



---

“ शिक्षा मानव को बन्धनों से मुक्त करती है और आज के युग में तो यह लोकतंत्र की भावना का आधार भी है। जन्म तथा अन्य कारणों से उत्पन्न जाति एवं वर्गीकृत विषमताओं को दूर करते हुए मनुष्य को इन सबसे ऊपर उठाती है।”

-इन्दिरा गांधी

---

## VOLUME II

### BLOCK 3: DIFFRACTION

### BLOCK 4: LASERS AND OPTICAL FIBRE

---

*“ Education is a liberating force, and in our age it is also a democratising force, cutting across the barriers of caste and class, smoothing out inequalities imposed by birth and other circumstances.”*

– Indira Gandhi

Block

# 4

## **LASERS AND OPTICAL FIBRE**

---

### **UNIT 12**

#### **Physics of Lasers**

**93**

### **UNIT 13**

#### **Properties and Applications of Lasers**

**121**

### **UNIT 14**

#### **Fibre Optics**

**143**

---

## Course Design Committee

---

Prof. A. K. Ghatak, *Retd.*  
IIT Delhi, New Delhi

Prof. Suresh Garg, *Retd.*  
School of Sciences  
IGNOU, New Delhi  
Vice Chancellor,  
Usha Martin University

Prof. R.M. Mehra, *Retd.*  
Dept. of Electronics,  
South Campus,  
University of Delhi, Delhi

Dr. Ashok Goyal, *Retd.*  
Dept. of Physics, Hansraj College  
University of Delhi, Delhi

Dr. Parthasarathy  
Dept. of Physics,  
Maharaja Agrasen College,  
University of Delhi, Delhi

Prof. M.S. Nathawat  
Former Director,  
School of Sciences,  
IGNOU, New Delhi

Prof. Vijayshri  
School of Sciences  
IGNOU, New Delhi

Prof. Sudip Ranjan Jha  
School of Sciences  
IGNOU, New Delhi

Prof. Shubha Gokhale  
School of Sciences  
IGNOU, New Delhi

Dr. Sanjay Gupta  
School of Sciences  
IGNOU, New Delhi

Dr. Subhalakshmi Lamba  
School of Sciences  
IGNOU, New Delhi

---

## Block Preparation Team

---

Prof. Shubha Gokhale (Units 12-14)  
School of Sciences  
IGNOU, New Delhi

Units 12 to 14 of this block are based on the Block 4 of the course Optics (PHE-09) of the earlier B.Sc. programme of IGNOU, for which Prof. A.K. Ghatak (IIT, Delhi), Prof. S.N. Biswas (Delhi University), Prof. S.C. Garg and Prof. S. R. Jha (SOS, IGNOU) had given their valuable contribution.

**Course Coordinators: Prof. S.R. Jha, Prof. Sanjay Gupta**

---

## Block Production Team

---

**Mr. Rajiv Girdhar**  
Assistant Registrar  
MPDD, IGNOU, New Delhi

**Mr. Hemant Kumar Parida**  
Section Officer  
MPDD, IGNOU, New Delhi

---

**Acknowledgement:** Shri Gopal Krishan Arora, EDP, SOS for CRC preparation.

The image on page 121 has been kindly provided by M/S Guardian Media & Entertainment Pvt. Ltd. Pune.

The images used in Fig. 13.5b on page 132 and the image on page 143 are taken from URLs: [https://upload.wikimedia.org/wikipedia/commons/c/c2/Speckle\\_fiber.JPG](https://upload.wikimedia.org/wikipedia/commons/c/c2/Speckle_fiber.JPG): shared by Christophe. Finot and <https://upload.wikimedia.org/wikipedia/commons/4/49/Fibreoptic.jpg>: shared by BigRiz respectively via Wikimedia Commons under CC BY-SA 3.0 License.

**October, 2021**

© Indira Gandhi National Open University, 2021

ISBN:

**Disclaimer:** Any materials adapted from web-based resources in this module are being used for educational purposes only and not for commercial purposes.

All rights reserved. No part of this work may be reproduced in any form, by mimeograph or any other means, without permission in writing from the Copyright holder.

Further information on the Indira Gandhi National Open University courses may be obtained from the University's office at Maidan Garhi, New Delhi-110 068 or the official website of IGNOU at [www.ignou.ac.in](http://www.ignou.ac.in).

**Printed and published on behalf of Indira Gandhi National Open University, New Delhi by the Registrar MPDD, IGNOU, New Delhi.**

**Printed at: Gita Offset Printers Pvt. Ltd., C-90, Okhla Industrial Area, Phase-I, New Delhi-20**

# **CONTENTS**

|                                                             |                   |
|-------------------------------------------------------------|-------------------|
| <b>Block and Unit Titles</b>                                | <b>87</b>         |
| <b>Credit page</b>                                          | <b>88</b>         |
| <b>Contents</b>                                             | <b>89</b>         |
| <b>BLOCK 4: Lasers and Optical Fibre</b>                    | <b>91</b>         |
| <b><u>Unit 12 Physics of Lasers</u></b>                     | <b><u>93</u></b>  |
| <b>12.1 Introduction</b>                                    | <b>94</b>         |
| <b>12.2 Light Emission and Absorption</b>                   | <b>94</b>         |
| 12.2.1 Quantum Theory: A Brief Outline                      | 95                |
| 12.2.2 Stimulated Emission: Einstein's Prediction           | 97                |
| 12.2.3 Einstein's Prediction Realised                       | 100               |
| <b>12.3 Components of Laser</b>                             | <b>102</b>        |
| 12.3.1 The Active Medium                                    | 103               |
| 12.3.2 Excitation (or Pumping)                              | 106               |
| 12.3.3 Feedback Mechanism: Optical Resonant Cavity          | 108               |
| <b>12.4 Types of Lasers</b>                                 | <b>110</b>        |
| 12.4.1 Solid State Lasers                                   | 110               |
| 12.4.2 Liquid Lasers                                        | 111               |
| 12.4.3 Gas Lasers                                           | 112               |
| <b>12.5 Summary</b>                                         | <b>114</b>        |
| <b>12.6 Terminal Questions</b>                              | <b>115</b>        |
| <b>12.7 Solutions and Answers</b>                           | <b>116</b>        |
| <b>Appendix 12A: Laser Diodes</b>                           | <b>119</b>        |
| <b><u>Unit 13 Properties and Applications of Lasers</u></b> | <b><u>121</u></b> |
| <b>13.1 Introduction</b>                                    | <b>122</b>        |
| <b>13.2 Properties of Lasers</b>                            | <b>122</b>        |
| 13.2.1 Monochromaticity                                     | 122               |
| 13.2.2 Directionality                                       | 126               |
| 13.2.3 Coherence                                            | 127               |
| <b>13.3 Applications of Lasers</b>                          | <b>133</b>        |
| 13.3.1 Communication                                        | 133               |
| 13.3.2 Industry                                             | 134               |
| 13.3.3 Medicine                                             | 135               |
| 13.3.4 Environmental Monitoring                             | 135               |
| 13.3.5 Basic Research                                       | 136               |
| 13.3.6 Holography                                           | 137               |
| <b>13.4 Summary</b>                                         | <b>139</b>        |
| <b>13.5 Terminal Questions</b>                              | <b>139</b>        |
| <b>13.6 Solutions and Answers</b>                           | <b>140</b>        |

|                                                                 |                   |
|-----------------------------------------------------------------|-------------------|
| <b><u>Unit 14 Fibre Optics</u></b>                              | <b><u>143</u></b> |
| <b>14.1 Introduction</b>                                        | <b>144</b>        |
| <b>14.2 Optical Fibre Waveguide</b>                             | <b>145</b>        |
| 14.2.1 Construction and Working of Optical Fibre                | 145               |
| 14.2.2 Some Definitions                                         | 146               |
| 14.2.3 Types of Optical Fibre                                   | 148               |
| <b>14.3 Losses in Optical Fibre</b>                             | <b>150</b>        |
| <b>14.4 Dispersion in Optical Fibre</b>                         | <b>152</b>        |
| 14.4.1 Pulse Dispersion                                         | 153               |
| 14.4.2 Material Dispersion                                      | 155               |
| <b>14.5 Advantages of Optical Fibre as Communication Medium</b> | <b>156</b>        |
| <b>14.6 Summary</b>                                             | <b>157</b>        |
| <b>14.7 Terminal Questions</b>                                  | <b>158</b>        |
| <b>14.8 Solutions and Answers</b>                               | <b>158</b>        |
| <br>                                                            |                   |
| <b>Further Readings</b>                                         | <b>161</b>        |
| <b>Table of Physical Constants</b>                              | <b>162</b>        |
| <b>List of Blocks and Units: BPHCT-137</b>                      | <b>163</b>        |
| <b>Syllabus: Waves and Optics (BPHCT-137)</b>                   | <b>164</b>        |

## **BLOCK 4 : LASERS AND OPTICAL FIBRE**

In the preceding blocks of Waves and Optics course you have learnt that light is an electromagnetic wave. It exhibits phenomena like polarization, interference, diffraction, which can be well understood in terms of the wave theory of light. This block, essentially deals with the applied aspects of optics. We discuss here mainly two things that have revolutionised the field of optics and are extensively used in various walks of life. The first one is laser, which is a very high intensity, monochromatic light source. The other one is optical fibre, which is used as medium to carry the light over a long distance with minimal losses.

Laser owes its invention to the quantum theory according to which, light energy consists of minute packets or quanta. The invention of lasers and related developments has once again brought the field of optics at the forefront of basic research and technological applications. Without fear of exaggeration, we may say that the present period in optics may be called the Laser Age.

In **Unit 12**, you will learn the working principle of lasers. In particular, we have discussed concept of stimulated emission of radiation and the pre-requisites for obtaining laser light. Though the first laser used ruby (solid) as active medium, now lasers which employ liquids and gases as the active medium are available. You will learn about different types of lasers in this unit.

Widespread use of light from laser is because of its high degree of coherence, exceptional monochromaticity, high directionality and unprecedented brightness. In **Unit 13** you will learn about these properties of lasers in details. You will also learn about the uses of lasers in various fields like communications, industries, medicine, environmental monitoring, basic research and holography.

The use of lasers has revolutionized communication technology. The monochromaticity of laser light makes it an efficient carrier of information. Communication – transmission of speech, video, data, etc., – at optical frequency is much faster and reliable compared to radio and microwave communication. However, optical communication suffers from the drawback that signals get attenuated by dust particles, rains, etc. Thus, for efficient terrestrial optical communication, optical fibres are used. How is light transmitted through optical fibres? What are the characteristics of such fibre? These and other related questions form the subject matter of **Unit 14**.

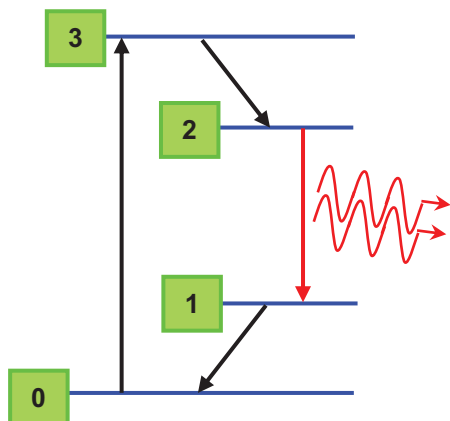
We are sure that you will enjoy this fascinating journey in the field of optics.

We wish you success.



# UNIT 12

## PHYSICS OF LASERS



Energy levels in a four-level pumping. Nd:YAG laser is a typical example, about which you will learn in this unit.

### Structure

- |      |                                             |      |                            |
|------|---------------------------------------------|------|----------------------------|
| 12.1 | Introduction                                | 12.4 | Types of Lasers            |
|      | Expected Learning Outcomes                  |      | Solid State Lasers         |
| 12.2 | Light Emission and Absorption               |      | Liquid Lasers              |
|      | Quantum Theory: A Brief Outline             |      | Gas Lasers                 |
|      | Stimulated Emission: Einstein's Prediction  | 12.5 | Summary                    |
|      | Einstein's Prediction Realised              | 12.6 | Terminal Questions         |
| 12.3 | Components of Laser                         | 12.7 | Solutions and Answers      |
|      | The Active Medium                           |      | Appendix 12A: Laser Diodes |
|      | Excitation (or Pumping)                     |      |                            |
|      | Feedback Mechanism: Optical Resonant Cavity |      |                            |

### STUDY GUIDE

So far you learnt about the electromagnetic wave nature of light. In this unit you will be learning about a special kind of source of light, which is based on the quantum theory which predicts a particulate nature of the light. It proposes that the light consist of small quanta of energy, known as photons. A stimulated emission of radiation gives rise to intense beam of light, which is highly coherent and very bright. You will learn the process of lasing and also get familiar with the types of lasers.

You will not require any special mathematical tools to study this unit. A knowledge of elementary calculus will suffice. Try to solve the SAQs and Terminal Questions given in this unit on your own.

***“When God said “Let there be light” he surely must have meant perfectly coherent light.”***

***Charles Townes***

## 12.1 INTRODUCTION

---

The quest for obtaining a light source with high intensity and good degree of coherence led to the invention of lasers. The name laser is an acronym for *Light Amplification by Stimulated Emission of Radiation*. You must note that the key words here are amplification and stimulated emission. The existence of stimulated emission of radiation, when radiation interacts with matter, was predicated by Einstein in 1916. His theoretical prediction was realized by C.H. Townes and co-workers in 1954 when they developed microwave amplification by stimulated emission of radiation (maser). The principle of maser was adapted for light in visible range by A. Schawlow and C.H. Townes in 1958 but the first laser device was developed by T.H. Maiman in 1960. Once the laser was invented, it has found applications in such diverse fields as basic research, industry, medicine, space, photography, communication, defence, etc.

In Sec. 12.2, you will learn about the quantum mechanical description of the emission and absorption of light. In particular, you will learn about spontaneous emission and stimulated emission of radiation. In Sec. 12.3, the physical principles involved in the operation of lasers viz. excitation (or pumping), the active medium and the feedback mechanism have been explained. Since the invention of laser by Maiman using small ruby rod as active medium, lasers have come a long way. Presently, lasers are built using solid or liquid or gas as active media. These types of laser are discussed in Sec. 12.4. Semiconductor laser diodes are widely used in communication these days. Their structure and working is described in Appendix 12-A.

### Expected Learning Outcomes

---

After studying this unit, you should be able to:

- ❖ explain the concept of stimulated emission of radiation and differentiate it from spontaneous emission;
- ❖ describe the need and methods of pumping;
- ❖ list the characteristics of the active medium for lasers; and
- ❖ describe different types of lasers.

## 12.2 LIGHT EMISSION AND ABSORPTION

---

As you are aware, most of the man-made sources of light are the solids and gases heated to high temperatures. For example, in case of incandescent bulb, the tungsten filament is heated, and in the case of mercury tube light, the gas is heated. The energy of heating source is absorbed by the atoms or molecules of the solid or the gas, which, in turn, emit light. The basic mechanism of the origin of light from within gas molecules, liquids and solids is similar in many respects to that from an individual atom. And the process of emission and absorption of light from atoms can be understood in terms of Bohr's atomic model. Though you might have studied Bohr's model in your school physics course, we briefly discuss it here for the sake of completeness.

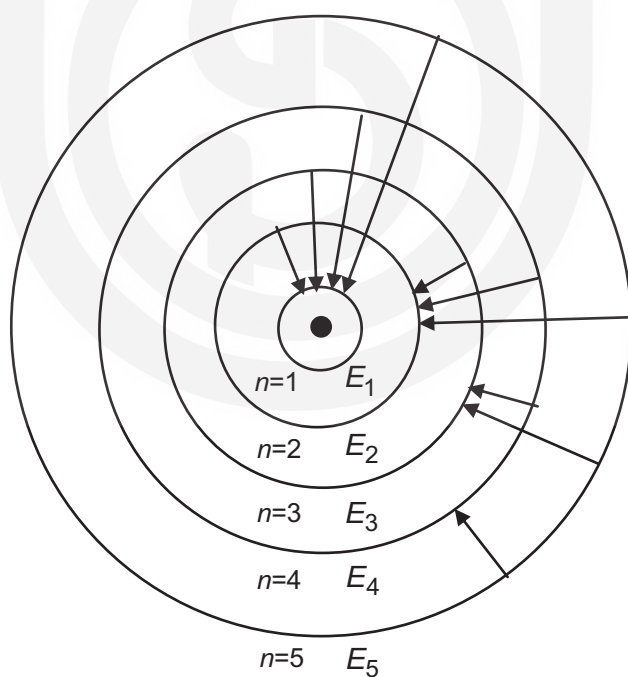
### 12.2.1 Quantum Theory: A Brief Outline

You may recall from your school physics course that according to Bohr's theory, the energy of an atom or a molecule can take on only definite (discrete) values. These are known as the energy levels of the atom. The transition of an atom from one energy level to another energy level occurs in a quantum jump. This was one of the basic assumptions of Bohr's theory. On the basis of this presumption, Bohr postulated that light is not emitted by an electron when it is revolving in one of its allowed orbits (and hence has a fixed value of energy). Light emission takes place when the electron makes a transition from an excited state (of energy  $E_i$ ) to a state of lower energy  $E_f$ .

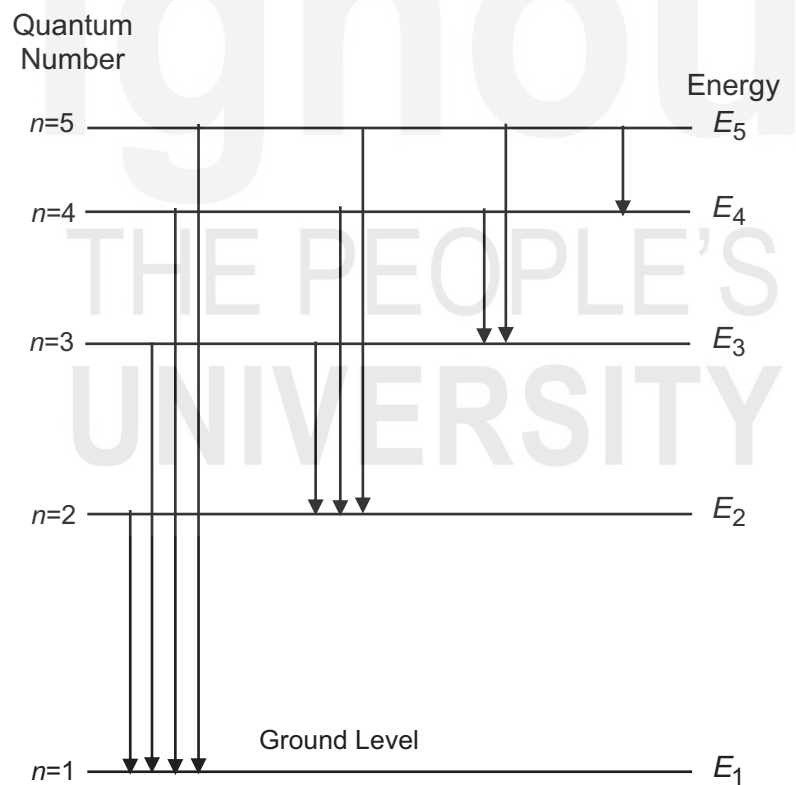
The frequency of the emitted radiation is given by

$$h\nu = E_i - E_f \quad (12.1)$$

where  $E_i$  is the energy of the initial orbit,  $E_f$  is the energy of the final orbit,  $\nu$  the frequency of the emitted light and  $h$  is the Planck's constant. The quantized orbits of the electron and the energy level diagram of the simplest atom –the hydrogen atom– are shown in Fig.12.1a and b.



(a)



(b)

**Fig. 12.1: a) Bohr circular orbits for the revolving electron of hydrogen atom, showing transitions, giving rise to the emitted light waves of different frequencies; b) energy level diagram for the hydrogen atom.**

The quantum mechanical explanation about the origin of light, as discussed above, applies to all the known light sources. To focus our attention on the atomic processes involved in the emission and absorption of light, let us consider only two energy levels of an atom. Let the energy of the lower level

be  $E_1$  and that of the upper level be  $E_2$ . An atom lying in level  $E_2$  will tend to make a transition to level  $E_1$  so that it occupies a state of lower energy. Such emission process is known as **spontaneous emission** because it occurs in the absence of any external stimulus. The process of spontaneous emission is shown in Fig. 12.2a. The photon emitted in spontaneous emission will have the energy  $(E_2 - E_1)$  while its other characteristics such as momentum, polarization, will be arbitrary. The light emitted by ordinary sources results due to spontaneous emission. Absorption of light is the converse process of emission. The atom in a lower energy state can absorb a photon of energy  $h\nu = (E_2 - E_1)$  and get excited to the upper level  $E_2$ . The absorption process is depicted in Fig. 12.2b.

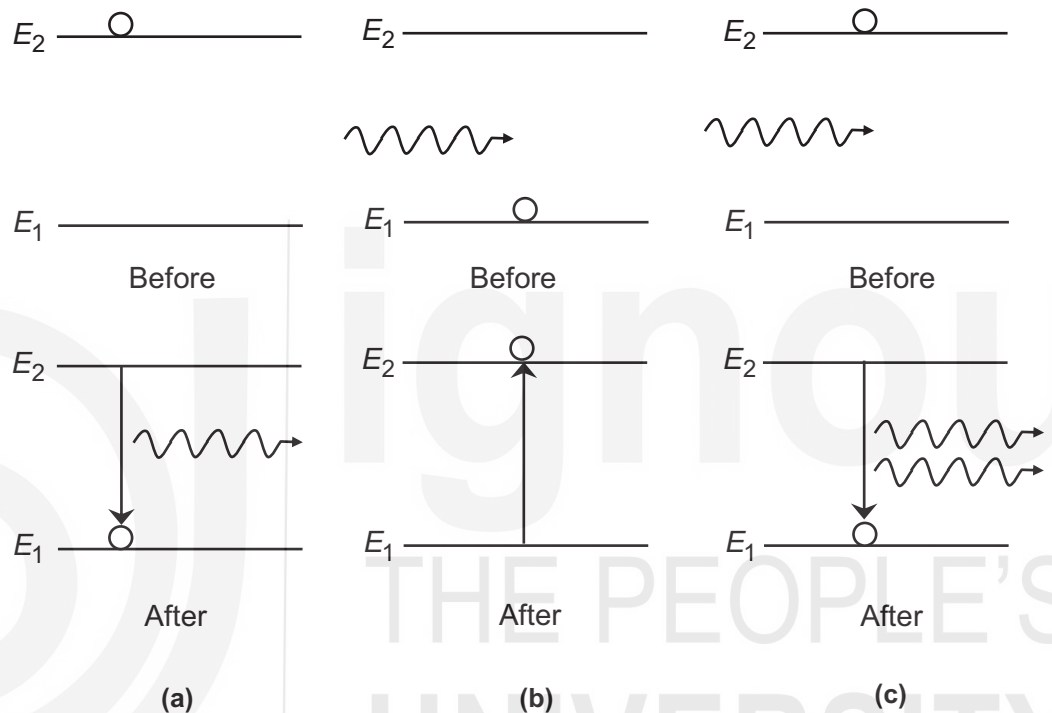


**Fig. 12.2: Light-matter interaction a) spontaneous emission; b) absorption; c) stimulated emission of light.**

Now, can you guess what will happen if an atom is in the higher energy level, and a photon of energy  $h\nu (= E_2 - E_1)$  interacts with it? Well, in such a situation, the photon may trigger the atom in the upper level to emit radiation. This emission process is known as **stimulated emission**. When the atom is already in the higher energy level, the photon, instead of being absorbed, may play the role of a trigger, and induce the transition from  $E_2$  to  $E_1$ . As a result, the atom falls into lower energy level and an additional photon of energy  $h\nu (= E_2 - E_1)$  is emitted. In this process of stimulated emission, shown in Fig. 12.2c, both the inducing and the induced photons have the same energy. The light from laser is due to the stimulated emission of radiation.

It is worth mentioning here that of the three processes mentioned above, only the first two that is, the spontaneous emission and the absorption of light were postulated on the basis of Bohr's theory. It was only when Einstein considered the whole idea of emission and absorption of radiation in terms of thermodynamic equilibrium between matter and radiation that stimulated emission of radiation could be predicted.

Let us learn about Einstein's theoretical arguments for the prediction.

### 12.2.2 Stimulated Emission: Einstein's Prediction

Now, you must have understood that the stimulated emission is the reverse of the process in which electromagnetic radiation or photons are absorbed by the atomic systems. When a photon is absorbed by an atom, the energy of the photon is converted into the internal energy of the atom. The atom is then raised to an excited (higher energy) state and it may radiate this energy spontaneously, emitting a photon and reverting to the ground (or some lower energy) state. However, during the period the atom is in the excited state, it can be stimulated to emit a photon if it interacts with another photon. This stimulating photon should have precisely the same energy as the one which would have emitted otherwise spontaneously. Let us look at the theoretical arguments put forward by Einstein for the existence of stimulated emission.

Refer to Fig. 12.3 which shows a system of two energy levels  $E_1$  and  $E_2$  with population of atoms  $N_1$  and  $N_2$  respectively. Let  $E_1 < E_2$ .

