Photonics: Concept, Devices and Applications

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Introduction

Sense of vision is very important for all of us, as it is our window to the world. Light coming from objects after reflection or scattering facilitates our eyes to observe the objects and hence the entire world with the help of light. We cannot imagine about the world without light. As study of polity is politics and study of economy is economics; in the same way, study of photon (light) is the photonics.

The term 'Photonics' can be understood in close analogy with the familiar term of electronics. Electronics involves control of electric charge flow whereas photonics involves the control of photons in vacuum or in matter. Photonics reflects the growing tie between optics and electronics forged by the increasing role that semiconductor materials and devices play in optical systems.

Photonics deals with the generation, propagation, manipulation, and use of information and energy of light. To understand photonics, it is essential to know about behaviour and properties of light. The light waves are a part of electromagnetic spectrum ranging from short wavelength of gamma rays and X-rays to long wavelength of radio waves. All the components of electromagnetic spectra obey some common basic laws and in this sense, study of light is applicable in some way to other components of electromagnetic spectra also. Wavelength of light varies approximately from 400 to 780 nm. Different colours correspond to different wavelengths.

According to the view of classical physics light is a wave consisting of electric and magnetic field with a smooth distribution of energy. Observed phenomenon of light like reflection, refraction, diffraction, polarisation and interference give direct experimental evidence of the wave properties of light. However, in the earlier years of twentieth century, theoretical and experimental investigations established that light sometimes has particle properties. According to this view, light acts like a particle like energy packets. These energy packets are called quanta of light or photons. As photon is central theme of the photonics, it will be interesting to know the emergence of the concept of photon.

Concept of Photon

It is worth mentioning here that every object (substance) emits thermal radiations above absolute zero temperature. We generally do not observe them because most of the radiations are in infrared region and our eyes are not sensitive to infrared region of the spectrum. Our eyes are sensitive only to the visible region of the electromagnetic spectrum. However, when objects are heated to higher temperatures, some of the thermal radiations get converted into light, i.e. objects emit light. Different objects have different emissive power (emissivity). There may be objects or bodies with high emissive power. An object with perfect emission power (at higher temperature) or perfect absorption power (at lower temperature) is termed as blackbody. The spectrum of a blackbody was a point of discussion for a long time. Rayleigh-Jeans law explained the higher wavelength side of blackbody spectrum, but it failed to explain the spectra at lower wavelengths. This failure is popularly known as "ultraviolet catastrophe". On the other hand, Wein's law was valid for lower wavelength region. There was no single theory which could explain the whole range of spectra. Planck, one of the pioneer of Quantum Mechanics, came up with very fascinating idea that atomic oscillators do not emit energy continuously rather they emit energy in packets and energy of one packet is Planck's constant multiplied by the frequency of the oscillator. Later on, in 1905 Einstein came up with the idea of quantum of light energy while explaining the photoelectric effect. This light quantum was termed as "Photon" first time by a chemist Gilbert N. Lewis in 1926. The name is derived from Greek (photo = light) and the "-on" at the end of the word indicates that the photon is an elementary particle belonging to the same class as the proton, the electron and the neutron.

Dual Nature of Light

Different views have been given from time to time regarding nature of light starting from Newton's corpuscular model to Huygen's wave model and to Maxwell's electromagnetic wave model. Newton's model treats light in particle form, while other two models treat it as wave. Later on, de Broglie concluded that light has dual nature. Some observed phenomena of light like interference, diffraction, polarisation, etc. can be explained by its wave nature, while some other phenomena like Photoelectric effect, Compton effect, etc. need particle nature of light to be understood. It has dual character in the same way as subatomic particles like electron, proton, etc., exhibit both particle as well as wave nature. These two natures are complementary to each other.

Maxwell's electromagnetic theory reveals that the speed of electromagnetic waves including light in free space is given by $c=1/\sqrt{\mu_0 E_0}$ where μ_0 is permeability of free space and E_0 is permittivity of free space. Speed of light is less than 3×10^8 m/s in other media. It gives a clue that there is interaction between light and matter.

Interaction of Light with Matter

In interaction of light with matter, light behaves as if it is made up of particles called photons. Each photon has energy hv and momentum $h\nu/c$ where c is the speed of light. The rest mass of photon is zero. However, it is never at rest. It moves with speed c relative to all frames of reference. The moving mass of photon is $m=E/c^2=h\nu/c^2$. All photons of particular frequency v have the same energy ($E= h\nu$) and momentum ($p= h\nu/c$), whatever the intensity of radiation may be. Photons are electrically neutral and are not deflected by electric and magnetic fields. In a photon-particle collision the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision. The photon may be absorbed or a new photon may be created.

