Laboratory Manual

Semiconductor Physics Lab (BBS09022)

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Students need to write sections 5, 8, 9, 10 and 7 of each experiment in their laboratory note book.

Experiment 1 : Determination of Planck's constant by Einstein's photoelectric effect equation

1. **Aim/Purpose of the Experiment:** To determine the Planck's constant and work function of the metal by using Einstein's photoelectric effect equation.

2. **Learning Outcomes:** Understand the Planck's constant, work function of metal and Photoelectric effect.

3. **Prerequisites:** Students should have knowledge about Photoelectric effect. They also should know the actual value of Planck's constant.

4. **Materials/Equipment/Apparatus/Devices/Software required:**

Photoelectric effect apparatus:

- Photo Sensitive Device: Vacuum photo tube.
- Light source: Halogen tungsten lamp 12 V/35 W.
- Monochromatic Filters: 635 nm, 570 nm, 540 nm, 500 nm, and 460 nm.
- Accelerating Voltage: Regulated Voltage Power Supply

5. Introduction and Theory:

From Einstein's photoelectric equation, we know

$$h\nu = h\nu_0 + \frac{1}{2}mv_{max}^2$$

$$= h\nu_0 + eV_s$$

$$= \phi + eV_s \qquad \dots\dots\dots (1)$$

where ν = frequency of incident light, ν_0 = threshold frequency,

h = Planck's constant,

m = mass of electron, e = charge of an electron, v_{max} = maximum possible velocity of electron,

V_s = stopping potential,

$\phi = h\nu_0$ = work function of the metal.

Now if we draw a graph (V_s vs ν) then from this graph we can get a slope $\frac{\partial V_s}{\partial \nu}$. Therefore, from the equation (1) we can write

$$h = e\frac{\partial V_s}{\partial \nu} \qquad \dots\dots\dots (2)$$

6. Operating Procedure:

(i) Set up a photoelectric apparatus consisting of a vacuum tube with a photosensitive material (such as a metal) as the cathode and a light source.

(ii) At a certain voltage, the photoelectric current will reach zero. This voltage is known as the stopping potential. Measure the stopping potential for different incident light frequencies by using different color filters.

(iii) Make sure to maintain a constant intensity of light while changing the color filters.

(iv) Plot a graph by plotting frequency along the x-axis and stopping potential along the y-axis.

(v) The graph should be a straight line.

(vi) Calculate the slope.

(vii) By measuring the slope from the graph, Planck's constant, h can be determined by using the formula $h = e \times \text{slope}$.

(viii) The minimum energy required to liberate a photoelectron from the metal surface is called the work functions of that metal. Work function can be determined by using the formula $\phi = \frac{h\nu_0}{e}$ (in eV), where ν_0 is the threshold frequency.

8. Observations:

Colour of filter	Wavelength λ (nm)	Frequency ν (Hz)	Stopping Potential V_s (Volt)
Red			
Yellow I			
Yellow II			
Green			
Blue			

9. Calculations & Analysis:

We have drawn a graph (V_s vs ν). From the graph, Slope = _________ Volt.s.
Planck's constant (h) = slope $\times\ e =$ __________ Js.

Threshold frequency (ν) = ________ Hz.

Work function (ϕ) = $\frac{h\nu_0}{e}$ eV = __________.

10. Result & Interpretation:

Standard value of Planck's constant = 6.626×10^{-34} Js.
Experimental value of Planck's constant = _______________ Js.
Work function = ____________ eV.

11. Follow-up Questions:

i) What is the photoelectric effect?
Ans: The photoelectric effect is a phenomenon in which electrons are emitted from a metal when it absorbs photons (particles of light) with sufficient energy. This effect was first explained by Albert Einstein in 1905 and played a crucial role in the development of quantum mechanics and our understanding of the particle nature of light.

ii) What is threshold frequency?
Ans: The threshold frequency is the minimum frequency of light (or photons) required to initiate the photoelectric effect for a specific material.
If the frequency of incident light is below the threshold frequency, no photoelectrons will be emitted from the material, regardless of the light intensity.

iii) What is the work function of metal?
Ans: The work function (ϕ) of a metal is the minimum energy required to remove an electron from the surface of the metal. It is usually measured in electron-volts (eV) or joules (J).

iv) What is the value and dimension of Planck's constant?
Ans: The value of Planck's constant is 6.626×10^{-34} Js. The dimension of Planck's constant is [ML^2T^{-1}].

v) What do you mean by stopping potential?
Ans: The minimum voltage required between the cathode and anode of the photocell which makes the photocurrent zero is called the stopping potential.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 2 : Forward bias I-V characteristics of a p-n junction diode and determination of r_{ac} and r_{dc}

1. **Aim/Purpose of the Experiment:** To study the current-voltage (I-V) characteristics of p-n junction diode in forward bias.

2. **Learning Outcomes:** Determination of dynamic (r_{ac}) and static (r_{dc}) resistances of p-n junction diode in forward bias.

3. **Prerequisites:** It is essential to have a basic understanding of how a p-n junction diode works in forward bias and a basic knowledge of plotting graphs on graph paper.

4. **Materials/Equipment/Apparatus / Devices/Software required:** Power supply, Ammeter, Voltmeter, p-n junction diode, Circuit Board, Connecting Wires.

5. **Introduction and Theory:**

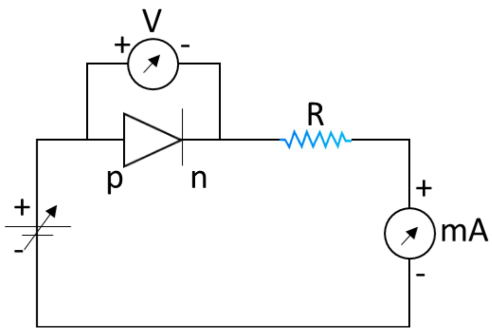


Fig: Circuit diagram of p-n junction diode under forward bias

When a p-side and n-side of a p-n junction diode are connected with the +ve and −ve terminals of a battery, respectively, then the diode is said to be forward-biased. If the applied forward voltage is V volt across the diode, current flowing through it is given by,

$$I = I_S\, exp\left(\frac{eV}{\eta k_B T}\right) \qquad \text{................. (1)}$$

where, I_S = reverse saturation current,
e = magnitude of electron's charge,
k_B = Boltzmann constant,
T = absolute temperature,
η = numerical constant depending on the material of the diode (for Ge, $\eta = 1$ and Si, $\eta = 2$).

If the diode current I is plotted as a function of the forward voltage V, the resulting curve is known as the static characteristics curve. At a specified point P, the dc and ac resistance of the diode can be determined from I-V characteristics curve by using the relation at a relevant point (P).

$$r_{dc}\ (\text{at } P) = \frac{V}{I}$$

$$r_{ac}(\text{at } P) = \frac{\partial V}{\partial I}.$$

6. Operating Procedure:

(i) Set up the circuit of forward bias of p-n junction diode on the circuit board. Connect the p-side of the p-n junction diode to the positive terminal of the power supply and n-side of the diode to the negative terminal of the power supply to make forward biasing of p-n junction diode. Add a series resistor in line with the diode to limit the current and prevent damage.

