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Lecture :

Optoelectronics

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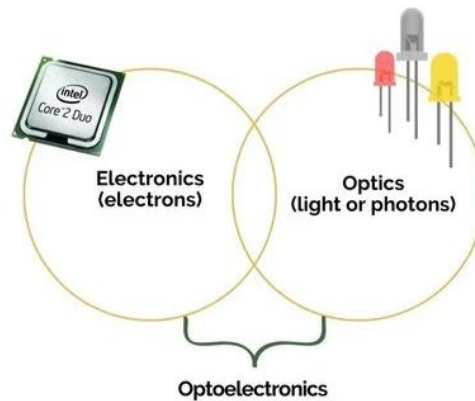
University year : 2024-2025

Foreword

The handout below is used for the Optoelectronics course, which is primarily aimed at students in their first year of a Master degree in Instrumentation electronics.

This handout contains the official program taught in the Telecommunications department of the Ahmed Ben Yahia El Wancharissi Tissemsilt University. This handout describes in a methodical and detailed manner the various components of optical links, such as optical transmitters, optical receivers, and various types of optical fibers. It also describes the degradation mechanisms of light signals during their propagation in optical fibers, such as attenuation and dispersion. It is thus written in the form of detailed chapters. In fact, this lecture is presented in a very simple manner, allowing students to understand very quickly the principles of optoelectronics. Which is an emerging discipline that uses electronics and optics together. It has significant scopes in various fields, particularly in computer science, medical electronics and telecommunications. Therefore, the aim of this lecture is to enable students to understand the operating principles and characteristics of the different elements of a fiber optic transmission chain through the study of components capable of emitting, transmitting and receiving a light signal.

Contact sheet of the lecture



- Course name / Teaching unit & level: Optoelectronics (NI772)/ UED/ M1 Instrumentation (S1).
- Name of Lecture leader: AZIL Kenza
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- Course dates or period: First semester in Master degree
- Number of credits: 1
- Coefficient: 1
- Course description i.e. the general aim of the course: is to introduce the student to the main optoelectronic components, their characteristics, their operating principle and the fields of use.
- Aim of this lecture: For students in the instrumentation field, this lecture provides essential knowledge that will help you design and integrate optical and optoelectronic systems into real-world applications. Here are some key takeaways to guide your learning and career development:

Master the Basics of Light-Semiconductor Interaction

- ❖ Understanding how light behaves in different materials will help you select and optimize optical sensors for precise measurements.

Gain Hands-on Experience with Optoelectronic Components

- ❖ Work with LEDs, laser diodes, photodiodes, and optical sensors in laboratory settings to deepen your practical understanding.

Learn About Signal Processing in Optical Systems

- ❖ Many optical sensors require proper signal conditioning and data processing. Strengthen your skills in electronics, analog-to-digital conversion, and noise reduction techniques.

Understand the Importance of Calibration and Maintenance

- ❖ Optical and optoelectronic instruments require accurate calibration for reliable measurements. Learn best practices for maintaining and troubleshooting these devices.

Stay Updated on Emerging Technologies

- ❖ Fields like fiber optics, LiDAR, and advanced photonics are evolving rapidly. Keeping up with new developments will give you an edge in your career.

Think About Real-World Applications

- ❖ Whether in industrial automation, biomedical instrumentation, or environmental monitoring, understanding how optoelectronic devices are used in the industry will help you apply your knowledge effectively.

Develop Problem-Solving Skills

- ❖ As an instrumentation engineer, you'll often need to analyze and troubleshoot sensor-related issues. Focus on critical thinking and problem-solving techniques to excel in this field.
- Prerequisites required:
 - ✓ Basic in electronics.
 - ✓ Basic in optics.
 - ✓ Optoelectronic devices.
- Learning Assessment Method (Final Exam: 100%)
- Course operating rules: Participation of students in the course is encouraged. Students who wish to ask questions can do so in an orderly manner.

Summary

1	Chapter 1: Elements of Photometry	4
1.1	Introduction & glossary	4
1.1.1	Light	4
1.1.2	Photometry	5
1.2	Optical sources	6
1.3	Geometric quantities	6
1.3.1	Plan Angle Recall	6
1.3.2	Solid angle	7
1.3.3	Elementary solid angle	7
1.4	Quantities and Photometric Units	8
1.4.1	Radiation flux	8
1.4.2	Light intensity	10
1.4.3	Lighting	11
1.4.4	Luminance	12
1.4.5	Summary	12
1.4.6	Application	13
1.5	Black body	14
1.5.1	Black body definition	14
1.5.2	Temperature - colour relation	14
1.6	Lambert's Law	15
1.6.1	Lambertian light source	16
1.6.2	Example	16
2	Chapter 2: Photo emitters	17
2.1	Introduction	17
2.2	Band Theory	17
2.3	Light Emission by Semiconductors	18
2.4	Light-Emitting Diodes (LEDs)	19
2.4.1	Basic Structure and Operation	19
2.4.2	Electrical Characteristics:	20
2.4.3	Overall Efficiency (η)	20
2.5	Laser Diodes	21
2.5.1	Definition	21
2.5.2	Materials Used	22
2.5.3	Light Amplification	22

2.5.4	Characteristics of Laser Diodes.....	22
3	Chapter 3: Photoreceptors	24
3.1	Introduction	24
3.2	Operating parameters of photodetectors	24
3.2.1	Absorption coefficient.....	24
3.2.2	Internal quantum performance.....	25
3.2.3	Spectral sensitivity:	25
3.2.4	Time response and bandwidth:	25
3.3	Photorésistance ou cellule photoconductrice (LDR)	26
3.3.1	Principe:.....	26
3.4	Photodiode.....	27
3.4.1	Principle of operation of photodiodes	27
3.4.2	Photodiode response time	32
3.4.3	Photodiode equivalent scheme	33
3.4.4	Quantum efficiency of the photodiode.....	34
3.4.5	Derived structures	36
3.5	Phototransistor	37
3.5.1	Symbol.....	38
3.5.2	Principle of operation	38
3.5.3	Technological properties.....	39
3.5.4	Coding and typical values.....	39
3.5.5	Application	39
3.6	Photovoltaic cells.....	40
3.6.1	Photovoltaic (PV) cells composition.....	40
3.6.2	Operation of photovoltaic cells	42
3.6.3	Types of PV cells	42
3.6.4	Efficiency and performance.....	43
3.6.5	Applications of photovoltaic cells	43
3.6.6	Conclusion	44
3.7	Charge Coupled Device (CCD)	44
3.7.1	Structure of a CCD sensor	44
3.7.2	Operation of a CCD sensor	45
3.8	Applications of CCD sensors.....	46
4	Chapter 4: Application examples (Optical Sensors and Photovoltaic Generators).....	47
4.1	Motion Sensor (Fork Optocoupler)	47
4.2	Optocoupler for Galvanic Isolation	47

4.3	Luminescence Detector	48
4.4	Contrast Detector	48
4.5	Color Detector	49
4.6	Photovoltaic Generator	49
5	Chapter5: Optical fibers	51
5.1	Introduction to Optical Fiber.....	51
5.2	Structure and Working Principle	51
5.3	The propagation of light in optical fibre.	52
5.4	Optical Fibers classification.....	53
5.4.1	Based on refractive index:.....	53
5.4.2	Based on Mode of propagation.....	54
5.4.3	Based on Material.....	55
5.4.4	Combination of optical fibres	56
5.5	Parameters of optical fibres.....	56
5.5.1	Radius of the core	56
5.5.2	Numerical aperture (NA).....	56
5.5.3	Acceptance angle.....	57
5.6	Advantages of Optical Fiber	57
5.7	Applications of Optical Fiber	57
5.8	Some losses in optical fibres	58
5.8.1	Transmission loss/attenuation (α).....	58
5.8.2	Other possible losses in optical fibre	59
5.9	Optical fibres as sensor	62
5.9.1	Temperature sensor.....	62
5.9.2	Displacement sensor.....	62
5.10	Challenges and Future Developments.....	63
5.11	Conclusion.....	63
6	Bibliographie.....	65

General introduction

Optoelectronics is a word combining optics and electronics. In the literature, "optronics" and "electro-optics" are used in the same meaning. This term covers broad concepts involving light emitting devices and elements, information displays, image pickup devices, optical storages, optical communications, remote sensing systems.

Optoelectronics involves the interaction of light with specific semiconducting materials to produce electrical responses. Semiconducting materials are the preferred choice due to their ability to change electrical conductivity significantly with temperature, optical excitation, and impurity content. Optoelectronic devices facilitate interaction and convert optical energy to electrical energy or vice versa.

The first chapter, "Elements of photometry", explores the fundamental properties of light and its interaction with semiconductor materials. It covers key concepts such as luminous flux and luminance, as well as the wave-particle duality of light, illustrating its behavior as both an electromagnetic wave and a photon stream. The electromagnetic radiation spectrum is also studied, highlighting the different wavelengths involved in these interactions. Finally, the chapter details several physical phenomena resulting from the interaction between light and semiconductors, such as photoconductivity, photoionization, the photoelectric effect, and the photovoltaic effect, which form the foundation of optoelectronic technologies and solar cells.

Further, this chapter examines in detail the electronic structure of semiconductors and their interaction with light. It introduces band structure, explaining the concepts of the conduction band and the valence band, which determine the electrical and optical properties of these materials.

The second chapter, "Light Emitters", focuses on semiconductor devices capable of emitting light, particularly light-emitting diodes (LEDs) and laser diodes. It explores the operating principle of LEDs, which is based on the recombination of charge carriers in a semiconductor junction, producing light emission. The chapter also details their electrical and spectral characteristics.

Next, the study of laser diodes examines the phenomenon of laser oscillation, explaining how the amplification of light by stimulated emission enables the generation of a coherent and monochromatic beam. The chapter concludes with an analysis of the electrical and spectral characteristics of laser diodes, along with the various categories of semiconductor lasers widely used in telecommunications, imaging, and other advanced technological fields.

The third chapter, "Light Detectors", covers devices capable of converting light into an electrical signal, essential in many optoelectronic applications. It begins with the photoresistor, a component whose resistance varies according to the received light intensity, describing its operation, technology, symbols, and applications. Then, it discusses the photodiode, explaining its working principle, electrical and optical characteristics, and its role in various electronic circuits.

The chapter also explores the phototransistor, an amplified version of the photodiode, detailing its principle, characteristics, and applications. Special attention is given to photovoltaic cells, which utilize the photovoltaic effect to directly convert light into electricity, with an overview of solar cell manufacturing processes. Finally, the chapter concludes with an introduction to liquid crystal displays (LCDs), photomultipliers, and image sensors, which play a crucial role in display technologies, light amplification, and high-resolution image acquisition.

The fourth chapter presents several practical applications of optical sensors and photovoltaic generators. It first explores motion sensors, notably the optocoupler fork, used to detect the presence or interruption of a light beam. Then, it examines the optocoupler for galvanic isolation, highlighting its role in separating electrical circuits while ensuring signal transmission. Other sensors, such as luminescence, contrast, and color detectors, are also studied, each with specific applications in industry and automation. Finally, the chapter concludes with an overview of the photovoltaic generator, explaining its operation and importance in converting solar energy into electricity.

The fifth chapter, "Optical Fibers", explores the principles and operation of optical fibers, which are essential components in telecommunications and data transmission. After an introduction to the basics of geometrical optics, the chapter describes in detail the structure of optical fibers, explaining their design and role in guiding light. It presents the different types of fibers, notably single-mode and multi-mode fibers, highlighting their specific applications.

The chapter also addresses the phenomena influencing fiber performance, such as attenuation (loss of optical signal power) and dispersion (temporal spreading of the signal), which impact

transmission quality. It explains wave guiding within fibers, the parameters affecting light propagation, and nonlinear phenomena that may influence their operation.

1 Chapter 1: Elements of Photometry

1.1 Introduction & glossary

The radiation belongs to different spectral domains, characterized by ranges of wavelengths ranging from the gamma (γ) to radio waves [1, 2].

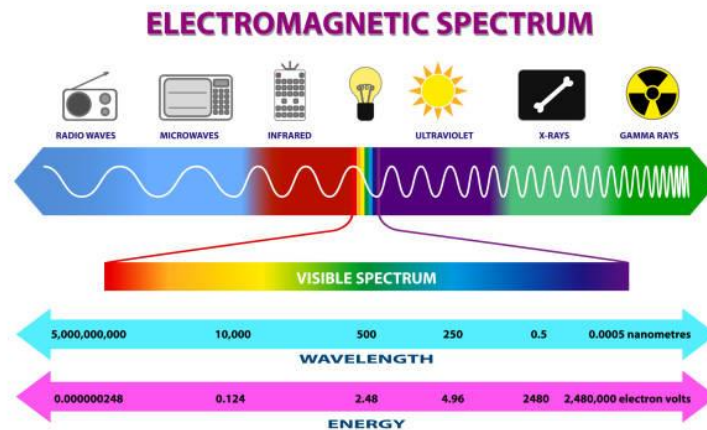


Figure 1.1: Spectrum of electromagnetic waves.

The visible radiation range: $400\text{nm} < \lambda < 700\text{nm}$ (1.1)

1.1.1 Light

Light has a dual nature:

1.1.1.1 Wave nature

Light is an electromagnetic wave. This wave propagates with a speed finite. The speed of light in a vacuum is a very important physical constant ($c = 3 \cdot 10^8 \text{ m.s}^{-1}$), c : speed of light (m.s^{-1}) and in a medium with refractive index n (n in the vacuum $n = 1$) [1] is:

$$\nu = \frac{c}{n} \quad (1.2)$$

Like all waves, light is characterized by:

- Its amplitude A
- Its frequency ν in Hz which characterizes the color of light.

The period T (in s) is the inverse of the frequency (Hertz: s^{-1}): $T = 1/\nu$

The wavelength λ (in m) is the distance travelled by light during a period:

$$\lambda = \frac{c \cdot T}{n} \quad (1.3)$$

1.1.1.2 Corpuscular nature

To describe more precisely the interaction between light and matter, one must model light in a corpuscular way. We then introduce the notion of photons which are the quanta of light energy. For a frequency ν each photon has then an E_{ph} energy given by:

$$E_{ph} = h\nu = \frac{h \cdot c}{\lambda} \quad (1.4)$$

Where h is the Planck constant ($6.625 \cdot 10^{-34}$ j.s)

This law is called the Planck's law, it indicates that all radiation is carrying an energy which is proportional to its frequency and inversely proportional to its wavelength. It is then described by a flow of particles 'photons' (quanta of energy) [3].

1.1.2 Photometry

Photometry is the energy study of electromagnetic radiation and energy transfers between two objects, the transmitter (source) and the receiver. Photometry measurement of radiation quantities. These different quantities are: the flux, intensity, illumination, and luminance [1].

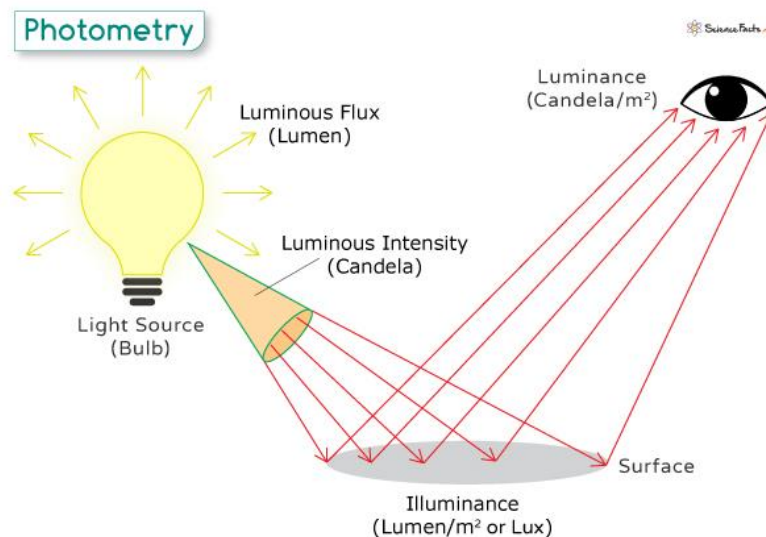


Figure 1.2: Diagram links the four factors of photometry.

The photometric quantities are related as follows: The Sun is the primary source with a candela intensity emits a lumen luminous flux. The moon receives a certain flux luminous in lumen which gives an illumination in lux and reflects a part of it (luminance in candela/m²) to Earth.

Energy photometry: evaluates visible light according to the energy it transmits.

Visual photometry: evaluates visible light according to its action on the eye.

1.2 Optical sources

- **Primary source:** it “creates” light (e.g., sun and stars, bulbs, lamps, etc.) spotlights).
- **Secondary source:** it “diffuses” or “transmits” light (e.g., the Moon and planets, reflective objects).
- **Monochromatic and polychromatic sources:**

A light source is called monochromatic when the light it emits is monochromatic, that is to say made up of a single radiation.

A source is called polychromatic when the light emitted is polychromatic, that is to say, made up of several radiations [4].

1.3 Geometric quantities

1.3.1 Plan Angle Recall

Angle plane, formed by two straight halves, is defined on the circle by the length of the arc $\widehat{AB}$ divided by the radius R .

On appelle l'angle α :

$$\alpha = \frac{\widehat{AB}}{R}$$

Radian (rad) is the unit used to describe it.

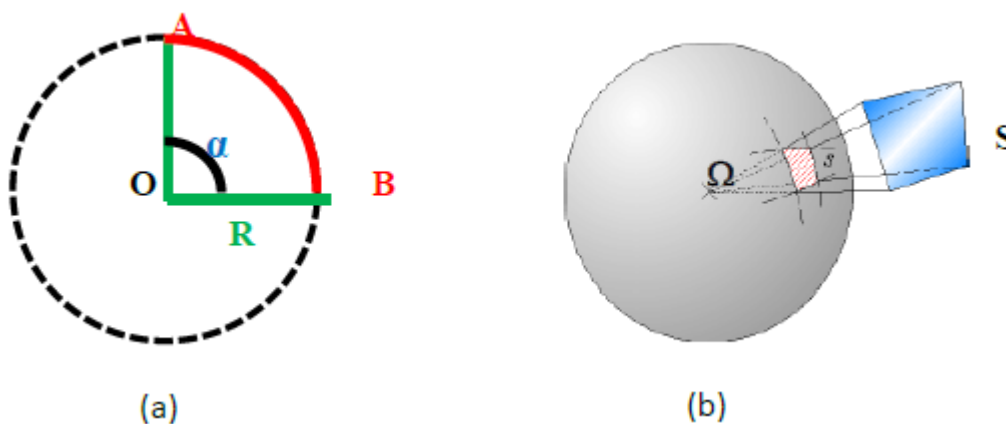


Figure 1.3: Construction of the plane angle (a) and solid angle (b).