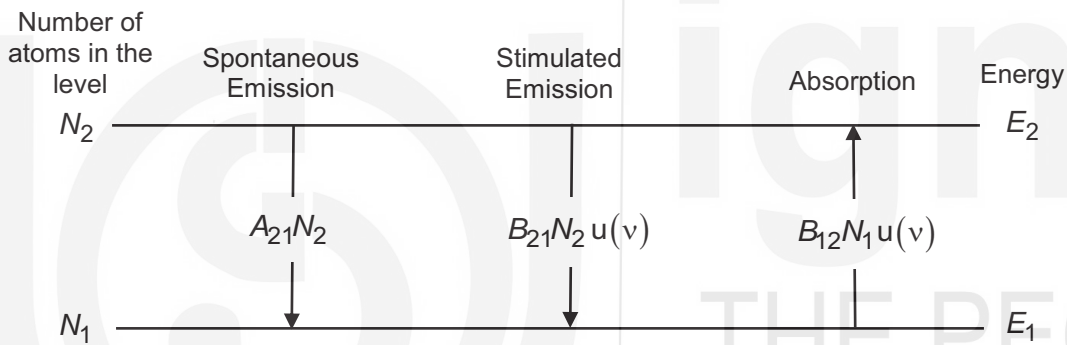


**Fig. 12.3: An atomic system of two energy levels showing different emission and absorption processes.**

You may recall from the Unit 13 of the course on Thermal Physics and Statistical Mechanics (BPHCT-135) that according to Maxwell-Boltzmann distribution, the ratio of population of atoms in different levels for a system in thermal equilibrium is given as

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/k_B T}$$

$$\text{or} \quad N_2 = N_1 e^{-h\nu/k_B T} \quad (12.2)$$

where,  $k_B$  is the Boltzmann constant and  $T$  is the absolute temperature.

Now what will be the ratio of the population of the energy levels if radiation of energy  $h\nu$  is introduced into the system? Einstein proposed that if this system of energy levels and the radiations is to remain in thermal equilibrium, the rate of downward transition (due to spontaneous and stimulated emission) must be equal to the rate of upward transition (due to absorption). He, therefore, arrived at the relation (see box on the next page),

$$\frac{N_2}{N_1} = \frac{B_{12} u(\nu)}{A_{21} + B_{21} u(\nu)} \quad (12.3)$$

where,  $u(\nu)$  is the energy density of radiation at frequency  $\nu$  and  $B_{12}$ ,  $A_{21}$  and  $B_{21}$  are Einstein's coefficients.  $A_{21}$  is associated with spontaneous emission,  $B_{21}$  is associated with stimulated emission and  $B_{12}$  is associated with absorption.

Following Einstein, let us write down the rates of spontaneous and stimulated emission and the rate of absorption of radiation. The rate of spontaneous emission will be independent of the energy density of the radiation field because, for this process to occur, presence of photon is not required. This emission process will be proportional to the number of atoms,  $N_2$ , in the higher energy state. So, we may write the rate of spontaneous emission as

$$P_{21}(\text{spontaneous}) = N_2 A_{21} \quad (\text{i})$$

where  $A_{21}$  is a constant of proportionality.

Assume next that the system of atoms is subjected to some external radiation field. In that case, as mentioned earlier, one of the two processes, namely, the stimulated emission and absorption, may occur. The probability of their occurrence depends on the energy density of radiation at the particular frequency separating the two levels and the population of states from which transition takes place. Therefore, the rate of stimulated emission will be proportional to the energy density of the radiation and the population of higher energy state,  $N_2$ . Thus, the rate of stimulated emission will be

$$P_{21}(\text{stimulated}) = N_2 B_{21} u(\nu) \quad (\text{ii})$$

where  $B_{21}$  is another constant of proportionality and  $u(\nu)$  is energy density of radiation at frequency  $\nu$ .

On the other hand, the rate of absorption will depend on  $u(\nu)$  and the population of the lower energy state,  $N_1$ . Thus, the rate of absorption

$$P_{12} = N_1 B_{12} u(\nu) \quad (\text{iii})$$

where  $B_{12}$  is yet another constant of proportionality. The constants  $A_{21}$ ,  $B_{21}$  and  $B_{12}$  are known as Einstein's coefficients.

With the system in thermal equilibrium, the net rate of downward transition must be equal to the net rate of upward transition. Thus, we may write

$$N_2 A_{21} + N_2 B_{21} u(\nu) = N_1 B_{12} u(\nu) \quad (\text{iv})$$

Dividing both side by  $N_1$ , we get

$$\frac{N_2}{N_1} A_{21} + \frac{N_2}{N_1} B_{21} u(\nu) = B_{12} u(\nu)$$

$$\text{or} \quad \frac{N_2}{N_1} [A_{21} + B_{21} u(\nu)] = B_{12} u(\nu)$$

$$\text{so that} \quad \frac{N_2}{N_1} = \frac{B_{12} u(\nu)}{A_{21} + B_{21} u(\nu)} \quad (\text{v})$$

From Eqs. (12.2) and (12.3), we have

$$\frac{B_{12}u(\nu)}{A_{21} + B_{21}u(\nu)} = e^{-h\nu/k_B T}$$

or 
$$u(\nu) = \frac{A_{21}}{B_{12}} \frac{1}{e^{h\nu/k_B T} - (B_{21}/B_{12})} \quad (12.4)$$

Now, you may recall from Unit 14 of the course BPHCT-135 that the energy density of black body radiation is given by Planck's radiation law:

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/k_B T} - 1} \quad (12.5)$$

Equation (12.5) must be same as Eq. (12.4). So we must have

$$B_{21} = B_{12} \quad (12.6)$$

and

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad (12.7)$$

From Eq. (12.6) we can write:

$$\frac{A_{21}}{B_{12}} = \frac{A_{21}}{B_{21}}$$

These are **Einstein's relations**. On the basis of Einstein's relations, we can conclude the following:

- Eq. (12.6) indicates that the probabilities of absorption and stimulated emission are the same. In other words, when an atomic system is in equilibrium, absorption and stimulated emission take place side by side. Normally,  $N_2 < N_1$  and absorption dominates stimulated emission. An incident photon is more likely to be absorbed than to cause stimulated emission. But, if we could find a material that could be induced to have a majority of atoms in the higher state than in the lower state, i.e.  $N_2 > N_1$ , the stimulated emission may dominate absorption. This condition of the atomic system (where  $N_2 > N_1$ ) is known as **population inversion**. And when the stimulated emission dominates over absorption in the atomic system, it is said to lase.
- If we substitute  $B_{12} = B_{21}$  in equation (12.4), we get the ratio of the number of spontaneous emission to stimulated emission

$$\frac{A_{21}}{B_{21}u(\nu)} = e^{h\nu/k_B T} - 1 \quad (12.8)$$

When the system is in thermal equilibrium at temperature  $T$ , for  $h\nu \ll k_B T$ , Eq. (12.8) suggests that stimulated emission will dominate spontaneous emission. On the other hand when  $h\nu \gg k_B T$ , spontaneous emission will dominate stimulated emission. Now which of these two processes will dominate for ordinary thermal sources of light? To know that, you should solve the following SAQ.

### SAQ 1 – Emission in case of ordinary source of light

The absolute temperature,  $T$ , for an ordinary source of light is typically of the order of  $10^3$  K. With the help of Eq. (12.8), show that in such sources, the process of spontaneous emission will dominated over the stimulated emission.

Einstein's theoretical prediction of stimulated emission was proven right when experimentalists demonstrated the laser light in laboratory in the sixth decade of the twentieth century. Let us now take an overview of the development of laser sources.

#### 12.2.3 Einstein's Prediction Realised

You now know that, as per Einstein's prediction, when matter and radiation are in thermal equilibrium, besides spontaneous emission and absorption of radiation by the matter, there must be a third process, called stimulated emission. This prediction did not attract much attention until 1954, when American physicist Charles H. Townes and co-workers developed a microwave amplifier (MASER) using  $\text{NH}_3$ . In 1958, Schawlow and Townes showed that the maser principle could be extended into visible region. In 1960, the prediction was realized by Maiman who built the first laser using ruby as an active medium. Maiman found that a suitable active component for a laser could be made from a single crystal of pink ruby – aluminium oxide ( $\text{Al}_2\text{O}_3$ ) coloured pink by addition of about 0.5 percent chromium. For any laser action to take place, a condition of population inversion must be met. By population inversion we mean that the number of atoms in higher energy state is larger than the ground (or some lower energy) state. The energy states of the chromium atom, as shown in Fig. 12.4, are ideal for obtaining population inversion in ruby laser. The main characteristic of the energy levels of chromium atom is that the levels labelled as  $E_1$  and  $E_2$  have a life time of  $10^{-8}$  s whereas the state marked  $M$  has a life time of  $3 \times 10^{-3}$  s. The energy state  $M$  with such a long life time (as compared to other excited states) is called a metastable state.

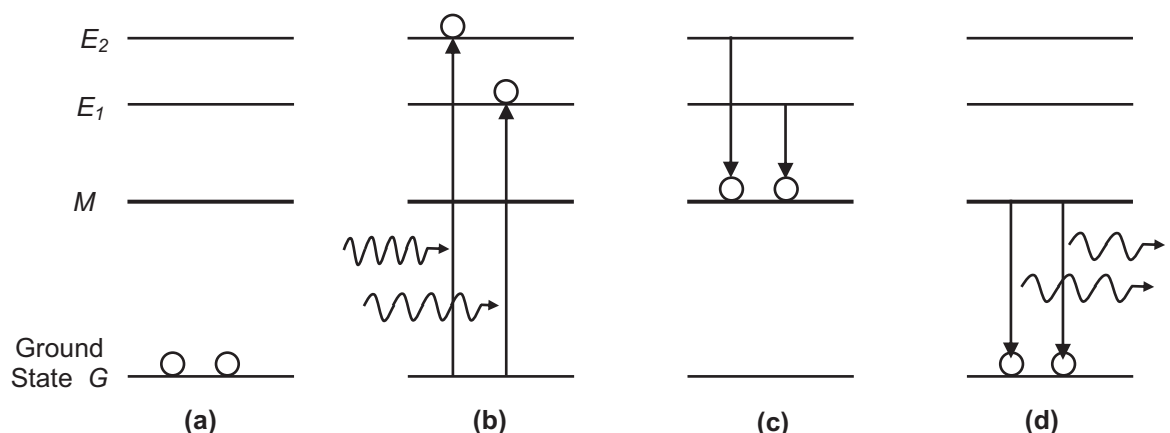


**Fig. 12.4: Energy levels of chromium atom: a) atoms in the ground state, b) on absorbing photons, atoms are excited to one of the two energy levels  $E_1$  or  $E_2$ , c) atoms give up some of their energy to the crystal lattice and fall to a metastable level,  $M$ , d) when stimulated by photons, the atoms in metastable level emit photon and fall to ground state.**

A chromium atom in its ground state can absorb a photon of  $\lambda = 5500 \text{ \AA}$  and make a transition to the level  $E_1$ . It could also absorb a photon of  $\lambda = 4000 \text{ \AA}$  and make a transition to the level  $E_2$ . In either case, it subsequently makes a non-radiative transition, in time  $10^{-8} \text{ s}$  to the metastable state  $M$ .

Since the state  $M$  has a very long life, the number of atoms in this state keeps on increasing and we may have large number of atoms in the level  $M$  compared to those in the state  $G$ . Thus we can achieve a population inversion between the state  $M$  and the ground state,  $G$ . Once population inversion is achieved, light amplification can take place at  $\lambda = 6943 \text{ \AA}$ .

When an atom undergoes a non-radiative transition the energy is not released in the form of photons; rather, the energy is transferred via processes like atomic collisions, collisions with the crystal lattice etc.

In the original set up of Maiman, pink ruby was machined into a rod of length nearly four centimetre and diameter half a centimetre. Its ends were polished optically flat and parallel and were partially silvered. The rod was placed near an electronic flash tube (filled with xenon gas) that provided intense light for pumping chromium atoms to higher energy states. The set-up of ruby laser is shown in Fig. 12.5. When the required population inversion was achieved with the help of electronic flash tube, the first few photons released (at random) by atoms dropping to the ground state stimulated a cascade of photons, all having the same frequency.

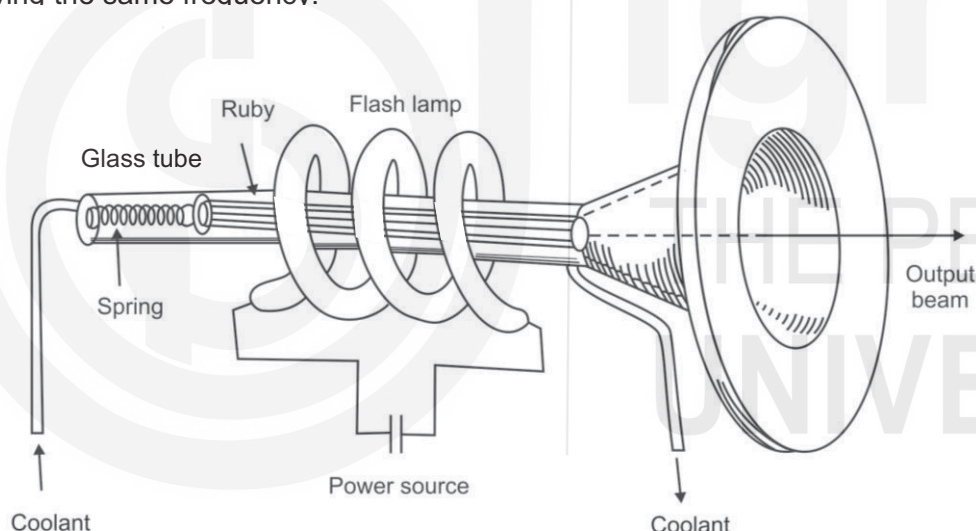


Fig. 12.5: Schematic diagram of a ruby laser

After understanding the principle of working of ruby laser you may like to attempt an SAQ.

### SAQ 2 – Ruby laser

Is it possible to lase a ruby laser with excitation wavelength of  $7000 \text{ \AA}$ ? Justify your answer.

You now know how a ruby laser, developed by Maiman works. Before proceeding further, we will briefly summarise the points you have learnt so far.

*Recap***LIGHT EMISSION AND EINSTEIN'S PREDICTION**

- During the interaction between matter and electromagnetic radiation three types of processes occur:
  - Spontaneous emission
  - Absorption
  - Stimulated emission
- Ordinary sources emit light due to spontaneous emission.
- Einstein predicted stimulated emission of radiation.
- Maiman demonstrated first laser using Ruby as active medium.
- Stimulated emission dominates spontaneous radiation under the condition of population inversion; where the number of atoms in the excited state is more than those in the lower energy state.

You will appreciate that production of laser light demands fulfilling of certain pre-conditions. In this respect we need to discuss about certain prerequisites to obtain lasing action. Firstly, is it possible to achieve laser light from any medium? If not, what are the characteristics of the medium which can produce laser light after proper excitation? The media capable of producing laser light are called **active media**. Secondly, as discussed earlier, population inversion is necessary for lasing action. How do we achieve population inversion? Further, for sustained laser light, it is necessary to feed some of the output energy back into the active medium. This is known as feedback and is achieved by resonant cavity. What is the nature of this resonant cavity for lasers? These are some of the important aspects of laser operation and design about which you will learn now.

### 12.3 COMPONENTS OF LASER

A laser requires three components for its operation. Firstly, there should be an **active medium** which, when excited, supports **population inversion** and subsequently lases. Secondly, we should ensure **pumping** mechanism that raises the system to an **excited state**. And lastly, in most cases, there is an **optical cavity** that provides the feedback necessary for laser oscillation. These are shown schematically in Fig. 12.6.

In a typical laser operation, energy is transferred to the active medium, which is raised to the excited state, and ultimately lases in various ways. The medium may be a solid, liquid or gas and it may be one of the thousands of materials that have been found to lase. The process of raising the medium to the excited state is called **pumping**, in analogy to pumping of water from lower to a higher level of potential energy. Most lasers are laser oscillators. For sustained laser oscillations, some kind of feedback mechanism is needed. The feedback mechanism is provided in the form of optical resonant cavity. However, some lasers are built as laser amplifier. They need no optical cavity.

In both laser amplifiers and oscillators, the first few photons of radiation will probably be emitted spontaneously and will trigger stimulated emission.

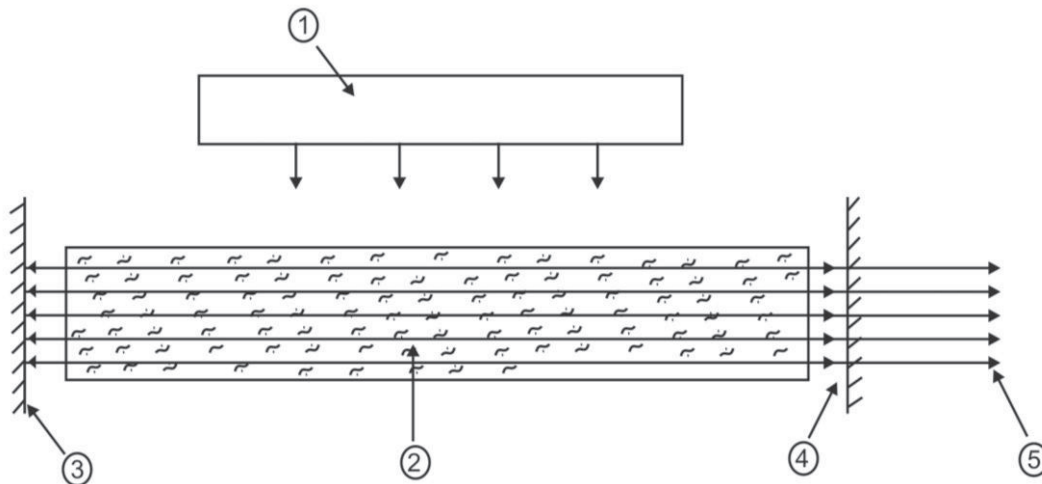


**Fig. 12.6: Basic components of a laser oscillator: Energy source (1) supplies energy to active medium (2). Medium is contained between two mirrors (3 and 4). Mirror 3 is fully reflective while mirror 4 is partially transparent. Laser radiation (5) emerges through partially transparent mirror.**

Let us now discuss the above mentioned three components of a laser.

### 12.3.1 The Active Medium

The heart of laser is a certain medium – solid, liquid or gaseous – called an **active medium**. Since Maiman's discovery of ruby, many other new laser materials have been discovered, They include crystals, glasses, plastics, liquids, gases and even plasma (the state of matter in which some of the electrons are dissociated from their atoms). What should be the characteristics of an active medium? The only general requirement of an active medium is that it provides an upper energy state into which the atoms can be pumped and a lower state to which they will return with the spontaneous emission of photons. The medium must also allow a population inversion between the two states. It may happen that the active species or centres, which provide lasing levels, constitute a small fraction of the medium. For example, in case of ruby, which is  $\text{Al}_2\text{O}_3$ , with some of the Al atoms replaced by Cr atoms, only the later (Cr) is the active centre. Typical number of active species per cubic centimetre in solids and liquids is  $10^{19}$  to  $10^{20}$  and that for gaseous media their number is about  $10^{15}$  to  $10^{17}$ .

How does the light beam gets amplified when it passes through an active medium? To get the answer, we examine the process of population inversion.

#### Population Inversion

Why is the condition of population inversion between the lasing levels necessary for operation of lasers, i.e. for amplification of light to occur? We can understand this by calculating the change in the intensity of the light beam passing through an active medium. Refer to Fig. 12.7. A collimated beam of light having intensity  $I_v$  travels along the x-axis through an active medium of thickness  $dx$ .

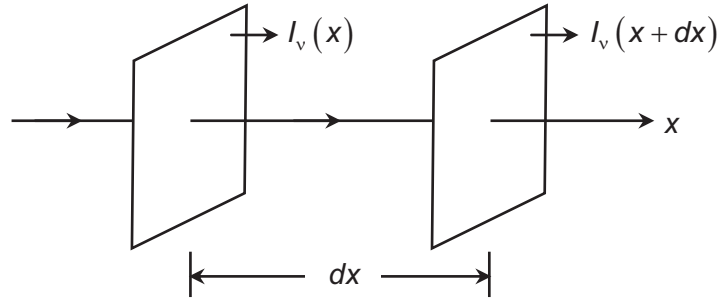


**Fig. 12.7: Light beam of intensity  $I_v$  passing through an active medium along the x-axis.**

If the cross-sectional area of each of the planes is  $S$ , volume of the layer will be  $Sdx$ . Let  $N_1(\nu)d\nu$  represent the number of atoms per unit volume which are capable of absorbing radiation whose frequency lies between  $\nu$  and  $\nu + d\nu$ . The number of upwardly transmitted ( $E_1 \rightarrow E_2$ ) atoms per unit time in the layer of volume  $Sdx$  would be (refer to Eq. (iii) in the box in Sec. 12.2.2)

$$N_1(\nu)d\nu B_{12}u(\nu)Sdx$$

In each transition, a photon of energy  $h\nu$  is absorbed. Thus, energy lost per unit time from the incident radiation is

$$h\nu [N_1(\nu)d\nu B_{12}u(\nu)]Sdx$$

Similarly, let  $N_2(\nu)d\nu$  represent the number of excited atoms per unit volume which are capable of undergoing stimulated emission by falling down to energy level  $E_1$ . The frequency of these photons lie between  $\nu$  and  $\nu + d\nu$ .

Then the number of stimulated photons emitted per unit time in the layer is

$$N_2(\nu)d\nu B_{21}u(\nu)Sdx$$

In each transition, photon of energy  $h\nu$  is emitted and this reinforces the propagating beam. Thus the energy gain by the incident radiation per unit time is

$$h\nu [N_2(\nu)d\nu B_{21}u(\nu)]Sdx$$

You may have noticed that in the intensity of beam, we have neglected the contribution of spontaneous emission. This is because a photon emitted via spontaneous process is in a random direction; and, as such, does not contribute appreciably to the intensity of the beam.

As a result of above processes, will the intensity of the light beam increase or decrease with time? Since  $u(\nu)d\nu Sdx$  represents the energy in the layer within frequency range  $\nu$  and  $\nu + d\nu$ , we can write the rate of change of the energy with time as

$$\frac{\partial}{\partial t} u(\nu)d\nu Sdx = h\nu [-N_1(\nu)B_{12}u(\nu) + N_2(\nu)B_{21}u(\nu)]d\nu Sdx$$

$$\text{or} \quad \frac{\partial u(\nu)}{\partial t} = -h\nu [B_{12}N_1(\nu) - B_{21}N_2(\nu)]u(\nu) \quad (12.9)$$

If  $I_\nu$  represents intensity,  $I_\nu d\nu$  signifies the energy crossing a unit area per unit time whose frequency lies between  $\nu$  and  $\nu + d\nu$ . Then

$$[I_\nu(x+dx)d\nu - I_\nu(x)d\nu]S$$

denotes the rate at which the energy flows out of the layer. Since  $u(\nu)d\nu Sdx$  represents radiation energy contained in the layer with frequency in the range  $\nu$  and  $\nu + d\nu$ , we will have

$$[I_\nu(x+dx) - I_\nu(x)]d\nu S = \frac{\partial}{\partial t} [u(\nu)d\nu Sdx]$$

$$\text{or} \quad \frac{\partial u(\nu)}{\partial t} = \frac{I_\nu(x+dx) - I_\nu(x)}{dx} = \frac{\partial I_\nu}{\partial x} \quad (12.10)$$

From Eq. (12.9) and (12.10), we have

$$\frac{\partial I_\nu}{\partial x} = -h\nu [B_{12}N_1(\nu) - B_{21}N_2(\nu)]u(\nu)$$

$$\text{But} \quad I_\nu = u(\nu)\nu \quad (12.11)$$

where  $\nu$  is the velocity of light in the active medium ( $=c/n$  with  $n$  = refractive index of the medium), Thus, we get

$$\frac{\partial I_\nu}{\partial x} = -\frac{h\nu B}{\nu} (N_1 - N_2)I_\nu$$

where  $B (= B_{12} = B_{21})$  denotes either Einstein's coefficient. Hence

$$\frac{\partial I_\nu}{I_\nu \partial x} = -\frac{h\nu n}{c} (N_1 - N_2)B \quad (12.12)$$

If the light beam is propagating in absorbing media, the loss of intensity,  $-dI_\nu$  will be proportional to  $I_\nu$  and  $dx$ ;

$$dI_\nu = -\alpha_\nu I_\nu dx$$

where  $\alpha_\nu$  is absorption coefficient. We can rewrite the relation as

$$\frac{\partial I_\nu}{I_\nu} = -\alpha_\nu dx \quad (12.13)$$

on integration we find that

$$I_\nu = e^{-\alpha_\nu x} \quad (12.14)$$

If we compare Eqs. (12.12) and (12.13), we get the expression for absorption co-efficient:

$$\alpha_\nu = \frac{h\nu n}{c} (N_1 - N_2)B \quad (12.15)$$

At thermal equilibrium,  $N_1 > N_2$ , that is, the population of ground state is greater than the population of the excited state and as can be seen from Eq. (12.15),  $\alpha_v$  is positive. For positive  $\alpha_v$ , Eq. (12.14) implies that the intensity of the beam decreases as it propagates through the material. The lost energy is used up in the excitation of atoms to higher energy states.