(ii) Set the forward bias voltage to a low value and gradually increase the voltage across the diode using the power supply while noting the corresponding current values from the ammeter.

(iii) Record multiple voltage-current pairs for various forward bias voltage values.

(iv) Plot a graph with voltage on the x-axis and current on the y-axis. This graph will show the forward bias I-V characteristics of the diode.

Determination of r_{ac} and r_{dc}:

(i) For the I-V characteristics of p-n junction diode, observe the slope of the curve around the operating point P (where the diode is operating in the normal conducting region). The dynamic resistance r_{ac} can be approximated as the reciprocal of the slope of the I-V curve at that point:

$$r_{ac} = \frac{1}{\text{slope}} = \frac{1}{\frac{\partial I}{\partial V}} = \frac{\partial V}{\partial I}.$$

(ii) The static resistance r_{dc} can be approximated at any specified point P on the I-V characteristics curve by the following formula:

$$r_{dc} = \frac{V}{I}.$$

7. Precautions and/or Troubleshooting:

I. The voltmeter and the ammeter should be connected in parallel and in series, respectively, to the diode.

II. Connection should be proper and tight.

III. The supply switch 'ON' should be pressed after completing the circuit.

IV. DC supply should be increased slowly in steps.

V. Reading of the ammeter and voltmeter should be taken, avoiding parallax.

8. Observations:

No. of observation	Forward voltage(V) in volt	Forward current (I) in mA
1		
2		
3		
4		
.		
.		

9. Calculations & Analysis:

At a specified point P on the I-V curve r_{dc} and r_{ac} can be calculated by using the following relations:

$$r_{dc}(at\ P) = \frac{V}{I}$$

$$r_{ac}(at\ P) = \frac{\partial V}{\partial I}$$

10. Result & Interpretation:

Forward bias characteristics for a p-n diode are observed. Exponential increase of I with increase of V is found under forward bias.
The obtained value of static resistance from I-V characteristics curve, $r_{dc}(\text{at } P) =$ ________ Ω.
The obtained value of dynamic resistance from I-V characteristics curve, $r_{ac}(\text{at } P) =$ ________ Ω.

11. Follow-up Questions:

i) What is a p-n junction diode?

Ans: A p-n junction diode is a two-terminal semiconductor device that allows current to flow in one direction (from the p-side to the n-side) while blocking current in the opposite direction. It is a device created by combining p-type and n-type semiconductor materials.

ii) What is I-V characteristics of p-n junction diode?

Ans: The I-V (current-voltage) characteristics of a p-n junction diode describe how the current through the diode varies with the voltage applied across it. The I-V characteristics of a p-n junction diode can be summarized as follows:
Forward Bias: Initially low current, followed by a gradual increase and then a rapid increase as voltage increases beyond the threshold voltage.
Reverse Bias: Low reverse leakage current followed by a sudden increase in reverse current (avalanche breakdown) when the breakdown voltage is exceeded.

iii) What is forward and reverse biasing of p-n junction diode?

Ans: Forward and reverse biasing are two common ways of applying an external voltage to a p-n junction diode.
Forward Bias: In forward bias, the p-side of the diode is connected to the positive terminal and the n-side is connected to the negative terminal of a voltage source.
Reverse Bias: In reverse bias, the p-type side of the diode is connected to the negative terminal of a voltage source, and the n-type side is connected to the positive terminal.

iv) Can you identify the material of the diode by just looking at the I-V characteristics curve?

Ans: The forward current in a diode does not assume a significant value unless the forward voltage exceeds a certain critical value, known as cut-in voltage. For a Ge diode the cut-in voltage is 0.2 V and for Si the cut-in voltage is 0.6 V.

v) What is r_{dc} and r_{ac} on p-n unction diode?

Ans: Static Resistance is the normal ohmic resistance in accordance with Ohm's Law. Static resistance is also defined as the ratio of DC voltage applied across diode to the DC current or direct current flowing through the diode.

$$r_{dc} = \frac{V}{I}$$

The dynamic resistance is the resistance offered by the p-n junction diode when AC voltage is applied. It is also defined as the ratio of the change in voltage to the change in current.

$$r_{ac} = \frac{\partial V}{\partial I}$$

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment No 3 : I-V characteristics of Zener diode in reverse bias condition and Determination of r_{ac} and r_{dc}

1. **Aim/Purpose of the Experiment:** To study the current-voltage (I-V) characteristics of a Zener diode in reverse bias condition.

2. **Learning Outcomes:** Determination of dynamic (r_{ac}) and static (r_{dc}) resistance of Zener diode in reverse bias condition.

3. **Prerequisites:** It is essential to have a basic understanding of how a Zener diode works in reverse bias condition and a basic knowledge of plotting graph on a graph paper.

4. **Materials/Equipment/Apparatus/Devices/Software required:** Power supply, Ammeter, Voltmeter, Zener diode, Circuit Board, Connecting Wires

5. **Introduction and Theory:**

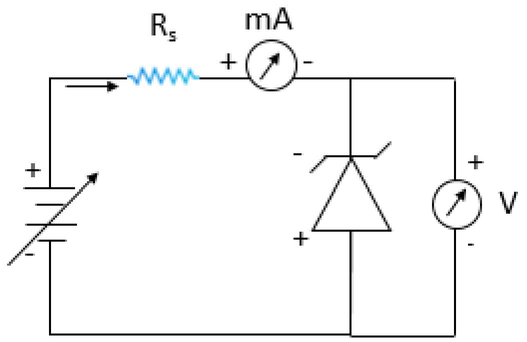


Fig: Circuit diagram of reverse-biased Zener diode

When a Zener diode is reverse biased (positive voltage is applied to the n-side with respect to the p-side) the current flowing through the diode is very small at the start. Above a certain value of reverse voltage (breakdown voltage), the current increases rapidly although the voltage remains nearly constant. The diode is then said to be operating in the breakdown region.
The dc or static resistance of the Zener diode at a point P (say) is given by

$$r_{dc} = \frac{V_Z}{I_Z}$$

and the ac or dynamic resistance of the Zener diode is given by

$$r_{ac} = \frac{\partial V_Z}{\partial I_Z}.$$

Both r_{dc} and r_{ac} can be determined from the current-voltage (I-V) characteristics curve of the Zener diode.

6. **Operating Procedure:**

(i) At first identify the anode (p-side) and the cathode (n-side) of the Zener diode and make the circuit connections as shown in the given figure.

(ii) Keeping the control knob of the power supply to the minimum position switch on the ac mains operating the power supply.

(iii) Now gradually increase the reverse voltage in small steps and in each step note the reverse current from the given ammeter.

(iv) Continue the process up to a suitable value of reverse current which must lie well below the maximum allowable reverse current.

(v) Draw a curve by plotting the reverse voltage (V) in V along the (– ve) x-axis and the corresponding reverse current (I) in mA along (–ve) y-axis.