Photon interacts with matter in three ways depending on its energy. When it has a low energy in few electron volts and is made incident on a metal surface with low ionisation potential, it knocks out the loosely bound electrons on the surface and these electrons are known as photo electrons contribute in producing electric current. This effect of photons with matter is known as photo electric effect. Cells, made to be operated using this phenomenon are known as photo cells.

If energy of an interacting photon is more than 1.02 MeV then it is able to produce a pair of electron and a positron (particle-antiparticle) both having same rest masses of 0.51 MeV, with opposite charges. This phenomenon is termed as Pair Production. This is one of the best examples where energy (non matter in terms of photons) is converted into mass (in terms of massive particles – electron and positron). The annihilation of an electron with a positron again provides photons.

When the required energy of photon is not very low for photo electric effect and not so high for pair production, Compton scattering takes place where scattered photon has longer wavelength. This change in wavelength results in a Compton shift or Compton profile which is used in characterisation of materials.

The interaction between light and matter is at the heart of Photonics. Let us discuss about photoelectric effect in more detail.

Photoelectric Effect

Emission of electrons from the surface of certain materials when exposed to light is known as the photoelectric effect. The effect was discovered by Hertz in 1887 during his investigations of electromagnetic wave propagation by means of spark discharge. Hertz observed the increase in high voltage sparks across the detector loop when the emitter plate was illuminated by ultraviolet light from an arc lamp. Later on, during 1886-1902, Wilhelm Hallwachs and Philipp Lenard investigated the phenomenon of photoelectric emission in detail. They studied how the photo current varied with collector plate potential, and with frequency and intensity of incident light and also observed that electrons were emitted only when they used ultraviolet light of frequency greater than a certain minimum value, called the *threshold frequency*. This minimum frequency depends on the nature of the material of the emitter plate.

The phenomenon of photoelectric emission could be understood qualitatively on the basis that when light is absorbed by the surface, it transfers energy to electrons near the surface and that some of the electrons acquire enough energy to overcome the potential energy barrier at the surface and escape from the material into space. All the photosensitive substances emit electrons when they are illuminated by light.

Experimental features of photoelectric emission

The experimental features of the photoelectric emission encompasses that (i) for a given photosensitive material and frequency of incident radiation above some minimum frequency, photoelectric current is directly proportional to the intensity of light, (ii) saturation current is found to be proportional to the intensity of radiation whereas the stopping potential is independent of intensity, (iii) below a certain minimum cut off frequency, called threshold frequency, no emission of photoelectrons takes place.

Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity, and (iv) the photoelectric emission is an instantaneous process without any apparent time lag ($\sim 10^{-9}$s) even when the incident radiation is made exceedingly dim.

Photoelectric effect and quantum theory of radiation

The wave nature of light was well established by the end of the nineteenth century. The phenomena of interference, diffraction and polarisation were explained in a natural and satisfactory way by the wave picture of light. But the wave picture is unable to explain the most basic features of photoelectric emission. In 1905, Einstein proposed a radically new picture of electromagnetic radiation to explain photoelectric effect. In this picture, continuous absorption of energy from radiation is not the cause of photoelectric emission. Rather energy is built up of discrete units, i.e. quanta of energy of radiation named as photon. Each quantum has energy h*v* where h is Planck's constant and *V* the frequency of light. In photo electric effect, a quantum of radiation with energy h*v* is used by electron to overcome the surface barrier and have some kinetic energy after liberation. Einstein's photoelectric equation given by $h\upsilon = h\upsilon_0 + K_{max}$ (where $\phi_0 = h\upsilon_0$ is work function of the material, K_{max} is maximum kinetic energy of photo electron, υ is frequency of incident light, υ_0 is threshold frequency and h is Planck's constant) gives the explanation of all the experimental observations on photoelectric effect in a very simple and elegant manner.

Emergence of Photonics

Emergence of photonics is an important area of research and technology because of the recent advances in the last few decades, i.e. the invention of laser, optical fibers and semiconductor optical devices. Let us discuss these briefly one by one.

LASER

A laser is a device in which Intensity of particular electromagnetic wave (say light) is amplified by the process of stimulated emission. Laser light is highly directional, monochromatic and of high intensity. Lasers are of variable sizes ranging from approximately few micrometres to few metres. Power of a laser beam is enormous ranging from nanowatts to zettawatts (10^{21} W) for very short bursts or pulses of very short duration ($\sim 5\times10^{-15}$ s). Laser light is generally not used for lighting in our homes or streets. This is because they are costlier than their ordinary light counterpart of the same power and the same colour. Moreover, there are serious safety issues involved.