1.3.2 Solid angle

Solid angle Ω in steradian (sr), is defined on the sphere by the surface S of a sphere divided by the square R -radius [1].

$$\Omega = \frac{S}{R^2} \quad (1.6)$$

1.3.3 Elementary solid angle

If the angle is very small $d\Omega$, the surface of the sphere portion is assimilable to the surface of a disc d .

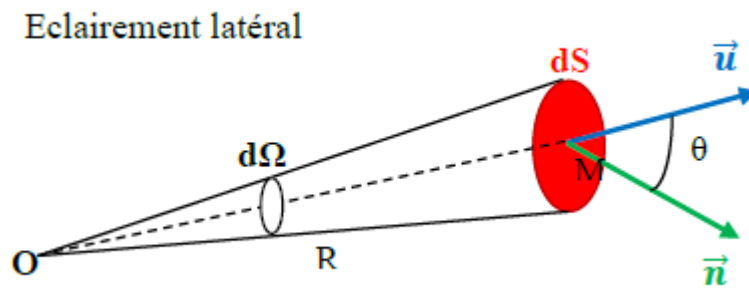


Figure 1.4: Elementary solid angle $d\Omega$.

The elementary solid angle $d\Omega$ under which a surface element $\overrightarrow{dS} = dS \cdot \vec{n}$

(Normal in M: with $\|\vec{n}\| = 1$) seen from $OM = \|\overrightarrow{OM}\|$. $\vec{u}$ (u unit vector) is:

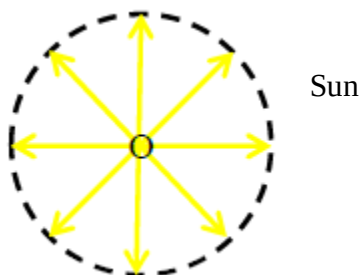
$$d\Omega = \frac{\vec{n} \cdot \vec{u}}{R^2} dS = \frac{dS \cos \theta}{R^2} \quad (1.7)$$

With: $R = \|\overrightarrow{OM}\|$ and $\vec{n} \cdot \vec{u} = \|\vec{n}\| \cdot \|\vec{u}\| \cdot \cos(\vec{n} \cdot \vec{u})$

When the surface element is viewed from a direction perpendicular to its surface [1]

$$d\Omega = \frac{dS}{R^2} \quad (1.8)$$

1.3.3.1 Special case

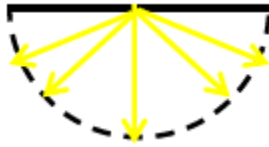


- Calculation of the solid angle in all space around point O

$$\Omega = \int_{\text{sphere}} d\Omega = \int_{\text{sphere}} \frac{dS}{R^2} = \frac{S_{\text{sphere}}}{R^2} = \frac{4\pi R^2}{R^2} \quad (1.9)$$

$$\Omega_{\text{space}} = 4\pi \text{ sr} \quad (1.10)$$

Space



Where:

- Solid angle $\Omega_{1/2}$ below which a half-space is seen:

$$\Omega_{\text{half-space}} = 2\pi \text{ sr} \quad (1.11)$$

Half-space

1.4 Quantities and Photometric Units

1.4.1 Radiation flux

If we are only interested in the energy aspect, then we place ourselves within the framework of the energy photometry.

1.4.1.1 Radiation energy flux

The energy flux Φ_e (in Watt (W)) is the power of the radiation electromagnetic emitted by a source, carried by a beam or received by a receiver.

Example: the flux emitted by the Sun is: $\Phi_e = 3.92 \cdot 10^{26} \text{ W}$.

Energy photometry makes no difference between the light energy that the eye will actually perceive and the energy to which is not sensitive. So you must move on to the Visual photometry that takes into account the properties of the human eye

1.4.1.2 Luminous flux

Luminous flux or visual flux is the amount of energy emitted by a source in the form of radiation visible in all directions.

It is denoted Φ_v and its unit is Lumen (lm).

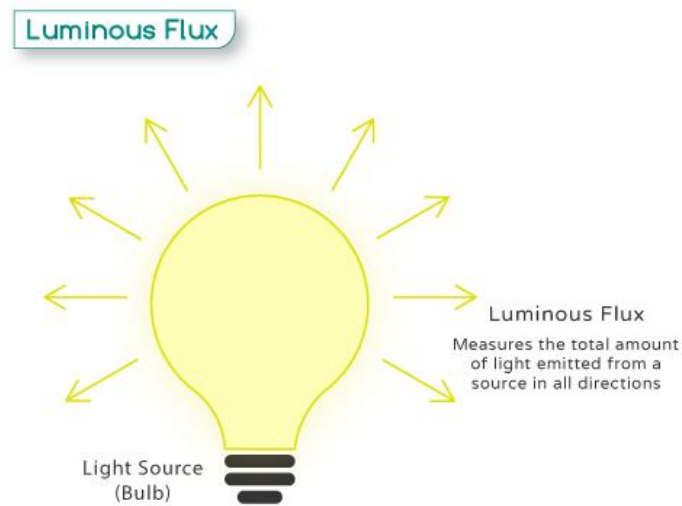


Figure 1.5: Luminous flux

Example:

<i>Source optique</i>	<i>flux lumineux</i>
<i>Bougie</i>	12 lm
<i>Lampe à incandescence 60 W</i>	750 lm
<i>LED 1 W</i>	130 lm

The energy flux Φ_e of a radiation and the corresponding visual flux Φ_v are related by a relationship of form [1]:

$$\Phi_v(\lambda) = k(\lambda) \cdot \Phi_e(\lambda) \quad (1.12)$$

k is the luminous efficiency and its unit: $\text{lm} \cdot \text{W}^{-1}$

1.4.1.3 Luminous efficacy

It is the quotient of the amount of light emitted by the electrical power that consumes the source. It characterizes the source from a performance point of view.

$$k(\lambda) = \frac{\Phi_v(\lambda)}{\Phi_e(\lambda)} \quad (1.13)$$

It depends on the sensitivity of the eye defined by the light efficiency function relative spectral $V(\lambda)$ in the photopic domain and $V'(\lambda)$ in the scotopic domain.

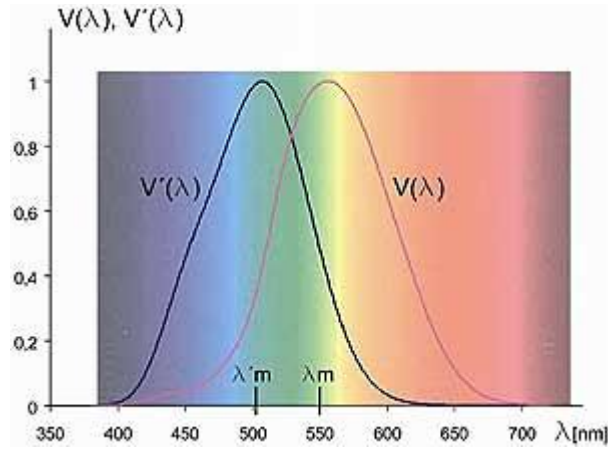


Figure 1.7: Relative spectral luminous efficacy of human eye

In day vision (photopic vision), the luminous efficacy $k(\lambda)$ passes through a maximum $k_m = 686 \text{ lm.W}^{-1}$ for $\lambda = 555 \text{ nm}$, given by:

$$k(\lambda) = k_m \cdot V(\lambda) \quad (1.14)$$

For night vision (scotopic vision), the maximum sensitivity is then obtained for 507 nm and the maximum spectral luminous efficacy is $k'_m = 1700 \text{ lm.W}^{-1}$ given by:

$$k(\lambda) = k'_m \cdot V'(\lambda) \quad (1.15)$$

1.4.2 Light intensity

The light intensity I is a quantity which expresses the capacity of light illuminated by source point in a given direction. The intensity luminous I characterizes the proportion of the luminous flux emitted in a portion of the space [5]. The light intensity is given by:

$$I = \frac{d\phi}{d\Omega} \quad (1.16)$$

Its unit is the candela (cd), which corresponds to the lumen per steradian (lm/sr).

Note:

- The intensity does not take into account the distance between the source and the observer.
- The intensity decreases as a function of the absorption by medium.
- Intensity may vary with the solid space element.

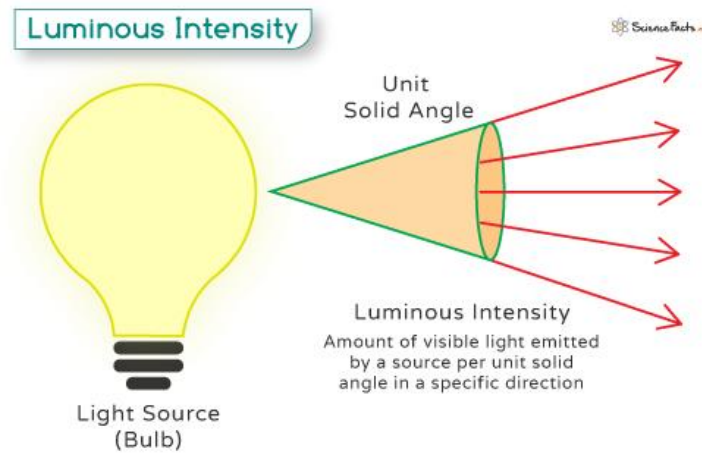


Figure 1.8: Light intensity

1.4.3 Lighting

The illumination (E) of a surface is the flux light received per unit area. Its unit is the lux (lx), equivalent to lm/m^2

$$I = \frac{d\Phi}{d\Omega} \quad (1.17)$$

$$E = \frac{I}{d^2}$$

The illuminance is measured with a light meter.

Note

The illumination is not limited to flat surfaces but also applies to the spherical, cylindrical illumination...

The illumination is independent of the nature of the surface, but depends on the intensity light coming from a given direction, the distance to the source and the inclination of the illuminated surface [1].

Example of lighting produced by:

Night sky: $3 \cdot 10^{-4} \text{ lx}$;

Full sun: 10^5 lx .

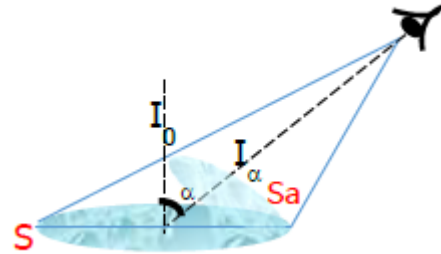
1.4.4 Luminance

The luminance (L) is a photometric quantity which characterizes the brightness of a surface. This is the amount of light reflected to an observer's eye. The luminance is expressed in candelas per square metre (cd/m^2), given by:

$$L_a = \frac{I_a}{S_a} \quad (1.18)$$

With $S_a = S \cos(\theta)$ with S_a : the apparent surface

Normal observer i.e.: $\alpha=0$.



$$L_0 = \frac{I_0}{S_a} \quad (1.19)$$

The Lambert source: luminance does not depend on α .

The sun, for example, as a disk that is equally bright at all points on its surface, is a source Lambertian [1].

1.4.5 Summary

Luminous quantities	Energetic quantities
Luminous flux Φ_v (lumen, lm) $\Phi_v = k \cdot \Phi_e$	Energy flow Φ_e (W): radiated power
Light intensity I_v (lm. sr^{-1} = cd, candela) $I_v = \frac{\Phi_v}{\Omega}$	The light intensity ($\text{W} \cdot \text{sr}^{-1}$) $I_e = \frac{\Phi_e}{\Omega}$
Visual Lighting E_v (lx) $E_v = \frac{\Phi_v}{S}$	Lighting ($\text{W} \cdot \text{m}^{-2}$) $E = \frac{\Phi_e}{S}$
Visual Luminance L_v (cd/m^2), $L_v = \frac{I_v}{S_a}$	Energy luminance ($\text{W} \cdot \text{m}^{-2}$) $L = \frac{I_e}{S_a}$

1.4.6 Application

Exercise 1:

Calculate the luminous flux of a laser pointer emitted a power of 5mw and wavelength of $\lambda = 680\text{nm}$.

With the photopic $V(\lambda)$ is given by:

$\lambda(\text{nm})$	555	600	620	640	660	680	700
$V(\lambda)$	1	0.631	0.381	0.175	0.061	0.017	0.0041

We have: $\Phi_v = k_m \cdot \Phi_e \cdot V_{680}$

Thus: $\Phi_v = 0.058 \text{ lm}$

Exercise 2:

A 150 W electric power lamp has a luminous efficacy equal to $40 \text{ lm} \cdot \text{W}^{-1}$.

-Calculate the luminous flux emitted by this lamp.

We have: $\Phi_v = k \cdot \Phi_e$

Thus: $\Phi_v = 150 \times 40$

Thus: $\Phi_v = 6000 \text{ lm}$

Exercise 3:

A beam from a source S (solid angle $\Omega = 7.86 \times 10^{-6} \text{ sr}$) carries a flux luminous flux of $31.44 \times 10^{-12} \text{ lm}$.

-Calculate the light intensity radiated by this isotropic source.

We have: $I = \frac{\Phi}{\Omega}$ thus: $I = \frac{31.44 \times 10^{-12}}{7.86 \times 10^{-6}}$ thus: $I = 4 \times 10^{-6} \text{ cd}$

1.5 Black body

1.5.1 Black body definition

Black body is an object that absorbs all radiation regardless of the length of the wave and also an ideal emitter whose radiation depends only on the temperature.

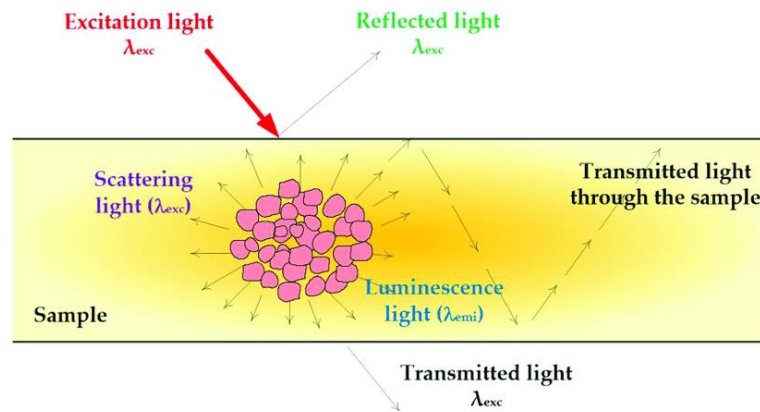


Figure 1.9: Matter radiation interaction processes.

Emission of a black body: $M = \sigma \cdot T^4$

$\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ is the constant of Stefan-Boltzmann

The spectral emission of a black body is maximum for a wavelength λ_{max} inversely proportional to the temperature T of the black body (Wien law) [1];

$$\lambda_m \cdot T = 2889 \text{ } \mu\text{m} \cdot \text{K}$$

1.5.2 Temperature - colour relation

The Wien relation links a temperature and a wavelength, and creates a link between a temperature and a color, which allows to define the temperature related to the color of the object.

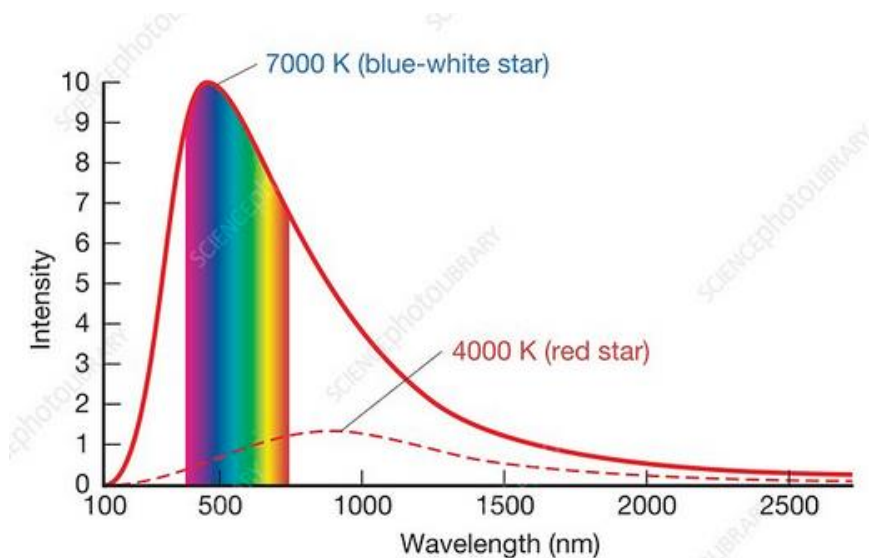


Figure 1.10: Wien displacement law.

Color temperature is low for red-rich lights (warm light) and high for blue-rich (cold light) lights. It is expressed in degrees Kelvin: $1\text{ K} = -273.15^\circ\text{C}$ [1]

Example:

Object (black body)	Temperature (K)	λ_m	spectral domain
Etoile type O	50 000	60 nm	UV
Soleil	6 000	$0.5\mu\text{m}$	visible
Terre	300	$10\mu\text{m}$	IR

Exercise 2

The human body temperature is 37.5°C , or about 310 K .

The wavelength corresponding to the maximum emission of the human body is:

$$\lambda_{\text{max}} = (2.9 \cdot 10^{-3}) / 310$$

$$\text{So } \lambda_{\text{max}} = 9.35 \cdot 10^{-6}\text{m} = 9350\text{ nm}$$

The maximum light emission of the human body is therefore in the infrared.

1.6 Lambert's Law

Lambert's law states that, for an orthotropic light source, the exitance is proportional to the luminance and the proportionality coefficient is π . In other words, if one designates the exitance and the luminance, for an orthotropic light source, one has:

$$M = \pi \cdot L$$

Where: **M**: the existence and **L** is the luminance

1.6.1 Lambertian light source

An orthotropic light source or a Lambertian light source, because it follows the Lambert law, is a light source whose luminance is uniform angularly, that is to say identical in all directions [1].

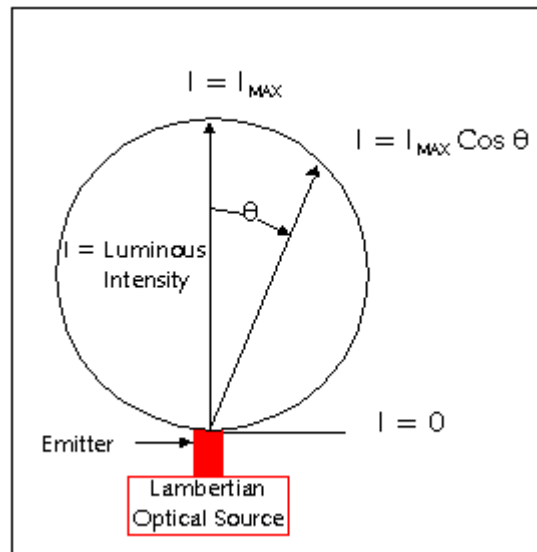


Figure1.11: Lambertian optical source

1.6.2 Example

In radiometry, it is common to consider a surface as being Lambertian. This approximation is acceptable for rough or matte surfaces, but not for metallic, glossy or polished surfaces.