(vi) Identify a small portion of the I-V curve in the breakdown region where the current and voltage variations are small. This is typically a small signal variation around the operating point.

(iii) For the reverse characteristics of Zener diode, observe the slope of the curve around the operating point P. The dynamic resistance is approximated as the reciprocal of the slope of the I-V curve at that point.

$$r_{ac} = \frac{1}{\text{slope}} = \frac{1}{\frac{\partial I}{\partial V}} = \frac{\partial V}{\partial I}.$$

(iv) The static resistance r_{dc} can be approximated at any specified point P on the I-V characteristics curve by the following formula:

$$r_{dc} = \frac{V}{I}.$$

7. Precautions and/or Troubleshooting:

I. Care should be taken so that the current through the Zener diode does not exceed the maximum read value. For this purpose, series resistance (R_S) of proper value is used.

II. In the Zener breakdown region, voltage across the diode changes very little. Therefore, a voltmeter with a very small gradation should be used.

8. Observations:

No. of observation	Zener reverse voltage (V) in volt	Zener reverse current (I) in mA
1		
2		
3		
4		
.		
.		

9. Calculations & Analysis:

$$r_{dc}\,(\text{at } P) = \frac{V_Z}{I_Z}$$

$$r_{ac}(\text{at } P) = \frac{\partial V_Z}{\partial I_Z}.$$

10. Result & Interpretation:

From the I-V characteristics, the obtained value of r_{dc} (at P) =_______Ω and r_{ac} (at P) = _______Ω.
Zener Breakdown is obtained (From graph) at ~________ V.

11. Follow-up Questions:

i) What is Zener diode?
Ans: A Zener diode is a silicon semiconductor device that permits current to flow in either a forward or reverse direction. The diode consists of a special, heavily doped p-n junction, designed to conduct in the reverse direction when a certain specified voltage (break down voltage) is reached

ii) What is reverse biasing of Zener diode?
Ans: Reverse biasing of a Zener diode refers to applying a voltage in the reverse direction across the diode's terminals, meaning that the P-type side of the diode is connected to the negative terminal of the power supply, and the N-type side is connected to the positive terminal of the power supply. In this configuration, the diode is operated in its breakdown region, known as the Zener breakdown.

iii) What is Zener breakdown?
Ans: Zener breakdown happens in heavily doped PN junction diodes. In these diodes, if the reverse bias voltages reach closer to Zener Voltage, the electric field gets stronger and is sufficient enough to pull electrons from the valance band. These electrons then gain energy from the electric field and break free from the atom. Thus, for these diodes in the Zener breakdown region, a slight increase in the voltage causes a sudden increase in the current.

iv) What is Avalanche Breakdown?
Ans: Avalanche breakdown is a phenomenon that occurs in semiconductor devices, particularly p-n junction diodes, when they are operated in reverse bias. It involves the sudden and rapid increase in current due to the generation and multiplication of electron-hole pairs within the depletion region of the diode. This breakdown mechanism is characterized by a chain reaction of carrier generation and impact ionization, leading to a significant increase in current flow.

v) Write down some applications of Zener diode.
Ans: Zener diodes are widely used in all kinds of electronic circuits. The two main applications are voltage regulator and over voltage protection.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 4 : To draw the load and line regulation characteristics of a Zener diode and determination of percentage regulation

1. **Aim/Purpose of the Experiment:** To study the load and line regulation characteristics of a Zener diode and hence to determine the percentage regulation.

2. **Learning Outcomes:** To understand the performance of Zener diode as a voltage regulator.

3. **Prerequisites:** It is essential to have a basic understanding of how a Zener diode works in reverse bias conditions and a basic knowledge of plotting graphs on graph paper.

4. **Materials/Equipment/Apparatus / Devices/Software required:** Power supply, Ammeter, Voltmeter, Zener diode, Circuit Board, Connecting Wires.

5. **Introduction and Theory:**

The voltage across a Zener diode in the breakdown region is almost constant. This property enables the application of the Zener diode as a voltage regulator.

a) Line regulation: In this type of regulation, series resistance and load resistance are fixed. Only the input voltage is varied. The output voltage remains the same as long as the input voltage is maintained above a minimum value.

$$\text{Percentage of Line Regulation } (S_{Line}) = \frac{\Delta V_o}{\Delta V_i} \times 100\%$$

where V_0 is the output voltage and V_i is the input voltage. ΔV_0 is the change in the output voltage for a particular change in the input voltage, ΔV_i.

b) Load regulation: In this regulation, the input voltage is fixed and the load resistance is varied. The output voltage remains the same as long as the load resistance is maintained above a minimum value.

$$\text{Percentage of Load Regulation } (S_{Load}) = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

where V_{NL} is the no-load voltage – the output voltage corresponding to zero load current, i.e., infinite load resistance (open-load condition) and V_{FL} is the full-load voltage – the output voltage corresponding to the maximum load (current), i.e., the minimum load resistance.

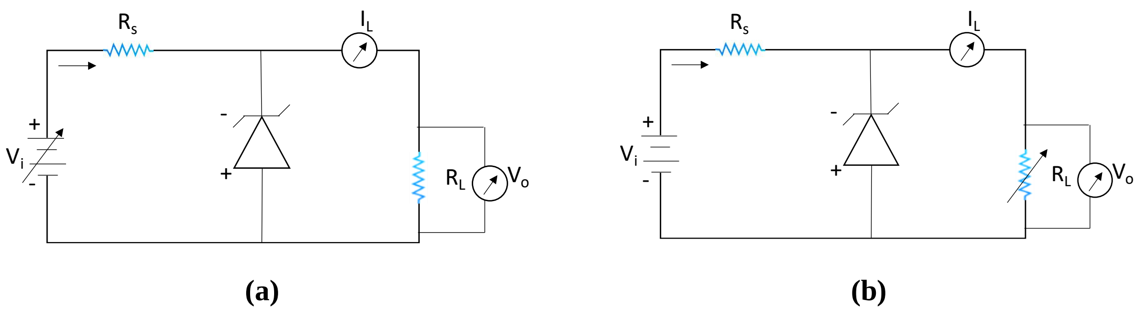


Fig: Circuit diagram of (a) line regulation & (b) load regulation

6. Operating Procedure:

Line Regulation:

(i) To study the line regulation set the input voltage V_i to a suitable low value such that the voltage across the Zener diode does not go below V_z.

(ii) Adjust the load current I_L to a suitable fixed value by changing R_L.

(iii) Note the input (V_i) and the output $(V_L = V_o)$ voltages from the connected two voltmeters respectively.

(iv) Now increase the input voltage in small steps and at each step note V_i and V_L $(= V_o)$.

(v) Check the constancy of the load current at each step and if necessary, adjust it to the chosen fixed value by changing R_L.

Load Regulation:

(i) To study the performance of the Zener diode as a voltage regulator, make the circuit connections as shown in the figure.

(ii) Keep the input voltage V_i fixed at a value much higher than V_z, Zener voltage.

(iii) Disconnect R_L (load Resistance). This makes $I_L = 0$. Note the output voltage from the voltmeter which is connected across R_L. This voltage is V_{NL}.

