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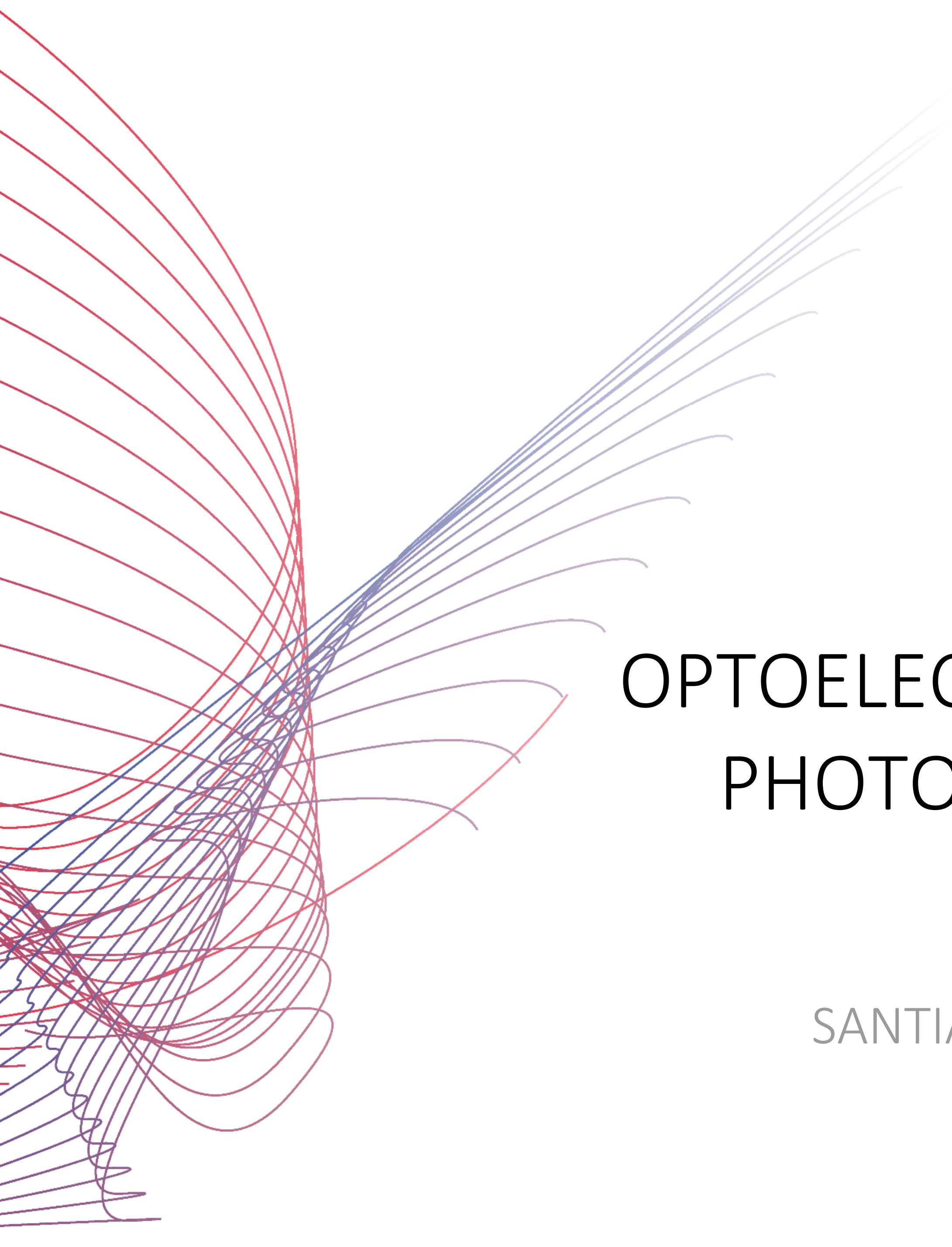

OPTOELECTRONICS, PHOTONICS AND SENSORS

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EXPLANATORY NOTES

$E=m\cdot c^2$	Definition
⚑	Interesting
i	Note
🧪	Example
🧩	Summary
+	Advantage
−	Disadvantage

ANNOTATION

This is an introductory course to optoelectronics. In the firsts chapters basic concepts on light transmission are introduced. Then, physical mechanisms related to optoelectronic devices are described in chapter four. Main optoelectronic devices are presented in chapter five. Finally chapter 6 and 7 describe the principles of fibre optic communications and main applications of optoelectronics.

OBJECTIVES

At the end of the study of this course the student will be able to understand basics on optoelectronics, important issues related to light transmission and identify main optoelectronic devices and applications.

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1 Introduction to Optoelectronics: History and fundamentals

This chapter describes some important highlights in the history of optoelectronics and also includes a short list of some important applications related to this field of physics.

Optoelectronics is a part of photonics science related to the study and application of electronic devices that interact with light, systems where electrons and photons coexist. Optoelectronic devices operate as electrical-to-optical or optical-to-electrical transducers.

Some highlights in optoelectronics history are the following:

- First observation of electroluminescence from SiC crystals was reported in the year 1907 by Captain Henry Joseph Round (England).
- Some decades later, in 1927, Oleg Vladimirovich Losev (Imperial Russia) observed light emission from zinc oxide and silicon carbide crystal rectifier diodes used in radio receivers when a current was passed through them [1].
- In 1961 Ali Javan (Bell Labs) invented the first gas or helium neon laser. One year later, Robert Hall invented the semiconductor injection laser.
- Nick Holonyak (USA) invented the first practically useful visible **LED** (***light emission diode***) in 1962.
- The first transmission trunk using glass fibres invented by Corning glass, and installed by AT&T in 1983, from New York to Washington, D. C., at 45 megabits per second.

Nowadays optoelectronics has become an emerging new technology. The optoelectronics market is growing every year worldwide, 30% growth every year since 1992.

Optoelectronics allows generating, transporting and manipulating data at very high rate. Main applications of optoelectronics are in the field of communications, including fibre optic communications and laser systems.

However, the applications of optoelectronics extend throughout our everyday lives, including the fields of computing, communication, entertainment, optical information systems, education, electronic commerce, environmental monitoring, health care and transportation.

Optoelectronics is also important in defense applications that include infrared imaging treatment, radar, aviation sensors, and optically guided weapons.

2 Optical Spectrum. Refraction, reflection, attenuation and dispersion

In this chapter, some basic equations are presented in the introduction in order to understand important concepts related with optoelectronics. After that, some important mechanisms of light transmission as refraction, reflection, attenuation and dispersion are introduced in this chapter. An important concept: TIR (total internal reflection), used in optical communications is also defined.

2.1 Introduction

Light as an electromagnetic wave is characterised by a combinations of time-varying **E** (*electric field*) and **H** (*magnetic field*) propagating through space according to the Maxwell equations introduced by James Clerk Maxwell in the late 19th century.

Light can be characterized using several spectral quantities, such as frequency, υ,

$\upsilon = \frac{\omega}{2\pi}$, where ω is the angular frequency or wavelength λ,

$\lambda = \frac{c}{\upsilon}$, being $\boldsymbol{c}$ the speed of light in vacuum

---

$E=m\cdot c^2$

$\boldsymbol{c}$ is a universal physical constant and its value is exactly 299 792 458 m/s.

Usually a value of c= 3 10^8 m/s is used as a good approximation.