On the other hands, if we have a situation in which  $N_2 > N_1$ ,  $\alpha_v$  will be negative and intensity of the light beam would increase, that is, it will get amplified as it propagates through the material. This process is **light amplification**. Since this occurs when there is a higher population in excited state than in the ground (or lower energy) state, the material is said to be in the state of **population inversion**. Thus, the condition of population inversion is necessary for amplification of intensity of light beam.

### 12.3.2 Excitation (or Pumping)

In the previous sub-section, you have learnt about the necessity of population inversion in the active medium for obtaining laser light. The process of obtaining population inversion is known as excitation or pumping. The aim of pumping is to see that upper energy level is more intensely populated than the lower energy level. Alternatively, we can obtain the population inversion by depopulating lower energy level (other than ground state) faster than the upper energy level. There are several ways of pumping a laser and achieving the population inversion necessary for stimulated emission to occur.

The most commonly used methods are the following:

1. optical pumping
2. electric discharge
3. inelastic atomic collision
4. direct conversion

In **optical pumping**, a source of light is used to supply energy to the active medium. Most often this energy comes in the form of short flashes of light. This method was first used in Maiman's ruby laser and is widely used even today in **solid-state lasers**. The laser medium is placed inside a helical xenon flash lamp of the type which is widely used in photography. The xenon flash lamp for pumping is depicted in Fig. 12.5.

Another method of pumping is by direct **electron excitation** as it occurs in an electric discharge. This method is preferred for pumping gas lasers. The argon laser is a good example of this type of excitation. In a discharge tube, the electrons emitted by the cathode are accelerated towards the anode by applying an electric field (typically several  $\text{kV m}^{-1}$ ). Some of the electrons will impinge (electron impact) on the atoms of the active medium (gas) and raise them to the excited state. As a result, the population inversion is achieved in the active medium.

In the **inelastic atomic collision** method of pumping, the electric discharge provides the initial excitation which raises one type of atoms to their excited state or states. These atoms subsequently collide inelastically with another type of atoms. The energy transferred inelastically raises the later type of

atoms to the excited states and these are the atoms which provide the population inversion. An example is helium-neon (He-Ne) laser, to be discussed later, in which such a pumping process is employed.

A **direct conversion** of electrical energy into radiation occurs in laser diodes, which are solid state semiconductor lasers. You can read about it in Appendix 12A.

These are some of the processes used for pumping atoms of an active medium to achieve population inversion. Atoms (or molecules) used as active centres often exhibit rather complex system of energy levels. However, for all the variety of these systems, the actual pumping mechanisms may be narrowed down to a few rather simple diagrams correctly showing the pumping process. Typically, these pumping schemes involve three to four levels. Let us consider some of the pumping schemes.

We first identify different energy states necessary to understand the pumping schemes: the ground state as 0; the lower lasing state as 1; the upper lasing state as 2; and the pumping state as 3. We shall indicate pumping transition by upward arrow, the lasing transition by downward arrow and non-radiative fast decay by slanted arrows. Now let us consider a **three-level** pumping scheme shown in Fig.12.8a. Assume that by one of the pumping methods, more than half the number of atoms of active species have been pumped from ground state to pumping state 3. The pumped atoms in state 3 decay non-radiatively to upper lasing state 2. This decay is very fast, (life time is typically of the order to  $10^{-8}$  s). The upper lasing state 2 is generally a metastable state i.e. the life time of this state ( $\sim 10^{-3}$  s) is much higher than the pumping state (or the excited state). Therefore, we have a situation of population inversion between lasing states 2 and 1 and hence lasing may take place.

**Ruby laser** is an example of this pumping scheme. You may note that here the ground state (0) and the lower lasing state (1) is the same state. This feature of the pumping scheme proves too demanding for the pumping process because in normal circumstances, the ground state is highly populated. And, as you can appreciate, an ideal lower lasing state (1) should be empty or very thinly populated. How to get rid of this problem?

Atoms or molecules tend to occupy lowest energy state. Therefore, the population of the ground state (lowest energy state) is high.

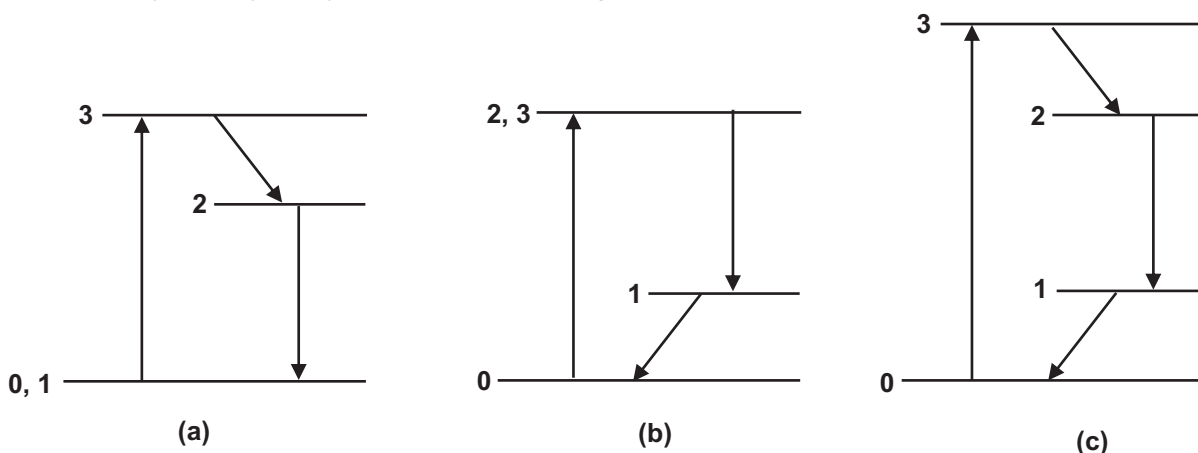


**Fig. 12.8: Three level pumping schemes: a) the ground state (0) and lower lasing state (1) are the same; b) pumping state (3) and upper lasing state (2) are the same; c) Four level pumping scheme.**

This problem can be solved if the pumping scheme is as shown in Fig. 12.8b. As you can see, the atoms in the lower lasing state (1) undergo non-radiative

You have studied the uncertainty principle in +2 physics. According to this principle,  $(\Delta E \cdot \Delta t) \sim \hbar$ . Since  $\Delta E = \hbar \Delta \nu$ , we have,  $(\Delta \nu \cdot \Delta t) = \text{constant}$ . Hence, an energy state with longer life time will have narrow frequency band.

transition to the ground state (0). Since this transition is very fast ( $\sim 10^{-8}$  s) the lower lasing level is empty for all practical purposes. You may, however, note that the same energy state acts as pumping state (3) and the upper lasing state (2). This situation has its own shortcoming. If the pumping state has to act as upper lasing state, it must have a longer life time (metastable state) which implies that it must have very narrow frequency width. On the other hand, for proper utilization of pumping energy, this state must have a wide frequency width so that more and more atoms get accommodated there. So, you will see that there are conflicting requirements put on a single energy state.

The pumping scheme free from the shortcomings mentioned above with reference to three-level pumping scheme is what we call four-level pumping scheme shown in Fig. 12.8c. In this case, the pumping state (3) and the upper state (2) are separate; atoms between pumping state (3) and the upper lasing state (2) and between the lower lasing state (1) and the ground state (0) undergo non-radiative transitions

You may now ask: Which pumping scheme is better and preferred? Each pumping scheme has its own advantages and disadvantages. The choice of the pumping scheme in designing a laser depends upon various factors like the active media, the application area, where we want to use the laser light, etc. We will discuss these aspects a little later. You may now like to answer an SAQ.

---

### SAQ 3 – Pumping mechanism

If laser action occurs by the transition from an excited state to the ground state and it produces light of 6930 Å wavelength, what is the energy of the excited state? Take the energy of the ground state to be zero.

---

Now we will discuss about another essential component of laser. It is the amplification of light, which is responsible for imparting the brightness to the laser beam.

### 12.3.3 Feedback Mechanism: Optical Resonant Cavity

From our discussion so far you know that when the state of population inversion exists in an active medium, a light beam of particular frequency passing through it would get amplified. It happens because in such a situation, stimulated emission dominates spontaneous emission. This is the basic principle of an **optical amplifier**. But a laser is much more than a simple optical amplifier. Although the laser is characterized by a highly coherent beam of light, its stimulated emission is not initiated by a coherent light. Instead, it is the spontaneously emitted photon from upper lasing state which stimulates the emission of new photons. Each spontaneous photon can initiate more stimulated transitions which, in turn, may cause light amplification. In this way, we get amplification of light by stimulated emission. But, how is coherence of this amplified light ascertained? In other words, how can we ensure that the laser light has a very narrow bandwidth

(monochromaticity) and a high degree of phase correlation? As such, the amplified light from laser is not coherent, because the spontaneous photons are independent of each other and travel in different directions. Therefore, the corresponding stimulated photons will also travel in different directions.

Can you think of a way for obtaining a highly coherent laser beam? For obtaining a coherent light beam, we need to have a mechanism by which a condition is created such that spontaneous emission only in certain selected direction can develop stimulated emission; while the spontaneous photons emitted in other directions leave the active medium without initiating significant stimulated emission. This mechanism is known as **feedback mechanism**.

Now, you may ask, how do we actually achieve this favourable condition for spontaneously emitted photons in some preferred direction to further stimulate emission? Well, this is accomplished by means of an **optical resonator** - an essential component of a laser. Let us understand how an optical resonator works.

Optical cavity resonator can have many configurations. The schematic arrangement of a simple resonator is shown in Fig. 12.9.

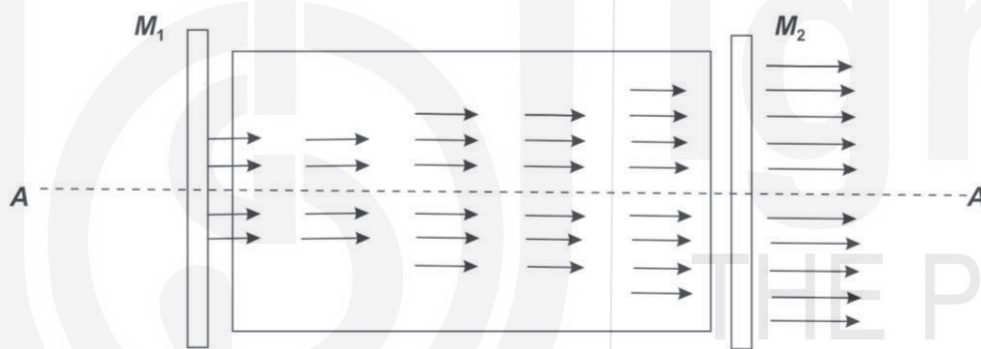


**Fig. 12.9: Optical resonator consisting of two mirrors  $M_1$  and  $M_2$  :  $M_1$  is totally reflecting whereas  $M_2$  is semi-transparent. The axis of the mirrors is aligned with that of the active material.**

It consists of a pair of plane mirrors,  $M_1$  and  $M_2$  set on an optical axis which defines the direction of the laser beam. The active material is placed in between these mirrors. The photons emitted spontaneously along the A-A direction or sufficiently close to it travel a relatively longer distance within the active material and generate more stimulated emission in that direction. It is so because the photons travelling along A-A will be reflected back and forth by the mirrors  $M_1$  and  $M_2$ .

You will learn in the next unit that the resonant cavity is the most vital component that decides the two crucial properties of the laser light viz. coherence and monochromaticity.

After learning the basic constituents of a laser, let us discuss about different types of lasers. Since the invention of ruby laser by Maiman in 1960, the research and development in this field has produced a variety of lasers. It is not possible to discuss all of them in detail here. However, we will discuss some of the important types of laser now.

## 12.4 TYPES OF LASERS

Lasers can be classified in a variety of ways. One of these is in terms of their active media. As mentioned earlier, materials in all the three states of matter, namely, solid, liquid and gas, have been used as active medium to produce laser beam. Further, lasers have also been constructed using semiconductors and plasma as active medium. In the following, let us know about some of them with particular reference to the physical properties of the active medium and the pumping methods employed.

### 12.4.1 Solid State Lasers

These lasers use an active material which is an insulator doped with ions of impurity acting as active centres in the host structure. These lasers invariably use optical pumping to obtain the condition of population inversion. The sources for optical pumping may be discharge flashtubes, continuously operating lamps or even an auxiliary laser. The active centres in these lasers are transition element ions doped in the dielectric crystal. The host materials for these active centres are generally oxide crystals.

You have learnt the functioning of this laser in section 12.2. In solid-state lasers, the optical pumping is done by placing the active material (in the form of rod) at one focus and the pumping source (in the shape of a right cylinder) at another focus of an **elliptical reflector** as shown in Fig. 12.10a. The advantage of such an arrangement is that any light leaving one focus of the ellipse will pass through the other focus after reflection from the silvered surface of the pump cavity. All of the pump radiation, therefore, is maximally focused on the active material, as shown in Fig. 12.10b.

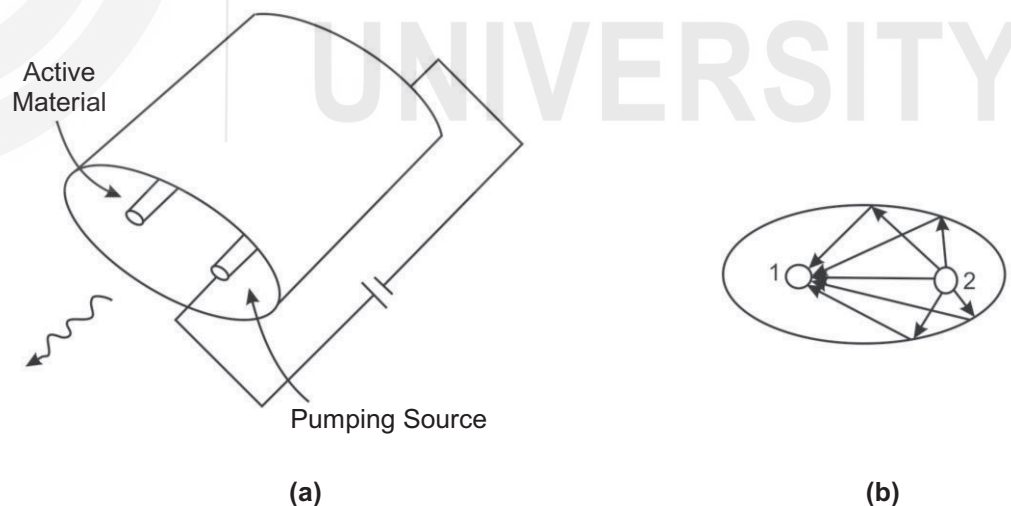


Fig. 12.10: Pumping arrangement in elliptical reflector for solid-state lasers.

The most popular type of solid-state lasers are the ruby laser and Nd:YAG (neodymium: yttrium, aluminium garnet) laser. Ruby is  $\text{Al}_2\text{O}_3$  crystal (corundum) doped with triply ionized chromium atom ( $\text{Cr}^{3+}$ ), about which you have learnt in details already. Now we will describe the Nd:YAG laser, which works on a four level pumping scheme.

### The Nd: YAG Laser

Nd:YAG crystal has triply ionized neodymium ( $\text{Nd}^{3+}$ ) ions replacing small fraction ( $< 1\%$ ) of yttrium ions in the YAG host crystal.  $\text{Nd}^{3+}$  ions act as active centres in the medium.

The energy levels of the neodymium (the active species) are shown in Fig. 12.11. In order to keep the discussion simple, we have not used the spectroscopic notations for different energy levels in this diagram. Rather, energy levels have been marked  $E_0$ ,  $E_1$  and so on. The optical pumping raises the Nd atoms in the ground state ( $E_0$ ) to a few excited states ( $E_7$ ,  $E_8$ ). The energy levels marked  $E_4$  and  $E_1$  are the lasing levels. The pumped atoms in the excited states undergo non-radiative transition to the upper lasing level,  $E_4$ . Out of the group of lower lasing levels, the major portion of energy is emitted in the transition  $E_4 \rightarrow E_1$ . In this way, the Nd: YAG laser is an example of four-level laser.

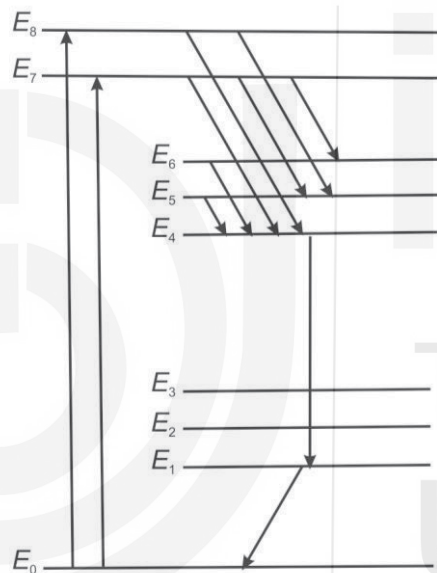


Fig. 12.11: Energy level diagram of Nd (neodymium) ion in Nd: YAG.

The solid-state laser has two advantages: (a) it has a low excitation threshold and (b) has a high thermal conductivity. Due to high thermal conductivity, it can be used for generating light pulses at a high repetition rate or for continuous operation.

### 12.4.2 Liquid Lasers

In this class of lasers, as the name indicates, the active media are either the liquid solutions of organic dyes or specially prepared liquids doped with rare-earth ions like  $\text{Nd}^{3+}$ . However, majority of liquid lasers use a solution of an organic dye as active medium and hence are also called **organic dye lasers**. Solvents used for the purpose are water, methanol, benzene, acetone etc. The liquid lasers are optically pumped. The energy states taking part in the lasing transition are the various vibrational energy states or different electronic energy states of the dye molecule. Since you may not be familiar with the

vibrational energy states of molecules, we will not discuss the pumping scheme of this class of lasers.

In contrast to solids, liquid do not crack or shatter and can be made in any sizes and shapes. Another advantage of liquid lasers is that the organic dyes have wide absorption bands in the visible and near ultraviolet portion of the electromagnetic spectrum. Therefore, liquid lasers are an ideal candidate for **tunable laser** i.e. the frequency and hence energy of the output laser beam can be easily selected.

### 12.4.3 Gas Lasers

In gas lasers rarefied gases are used as the active media. Their most attractive feature is that they can be designed to produce output beams over a wide range of wavelengths. Except for the caesium (Cs) vapour laser, gas lasers are pumped electrically rather than optically. Can you say why? It is because the condition for amplification by stimulated emission, at one wavelength or another, is satisfied by an electrical discharge through almost any gas. Another reason for employing electrical pumping for gas lasers is that, unlike solids and liquids, the absorption lines of active centres in gaseous media exhibit substantially narrow widths. Therefore, optical pumping would prove very inefficient for gas lasers because the pumping radiation obtained from optical sources do not have line spectrum of very narrow frequency spread. In other words, the energy of optical pump radiation has a considerable spread in its value; whereas the gaseous active media will absorb radiation of almost single energy, and most of the pumping energy will go waste. Hence, optical pumping is not used for gas lasers. Further, gas lasers have advantage over solid state and liquid lasers in that they are free from local irregularities. Most gaseous systems have a high degree of optical perfection simply because the density of the gas is uniform.

We will now describe about the He-Ne laser which was first successfully operated gas laser.

#### The Helium-Neon Laser

As the name suggests, in the helium-neon laser, a mixture of helium (He) and neon (Ne) gases is used as active medium. Lasing levels are provided by the excited states of the Ne atoms, whereas the He atoms play an important role in pumping Ne atoms to the excited states.

The He-Ne laser is shown schematically in Fig. 12.12.

The pumping is done by a stationary glow discharge fired by a direct current. When the potential difference between the anode and cathode is about 1000V, a glow discharge is initiated in the working capillary (containing He-Ne mixture) of a few millimetre diameter.

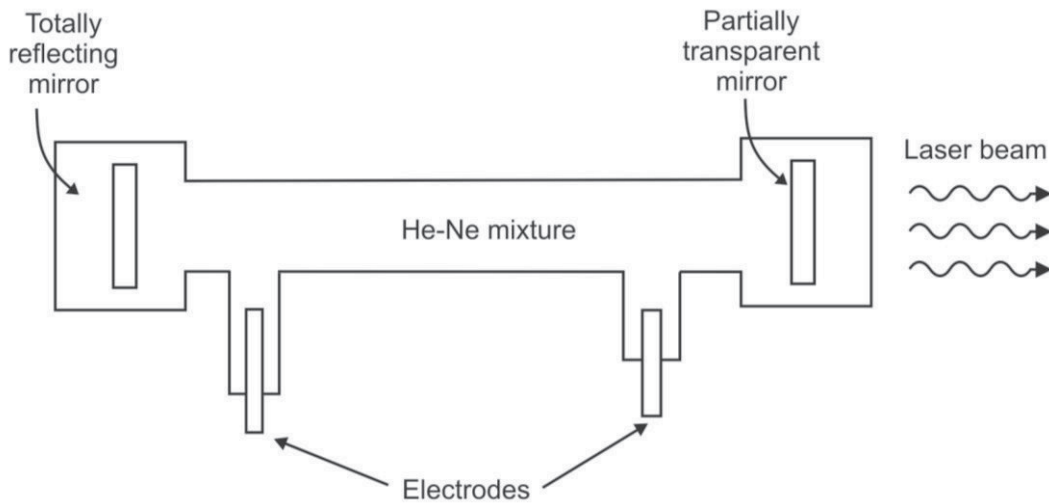


**Fig. 12.12: Schematic diagram of He-Ne laser.**

Now, let us look at the pumping scheme of the He-Ne laser. Refer to Fig.12.13 which shows the energy level diagram of He-Ne laser.

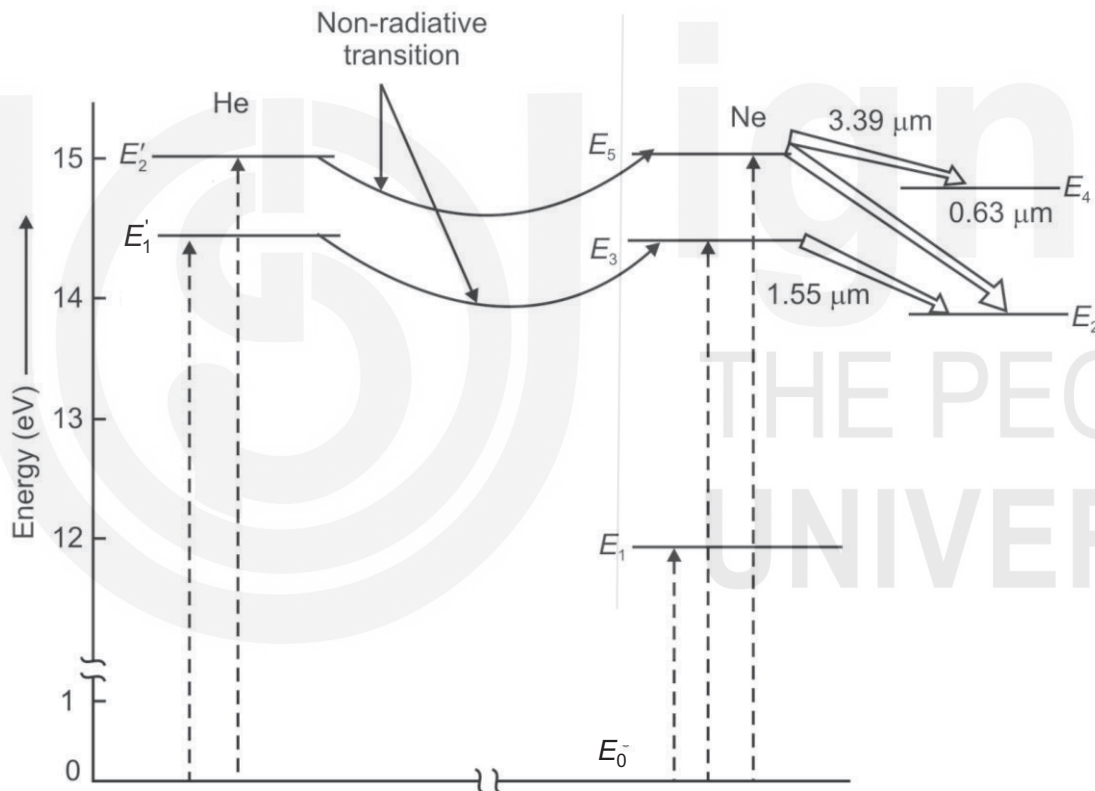


**Fig. 12.13: Energy level diagram of helium-neon laser. Arrows ( $\Rightarrow$ ) indicate the lasing transition.**

When free electrons produced during the gas discharge pass through the He-Ne mixture, they collide with the helium and neon atoms and excite them by impact energy transfer. Such transitions occurring by absorption of energy from impacting electrons are shown by dashed arrows in the figure. The excited states of helium (i.e.  $E_1'$  and  $E_2'$ ) are metastable. Thus, helium atoms excited to these states stay there for a long time before losing energy by collision. The interesting feature of the He-Ne energy diagram is that the excited states of neon, namely  $E_3$  and  $E_5$  have approximately same energy as that of  $E_1'$  and  $E_2'$  of helium atom. Therefore, when He-atoms in  $E_1'$  and

$E_2'$  states collide with Ne-atoms in ground state, the He-atoms transfer their energy to Ne-atoms and raise them to the states  $E_3$  and  $E_5$ . Such an exchange of energy is known as **resonant collision energy transfer**. Due to this energy transfer, He-atoms fall back to ground state. As a result, the excited states  $E_3$  and  $E_5$  of Ne-atoms have a sizable population which is much more than that of the states  $E_2$  and  $E_4$ . Thus a condition of population inversion is achieved between the upper lasing levels  $E_5$  (or  $E_3$ ) and lower lasing levels  $E_4$  (or  $E_2$ ). In such a situation, any spontaneously emitted photon can trigger laser action between these levels. The neon atoms then drop down from the lower lasing levels  $E_2$  or  $E_4$  to the level  $E_1$  through spontaneous emission.