(iv) Insert suitable high load resistance R_L to get a minimum load current I_L.

(v) Note this value of I_L from the given ammeter and the corresponding output load voltage V_L from the voltmeter.

(vi) Increase the load current I_L in small steps and at each step note the readings for I_L and V_L.

(vii) Check the constancy of the input at every step and if necessary, adjust it.

(viii) Make sure that R_L is not short-circuited in any case.

7. Precautions and/or Troubleshooting:

I. Care should be taken so that the current through Zener diode does not exceed the maximum specified value. For this purpose, a series resistance (R_S) of proper value is used.

II. In the Zener breakdown region, the voltage across the diode changes very little. Therefore, a voltmeter with a very small gradation should be used.

8. Observations:

Line Regulation:

Fixed load current = ... mA

No. of observation	Input voltage(V)	Load Voltage(V)

Load Regulation:

Fixed input voltage = ……….. Volt

No. of Observation	Load Current (mA)	Load Voltage (V)

9. Calculations & Analysis:

From the line regulation graph,

$\Delta V_o =$ ………. Volt, $\Delta V_i =$ ………. Volt.

$$\text{Percentage Line Regulation } (S_{Line}) = \frac{\Delta V_o}{\Delta V_i} \times 100\%.$$

From the load regulation graph, $V_{NL} =$ ………. Volt, $V_{FL} =$ ……… Volt.

$$\text{Percentage load regulation } (S_{Load}) = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%.$$

10. Result & Interpretation:

As the line and load regulation percentages are obtained as _______ and _______, respectively, the Zener diode is working as _______ voltage regulator.

11. Follow-up Questions:

i) How is a Zener diode used for voltage regulation?
Ans: Zener diodes are often used in voltage regulation circuits to maintain a stable output voltage regardless of fluctuations in the input voltage. By connecting a Zener diode in reverse bias across the load, it acts as a voltage reference, maintaining a nearly constant voltage drop across itself. This helps in stabilizing the output voltage.

ii) What is line regulation?
Ans: In this type of regulation, series resistance and load resistance are fixed, only input voltage is changing. Output voltage remains the same as long as the input voltage is maintained above a minimum value.

iii) What is load regulation?
Ans: In this type of regulation, input voltage is fixed and the load resistance is varying. Output volt remains same, as long as the load resistance is maintained above a minimum value.

iv) What is the difference between p-n diode and Zener diode?

Ans:

Basis for comparison	**P-N diode**	**Zener diode**
Definition	It is a diode which conducts only in one direction, i.e. in forward direction.	This diode allows the current to flow in both forward and reverse direction.
Doping Level	Low	High
Applications	Rectification	Voltage regulator

v) In a voltage regulation circuit using a Zener diode, what role does the series resistor play?
Ans: In a voltage regulation circuit using a Zener diode, the series resistor plays a crucial role in limiting the current through the Zener diode and ensuring stable operation of the voltage regulator.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 5 : To Determine the numerical aperture of optical fiber

1. **Aim/Purpose of the Experiment:** To find the numerical aperture of a given optic fiber and hence to find its acceptance angle.

2. **Learning Outcomes:** Understand the working procedure of optical fiber.

3. **Prerequisites:** Students should have basic knowledge about optical fiber.

4. **Materials/Equipment/Apparatus / Devices/Software required:** Laser source, optical fiber, numerical aperture kit, numerical aperture scale.

5. **Introduction and Theory:**

If θ_0 is the semi- vertical angle of the acceptance cone of the fiber, the numerical aperture (abbreviated as N.A.) of the fiber is defined as $\sin\theta_0$. It can be shown that

$$\mathrm{N.A.} = \sin\theta_0 = n_{core}\left[2 \times \frac{n_{core}-n_{cladding}}{n_{core}}\right]^{\frac{1}{2}} = n_{core}[2\Delta]^{\frac{1}{2}} \qquad \text{..........(1)}$$

n_{core} = refractive index of the core,
$n_{cladding}$ = refractive index of the cladding,

$$\Delta = \frac{n_{core}-n_{cladding}}{n_{core}} \qquad \text{..........(2)}$$

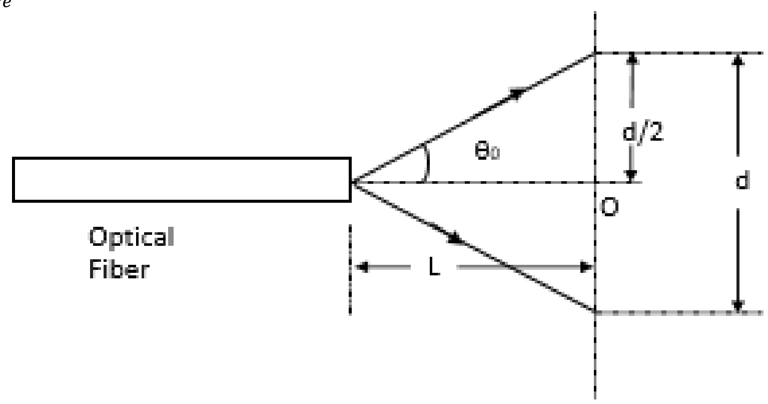


Fig.: Schematic ray diagram of optical fiber indicating the acceptance angle.

Let d be the diameter of the circular spot on the screen at a distance L from the fiber end, then we can write

$$\mathrm{N.A.} = \sin\theta_0 = \frac{\frac{d}{2}}{\sqrt{L^2+\frac{d^2}{4}}} = \frac{d}{\sqrt{(4L^2+d^2)}} \qquad \text{............ (3)}$$

Thus, measuring d and L, N. A. can be calculated.

6. **Operating Procedure:**

i) The measurement of numerical aperture step by step procedure is as follows:
ii) First switch on the power supply of the numerical aperture kit. Red light should appear at the end of the optical fiber.
iii) Hold a white screen (paper/graph paper) at a fixed distance from the optical fiber.

iv) Measure the distance L from the optical fiber to the screen and also the diameter (d) of the laser spot on the paper.

v) Substitute the measured values of L and d in the N.A. formula

vi) $\mathrm{N.A.} = \sin\theta_0 = \frac{\frac{d}{2}}{\sqrt{L^2+\frac{d^2}{4}}} = \frac{d}{\sqrt{4L^2+d^2}}.$

vii) Repeat the experiment by increasing the distance between the paper screen and the optical fiber.

7. Precautions and/or Troubleshooting:

I. Smaller N.A. makes it harder to launch power into the fiber.

II. In case the intensity within the circular spot is not evenly distributed, some turns of the fiber should be wound on the mandrel.

8. Observations:

Obs. No.	$L\ (mm)$	$d(mm)$	$\mathrm{N.A.} = \sin\theta_0$	θ_0°

9. Calculations & Analysis: $\mathrm{N.A.} = \sin\theta_0 = \frac{d}{\sqrt{4L^2+d^2}}.$

L is the distance from the optical fiber to the screen and d is the diameter of the laser spot on the paper.