Among the primary light sources, the black body, the ideal incandescent primary source, is an orthotropic source.

2 Chapter 2: Photo emitters

2.1 Introduction

Depending on their operating mode, optoelectronic components are classified into two types:

Photodetectors (photoreceptors): Components that convert an optical signal into an electrical signal.

Photo emitters: Components that convert an electrical signal into an optical signal.

Both types of components are made from semiconductor materials, and their operation is based on radiation-semiconductor interactions.

The fundamental element in manufacturing these components is the semiconductor material. Semiconductors are defined by their resistivities (ρ), intrinsic carrier concentrations (n_i), and bandgap energies (E_g). These materials are crystalline solids whose properties lie between those of insulators (resistivity greater than $10^{12} \Omega \cdot \text{cm}$) and metals (resistivity lower than $10^{-5} \Omega \cdot \text{cm}$). Semiconductors act as insulators at low temperatures and become more conductive as temperature increases.

The nature and energy of the bandgap (E_g) of a semiconductor play a key role in selecting materials for optoelectronic components.

Common semiconductors used in the industry include silicon (Si) and germanium (Ge) [6, 7].

2.2 Band Theory

In solid-state physics, band theory models the possible energy levels of electrons in a solid. Generally, electrons can only occupy specific energy ranges, separated by "forbidden energy bands."

This model explains the different electrical behaviors of insulators, semiconductors, and conductors.

At absolute zero temperature, two energy bands play a crucial role:

- The valence band (completely filled with electrons).
- The conduction band (empty or partially filled).
- The energy gap between these bands is called the bandgap (E_g).

At very low temperatures, three cases arise:

Insulator: If the conduction band is empty and the bandgap is large ($\sim 10 \text{ eV}$), no electrons can participate in conduction.

Semiconductor: If the conduction band is empty but the bandgap is small ($\sim 1\text{--}2\text{ eV}$), increasing the temperature excites electrons from the valence band to the conduction band, increasing conductivity.

Conductor: If the conduction band is partially filled at absolute zero, even a small electric field can move electrons, making the material conductive [1].

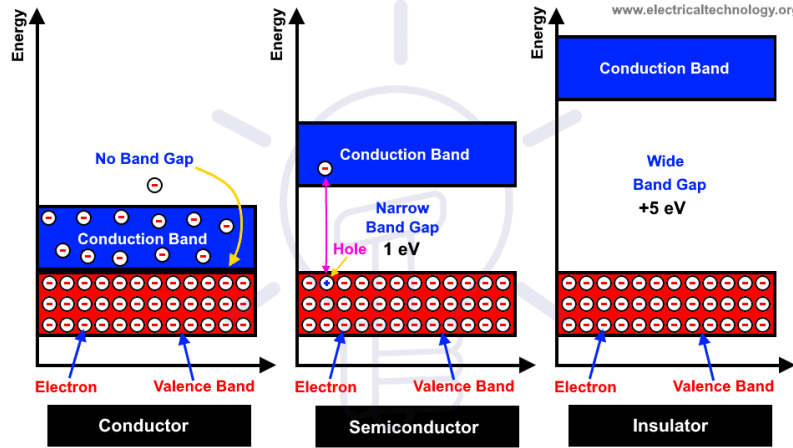


Figure 2.1: conductor, semiconductor and insulator

2.3 Light Emission by Semiconductors

The bandgap energy of semiconductors is typically between 0.5 eV and 4 eV, often around 1 eV.

Whether through absorption or emission, the energy of a photon follows the relation:

$$E = h \cdot \nu = h \cdot \frac{c}{\lambda} \quad (2.1)$$

Where:

$$h = 4.136 \times 10^{-15} \quad h = 4.136 \times 10^{-15} \text{ eV} \cdot \text{s (Planck's constant),}$$

$$c = 3.0 \times 10^8 \quad c = 3.0 \times 10^8 \text{ m/s (speed of light in vacuum),}$$

$$E = E_c - E_v = E_g \quad (\text{energy difference between conduction and valence bands}).$$

The relation between photon wavelength (λ) and the bandgap energy (E_g) is:

$$E_g (\text{eV}) \cdot \lambda (\mu\text{m}) = 1.24 \quad (2.2)$$

For example, for gallium arsenide (GaAs) with a bandgap of 1.43 eV, the corresponding photon wavelength is calculated using this formula.

$$\lambda (\mu\text{m}) = \frac{1.24}{1.43} = 0.867$$

With: $1 \text{ eV} = 1,602\,176\,565(35) \times 10^{-19} \text{ J}$ [8].

Types of Semiconductor Emitters:

Light-emitting diodes (LEDs):

- Emit monochromatic, incoherent light with low power.
- Cover the entire visible spectrum.
- Can be modulated at up to 100 MHz

Laser diodes:

- Essential in fiber optic communications.
- Emit coherent radiation with a modulation bandwidth of several GHz.
- Can reach optical power outputs of a few watts [9].

2.4 Light-Emitting Diodes (LEDs)

2.4.1 Basic Structure and Operation

LEDs (Light Emitting Diodes) are PN junction diodes made from highly doped semiconductors with radiative recombinations.

- The emitted radiation is incoherent, originating from spontaneous photon emissions.
- The emission pattern is controlled using an external lens.
- LEDs operate under forward bias and require current regulation to prevent damage.

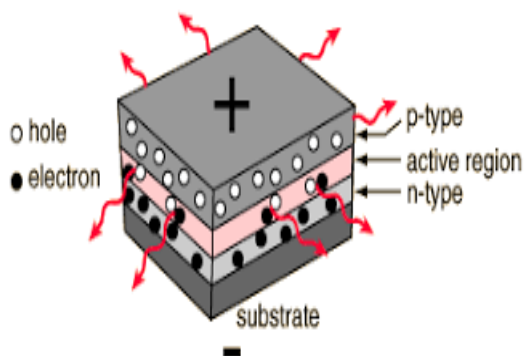


Figure 2.2: band structure of LED

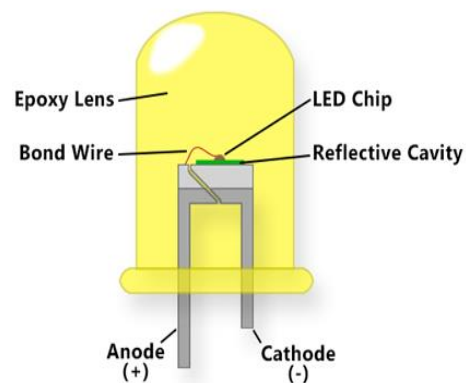


Figure 2.3: usual LED

The light-emitting diode operates under forward bias. When the supply voltage is high enough, the LED must be protected by a resistor to limit the current flowing through it to values lower than the maximum tolerated current intensity. Thus, the LED is powered by current rather than voltage, and this through the resistor present in the circuit (figure 2.4), which allows the current value to be set or limited as well as the luminous power emitted [9].

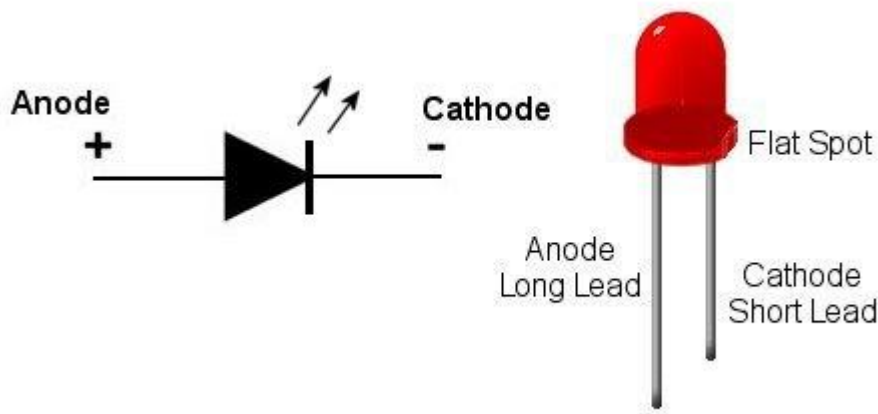


Figure 2.4: polarization circuit of LED

2.4.2 Electrical Characteristics:

- Threshold voltage (V_{th}):
- ~1.1 V for infrared LEDs.
- 1.8 V to 2.5 V for red, yellow, and green LEDs.
- Above 3.5 V for blue and violet LEDs.
- Operating current: Typically 10–50 mA depending on wavelength.
- Reverse voltage tolerance: Lower than conventional diodes (~4–5 V) [10].

2.4.3 Overall Efficiency (η)

Efficiency is given by the ratio of emitted optical power to absorbed electrical power:

$$\eta = \frac{W_{opt}}{W_{el}} \quad (2.3)$$

For a monochromatic light source with N_{ph} photons of energy $h \cdot \nu$, the emitted power is:

$$P_{opt} (W) = N_{ph} \cdot h \nu \quad (2.4)$$

And, the electrical power absorbed is given by the product $V \cdot I$ where V is the voltage applied to the diode and I the current delivered. I represents the quantity of charges that cross the junction per second, i.e.:

$$I = N_{el} \cdot e \quad (2.5)$$

Thus, efficiency is:

$$\eta = \frac{N_{ph} \cdot h\nu}{N_e \cdot e \cdot V} = \eta_e \frac{h\nu}{eV} \quad (2.6)$$

The luminous power emitted by an LED depends directly on the current flowing through it. The emitted power-polarization current characteristic shown in Figure 5 shows a linear growth without the presence of a threshold current [10].

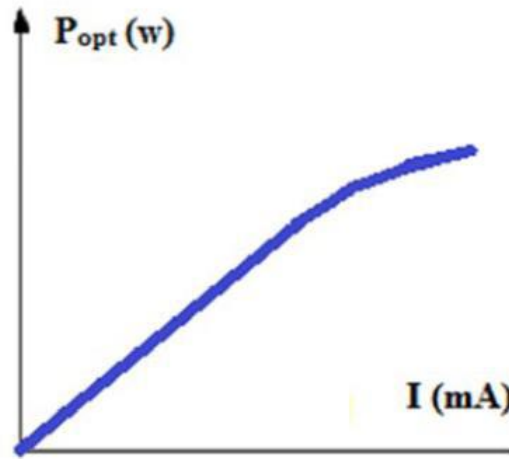


Figure 2.5: Luminous power as a function of current in the light-emitting diode.

2.5 Laser Diodes

2.5.1 Definition

LASER (Light Amplification by Stimulated Emission of Radiation) produces monochromatic, directional, coherent, and high-intensity light.

A laser consists of:

- ✓ Active medium (where photon emission occurs).
- ✓ Excitation mechanism (to supply energy).
- ✓ Optical cavity (to amplify light).

A laser diode is similar to an LED, but it uses stimulated emission instead of spontaneous emission, resulting in coherent light [11].

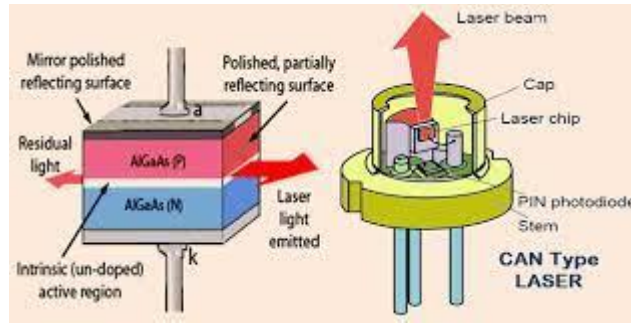


Figure 2.6: Basic structure of a laser diode

The resonant cavity has a length L that is a multiple of half the emitted wavelength, ensuring wave amplification through multiple reflections.

$$L = m \frac{\lambda}{2} \quad (2.7)$$

With: $m=1, 2, 3, \dots$

2.5.2 Materials Used

The wavelength of a laser diode is determined by:

- The semiconductor material in the active region.
- Dopant concentration.
- Structure of the active region.

Materials used for LEDs are also used for laser diodes.

2.5.3 Light Amplification

- Spontaneous emission generates the first photons.
- Stimulated emission amplifies photons as they reflect within the resonant cavity.
- Once stimulated emission dominates, laser oscillation begins.

2.5.4 Characteristics of Laser Diodes

2.5.4.1 Power vs. Current Curve

- The optical power output depends on injection current.
- A threshold current exists, beyond which laser emission starts.
- Temperature affects threshold current, requiring thermal stability [9].

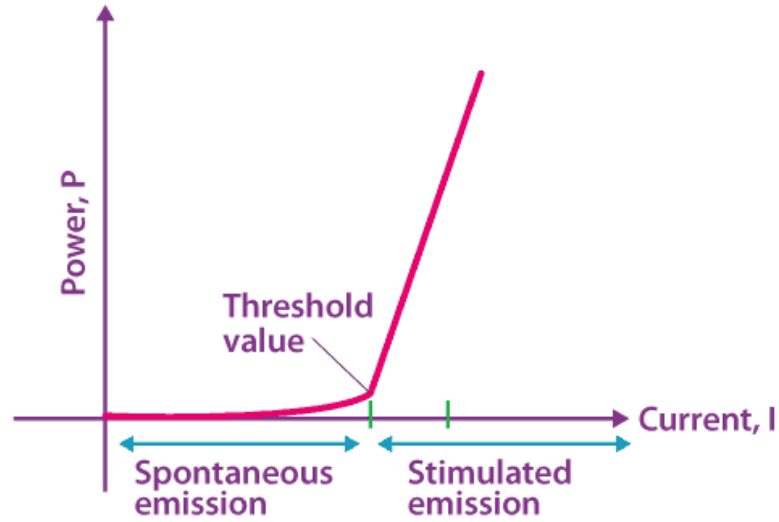


Figure 2.7: Power-current characteristic of the laser diode.

2.5.4.2 External Differential Quantum Efficiency (η_{diff})

Defines how efficiently electrical energy is converted into light.

Expressed as:

$$\eta_{diff} = 2 \cdot \frac{\Delta\Phi}{\Delta I} \cdot \frac{e}{h\nu} = \frac{2}{E_g(eV)} \cdot \frac{\Delta\Phi(W)}{\Delta I(A)} \quad (2.8)$$

Typical values: 100–200 mW/A.

The external quantum efficiency is around 60%.

2.5.4.3 Temperature Effects

- The threshold current increases with temperature.
- Higher temperatures lead to higher power dissipation.
- This is due to changes in carrier concentration and increased non-radiative recombination.

$$I_s(T) = I_{s0} \cdot e^{\frac{T}{T_0}} \quad (2.9)$$

Where T_0 is the characteristic temperature of the diode. Its value varies depending on their construction materials. I_{s0} is the characteristic threshold current [12].

3 Chapter 3: Photoreceptors

3.1 Introduction

As there are several methods to send information via light signal, there are different techniques to recover it photodetectors are components that can convert light signals in electrical signals is the photoelectric effect

When creating a pair of electron holes in a semiconductor, if these free carriers are collected before recombining, a photocurrent. There are two main categories of photodetectors depending on the nature of the electric field which secures the separation of charges of photogenerated electron-hole pairs:

- ✓ Photoconductors are made up of a simple semiconductor rod on which two ohmic contacts are arranged, where the electric field for photoporation collection is provided by the application of a bias voltage between end contacts
- ✓ Photovoltaic plants that use the internal electric field of a PN junction or Schottky (semiconductor metal type to ensure this separation of carriers [5, 10]

3.2 Operating parameters of photodetectors

3.2.1 Absorption coefficient

The flux of the photon entering the samples is given by:

$$\phi_t = \phi (1-R) = \phi_i \cdot T \quad (3.1)$$

ϕ_t : photon's flux

T: transmission coefficient of semi-conductor

$R = \left(\frac{n-1}{n+1}\right)^2$: reflexion coefficient of semi-conductor

□ The absorption coefficient α of the material is defined by: $\alpha = -\frac{1}{\phi} \frac{d\phi}{dx}$ [cm⁻¹]

□ If ϕ is considered at a distance x from the semiconductor surface : $\phi(x) = \phi_t e^{-\alpha x}$

Replacing yields ϕ_t , we obtain:

$$\phi_x = \phi (1-R) e^{-\alpha x}$$

R: between 0.25 and 0.35.

• In Si, there is an absorption if $\lambda < 1.1 \mu m$.

•In *GaAs*, there is an absorption if $\lambda < 0.9\mu\text{m}$.

3.2.2 Internal quantum performance

This is a parameter that measures the number of pairs (electron-hole) photo generated at the number of incident photons:

$$\eta_{\text{int}} = \frac{\text{number of electrons}}{\text{number of photons}} = \frac{I_{ph}/q}{\phi_i/h\nu} \quad (3.2)$$

I_{ph} : Photocourant

ϕ_i : incident Flux in Watt

The incident flow in watts (the power of the energy the photon flux in photons per second multiplied by the energy of a photon $E=h\nu$, [10]).

3.2.3 Spectral sensitivity:

3.2.3.1 2. Parameters of operation of the photodetectors

Spectral sensitivity is defined by:

$$S(\lambda) = \frac{\text{electric current } (I_p) \text{ supplied by the detector}}{\text{energetic flux } (\phi_i) \text{ that received by this detector}}$$

$$S(\lambda) = \frac{I_p(\lambda)}{\phi_i(\lambda)} \quad [\text{A/W}] \quad (3.3)$$

Or:
$$S(\lambda) = \frac{\text{the number of electrons } q}{\text{number of photons } h\nu} = 0.8 \cdot \eta_{\text{int}} \cdot \lambda(\text{um})$$

The spectral sensitivity is defined by:

$$R(\lambda) = \frac{S(\lambda)}{S(\lambda_p)} \quad (3.4)$$

λ_p : the peak wave width

3.2.4 Time response and bandwidth:

The response of a photodetector can be limited by capacitive effects, by trapping the carriers or by the saturation speed limit of carriers in the semiconductor.

The time response of a photodetector is characterized by time of decline (or time of ascent), which is by definition the necessary time the photodetector to fall from 90% to 10% of its maximum or increase from 10% to 90% of the total [10].

