments before the desired measurements can be performed. Focusing and levelling of the spectrometer for the parallel rays is to be done as per previous prism experiment.

To set the telescope axis perpendicular to that of the collimator:

Illuminate the slit with the light source. Turn the telescope of the spectrometer to view the image of the illuminated slit directly as shown in Fig. 10.2(a). The source should directly
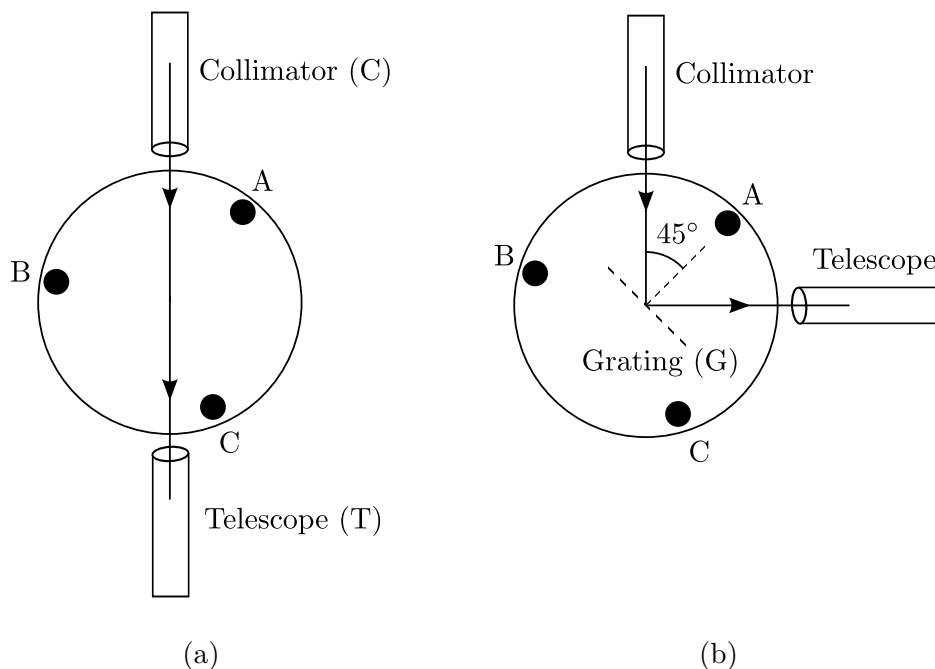

Figure 10.2: Grating settings

be in front of the slit such that maximum light falls on the slit. Adjust the cross-wires such that the image of the slit falls in the middle of the intersection of the cross-wires. Fix the prism table with the fixing screw and read any of the two verniers. Let this angle be α. Rotate the telescope by an amount $90 \pm \alpha$ such that it is exactly perpendicular to the collimator. Fix the telescope in this position and unfix the prism table.

Fix the grating (G) in the grating holder such that the grating lines are perpendicular to the prism table and the ruled surface extend equally on both sides of the center. The grating is set parallel to the line joining the prism table screws B and C as shown in Fig. 10.2. Turn the prism table such that light from the collimator is reflected into the telescope. The reflection should be by the unruled surface of the grating. To determine the unruled surface use the following procedure. Allow light to be reflected by both the grating surface one at a time and view the corresponding image via the telescope. The surface from which the image of the slit appears sharper is in fact the unruled surface of the grating.

Once the unruled surface has been determined, view the reflection only via the unruled surface while the setup is as shown in Fig. 10.2(b). If the center of the grating displace either above or below the intersection of the cross-wires, then the grating surface is not vertical. To ensure that the grating surface is vertical, turn the prism table screws B and C equally in opposite directions until the center of the image coincides with the intersection of the cross-wires.

Turn the unruled surface of the grating by an angle 45° such that the light from the collimator falls normally on the unruled surface of the grating. Fix the prism table in this position and unfix the telescope.