In any other medium different of vacuum, the light phase velocity, v (the speed at which the crests or the phase of the wave moves), depends on the refractive index, n, of the medium as follows [2] :

$v = \frac{c}{n}$, where n can be defined by the following equation:

$n = \sqrt{\varepsilon_r \mu_r}$, being ε_r and μ_r the relative electrical permittivity and magnetic permeability of the medium respectively [3]. The refractive index is a function of the wavelength.

The relationships among electricity, magnetism, and the speed of light in a medium are summarized by the following equation:

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}}$$

$E=m\cdot c^2$

Wave-particle duality: Every elementary particle or quantic entity exhibits the properties of not only particles, but also waves. Electromagnetic radiation propagates following linear wave equations, but can only be emitted or absorbed as discrete elements: **Photons**, thus acting as a wave and a particle simultaneously.

The energy of a photon, E, is proportional to its frequency,υ, and can be calculated by using the Planck–Einstein relation also known as Planck equation [4] :

$$E = h\upsilon = h\frac{c}{\lambda}$$

where h is the Planck's constant, $h = 6.62\cdot10^{-34}$ Js or $4.1356\cdot10^{-15}$ eVs.

The constant: $hc = 1.24$ eVμm.

The value of the relative permittivity of silica (silicon dioxide: SiO_2) is $\varepsilon_r = 3.9$, and the relative magnetic permeability of SiO_2 is $\mu_r = 0.53$. Calculate the refractive index of silica.

SOLUTION

The refractive index of SiO_2 is: $n = \sqrt{\varepsilon_r \mu_r} = 1.4377$

2.2 Optical Spectrum

The optical spectrum is a small part of the electromagnetic spectrum. Human eyes can detect lights of wavelength in the range of 450 nm to 650 nm. This part of the electromagnetic spectrum is called optical spectrum or visible light. Figure 1 shows the electromagnetic spectrum and the colours associated to the optical spectrum.

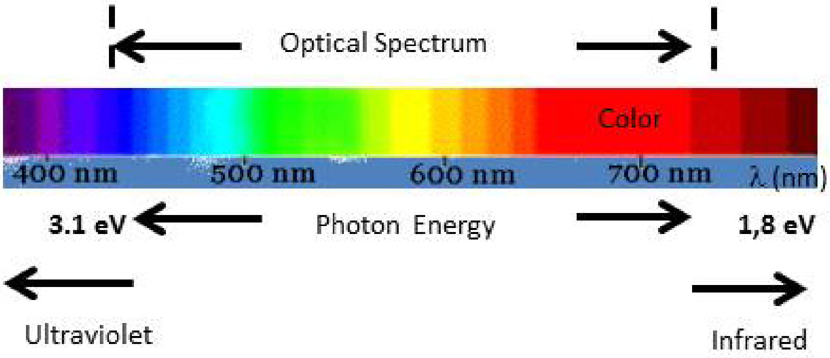

Fig. 1. Optical spectrum.

2.3 Refraction, reflection, attenuation and dispersion

When light reaches the plane boundary between two media, a transmitted light in medium 1 and a reflected light in medium 1 appear. The transmitted light is the refracted light. The angles associated to the directions of the transmitted, refracted and reflected light are shown in Fig.2.

The angle of incidence, φ_1, is equal to the angle of reflection angle φ_3.

Refraction is the changing direction of light when it goes into a material of different refractive index, *n*.

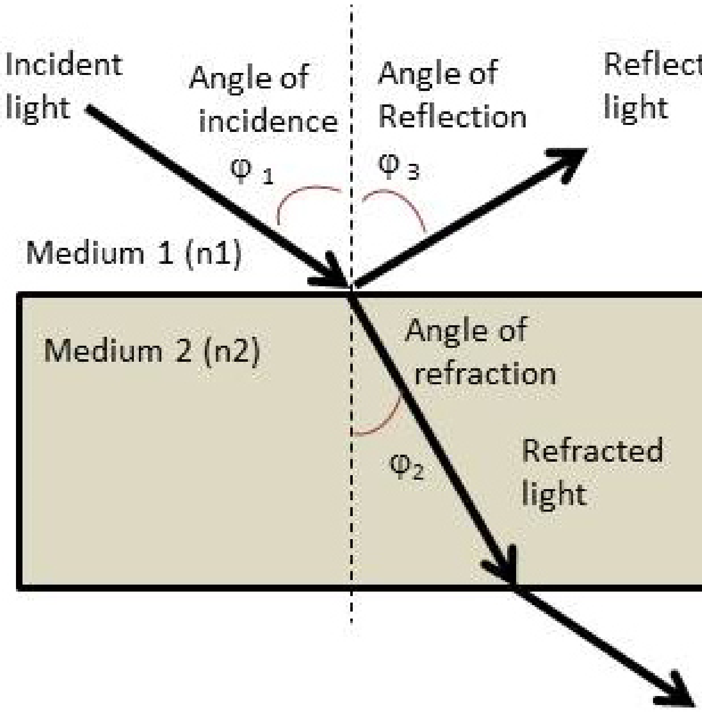

Fig. 2. Refraction and reflection angles.

Snell's law gives the relationship between the sine's of the incident and refraction angles and the refractive indexes of the media as follows:

$$\frac{\sin(\varphi_1)}{\sin(\varphi_2)} = \frac{n_2}{n_1}$$

For angles larger than the critical angle we have **TIR** (***total internal reflection***) [5]. Critical Angle, φ_{1c} , occurs at $\varphi_2 = 90^\circ$.

$$\varphi_{1c} = \arcsin\left(\frac{n_2}{n_1}\right)$$

If the light hits the interface between two media at any angle larger than this critical angle, it will not pass through to the second medium at all. Instead, all of it will be reflected back into the first medium, a process known **TIR**. This principle is applied by traditional waveguides as optical fibres and is shown by Fig.3.

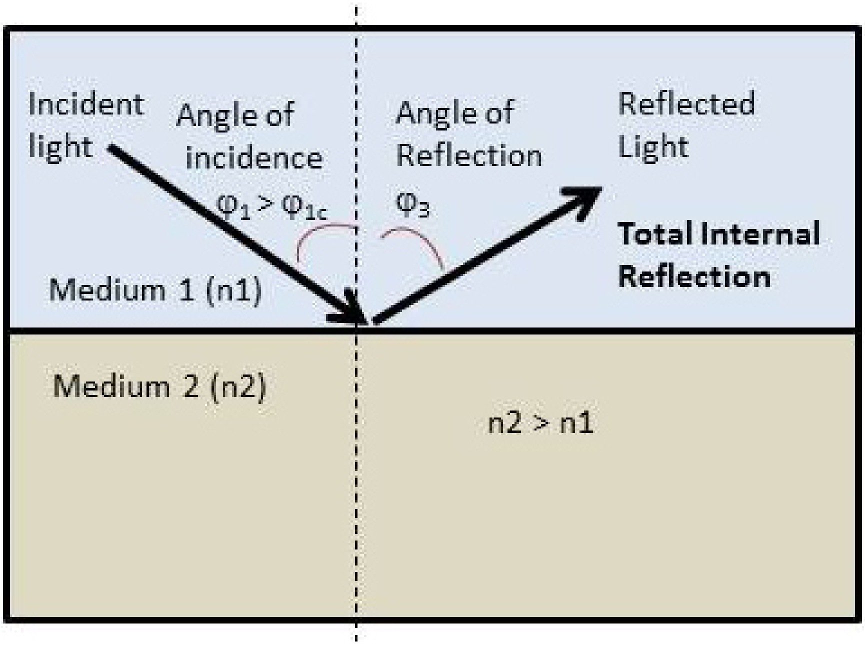

Fig. 3. TIR effect.