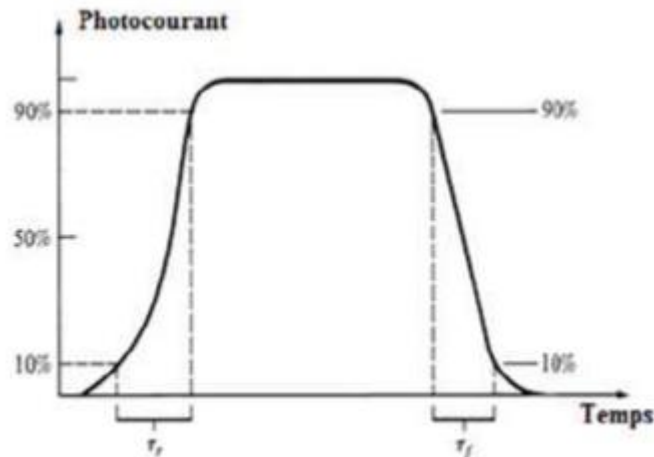


Figure 3.1: Time response and bandwidth of signal

3.3 Photorésistance ou cellule photoconductrice (LDR)

A photoresist is an electronic component whose resistivity varies depending on the amount of incident light. We can also call it photo-dependent resistance (light-dependent resistor (LDR))

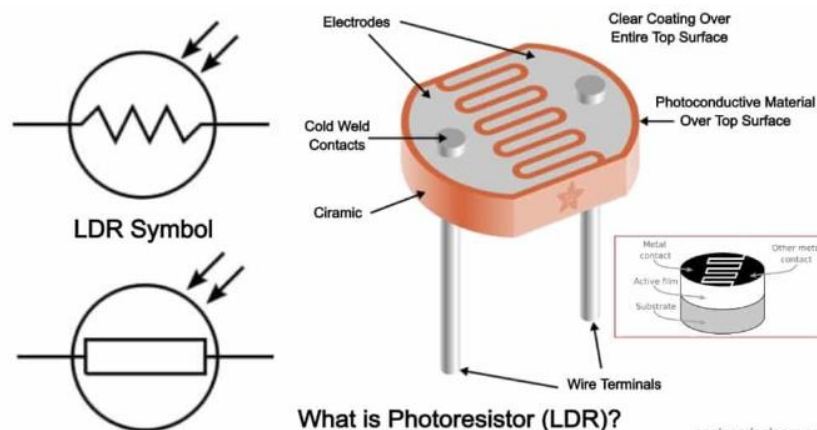


Figure3.2: Photoresistor LDR.

3.3.1 Principle:

A photoresist is composed of a high-frequency semiconductor resistivity. If the incident light is of sufficiently high frequency (thus of a wavelength lower than the threshold wavelength), it carries a significant energy. Beyond a certain level of material, the photons absorbed by the semiconductor will give electrons bound enough energy to pass from valence band to band. The understanding of this phenomenon is part of the theory of bands free electrons and electron holes as well products reduce the resistance of the material.

When the incident photon is sufficiently energetic for the production of electron-hole pairs is all the more important as the luminous flux is intense. The resistance evolves therefore as the

inverse of the illuminance this relationship can be considered as linear over a range of limited use.

A low temperature semiconductor crystal contains few electrons free and its conductivity is very low, and if the semiconductor is subjected to a light radiation, the energy provided by photons may be sufficient to release some electrons. The more intense the luminous flux, the more electrons available to ensure the conduction will be great As well as photo resistance (LDR) is inversely proportional to the light received

The materials used in photoresistors are most often of the compounds of columns II-VI periodic table of elements for low cost visible field use, the more often cadmium sulphide (or selenide of cadmium (For uses in the infrared we use the Lead sulphide) [10, 11]

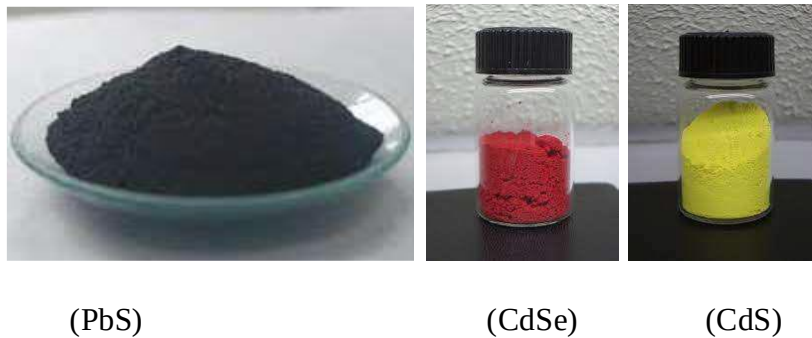


Figure3.3: materials used for fabrication a photoresistors.

3.4 Photodiode

3.4.1 Principle of operation of photodiodes

The photodiode is a diode that has not been encapsulated and is therefore sensitive to external radiation; its principle of operation is based on the conduction mechanisms in an inversely polarized PN junction and subjected to a radiation.

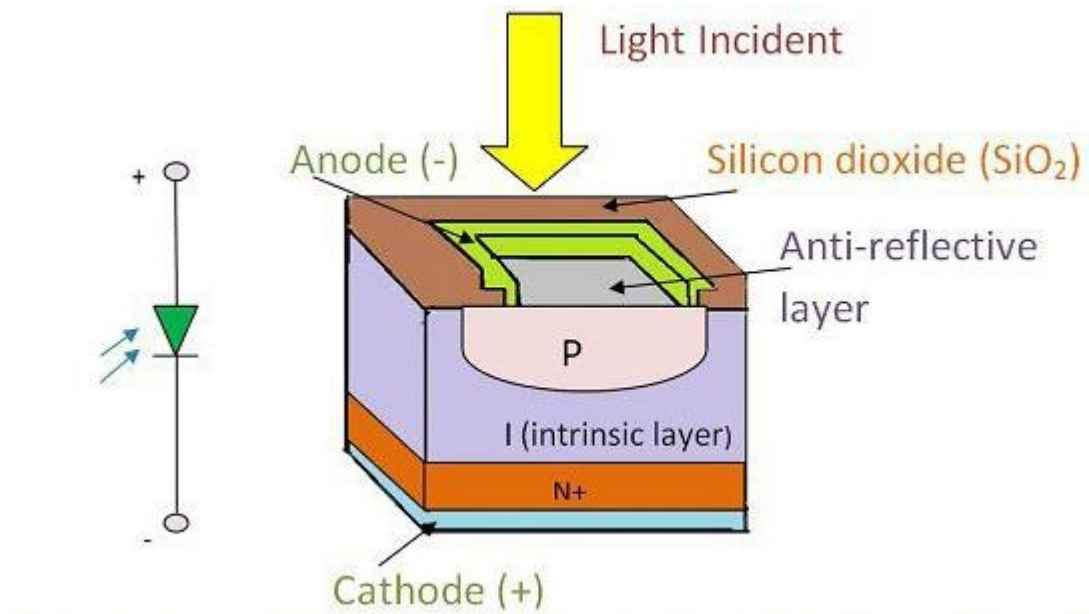


Figure3.4: photodiode symbole & construction of photodiode.

The photo generated carriers are separated and accelerated by a field electric then collected for contribute to the measured current.

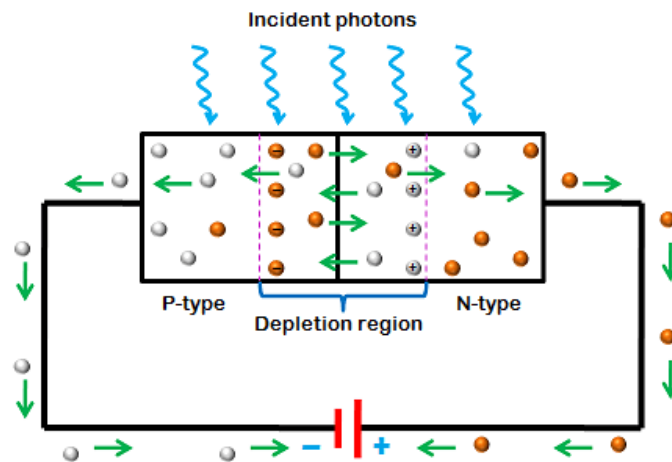


Figure 3.5: PN junction photodiode

The current flowing through a diode is given by the expression:

$$I = I_s (e^{\frac{V}{U_T}} - 1) \quad (3.5)$$

Where I_s is the saturation current, $U_T \approx 26\text{mV}$ at 0 K and V the applied voltage

When the diode is polarized inversely, and for: $V \gg U \rightarrow I \approx -I_s$

The measured current is due to the minority carriers of the P and N regions and the generation of electron-hole pairs in the space charge zone (SCZ) In the case of the photodiode, the absorbed radiation increases this current by the creation of carriers in the space charge zone (SCZ).

Consider the diagram in the following figure:

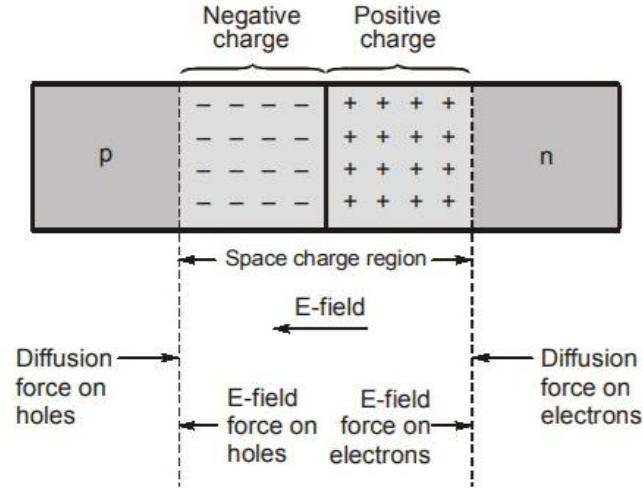


Figure 3.6: Generation of carriers by absorption of light in the different areas of the diode.

Incident photons create electron-hole pairs in each of the p, SCZ and n regions. In the neutral p and n regions, minority carriers diffuse. Those that reach the space charge are attracted by the field and contribute to the current by their diffusion creating a diffusion photocurrent (I_{diff})

-In the SCZ, the electron-hole pairs created are dissociated by the electric field, the electron is propelled towards the n region and the hole towards the p region these two photo carriers give rise to a generation photocurrent (I_g) [10].

The two mechanisms are added to give birth to the photocurrent I_{ph} :

$$I_{ph} = I_{ndiff} + I_{pdiff} + I_g \quad (3.6)$$

This photocurrent then contributes to the increase of the reverse current of the diode:

$$I = I_s (e^{T \frac{V}{U_t}} - 1) - I_{ph} \quad (3.7)$$

The photocurrent is practically independent of the polarization voltage. The characteristic of the diode in darkness and under illumination is given in the figure [10]:

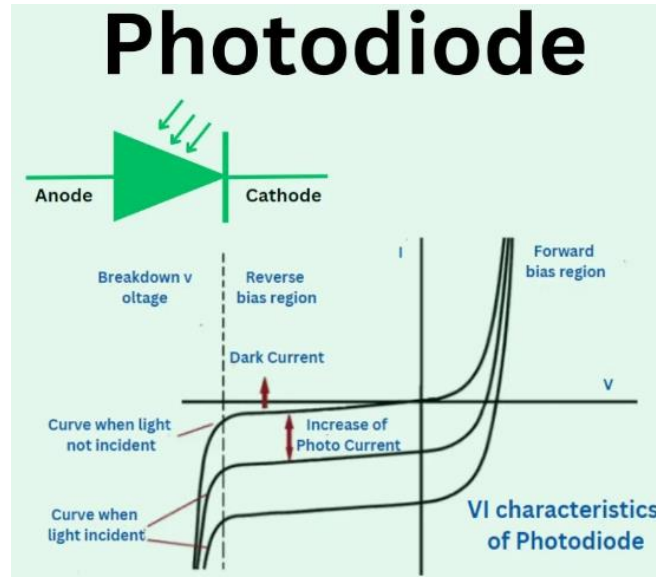


Figure 3.7: I (V) characteristics of the photodiode in darkness and under lighting.

In practice, a photodiode can be used in two modes of operation:

- Photovoltaic mode: $I = 0$

The diode, without external polarization, is in open circuit (solar cells case).

In this case, the photo voltage that appears at the terminals of the diode is measured:

$$I = I_s (e^{V_{co}/U_T} - 1) - I_{ph} = 0 \quad (3.8)$$

That give :

$$V_{co} = U_T \ln\left(\frac{I_{ph}}{I_s} + 1\right) \quad (3.9)$$

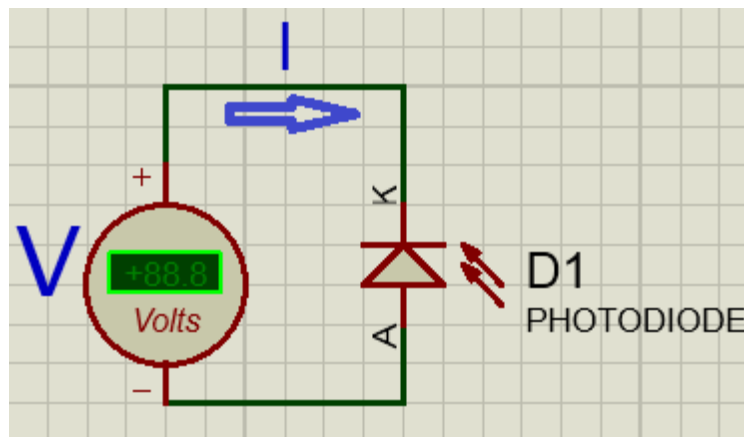


Figure: 3.8: Photovoltaic mode: $I = 0$

V_{co} : open circuit voltage, is proportional to the natural logarithm of the photocurrent, so the measured voltage V is proportional to the natural logarithm of the radiation intensity

- **Reverse bias mode ($V_0 < 0$)**

The diode is reversed polarized (in the case of photodiodes) In this case, the photocurrent is measured charged by the diode:

$$= I_s (e^{\frac{V_0}{U_T}} - 1) - I_{ph} \quad (3.10)$$

Photodiodes are generally polarized by voltages of the order of 5V and lower than the avalanche voltage.

In this case it can be assumed that the voltage V_0 is very large in front of U_T , which allows us to write

$$I = - (I_s + I_{ph}) \approx -I_{ph} \quad (3.11)$$

The measured current is then proportional to the intensity of incident light.

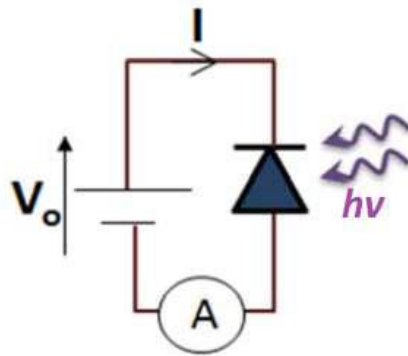


Figure 3.9: Function of photodiode, inversed polarisation.

The figure below summarises the evolution of the I-V characteristic of the photodiode with the applied voltage and the incident light flux ($\Theta_1 < \Theta_2$) [4, 10]

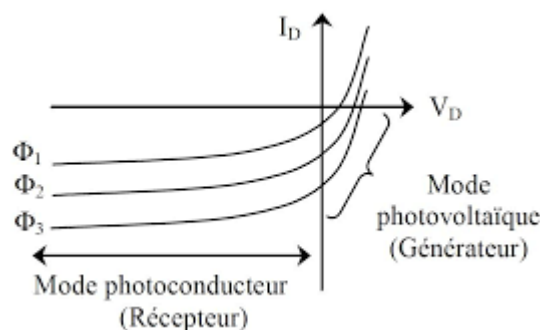


Figure 3.10: Photodiode I-V characteristic under different illuminations

Note:

When the photodiode is short-circuited, either at $V_0=0$, the current measured for a given light flux is the short circuit current I_{cc} (intersection point of the characteristic with the axis of the currents), it corresponds to the photocurrent.

The current from a photodiode is very low, it varies from a few pico amperes to a few micro amperes depending on the intensity of light and the surface of the photodiode. An amplification of the photocurrent is then often carried out using mounts based on operational amplifiers which ensures at the same time the conversion of the photocurrent from the diode into a voltage. An example of circuits is given in the following figure [8]:

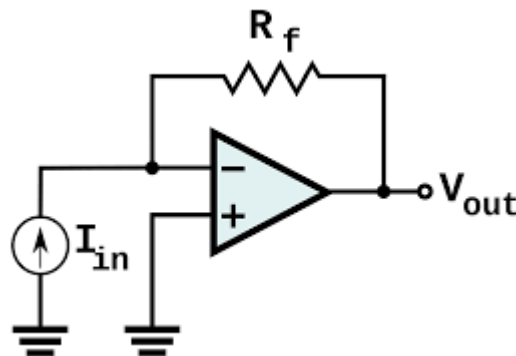


Figure 3.11: Trans-impedance amplifier

3.4.2 Photodiode response time

This is the time it takes for the photodiode to respond to an incident light signal and to give, from the accumulated load, an electrical current at output.

It is usually expressed as the rise time or cut-off frequency. The rise time being the time needed for the output signal to go from 10% to 90% of its peak value.

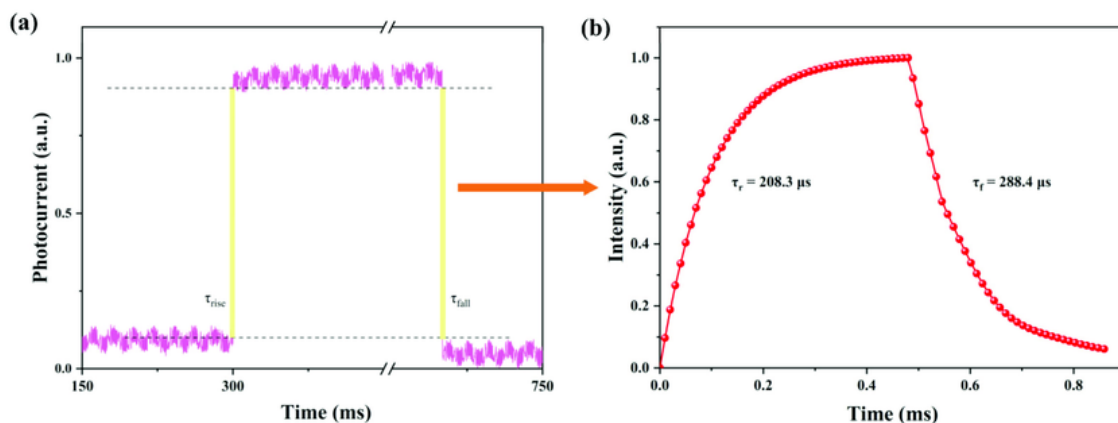


Figure 3.12: Photodiode response time.