The wavelengths of transition between levels  $E_5 \rightarrow E_4$ ,  $E_5 \rightarrow E_2$ ,  $E_3 \rightarrow E_2$  are  $3.39 \mu\text{m}$ ,  $0.63 \mu\text{m}$  and  $1.55 \mu\text{m}$  respectively. As you can easily make out, radiations corresponding to  $3.39 \mu\text{m}$  and  $1.55 \mu\text{m}$  fall in the infrared region of the electromagnetic spectrum. However, the radiation corresponding to  $0.63 \mu\text{m}$ , gives the red light – characteristic light – of He-Ne laser. Proper selection of different frequencies may be made by choosing the end mirrors of the resonant cavity, which have high reflectivity over only the selective (desired) wavelength range.

Before we conclude our discussion about types of lasers, you must know that apart from those mentioned above, there are many other types of lasers. We may particularly mention molecular lasers (carbon dioxide laser), chemical lasers, plasma lasers, semiconductor lasers, etc. We have not discussed these here since for an understanding of their pumping schemes, you need to know molecular spectroscopy, semiconductor physics etc. It is, however, worth mentioning here that the essential principles in so far as lasing action is concerned, remain the same in all type of lasers.

Let us now summarize the points discussed in this unit.

## 12.5 SUMMARY

| Concept                                              | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Emission of EM radiation from atoms</b>           | <p>■ According to the Bohr's theory, if an atom makes a transition from an excited state (of energy <math>E_i</math>) to a state of lower energy <math>E_f</math>, emission of electromagnetic radiation (photons) take place. The energy of the emitted photon is</p> $h\nu = E_i - E_f.$                                                                                                                                                                                                                                                                                                                                        |
| <b>Stimulated emission and Einstein coefficients</b> | <p>■ The existence of stimulated emission of radiation was predicted by Einstein on the basis of thermodynamic considerations. Let the population of the energy level <math>E_1</math> be <math>N_1</math> and that of <math>E_2</math> be <math>N_2</math> (<math>E_1 &lt; E_2</math>) then, the ratio of the population of the two states is given as</p> $\frac{N_2}{N_1} = \frac{B_{12} u(\nu)}{A_{21} + B_{21} u(\nu)}$ <p>where, <math>u(\nu)</math> is the energy density of radiation at frequency <math>\nu</math> and <math>B_{12}</math>, <math>B_{21}</math> and <math>A_{21}</math> are Einstein's coefficients.</p> |

**Einstein relations** ■ Einstein coefficients are related to each other through the relations

$$B_{21} = B_{12}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

**Condition for stimulated emission**

- Einstein's relation clearly indicates that stimulated emission may dominate spontaneous emission provided the condition of population inversion exists. And in an atomic system where a condition of population inversion exists, we may have amplification of light, which is laser light.

**Realization of working laser**

- Einstein's prediction was first realized in the optical frequency range by Maiman who developed a laser using a ruby rod.

**Essential components for laser operation**

- There are three essential components for laser operation:
  - i) Active medium
  - ii) Pumping
  - iii) Optical resonant cavity

**Intensity of light in active medium**

- The change in the intensity of a light beam passing through an active medium is given by

$$\frac{\partial I_v}{\partial x} = -I_v \frac{h\nu n}{c} (N_1 - N_2) B$$

where  $n$  is refractive index and  $B$  is the Einstein's coefficient.

This relation clearly indicates that for enhancement in the intensity of the light beam as it traverses the active medium,  $N_2 > N_1$ , i.e. a condition of population inversion, must exist.

**Pumping methods**

- Usually employed pumping methods are optical pumping, electronic discharge, inelastic atomic collisions etc. The choice of pumping process mainly depends upon the nature of the active medium.

**Pumping schemes**

- There are two types of pumping schemes: three level and four-level.

**Feedback mechanism**

- Optical resonant cavity helps in light amplification and obtaining sustained laser light.

## 12.6 TERMINAL QUESTIONS

1. Assume that an atom has two energy levels separated by an energy corresponding to a frequency  $4.7 \times 10^{14}$  Hz (as is in the case of He-Ne laser). Let us assume that all the atoms are located in one or the other of these two states. Calculate the fraction of atoms in the upper state at room temperature ( $T = 300$  K).

2. A pulsed laser used for welding produces 100 W of power during 10 ms. Calculate the energy delivered to the weld.

## 12.7 SOLUTIONS AND ANSWERS

### Self-Assessment Questions

1. The ratio of the number of spontaneous to stimulated emission is given as

$$\frac{A_{21}}{B_{21}u(\nu)} = e^{h\nu/k_B T} - 1$$

The absolute temperature of an ordinary source of light has been gives as  $T = 10^3 \text{ K}$ .

Let us take the wavelength of light,  $\lambda = 6000 \text{ Å}$ . Hence the corresponding frequency,

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ ms}^{-1}}{6000 \times 10^{-10} \text{ m}} = 0.5 \times 10^{15} \text{ Hz.}$$

Plank's constant,  $h = 6.6 \times 10^{-34} \text{ Js}$

Boltzmann constant,  $k_B = 1.38 \times 10^{-23} \text{ JK}^{-1}$

Hence,

$$\begin{aligned} \frac{A_{21}}{B_{21}u(\nu)} &= \exp \left[ \frac{6.6 \times 10^{-34} \text{ Js} \times 0.5 \times 10^{15} \text{ s}^{-1}}{1.38 \times 10^{-23} \text{ JK}^{-1} \times 10^3 \text{ K}} \right] - 1 \\ &= \exp[23.9] - 1 = 2.4 \times 10^{10} \end{aligned}$$

Thus, for ordinary sources of light, the number of spontaneous emission is much greater than the number of stimulated emission.

2. It is not possible to lase a ruby laser with 7000 Å wavelength excitation radiation. This is because, the laser light coming out of ruby laser has a wavelength of 6943 Å. Energy of this radiation is larger than the excitation energy we are applying by using 7000 Å radiation. In order to achieve an excited state of atom, we must provide larger energy than the laser energy being radiated.
3. Let the energy of the excited state (upper lasing state) be  $E_2$  and that of the ground state (lower lasing state) be  $E_1$ . The laser light is due to the atomic transitions from  $E_2$  to  $E_1$ . Thus, the frequency of the laser light will be

$$\nu = \frac{E_2 - E_1}{h}$$

It is given that,

$$E_1 = 0, \lambda = 6930 \text{ \AA} = 6930 \times 10^{-10} \text{ m};$$

and we have to determine  $E_2$ .

We first calculate the frequency of radiation.

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ ms}^{-1}}{6930 \times 10^{-10} \text{ m}} = 4.3 \times 10^{14} \text{ Hz}.$$

Substituting the value of ground energy we get

$$E_2 - E_1 = E_2 - 0 = h\nu$$

Using the value of Plank's constant,  $h = 6.6 \times 10^{-34} \text{ Js}$

We get,

$$\begin{aligned} E_2 &= (6.6 \times 10^{-34}) \text{ Js} \times (4.3 \times 10^{14}) \text{ s}^{-1} \\ &= (28.38 \times 10^{-20}) \text{ J} = 1.77 \text{ eV}. \end{aligned}$$

### Terminal Questions

1. Let the two energy levels be  $E_1$  and  $E_2$  (such that  $E_1 < E_2$ ) and their population be  $N_1$  and  $N_2$  respectively. According to the Boltzmann distribution

$$\frac{N_2}{N_1} = e^{-h\nu/k_B T} = e^{-(E_2 - E_1)/k_B T}$$

We know that

$$\begin{aligned} E_2 - E_1 &= h\nu \\ &= (6.6 \times 10^{-34}) \text{ Js} \times (4.7 \times 10^{14}) \text{ s}^{-1} \\ &= 31.02 \times 10^{-20} \text{ J} \end{aligned}$$

and at  $T = 300 \text{ K}$ ,

$$k_B T = (1.38 \times 10^{-23}) \text{ JK}^{-1} \times 300 \text{ K} = 4.14 \times 10^{-21} \text{ J}$$

Hence,

$$\begin{aligned} \frac{N_2}{N_1} &= \exp \left[ \frac{31.02 \times 10^{-20}}{4.14 \times 10^{-21}} \right] \\ &= \exp [74.9] = 2.96 \times 10^{-33} \end{aligned}$$

So it is evident that at room temperature, the occupancy of upper level is negligible.

2. You know that power is the energy delivered per unit time.

Hence,

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

It is given that Power = 100 W = 100 Js<sup>-1</sup>

In 10 ms, energy delivered is

$$= 100 \text{ Js}^{-1} \times (10 \times 10^{-3}) \text{ s} = 1 \text{ J.}$$

Hence the energy delivered to the weld is 1 joule.



## APPENDIX 12A: LASER DIODES

You have learnt that for lasing action, it is necessary to achieve population inversion. This carrier population inversion is achieved in an intrinsic (undoped) semiconductor by the injection of electrons into the conduction band of the material. This is illustrated in Fig. 12A.1 where the electron energy and the corresponding filled states are shown. Fig. 12A.1a shows the ideal situation at absolute zero when the conduction band contains no electrons. Electrons injected into the material fill the lower energy states in the conduction band up to the injection energy level for electrons. Since charge neutrality is conserved within the material, an equal density of holes is created in the top of the valence band by the absence of electrons, as shown in Fig. 12A.1b.

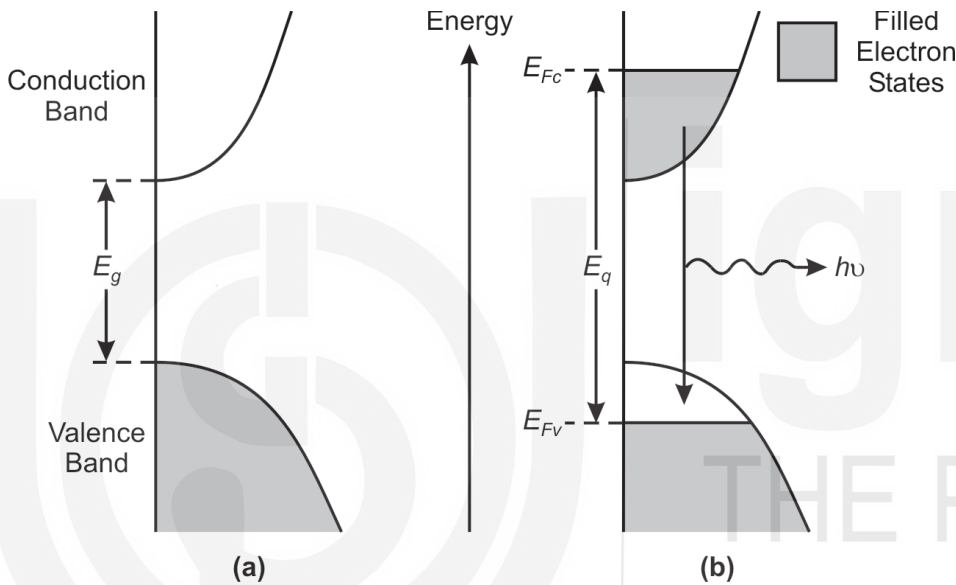


**Fig. 12A.1: The filled electron states for an intrinsic direct bandgap semiconductor: a) at absolute zero in equilibrium; b) with high carrier injection**

Incident photons with energy  $E_g$  but less than the separation energy of the quasi-Fermi levels  $E_q = E_{Fc} - E_{Fv}$  cannot be absorbed because the necessary conduction band states are occupied. However, these photons can induce a downward transition of an electron from the filled conduction band states into the empty valence band states, thus stimulating the emission of another photon. The basic condition for stimulated emission is therefore dependent on the quasi-Fermi level separation energy as well as the band gap energy and we can write

$$E_q > h\nu > E_g. \quad (12A.1)$$

Population inversion may be obtained at a  $p$ - $n$  junction by **heavy doping** (also known as **degenerative doping**) of both the  $p$ - and  $n$ -type material. Heavy  $p$ -type doping with acceptor impurities causes a lowering of the Fermi level into the valence band as shown in Fig. 12A.2a. Similarly, degenerative  $n$ -type doping causes the Fermi level to enter the conduction band of the material. This figure depicts the position of the Fermi level and the electron occupation

(shading) with no applied bias. Since in this case the junction is in thermal equilibrium, the Fermi energy has the same value throughout the material.

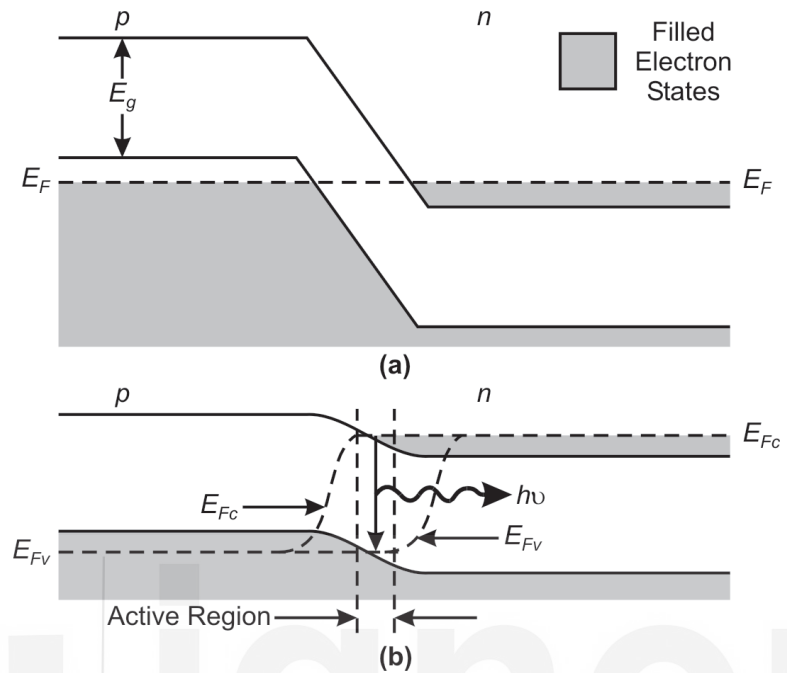


**Fig. 12A.2: Degenerate  $p$ - $n$  junction a) with no applied bias; b) with large forward bias**

Fig. 12A.2b shows the  $p$ - $n$  junction when a forward bias nearly equal to the bandgap voltage is applied and hence there is direct conduction. In such a degenerately doped semiconductor junction, there exists an active region near the depletion layer that contains simultaneously degenerate populations of electrons and holes. For this region the condition for stimulated emission is satisfied for electromagnetic radiation of frequency  $\nu$ , satisfying the condition  $E_g / h < \nu < (E_{Fc} - E_{Fv}) / h$ . Therefore any radiation of this frequency, which is confined to the active region, will be amplified.



Laser illuminated art-pieces enhance viewing experience. You will learn about various applications of lasers in this unit. Photo credit: M/S Guardian Media & Entertainment Pvt. Ltd.. Pune.

# UNIT 13

## PROPERTIES AND APPLICATIONS OF LASERS

### Structure

- 13.1 Introduction
  - Expected Learning Outcomes
- 13.2 Properties of Lasers
  - Monochromaticity
  - Directionality
  - Coherence

- 13.3 Applications of Lasers
  - Communication
  - Industry
  - Medicine
  - Environmental Monitoring
  - Basic Research
  - Holography
- 13.4 Summary
- 13.5 Terminal Questions
- 13.6 Solutions and Answers

### STUDY GUIDE

So far, you learnt about the process of laser light emission and various types of lasers. In this unit, you will be learning about the special properties of lasers that make them different from the other light sources. We will also discuss about the applications of the lasers in various walks of life.

You will not require any special mathematical tools to study this unit. You should just brush up your knowledge about the properties of light like wavefront, coherence, monochromaticity etc. to understand the discussion in this unit. Try to solve the SAQs and Terminal Questions given in this unit on your own.

*“There are relatively few experiments in atomic physics these days that don’t involve the use of a laser.”*

**Eric Allin Cornell**

## 13.1 INTRODUCTION

---

In the last unit you learnt about the mechanism of lasing action and production of light. Various types of lasers were also discussed. You must have noticed that the lasers have many applications ranging from high density data storage media like DVDs (Digital Versatile Disks) to large guided missiles used for defence purposes. These applications essentially emanate from the special properties of laser radiation. In this unit you will learn about these distinctive properties of lasers and some important applications of lasers.

Laser is characterized by its monochromaticity (narrow spectral width), good directionality and coherent nature. In Section 13.2 you will learn about different properties of laser.

Due to the peculiar properties of lasers, they find application in various fields ranging from medicine to defence. In the communication area, optical fibre has proved to be a very efficient medium for signal transmission. You will learn about it in the next unit. For sending the signal through an optical fibre, an intense narrow (highly directional) beam of light is required, which is made possible by laser diodes. In the medicine field, laser is extensively used in surgery to perform operation on a restricted area of a body part, leaving the other parts unaffected. In the manufacturing sector, the industries use laser for high-precision machining processes, as well as in semiconductor processing for integrated circuit fabrication. Lasers also find wide application in the areas of environment monitoring, displays, data storage and basic science research. Lasers have been instrumental in development of a novel technique of photography known as holography. It is a technique of obtaining the complete picture of an object or a scene by using a 3-dimensional recording of an object. You will read about all these in Section 13.3.

### Expected Learning Outcomes

---

After studying this unit, you should be able to:

- ❖ explain the cause of monochromaticity of laser light;
- ❖ describe the origin of high directionality of laser beams;
- ❖ explain the coherence of laser radiation;
- ❖ describe the cause of speckle pattern in laser;
- ❖ enumerate the applications of laser in various fields; and
- ❖ explain the process of hologram formation.

## 13.2 PROPERTIES OF LASERS

---

You may have read about some of the special properties of lasers in your +2 physics classes. Now we will discuss these properties in some details.

### 13.2.1 Monochromaticity

---

When we see any single colour (like green, red, blue etc) with our eyes, we tend to think it to be monochromatic. However, the definition of monochromaticity requires that the light should contain a single frequency ( $\nu$ ).

In practice, any single colour light source will always have some spread of frequency around a central frequency. A general source like incandescent lamp used for home lighting is a white light source; means it has all the wavelengths present in it. Radiation coming out of neon or sodium or mercury discharge lamps does not have as continuous spread of frequencies as white light source but has a series of lines of different colours. So the nature of light depends on the method of its generation. The laser light is highly monochromatic due to very nature of its origin – the stimulated emission. That is because, as described in the last Unit in Sec. 12.2.2, as per Einstein's prediction, the spontaneously emitted photons whose frequencies do not match with the frequency difference between lasing levels will not give rise to stimulated emission. Thus, the band of wavelengths emitted during spontaneous emission which take part in initiating lasing action is narrowed down. The monochromaticity of the laser light can further be enhanced by the optical resonant cavity, as you will discover now.

A hot filament in the incandescent lamp emits radiation of all frequencies while the discharge lamps emit radiation only by de-excitation of selective atomic excitations, giving it discrete nature.

The monochromaticity can be quantitatively expressed by the spread in the frequency ( $\Delta\nu$ ) of a particular line in a spectrum. It is called the **line width**. Depending on the light source, the line width can be 3000 Å for a white light source to 0.1 Å for a gas discharge line. By using appropriate filter, we can isolate a single line from the gas discharge spectrum. If this gas is made to emit by lasing action this particular line comprises a series of still narrower lines as will be discussed below. By suppressing all the lines except one by a method of *single moding* we can obtain extremely narrow linewidth radiation. Remember that however narrow line we may observe, it will still have certain linewidth  $\Delta\nu(\neq 0)$ . So in practice, no light source, including laser is able to produce absolutely monochromatic light; we can make only better approximation towards ideal case.

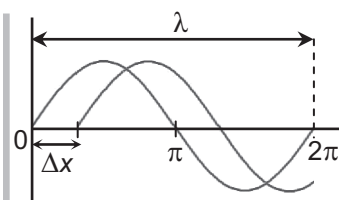
In the course on Electricity and Magnetism: Laboratory (BPHCL-134) you have performed experiments on resonant (L-C-R) circuits, where you learnt that a high Q circuit has very narrow frequency band with very less losses.

For obtaining a selective frequency of laser radiation we make use of the cavity resonator discussed in the last unit. From Fig. 12.9 you will recall that the cavity resonator consists of cavity between two mirrors, one of them being totally reflecting and the other one semi-transparent. The laser beam travels several times between the two mirrors before emerging out of the semi-transparent mirror. The optical cavity acts as a resonator with extremely high Q (quality factor).

But this high-Q condition does not hold for all the frequencies contained in a laser transition in the source. Frequencies of only some values fulfil the resonance condition. Let's see, why this happens.

Consider a plane wave travelling between the two mirrors of a cavity separated by distance  $D$ . Let the wave be moving along the line normal to the mirrors. So, the wave travels a distance  $2D$ , during one round trip between the mirrors.

Now, the total phase change experienced by a wave of wavelength  $\lambda$ , travelling a distance  $D$  and getting reflected to return to the same initial point (i.e. round trip distance  $2D$ ) can be written as



One wavelength  $\lambda$  corresponds to  $2\pi$  radians; hence the phase difference  $\delta$  corresponding to length  $\Delta x$  can be expressed as

$$\delta = \frac{2\pi\Delta x}{\lambda}$$

$$\Delta\phi = 2\pi \frac{2D}{\lambda} = \frac{4\pi D}{\lambda} \quad (13.1)$$

If the reflected wave has same amplitude as the original wave, but  $180^\circ$  phase difference, the amplitudes of the two waves will get cancelled and there will not be any net field corresponding to this wave in the cavity. Hence there won't be any energy density to stimulate the atoms to emit the radiation, even if the condition of population inversion is attained.

So you will appreciate that not all the wavelengths will be replicated and sustained in the cavity. Only those waves will survive that have original and reflected waves in the same phase ( $\Delta\phi=2\pi n$ , where  $n$  is an integer). That is, the cavity acts as a resonator for only such frequencies that fulfil this condition. If we substitute this condition in Eq. (13.1), we arrive at the conclusion that only those wavelengths will be replicated in the cavity, for which the length of the cavity is an integral multiple of half-wavelength.

$$\text{i.e., } D = n \frac{\lambda}{2}, \text{ where } n \text{ is an integer.} \quad (13.2)$$

The waves which are sustained in the cavity are called the **longitudinal** (or *axial*) **modes** of the cavity, and the cavity resonates only at these frequencies. Value of  $n$  is usually very high, as you will find after solving the following SAQ.

### SAQ 1 - Modes sustained in a cavity

A laser radiation of  $6000 \text{ \AA}$  is sustained in a cavity in which mirrors are separated by  $30 \text{ cm}$  distance. Estimate the value of number of modes,  $n$ .

Many a times, it is convenient to refer to the longitudinal modes by their frequency rather than the wavelength. Using the condition of sustained modes given by Eq. (13.2), we can write,

$$v = \frac{c}{\lambda} = \frac{c}{2D/n} = n \frac{c}{2D} \quad (13.3)$$

where  $c$  is the velocity of light in vacuum. We can identify the frequency of each mode by suffixing it with the corresponding  $n$  value ( $v_n$ ).

By subtracting the frequencies of two consecutive modes, we can calculate the separation between the mode frequencies,  $\Delta v$ .

$$\Delta v = v_{n+1} - v_n = (n+1) \frac{c}{2D} - n \frac{c}{2D}$$

$$\text{i.e. } \Delta v = \frac{c}{2D} \quad (13.4)$$

You will notice that the separation between the mode frequencies is independent of the frequency as well as  $n$  and is a function of only the distance between the mirrors.

To get an estimate of the frequency corresponding to the mode separation, attempt the following SAQ.

### SAQ 2 - Modes separation

Calculate the mode separation for the cavity mentioned in SAQ 1.

After solving SAQ2, you must have understood that the frequency separation between the modes of practical cavities is few hundreds of megahertz. Many laser transitions are much broader than this frequency and hence many modes can be sustained within the width of a line, as is clear from Fig. 13.1a. Since only the modes supported by the cavity can result into sustained laser action, the output of a laser contains discrete frequencies separated by  $\Delta\nu$  interval shown in Fig.13.1b.