Even though we have made the plane of the grating vertical and the rulings perpendicular to the table surface, the rulings of the grating may not be vertical. In order to set the rulings vertical, rotate the telescope in its own plane on both side of the central image. On both sides on the central image different orders of image are seen as shown in

Fig. 10.3. In the first order images on both sides, if the image on the left is higher than
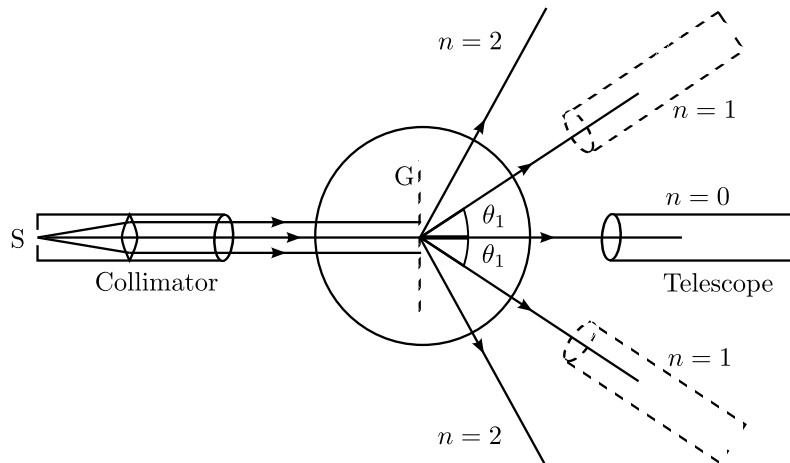

Figure 10.3: Grating images of higher order

that of the image on the right or vice-versa, then turn the third screw A on the prism table until the images on both the sides are on the same level.

Caution

- The diffraction grating is a photographic reproduction and should NOT be touched. Make sure that the glassy base of grating shouldn't faces towards the source light.

- Now your setup is ready to report the experimental observations.

Observation

1. Check to make sure that the grating is not too high or low relative to the collimator. Affirm maximum brightness for the straight through beam by adjusting the source slit alignment. At this step, the slit should be narrow, perhaps a few times wider than the hairline. Search for the spectrum by moving the telescope to one side or the other. This spectrum should look much like the visible spectrum observed with the prism. This is the first order spectrum. Record for each color diffraction angle θ_R (along right side) and θ_L (along left side) from the straight trough beam.

2. Search for the second order spectrum and record θ_R and θ_L for each color.

3. For each of the seven colors in the mercury spectrum, measure the angles θ_R and θ_L to the nearest tenth of a degree by placing the hairline on the stationary side of the slit.

4. You are at least expected to observe the 1st and 2nd order diffraction pattern and corresponding readings.

5. From your observations calculate various wavelengths of visible radiations from the mercury source.

Sl.	Colour	LHS			RHS			$2\theta = \theta_L - \theta_R$	θ	$\lambda = \frac{d\sin\theta}{m=1}$
		CSR	VSR	Total (θ_L)	CSR	VSR	Total (θ_R)			
1	Violet									
2	Indigo									
3	Blue									
4	Green									
5	Yellow									
6	Orange									
7	Red									

Table 10.1: For first order ($m = 1$). CSR - Circular scale reading, VSR - Vernier scale reading.

Sl.	Colour	LHS			RHS			$2\theta = \theta_L - \theta_R$	θ	$\lambda = \frac{d\sin\theta}{m=2}$
		CSR	VSR	Total (θ_L)	CSR	VSR	Total (θ_R)			
1	Violet									
2	Indigo									
3	Blue									
4	Green									
5	Yellow									
6	Orange									
7	Red									

Table 10.2: For second order ($m = 2$). CSR - Circular scale reading, VSR - Vernier scale reading.

Calculation

1. Average the right and left angles for each colour.

2. Use the grating equation with $d = (1/6000)$ cm to find the wavelength λ for each colour.

3. Calculate % error for your reported λ measurement.

Result

1. Percentage measurement error for your analysis.

2. Use the grating equation with the tabulated values of λ from last time and your measured values of θ to calculate seven different values of N, the grating constant $(N = 1/d)$.

3. A certain colour emerges at 15° in the first order spectrum. At what angle would this same colour emerge in the second order if the same source and grating are used?

4. What could be causing any discrepancy?

5. Why is it necessary that the base side of the grating face toward the light source? Draw a ray diagram for the two cases:

   a) Base toward the source (correct).

   b) Grating toward the source (incorrect).

6. Mention your special comments for each statement in your lab report as a part of experimental outputs.

Experiment 11

Measurement of band gap of semiconductor

Purpose

- Measurement of resistivity of a semiconductor at room temperature

- Measurement of variation of resistivity with temperature.