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The process of stimulated emission of radiation was first identified by Einstein. The electrons in the atom are found in particular energy levels. They are moved to higher-lying (say excited) levels by getting energy from the external source. These excited electrons come back to lower-lying (say ground) levels within a period of time called the lifetime of the level. When light beam interacts with atoms that have electrons residing in various energy levels, three types of processes (spontaneous emission, absorption and stimulated emission) can happen (Fig. 1).

First, when an electron spontaneously jumps from excited state to the ground state, a photon of particular frequency is radiated out. This process is known as spontaneous emission as indicated in Fig. 1(a). The frequency of emitted photon depends on the energy difference ($E_{21}=h\nu_{21}=hc/\lambda_{21}$) of the two energy levels (2 and 1 in this case). Most of the excited energy levels undergo spontaneous emission. Lifetime of excited energy level is determined by the interactions of the electron with the other electrons and nuclei of that atom. It is of the order of 10–100 ns for visible portion of the spectrum. The ground state has infinite lifetime as it cannot decay further. The energy levels of different materials are arranged differently and thus we get different colours of light emitted by them which are specific to the material. Spontaneous emission is responsible for nearly all the light we see.

The second process is absorption, shown in Fig. 1(b), which occurs if the atom has its electron in level 1 and a photon of light of energy E_{21} collides with the atom. In this process, the photon is absorbed by the atom and the electron is moved up to the higher energy level 2. This process is the way light interacts with practically all of matter. It enhances the energy of the atom and incident photon is disappeared (eliminated). Absorption often leads to heating of the absorbing material.

The third process, shown in Fig. 1(c), is referred to as stimulated emission. It results when an electron is already in a higher-lying level, such as level 2, and a photon of energy E_{21} collides with the atom. This photon

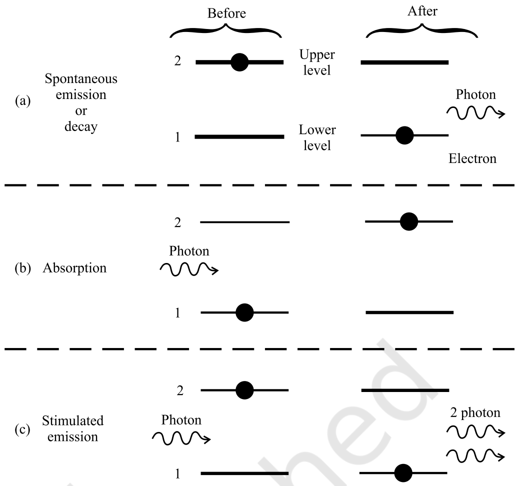

Fig. 1 The three radiation processes that can occur when light interacts with matter (atoms)

stimulates the atom to radiate a second photon having exactly the same energy E_{21} as that of the incident photon and travelling in exactly the same direction in order to satisfy the laws of conservation of energy and momentum. Hence, one photon leads to two identical photons, leading to an amplification process. The amplification of light is at the expense of the loss of energy stored within the atom. This process is responsible for the operation of laser.

Generally the electrons in the higher-lying levels are less than that in the lower-lying levels at room temperature. When number of electrons is increased in the higher-lying levels by pumping them from external source, the population in lower-lying levels is decreased and this situation is known as population inversion. Population inversion resulting in stimulated emission is the basic requirement for getting a laser action. Moreover, for continuous amplification of light, the emitted photons of same energy should not be lost from the material except in the form of exit beam. Keeping these in view, the following are the requirements for a typical laser device (Fig. 2):

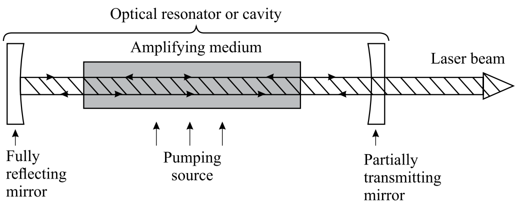

Fig. 2 Basic laser components including gain medium, pumping source, and mirror cavity

1. Amplify or gain medium
2. Pumping source to input energy into the device, and
3. An optical cavity or mirror arrangement that reflects the beam of light back and forth through the gain medium for further amplification.

Laser gain medium

Laser gain medium refers to radiating species, where electrons in excited states jump to lower-lying levels as a result of stimulation by the pumping agency. These radiating species can include: atoms such as in the red helium-neon (He-Ne) laser, molecules such as in the infrared carbon dioxide (CO_2) laser, liquids such as those involving various organic dye molecules dilutely dissolved in various solvent solutions, dielectric solids such as those involving neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers, semiconductor materials such as gallium arsenide or indium phosphide crystals. In each of the above species, there is a lowest energy level referred to as the ground state and various excited energy states.