Light of different frequencies propagate at different speeds through the medium. Moreover, the refractive index depends on the wavelength. Due to these effects, some dispersion appears in the medium.

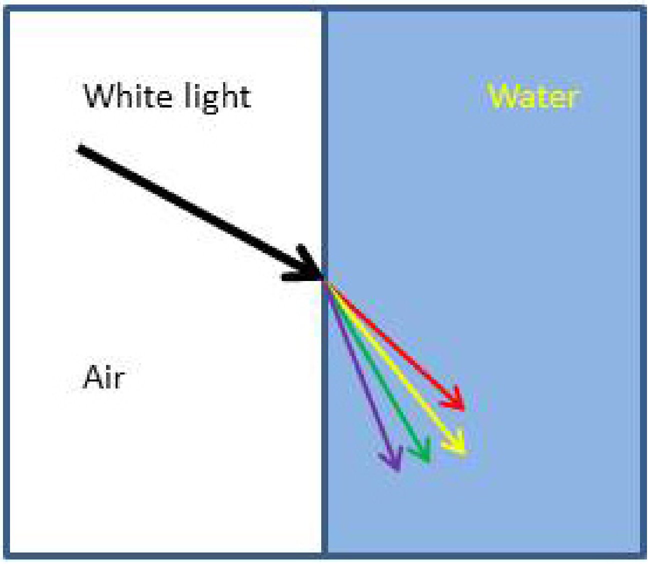

Fig. 4. Dispersion effect.

Attenuation is the loss of the optical power. Attenuation is mainly due to absorption and scattering that give rise to a loss of energy in the direction of propagation. The specific attenuation: Power loss in dB per unit length, depends on the wavelength of the radiation travelling along the medium. The attenuation coefficient, α, is given by the following equation

$$\alpha = \frac{10}{L}\log\left(\frac{P(L)}{P(0)}\right)$$

where $P(0)$ is the initial power or incident power, $P(L)$ is the power at a distance L from the initial point.

Consider a ray of light traveling in a medium of refractive index $n_1 = 1.44$ becomes incident on a second medium of refractive index $n_2 = 1.4$. The wavelength of the light is 1.1 µm.

Calculate the incident angle to have TIR.

SOLUTION

Snell's Law: $\frac{\sin(\varphi_1)}{\sin(\varphi_2)} = \frac{n_2}{n_1}$

Critical Angle, φ_{1c} , occurs at $\varphi_2 = 90\,^{\mathrm{o}}$, then $\varphi_{1c} = \arcsin\left(\frac{n_2}{n_1}\right) = \arcsin\left(\frac{1.4}{1.44}\right) = 76.5\,^{\mathrm{o}}$

3 Light transmission, sources and detectors

In this chapter, main sources of light and detectors commonly used in optical communication systems are presented. Optical communications offer important advantages respect to conventional communications supported by copper wires. Some of these advantages are introduced in this chapter.

3.1 Introduction

Optical communication systems transmit information by means of light. Compared to copper wire used in electrical communications, optical fibres have lower cost, weigh less, have less attenuation and dispersion and provide more bandwidth. Optical fibre can support ultra-high data rates: Terabits per second and can be used to transmit light and thus information over long distances. Moreover, there are no problems associated to **EMC** (***Electromagnetic Compatibility***) interference immunity and there is no fire hazard because of the pass of electricity through the communication channel is eliminated.

Figure 5 shows the typical block diagram of an optical communication system. The electrical signal (information) controls the source of light; the light emitted by the source is coupled to the transmission channel: Optical fibre, waveguide or free space. The light is transmitted through the transmission channel up to the light detector that is coupled with the channel. The light detector transforms the light into electrical signal and the information is received.

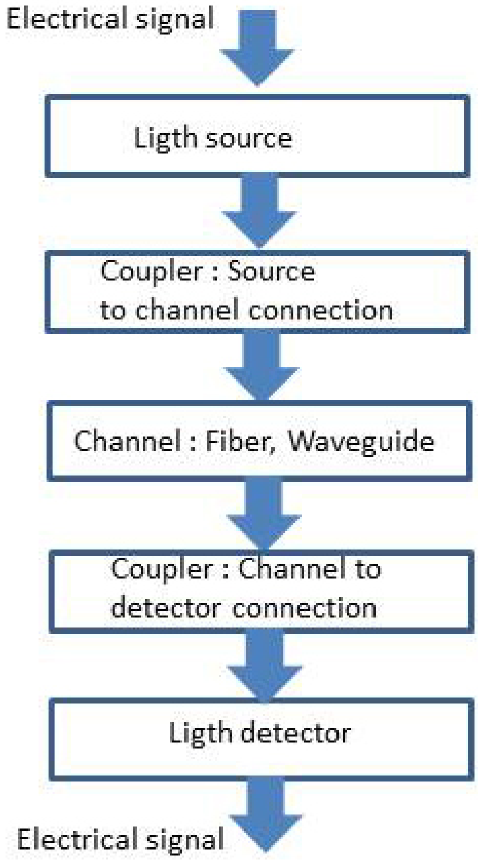

Fig. 5. Optical communication system block diagram.

3.2 Sources and detectors of light

LED : Light-emitting diode

Light sources are used to generate input signals of the optical communications systems. Optical communication systems often use semiconductor optical sources such as **LEDs** (***light emitting diodes***) and semiconductor **LDs** (***laser diodes***).

LASER : Light Amplification by Stimulated Emission and Radiation

These kinds of semiconductor optical devices offer high efficiency and reliability. Moreover, they allow an accurate selection of the wavelength range and emissive areas compatible with optical fibre core dimensions. The following table summarizes main characteristics and structures of **LEDs** and **LDs** used in optical communication systems through optical fibres.

Semiconductor optical sources	**Characteristics**	Structures
LEDs	LEDs used in optical communications must have a high radiance (light intensity), fast response time and high QE (quantum efficiency).	Planar, dome, edge-emitting led or surface-emitting led.
LDs	LDs used in optical communications should have coherent light, narrow beam width and high output power.	Spontaneous emission. Stimulated emission

At the end of the optical communication systems optical sensors (detectors of light) are used in order to recover the transmitted information and convert it again into an electrical signal through the photoelectric effect. The role of a photodetector is to recover the data transmitted through the optical fibre communication system.

Photodetectors are optoelectronic devices that convert an incident radiation (light) to an electrical signal, such as voltage or current.

Light detectors or photodetectors are usually based on **PDs** (***photodiodes***), photoconductive detectors and phototransistors. Photoconductive detectors have the simplest structure of this family of light detectors and can be obtained by attaching two metal electrodes to a semiconductor material. The conductivity of the semiconductor increases when some incident photons are absorbed in the semiconductor. As result, an increase of the external current appears when a voltage bias is applied to the electrodes. Solar cells are a specific type of photodetectors used in photovoltaic solar energy generation systems, not in communication systems.

A photodiode is a semiconductor diode that functions as a photodetector. It is a p-n junction or p-i-n structure. When a photon of sufficient energy strikes the diode, it excites an electron thereby creating a mobile electron and a positively charged electron hole.