- Evaluation of band gap of the given semiconductor from the plotting of acquired data.

- Understanding of the concept of four probe method.

Apparatus

Four probe experimental setup.

Theory

Semiconductor

Semiconductor is a very important class of materials because of wide applications in this modern world. The following are the properties which gives a rough description of a semiconductor.

1. The electrical conductivity of a semiconductor is generally intermediate in magnitude between that of a conductor and an insulator. That means conductivity is roughly in the range of 10^3 to 10^{-8} siemens per centimeter.

2. The electrical conductivity of a semiconductor varies widely with doping concentration, temperature and carrier injection.

3. Semiconductors have two types of charge carriers, electrons and holes.

4. Unlike metals, the number of charge carriers in semiconductors largely varies with temperature.

5. Generally, in case of semiconductor, increase of temperature enhances conductivity while in case of metals increase of temperature reduces conductivity.

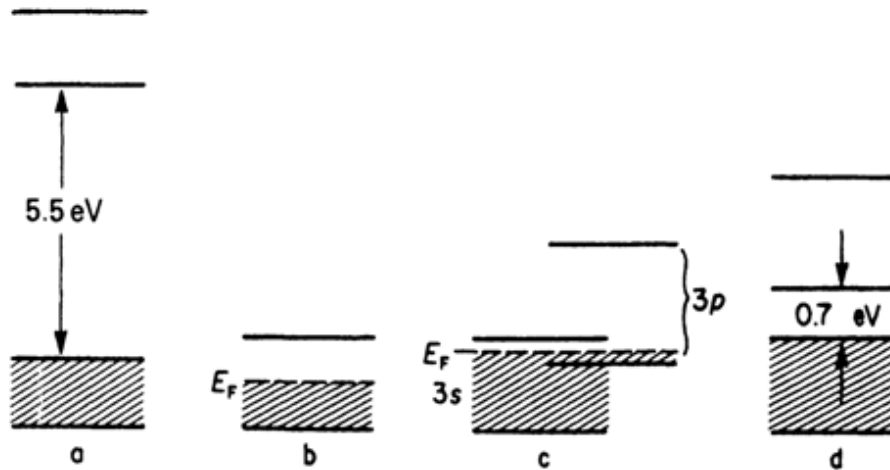6. The semiconductor can be best understood in the light of energy band model of solid.

Figure 11.1: Band gaps shown for (a) Insulator (b) Alkali Metal (c) Other Metal (d) Ge-semiconductor

Energy band structure of solid

Atom has discrete energy levels. When atoms are arranged in a periodic arrangement in a solid the relatively outer shell electrons no longer remain in a specific discrete energy level. Rather they form a continuous energy level, called energy band. In case of semiconductor and insulator, at temperature $0K$ all the energy levels up to a certain energy band, called valence band, are completely filled with electrons, while next upper band (called conduction band) remains completely empty. The gap between bottom of the conduction band and top of the valence band is called *fundamental energy band gap (E_g)*, which is a forbidden gap for electronic energy states. In case of metals, valence band is either partially occupied by electrons or valence band has an overlap with conduction band, as shown in Fig. 11.1(b and c).

In case of semiconductor, the band gap ($\sim 0 - 4eV$) is such that electrons can move from valence band to conduction band by absorbing thermal energy. When electron moves from valence band (VB) to conduction band (CB), it leaves behind a vacant state in valence band, called hole. When electric field is applied, movement of large number of electrons in the valence band can be visualized by the movement of hole as a positive charge particle. The E_g is a very important characteristic property of semiconductor which dictates it's electrical, optical and optoelectrical properties. There are two main types of
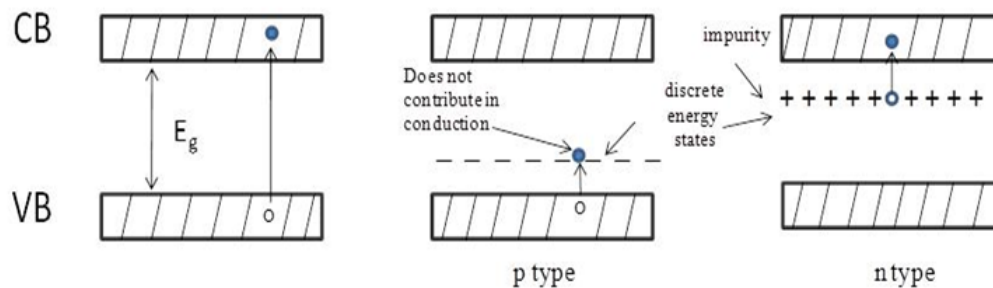