10. Result & Interpretation:

Average $\mathrm{N.A.}$ = …………………

Average Acceptance angle = ………………

11. Follow-up Questions:

i) What is the numerical aperture of optical fiber?

Ans: The numerical aperture (NA) of an optical fiber is a fundamental parameter that characterizes the light-gathering ability and light-confining ability of the fiber. Mathematically, the numerical aperture of an optical fiber is given by: NA = n * sin(θ), where: NA is the numerical aperture, n is the refractive index of the medium surrounding the fiber (usually air), θ is the maximum angle with respect to the fiber axis at which light can enter the fiber and still be guided by total internal reflection.

ii) What is optical fiber?

Ans: An optical fiber is a thin, flexible, and transparent filament made of glass or plastic that is used for transmitting light signals over long distances. It serves as a waveguide, guiding light along its length through multiple internal reflections.

iii) What is the principle on the basis of which optical fibers work?

Ans: Optical fibers works on the principle of total internal reflection of light. When light ray strikes at the internal surface of optical fiber called core such that incidence angle is greater than critical angle, then incident light ray reflects in the same medium and this phenomenon repeats. In this way light signal travels from one end of the cable to another end.

iv) Write down the numerical aperture of optical fiber in terms of refractive index of material of optical fiber.

Ans: The numerical aperture in terms of the refractive indices of the core and cladding becomes $\mathrm{N.A.} = \sqrt{n_1^2 - n_2^2}$ where, n_1 is the refractive index of the core and n_2 is the refractive index of the cladding.

v) What are the uses of optical fibers?

Ans: Optical fibers have a wide range of applications across various fields due to their ability to transmit light signals over long distances with minimal signal loss. Some key applications of optical fibers are telecommunications, internet connectivity, cable television, medical imaging, laser delivery etc.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 6 : To determine the attenuation coefficient in optical fiber

1. **Aim/Purpose of the Experiment:** Determination of attenuation co-efficient in optical fiber.

2. **Learning Outcomes:** Understand the application of optical fiber.

3. **Prerequisites:** Students should have basic knowledge about optical fiber.

4. **Materials/Equipment/Apparatus/Devices/Software required:** Optical fiber trainer kit, optical fiber and laser source.

5. **Introduction and Theory**

In order to find attenuation loss in decibels per meter (Abbreviated as dB/m), the working formula should be as

$P_{output} = P_{input} 10^{\frac{-\alpha z}{10}}$ .... (1)

where 'z' is the length of the fiber in meter, α is the attenuation coefficient in dB/m,

P_{input} is the power to the input of the fiber i.e. at z = 0 and P_{output} is the power at the output end i.e. at

$z = z_0$.

Let us consider two fibers of lengths L_1 and L_2 ($L_2 > L_1$), both being fed by same input (P_{input}). Let the respective outputs be P_2 and P_1.Accordingly, from (1) we can write

$P_1 = P_{input} 10^{\frac{-\alpha L_1}{10}}$ .... (2)

$P_2 = P_{input} 10^{\frac{-\alpha L_2}{10}}$ .... (3)

Dividing (2) by (3) we get

$$\frac{P_1}{P_2} = 10^{\frac{-\alpha}{10}(L_1 - L_2)}$$

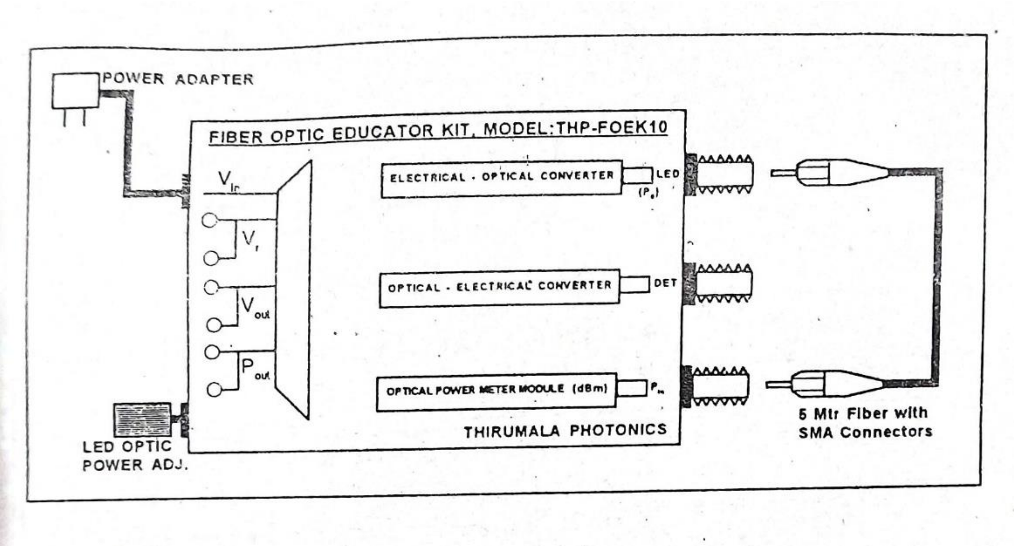
or, $\log_{10}\frac{P_1}{P_2} = -\frac{\alpha}{10}(L_1 - L_2)$

or, $\alpha = \frac{10}{(L_1 - L_2)}\log_{10}\frac{P_1}{P_2}$ .... (4)

α in dB/m.

6. Operating Procedure

The schematic diagram of the Optical Fiber loss measurement is shown in figure



Step 1 :

Connect one end of the '1' Meter Optical Fiber PatchCord to LED (P_0) of the THP-FOEK10 and the another end to the 'P_{in}' of the THP-FOEK'10 (i.e. launching output power of a FO LED at 660 nm into OF cable and output of OF cable is launching into power meter module). Check out the Fiber is free of all twists and strains.

Step 2 :
Connect DMM test leads to 'Pout' red lead to red socket and black lead to black socket respectively and set the DMM to 2000 mV range. Now, Power Meter is ready to function.

Step 3 :

Connect Power Adapter plug to THP-FOEK10 socket 'V_{in}' and Plug the adapter to 230 VAC line. Switch on ON/OFF switch of THP-FOEK10.

Step 4:

Adjust the 'SET P_o /If ' knob to set output power of the FO LED to the value, -13.5 dB m i.e. DMM reading will be -135 mV.

Note this as P_{01} .

Note : The Power Meter Module is calibrated at -13.5 dBm.

Step 5:

Remove the '1' Meter OF PatchCord from THP-FOEK10 and connect '5' Meter OF PatchCord as given in Step 1.Do not disturb 'SET P_o /If' ,note the DMM Reading/10 as P_{02} .

Step 6:

Remove the one end of the '5' Meter PatchCord at 'P_{in}' then connect this to one side of the provided SMA Mating Sleeve. Another side of SMA Mating Sleeve connect with the one end of the '1' Meter PatchCord connect to the 'P_{in}' of THP-FOEK10. Note DMM reading/10 as P_{o3} .

(P_{o2} - P_{o3}) gives loss in '1' Meter OF Cable plus due to the SMA Mating Sleeve. (P_{o1} - P_{o3}) gives loss in the '5' Meter OF Cable plus loss due to the SMA Mating Sleeve. Here, it is assumed that 4.8 dB is the loss in the SMA Mating Sleeve.