Phototransistors are **BJTs** (***bipolar junction transistors***) that operates as photodetectors and offer as well photo-current gain. These devices are semiconductor light sensors formed from a basic transistor with a transparent cover.

Semiconductor optical detectors	**Characteristics**	Examples of structures
Photodiodes	Based on pn junctions.	pn or p-i-n diodes. APDs (Avalanche photodiodes). Heterojunction photodiodes.
Schottky junction	Junction formed by an n-type semiconductor in contact with a metal.	Schottky contacts.
Solar cells	Solar cells convert the incident radiation energy into electrical energy.	cSi (crystalline silicon) aSi:H (amporphous silicon). HiT (heterojunction intrinsic layer thin film solar cell). GaAs
Phototransistors	Light-sensitive transistors. Phototransistors amplify variations in the light striking it.	npn BJTs pnp BJTs
Photoconductive detectors	Conductivity variation due to absorption of light.	**LDR** (***light-dependent resistor***). PbS (lead sulfide) **IR** (***infrared detector***). Lead selenide (PbSe) **IR** detectors.

4 Physical mechanisms: Absorption, photoconductivity, photon emission

Main physical mechanisms related to the effects of energy conversion in semiconductor materials are introduced in this chapter.

4.1 Light absorption

When light propagates through a material there is a conversion of part the photons energy to other forms of energy (e.g. Heat). This lost energy is absorbed by the material. Electrons of atoms can move to the higher-energy states and be excited from the VB (valence band) to the CB (conduction band) by absorption of the energy of photons and pairs e^{-}-h^{+} (electron-hole) are created by this mechanism.

The most important process of light absorption in a semiconductor is the creation of those pairs e^{-}-h^{+}. Each absorbed photon causes a transition from the valence band to the conduction band. A photon is absorbed by a semiconductor if the photon energy is greater than the band gap of the material, Eg.

The band gap, Eg, generally refers to the energy difference, in eV (electron volts) between the top of the VB and the bottom of the CB in insulators and semiconductors. The electron affinity of a semiconductor,χ, is the width of the CB in eV. The Fermi energy, E_F, indicates the highest energy states occupied energy at 0 K. Energy states above E_F are empty up to the vacuum level.

$$Eg = Ec - Ev$$

where Ec and Ev are the energy corresponding to the top of the VB and the bottom of the CB. Fig. 6 shows the absorption mechanism and the energy band diagram.

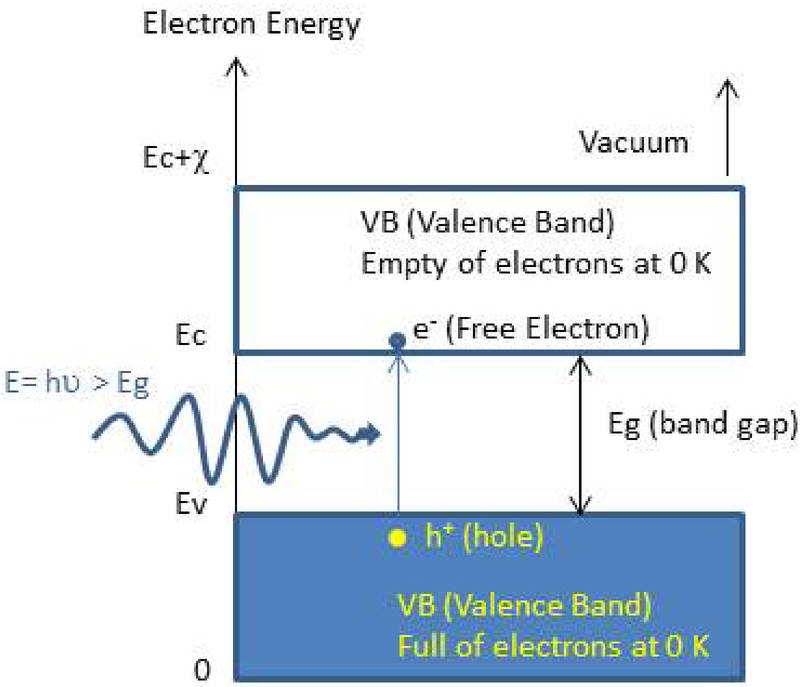

Fig. 6. Energy band diagram and absorption mechanism.

Typical properties of some semiconductors at 300 K

Semiconductor	**Eg (eV)**	**χ(eV)**
Silicon : Si	1.11	4.05
Gallium Arsenide :GaAs	1.42	4.07
Germanium: Ge	0.66	4.13
Indium Phosphide : InP	1.35	4.5
Gallium Phosphide : GaP	2.26	3.8

For each wavelength, λ, of the incident beam of light, Io, passing through the material, the intensity of the light beam, I, is attenuated by scattering and absorption mechanisms. Lamber's law defines transmission and absorption as follows

$I = Io \cdot \mathrm{e}^{-\alpha L}$

where α is the absorption coefficient; α (m^{-1}) is a function of λ.

4.2 Photoconductivity and photoelectric effect

Photoconductivity is an optoelectronic phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation such as light.

Photoelectric effect: Many metals emit electrons when light shines upon them. In the photoemission process, if an electron within some material absorbs the energy of one photon and acquires more energy than the work function of the material, it is ejected.

Einstein was awarded the Nobel Prize in 1921 for his research on the photoelectric effect. The energy required to remove an electron from the material is called the work function of the metal, ϕ.

Photon emission: When an electron falls into a lower energy level and meets a hole, it releases energy in the form of a photon. The wavelength of the light depends on the band gap of the semiconductor material. Light is emitted in multiples of a certain minimum energy unit. The size of that unit is the photon energy.

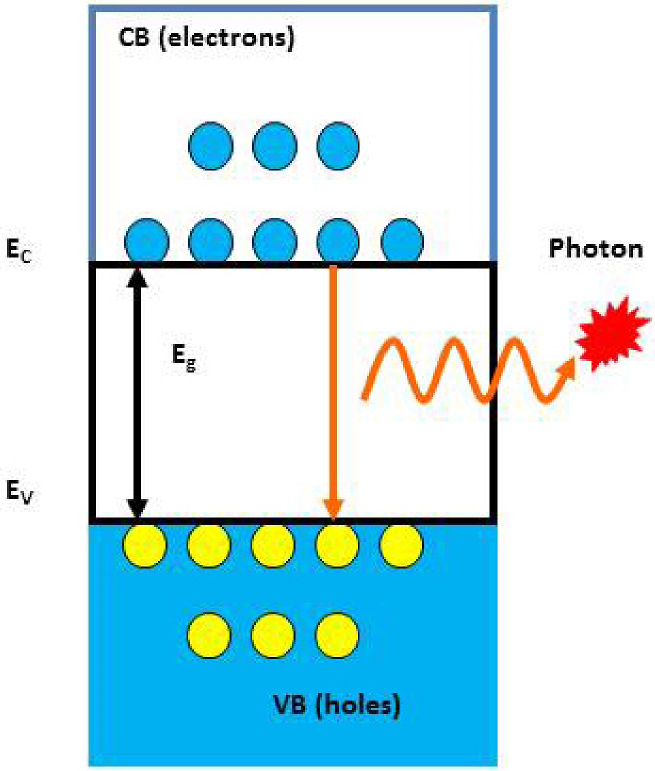

Fig. 7. Photon emission.