Figure 11.2: Energy band diagram of a semiconductor

semiconductor materials: intrinsic and extrinsic. Intrinsic semiconductor doesn't contain impurity. Extrinsic semiconductors are doped with impurities. These discrete impurity energy levels lie in the forbidden gap. In p-type semiconductor, acceptor impurity, which can accept an electron, lies close to the valence band and in n-type semiconductor, donor
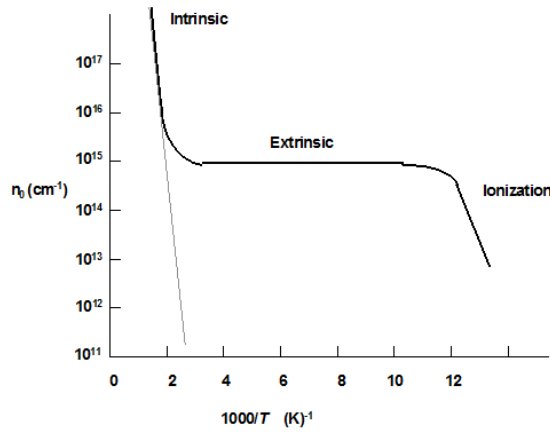
Figure 11.3: Temperature variation of carrier concentration

impurity, which can donate an electron lies close to conduction band.

Temperature variation of carrier concentration

Fig. 11.3 shows the variation of carrier concentration (concentration of holes) in a p-type semiconductor with respect to $1000/T$, where T is the temperature. Initially as temperature increases from $0K$ (i.e. ionization region), the discrete impurity vacant states starts getting filled up from valence band, which creates holes in valence band. Beyond a certain temperature all the impurity states will be filled up with electrons, which lead to the saturation region.

As temperature increases to further higher values, electrons, in the valence band, get sufficient energy to occupy empty states of conduction band (C.B). This region is called intrinsic region. The temperature above which the semiconductor behaves like intrinsic semiconductor is called "Intrinsic temperature".

Conductivity of a semiconductor

The conductivity of a semiconductor is given by

$$\sigma = e(\mu_n n + \mu_p p) \tag{11.1}$$

Where μ_n and μ_p refer to the mobilities of the electrons and holes, and n and p refer to the density of electrons and holes, respectively. The mobility is drift velocity per electric field applied across the material, $\mu = V_d/E$. Mobility of a charge carrier can get affected by different scattering processes.

Effects of temperature on conductivity of a semiconductor

In the semiconductor, both mobility and carrier concentration are temperature dependent. So conductivity as a function of temperature can be expressed by

$$\sigma = e\left(\mu_n(T)n(T) + \mu_p(T)p(T)\right) \tag{11.2}$$

One interesting special case is when temperature is above intrinsic temperature where mobility is dominated by only lattice scattering ($\propto T^{-3/2}$). That means in this temperature region mobility decreases with increase of temperature as $T^{-3/2}$ due to increase of thermal vibration of atoms in a solid.

In the intrinsic region, $n \approx p \approx n_i$, where n_i is the intrinsic carrier concentration. The intrinsic carrier concentration is given by

$$n_i(T) = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} \exp \left(\frac{-E_g}{2kT} \right), \tag{11.3}$$

where, m_n^* and m_p^* are effective mass of electron and hole. Here the exponential temperature dependence dominates $n_i(T)$. The conductivity can easily be shown to vary with temperature as

$$\sigma \propto \exp \left(\frac{-E_g}{2kT} \right). \tag{11.4}$$

In this case, conductivity depends only on the semiconductor band gap and the temperature. In this temperature range, plot of $\ln \sigma$ vs $1000/T$ is a straight line. From the slope of the straight line, the band gap (E_g) can be determined. The procedure of measurement of conductivity is given below.