Given the dual origin of photocurrent, the response time of the photodiode, which is particularly related to the life of the excess carriers, is conditioned by:

- The spread of minorities from p and n neutral regions to the load zone of space, the t_1 duration of this diffusion is in the range of 10^8 s to 10^9 s
- The t_2 transit time of the photo porters generated through the load zone of space which is in the order of 10^{-10} s to 10^{11} s. This time depends on the width of the space load zone

$$= \frac{W}{v_t}$$

V_d being the speed of electron movement in the space charge zone.

In practice, to reduce response time, the generation mechanism is favoured over the diffusion mechanism.

The diode is then made with a fairly small frontal area and a sufficiently large SZC to absorb most of the radiation [6, 12].

3.4.3 Photodiode equivalent scheme

The photodiode is usually polarised in reverse, its equivalent scheme is that of an inverse diode in parallel with an I_p current generator.

This is reflected in the circuit of the following figure:

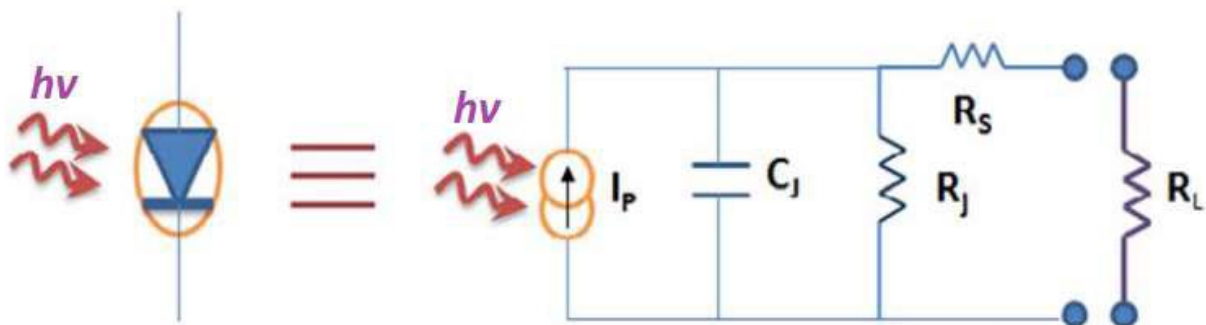


Figure 3.13: Equivalent photodiode diagram

R_J is the dynamic resistance of the inversely polarized junction, its value is very high, and it is of the order of $10^{10}\Omega$.

R_S is the series resistance: it is the access resistance, it is essentially due to substrate resistance and contact resistance. R_S is very low, it is of the order of 10Ω .

C_J is the capacity of the space load zone, often simply referred to as by "or "electrical capacity", is effectively inversely proportional to the width of the space load zone W This relationship is governed by the following formula [10]

$$C_J = \epsilon_0 \epsilon_r \frac{A}{W} \quad (3.12)$$

Where:

ϵ_r is the relative permittivity of the dielectric material (insulating material) between the capacitor plates.

ϵ_0 is the permittivity of the vacuum (a constant).

A is the surface of the capacitor plates (photodiode surface).

The thickness of the space load area W is proportional to the polarization inversely, this capacity ranges around 100 pF for low-polarization few tens of pF for high polarizations

If the current is injected into a load resistor R_L and neglects the effect of R_s and R_j the circuit in Figure is summed up as a frequency filter R_C of cut off f_c equal to

$$f_c = \frac{1}{2\pi} R_L \cdot C_j \quad (3.13)$$

Thus, the photodiode bandwidth is limited by its response time.

Note

- The photodiode has a small surface area, which reduces its junction capacity and increases its cut-off frequency
- The load resistance affects the bandwidth a large value of R_L reduces the cut-off frequency but increases the measured voltage [10].

3.4.4 Quantum efficiency of the photodiode

The quantum efficiency of the photodiode is defined by the ratio:

Where:

$$\eta_e = \frac{\text{Number of carriers collected (electrons)}}{\text{Number of Incident Photos}} = \frac{I_{ph}/q}{\Theta_i/h\nu}$$

Θ_i Incident flow in Watts.

The incident flux in watts (the power of light energy)= photonic flux in photons per second, multiplied by the energy of a photon $E=h\nu$

Therefore : $\phi = \frac{\Theta_i}{h\nu}$

To calculate η_e consider the ideal case (figure below)

A structure where the thicknesses, d_1 and d_2 of the regions P and N are very low in front of the space load zone W .

Where all generated photo pairs are collected (no recombination).

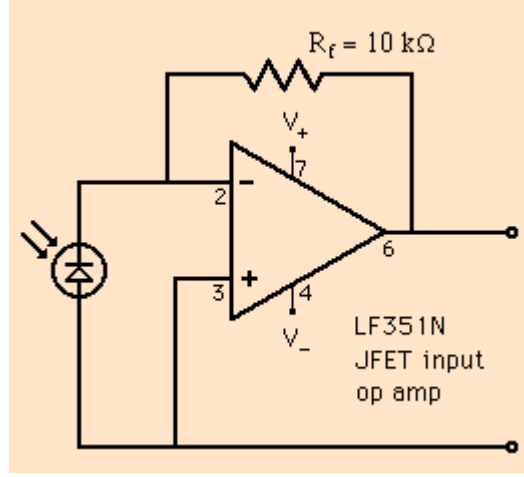


Figure 3.14: Ideal photodiode.

For a light flux incident I (the flux entering the diode, following discontinuity, the evidence is:

$$\Phi_0 = \Phi(1-R)$$

The flow remaining after a penetration depth x is:

$$\Phi_0 = \Phi(1-R)e^{-\alpha x} \quad (3.14)$$

By neglecting d before W the loss of power by absorption in W est:

$$\Phi(W) = \Phi_i(1-R)(1-e^{-\alpha W}) \quad (3.15)$$

This quantity corresponds to the photons that are at the origin of the generation of electron hole pairs.

By neglecting the diffusion current in front of the generation photocurrent in the space load zone, the current can be expressed as:

$$I_{ph} = \frac{q\Phi_i(1-R)(1-e^{-\alpha W})}{h\nu} \quad (3.16)$$

Thus the quantum efficiency of the photodiode is:

$$\eta_e = \frac{I_{ph}/q}{\Phi_i/h\nu} \quad (3.17)$$

Where: $\eta_e = (1-R)(1-e^{-\alpha W})$

Moreover, for a given wavelength, this quantum efficiency is connected to the spectral response of the photodiode by [10]:

$$\eta_e(\lambda) = \frac{hc}{\lambda} \quad (3.18)$$

3.4.5 Derived structures

The PIN photodiode is a diode that presents itself with a large area intrinsic (very low or undoped area] between zones (and (hence the name p i n this area corresponds to an increase artificial space load zone. In addition, the region I is generally wide so that photons which enter the component have a greater probability of absorption in the intrinsic region, rather than in p and n regions



Figure 3.15: PIN photodiode.

3.4.5.1 Photodiode PIN

PIN photodiode is fast. The space load zone W is very wide, close to the 20 input zone at $50\text{ }\mu\text{m}$; so the diode's capacitance is low and its cut-off frequency is high. There is little diffusion of load carriers (outside the space load zone). In fact, there is a lot of generation (in the space load area).

3.4.5.2 Avalanche Photodiode (APD)

Higher output signals can be reached avalanche diode. The component uses low internal current to generate a stronger current output

Thus, the avalanche photodiode is a PIN photodiode in which the electrons created in the intrinsic zone are multiplied by avalanche effect.

Contrary pin diode, the structure of the avalanche photodiode comprises an additional narrow layer and strongly doped p or n the junction n p, so formed, is an avalanche zone where the electric field E exceeds the field ionisation critical (the electric field E of the order of $4\text{ to }5 \cdot 10^5\text{ T V/cm}$). It acts as a zone of multiplication and generates the internal gain of the avalanche photodiode [2].

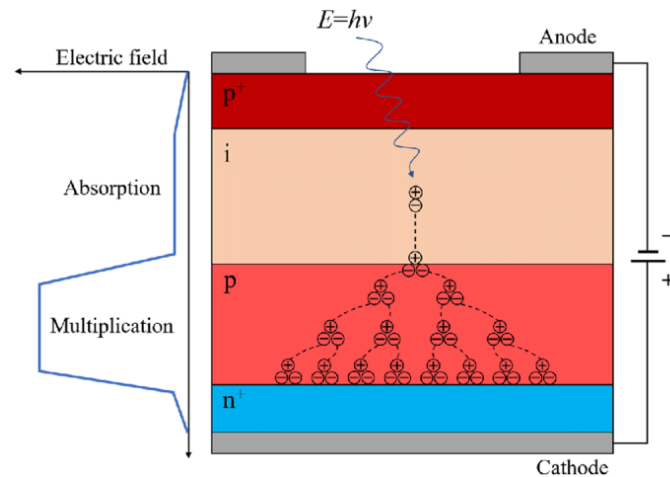


Figure 3.16: Avalanche effect in APD

3.5 Phototransistor

A phototransistor is an electronic component that reacts to light by changing its electrical conductivity. It is essentially a transistor that is sensitive to light which means that it can be used to detect the presence or intensity of light

The phototransistor is made of three layers of semiconductor materials, just like a conventional transistor. However, one of these layers is photosensitive, that is to say it can generate electrons under the influence of incident light. When light hits the photosensitive layer, it generates charge carriers (electrons and holes) which change the conductivity of the layer. This allows to control the current flowing between the other two layers of the phototransistor [10]

What is Phototransistor

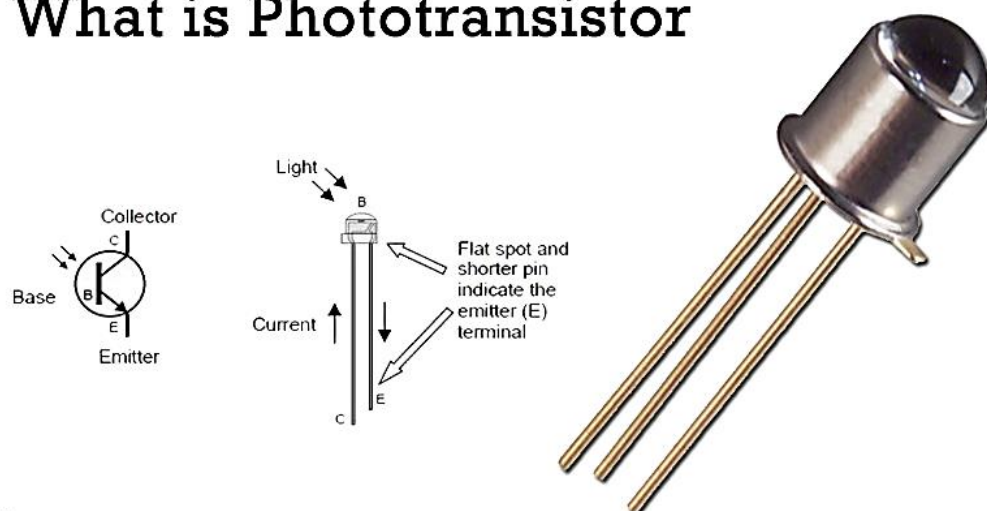


Figure 3.17: phototransistor principle.

3.5.1 Symbol

Phototransistors are available as a two-way or three pins. In a two-pin phototransistor the base terminal is electrically unavailable and the device is entirely dependent on light. In a three-pin phototransistor the use of the terminal base is optional. When the base is used, it acts as a JBT (ordinary junction bipolar transistor) and when not in use, it acts as a photo transistor. [5, 12]



Figure 3.18: phototransistor symbol.

3.5.2 Principle of operation

A phototransistor is a bipolar transistor whose base is sensitive to light radiation. The base is then said floating since it is devoid of connection. When the base is not illuminated, the transistor is passed through by the leakage current I_{CE0} . The illuminance of the base leads to an I_{ph} photocurrent which can be called the control current of the transistor.

This appears in the base collector junction as

$$I_C = \beta I_{ph} + I_{CE0}$$

When the base is lit the phototransistor is equivalent to a closed switch between the transmitter and the collector and when the base is not illuminated, it is equivalent to an open switch.

The illumination current of the phototransistor is the photocurrent of the base collector photodiode multiplied by amplification β of the transistor. Its reaction photosensitive is therefore significantly higher than that of a photodiode (100 to 400 times more).

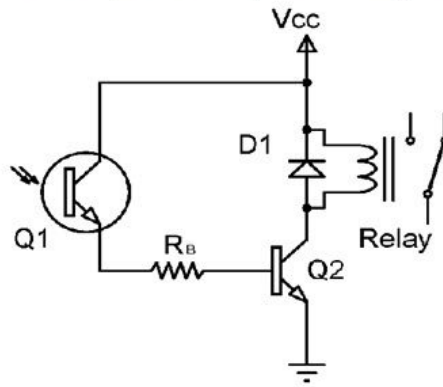


Figure 3.19: phototransistor as a closed switch

3.5.3 Technological properties

- Sensitivity, very sensitive to light, can detect very low light levels
- Fast response, very fast through to other optical components, hence quick detection of brightness changes
- High gain, highly amplified output signal
- Low noise, having low background noise, it can detect weak optical signals with high accuracy
- Long-term stability, generally very stable, can operate for many years without requiring maintenance
- Small size, small in size it is easy to integrate into electronic devices [5]

3.5.4 Coding and typical values

Phototransistors are generally coded according to their housing, their mounting type and their response wavelength range

- TO-18 Cylindrical metal case TO-92 Shaped plastic case of transistor
- NPN Assembly, Darlington bipolar junction transistor, two NPN transistors connected Cascade PNP bipolar junction transistor
- UV, Visible, IR [5]

3.5.5 Application

Phototransistors are commonly used in a variety of applications, including detection of ambient light, infrared communication, the motion sensors, flow meters, the bar code readers, security devices and many others. They offer high sensitivity to the light and can be used to amplify a signal low optics in stronger electrical signal [6]

3.6 Photovoltaic cells

The Photovoltaic cells are the core of all energy systems solar. They operate on the principle of photovoltaic effect, which has been discovered by Alexandre Edmond Becquerel in 1839 when the Sunlight hits the surface of a photovoltaic cell, it generates electricity.

1839: Photovoltaic Effect Is Discovered. French scientist Edmond Becquerel first discovered the photovoltaic effect in 1839. This process occurs when light is absorbed by a material and creates electrical voltage. Most modern **solar cells** use silicon crystals to attain this effect.

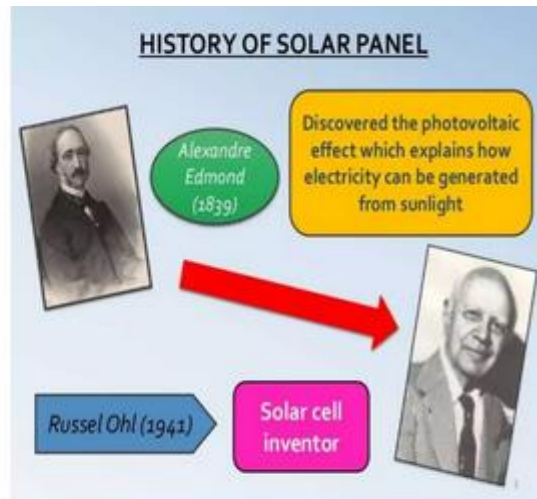


Figure 3.20: discovery of photovoltaic cells

3.6.1 Photovoltaic (PV) cells composition

Photovoltaic (PV) cells, also known as solar cells, are made up of several key materials that work together to convert sunlight into electricity. The main components of a typical photovoltaic cell include:

1. Semiconductor Material (Light Absorber)

- The core component of a solar cell is a semiconductor, usually silicon (Si), which absorbs sunlight and generates electron-hole pairs.
- Types of silicon used:
 - Monocrystalline Silicon (Mono-Si) – High efficiency, expensive.
 - Polycrystalline Silicon (Poly-Si) – Moderate efficiency, lower cost.
 - Amorphous Silicon (a-Si) – Used in thin-film solar cells, flexible but lower efficiency.
- Other materials:
 - Cadmium Telluride (CdTe) – Used in thin-film solar cells, cost-effective.
 - Copper Indium Gallium Selenide (CIGS) – High absorption efficiency in thin-film technology.
 - Perovskite materials – Emerging technology with high efficiency and lower cost.

2. Antireflective Coating (ARC)

- A thin layer on the surface of the cell reduces reflection and enhances light absorption.
- Usually made of silicon nitride (Si_3N_4) or titanium dioxide (TiO_2).

3. Transparent Conductive Layer

- A conductive layer that allows light to pass through while conducting electricity.
- Common materials:
 - Indium Tin Oxide (ITO)
 - Fluorine-doped Tin Oxide (FTO)

4. PN Junction (Doping Layers)

- Formed by doping silicon to create N-type (electron-rich) and P-type (hole-rich) layers.
- Doping elements:
 - Phosphorus (P) for N-type silicon.
 - Boron (B) for P-type silicon.

5. Metal Contacts (Electrodes)

- Conductive metal lines collect and transport generated electricity.
- Common metals used:
 - Silver (Ag) for front contacts (grid).
 - Aluminum (Al) or Copper (Cu) for back contacts.

6. Encapsulation & Protective Layers

- Protects the cell from environmental damage (moisture, dust, mechanical stress).
- Typically made of EVA (ethylene vinyl acetate) or glass.

7. Backsheet

- The bottom layer providing insulation and protection.
- Made from materials like polymer films (TPT, PET).

These components work together to efficiently capture sunlight, generate electron flow, and convert it into usable electrical energy [6, 7]

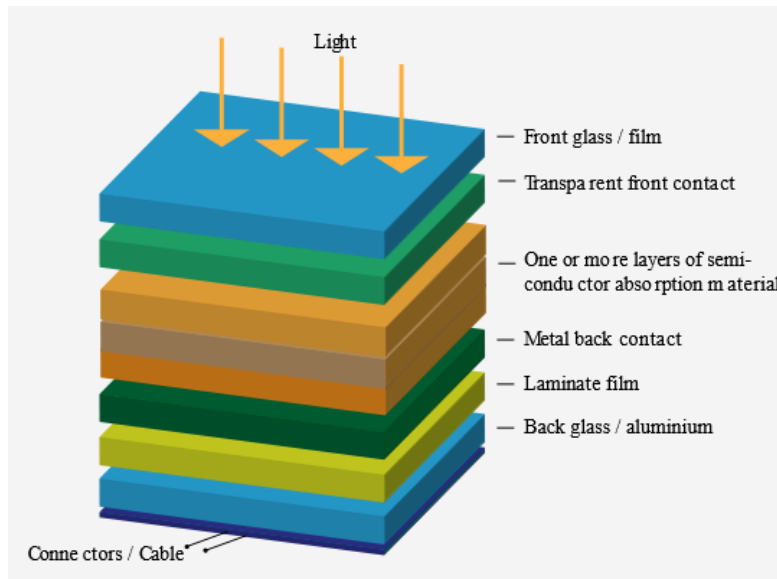


Figure 3.21: example of PV materials.