The photon energy is: $E = h\upsilon = h\dfrac{c}{\lambda}$, being c the speed of light in vacuum.

Calculate the range of wavelengths not absorbed by Germanium: Ge, by taking into account the bandgap of Ge = 0.66 eV.

SOLUTION

Light absorption in a semiconductor creates pairs e^{-}-h^{+} when the energy of incident photons is greater than the band gap of the material, Eg. In case of Ge, the minimum value of energy for photons to get absorbed will be:

$E = h\dfrac{c}{\lambda} > \mathrm{Eg(Ge)} = 0.66\ \mathrm{eV}$. So the photons having wavelengths: $\lambda < h\dfrac{c}{\mathrm{Eg(Ge)}}$ will be absorbed by the semiconductor.

Considering hc = 1.24 eVμm. The maximum value of photons wavelength to generate pairs e^{-}-h^{+} in Ge is: $\lambda < 1878$ nm.

All physics effects described in this chapter have specific application in optoelectronic technologies as well as in other related physical sciences.

5 Optoelectronic Devices and Sensors

This chapter describes main optoelectronic devices and sensors forming part of most photonics applications. Some basic concepts on semiconductor physics are also introduced in order to understand the internal characteristics and behaviour of these devices, mainly the direct conversion between electrons and photons.

5.1 Introduction

Optoelectronic devices and light sensors are fabricated by using semiconductor materials.

A semiconductor material has an electrical conductivity value falling between that of a conductor, such as copper, and an insulator, such as glass.

The electrical conductivity of a semiconductor material increases with increasing temperature, which is behaviour opposite to that of a metal. Nowadays, **Si** (***silicon***) is the semiconductor more used in electronic applications. Intrinsic semiconductors or i-type semiconductors are pure semiconductors without any dopant species present in the material (undoped). The number of charge carriers, electrons and holes, is therefore determined by the properties of the material itself. In an intrinsic semiconductor the number of excited electrons and the number of holes are equal:

$n = p = n_i$ (carriers cm^{-3}), the value of n_i depends on the gap of the semiconductor, Eg, and varies with temperature as follows:

$$n_i = AT^{3/2}e^{-\frac{\mathrm{Eg}}{2k_BT}}$$

Where T is the temperature in K, k_B it the Boltzmann constant: $k_B = 8.62\cdot10^{-5}$ eV/K and A is a constant.

Semiconductor devices can display a range of useful properties such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat. The introduction of specific impurities into pure crystal i-semiconductors allows obtaining extrinsic semiconductors: Semiconductors in which the concentration of one type of carrier, electrons or holes, is much in excess of the other type. When the electron concentration is much larger than the holes concentration the semiconductor is called n-type. By opposite, if the density of holes is much larger than the one of electrons the semiconductor is a p-type semiconductor.

Some sensors and devices described in this chapter are based on p-n junction principles.

A p-n junction is a boundary or interface between two types of semiconductor material, p-type and n-type, inside a single crystal of semiconductor. Diodes are semiconductor devices formed by a semiconductor material with a p–n junction connected to two electrical terminals.

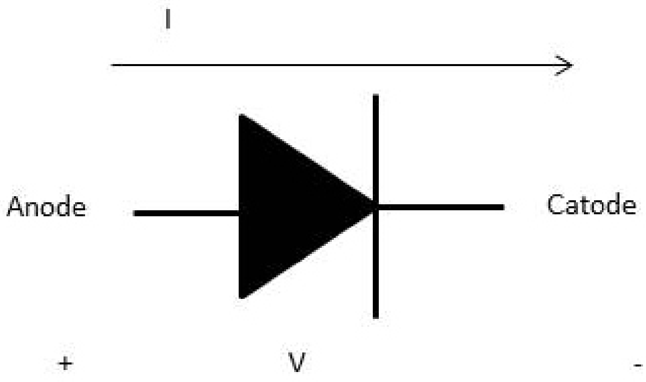

Fig. 8. Electronic symbol of a diode.

5.2 LEDs

LEDs ***(Light-emitting diodes)*** are semiconductor diodes that emit incoherent narrow-spectrum light when the p-n junction is forward biased.

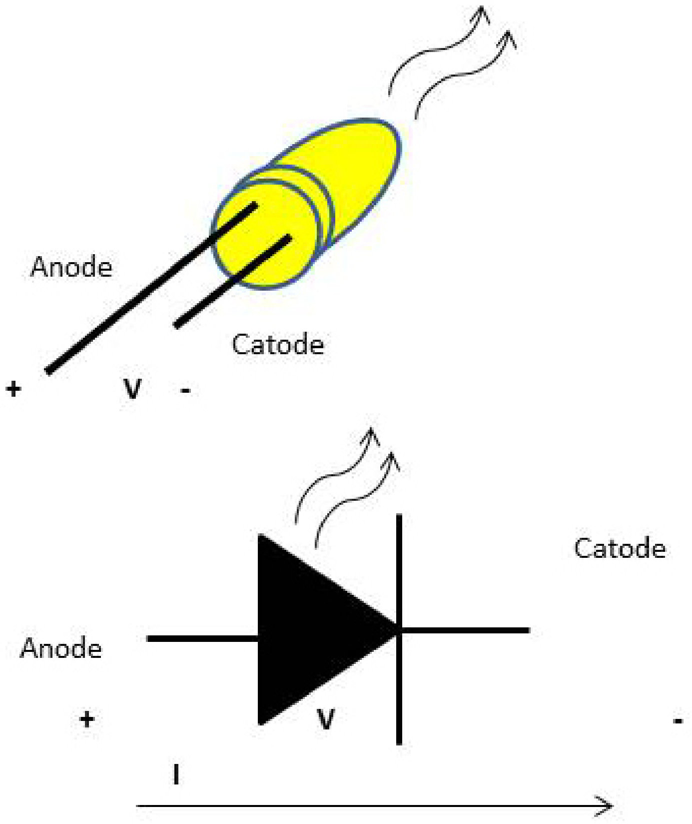

Fig. 9. LED.

The normally empty **CB** (***conduction band***) of semiconductors is populated by electrons injected into it by the forward current through the junction. As we saw in chapter 4, when an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon. This photon emission is the mechanism by which light is emitted from LEDs. When the electron can undergo the down-ward transition by itself, the photon emission process is called **spontaneous emission**.

The light is generated when electrons recombine with holes and the wavelength of the light depends on the band gap of the semiconductor material, Eg. The following table shows the colours associated to the wavelengths of the light emitted by LEDs made by different semiconductor materials.

Leds made from semiconductors presenting a direct bandgap emit more light than leds fabricated by using indirect bandgap semiconductors.

Semiconductor materials and LED colours

Semiconductor	Colour	Brightness
GaAs; GaAlAs	Infrared	General (normal)
GaAs; AlGaAs; GaP	Red	General (normal)
GaN	Blue	General (normal)
GaP	Green	General (normal)
GaAlAs; GaAsP; InGaAlP;	Red	High (super & ultra)
GaN	Blue	High (super & ultra)
GaP ; InGaN	Green	High (super & ultra)
InGaAlP; GaAsP	Yellow	High (super & ultra)

LEDs are applied in many fields such as displays, solid-state lighting, remote control and optical communication systems. In last year's LEDs are commonly used also in general illumination such as many integrated LED lamps and LED luminaires. Different LED packages can be found in the market depending on the applications. Some kinds of lens are normally included in the packaging of LEDs in order to control the output light beam angle. This is one of the characteristics given by manufacturers in datasheets as well as luminous intensity (mcd), flus (lm), dominate wavelength (nm) and colour. Specific values (typical and thresholds) of electrical parameters as **Vf** (***forward voltage***), **If** (***forward current***) are also given by manufacturers.