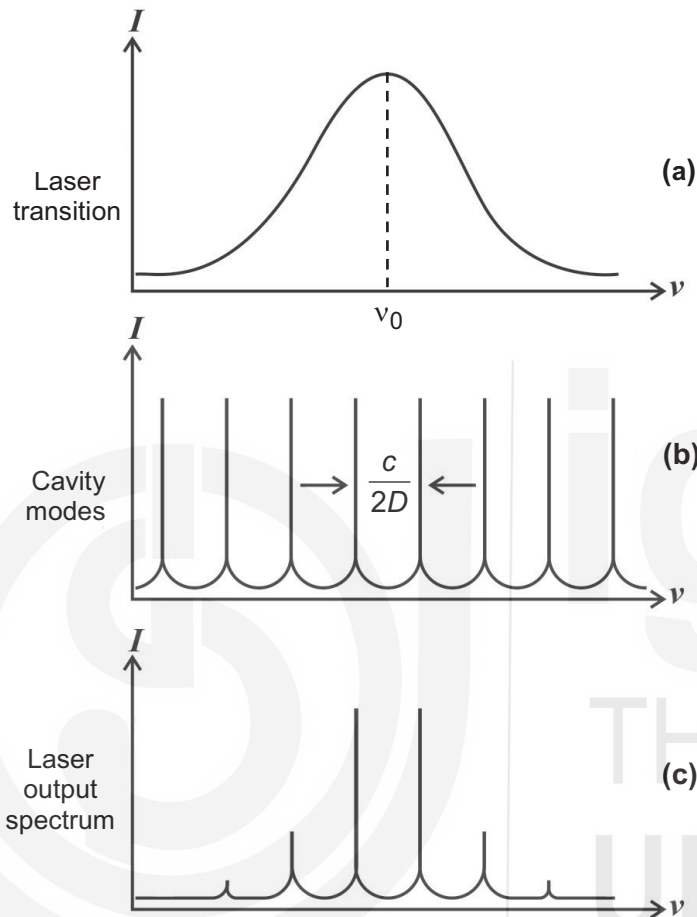


**Fig. 13.1: a) Spectral output of a laser transition; b) cavity modes; and c) output spectrum emerging out of the cavity.**

The resultant spectrum emerging out of the cavity will be a combination of lasing transition line shape and cavity modes. Although the sustained modes in the cavity have equal amplitude for all the frequencies, the amplitude of laser transition has a bell shaped around its central frequency. Hence the output from the cavity is in the form of equally spaced narrow lines whose amplitude is determined by the shape of transition line spectrum. This is shown in Fig.13.1c. So you will appreciate that by using a cavity resonator, we can obtain much sharper spectral lines than those emitted during the laser transition. If we adjust the separation between the mirrors in such a way that one of the resonant frequency modes coincides exactly with the central frequency  $\nu_0$  of the transition spectrum, then we can obtain an intense laser beam with extremely narrow linewidth. This will lead to an almost ideal monochromatic light of the laser. Since we are choosing a single prominent mode of laser radiation by this method, it is called the *single moding* technique.

Let us recapitulate the points learnt so far before proceeding further.

### Recap

## MONOCHROMATICITY OF LASERS

- The laser light has better monochromaticity as compared to other sources with a very narrow spread around the central frequency.
- Selective cavity modes are sustained in a laser. The separation between the consecutive modes is given by  $\Delta\nu = \frac{c}{2D}$ , where  $D$  is the distance between the mirrors in the cavity resonator of the laser.

After learning about the monochromatic nature of laser light, let us now consider about the directionality of lasers.

### 13.2.2 Directionality

So far we have discussed that the light wave is confined in the cavity and undergoes several reflections between the mirrors before emerging out of the system. Refer to Fig. 13.2.

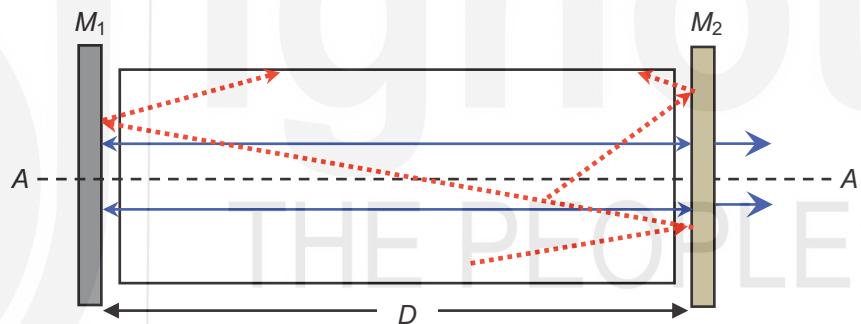


Fig.13.2: Directionality of laser radiation induced by cavity.

The photons travel in the active medium between the mirrors  $M_1$  and  $M_2$ . Those photons (shown in blue colour), travelling parallel to the central axis A-A (perpendicular to the plane of mirrors) remain confined within the cavity. After suffering many reflections they emerge out from the semi-transparent mirror  $M_2$ , almost parallel to the direction of the axis. However, if there are some photons travelling in the direction other than the direction of central axis (shown in red colour), after suffering a few reflections, they get lost by striking the walls of the cavity. Hence such photons do not contribute to the laser radiation obtained from the system.

Thus the optical resonant cavity provides the desired selectivity of propagation direction and gives out highly directional laser beam. Now, since the entire light output coming out of the laser is confined in a beam of very small area ( $\sim 1$  mm diameter), the intensity of the light is extremely high. You can understand this fact with one example.

For us, Sun is one of the brightest sources of light, emitting around  $3.85 \times 10^{26}$  W power. However, as shown In Fig.13.3a, it radiates its power in all the directions. Applying the basic solid geometry, you will understand

that this radiation is given out in a  $4\pi$  steradian solid angle. If we consider the radius of Sun and the distance between the Earth and the Sun, only about  $0.1 \text{ W cm}^{-2}$  power (2.2 billionth of the total emitted power) is received on the Earth's surface on any bright, cloudless day.



Fig. 13.3: a) Irradiation of Sun on Earth surface; b) output of laser.

In contrast, if we consider just a 5 mW laser of 1 mm beam diameter (whose divergence is less than 1 millirad), like the one shown in Fig. 13.3b, the power at 1 m distance from the laser is about  $0.16 \text{ W cm}^{-2}$ . Hence the laser is a very bright source of light, due to its highly directional nature.

Before proceeding further, let us recapitulate the points discussed so far.

### DIRECTIONALITY OF LASERS

*Recap*

- Laser light has highly directional nature.
- Directionality arises due to multiple reflections between the mirrors in the confines of the cavity.
- Directionality also results into very high irradiance of light power in a limited area of beam.

The most significant property of laser radiation is its coherence. Many of the applications of lasers emanate from coherence. Now we will discuss in brief about it.

### 13.2.3 Coherence

While learning about the Young's double slit experiment in Unit 6, you came across the term coherence, which means that the light waves from the two slits have a constant phase relationship. Most elementary definition of coherence says that the phases of the coherent waves have a predictable relationship at different points and at different times in space. This space and time predictability of the phase relationship of waves gives rise to two types of coherence, namely, *spatial coherence* and *temporal coherence*. The concept of temporal coherence refers to the phase relationship at a point, at different times; whereas the spatial coherence relates to coherence of two waves travelling side by side.

Generally the sources and the waves they emit are said to be coherent if they

- have equal frequency; and
- maintain a phase difference that is constant in time.

You have learnt that the interference pattern from such waves will have good contrast between the dark and bright fringes.

### Temporal Coherence

While considering the interference and diffraction of light, so far we assumed that the electromagnetic waves remained perfectly sinusoidal all the time. This type of waves is impossible to get from ordinary light sources, since the light emitted from ordinary sources is in the form of finite size wave trains. Each train is sinusoidal in itself and has a characteristic frequency (or wavelength) and phase. However, the collection of wave trains is not sinusoidal. Thus the light coming out of an ordinary source cannot have one single frequency (monochromatic). Instead, it has a range of frequencies, that is a finite bandwidth. This aspect of light (monochromaticity) refers to its temporal coherence, as you will learn shortly.

The temporal coherence can be identified qualitatively as the interval of time over which the phase of the wave motion changes in a predictable manner as it passes through a fixed point in space. In the wave motion corresponding to light from any source, a predictable phase relationship can be observed only within the average length of the wave trains on time scale.

To understand the concept of temporal coherence better, refer to Fig. 13.4. It shows a typical time variation of the amplitude of an electromagnetic wave.

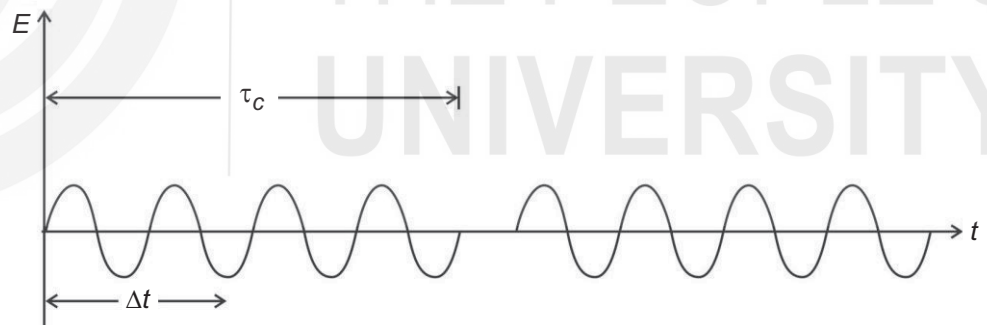


**Fig. 13.4: Variation of amplitude of an electromagnetic wave on time scale.**

In this diagram  $\tau_c$  represents the average duration of a wave train and is known as **coherence time** of the radiation. You will notice that the electric field at time  $t$  and  $(t + \Delta t)$  will have definite phase relationship only if  $\Delta t < \tau_c$ . It is clear that there will not be any predictable phase relationship if  $\Delta t > \tau_c$ . So, the wave remains coherent for time  $\tau_c$ .

The path length corresponding to  $\tau_c$  given as  $L_c = c \times \tau_c$  is called the **coherent length** of the radiation, where  $c$  is the velocity of light. It corresponds to the physical distance travelled by a wave in space, over which it retains its coherence.

To get the idea about the values of coherence time and length, you may like to attempt the following SAQ.

### SAQ 3 - Temporal coherence

If the light of 6600 Å has a wave train  $20\lambda$  long, calculate its coherence length and coherence time.

Now, is there a correlation between the temporal coherence and monochromaticity of the radiation?

To discover the answer to this question, let us recall the Michelson interferometer experiment discussed in Unit 8. You get a fringe pattern due to the two beams generated from a single source (ensuring that they are coherent) that meet after travelling equal distance. You have learnt that as one of the mirrors is moved the visibility and hence the contrast of the fringes will become poorer, and eventually, the fringe pattern will disappear. Let's see the reason for this.

Refer to Fig. 8.1 once again. When you move one mirror by distance  $d$ , it will introduce an additional path  $2d$  for the beam getting reflected from that mirror. As a result, this beam will interfere with the other beam (reflected from the stationary mirror), which originated  $(2d/c)$  seconds later from the source. Clearly, if this time delay is greater than coherence time ( $\tau_c$ ), then the waves reaching the eye after reflections from the two mirrors will not have any definite phase relationship. In other words, the two waves reflected from the mirrors are incoherent. Thus no interference fringes will be seen. On the other hand, if  $2d/c \ll \tau_c$ , then both the superposing waves will be derived from the same wave train and hence will be temporally coherent and possess a definite phase relationship. This will result into interference fringes with good contrast.

Further, you have learnt in Unit 8 the use of Michelson interferometer to determine the wavelengths of closely spaced spectral lines like yellow spectral doublet emitted by sodium lamp at  $\lambda_1 = 5896 \text{ Å}$  and  $\lambda_2 = 5890 \text{ Å}$ . You will remember that when both the mirrors have equal axial distance from the plate  $P_1$ , the fringe patterns corresponding to both the wavelengths will overlap. If a mirror is moved away from the plate by distance  $d$ , the maxima corresponding to the two wavelengths will appear at different angles, because the spacing between the fringes of  $\lambda_1$  and  $\lambda_2$  will be different. If the distance  $d$  is such that the bright fringes for  $\lambda_1$  coincides with the dark fringe corresponding to  $\lambda_2$ , we have

$$2d = m\lambda_1 \quad (\text{bright fringe}) \quad (13.5a)$$

$$\text{and} \quad 2d = \left(m + \frac{1}{2}\right)\lambda_2 \quad (\text{dark fringe}) \quad (13.5b)$$

This will result into disappearance of the fringe pattern. Combining the above two equations, the condition for disappearance of fringes can be expressed as

$$\frac{2d}{\lambda_2} - \frac{2d}{\lambda_1} = \frac{1}{2}$$

Since  $\lambda_1 \approx \lambda_2$  we can consider  $\lambda_1 \lambda_2 \approx \lambda^2$  and write,

$$2d = \frac{\lambda_1 \lambda_2}{2(\lambda_1 - \lambda_2)} = \frac{\lambda^2}{2(\lambda_1 - \lambda_2)} \quad (13.6)$$

Now, if we assume that the light beam consists of all wavelengths lying between  $\lambda$  and  $\lambda + \Delta\lambda$ , the fringes will not be observed if

$$2d \leq \frac{\lambda^2}{\Delta\lambda} \quad (13.7)$$

You can arrive at Eq. (13.7) by solving the following SAQ.

---

### **SAQ 4 - Spectral width and temporal coherence**

Starting from Eq.(13.6) which gives the path difference ( $2d$ ), in terms of two distinct wavelengths  $\lambda_1$  and  $\lambda_2$ , for which the fringes disappear, derive Eq.(13.7) applicable for all the wavelengths lying between  $\lambda$  and  $\lambda + \Delta\lambda$ .

---

Now, you can see that the basic reason for disappearance of the fringe pattern is related to the finite width  $\Delta\lambda$  of the spectral line. This is essentially caused because of non-monochromatic nature of the radiation. Since  $\Delta\lambda$  appears in the denominator of Eq.(13.7), as the spread in the wavelength becomes small (that is the monochromaticity increases), the path difference ( $2d$ ) for disappearance of the fringes becomes large. Larger the value of path difference for which fringe pattern does not disappear, more temporally coherent the light beam is. Hence the temporal coherence is closely associated with the monochromaticity (or sinusoidal nature) of the light. In this way, the temporal coherence of the beam is associated with the width of the spectral line. Since no fringe pattern is observed if the path difference  $2d$  exceeds the coherence length  $L_c$ , we may assume that the beam consists of all the wavelengths lying between  $\lambda$  and  $\lambda + \Delta\lambda$  with

$$\Delta\lambda = \frac{\lambda^2}{L_c} \quad (13.8)$$

This gives the relation between coherence length and spread in wavelength of a light beam. Further since frequency  $\nu = c/\lambda$ , on differentiation, the spread in the frequency  $\Delta\nu$  is

$$\Delta\nu = \frac{c}{\lambda^2} \Delta\lambda$$

Substituting from Eq. (13.8) we get

$$\Delta\nu = \frac{c}{L_c} \quad (13.9)$$

The coherence time is defined as  $\tau_c = L_c/c$ . Therefore we have

$$\Delta\nu \sim \frac{1}{\tau_c} \quad (13.10)$$

In this way, the frequency spread of a spectral line is of the order of the inverse of the coherence time. Since laser light has good monochromaticity as you learnt in the earlier sub-section, it possesses good temporal coherence.

### Spatial Coherence

You will remember that while learning about Young's double slit experiment in Unit 6, we had considered a point source of radiation, which was used to observe the interference of the waves passing through the two slits. This was essentially done to ensure that the two interfering waves were coherent. Just like the waves have temporal coherence in time domain, they have predictable phase relationship in space. When two waves are travelling simultaneously and if there is a phase relationship between these two waves, at time instant  $t$ , then those two waves are said to have spatial coherence. Now, instead of a point source, if we consider an extended source with finite length, then the waves originating from different parts of the source may have phase correlation, if there is spatial coherence between them. We will not go into the details of the derivations but it essentially depends on the correlation between the light emitting sites in the source. Since the laser light is emitted by stimulated emission process, there is good correlation between the emitted waves. This results into a very good spatial coherence in case of laser light.

Here is a recap of the points you learnt about coherence property.

#### COHERENCE PROPERTIES

#### Recap

- Temporal coherence refers to predictability of the phase of radiation as a function of time. It can be identified as the interval of time during which the phase of the wave changes in a predictable manner as it passes through a fixed point in space. This interval is the **coherence time**,  $\tau_c$ . The path length corresponding to  $\tau_c$  is the **coherence length**,  $L_c = c\tau_c$ .
- Temporal coherence is related with the width of the spectral line. The spread in wavelength is given as  $\Delta\lambda = \frac{\lambda^2}{L_c}$ . The corresponding spread in the frequency of the spectral line is  $\Delta\nu \propto 1/\tau_c$ .
- Spatial coherence pertains to the phase correlation between the light emitted from different points of the source, separated in space.

You know that the consequence of coherence is formation of interference pattern with good contrast. In case of lasers, this phenomenon is visible very easily in the form of **speckle pattern**. Any ordinary source of light, when shone on any surface, gives rise to a uniformly illuminated field of view as shown in Fig. 13.5a. However, if you shine a laser light on a surface, you get a random granular texture to the light as seen in Fig. 3.5b.

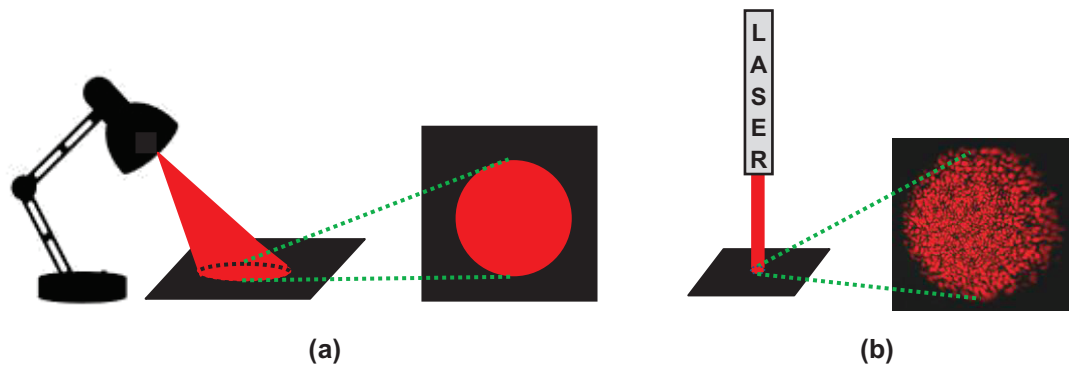


**Fig. 13.5: Comparison of illuminated fields: a) by an ordinary source; b) by a laser source.** (Acknowledgment: The speckle pattern in Fig. 13.5b has been taken from URL: [https://upload.wikimedia.org/wikipedia/commons/c/c2/Speckle\\_fiber.JPG](https://upload.wikimedia.org/wikipedia/commons/c/c2/Speckle_fiber.JPG); which is shared by Christophe.Finot, under License CC BY-SA 3.0).

The speckle pattern is essentially caused by the mutual interference of set of coherent wavefronts when they fall on a rough surface. (Roughness is a relative term. A smooth surface of a paper can be considered to be a rough surface, when compared with the dimensions of the wavelength of the light). The formation of speckle pattern is explained in Fig. 13.6.

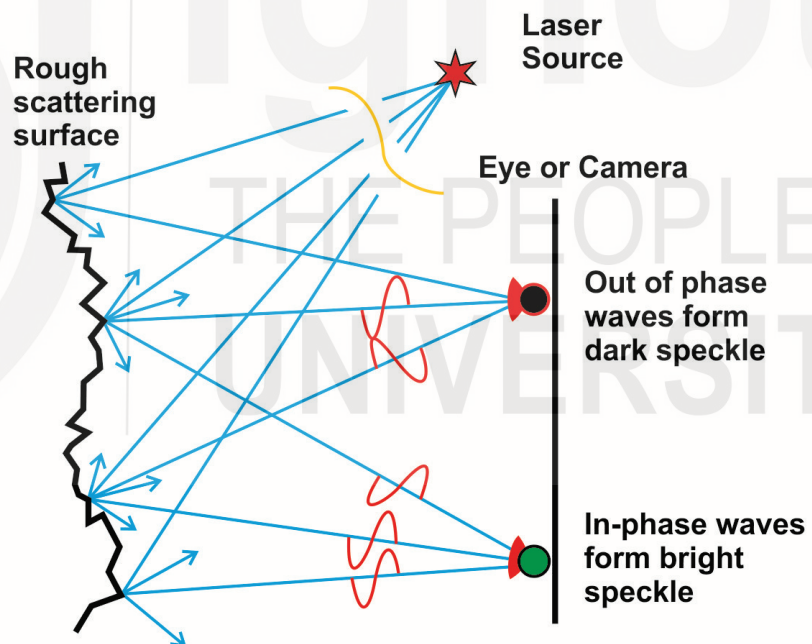


**Fig. 13.6: Formation of speckle pattern of laser radiation.**

Suppose the laser light is incident on a rough surface. From each point on the illuminated part of the surface, the incident light will be scattered in all the directions. So the entire surface can be considered to be formed of an array of point sources emitting out spherical wavefronts. Since all the points received the light from the same laser source, it is coherent, but, due to the random roughness of the surface, after reflection, the relative phases of these point sources will be random as shown in the figure. So, when these waves meet on the screen or imaging device or our eye, they form an interference pattern. Since the roughness of the surface is random, the generated pattern will be a

combination of random dark and bright spots. This results into a granular texture of the illuminated area, giving rise to a speckle pattern.

After understanding the interesting properties of the lasers, let us now discuss some of their uses.

### 13.3 APPLICATIONS OF LASERS

Applications of any device essentially stem from its unique features. What are the unique features of a laser from the applications point of view? First and the foremost, laser light is highly coherent. This characteristic has enabled us to use lasers for information signal transmission and processing, precision measurements, 3-dimensional photography (holography), etc. Secondly, laser light has unprecedented brightness (energy per unit area). You learnt that the brightness of laser light can be many orders of magnitude greater than the brightest of the light produced by conventional sources. Further, laser beams are highly directional. The brightness and directionality of laser beam are exploited to produce targeted effects in materials. These applications include material processing (such as area specific heat treatment, welding, cutting, hole burning etc.) isotope separation, medical diagnostics, etc. In the following, you will learn some of these applications of lasers.

While using and working with lasers you must remember:

#### Some words of caution:

- **Laser light can be highly damaging, especially for the eyes and skin, because it can focus high power densities over a small area.**
- **Never look at the laser beam directly, or its reflection from any surface with naked eyes. Always use proper goggles while operating the laser. (Laser goggles are different than the comely used ordinary sun-goggles.)**
- **Be careful even while using low power lasers like in the laser-pointers. Don't let the beam fall on your eyes directly.**



Now you will learn about some important applications of lasers.

#### 13.3.1 Communication

You may be aware that in a typical communication system, information is communicated (between the transmitter and the receiver) through electromagnetic waves, which are known as carrier waves. These are modulated by the information signal (the oscillations of the information) to be communicated. Normally the information signal frequency is appreciably lower than the frequency of the carrier wave. Moreover, higher the carrier frequency, wider frequency range it can modulate. In other words, the capacity of a communication channel is proportional to the frequency of the carrier wave. The frequency in the centre of the visible spectrum is about 100,000 times greater than the frequency of 6 cm waves used in microwave-radio

communication systems. Consequently, the theoretical information capacity of a typical light wave is about 100,000 times greater than that of a typical microwave.

Long distance communication systems rely on the principle of multiplexing—the simultaneous transmission of many different messages (information) over the same pathway. The ordinary human voice conversation takes place within the frequencies from 200 Hz to 4 kHz, a band 3800 Hz wide. A telephone call, therefore, can be transmitted on any band that is 3800 Hz wide. For example, it can be carried in the MHz range, by a coaxial cable, in the frequency band (say) between 1,000,200 Hz and 1,004,000 Hz, or by a He-Ne laser beam ( $\lambda = 6328 \text{ \AA}$ ,  $\nu = 4.738 \times 10^{14} \text{ Hz}$ ) in the frequency range between 473,800,000,000,200 Hz and 473,800,000,004,000 Hz. You may note here that the telephone message require about 0.4 percent of the available co-axial cable carrier frequency; while the same telephone message requires less than one-billionth of 1 percent of the available laser-beam frequency. Thus, the information carrying capacity could be enhanced tremendously if laser beams are employed as carriers.

Now you may ask: Light, as such, was available to us from time immemorial, then why are we using it for communication purposes only now? Is it related to the discovery of a laser in any way? Yes, it is. The communication on long distance is done by using a method of *modulation*, where the parameters like amplitude or frequency (or phase in some advanced cases) of the high frequency carrier wave are modified by the information signal we wish to transmit. This requires very stable carrier wave parameters. For example its frequency should be ideally perfect sine wave (single frequency) and should not have any variation in its value. This criterion can be fulfilled in case of the radio waves from an electromagnetic oscillator (in MHz range); but the conventional light sources, as we discussed, have quite broad bandwidth. However, the monochromaticity of laser light helps us in this matter. So now the use of light wave carriers for signal transmission has been popular using laser sources.

Now, what is the medium through which laser beam travels while it carries information? The signal carrying laser beams can be transmitted through free (unguided) space, or by light guides. Light guides in the form optical fibres have found wide use in optical communication. You will learn about the details of fibre optics in the next Unit.

### **13.3.2 Industry**

Invention of lasers has made it possible to develop sophisticated tools of material working processes (such as cutting, drilling, welding, etc.) used in manufacturing industries. With appropriate choice of lasers, a laser beam can be focused into a light spot of diameter 10-100 $\mu\text{m}$ ! Can you imagine this dimension? – it will be almost comparable to the thickness of human hair! Due to this sharp focusing, a very high concentration of energy is available within a small spot on the surface of the material. This makes laser an effective tool for drilling very fine hole through the materials.