Four probe technique

Four probe technique is generally used for the measurement of resistivity of semiconductor sample. Before we introduce four probe technique, it is important to know two probe techniques by which you measured resistivity of a nicrome wire. In two probe technique, two probes (wires) are connected to a sample to supply constant current and measure voltage. In the case of nicrome wire (1st experiment), connections are made by pressing the multimeter probes on nichrome wire. The contact between metal to metal probe of multimeter does not create appreciable contact resistance. But in the case of semiconductor the metal – semiconductor contact gives rise to high contact resistance. If two probe configuration is followed for semiconductor sample, voltmeter measures the potential drop across the resistance of the sample as well as the contact resistance. This is shown in the Fig. 11.4(a).

The potential drop across high contact resistance can be avoided by using four probe technique. In the four probe configuration, two outer probes are used to supply current and two inner probes are used to measure potential difference. When a digital voltmeter with very high impedance is connected to the inner two probes, almost no current goes through the voltmeter. So, the potential drop it measures, is only the potential drop across the sample resistance. This is shown in the equivalent circuit diagram given in Fig. 11.4(b). From the measurement of current supplied and voltage drop across the sample, the resistance can be found out. Resistivity of a sample is given by $\rho = cV/I$, where c is a constant.

For the specific arrangement, where the probes are equispaced with the distance between two successive probes as a, and the thickness of the sample is h, the resistivity can be calculated by the following formulas.

Case I: $h \gg a$. In this case it is assumed that the four probes are far from the edge of the sample and the sample is placed on an insulating material to avoid leakage current. The resistivity in this case is given by

$$\rho = 2\pi a \frac{V}{I} \tag{11.5}$$

This is the setup used for our experiment.

Case II: $h \ll a$. In this case the resistivity is given by

$$\rho = \frac{\pi h}{\ln 2} \left(\frac{V}{I} \right) \tag{11.6}$$

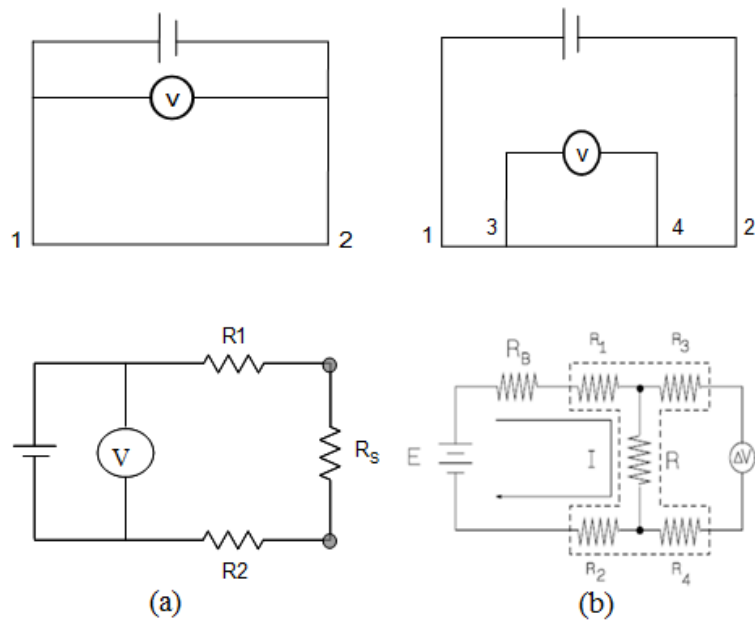Derivation for this is given at the end.

Figure 11.4: (a) Equivalent circuit for two probe measurement. R_1, R_2 are the contact resistances (b) Equivalent circuit for four probe measurement. R_1, R_2 and R_3, R_4 are the contact resistances of current and voltage probes.

Once resistivity (ρ) is determined, conductivity (σ) can be calculated by taking reciprocal of it $(\sigma = 1/\rho)$.

Advantages of using four probe method

- The key advantage of four-terminal sensing is that the separation of current and voltage electrodes eliminates the impedance contribution of the wiring and contact resistances.