3.6.2 Operation of photovoltaic cells

When the solar cell is hit by sunlight, the electrons in the semiconductor material absorb the energy of photons and become excited. This excitation creates a current electric when electrons move through the cell. The contact layers of the cell collect this current and transmit it to external electrical circuit

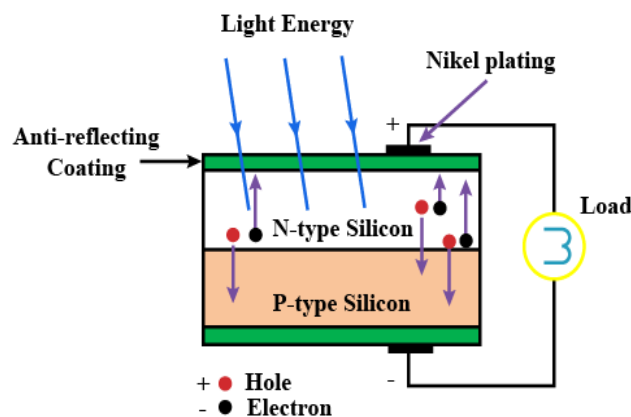


Figure 3.22: operation of PV

3.6.3 Types of PV cells

Photovoltaic (PV) cells are mainly categorized into three types: monocrystalline, polycrystalline, and thin-film. Monocrystalline PV cells are made from a single crystal of silicon, offering high efficiency and durability but at a higher cost. Polycrystalline PV cells are composed of multiple silicon fragments melted together, making them more affordable but slightly less efficient. Thin-film PV cells use layers of semiconductor materials like cadmium telluride or amorphous silicon, making them lightweight and flexible, though they typically

have lower efficiency compared to crystalline silicon cells. Each type has its own advantages depending on the application and budget [2, 11].



Figure 3.23: types of PV cells

3.6.4 Efficiency and performance

The efficiency of a photovoltaic cell measures its ability to convert sunlight into electricity. The most efficient photovoltaic cells currently achieve an efficiency of about 20 to 25. The yield depends on many factors, including the quality of materials design of the cell the angle of incidence of the solar light and environmental conditions.

3.6.5 Applications of photovoltaic cells

Photovoltaic cells are used in various applications, in particular:

1. Residential and commercial solar panels to produce electricity from the sun
2. Autonomous solar systems to power equipment remote, such as signal lights, traffic monitoring and weather stations
3. Solar vehicles to power cars, boats and solar aircraft
4. Space applications to supply power to satellites and to space stations
5. Energy storage systems to store the electricity produced for future use [10].

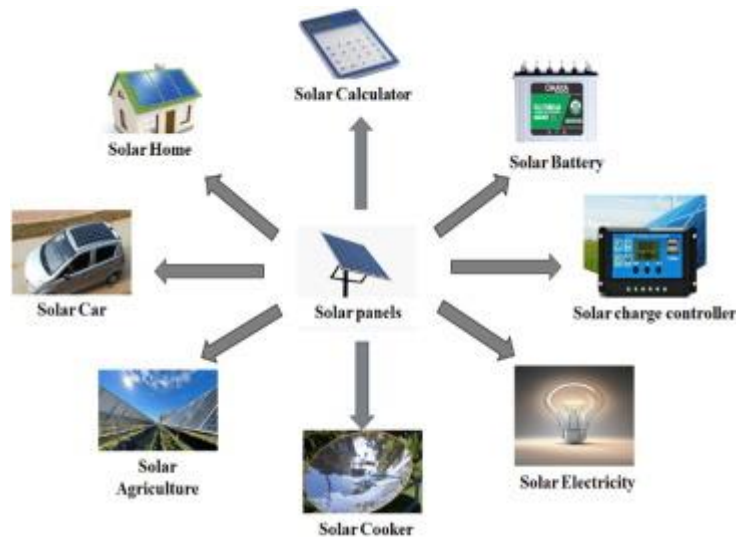


Figure 3.24: application of PV cells

3.6.6 Conclusion

Photovoltaic cells are essential for energy exploitation Solar. They play a key role in Transition to more energy sources Clean and renewable s constant advances in technology photovoltaic cells, efficiency and solar energy efficiency increase this which makes it an increasingly attractive to meet the needs global energy [10].

3.7 Charge Coupled Device (CCD)

A Charge Coupled Device (CCD) sensor, in French, a load transfer device, is a component electronic used for image and video capture It is commonly used in digital cameras, camcorders, electron microscopes, electronic scanners and other imaging devices [10].

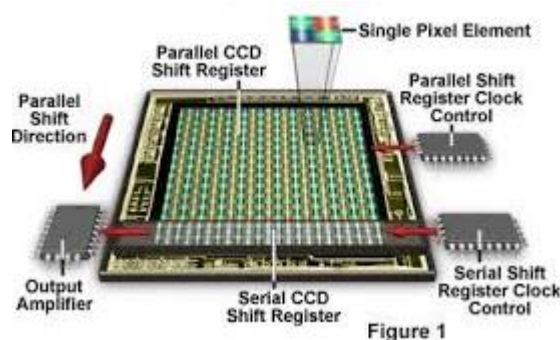


Figure 3.25: CCD sensor architecture

3.7.1 Structure of a CCD sensor

A CCD sensor is made up of millions of photosensitive cells, also called pixels. Each pixel is able to convert light into an electric charge. Pixels are organized in a grid, forming a two-

dimensional matrix. The resolution of the image is determined by the number of pixels in this matrix.

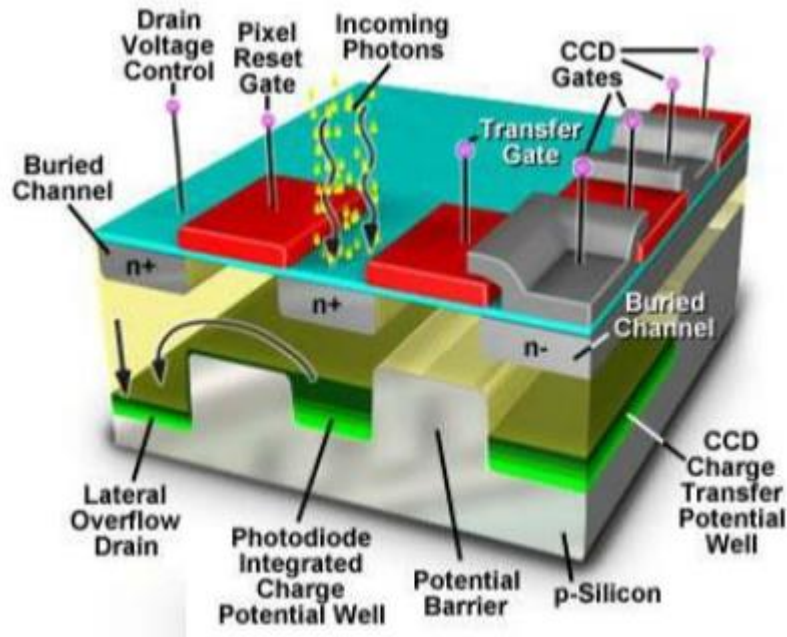


Figure 3.26: Anatomy of CCD sensor

3.7.2 Operation of a CCD sensor

- When a photon of light hits a pixel in the CCD sensor, it generates electrons in the photosensitive cell. More photons mean more of electrons
- Electrons are stored in charge wells located below each pixel
- To read the stored information, an electrical signal is applied to each array of pixels, causing the electrons to transfer from one pixel to another on row length. This transfer is made via displacement devices charges
- Once the electrons are transferred out of the CCD sensor, they are amplified and converted to digital signals to form an image [11].

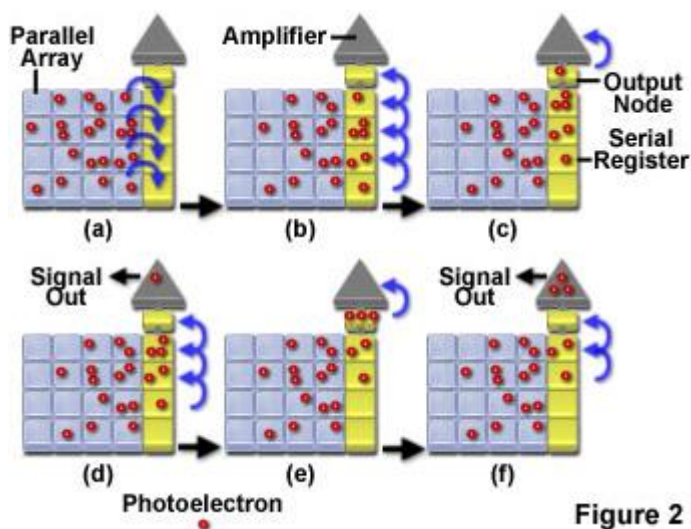


Figure 2

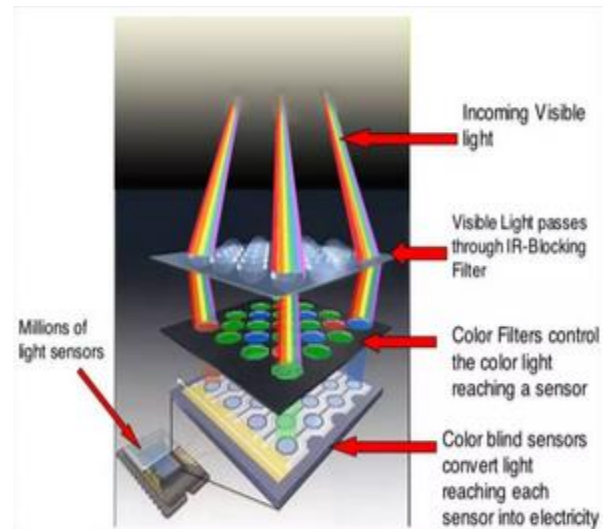


Figure 3.27: operation of a CCD sensor.

3.8 Applications of CCD sensors

- Digital photography Digital cameras traditional CCD sensors for their image quality.
- Astronomy Telescopes and astronomical cameras often use CCD sensors to capture images of the sky.
- Electron microscopy CCD sensors are used for imaging in high-resolution electron microscopy resolution.
- Life sciences: They are used in microscopy and Imaging of biological cells and tissues.

4 Chapter 4: Application examples (Optical Sensors and Photovoltaic Generators)

4.1 Motion Sensor (Fork Optocoupler)

A fork optocoupler is a type of optical sensor designed for motion and object detection. It consists of an infrared emitter and a receiver positioned opposite each other in a U-shaped structure. When an object moves through the gap between the emitter and receiver, it interrupts the infrared beam, causing a change in the output signal. This interruption is used to detect motion or the presence of an object. Fork optocouplers are widely used in automation, such as conveyor systems, counting applications, and safety mechanisms, ensuring precise detection without physical contact. Their fast response time and high reliability make them essential in industrial environments where speed and accuracy are critical.

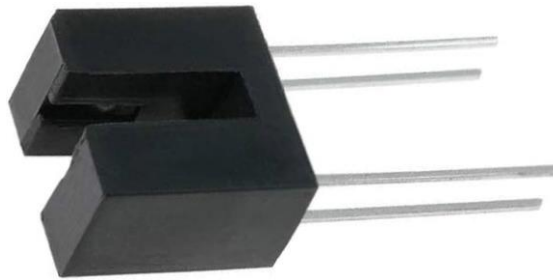


Figure 4.1: motion sensor

4.2 Optocoupler for Galvanic Isolation

Optocouplers are electronic components used for galvanic isolation between circuits, allowing signal transmission without direct electrical connection. They consist of an LED and a phototransistor or photodiode enclosed in a single package. The LED emits light when an electrical signal is applied, which is then detected by the phototransistor, activating the output circuit. This design ensures complete electrical isolation, protecting low-voltage control circuits from high-voltage fluctuations, noise, and transients. Optocouplers are extensively used in power electronics, microcontroller interfaces, and industrial automation systems where electrical safety and signal integrity are crucial [13].

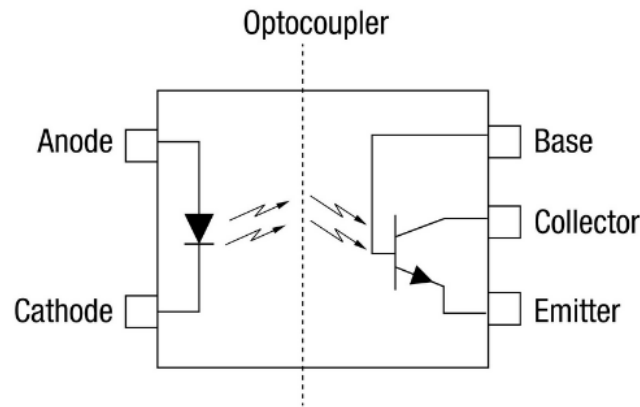


Figure 4.2: Optocoupler

4.3 Luminescence Detector

A luminescence detector is an optical sensor that identifies materials emitting light when exposed to ultraviolet (UV) or infrared radiation. Certain substances, such as phosphors and fluorescent markers, absorb this radiation and emit visible light, allowing detection even in low-light conditions. These detectors are widely used in quality control, counterfeit detection, and forensic analysis, where invisible markings or coatings need to be identified. In industrial applications, luminescence sensors are employed for detecting labels, adhesives, and chemical residues in production lines, ensuring high precision and reliability in automated processes [14].

4.4 Contrast Detector

Contrast detectors are used to distinguish between light and dark areas on a surface, making them valuable in high-speed industrial applications such as printing, packaging, and material handling. These sensors operate by analyzing the intensity of reflected light from an object, enabling the detection of edges, marks, and patterns. In the packaging industry, for instance, contrast detectors ensure that labels are accurately placed and that cutting machines align correctly with printed marks. Their ability to quickly and precisely identify contrast variations enhances efficiency and reduces errors in automated processes [15].

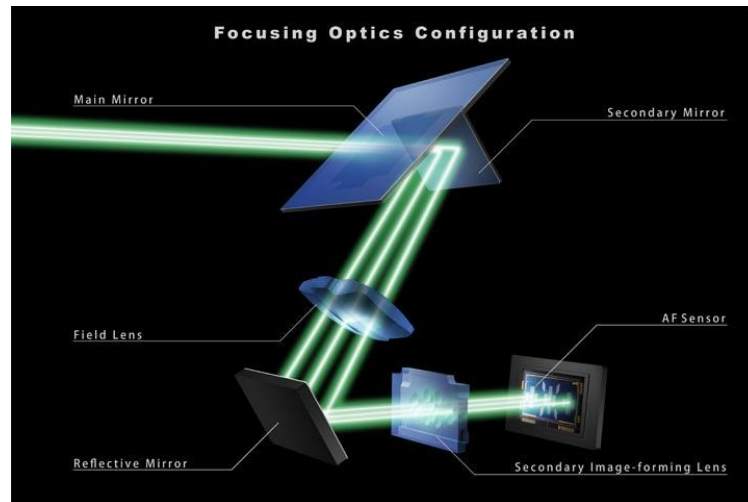


Figure 4.3: contrast autofocus detection

4.5 Color Detector

Color detectors analyze the intensity of red, green, and blue (RGB) light reflected from an object to determine its color. These sensors are essential in industries where color differentiation is critical, such as textile manufacturing, food sorting, and pharmaceutical packaging. By comparing the reflected light with pre-set color references, the detector can identify and classify objects based on their color properties. In automated sorting systems, for example, color sensors help separate products, detect defective items, and ensure consistency in production. Their high precision and adaptability make them indispensable in modern automation and quality control systems [16].



Figure 4.4: Color detection

4.6 Photovoltaic Generator

A photovoltaic generator is a device that converts sunlight into electrical energy using the photovoltaic effect. It consists of solar cells made from semiconductor materials, such as silicon, that generate an electric current when exposed to light. These generators are widely used in renewable energy systems, powering homes, industries, and remote locations.

Photovoltaic technology is a sustainable alternative to fossil fuels, reducing environmental impact and providing an independent energy source for off-grid applications. With advancements in efficiency and storage capabilities, photovoltaic generators are becoming increasingly essential in the transition toward clean and renewable energy solutions [17]

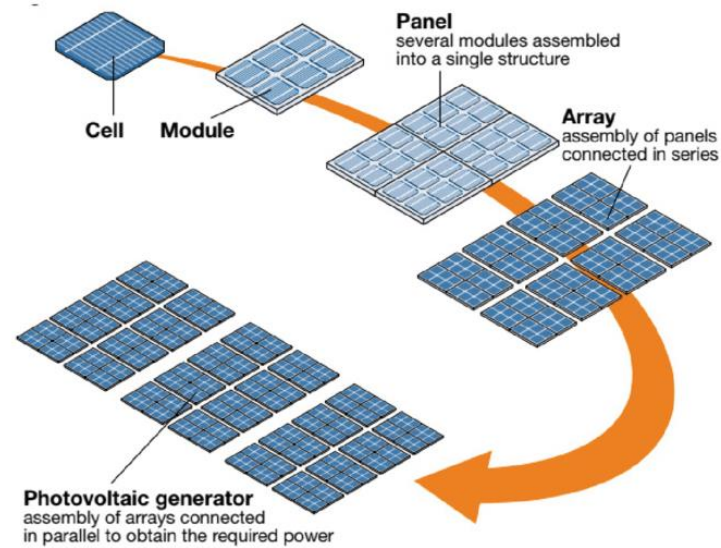


Figure 4.5: photovoltaic generator.

5 Chapter5: Optical fibers

5.1 Introduction to Optical Fiber

Optical fiber is a revolutionary technology that enables high-speed data transmission through light signals. It is widely used in telecommunications, medical applications, and industrial automation. Optical fibers are thin strands of glass or plastic that guide light through the principle of total internal reflection, ensuring efficient and long-distance data transfer with minimal loss [18].

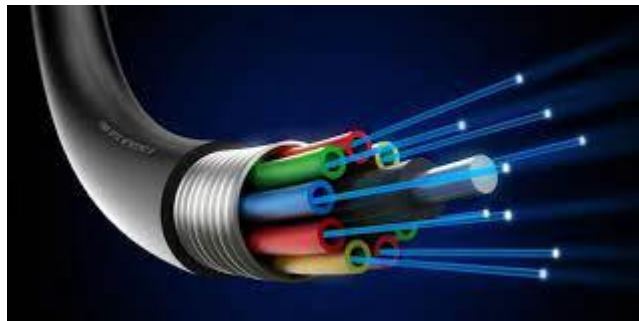


Figure 5.1: optical fiber.