The energy efficiency of a LED, η, is typically characterized in basic terms as the ratio of power input to light output—or more technically: Emitted flux (lumens) divided by power draw (W). Commercial LEDs present efficiencies ranging from 50–70 %.

Fig. 10. Infrared LEDs.

5.3 LDs, laser diodes

Laser: Light Amplification by Stimulated Emission. The energy of an incoming photon, $E = h\square$, stimulates the emission process by inducing an electron to pass to a lower energy level. This process allows obtaining photon amplification: One incoming photon results in two outgoing photons that have the same direction, wavelength and phase.

LEDs presented in previous chapter are based in the spontaneous emission mechanism while **LDs** (***laser diodes***) are based on the stimulated emission principle.

In order to achieve an amplification of the light by stimulated emission, the probability of a photon emission must be above that of absorption for the spectral range concerned. When the stimulated emission is dominant, the light is amplified, and laser occurs. Stimulated emission is the dominant mechanism when the probability of finding an electron in CB is greater than the probability of finding an electron in the VB. This happens in presence of a population inversion. The population inversion is achieved when the difference between Fermi energy of electrons, E_{FN}, and Fermi energy of holes, E_{FN}, is bigger than the bandgap, Eg. In order to separate these Fermi energy levels is necessary to pump energy in form of electrical current into the semiconductor. Then, by **pumping** the laser, when a threshold current is injected, the semiconductor is shifted into a state of population inversion.

Optical cavities, such as the **FP** (***Fabry-Perot***) or dielectric mirrors **DBRs *(distributed Bragg reflectors***), containing a laser between two reflecting surfaces are used as optical resonators. In steady state, there are stationary **EM** (***electromagnetic***) oscillations in the optical cavity. These oscillations reflect on the reflecting surfaces of the optical cavity. The optical cavity axes perpendicular to the current flow. At each reflection, the wave is partially transmitted through the reflective facets. Laser oscillation begins when the amount of amplification becomes equal to the total amount lost through the sides of the resonator, scattering along propagation in the medium and through absorption by the crystal.

There are two main types of LDs: Edge Emitting and surface emitting LDs. Edge emitting LDs have wide and astigmatic emission, while surface emitting LDs present narrower beam emission.

VCSELs (***vertical cavity surface emitting lasers***) are lasers with a very short active region that have the optical cavity axis along the direction of current flow.

In these lasers, light emission occurs in a direction perpendicular to the active region. CVSELs allow data communications up to 10 Gbs^{-1}.

An **EOM** (***electro-optic modulator***) is a device which can be used for controlling the power, phase or polarization of a laser beam by means of an electrical control signal.

LDs are the most common type of lasers and are used in a wide range of applications. These devices have small size; relatively low price and a long lifetime making them a good component for multiple applications that include, but are not limited to, optical communications, barcode readers, laser pointers, CD/DVD/Blu-ray Disc reading and recording, laser scanning and printing or directional lighting sources.

5.4 PDs, photodiodes

A **photodiode** is a semiconductor device that converts light into electrical current. The current is generated when photons are absorbed in the photodiode. It is based on a p-n junction or p-i-n structure. When a photon of sufficient energy strikes the diode, it excites an electron thereby creating a mobile electron and a positively charged electron hole.

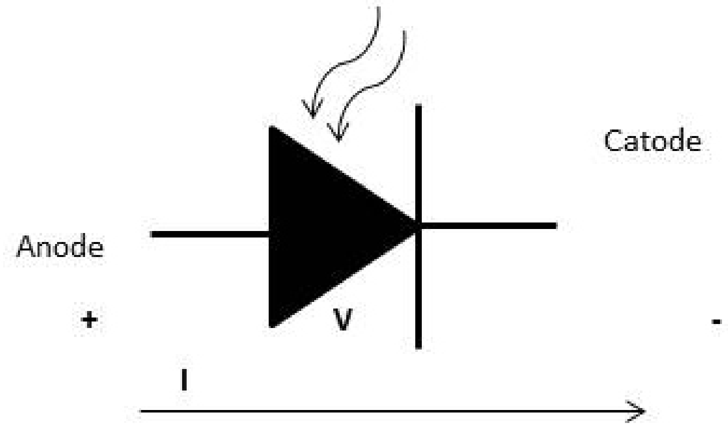

Fig. 11. Photodiode.

5.5 Solar cells

A solar cell is a **PV** (***photovoltaic***) device that converts into electrical energy the incident radiation.

Semiconductor based solar cells can be single p-n junctions, heterojunctions or multi-junctions.

Main semiconductors used in solar cell fabrication are Si and GaAs.

The solar cell efficiency is given as the relationship between the maximum electrical power respects to the total incident power of light.

$$\eta = \frac{Vm\ Im}{G\ A}$$

Where Vm and Im are the coordinates of the **MPP** (***maximum power point***) at the device output, G is the irradiance (W/m^2) and A is the active area of the device.

Crystalline Si based solar cells have achieved efficiencies up to 25 % and multi-junction solar cells working under concentrated light present efficiencies up to 43.5 %.

The solar cell efficiency as well as main parameters of the device are given by manufacturers at **STC** (***standard conditions of work***): AM1.5 spectrum, G = 1000 W/m^2 and T = 25 ºC.

Solar cells are connected in series to form strings in PV modules. A PV module consists in one or more strings parallel connected.

5.6 Optical amplifiers

In order to transmit signals over long distances (>100 km) it is necessary to compensate for attenuation losses within the optical fibre (optical transmission channel). This is the objective of optical amplifiers.

Typical optical fibre loss around 1.5 µm is in the range of 0.2 dB/km. It is possible to convert the optical signal to electrical signal and use conventional electronic amplifiers to compensate transmission losses and then convert back again the signal to optical. However, these signal conversions require costly and high speed electronic elements.

An **optical amplifier** amplifies an optical signal directly, without the need to first convert it to an electrical signal.

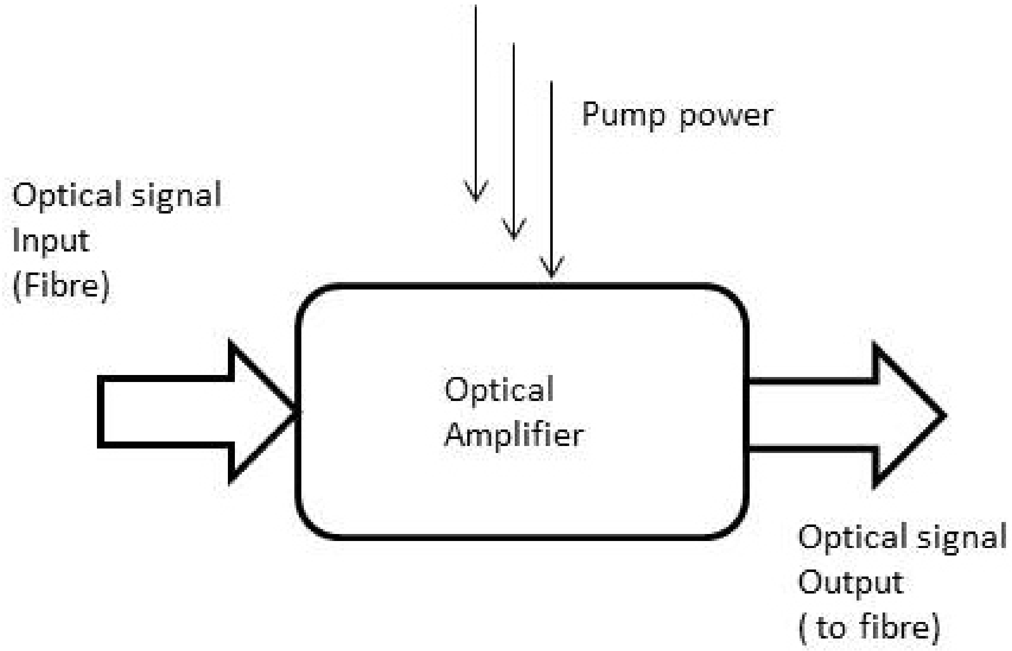

Fig. 12. Optical amplifier scheme.