As compared to other cutting processes, laser cutting offers several advantages, e.g. possibility of fine and precise cuts, minimal amount of mechanical distortion and thermal damage of the material being cut, chemical purity of the cutting process, etc. Laser cutting is extensively used in industry. For example, the fashion designers widely use laser cutting in garment manufacturing. Laser cutting is particularly useful for synthetic fabrics, since it produces well-finished edges as the laser melts and fuses the edges. This avoids the problem of fraying produced by conventional scissors/ knife cutters. And, laser cutting is also employed in the fabrication of spacecraft to cut the sheets of titanium, steel and aluminium. In cutting and most of the industrial applications carbon-dioxide ( $\text{CO}_2$ ) lasers are used.

Lasers are also finding wide application in semiconductor integrated circuit (IC) chips fabrication as well as in data storage devices. You may have seen the compact discs used for storing audio or video or other information files. On these optical discs, the information is recorded using a laser. The laser beam is modulated, depending upon the digital pulses (1's and 0's) to be written. The beam heats up and distorts a thermally sensitive layer on the disk, recording each bit of data as a depression in the surface. The depressions are smaller than a micrometre in size, and are separated by grooves spaced few micrometres apart. For reading the stored data, a low power (3 mW), continuous wave diode laser is used. The disk is rotated and the read head containing the laser and a photo- detector scans across it. The beam gets reflected from the depressions on the optical disk, and the detector reads variations in the intensity and polarization of the light. These variations are decoded and converted to an electrical signal, which can be further used to listen the music on the audio system, or watch the movie on the television screen, or sent to a computer for data analysis, etc.

### **13.3.3 Medicine**

A properly focused laser beam is an excellent tool for surgery. The advantage of laser surgery is that it is bloodless since the beam not only cuts; it also “welds” blood vessels. It is highly sterile procedure, since there is no contact of tissues with any surgical tools. Also, the laser surgery is painless and operations are very fast. Laser beams are being widely used for performing eye and stone surgeries. The laser surgeries are carried out by expert doctors with special training of handling the lasers.

### **13.3.4 Environmental Monitoring**

You may be aware of the conventional technique of determining the concentration of various atmospheric pollutants such as gases (carbon monoxide, sulphur dioxide, oxides of nitrogen, etc.) and a variety of material particles (dust, smoke, fly-ash etc.). In this method, the air samples are collected from various parts of the city and the concentration of pollutants is determined by their chemical analysis in a laboratory. The major deficiency of this method is that it does not provide real-time data. The technique developed with lasers for measuring the concentration of pollutants is

essentially the 'remote-sensing' technique which does not require sample to be analysed in laboratory. Since it provides information about the change in the atmospheric composition with time, it can serve well for real-time monitoring of the environmental pollution.

For determination of particulate pollutants, LIDAR (light detection and ranging) technique based on the scattering of light is used. LIDAR works on the similar principle as that of RADAR. A pulsed laser light is passed through the location under investigation and the back scattered light is detected by a photodetector kept near the laser source. For the determination of gaseous pollutants, the basic principle involved is the selective absorption of light by the gaseous atoms or molecules. As different gas absorbs at different wavelengths, passing laser beams of different wavelengths provides information about the gaseous constituents of the environment.

### 13.3.5 Basic Research

Lasers are widely used in the field of basic and applied science research. Here we will discuss only some of the important applications of lasers in the areas of research.

#### Laser Raman Spectroscopy

The development of lasers has greatly benefited the research in the field of materials science. You must have heard about the Raman effect. It is widely used for studying properties of the materials (compounds). When light from a laser in the ultraviolet, visible or infrared (UV-Vis-IR) range of a known frequency and polarization is incident on a sample of the material under study, it interacts with molecular vibrations, phonons, or other possible excitation sources present in the material. It results in a shift in the energy of the scattered laser photons. The shift in energy provides vital information about the inherent vibrational modes of the molecules in the material under investigation.

#### Thermonuclear Reactions

Lasers are also used in the field of thermonuclear fusion. For effective fusion to take place, extremely high temperature ( $\sim 10^8$  K) must be maintained. In principle, such high temperatures can be achieved by powerful laser beams.

#### Isotope Separation

Yet another remarkable application of lasers is in isotope separation. You may recall that one of the basic requirements of harnessing nuclear energy from uranium is to have 2-3% of uranium isotope ( $^{235}\text{U}$ ) in the fuel. In natural uranium, however, the percentage of  $^{235}\text{U}$  is only 0.7. (The major constituent of natural uranium is  $^{238}\text{U}$ .) To have fuel enriched in  $^{235}\text{U}$ , we can use laser beams. Each of these isotopes absorbs radiation of different frequency. So when a laser beam of a particular frequency is passed through the mixture of  $^{235}\text{U}$  and  $^{238}\text{U}$  the atoms of  $^{235}\text{U}$  absorb the radiation and get excited. The excited atoms of the desired isotope are further excited so that they get

ionized. Once ionized, it can be easily separated by applying a dc electric field. This is one of the several methods of using laser beam for isotope separation.

### **13.3.6 Holography**

You already know that the conventional photographic process consists of recording an illuminated three-dimensional object or scene as a two-dimensional image on a photosensitive surface. The light reflected from the object is focused on the photo sensitive surface by some kind of image forming device, which can be complex series of lenses or simply a pin-hole in an opaque screen. This gives us a flat image of the object, which is not a very realistic picture of the actual scene or the object, as we would perceive while watching it directly with our eyes.

The *coherent* nature of the *laser* beam has brought about a completely new method of photography without any lens system. This new method called **holography** allows recoding of three-dimensional (that is, complete) pictures of a given object or a scene. Holography (also known as photography by wave-front reconstruction) does not, as such, record an image of the object being photographed; it records the reflected light waves themselves. We essentially record both the amplitude and the phase of a wave by using interferometric principles. The photographic record so obtained is called **hologram**. The hologram bears no resemblance to the original object. It, however, contains – in a kind of optical code – all the information about the object that would be contained in an ordinary photograph. If you look at a hologram, you will realize that it does not even remotely resemble the object. However, when this recorded pattern is illuminated by a suitably chosen *reconstruction wave*, out of the many component waves emerging from the hologram, one wave completely resembles the object wave in both amplitude, and phase. Thus, when you look at this wave, you perceive the object still being in position even though the object may not be present there. Since during reconstruction (that is, image production), the object wave itself is emerging from the hologram, the image has all the effects of three-dimensionality. You can indeed shift your viewing position and “look behind” the objects.

Let us understand the basic concept involved in holography with the help of a simple example. Incident light, shown in Fig. 13.7a, is diffracted by a point object. It gives rise to a series of bright and dark concentric rings. The pattern is recorded photographically and made into a transparency. This pattern, called a *Gabor zone plate*, is similar to a Fresnel zone plate we had described discussed in Unit 9. In the second step (top right) light is shone on the ring pattern (i.e. the Gabor zone plate), which gets focused into a point, as by a zone-plate, and reconstructs the image of the original object.

Now, refer to Fig. 13.7b, in which object consists of two points (pixels). The diffraction pattern then consists of two sets of concentric rings. When the pattern is illuminated, each of the two sets focus, and the reconstructed image consists of two points.

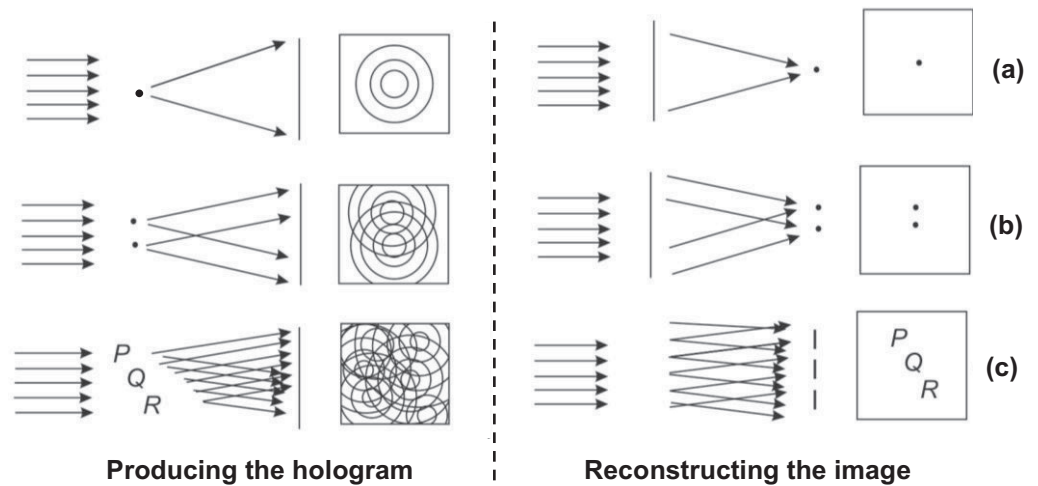


**Fig. 13.7: The principle of holography: a) Point object forming concentric diffraction rings as in zone plate; reconstruction of zone plate gives point image (top right). These features are shown in b) for two points and c) for a more complex object.**

When the object is an aggregate of many points, its diffraction pattern is shown in Fig. 13.7c. This recorded pattern is a combination of superposed zone plates – an unrecognizable complex pattern of lines and rings. Each point in the object forms its own set of fringes. Within each set, the light interferes but between the sets, there is no fixed phase relationship and hence no interference.

In order to make the different signals compatible in phase, another wave, called *reference wave* is added. Refer to Fig.13.8. Here a sufficiently strong reference beam is added to random-phase signals. In such case, the phase of the resultant of the addition of reference and the signals becomes similar to that of the reference alone. Thus contributions from different points produce an interference fringe pattern.

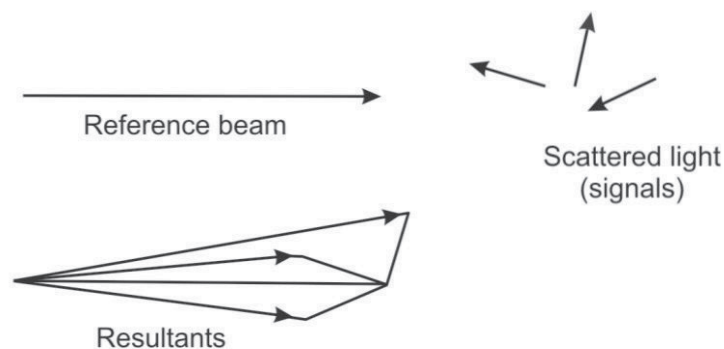


**Fig. 13.8: Addition of a strong coherent reference beam (top left) with random-phase signals (top right) gives similar resultant (bottom).**

So, in holography, the process of image formation is divided in two steps. In the first step, the object is transformed into a photographic record, called the hologram and in the second step called reconstruction, the hologram is transformed into image. No lens is needed in either step.

The three-dimensional output of holographic images find wide applications, like in entertainment industry for creating real-life experience of viewing, microscopy for viewing the objects with depth, information storage on a small area, articles or vehicle tracking using holographic markings, and many more.

In this way lasers find wide uses in various walks of life. Let us now summarize the points you learnt in this unit.

## 13.4 SUMMARY

| Concept                              | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Monochromaticity</b>              | <ul style="list-style-type: none"> <li>Monochromaticity of lasers is good because only selective modes are sustained in the cavity. The separation between the consecutive modes is <math>\Delta\nu = \frac{c}{2D}</math>, where <math>D</math> is the distance between the mirrors in the cavity resonator of the laser.</li> </ul>                                                                                                                                                |
| <b>Directionality</b>                | <ul style="list-style-type: none"> <li>High directionality of laser beam arises due to multiple reflections between the mirrors in the cavity. It also gives the laser its extremely brightness.</li> </ul>                                                                                                                                                                                                                                                                         |
| <b>Temporal coherence</b>            | <ul style="list-style-type: none"> <li>It is the time interval during which the phase of the wave changes in a predictable manner as it passes through a fixed point in space. This interval is the <b>coherence time</b>, <math>\tau_c</math>. The path length corresponding to <math>\tau_c</math> is the <b>coherence length</b>, <math>L_c = c\tau_c</math>. It is related with the width (spread) of the spectral line.</li> </ul>                                             |
| <b>Spatial coherence</b>             | <ul style="list-style-type: none"> <li>Spatial coherence pertains to the phase correlation between the light emitted from different points of the source, separated in space.</li> </ul>                                                                                                                                                                                                                                                                                            |
| <b>Speckle pattern of laser beam</b> | <ul style="list-style-type: none"> <li>High coherence of the laser gives rise to an interference pattern, when it falls on a rough surface resulting into a granular texture to its display.</li> </ul>                                                                                                                                                                                                                                                                             |
| <b>Applications of lasers</b>        | <ul style="list-style-type: none"> <li>Lasers find application in various fields:               <ol style="list-style-type: none"> <li>as high data capacity carrier waves for communication;</li> <li>manufacturing processes like cutting, drilling, welding, etc.;</li> <li>medical procedures like eye surgery and other bloodless surgeries;</li> <li>environmental monitoring by real-time tracking of pollutants;</li> <li>basic scientific research.</li> </ol> </li> </ul> |
| <b>Holography</b>                    | <ul style="list-style-type: none"> <li>Development of lasers (due to their highly coherent nature) allows recording of three-dimensional pictures (Hologram) of a given object. Here the image is indirectly recorded as both the amplitude and the phase of a wave by using interferometric principles. The hologram is reconstructed by shining a reference beam on the hologram.</li> </ul>                                                                                      |

## 13.5 TERMINAL QUESTIONS

- The sodium light at  $\lambda=5890 \text{ \AA}$ , produced in a low-pressure discharge lamp, has a spread in wavelength  $\Delta\lambda= 0.0194 \text{ \AA}$ . Calculate a) the coherence length, b) line width in hertz and c) coherence time.

2. a) How is the process of holography different from ordinary photography?  
b) Discuss some of the salient features of a hologram.
3. What are the disadvantages of speckle pattern when laser is used for projecting an image or illuminating any object?

## 13.6 SOLUTIONS AND ANSWERS

### Self-Assessment Questions

1. From Eq. (13.2) we can write the maximum number of modes sustained in a cavity as

$$n = \frac{2D}{\lambda}.$$

It is given that,  $D = 30 \text{ cm} = 0.3 \text{ m}$ ,

and  $\lambda = 6000 \text{ \AA} = 6000 \times 10^{-10} \text{ m}$ .

$$\text{Hence, } n = \frac{2 \times 0.3}{6000 \times 10^{-10}} = 10^6 \text{ modes.}$$

2.

$$\Delta v = \frac{c}{2D}$$

$$\Delta v = \frac{3 \times 10^8 \text{ ms}^{-1}}{2 \times 0.3 \text{ m}} = 5 \times 10^8 \text{ Hz} = 500 \text{ MHz}$$

3. It is given that  $\lambda = 6600 \text{ \AA} = 6.6 \times 10^{-7} \text{ m}$  and  $n = 20\lambda$ .

Hence, coherence length,

$$L_c = n \times \lambda = 20 \times 6.6 \times 10^{-7} = 13.2 \text{ } \mu\text{m}.$$

Now, coherence time.

$$\tau_c = \frac{L_c}{c} = \frac{13.2 \times 10^{-6} \text{ m}}{3 \times 10^8 \text{ ms}^{-1}} = 4.4 \times 10^{-14} \text{ s}.$$

4. Eq. (13.6) gives the path difference for the disappearance of fringe pattern due to light of wavelengths  $\lambda_1$  and  $\lambda_2$ . When this expression is to be used for the disappearance of the fringe pattern due to the light beam consisting of all wavelengths lying between  $\lambda$  and  $\lambda + \Delta\lambda$ , we must divide the interval (width) into two equal parts of  $\Delta\lambda / 2$ . Thus the fringe pattern will be produced by wavelength values

$$\lambda_1 = \lambda + (\Delta\lambda / 2)$$

$$\text{and } \lambda_2 = \lambda.$$

With substitution of these values Eq.(13.6) reduces to

$$2d = \frac{\lambda^2}{2((\lambda + (\Delta\lambda / 2) - \lambda))} = \frac{\lambda^2}{2(\Delta\lambda / 2)} = \frac{\lambda^2}{\Delta\lambda}$$

which is Eq.(13.7).

Now, for each wavelength lying between  $\lambda$  and  $\lambda + (\Delta\lambda / 2)$ , there will be a corresponding wavelength lying between  $\lambda + (\Delta\lambda / 2)$  and  $\lambda + \Delta\lambda$ , such that the minima of one falls on the maxima of the other. Therefore, the fringe pattern will disappear.

### Terminal Questions

1. It is given that,  $\lambda = 5890 \text{ \AA} = 5890 \times 10^{-10} \text{ m}$

and  $\Delta\lambda = 0.0194 \text{ \AA} = 0.0194 \times 10^{-10} \text{ m}$

a) From Eq. (13.8) we have

$$\Delta\lambda = \frac{\lambda^2}{L_c}, \text{ where } L_c \text{ is the coherence length.}$$

$$\Rightarrow L_c = \frac{\lambda^2}{\Delta\lambda} = \frac{(5890 \times 10^{-10})^2 \text{ m}^2}{0.0194 \times 10^{-10} \text{ m}}$$

$$= 0.18 \text{ m.}$$

b) The relation between the spread in the frequency,  $\Delta\nu$  (line width in hertz) and the coherence length is given by Eq. (13.9).

$$\Delta\nu = \frac{c}{L_c} = \frac{3 \times 10^8 \text{ m s}^{-1}}{0.18 \text{ m}} = 1.67 \times 10^9 \text{ Hz.}$$

c) From Eq. (13.10) we can find coherence time

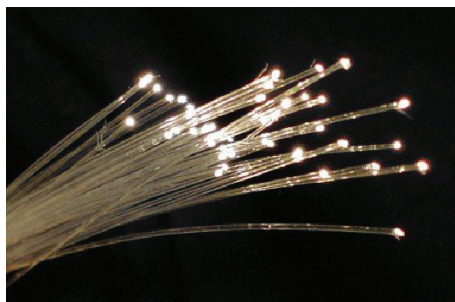
$$\tau_c \square \frac{1}{\Delta\nu} = \frac{1}{1.67 \times 10^9} \square 0.6 \times 10^{-9} \text{ s} = 0.6 \text{ ns.}$$

2. a) The technique of holography (photography by wavefront reconstruction) differs from that of ordinary photography in three aspects. Firstly, in ordinary photography, the light reflected from the object is received on the photographic plate or other image forming devices, with the help of lenses. Amplitude of the light wave, reflected from each point of the object, is recorded at corresponding point on the photographic plate. On the other hand, in holography, no lens or other image forming device is needed and hence, as such, no image is formed on the hologram. Here, essentially an interference pattern due to the light reflected from the object and the reference beam is obtained. Secondly, for obtaining hologram, coherent light is used whereas in case of normal photography, no such special source of light is required. The need of coherent light is due to the fact that the hologram is an interference pattern. Thirdly, in holography, a set of mirrors is used to render the reference and object beam on the photographic plate.

b) Hologram has several interesting properties. Some of them are given below:

- i) The image obtained from the hologram has three-dimensional character unlike normal photographs which are two-dimensional. Due to the three-dimensional character of the image obtained in holography, you can observe different perspective of the object by changing the viewing position.
  - ii) We do not obtain negative in holography. You may have noticed that when the negative of an ordinary photograph is seen through, we do get a feel of the object or the scene photographed. On the other hand, when we look at a hologram we observe a random combination of various irregular shapes; it has no resemblance whatsoever with the original object.
3. The speckle is a random pattern of bright and dark spots giving rise to a granular finish to the illuminated field. Many times, laser light is used to illuminate the objects, as seen in the cover picture of this unit; or in projectors, which can project clear images with super brightness and high contrast. But in such cases a granular random dark-bright pattern may appear on the objects in the uniform image. Hence, the minute details in the displayed picture or illuminated object get hidden under the speckle pattern.

Speckle is usually characterized by its contrast. The problem encountered in displays due to speckle can be reduced by creation of many independent speckle patterns, so that they average out on the retina of the eye or display device. Here, we essentially disturb the high coherence between the laser beams. This can be done by, either illuminating the object from different angles (called angle diversity technique) or by using the light with different polarization states (called polarization diversity technique), or by using laser sources with slightly different wavelengths (called wavelength diversity technique).



# UNIT 14

## FIBRE OPTICS |

Light is conducted through optical fibre from end to end with very less losses, about which you will learn in this unit.

This image is taken from:

<https://upload.wikimedia.org/wikipedia/commons/4/49/Fibreoptic.jpg>

### Structure

---

- |      |                                           |      |                                                     |
|------|-------------------------------------------|------|-----------------------------------------------------|
| 14.1 | Introduction                              | 14.4 | Dispersion in Optical Fibre                         |
|      | Expected Learning Outcomes                |      | Pulse Dispersion                                    |
| 14.2 | Optical Fibre Waveguide                   |      | Material Dispersion                                 |
|      | Construction and Working of Optical Fibre | 14.5 | Advantages of Optical Fibre as Communication Medium |
|      | Some Definitions                          | 14.6 | Summary                                             |
|      | Types of Optical Fibre                    | 14.7 | Terminal Questions                                  |
| 14.3 | Losses in Optical Fibre                   | 14.8 | Solutions and Answers                               |

### STUDY GUIDE

---

So far you learnt about lasers and its applications. One of the important applications is in the field of communication. In this unit you will be learning about a special kind of medium used for conducting light with very less losses, which helps in effective optical communication. It is optical fibre, usually made of glass or plastic and working on the principle of total internal reflection. You will learn the mechanism of light conduction through the fibre and also get familiar with its types.

You will not require any special mathematical tools to study this unit. A knowledge of elementary calculus will suffice. Try to solve the SAQs and Terminal Questions given in this unit on your own.

*"I was just a precocious kid taking a college physics course when one day the professor told us that light 'always travels in a straight line'. But that can't be true. I thought, it must be bent sometimes."- While describing his pioneering work on Optical Fibres."*

**Narinder Singh  
Kapany**

## 14.1 INTRODUCTION



Padma-vibhushan Dr. Narinder Singh Kapany (1926-2020) was an Indian-American physicist. After completing his graduation from Agra University, he pursued his Ph.D. in Optics in London University. He carried out work on light transmission through guided medium, and was successful in capturing good quality medical images using a bundle of glass fibres. He coined the word **Optical Fibre** for this transmission medium, and is fondly remembered as the “father of fibre-optics”.

You might have seen colourful illuminated fountains made of tiny plastic or glass fibres in the showcases or display windows of shops. These are made up of **optical fibres**. While looking at these, you might also have noticed that light seems to travel along curved path. In these optical fibres, most of the incoming light is contained within the boundaries of the medium (glass or plastic) due to the phenomenon of **total internal reflection**. And since the medium itself has a curved shape, the light travelling through it appears to travel along a curved path. Due to thin and flexible nature of optical fibre, it can be used for obtaining images of inaccessible regions e.g. endoscopes used to image the interior parts of human body. The ability of conducting light over long distances with very less loss of signal, optical fibres are the backbone of data transmission for Internet.

The real potential of the optical fibres was revealed only after the discovery of lasers, which provided a narrow intense source of light. You may recall from Unit 13 of this course that the discovery of lasers – a source of coherent and monochromatic light – raised the hope of realizing communication at optical frequencies. Since increase in frequency of the carrier wave enables it to carry more information, communication at optical frequencies ( $\sim 10^{15}$  Hz) has obvious advantages over communication at radio wave ( $\sim 10^6$  Hz) and microwave ( $\sim 10^9$  Hz) frequencies. But, early attempts of communication at optical frequencies faced a major problem. When optical radiation travels through the Earth's atmosphere, it is attenuated by dust particles, fog, rain etc. Thus, a need for an optical waveguide was felt and the answer was the optical fibre. Optical fibres are an integral part of optical communication – transmission of speech, data, picture or other information – by light.

In Sec.14.2 we explain the construction of optical fibre, mechanism of light transmission through fibre and types of fibres. The losses in signal strength caused by optical fibre are discussed in Sec.14.3.

Usually, the data transmission through optical fibre takes place in the form of pulse signals. Dispersion (elongation) of signal pulse on time scale is a major factor limiting the data carrying capacity or bandwidth of the fibre. In Sec. 14.4 you will learn about the causes of dispersion and ways to overcome this hurdle. In Sec. 14.5 we discuss the advantages of optical fibres in communication systems.

### Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ explain the light transmission through optical fibre;
- ❖ define critical angle, acceptance angle and numerical aperture;
- ❖ distinguish between different modes of propagation in optical fibres;
- ❖ explain the different types of optical fibres;
- ❖ describe various reasons of signal losses incurred in a fibre;
- ❖ derive expression for pulse dispersion in optical fibres; and
- ❖ list the advantages of optical fibre as a medium of communication.

## 14.2 OPTICAL FIBRE WAVEGUIDE

Let us begin with the discussion about the working of an optical fibre as a waveguide. It is important to know the construction of optical fibre to understand the mechanism of light transmission through it.