5.2 Structure and Working Principle

An optical fiber consists of three primary components:

- **Core:** The central part where light travels. It is made of highly transparent glass or plastic.
- **Cladding:** A surrounding layer with a lower refractive index than the core, ensuring that light remains confined within the core due to total internal reflection.
- **Buffer Coating:** A protective outer layer that shields the fiber from mechanical damage and environmental effects [3].

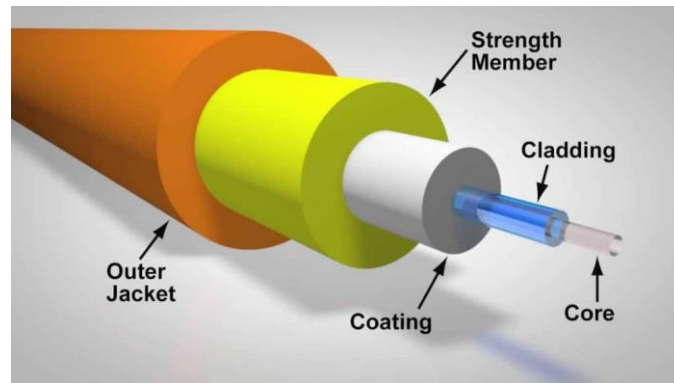


Figure 5.2: Optical fiber concept

Light propagates through the fiber by continuously bouncing off the core-cladding interface. This principle, known as total internal reflection, allows the fiber to carry signals over long distances with minimal attenuation [3, 18].

5.3 The propagation of light in optical fibre.

The light propagates through optical fibre through “Total internal reflection”. The total internal reflection appears due following reasons.

- When light traverse from optically rarer medium (like air) to denser medium (glass) the refracted ray moves towards the normal drawn on the interface of media as in Snell’s law. Conversely, if light traverse from denser to optically rarer medium, the refracted ray moves away from the normal drawn on the interface of the medium fig. (1a)
- If the angle of incidence increases (fig.1b), to certain value for which the refracted ray happen to be on the interface of medium. The angle of incidence s known as critical angle (θ_c) (fig.1c).
- If the incident angle (fig.1d) increases more than critical angle, then the refracted ray falls on the same denser medium with no refraction. “This reflection of light is called total internal reflection”. Thus, following are the conditions for total internal reflection:
 1. The ray of light should be traverse from denser to rare medium.
 2. The incident angle should be more than the Critical angle ($\theta_i > \theta_c$).

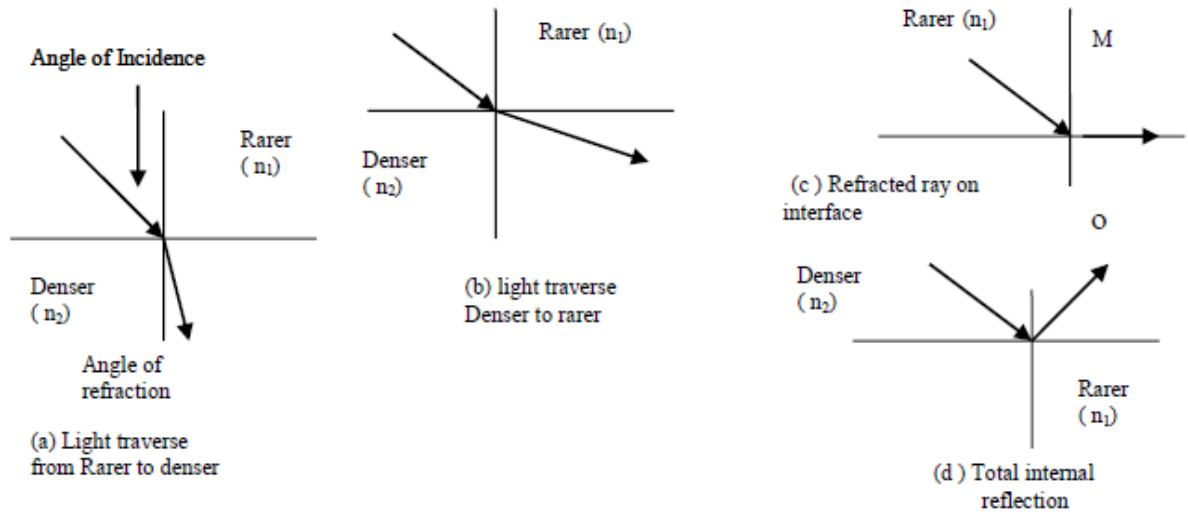


Figure 5.3: propagation of light from rarer to denser medium

Total internal reflection

If the incident ray exceeds the critical angle, the refraction would be turned in to reflection called total internal reflection. The critical angle is used for the mathematical expression to the occurrence of total internal reflection (fig.1c) [19]:

$$n_1 \sin \Theta_i = n_2 \sin 90^\circ \quad (\text{from Snell law}) \quad (5.1)$$

$$\sin \Theta_i = \frac{n_2}{n_1} \quad \text{since, } \sin 90^\circ = 1 \quad (5.2)$$

$$\sin \Theta_c = \frac{n_2}{n_1} \quad \text{since, } \Theta_i = \Theta_c$$

$$\Theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right) \quad (5.3)$$

Therefore, to propagate the light through optical fibre, the incident angle should be made higher than the critical angle at various points on the core, so that the light can be traversed by the total internal reflection at those points [18, 19].

To achieve the above, the size of core should be adjusted suitably which causes different types of optical fibre based on size, (no. of modes) refractive index and modes of propagation.

5.4 Optical Fibers classification

Optical fibers can be classified based on their mode and material composition:

5.4.1 Based on refractive index:

The types of optical fibre can be classified based on the refractive index are:

1. Step index fibres.
2. Graded index fibres.

5.4.1.1 Step index

If the refractive index of core remains the same from the centre of the core to the core-cladding interface; those optical fibres are known as step index fibres (fig.2a). The distance from centre of core to interface of fibre vs. refractive index is shown as below [19]:

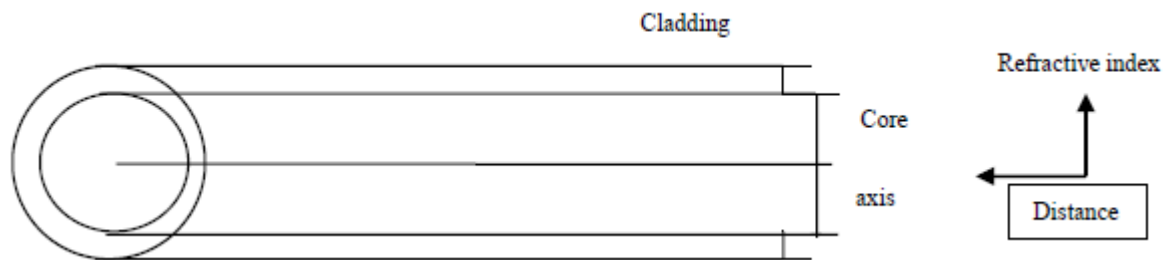


Figure 5.4: Step Index fibre profile

5.4.1.2 Graded index

These types are made of varying refractive index of core material. Therefore, the refractive index changes with distance from the centre of fibre to core-cladding interface. The profile of above is as shown in the fig 5.5 [19]:

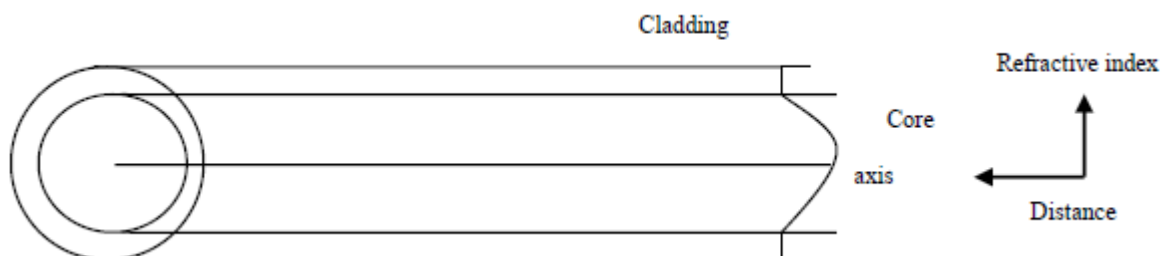


Figure 5.5: Graded Index fibre profile

5.4.2 Based on Mode of propagation

- *Single-Mode Fiber (SMF)*: Has a small core diameter (typically 8-10 microns) and supports only one light mode, allowing long-distance communication with minimal dispersion.
- *Multi-Mode Fiber (MMF)*: Has a larger core diameter (50-62.5 microns) and supports multiple light paths, making it suitable for short-distance communication [12].

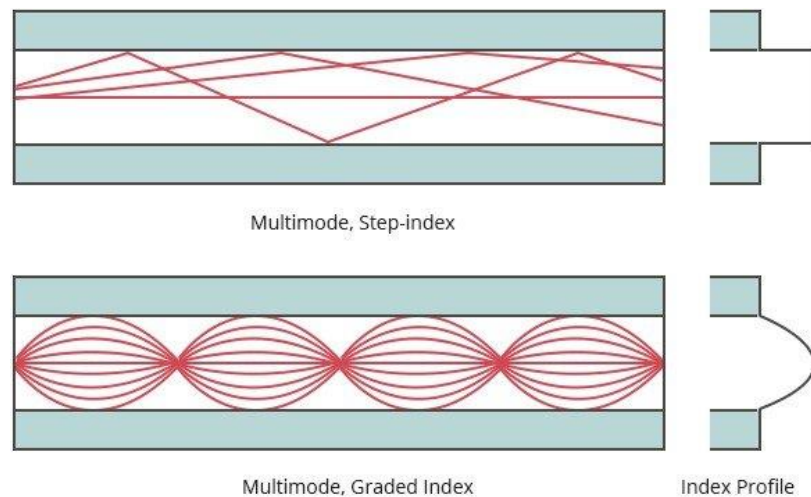


Figure 5.6: SMF and MMF optical fiber.

5.4.3 Based on Material

- **Glass Fiber:** Glass made fibre is also fabricated from flexible glass as core with suitable drawing technique in presence of impurities. Therefore, the above types of optical fibres are limited to some application.
- **Plastic Optical Fiber (POF):** The plastic made fibres are obtained from polymers of transparent to light, flexibility and interaction less to light etc. For example poly methyl metha acrylate (PMMA), polyethylene (PE), polystyrene (PS) are used as core materials [18].

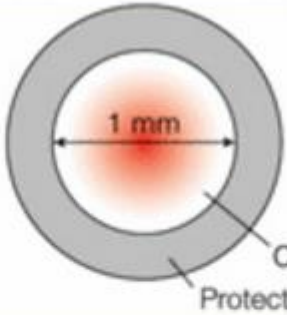
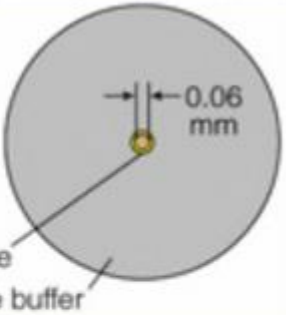
	Plastic optical fiber	Multimode glass fiber
		
Material	Plastic (PMMA)	Glass
Core diameter	1 mm	0.062 mm
Numerical aperture	0.5	0.275
Attenuation	200 dB/km (@650 nm)	2.9 dB/km (@850 nm)
Link length@100 MBit/s	100 m	2 km
Bandwidth	~10 MHz*km	200 MHz*km

Figure 5.7: Glass and POF optical fiber.

5.4.4 Combination of optical fibres

The refractive index of core and mode of propagation of light in optical fibre is used to form combination types of optical fibre.

- Step index-single mode fibres
- Step index-multi mode fibres
- Graded index-Single mode fibres
- Graded index-Multi mode fibres

5.5 Parameters of optical fibres

The parameters of optical fibres are:

- Radius of the core
- Numerical Aperture
- Acceptance angle

5.5.1 Radius of the core

The size of optical fibres plays crucial role in the light wave propagation through fibre. Therefore, radius of the core is significant to decide mode of propagation in fibre. The thickness/diameter of the core can be measured in spite of measurement of radius. For the purpose the profile projector can be used [19].

5.5.2 Numerical aperture (NA)

Numerical aperture (NA) is a light gathering property of optical fibre, which gives the quantity of light that brought into the centre of optical fibre in terms of incidence angle. To calculate NA, consider a longitudinal section of fibre as in fig. (3). Let n_0 , n_1 , n_2 are the refractive indices of air (outside optical fibre), core and cladding respectively [19].

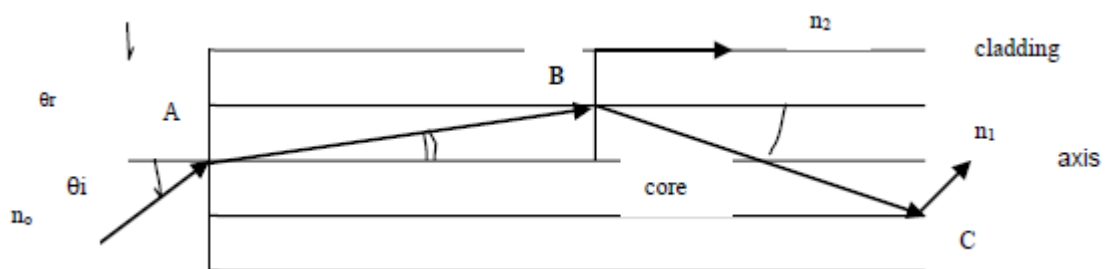


Figure: 5.8: Longitudinal Section of optical fibre.

θ_i , θ_r are incidence angle and refracted angle of the light through fibre.

Applying Snell's law at A:

$$n_0 \sin \theta_i = n_1 \sin \theta_r$$

$$\sin \Theta_i = \frac{n_1}{n_0} \sin \Theta_r = \frac{n_1}{n_0} \sqrt{1 - (\cos^2 \Theta_r)}$$

Applying Snell's law at B:

$$n_1 \sin (90 - \Theta_r) = n_2 \sin 90^\circ$$

$$n_1 \cos \Theta_r = n_2$$

$$\cos \Theta_r = \frac{n_2}{n_1}$$

Substituting (2) in (1):

$$\sin \Theta_i = \frac{n_1}{n_0} \sqrt{1 - \left(\frac{n_2^2}{n_1^2}\right)} = \frac{n_1}{n_0} \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

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

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

$$\text{Or: } NA = \sin \Theta_i = \sqrt{n_1^2 - n_2^2} \quad (\text{where } n_0 = 1 \text{ for air}) \quad (5.4)$$

5.5.3 Acceptance angle

It is a semi vectorial angle that formed by the set of incident rays at the centre of fibre, which helps to decide the size of core.

From:

$$NA = \sin \Theta_i = \sqrt{n_1^2 - n_2^2}$$

$$\sin \Theta_i = \sqrt{n_1^2 - n_2^2}$$

$$\Theta_i = \sin^{-1} (\sqrt{n_1^2 - n_2^2})$$

Replacing: $\Theta_a = \sin^{-1} (\sqrt{n_1^2 - n_2^2}) = \sin^{-1} (NA)$

5.6 Advantages of Optical Fiber

- **High Bandwidth:** Supports significantly higher data rates compared to traditional copper cables.
- **Low Attenuation:** Allows signals to travel long distances without much loss.
- **Immunity to Electromagnetic Interference:** Optical fibers are not affected by electromagnetic signals, making them ideal for industrial and medical applications.
- **Lightweight and Flexible:** Easier to install and handle compared to bulky copper cables.
- **Enhanced Security:** Optical fibers do not radiate signals, reducing the risk of eavesdropping [18].

5.7 Applications of Optical Fiber

A. Telecommunications

Optical fiber forms the backbone of modern internet and telecommunication networks, enabling high-speed broadband, fiber-to-the-home (FTTH) services, and undersea data transmission [18].

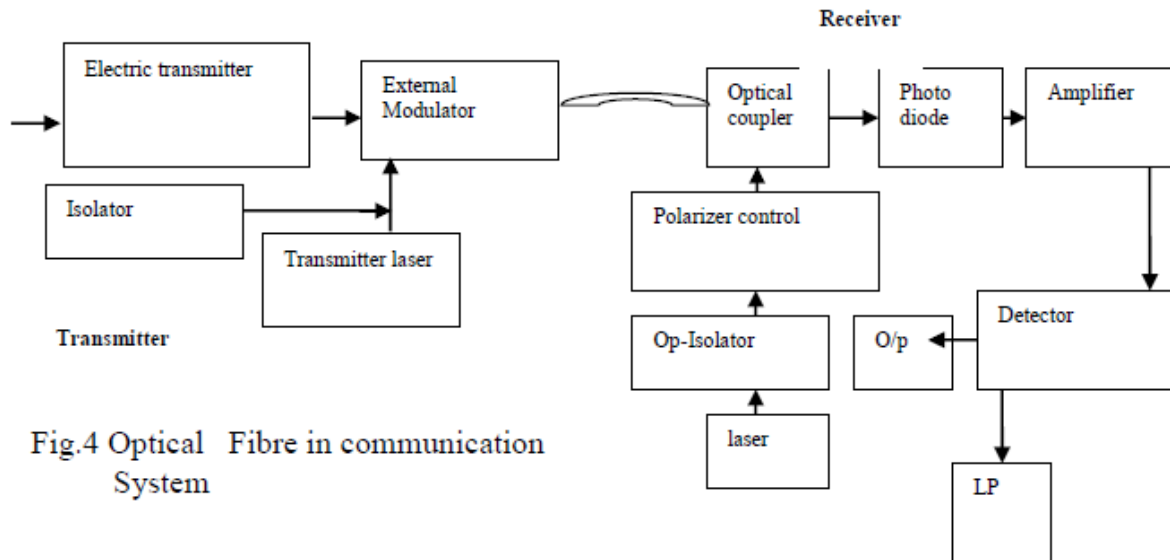


Fig.4 Optical Fibre in communication System

Figure 5.9: optical fiber in telecommunication.

B. Medical Applications

Used in endoscopy, laser surgeries, and biomedical imaging due to its flexibility and ability to transmit light in confined spaces.

C. Industrial and Military Uses

Employed in industrial sensors, aerospace, and military communication systems for secure and reliable data transmission.