- If the probes are separated by equal distance a, and $a \ll h$ then resistivity can be found out without knowing the exact shape and size of the sample.
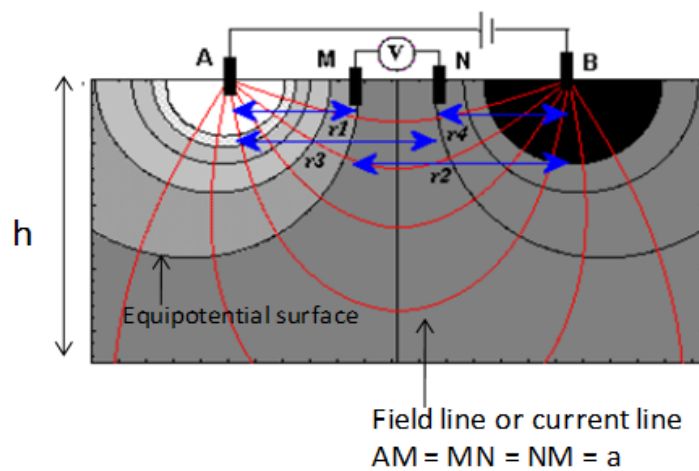

Figure 11.5: Pictorial representations of field lines generated by the applied potential.

Description of the experimental set-up

Probes arrangement It has four individually spring loaded probes. The probes are collinear and equally spaced. The probes are mounted in a teflon bush, which ensure a good electrical insulation between the probes. A teflon spacer near the tips is also provided to keep the probes at equal distance. The whole arrangement is mounted on a suitable stand and leads are provided for the voltage measurement.

Sample Germanium crystal in the form of a chip.

Oven It is a small oven for the variation of temperature of the crystal from the room temperature to about 200^oC (max).
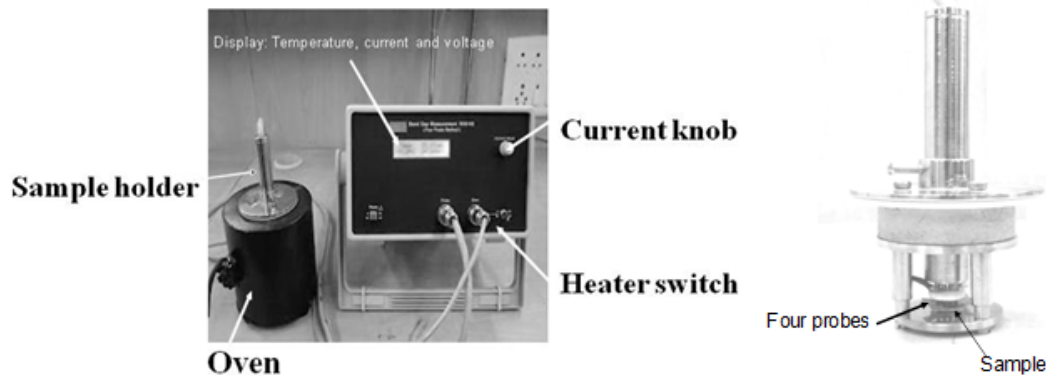

Figure 11.6: Four probe experimental setup.

Procedure

- Switch ON the band gap setup.

- Supply current to the crystal and keep it constant ($3\,mA$) throughout the experiment.

- Initially the temperature of the oven must be at room temperature ($\sim 27^oC$).

- Switch on the oven to start increasing the temperature.

- Note the voltage and temperature at intervals of 5^oC starting from room temperature.

- When temperature reaches 140^oC switch off the oven and note the voltage and temperature for decreasing temperature till it reaches room temperature.

- Find the mean of the two voltages, for increasing and decreasing temperatures. Calculate ρ for each temperature.

- Convert the temperature scale from ^0C to the Kelvin scale (K). The plot of $\ln \sigma$ vs $1/T$ should be a straight line. Calculate the slope (m) of the straight line and finally the band gap E_g from the given formula

$$\sigma = \sigma_o \exp\left(-\frac{E_g}{2KT}\right) \tag{11.7}$$

Observations

Sl.	Temp (T)	$1000/T$	Curr. during inc. temp.	Inc. volt.	Inc. V/I	Curr. during dec. temp.	Dec. volt.	Dec. V/I	Mean volt./curr.	ρ	$\sigma = 1/\rho$	$\ln \sigma$
No.	(^{o}C)	(K^{-1})	(I) (mA)	(V) (mV)	(Ω)	(I) (mA)	(V) (mV)	(Ω)	(Ω)	(Ω m)	($S\ m^{-1}$)	

Results

1.

2.