7. Precautions and/or Troubleshooting

I. Attenuation in fiber means loss of optical power in the fiber itself. This loss may arisedue to many aspects, some of which are as follows a) Material absorption/scattering losses, b) micro-bending /macro-bending, c) leakage from core, d) splice/joint losses, e) Inverse square law losses.

II. The attenuation is also a function of wavelength to be studied. Loss increases considerably when the operating wavelength is beyond 1550 nm.

III. The attenuation for silica fiber is as small as 0.154 dB/km at operating wavelength 1550 nm. But the attenuation can go up to 10 dB/m for fiber plastic.

8. Observations

Table 1 (Wavelength λ used = ……….. nm)

Different observations correspond to different gain of output amplifier

Obs. No.	P_1	P_2	Loss in dB/m	Average loss (dB/m)

Table 2 (Wavelength λ used = ……….. nm)

Different observations correspond to different gain of output amplifier

Obs. No.	P_1	P_2	Loss in dB/m	Average loss (dB/m)

9. Calculations & Analysis:

10. Result & Interpretation:

11. Follow-up Questions:

i) What is attenuation in optical fiber?

Ans: The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses. Optical losses of a fiber are usually expressed in decibels per kilometer (dB/km). The expression is called the fiber's attenuation coefficient α and the expression is

$$\alpha = \frac{10}{L_2 - L_1} \log_{10} \frac{P_1}{P_2} \quad \text{in dB/m}$$

where, P_1 and P_2 are the power at the distances L_1 and L_2.

ii) What are the main factors that contribute to attenuation in optical fibers?

Ans: Attenuation in optical fibers refers to the reduction in the intensity of an optical signal as it travels along the length of the fiber. Overall, a combination of absorption, scattering, bending losses, and other factors contribute to attenuation in optical fibers.

iii) What are the units of the attenuation coefficient in optical fibers?

Ans: The attenuation coefficient in optical fibers is typically measured in decibels per unit length (dB/m). This unit is commonly used in the field of fiber optics because it provides a logarithmic representation of how much signal strength is lost per unit length of the fiber.

iv) What is the core and cladding of optical fiber?

Ans: An optical fiber consists of two main components: the core and the cladding. The core is the innermost part of the optical fiber and serves as the pathway for the light signal to travel. The cladding surrounds the core and is made of a material with a slightly lower refractive index than the core.

v) Why the refractive index of the core is higher than cladding in optical fiber?

Ans: The refractive index of the core in an optical fiber is intentionally made higher than that of the cladding to achieve a phenomenon called total internal reflection. This phenomenon of total internal reflection allows the light signal to bounce back and forth within the core, effectively traveling along the length of the fiber. The core's higher refractive index creates a situation where light remains confined within the core, resulting in minimal loss of signal strength due to leakage or scattering.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 7 : Determination of bandgap of a given semiconductor by four probe method

1. **Aim/Purpose of the Experiment:** To study the temperature dependence of resistivity of a semiconductor (using four probe method) and to determine the bandgap of a given semiconductor material (Ge).

2. **Learning Outcomes:** Understand the basic knowledge of the band gap of a semiconductor.

3. **Prerequisites:** Students should have a basic idea about semiconductors.

4. Materials/Equipment/Apparatus / Devices/Software required

I. Four probe apparatus,
II. sample (a Ge crystal in the form of a chip),
III. oven,
IV. thermometer,
V. constant power supply,
VI. oven power supply,
VII. panel meters for measurement of current and voltage.

5. Introduction and Theory:

The energy gap between the top of the valence band (E_v) and the bottom of the conduction band (E_c) is known as the bandgap $E_g = E_c - E_v$.
The band gap of a semiconductor is given by

$$\ln\rho = \frac{Eg}{2k_BT} - \ln A \quad \text{.........................} (2)$$

where ρ is the resistivity of the semiconductor,
k_B is the Boltzmann constant ($= 8.6 \times 10^{-5}$ eV/K),
T is the absolute temperature and A is a constant.

The resistivity of the given semiconductor is given by

$$\rho = \frac{\rho_0}{G_7(W/S)} \quad \text{............................} (3)$$

The correction factor:

$$G_7(W/S) = \frac{2S}{W}\ln 2 \quad \text{........................} (4)$$

Again, $$\rho_0 = \frac{V}{I}2\pi S \quad \text{.......................} (5)$$

where, V is the voltage,
I is the fixed current,
W is the thickness of the sample $= 0.5$ mm $= 0.05$ cm,
S is the distance between any two probes of the four probes, used to measure the resistivity of the

semiconductor sample (see the follow-up questions).
Using eqs. (4) and (5), eq. (3) can be written as

$$\rho = \frac{\frac{V}{I}2\pi S}{\frac{2S}{W}\ln 2} = \left(\frac{\pi W}{I\ln 2}\right)V.$$

6. Operating Procedure

(i) Switch on the mains supply of four probe set up and put the digital panel meter in the current measuring mode through the selector switch. In this position LED facing mA would glow. Adjust the current to a desired value (low).

(ii) Now put the digital panel meter in voltage measuring mode. In this position LED facing mA would glow and the meter would read the voltage between the probes.

(iii) Switch on the temperature controller and adjust the set temperature.

(iv) The LED would light up indicating the oven is 'ON' and the temperature would start rising.

(v) Keeping the current constant increase the temperature of the oven in suitable steps and in each step note the temperature and the potential difference (V) across the specimen and calculate the resistivity by using the formula $\rho = \left(\frac{\pi W}{I\ln 2}\right)V$ (see the theory part).

(vi) Decrease the temperature of the oven in similar steps, allow sufficient time in each step to attain steady state, and then note the temperature and the potential difference (V) across the specimen and current I. Hence obtain the value of ρ at different temperatures.

(vii) Obtain the mean of the two values of ρ for each temperature.

(viii) For each temperature calculate the value of $\frac{1}{T}$ in K^{-1} and the value of $\ln\rho$.

(ix) Draw a curve by plotting $\frac{1}{T}$ in K^{-1} along the x-axis and $\ln\rho$ along the y-axis.

(x) From the curve find the slope and then calculate E_g in eV by following the formula $E_g = 2k_B \times \text{slope}$.

7. Precautions and/or Troubleshooting

I. Current should be kept constant throughout the experiment.
II. The germanium crystal being very brittle, minimum pressure is maintained for proper electrical contacts.
III. All the observations should be noted while the temperature decreases.

8. Observations

Fixed current (I) = ………… mA.

No. of obs.	Temperature, t (^{0}C)	Voltage (mV)	Temperature, $T = t + 273$ (K)	T^{-1} (K^{-1})	$\rho = \left(\frac{\pi W}{I\ln 2}\right)V$ (Ω.cm)	$\ln\rho$

9. Calculations & Analysis:

$$E_g = 2k_B \times \text{slope of } \ln\rho \text{ vs } \frac{1}{T} \text{ plot.}$$

10. Result & Interpretation: Standard value of bandgap E_g is 0.7 eV (in the case of Ge semiconductor). Experimentally we have determined the band gap as _________ eV.