### 14.2.1 Construction and Working of Optical Fibre

Generally, the optical fibre consists of two concentric glass (silica) cylinders as shown in Fig. 14.1. Sometimes, the fibre can also be made of plastic. The inner cylinder is called the **core**, while the outer is known as **cladding**. This entire structure is covered with a protective plastic cylinder called the sheath. The diameter of the core can be in the range of 2-50  $\mu\text{m}$  and the cladding has typical diameter of 125  $\mu\text{m}$ . The refractive index of the core is larger than that of cladding layer. Hence there is a refraction of the light, when it crosses the interface border between the core and cladding as shown in Fig. 14.2a.

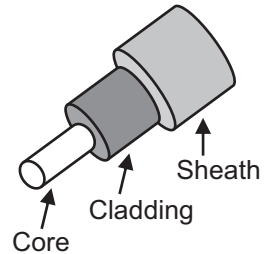


Fig. 14.1: Optical Fibre

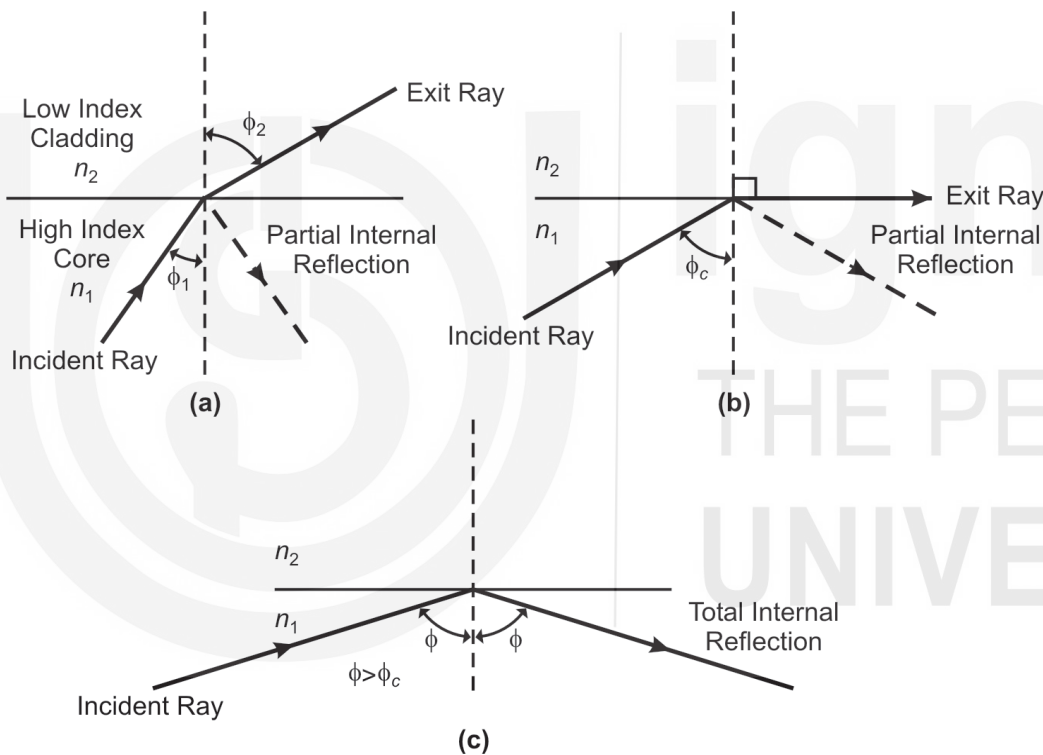


Fig. 14.2: a) Light ray on the boundary of core-cladding interface; b) limiting case of refraction at critical angle; c) total internal reflection.

The ray approaching the interface is propagating in a dielectric of refractive index  $n_1$  and is at an angle  $\phi_1$  to the normal at the surface of the interface. If the dielectric on the other sides of the interface index ( $n_2$ ) is less than  $n_1$ , then the refraction is such that the ray path in this lower index medium is at an angle  $\phi_2$  to the normal, where  $\phi_2$  is greater than  $\phi_1$ . The angles of incidence  $\phi_1$  and refraction  $\phi_2$  are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\text{or} \quad \frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1} \quad (14.1)$$

You will observe in Fig. 14.2a that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As  $n_1$  is greater than  $n_2$ , the angle of refraction is always greater than the angle of incidence. As angle  $\phi_1$  increase,  $\phi_2$  also increases and at certain values of  $\phi_1 = \phi_c$  ( $\phi_c < 90^\circ$ ), the refracted ray is perpendicular to the normal, i.e. it travels parallel to the interface as shown in Fig. 14.2b. This is the limiting case of refraction and the angle of incidence is now known as the **critical angle**,  $\phi_c$ .

From Eq. (14.1) the value of the critical angle is given by:

$$\sin \phi_c = \frac{n_2}{n_1} \quad (14.2)$$

At angle of incidence greater than the critical angle, the light is reflected back into the originating dielectric medium with high efficiency (around 99.9%). Hence, it may be observed in Fig. 14.2c that **total internal reflection** occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of high index, and the angle of incidence of the ray exceeds the critical value.

By this mechanism of total internal reflection the light at a sufficiently shallow angle ( $\phi > \phi_c$ ) propagates down an optical fibre with low loss. Fig. 14.3 illustrates the transmission of light ray in an optical fibre via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding.

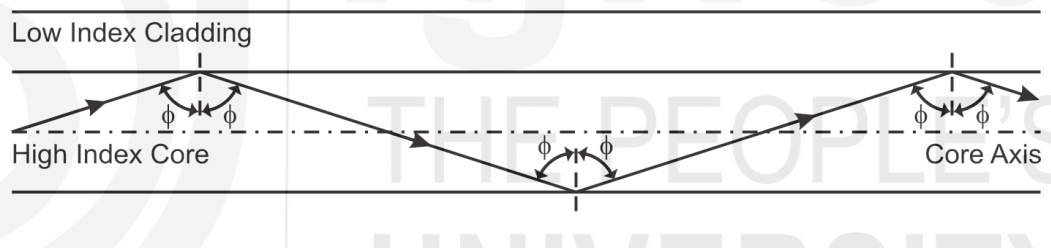


Fig. 14.3: Transmission of light ray in a perfect optical fibre.

The light transmission illustrated in this figure assumes a perfect fibre. Any discontinuities or imperfections at the core-cladding interface would probably result in refraction rather than total internal reflection, with a subsequent loss of the light ray into the cladding.

### 14.2.2 Some Definitions

#### a) Acceptance angle

As we discussed in the last subsection, in any optical fibre, only the rays with a sufficiently shallow grazing angle (i.e. with an angle greater than  $\phi_c$ ) at the core-cladding interface are transmitted by total internal reflection. In other words, not all rays entering the fibre core will continue to propagate down its length.

The geometry concerned with launching a light ray into an optical fibre is shown in Fig. 14.4, which illustrates ray A at the critical angle  $\phi_c$ . This ray enters the fibre core at an angle  $\theta_a$  to the fibre axis and is refracted at the air-core interface before transmission to the core-cladding interface at the critical angle. Hence, any ray which is incident into the fibre core at an

angle greater than  $\theta_a$ , will not be transmitted to the core-cladding interface at an angle greater than  $\phi_c$ , and will not be totally internally reflected. This situation is illustrated in the figure with incident ray *B* at an angle greater than  $\theta_a$ . This ray is refracted at the core-cladding interface and eventually lost by radiations.

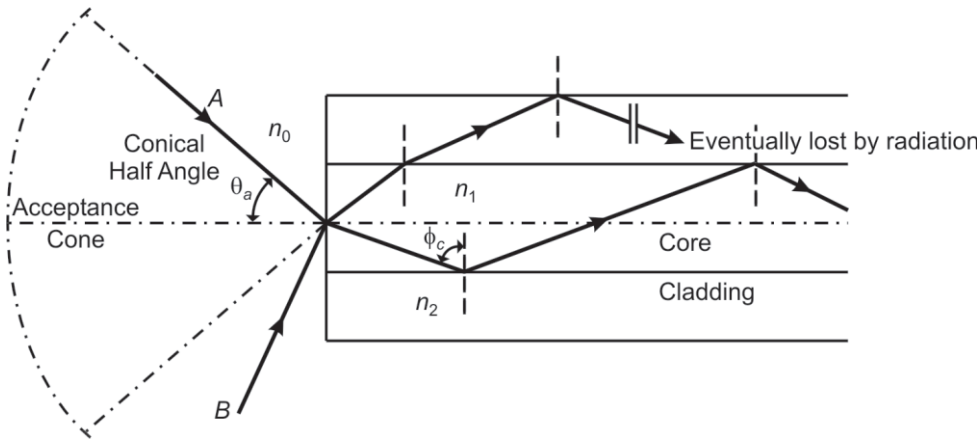


Fig. 14.4: Geometry of ray launching in fibre.

Thus for rays to be transmitted by total internal reflection within the fibre core, they must be incident on the fibre core within an acceptance cone defined by the conical half angle  $\theta_a$ . Hence  $\theta_a$  is the maximum angle to the axis at which light may enter the fibre in order to be propagated, and is often referred to as the **acceptance angle** for the fibre.

#### b) Numerical aperture

Using the ray propagation geometry, it is possible to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, cladding and air. This leads to the definition of a more generally used term, the **numerical aperture (NA)** of the fibre.

Fig. 14.5 shows a light ray incident on the fibre core at an angle  $\theta_1$  to the fibre axis which is less than the acceptance angle for the fibre  $\theta_a$ . The ray enters the fibre from a medium (air) of refractive index  $n_0$ , into the fibre core with refractive index  $n_1$ , which is slightly greater than the cladding refractive index  $n_2$ . Using Snell's law at the air-core interface we get,

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \quad (14.3)$$

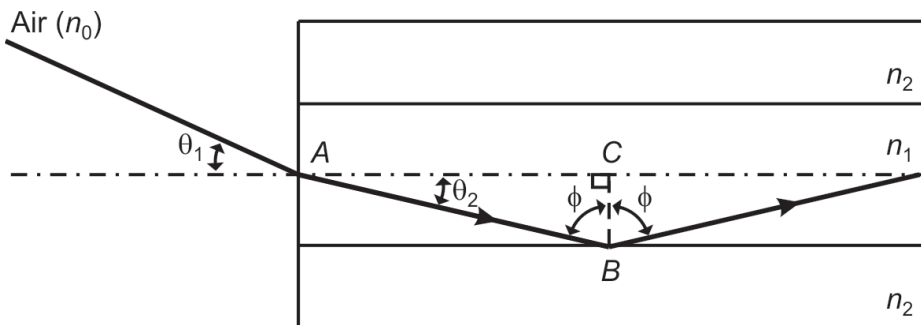


Fig. 14.5: The path for ray launched into an optical fibre in air at an input angle less than the acceptance angle for the fibre.

Considering the right-angle triangle *ACB*,

$$\phi = \frac{\pi}{2} - \theta_2 \quad (14.4)$$

where  $\phi$  is greater than the critical angle at the core-cladding interface.

Hence Eq. (14.3) becomes

$$n_0 \sin \theta_1 = n_1 \cos \phi \quad (14.5)$$

Using the trigonometrical relationship  $\sin^2 \phi + \cos^2 \phi = 1$  Eq. (14.5) may be written as

$$n_0 \sin \theta_1 = n_1 \sqrt{1 - \sin^2 \phi} \quad (14.6)$$

$$\begin{aligned} n_0 \sin \theta_a &= n_1 \sqrt{1 - \sin^2 \phi_c} \\ &= n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}} \end{aligned}$$

(from Eq. (14.2))

$$\therefore n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2}$$

When the limiting case for total internal reflection is considered  $\phi$  equals  $\phi_c$ .

Also in the limiting case  $\theta_1$  becomes the acceptance angle for the fibre  $\theta_a$ .

Combining these limiting cases into Eq. (14.6) and substituting from Eq. (14.2), we get,

$$n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2} \quad (14.7)$$

The quantity represented by Eq. (14.7) is called the **numerical aperture (NA)**.

Hence the NA is defined as:

$$NA = n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2} \quad (14.8)$$

Since the NA is often used with fibre in air where  $n_0$  is unity, it is simply equal to  $\sin \theta_a$ . The numerical aperture is a very useful measure of the light-collecting ability of a fibre. It is independent of the fibre core diameter and will hold for diameters as small as 8  $\mu\text{m}$ . The ray-treatment of light we have used so far does not hold good for small diameters, as the geometric optics approach is invalid. This is because the ray theory model is only a partial description of the character of light. It describes the direction a plane wave component takes in the fibre but does not take into account interference between such components. When interference phenomena are considered it is found that only rays with certain discrete characteristic propagate in the fibre core. Thus the fibre will only support a discrete number of guided modes.

You may now like to solve one SAQ.

### SAQ 1 - Optical fibre parameters

A silica optical fibre with a core diameter of 30  $\mu\text{m}$  has core refractive index of 1.50 and a cladding refractive index of 1.47. Calculate a) the critical angle at the core-cladding interface; b) the NA for the fibre; and c) the acceptance angle in air for the fibre.

After learning about the basic parameters of the optical fibre, let us now discuss its types.

### 14.2.3 Types of Optical Fibre

A **mode** is a stable propagation state in an optical fibre. The number of modes that can be propagated in a fibre depends on

- Refractive indices of core and cladding;

- core diameter; and
- wavelength of the propagating light.

For given values of refractive indices of core and cladding and the wavelength of light, the core diameter can be reduced to achieve single mode transmission. Based on the number of modes that can propagate in a fibre, the fibres can be classified as

- Single-mode (SM) fibre; and
- Multi-mode (MM) fibre.

There are three types of optical fibres based on the distribution profile of the refractive index of the core with respect to cladding (shown on the left side) and propagating modes (shown on the right side) in Fig. 14.6.

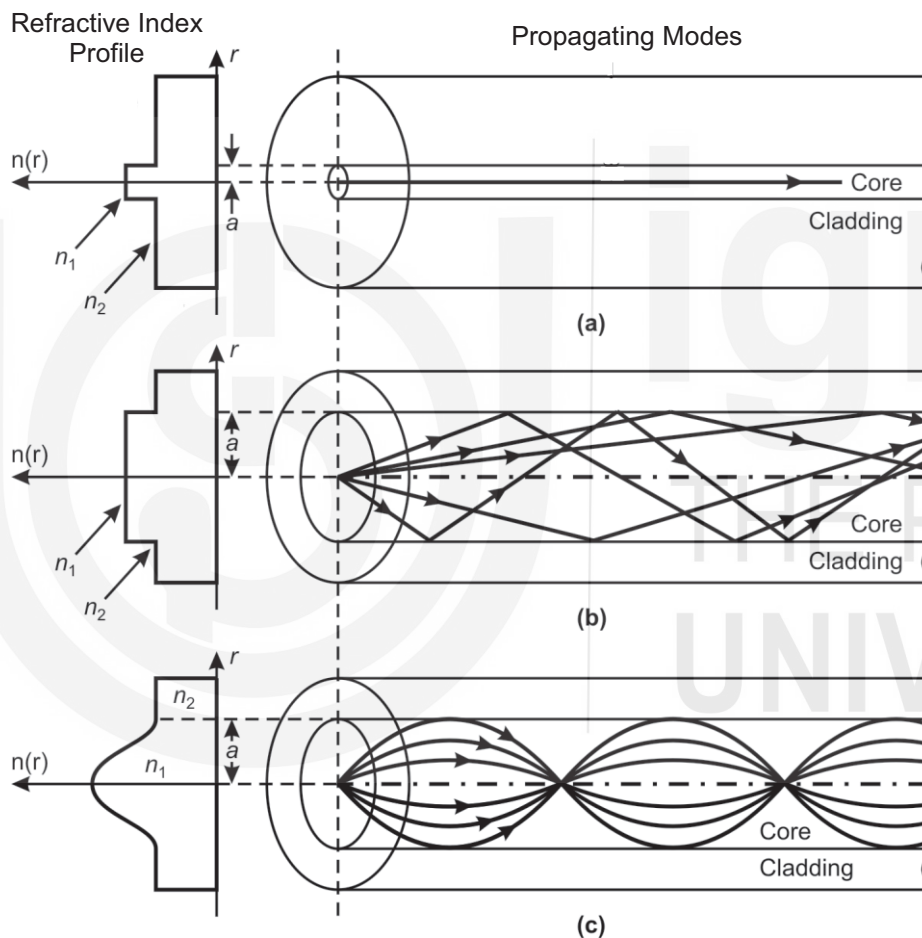


**Fig. 14.6: Types of optical fibre: a) step index single mode; b) step index multimode; c) graded index (GRIN) multimode.**

**a) Step index single mode (SI SM) fibre:**

It has uniform refractive indices for both core ( $n_1$ ) and cladding ( $n_2$ ) with  $n_1 > n_2$ . The fibre core is very narrow (typically 2 to 10  $\mu\text{m}$ ) and supports only a single mode propagation as shown in Fig. 14.6a. This type of fibre has very broad bandwidth.

**b) Step index multimode (SI MM) fibre:**

It has uniform refractive indices for both core ( $n_1$ ) and cladding ( $n_2$ ) with  $n_1 > n_2$  as in the case of single mode fibre, but the core diameter is above

50  $\mu\text{m}$  and many number of modes are propagated simultaneously, as shown in Fig. 14.6b.

**c) Graded index multimode (GRIN MM) fibre:**

This type of fibre has got a core with refractive index highest at the centre and gradually decreasing till it is the same as that of the cladding at core-cladding boundary as shown in Fig. 14.6c.

You may now like to attempt an SAQ.

## SAQ 2 - Types of optical fibre

Choose proper options:

- a) The number of Modes propagated in a fibre does not depend upon:
  - i) refractive index of core and cladding
  - ii) cladding diameter
  - iii) core diameter
  - iv) wavelength of light
- b) Which of these is not a type of optical fibre?
  - i) step index multimode fibre
  - ii) step index single mode fibre
  - iii) graded index multimode fibre
  - iv) graded index single mode fibre.

After getting the overview of light propagation in fibre, let us now discuss the causes of signal loss and distortion in a fibre.

## 14.3 LOSSES IN OPTICAL FIBRE

When the optical fibre is used for communication applications, it is expected to transmit the light signal between its two ends without any loss of signal strength. However, in practice the fibre causes attenuation of the signal due to fibre losses. The various types of losses in the fibres are depicted in Fig. 14.7.

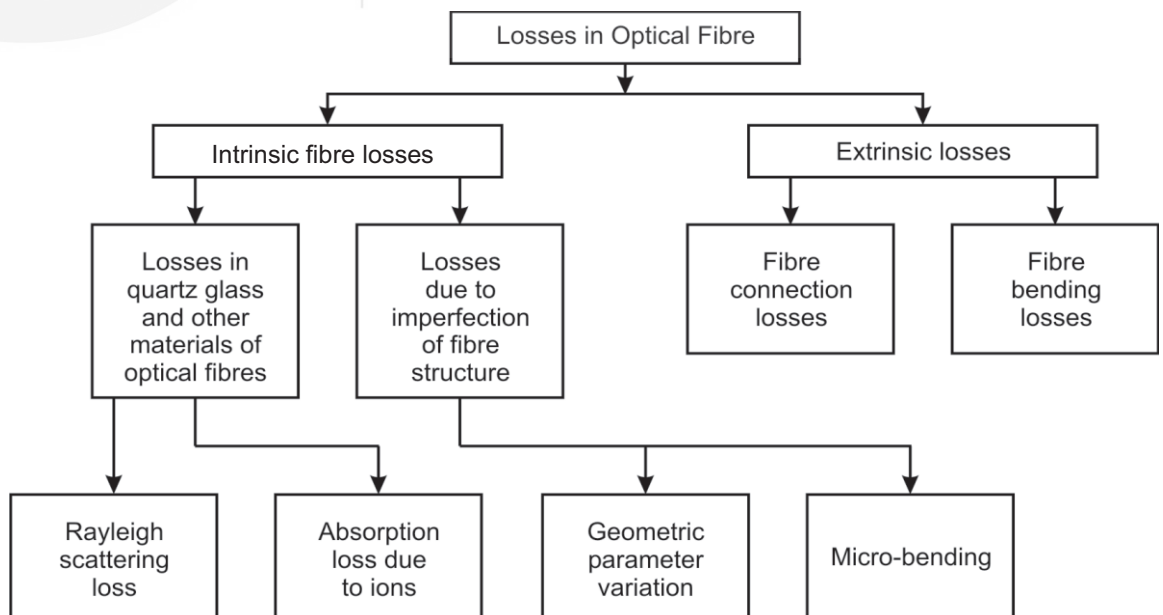


**Fig. 14.7: Losses in Optical fibre.**

The causes of these losses are clear from Fig. 14.8.

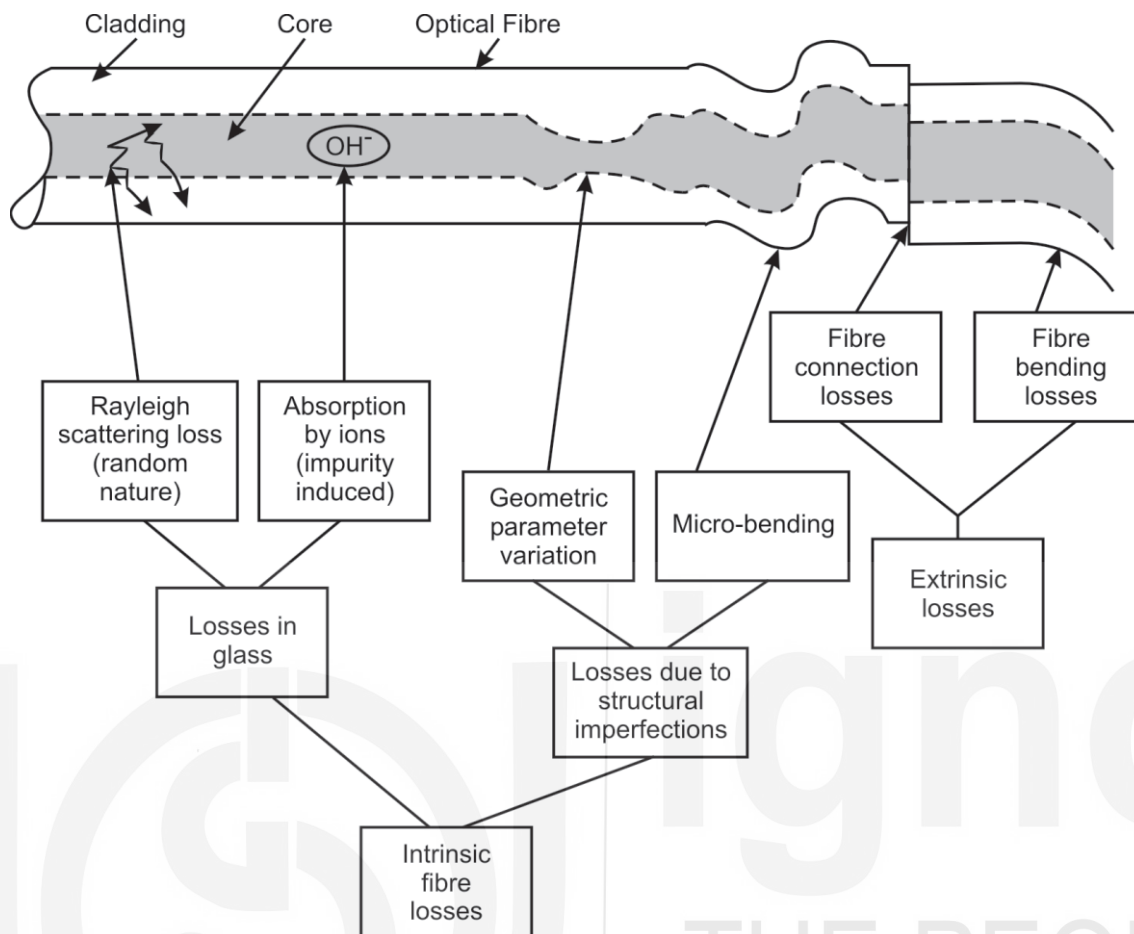


Fig. 14.8: Causes of losses in optical fibre.

Some salient points to note here are:

- Although in the electromagnetic spectrum optic refers to the frequencies in the infrared, visible and ultraviolet bands of the spectrum, there is heavy attenuation in the visible and the ultraviolet portions; and efficient optical communication takes place in the infrared band of the spectrum, as the loss is relatively less.
- Even though the infrared band is the chosen band for optical communication, the complete band is not useful for communication. There are strong absorption losses in the fibre due to the hydroxyl ( $\text{OH}^-$ ) ions dissolved in the glass. The absorption spectrum of silica has distinct sharp absorption peaks due to these ions. Between these peaks, it is possible to identify narrow windows, which are not affected by the  $\text{OH}^-$  absorption. Three such windows at 850 nm, 1310 nm and 1550 nm are identified as the best for optical fibre communication. They are called the *first*, the *second* and the *third telecommunication windows* respectively. Maximum number of optical fibre communication circuits work with sources belonging to one of the three windows.
- The refractive index inside the glass is not uniform due to the imperfections in the structure introduced during the manufacturing

process. These result into random molecular locations which scatter the light passing through the fibre. This type of loss is known as **Rayleigh scattering**.

- The attenuation of signal in the fibre is most vital parameter, since it decides the maximum length over which the optical communication can be carried out without using a repeater. You know that the attenuation of a signal in dB (decibel) is defined as

$$A = 10 \log_{10}(P_{in}/P_{out}) \quad (14.9)$$

where  $P_{in}$  and  $P_{out}$  are input and output powers of the signal respectively.