Main characteristics of optical amplifiers are: Gain (dB), range of operating frequencies or **BW** (***bandwidth***), gain saturation: Maximum output power, and output noise level. Gain is defined by the following equation

$G = \frac{Po}{Pi}$, where Po and Pi are the output and input power respectively.

There are three main types of optical amplifiers: The **EDFAs** (***erbium-doped fibre amplifiers***), the **SOAs** (***semiconductor optical amplifiers***), and the fibre Raman amplifiers. In EDFAs the amplifying medium is a glass optical fibre doped with erbium ions that are optically pumped to a state of population inversion with a separate optical input. SOAs are pumped with electrical current and the gain medium is formed by undoped semiconductors. These optical amplifiers are very useful in local networks due to their relative low cost and enough gain for short distances.

In Raman amplifiers, the amplification is based on stimulated **SRS** (***stimulated Raman scattering***). Raman scattering is a process in which light is scattered by molecules from a lower wavelength to a higher wavelength.

Some types of optical amplifiers	**Characteristics**	**Disadvantages**
SOAs 400 – 2000 nm	Similar to laser cavities (semiconductor lasers). Large **BW** and good gain	High noise figure and cross-talk levels.
Rare earth doped fibre amplifiers erbium – EDFA 1500 nm Praseodymium – PDFA 1300 nm	Amplification occurs primarily through the stimulated emission process. The gain depends both on the frequency and on the local beam intensity	Relatively large devices Cross-talk and gain saturation effects. Spontaneous noise emission
Raman and Brillouin amplifiers	Does not require a population inversion.	The Pump and amplified signals are at different wavelengths. High cost

6 Fibre optic: Working principle and classification; propagation modes. Photonic crystals

The optical fibre is nowadays the most used communication channel in optical communications. Main characteristics of optic fibres are introduced in this chapter to understand its characteristics and advantages respect to more conventional communication channels used in data communications in applications ranging from major telecommunications backbone infrastructure to Ethernet systems, broadband distribution, and high quality data networking.

6.1 Optical Fibre

The optical fibre is a flexible, transparent fibre made of glass (silica) or plastic, slightly thicker than a human hair. Optical fibers are used most often as a means to transmit light and is of wide usage in telecommunications.

Optical fibres are used as optical communication channels because of its high BW, data rates of Gbps, and capacity of transmission. Thousands of channels can be multiplexed together over one strand of fibre. Moreover, optical fibres have very low attenuation, about 0.2 dB/km, and relative low cost. All those characteristics result of great interest for communications over large distances.

Fig. 13 shows the structure of an optical fibre. The thin glass centre of the fiber where the light travels is called the core. The outer optical material surrounding the core that reflects the light back into the core is called the cladding. A buffer coating or jacket protects the optical surface.

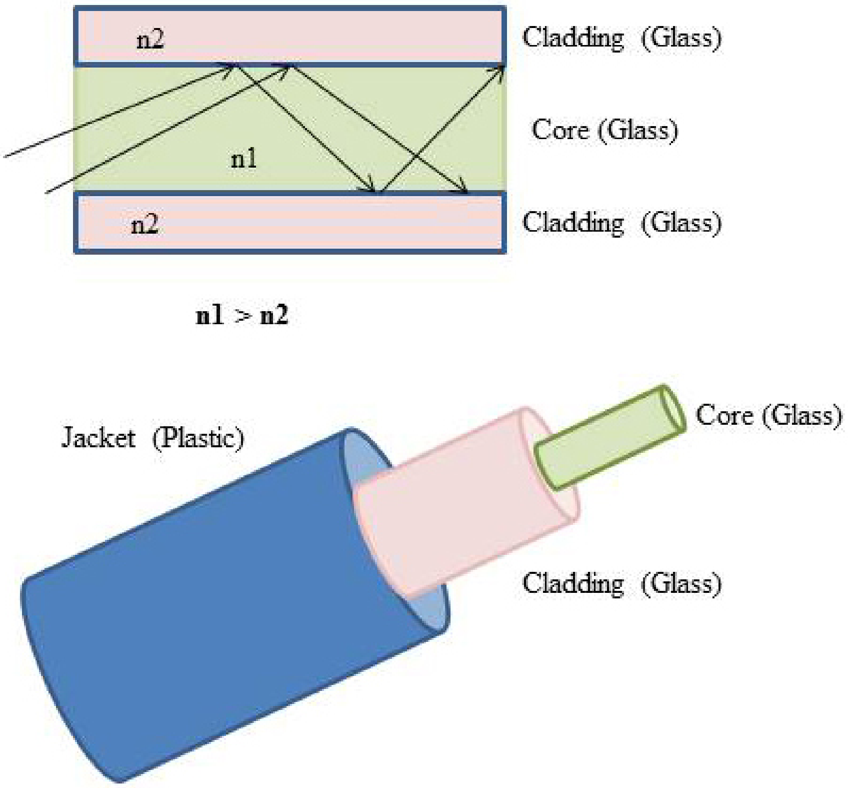

Fig. 13. Optical fibre.

An optical fibre has a central region, core, of higher refractive index n_1 than the surrounding region, cladding, which has a refractive index n_2. If the light hits the interface at any angle larger than the critical angle, φ_{1c} defined in section 2.3, it will not pass through to the second medium and it will be reflected back into the core due to the TIR process.

A fibre optic has a core of pure Si with refractive indexes:

n = 5.57 for wavelengths of 0.4 µm and n = 3.78 for wavelengths of 0.7 µm.

Calculate the times needed for lights of both wavelengths to travel along 2 km of that fibre optic.

Solution

The velocity of Light of different wavelengths in the core will be different due to the different values of the refractive index at the given wavelengths. This value is given by: $v = \frac{c}{n}$.