11. Follow-up Questions

i) What is bandgap?
Ans: It is the minimum energy gap between the valance band and the conduction band. It is also called the forbidden energy gap.

ii) What are the valance band and the conduction band?
Ans: The outermost energy band which is completely filled up is called the valance band. The band just above the valance band is called the conduction band.

iii) What are the values of E_g for Ge and Si?
Ans: $E_g = 0.7$ eV for Ge and $E_g = 1.2$ eV for Si at 0 K.

iv) Distinguish between conductor, semiconductor, and insulator in terms of energy bandgap.
Ans: For conductor energy band gap is $E_g = 0$ eV. For semiconductor: $0 \text{ eV} < E_g < 3 \text{ eV}$ and for insulator $E_g > 3$ eV.

v) What is the four probe method?
Ans: The four probe method, also known as the four-point probe method, is a technique used for accurately measuring the electrical resistivity or sheet resistance of a material, particularly thin films, semiconductors, and other materials with relatively high resistivity. This method involves four equally spaced electrical probes (Two probes are for current carrying and the other two are for voltage sensing).

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 8 : Determination of Hall coefficient of a semiconductor

1. **Aim/Purpose of the Experiment:** To determine the Hall voltage developed across a given semiconductor material and to calculate the Hall coefficient.

2. **Learning Outcomes:** Understand the basic knowledge of the Hall effect and its applications in semiconductor.

3. **Prerequisites:** Students should have knowledge about Hall effect and semiconductor devices.

4. **Materials/Equipment/Apparatus / Devices/Software required:**

Hall Effect experiment kit consists of the following:

- Hall probe (Ge crystal mounted on a PCB)
- Electromagnet
- Power supply for electromagnet
- Constant current power supply with two digital meters:
  a) Digital millivoltmeter 0-200 mV
  b) Digital milliammeter 0-20 mA
- Digital gauss meter with Hall probe
- Wooden stand for probes.

5. Introduction and Theory: We know the static magnetic field has no effect on the charges unless they are in motion. When charges flow, a magnetic field directed perpendicular to the direction of flux produces a mutually perpendicular force on the charges. When this happens, electrons and holes will be separated by opposite forces. They will in turn produce an electric field ($\vec{E}$) which depends on the cross product of magnetic field ($\vec{B}$) and the current density ($\vec{J}$):

$$\vec{E} = R_H\left(\vec{J} \times \vec{B}\right) \qquad \dots\dots\dots (1)$$

where R_H is called the Hall coefficient. Now we consider a bar semiconductor with its dimensions along the x-, y-, and z-axes. Let $\vec{J}$ be directed along the x-axis and $\vec{B}$ along the z-axis, then $\vec{E}$ will be along the y-axis.

In general, Hall voltage is not a linear function of the applied magnetic field. Thus, the Hall coefficient is not generally a constant, but a function of the applied magnetic field.

The working formula is: $$R_H = \frac{V_H t}{I_H B} \qquad \dots\dots\dots (2)$$

where, I_H is current flowing through the semiconductor,
t is the thickness of the semiconductor $= 0.5$ mm (supplied)
V_H is the Hall voltage.

6. Operating Procedure:

(i) Switch on the constant current source and measure the magnetic field by the gaussmeter by placing the gauss probe between the electromagnet by gradually increasing the current.

(ii) Plot a calibration curve by plotting current along the x-axis and magnetic field along the y-axis.

(iii) Switch on the Hall effect set up and adjust the current.

(iv) Place the semiconductor (Hall probe) between the poles of the electromagnet.

(v) Switch over the display to voltage side.

(vi) Switch on the electromagnet power supply and adjust the current to a fixed value so that the magnetic field is fixed.

(vii) Rotate the semiconductor (Hall probe) till it become perpendicular to magnetic field. Hall voltage will be maximum in this adjustment.

(viii) Measure Hall voltage for different current at constant magnetic field.

(ix) Plot a graph by plotting the Hall current (I_H) along the x-axis and the Hall voltage (V_H) along the y-axis.

(x) Calculate the slope from the V_H vs I_H plot.

(xi) Calculate the fixed magnetic field from the calibration curve.

(xii) Finally, calculate the Hall coefficient R_H by using the formula $R_H = \frac{V_H\, t}{I_H\, B}$ (see the theory part), t is the thickness of the semiconductor.

7. Precautions and/or Troubleshooting

I. To obtain uniform magnetic field the distance between the poles should be kept small.

II. Hall probe connections are made in such a way that maintain the ohmic (not rectifying) contact and it is imperative not to touch or adjust the connections, otherwise the entire experiment will become meaningless.

III. The sample is very brittle and hence careful handling is maintained.

IV. The Hall probe is properly centered and oriented in the magnetic field such that maximum Hall-voltage is generated.

V. The initial Hall-voltage without magnetic field is to be monitored continuously monitorthroughout the experiment and has been subtracted from the actual Hall-voltage reading.

VI. The sample current is not allowed to exceed beyond the prescribed limit.

VII. The movable pole pieces of the electromagnet are symmetrically moved in order to avoid asymmetry in the magnetic field.

8. Observations:

Table-1: **Calibration curve data table**

No. of obs.	Magnetizing current (I) in amp	Magnetic field (B) in gauss

Table-2: **Hall current vs Hall voltage data at constant magnetic field**

Magnetizing current (I') (Amp)	Magnetic field (B') (gauss)	Hall current (I_H) (mA)	Hall voltage(V_H) (mV)

9. Calculations & Analysis:

a. We draw a graph of magnetizing current (along x-axis) vs magnetic field (along y-axis).
b. We draw a graph Hall current I_H along x-axis and Hall voltage V_H along y-axis.
From the V_H vs I_H graph, at a particular point P on the straight line,

$V'_H =$______________
$I'_H =$______________
Therefore, $R_H = \frac{V'_H\, t}{I'_H\, B'} =$_________________

10. Result & Interpretation:

In this experiment we have determined the value of Hall coefficient, R_H of the the semiconductor as ……… $\Omega.\mathrm{m/T}$.

11. Follow-up Questions:

i) What is Hall effect?
Ans: The Hall effect is a fundamental physics phenomenon that occurs when an electric current flows through a semiconductor placed in a magnetic field. It results in the generation of a voltage perpendicular to both the direction of the current and the magnetic field. The Hall effect is named after the American physicist Edwin Hall, who discovered it in 1879.

ii) What is Hall coefficient?
Ans: The Hall coefficient (also known as the Hall constant) is a material-specific parameter that quantifies the relationship between the induced electric field created by the Hall effect and the external magnetic field and current applied to a material. The mathematical form of Hall coefficient is:

$$R_H = \frac{V_H t}{I_H B}$$

where, V_H is the Hall voltage, t is the thickness of the sample, I_H is the Hall current and B is the applied magnetic field.

iii) What is the significance of Hall coefficient?
Ans: The Hall coefficient has both magnitude and sign, and it provides valuable information about the type of charge carriers (electrons or holes) in the material and their mobility. The sign of the Hall coefficient indicates the polarity of the charge carriers. Positive R_H corresponds to positive charge carriers (holes), and negative R_H corresponds to negative charge carriers (electrons).

iv) What is the SI unit of Hall coefficient?
Ans: The SI unit of Hall coefficient is $\Omega.\mathrm{m/T}$.

v) What Hall effect experiment signifies?
Ans: 1. determination of types of semiconductors, 2. calculation of carrier concentration, 3. determination of mobility of the charge carriers, 4. determination of magnetic flux density, etc.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.