You may now like to attempt an SAQ.

### SAQ 3 - Losses in optical fibre

Various losses in an optical fibre are:

- |                    |                        |
|--------------------|------------------------|
| a) Scattering loss | b) Connection loss     |
| c) Micro bending   | d) Losses due to bends |

Choose the proper option from the following:

- a and b are intrinsic losses and c & d are extrinsic losses.
- a and d are intrinsic losses and c & b are extrinsic losses.
- a and c are intrinsic losses and b & d are extrinsic losses.
- a and c are extrinsic losses and b & d are intrinsic losses.

One of the major factors affecting the signal transmission through the fibre is dispersion. It has direct effect on the bandwidth (data carrying capacity) of the fibre. In the following, you will learn about the dispersion effects and their implications in detail.

## 14.4 DISPERSION IN OPTICAL FIBRE

When incident light pulses are applied at one end of the optical fibre, the light pulses emerging from the other end are wider than the incident light pulses as shown in Fig. 14.9. The light pulse waveform spreads in time during its propagation through the fibre. This spreading of waveform is called **dispersion**. It is expressed in terms of time per unit length.

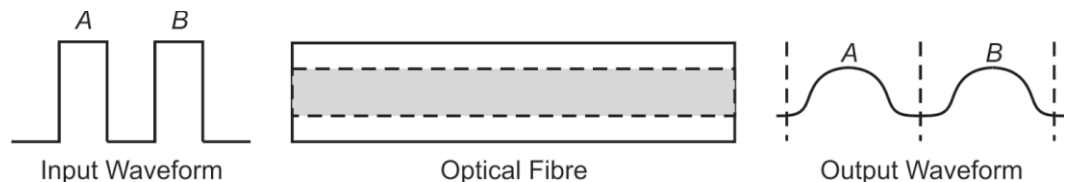


Fig. 14.9: Widening of pulse due to dispersion in fibre.

Since dispersion causes spreading of a pulse in time scale, it is possible that the output of pulse A may overlap with a part of pulse B. This is undesirable, since the data transfer in such case becomes unreliable. The transmission capacity of the fibre is determined by the number of pulses transmitted per unit time. For correct information retrieval, the pulses must remain resolvable

i.e. they should not overlap each other. Dispersion is critical as it limits the bandwidth of information carrying capacity of the fibre.

Dispersion is categorised into two main types:

- Pulse (or Modal) dispersion
- Material (or Chromatic) dispersion

### 14.4.1 Pulse Dispersion

#### Step Index Fibre

As shown in Fig. 14.10, in a multimode step index fibre, different modes, though enter the fibre at the same time instant, the path lengths traversed by each of them inside the fibre are different. Hence a pulse launched in different modes arrives at the end of the fibre at different time instances, thereby stretching the pulse in the time scale. Hence pulse dispersion is also known as Modal dispersion or multi-path dispersion. The modal dispersion is prominent in step index multimode fibres.

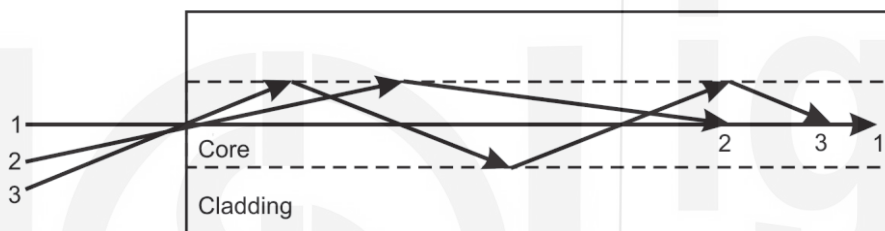


Fig. 14.10: Pulse (Modal) dispersion.

What effect does the pulse broadening have on the signal transmission capacity of the fibre? Actually, pulse broadening severely restricts the transmission capacity of the fibre, because it causes overlapping of consecutive pulses and they become unresolvable. To avoid this overlap, the time delay between two consecutive pulses must be increased. Therefore, the number of pulses that can be transmitted per unit time through the fibre will go down, that is, the transmission capacity of the fibre will be reduced.

To have a quantitative estimate about the pulse dispersion in case of propagation through step-index fibre, refer to Fig.14.11.

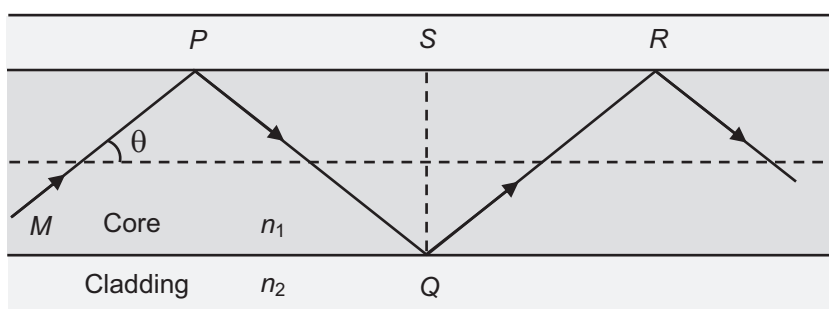


Fig. 14.11: Ray of light passing through step index fibre.

Consider a mode travelling along  $MPQR$  sustaining angle  $\theta$  with the axis of the fibre. The time taken by this ray to travel a distance  $PR$  can be easily calculated by the relation

$$t = \frac{PQ + QR}{c/n_1} \quad (14.10)$$

where  $(c/n_1)$  is the velocity of light in the core medium of refractive index  $n_1$ .

Hence we get,

$$\begin{aligned} t &= \frac{n_1}{c} \frac{1}{\cos \theta} (PS + SR) \\ &= \frac{n_1(PR)}{c \cos \theta} \end{aligned}$$

So you will notice that the time taken by the ray of light in travelling a distance through the fibre depends on the angle it makes with the axis of the fibre. Thus, for a fixed length  $L$  of the fibre, minimum time will be taken by a ray which travel along the axis of the fibre ( $\theta = 0$ )

We have

$$\theta_{max} = \left( \frac{\pi}{2} - \phi_c \right)$$

Using the identity

$$\cos(A-B) = \cos A \cos B + \sin A \sin B$$

we can write

$$\cos \theta_{max} = \sin \phi_c$$

And from Eq. (14.2) you can easily show that

$$\theta_{max} = \cos^{-1}(n_2/n_1)$$

$$t_{min} = \frac{n_1 L}{c} \quad (14.11)$$

and the maximum time will be taken by the ray for which  $\theta$  is equal to  $\left( \frac{\pi}{2} - \phi_c \right)$  where  $\phi_c$  is the critical angle at the core-cladding interface.

Thus,  $\theta_{max} = \cos^{-1}(n_2/n_1)$  and the maximum time

$$t_{max} = \frac{n_1 L}{c(n_2/n_1)} = \frac{n_1^2 L}{c n_2} \quad (14.12)$$

Thus, if all the input rays travel along the fibre simultaneously, the spread in time in traversing the distance  $L$  will be

$$\begin{aligned} \Delta t &= t_{max} - t_{min} \\ &= \frac{n_1 L}{c n_2} (n_1 - n_2) \end{aligned} \quad (14.13)$$

Now you may like to solve one numerical to get the idea about the pulse broadening in the practical systems.

### SAQ 4 - Pulse dispersion in step-index fibre

If the core and cladding refractive indices for a step-index fibre are 1.47 and 1.46 respectively, what will be the broadening of a pulse after 5 km distance?

After solving this SAQ, you must have realized that the signal transmission capacity of optical fibres is severely restrained due to pulse dispersion. Therefore, an efficient optical fibre should have least possible pulse dispersion so that it can carry larger number of pulses per unit time. Now the question is: Do we have any method to minimize the pulse broadening in optical fibres?

Yes, there are methods by which we may minimize the pulse broadening. One of them is to use gradient - index (GRIN) fibre. Now you will learn how GRIN-fibres help in reducing the pulse broadening.

### Graded Index Fibre

You will recall from Sec. 14.2.3 that core of the graded index (GRIN) - fibre offers gradually decreasing refractive index environment to a light ray as it moves away from the axis of the fibre. Let us see how this parabolic refractive index profile of the GRIN – fibre (Refer Fig. 14.6c) helps in reducing the pulse dispersion. You will observe that since the refractive index of core goes on reducing towards the periphery, the modes deviating away from the centre of the core travel at faster speed and hence the pulse travelling in different modes eventually reaches the end of the fibre at more or less same time, without causing any significant dispersion effect. Due to this reason, the pulse broadening is reduced in GRIN-fibre.

The volume of information which may be transmitted through GRIN – fibre is more or less free from pulse broadening due to above reason. The information carrying capacity of such fibre is only limited by material dispersion about which you will learn in the following.

### 14.4.2 Material Dispersion

So far we discussed about the pulse broadening in optical fibres arising because of the fact that light rays incident at different angles at the core-cladding interface take different times to traverse a fixed length of fibre. We also discussed how to reduce this dispersion by using GRIN-fibre. Now, suppose that the light beam travelling through the fibre is free from the pulse broadening due to above mentioned reason. Does it mean that the beam is completely free from pulse broadening? No, there is yet another source of pulse broadening known as **material dispersion**. Material dispersion arises due to the variation of refractive index with wavelength of light. That is this dispersion arises due to the dependence of velocity of light in the medium on its wavelength. You are aware that the light emitted from a source is not a single wavelength but a wavelength spectrum with a certain width. Therefore, different wavelengths in a pulse signal will travel with different velocities and hence will arrive at the end of the fibre at different times and causes broadening of the pulse. You may note that the material broadening is an intrinsic physical property of the fibre material and arises due to non-monochromatic nature of the signal pulse. Since it is caused due to the variation of wavelength (colour) in the light, this dispersion is also termed as **chromatic dispersion**. This type of dispersion is more prominent in single mode fibre.

After learning about light transmission through optical fibre, let us discuss in brief the advantages of using optical fibre as a medium of signal transmission.

## 14.5 Advantages of Optical Fibre as Communication Medium

---

Apart from wide bandwidth required for communication systems, there are other reasons too which have promoted the use of optical fibres:

**a) High information capacity of fibre**

Optical Fibres are inherently digital transmission media. Bit rates up to 1 Gbps ( $10^9$  pulses per second) are already available in our country. .

**b) Low attenuation and dispersion**

Fibre attenuation is now less than  $0.20 \text{ dB km}^{-1}$  and can be as low as  $0.18 \text{ dB km}^{-1}$ . In this case, the repeaters for strengthening the signal can be spaced at longer distances.

**c) Space saving**

Due to extreme thin dimensions of fibre the coefficient of *information capacity to cable cross section* is high; therefore efficient use of the duct space is made. This is a very significant advantage in the congested city environments.

**d) Low cross-talk signal**

The cross-talk between fibres in a well-designed optical fibre cable is very low and it does not generate any interference to other systems.

**e) Immunity to EMI**

The fibres have excellent immunity to electromagnetic interference (EMI). Thus the communications on the optical fibres are free from EMI pick ups, including the external sources such as lightening or sparking etc.

**f) Higher security**

Since there is no radiation of EM waves involved unlike in the cases of microwave or the satellite systems, it is very difficult for an intruder to detect the actual signal being transmitted.

**g) Abundance of basic resource**

The basic material used in the optical fibre is Silica which is available in plenty along the sea shores in the country. It is not a depleting resource.

**h) Easy maintainability**

Except in case of places where the possibility of damage due to man-made faults is high, the overall maintenance effort involved is less as compared to the other high capacity systems.

Let us now summarize the points discussed in this unit.

## 14.6 SUMMARY

| Concept                                        | Description                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Structure of optical fibre</b>              | <ul style="list-style-type: none"> <li>Optical fibre used for transmission of light waves consists of two concentric cylinders of glass or plastic. The inner cylinder is core, while the outer one is cladding.</li> </ul>                                                                                                                                                              |
| <b>Light transmission through the fibre</b>    | <ul style="list-style-type: none"> <li>The refractive index of core is larger than that of cladding material. This results in to total internal reflection of the light beam.</li> </ul>                                                                                                                                                                                                 |
| <b>Critical angle</b>                          | <ul style="list-style-type: none"> <li>Critical angle <math>\phi_c</math> is defined as <math display="block">\phi_c = \sin^{-1} \frac{n_2}{n_1}, \quad (n_1 &gt; n_2)</math> <p>where <math>n_1</math> is refractive index of core and <math>n_2</math> is that of cladding. A light ray experiences total internal reflection for angle more than <math>\phi_c</math>.</p> </li> </ul> |
| <b>Acceptance angle and numerical aperture</b> | <ul style="list-style-type: none"> <li>Acceptance angle <math>\theta_a</math> is the maximum angle at which the light can enter the fibre and propagate by total internal reflection.</li> <li>Numerical aperture is a measure of the light gathering capacity of the fibre. <math display="block">NA = n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2}</math> </li> </ul>                      |
| <b>Types of optical fibre</b>                  | <ul style="list-style-type: none"> <li>Depending on the refractive index profile of the core, optical fibres are classified as <ul style="list-style-type: none"> <li>➤ Step index single mode (SI SM);</li> <li>➤ Step index multimode (SI MM); and</li> <li>➤ Graded index multimode (GRIN MM).</li> </ul> </li> </ul>                                                                 |
| <b>Attenuation of signal</b>                   | <ul style="list-style-type: none"> <li>Attenuation of a signal in dB (decibel) is defined as <math display="block">A = 10 \log_{10} (P_{in} / P_{out})</math> <p>where <math>P_{in}</math> and <math>P_{out}</math> are input and output powers of the signal respectively.</p> </li> </ul>                                                                                              |
| <b>Losses in fibre</b>                         | <ul style="list-style-type: none"> <li>Fibre optic losses are of two types: <ul style="list-style-type: none"> <li>➤ Intrinsic losses; and</li> <li>➤ Extrinsic losses.</li> </ul> </li> </ul>                                                                                                                                                                                           |

**Pulse dispersion** ■ Pulse dispersion in a step index fibre of length  $L$  is

$$\Delta t = \frac{n_1 L}{c n_2} (n_1 - n_2)$$

This dispersion can be reduced by using graded index fibre.

**Material dispersion**

- It is caused because the refractive index (and hence the velocity of light) of a medium is a function of wavelength of light, and there is inherent frequency spread in the light source. Light of different frequency (wavelength) travels at different speed through a refractive medium. It is also known as chromatic dispersion.

## 14.7 TERMINAL QUESTIONS

1. Suppose you have two optical fibres  $A$  and  $B$ . The refractive indices of the core ( $n_1$ ) and the cladding ( $n_2$ ) materials of these fibres are:

$$\begin{aligned} (n_1)_A &= 1.52 & (n_2)_A &= 1.41 \\ (n_1)_B &= 1.51 & (n_2)_B &= 1.39 \end{aligned}$$

Which of the two fibres will have higher light gathering capacity?

2. Velocity of light in the core of a step index fibre is  $2.0 \times 10^8 \text{ ms}^{-1}$  and critical angle is  $80^\circ$ . Determine the numerical aperture and acceptance angle for the fibre in air. Consider velocity of light in air to be  $3 \times 10^8 \text{ ms}^{-1}$ .
3. When a mean optical power launched into 10 km long fibre is  $100 \mu\text{W}$ , the mean optical power output is  $2 \mu\text{W}$ . Calculate the attenuation per kilometre for the fibre.

## 14.8 SOLUTIONS AND ANSWERS

### Self-Assessment Questions

1. a) The critical angle  $\phi_c$  at the core-cladding interface can be written from Eq. (14.2) as:

$$\phi_c = \sin^{-1} \frac{n_2}{n_1} = \sin^{-1} \frac{1.47}{1.50} = 78.5^\circ$$

- b) From Eq. (14.8) the numerical aperture is:

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.50^2 - 1.47^2)} = 0.30.$$

- c) Considering Eq. (14.8) the acceptance angle in air (with  $n_0 = 1$ ),  $\theta_a$ , is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30 = 17.4^\circ$$

2. a) (ii);      b) (iv)
3. (iii)
4. The pulse broadening is given by Eq. (14.13)

$$\Delta t = \frac{n_1 L}{c n_2} (n_1 - n_2)$$

It is given that,

$$L = 5 \times 10^3 \text{ m}, \quad n_1 = 1.47, \quad n_2 = 1.46$$

and taking  $c = 3 \times 10^8 \text{ ms}^{-1}$ , we get

$$\begin{aligned} \Delta t &= \frac{1.47 \times 5 \times 10^3 \text{ (m)}}{3 \times 10^8 \text{ (ms)}^{-1} \times 1.46} (1.47 - 1.46) \\ &= \frac{7.35 \times 10^3 \text{ (m)}}{4.38 \times 10^8 \text{ (ms)}^{-1}} (0.01) = 0.17 \mu\text{s} \end{aligned}$$

### Terminal Questions

1. From Fig. 14.4,  $\theta_a$  is the maximum angle of incidence of the light beam at air-core interface which gives the measure of light gathering capacity of the fibre. From Eq. (14.7), the sine of this angle is given as

$$\sin \theta_a = \frac{1}{n_0} \sqrt{n_1^2 - n_2^2}$$

where,  $n_0$ ,  $n_1$  and  $n_2$  are the refractive indices of air, core and cladding respectively. We know that  $n_0$ , the refractive index of air = 1.

For the fibre A,

$$n_1 = 1.52 \quad \text{and} \quad n_2 = 1.41$$

$$\begin{aligned} \therefore (\sin \theta_a)_A &= \sqrt{(1.52)^2 - (1.41)^2} \\ &= \sqrt{0.3223} = 0.57 \end{aligned}$$

Therefore,  $(\theta_a)_A = \sin^{-1}[0.57] = 34.8^\circ$

Now, for the fibre B,

$$n_1 = 1.51 \quad \text{and} \quad n_2 = 1.39$$

$$\begin{aligned} \therefore (\sin \theta_a)_B &= \sqrt{(1.51)^2 - (1.39)^2} \\ &= \sqrt{0.348} = 0.59 \end{aligned}$$

$$\text{Therefore, } (\theta_a)_B = \sin^{-1} [0.59] = 36.2^\circ$$

Hence, the light gathering capacity of fibre *B* is greater than fibre *A*.

2. Refractive index of core

$$n_1 = \frac{c}{v} = \frac{3 \times 10^8 \text{ ms}^{-1}}{2 \times 10^8 \text{ ms}^{-1}} = 1.5$$

$\phi_c = 80^\circ$ , hence, the refractive index of cladding

$$n_2 = n_1 \sin \phi_c = 1.5 \sin 80^\circ = 1.48$$

$$\text{Numerical aperture} = \text{NA} = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.48)^2} = 0.24 .$$

$$\text{Acceptance angle } \theta_a = \sin^{-1} (\text{NA}) = 14.1^\circ .$$

$$3. \text{ Signal attenuation} = 10 \log_{10} \frac{P_{in}}{P_{out}} = 10 \log_{10} \frac{100 \times 10^{-6} \text{ W}}{2 \times 10^{-6} \text{ W}} = 17 \text{ dB}.$$

Assuming uniform attenuation over the fibre length, per km attenuation is

$$\frac{17 \text{ dB}}{10 \text{ km}} = 1.7 \text{ dB km}^{-1}$$

## **FURTHER READINGS**

1. **Optics**, Eugene Hecht, Fourth Edition, Pearson Education, Indian Reprint (2004).
2. **Optics**, Ajoy Ghatak, Seventh Edition (2021), McGraw Hill Education (India) Pvt. Ltd.



## TABLE OF PHYSICAL CONSTANTS

| Symbol             | Quantity                         | Value                                                            |
|--------------------|----------------------------------|------------------------------------------------------------------|
| $c$                | Speed of light in vacuum         | $3.00 \times 10^8 \text{ ms}^{-1}$                               |
| $\mu_0$            | Permeability of free space       | $1.26 \times 10^{-6} \text{ NA}^{-2}$                            |
| $\epsilon_0$       | Permittivity of free space       | $8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ |
| $1/4\pi\epsilon_0$ |                                  | $8.99 \times 10^9 \text{ Nm}^2 \text{ C}^{-2}$                   |
| $e$                | Charge of the proton             | $1.60 \times 10^{-19} \text{ C}$                                 |
| $-e$               | Charge of the electron           | $-1.60 \times 10^{-19} \text{ C}$                                |
| $h$                | Planck's constant                | $6.63 \times 10^{-34} \text{ Js}$                                |
| $\hbar$            | $h / 2\pi$                       | $1.05 \times 10^{-34} \text{ Js}$                                |
| $m_e$              | Electron rest mass               | $9.11 \times 10^{-31} \text{ kg}$                                |
| $-e / m_e$         | Electron charge to mass ratio    | $-1.76 \times 10^{11} \text{ Ckg}^{-1}$                          |
| $m_p$              | Proton rest mass                 | $1.67 \times 10^{-27} \text{ kg (1 amu)}$                        |
| $m_n$              | Neutron rest mass                | $1.68 \times 10^{-27} \text{ kg}$                                |
| $a_0$              | Bohr radius                      | $5.29 \times 10^{-11} \text{ m}$                                 |
| $N_A$              | Avogadro constant                | $6.02 \times 10^{23} \text{ mol}^{-1}$                           |
| $R$                | Universal gas constant           | $8.31 \text{ Jmol}^{-1} \text{ K}^{-1}$                          |
| $k_B$              | Boltzmann constant               | $1.38 \times 10^{-23} \text{ J K}^{-1}$                          |
| $G$                | Universal gravitational constant | $6.67 \times 10^{-11} \text{ Nm}^2 \text{ kg}^{-2}$              |

## **LIST OF BLOCKS AND UNITS: BPHCT-137**

### **BLOCK 1: WAVES – AN INTRODUCTION**

|        |                        |
|--------|------------------------|
| Unit 1 | Wave Motion            |
| Unit 2 | Superposition of Waves |
| Unit 3 | Acoustic Wave          |
| Unit 4 | Electromagnetic Wave   |
| Unit 5 | Polarisation of Light  |

### **BLOCK 2: INTERFERENCE**

|        |                                       |
|--------|---------------------------------------|
| Unit 6 | Interference by Division of Wavefront |
| Unit 7 | Interference by Division of Amplitude |
| Unit 8 | Michelson Interferometer              |

### **BLOCK 3: DIFFRACTION**

|         |                        |
|---------|------------------------|
| Unit 9  | Fresnel Diffraction    |
| Unit 10 | Fraunhofer Diffraction |
| Unit 11 | Diffraction Grating    |

### **BLOCK 4: LASERS AND OPTICAL FIBRE**

|         |                                       |
|---------|---------------------------------------|
| Unit 12 | Physics of Lasers                     |
| Unit 13 | Properties and Applications of Lasers |
| Unit 14 | Fibre Optics                          |

**Waves:** Transverse waves on a string, wave formation and propagation, relation between wavelength and frequency, wave velocity, mathematical description of wave motion; types of waves – plane waves and spherical waves (*qualitative description only*), energy carried by waves, intensity of waves. Superposition principle for waves, travelling and standing waves on a string, normal modes of a string, group velocity, phase velocity. Acoustic waves, production of sound waves – forced vibrations and resonance, intensity and loudness of sound, decibels, intensity levels, musical notes, musical scale, acoustics of buildings. Electromagnetic waves, wave equation for electromagnetic waves, electromagnetic nature of light, definition and properties of wave front, Huygens principle. Polarisation, transverse nature of light waves, production and analysis plane polarised light, Malus' law, Brewster's law, double refraction, Nicol prism, wave plates, circular and elliptical polarisation.

**Interference:** Division of amplitude and division of wave front, interference by division of wave front, Young's double slit experiment, white light fringes, displacement of fringes, Lloyd's mirror and Fresnel's biprism. Interference by division of amplitude, phase change on reflection – Stokes' treatment, interference in thin films, parallel films, qualitative description of Fringes of equal inclination (Haidinger fringes) and fringes of equal thickness (Fizeau fringes), interference in wedge-shaped films, Newton's rings – measurement of wavelength and refractive index. Michelson's interferometer, qualitative idea of the form of fringes, determination of wavelength, wavelength difference, refractive index and visibility of fringes.

**Diffraction:** Fresnel diffraction, Fresnel construction, half-period element, the zone plate, diffraction pattern of a straight edge, a slit and a wire using half-period zone analysis. Fraunhofer diffraction, evolution from Fresnel to Fraunhofer diffraction, diffraction from a single slit - observed pattern, intensity distribution; diffraction from a double slit – observed pattern, intensity distribution, position of minima and maxima, missing orders. Diffraction grating, Fraunhofer diffraction from multiple slits, intensity distribution, principal maxima, minima and secondary maxima, angular half-width of principal maxima.

**Lasers and Optical Fibre:** Basic principles of lasers, emission and absorption of light, spontaneous and stimulated emission, Einstein's relations (general idea only), population inversion, optical pumping, pumping mechanisms, three and four level pumping schemes, feedback mechanism, optical resonant cavity. Types of lasers and their applications, solid state, liquid and gas lasers, Helium-Neon laser, applications of lasers in communication, medicine, industry and photography. Optical fibre, core and cladding materials and their refractive indices, propagation of light through optical fibre - total internal reflection, types of fibres – step index and gradient index fibres, refractive index profiles, optical communication through fibres, qualitative idea of pulse dispersion and its reduction, material dispersion and power loss.