First we must calculate the velocities at each one of the wavelengths:

$$v_1(\lambda = 0.4\ \mu\mathrm{m}) = \frac{c}{n(0.4\ \mu\mathrm{m})} = \frac{3\cdot 10^8\ \mathrm{ms}^{-1}}{5.57} = 5.39\cdot 10^7\ \mathrm{ms}^{-1}$$

$$v_2(\lambda = 0.7\ \mu\mathrm{m}) = \frac{c}{n(0.7\ \mu\mathrm{m})} = \frac{3\cdot 10^8}{3.78}\mathrm{ms}^{-1} = 7.94\cdot 10^7\ \mathrm{ms}^{-1}$$

Then we can calculate the time needed to travel 2 km as follows:

$$t_1 = \frac{x}{v} = \frac{2000}{5.39\cdot 10^7} s = 37.1\ \mu\mathrm{s}$$

$$t_2 = \frac{x}{v} = \frac{2000}{7.94\cdot 10^7}\mathrm{s} = 25.2\ \mu\mathrm{s}$$

Multimode fibres are fibres than may carry more than one mode at a specific light wavelength. Some fibres have very small diameter core and they can carry only one mode, single mode fibres, which travels as a straight line at the centre of the core. To get a propagating wave along a guide it is necessary to have a constructive interference. All the rays interfere with each other. Only certain angles are allowed. Each allowed angle represents a mode of propagation.

The maximum acceptance angle of the fibre defines a cone that fix the light entering into the fibre that will propagate through the fibre in different propagation modes. The half-angle of this cone is the acceptance angle, ϕmax, determined only by the indices of refraction. The **NA** (***numerical aperture***) of the fiber is defined by the following equation:

$$NA = n\cdot\sin(\varphi\mathrm{max}) = \sqrt{n_1^2 - n_2^2}$$

where n is the refractive index of the medium light is traveling before entering into the optical fibre.

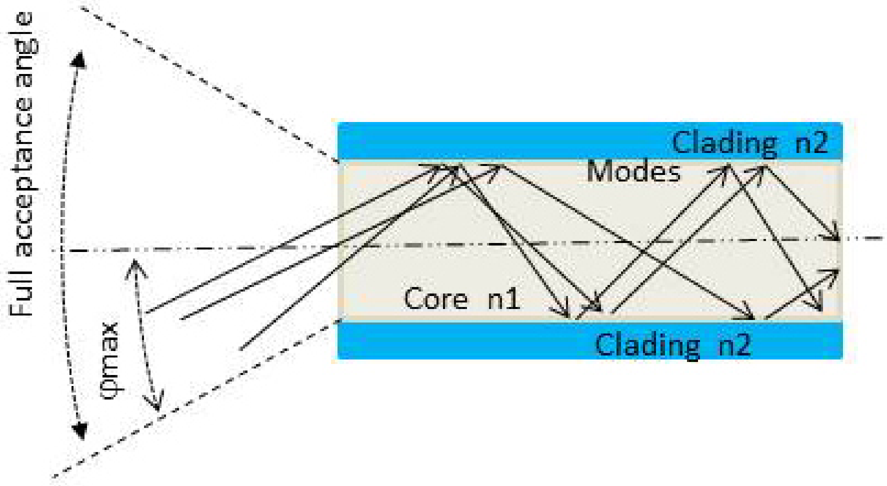

Fig. 14. Propagation modes and acceptance angle.

$E=m\cdot c^2$

The **number of propagation modes, *M***, depends on the optical fibre parameters as follows:

$M = \frac{V^2}{2}$, being V the V-number or normalized frequency, defined by the following equation:

$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$, where $2a$ is the core thickness.

When $V < 2.495$ there is only one mode of propagation in the fibre, the fundamental mode (single mode fibre). For values of $V > 2.495$ the fibre is multimode.

Main transmission losses in the fibre are related to absorption and scattering mechanisms. Rayleigh scattering due microscopic irregularities in the Fiber is an intrinsic source of losses. Absorption is due to the presence of impurities in the fiber material. In optical fibres fabricated from silica (SiO_2) there are three main peaks of attenuation due to absorption caused by OH^- ions at wavelengths of 1050 nm, 1250 nm and 1380 nm.

A second source of losses or attenuation is the fibre bending. Some radiation is lost in the region where the fiber is bent. The amount of losses depends on the curvature of the bending. If the curvature radius of the bending is similar to the diameter of the fibre including the cladding, D, we are in presence of microbendings, while bending with a curvature radius larger than D is called a macrobendings. Typically, macrobending occurs when the fiber is bent during the installation of a fiber optic link such as turning the fiber around a corner, while microbending effects are due to manufacturing flaws that can result in variations in the fiber geometry over small distances.

Types of optical fibres	**Characteristics**
Plastic	Losses around 10^2 dB/km Very flexible, inexpensive, lightweight
Other glass fibres	Materials : Chalcogenide, fluoroaluminate Used in long wavelengths communications
Fused Silica (SiO_2)	Can be extremely pure and then doped to obtain the desired concentration of carriers. Low loss and dispersion at $\lambda = 1.55$ µm

We can couple two fibres if they are of compatible types. The fibres must be accurately aligned with each other, matching of NA, and the ends of the fiber must be brought together in close proximity.

Comparison between optival fibres and coaxial cable or twisted pair.

Advantges	**Drawbacks**
Not affected by electromagnetic interference	High initial cost in installation
Lower attenuation than coaxial cable or twisted pair. Lower-power transmitters can be used.	Point to point communications system
No protections for grounding and voltage problems are needed	Jointing of fibre and splicing are not easy. Adding additional nodes is difficult.
High signal security because there is no radiated energy any antenna or detector cannot detects it.	More fragile than coaxial cable.
Wide bandwidth	More expensive to repair and maintain.

Photonic crystals are artificial multi- dimensional periodic structures with a period of the order of optical wavelengths. These materials are structured to have a periodic modulation of the refractive index.

It is possible to fabricate optical fibres by using photonic crystals. In these fibres, both the core and cladding use the same material, usually silica. One of the fibre regions, the core or the cladding, have air holes, while the other region is totally solid. The presence of air holes in one region, e.g. cladding, results in an effective refractive index that is lower than the solid core region.

On the other hand, it is possible to supress spontaneous emission by using photonic crystals.

7 Applications: Optical communications, biophotonics, optical sensing, lighting, and energy

This chapter shows a list of main applications of optoelectonics. However, new applications appear in the market each year. As result, the optoelectronic market is growing every year, a 30% growth every year since 1992.

7.1 Optoelectronics applications

Main applications of optoelectronics are detailed in the following table.

Aplications of optoelectronics.

Application	Characteristics
Fibre optics communications • Telecomunications • Computer networks • Cable TV	Fibre optics is used as a transmission chanel of information because of its intrinsic characteristics: Low cost and weigh, low attenuation and dispersion, and provide high bandwith. Other optoelectronic devices as LDs, photodetectors, sensors, optical amplifiers, optic modulators and demodulators, multiplexers and demultiplexers forms part of the optics communication systems. Optical data transmission is also used in equipment control and industrial automatization.
Consumer electronic products	A large set of consumer electronic product in the market include optoelectronic devices as photodetectors, leds, CCD sensors, photodiodes, phototransistors etc.. • Computers & Printers • CD readers • Thermal imaging • Cameras and Displays • Smart phones • Massive memory chips
LDs, Laser diodes	Main applications of LDs are in the field of telecommunications through optical fibres as light emitters. However, other applications of LDs are : • Cutting, surgery. • CD writing and reading. • Optical data storage. • Defense : Radar, laser guided weapons
Lighting, leds.	Leds are used in lighting applications in many fields as : • Residential. Buildings • Traffic signals, street lights. • Outdoor: runway in airports. • Digital clocks, electronic indicators.
Solar cells	Photovoltaic (PV) systems • Low power applications: Pocket calculators, clocks, indoor & outdoor lighting. • Stand-alone PV systems • Grid connected PV systems. • Aerospace applications.