D. Data Centers and Cloud Computing

Supports high-speed connections in data centers, enabling efficient cloud computing and large-scale data processing [3, 19]

5.8 Some losses in optical fibres

The optical fibre does not experience the loss in terms of intensity of light. However, the presence of impurities, scattering at the edges, geometry of structure and dispersion of light causes some losses.

5.8.1 Transmission loss/attenuation (α)

If the intensity of light at the second end of the optical fibre be I_{out} and intensity at first end be I_{in} .

The attenuation is expressed as follows:

$$\alpha = -\log \left(\frac{I_{out}}{I_{in}} \right)$$

In decibel the attenuation:

$$\alpha = -\frac{10}{L} \log \left(\frac{I_{out}}{I_{in}} \right) \text{ dB} \quad (5.5)$$

5.8.2 Other possible losses in optical fibre

The possible losses are absorption, scattering, radiation losses and geometric losses.

The absorption loss. The absorption losses appears as:

- Extrinsic losses
- Intrinsic losses
- Atomic defect losses

5.8.2.1 Extrinsic losses

The extrinsic loss appears due to presence of impurities which absorbed the light. The impurities may be due to presence of Fe, Cr, Co and Cu in the core material. The impurities could absorb the energy that may reemit the absorbed energy during the de excitation in different wavelength which causes loss of intensity to original light of specific wavelength.

5.8.2.2 Intrinsic loss

Since, the fibre core itself absorbs some quantity of energy which is known as intrinsic loss [18].

5.8.2.3 Scattering and radiation losses

Since, optic fibre contains glass as core, where impurities are present. The scattering of light at these impurities causes Rayleigh scattering where the energy of scattered wave directly proportional to 4th power ($E=1/\lambda^4$) of wavelength. Therefore, small change of energy causes 4th power of wavelength. The loss of energy at couplers and interfaces are known as radiative losses.

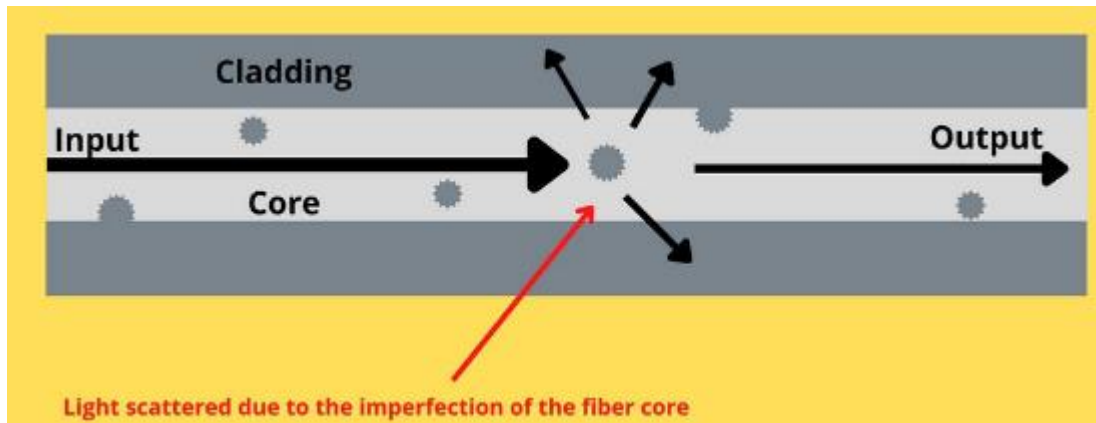


Figure 5.10: Light scattering losses.

5.8.2.4 Geometrical loss

Due to bending of optical fibres there are 2 types of losses from macroscopic bending and microscopic bending. If the fibre be rounded as big circle of known radius of curvature, the loss may be less called macroscopic bending loss.

For small bending of fibre the loss of energy in microscopic bending is larger. Sometime the irregularities in the dimensions cause geometrical losses [18].

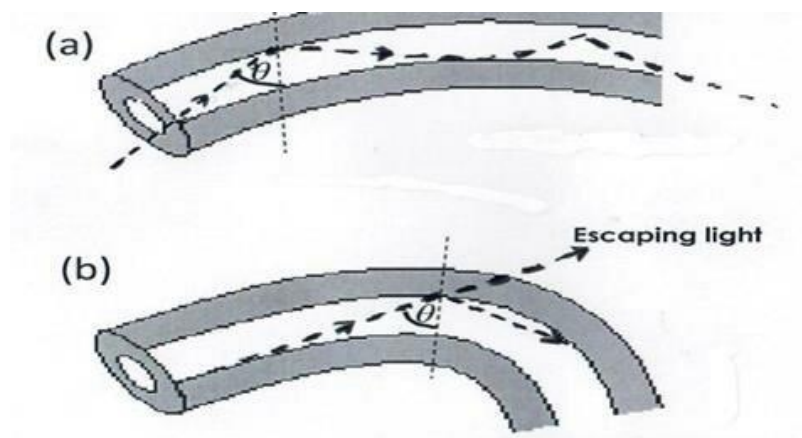


Figure 5.11: Geometrical illustration of macroscopic bending losses in optical fiber.

5.8.2.5 Dispersion loss

In the transmission of light through optical fibres the pulse width varies due to dispersion of light through the core. The loss of intensity caused as result of dispersion of light is due to:

- Material dispersion
- Waveguide dispersion
- Inter modal dispersion [18]

5.8.2.6 Material dispersion

The refractive index of core causes the changes in the wavelength/frequency called material dispersion. If narrow pulse passes through fibre, causes broadening of pulse width due to material property. It can be overcome by highly monochromatic source of light. The single mode fibre could reduce the material dispersion to maximum extent [18, 19, 20].

5.8.2.7 Waveguide dispersion

The optical fibre can be considered as circular wave guide where refractive index varies with modes of propagation with wavelength causes wave guide dispersion.

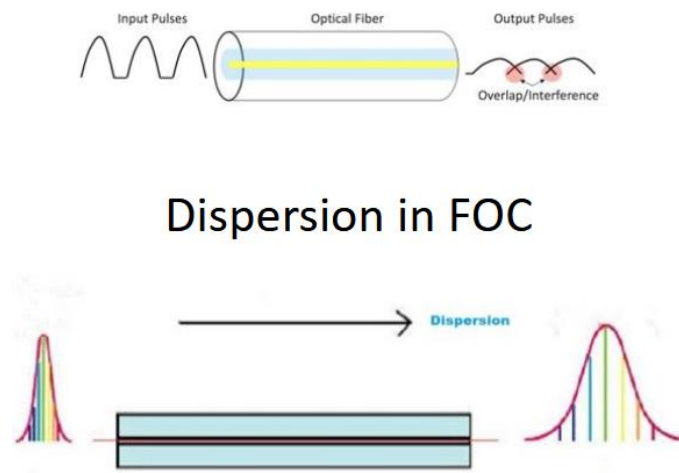


Figure 5.12: dispersion in optical fiber sensor.

5.8.2.8 Intermodal dispersion

The optical power in the pulsed wave distribution over the mode of light through the fibre decreases during the propagation, these changes are known as intermodal dispersion [19, 20].

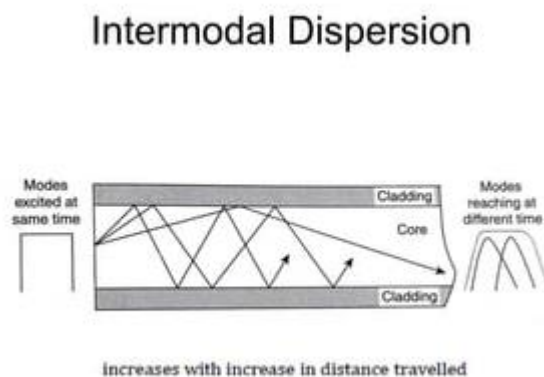


Figure 5.13: Intermodal dispersion.

5.9 Optical fibres as sensor

Generally, optic sensor consists of light source, optical fibres and detector. The sensors are two types viz., active sensors and passive sensors. The physical changes directly changes the electrical responses called active sensors; whereas the physical changes are indirectly recorded to sensing is called passive sensors [18].

5.9.1 Temperature sensor

The light can be arranged to fall on reflecting surface and the associated phase angle is be measured. The reflecting surface can be varied using temperature variation, which causes additional phase angle to light wave as seen in the fig.5. When light thrown on the reflector by optical fibre, the initial and final response can be compared for measure of temperature by relative correlation [1, 19, 20].

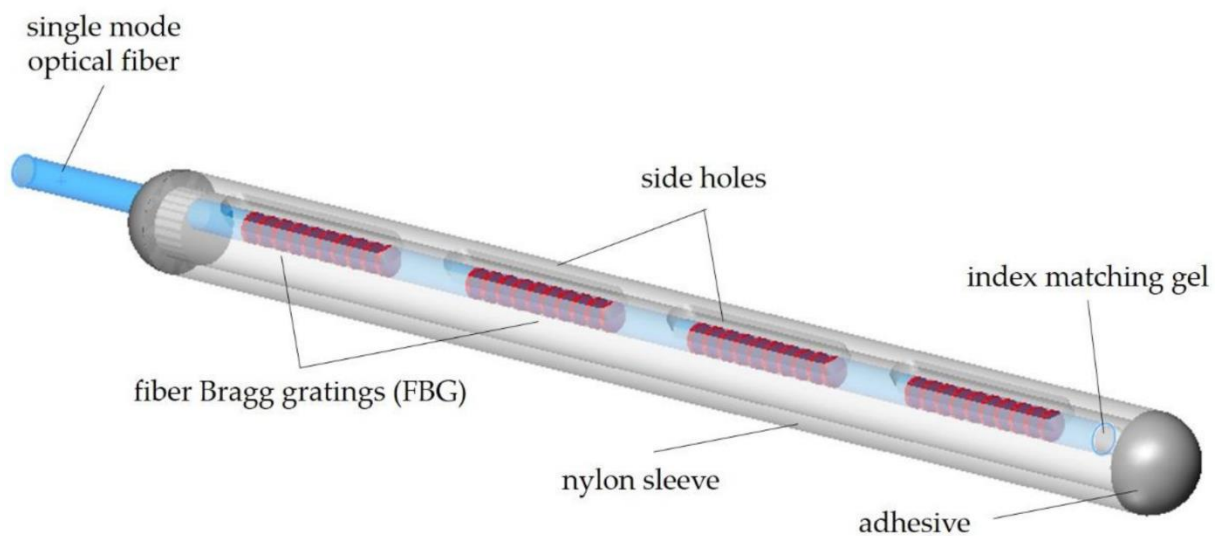


Figure 5.14: optical fiber sensor displacement.

5.9.2 Displacement sensor

The light is sent through transmitting fibre and further it is allowed to fall on moving target. The light ray falls on the surface and gets reflected. The incident ray could mix with reflected wave and forms standing wave to which the phase angle shift can be measured. The figure below indicates displacement sensors [19].

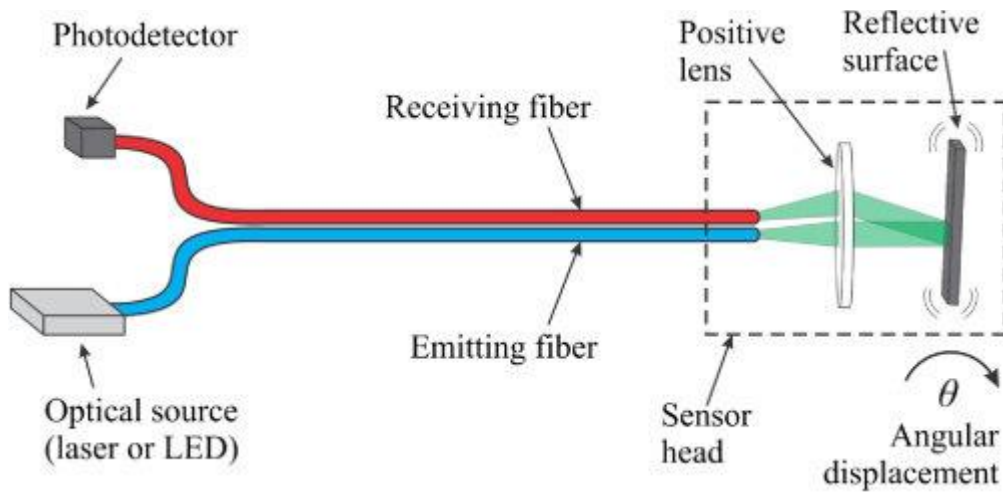


Figure 5.15: Displacement fiber sensor.

5.10 Challenges and Future Developments

Despite its numerous advantages, optical fiber technology faces challenges such as high installation costs and susceptibility to physical damage. However, ongoing advancements in fiber optics, including hollow-core fibers, photonic crystal fibers, and quantum communication, promise to further revolutionize data transmission and networking.

5.11 Conclusion

Optical fiber has transformed global communication, providing high-speed, secure, and efficient data transmission across various industries. As technology advances, fiber optics will continue to play a crucial role in shaping the future of digital communication and connectivity.

General conclusion

Throughout this lecture, we have explored the fundamental principles of light interaction with semiconductors and their crucial role in optoelectronic devices. We began by understanding the nature of light and how it interacts with semiconductor materials, leading to various phenomena such as the photoelectric and photovoltaic effects. These interactions form the foundation of light-emitting devices, such as LEDs and laser diodes, which are essential in modern technology, ranging from everyday lighting to high-speed communication systems.

We then examined light detection technologies, including photodiodes, phototransistors, and photovoltaic cells, which enable a wide range of applications in sensing, imaging, and solar energy conversion. Additionally, we explored the practical applications of optical sensors in automation, industrial systems, and renewable energy.

Finally, we delved into optical fiber technology, which has revolutionized data transmission by providing high-speed, low-loss communication networks. The study of fiber optics highlights the importance of minimizing attenuation and dispersion to ensure efficient signal transmission over long distances.

In summary, optoelectronics is a rapidly evolving field that bridges physics, engineering, and technology. Its applications span across telecommunications, medical imaging, renewable energy, and advanced electronics. As research continues, innovations in semiconductor materials, light sources, and detectors will further enhance the efficiency and capabilities of optoelectronic systems, paving the way for the future of high-performance optical technologies.

6 Bibliographie

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Abstract

This lecture offers a comprehensive overview of optoelectronics, a field that merges optics and electronics to exploit the interaction between light and matter in various semiconductor devices. The lecture begins by revisiting the fundamental properties of light—such as its dual wave-particle nature—and the electronic behavior of semiconductors, which form the foundation of optoelectronic devices.

A significant portion of the lecture is dedicated to explaining how semiconductors emit and detect light. It details the physical principles behind electroluminescence, photon absorption, and the photovoltaic effect. Key components such as light-emitting diodes (LEDs), laser diodes, and photodetectors (including PIN photodiodes and avalanche photodiodes) are examined both in terms of structure and function.

The lecture further explores the real-world applications of these devices in fields such as fiber-optic communication, medical diagnostics, imaging technologies, and environmental sensing. It also emphasizes the importance of materials science in the development of more efficient and specialized devices, such as those operating at specific wavelengths for infrared or ultraviolet applications.

Finally, the lecture touches on emerging trends in optoelectronics, including Nano photonics, integrated photonics, and quantum optoelectronics, highlighting the role of this rapidly evolving field in shaping the future of high-speed communication, computing, and sensing technologies.

Résumé

Ce cours propose une vue d'ensemble approfondie de l'optoélectronique, un domaine scientifique interdisciplinaire qui combine l'optique et l'électronique pour exploiter les interactions entre la lumière et la matière dans divers dispositifs à semi-conducteurs. La leçon débute par une révision des propriétés fondamentales de la lumière — notamment sa dualité onde-particule — ainsi que du comportement électronique des semi-conducteurs, qui constituent la base des dispositifs optoélectroniques.

Une grande partie du cours est consacrée aux mécanismes physiques par lesquels les semi-conducteurs peuvent émettre et détecter la lumière. Sont abordés en détail les principes de l'électroluminescence, de l'absorption photonique et de l'effet photovoltaïque. Les dispositifs majeurs comme les diodes électroluminescentes (LED), les diodes laser et les photo détecteurs (incluant les photodiodes PIN et à avalanche) sont étudiés tant au niveau de leur structure que de leur fonctionnement.

Le cours explore également les multiples applications pratiques de ces dispositifs, notamment dans les communications par fibre optique, le diagnostic médical, l'imagerie, et les capteurs environnementaux. Il met aussi en évidence l'importance des matériaux utilisés dans la conception de dispositifs toujours plus efficaces et adaptés à des plages spectrales spécifiques, telles que l'infrarouge ou l'ultraviolet.

Enfin, le cours aborde les tendances émergentes du domaine, comme la nano photonique, la photonique intégrée et l'optoélectronique quantique, en soulignant le rôle central de ces avancées dans l'avenir des technologies de communication, de calcul et de détection à haute performance.

الملخص

تقدم هذه المحاضرة نظرة شاملة على الإلكترونيات الضوئية، وهو فرع علمي يجمع بين علمي البصريات والإلكترونيات لاستغلال التفاعل بين الضوء والمادة في أجهزة أشباه الموصلات المختلفة. تبدأ المحاضرة بمراجعة الخصائص الأساسية للضوء، مثل طبيعته المزدوجة كموجة وجسيم، بالإضافة إلى السلوك الإلكتروني لأشباه الموصلات، والتي تشكل الأساس لأجهزة الإلكترونيات الضوئية.

تتناول المحاضرة بشكل موسّع كيفية إصدار الضوء وكشفه باستخدام أشباه الموصلات، حيث توضح المبادئ الفيزيائية للانبعاث الكهروضوئي، وامتصاص الفوتونات، والتأثير الكهروضوئي. كما تستعرض بالتفصيل أهم الأجهزة مثل الثنائيات (والثنائيات الانهيارية PIN بما في ذلك الثنائيات)، وثنائيات الليزر، والكواشف الضوئية (LEDs) الباعثة للضوء. وتستعرض المحاضرة تطبيقات هذه الأجهزة في مجالات متعددة مثل الاتصالات بالألياف البصرية، والتشخيص الطبي، وتقنيات التصوير، والاستشعار البيئي. كما تؤكد على دور علم المواد في تطوير أجهزة أكثر كفاءة وتخصصاً، مثل تلك التي تعمل في أطوال موجية محددة كالأشعة تحت الحمراء أو فوق البنفسجية.

وفي الختام، تسلط المحاضرة الضوء على الاتجاهات الحديثة في الإلكترونيات الضوئية، مثل الفوتونيات النانوية، والفوتونيات المتكاملة، والإلكترونيات الضوئية الكمومية، مشيرةً إلى الدور المحوري لهذا المجال في تشكيل مستقبل تقنيات الاتصال السريع، والحوسبة، والاستشعار.