Experiment 9 : To find the resonant frequency of a series L-C-R circuit and also to determine its quality factor

1. **Aim/Purpose of the Experiment:** To find the resonant frequency and quality factor of the series L-C-R circuit.

2. **Learning Outcomes:** To understand and analyze the behavior of series L-C-R circuits at the resonant frequency, as well as to calculate and interpret the quality factor of such circuits in various practical scenarios.

3. **Prerequisites:** It is essential to have a basic understanding about inductor (L), capacitor (C), resistor (R) and resonant frequency and a basic knowledge of plotting graph on a graph paper.

4. **Materials/Equipment/Apparatus / Devices/Software required:** An air-cored or ferrite-cored inductor, a mica capacitor, a non-inductive resistance box, an electronic ac voltmeter, an audio oscillator with low output impedance and good amplitude stability.

5. **Introduction and Theory:**

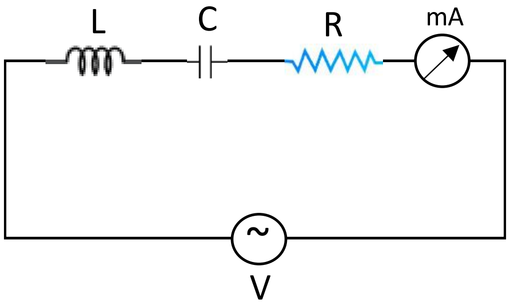


Fig: Circuit diagram showing L-C-R series connection

For a series L-C-R circuit, the resonance frequency (f_0) is given by

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

Plot of current vs frequency (I vs f) shows a maximum current I_0 at f_0. If the two half-power frequencies which corresponds to current $\frac{I_0}{\sqrt{2}}$ is indicated as f_1 and f_2, then the quality factor is given by

$$Q = \frac{f_0}{|f_1 - f_2|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

The practical value of Q given by (2) can be compared with theoretical value given as

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\sqrt{LC}}\frac{L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (\omega_0 = 2\pi f_0) \ \ldots\ldots\ldots\ldots\ldots(3)$$

6. Operating Procedure:

i) Connect the inductor (L), capacitor (C), and resistor (R) in series to form an L-C-R circuit.
ii) Make the circuit connections on the circuit board as shown in the figure.
iii) Ensure proper values for L, C, and R are chosen according to the desired frequency range.
iv) Measure the (ac) current I using an ammeter.
v) Start with a lower frequency range that encompasses the expected resonant frequency, f_0.
vi) Gradually increase the frequency, f of the signal generator while recording the current, I.
vii) The resonant frequency, f_0 is the frequency at which I reaches its maximum value, I_0.
viii) Take data in smallest possible steps around the resonance frequency, f_0.
ix) Record the resonant frequency, f_0.
x) Draw the resonance curve by plotting f along x-axis and I along y-axis.
xi) From the curve find the resonant frequency f_0, the half-power frequencies f_1 (lower half-power frequency) and f_2 (upper half power frequency). At the half-power frequencies, the current I falls to (1/√2) of its maximum value, I_0.
xii) Calculate the quality factor Q using the relation, $Q = \frac{f_0}{f_2 - f_1}$.
xiii) The theoretical value of resonant frequency and quality factor can be calculated by using the formula $f_0 = \frac{1}{2\pi\sqrt{LC}}$ and $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$, respectively.
xiv) Compare the experimentally obtained values of f_0 and Q with their respective theoretical values.

7. Precautions and/or Troubleshooting:

I) Connections must be tight.
II) Since inductance and capacitors both possess resistive parts, actual resistance used in the circuit should be large enough so that the said extra resistive effect can be neglected.
III) Supply voltage may change with frequency and so if it happens one should adjust the supply voltage so as to keep it constant throughout.

8. Observations:

Used values: L = ……. mH, C = ……… μF, R = …… Ω.

Table 1: Input frequency and corresponding current flowing in the circuit

No. of obs.	Frequency (f) in kHz	Current (I) in mA
1		
2		
3		
4		
.		

9. **Calculations & Analysis:**

The theoretical value of resonant frequency = $f_0 = \frac{1}{2\pi\sqrt{LC}} = ... \text{Hz}.$

The theoretical value of Quality factor = $Q = \frac{1}{R}\sqrt{\frac{L}{C}} = ...$

The Quality factor Q can be calculated from the graph by using the relation $Q = \frac{f_0}{f_2 - f_1}$, where, f_1 is the lower half-power frequency and f_2 is the upper half-power frequency.

10. Result & Interpretation:

Table 2: Calculated and experimentally obtained results

Theoretically calculated		**Experimentally obtained**			
Theoretical value of $f_0 = \frac{1}{2\pi\sqrt{LC}}$ (KHz)	Theoretical value of $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$	f_0 (KHz)	f_1 (KHz)	f_2 (KHz)	$Q = \frac{f_0}{f_2 - f_1}$

11. Follow-up Questions:

i) Define resonance.

Ans: When the natural frequency of the system matches with the applied frequency, the system is said to be under resonance.

ii) Define resonant frequency of LCR series circuit.

Ans: Resonance frequency is defined as the frequency at which the impedance of the LCR circuit becomes minimum or current in the circuit becomes maximum.

Resonance frequency, $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

iii) What is quality factor of resonance in series LCR circuit?

Ans: The quality factor or Q-factor of a series resonant circuit is defined as the ratio of a voltage developed across the inductance or capacitance at resonance to the voltage applied across R.

$$Q = \frac{\omega_0 L}{R}.$$

iv) What is inductive and capacitive reactance?

Ans: Inductive reactance and capacitive reactance are terms used to describe the opposition to the flow of alternating current caused by inductors and capacitors, respectively.

Inductive reactance is the opposition to the flow of ac current through an inductor. It is denoted by $X_L = \omega L = 2\pi f L$.

Capacitive reactance is the opposition to the flow of ac current through a capacitor. It is denoted by $X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$.

v) What is half-power frequency?

Ans: Half-power frequencies for a given LCR are the frequencies for which the power in the circuit is half of the maximum power in the circuit.

vi) How are the behavior of inductive reactance and capacitive reactance with frequency?

Ans: Inductive reactance X_L increases with f linearly where capacitive reactance X_C decreases with increasing f. At the resonance frequency, $f_0, X_L = X_C$.

12. Extension and Follow-up Activities (if applicable):

13. Assessments:

14. Suggested readings: Textbooks and reference books as per syllabus.