Laser pumping sources

The means, by which energy is transferred into the laser gain medium to produce the required population inversion, are known as laser pumping sources. Two types of pumping is generally used— electron pumping and optical pumping.

Electron pumping is used primarily in gaseous or semiconductor gain media. When few initial electrons are accelerated by an electric field in gaseous media and they collide to atoms, some of the atoms are ionized. Electrons are liberated in the ionization process. These liberated electrons are also accelerated and an avalanche of electrons is produced. In semiconductors, the electrons flow through the semiconducting material by applying a voltage across the *p-n* junction with the positive voltage on the side of the p-type material. This leads to recombination radiation when the electrons combine with the holes in the junction. Optical pumping of lasers generally applies to the pumping of liquid (dye) lasers and to dielectric solid-state lasers and is provided by either flash lamps or other lasers. A voltage is applied across the electrodes of the flash lamp and current flows through the gas, populating excited levels of the atoms within the gas that radiate and produce intense light emission. Xenon is the most common species used in flash lamps.

Laser mirrors

The properties of laser beam such as direction and divergence of the beam, the beam profile, and the wavelength and frequency characteristics of the laser are determined largely by the laser mirrors. The factors determining those properties include mirror curvature, surface quality, and reflectivity as well as separation and location, assuming that the structure holding the mirrors is a secure, vibration-free structure. The unique electromagnetic wave properties produced by the mirrors are referred to as modes.

Examples of common lasers are He-Ne laser, Argon ion and Krypton ion laser, He-Cd laser, Copper vapour laser, CO_2 laser, Excimer laser, Organic dye laser, Ruby laser, Nd:YAG and Nd:glass laser, Ti:Al_2O_3 laser, Erbium fiber laser, Semiconductor lasers (solid state). Some of the laser properties which make them extremely useful for diverse applications are collimation, monochromaticity, coherence, intensity and focusability. Most of these properties are interrelated. Still, only one of the properties is typically sought for a specific application.

Optical Fiber

Communication is an essential need of human being and it is becoming fast and more reliable in spite of the enormous increase in signal traffic. This became possible largely due to the availability of optical fibers. It is an established fact that the carrier frequencies associated with TV broadcast (~50–900 MHz) are much higher than those associated with AM radio broadcast (~600 kHz–20 MHz). More information can be sent by increasing the carrier frequency. The visible light has its frequency in the range of 10^{14} to 10^{15} Hz and one can expect tremendously large information-transmission capacity as compared to radio waves or microwaves.

It is worth to mention here that the idea of using light waves as a carrier wave was tried way back in 1880 by Alexander Graham Bell, who invented the photophone shortly after he invented the telephone in 1876. In this remarkable experiment, speech was transmitted by modulating a light beam, which travelled through air to the receiver. The flexible reflecting diaphragm (which could be activated by sound) was illuminated by sunlight. The reflected light was received by a parabolic reflector placed at a distance of about 200 m. The parabolic reflector concentrated the light on a photoconducting selenium cell, which formed a part of a circuit with a battery and a receiving earphone. Sound waves present in the vicinity of the diaphragm vibrated the diaphragm, which led to a consequent variation of the light reflected by the diaphragm. The variation of the light falling on the selenium cell changed the electrical conductivity of the cell, which in turn changed the current in the electrical circuit. This changing current reproduced the sound on the earphone.

After succeeding in transmitting a voice signal over 200 metres using a light signal, Bell wrote to his father: "I have heard a ray of light laugh and sing. We may talk by light to any visible distance without any conducting wire." To quote from Maclean: "In 1880 he (Graham Bell) produced his 'photophone' which to the end of his life, he insisted was '.... the greatest invention I have ever made, greater than the telephone...' Unlike the telephone, though, it had no commercial value."

The idea of using light waves as carrier waves for telecommunication didn't become a reality, because no suitable light source was available. The hopes were again high after the discovery of the laser in 1960. Still, there were no optical analogues of conventional communication systems because guiding the laser beam to long distances was a difficult task due to scattering and absorption by the atmosphere. This guiding of the light is done by the optical fiber, a hair-thin structure. The light is confined within the fiber because of total internal reflection. Transmission speed of about 2.5 Gbit/s (35,000 or more simultaneous telephone conversations) is possible through one glass fiber. Optical fibers are also characterised by extremely low losses (< 0.2 dB/km). It is worth to mention that it was historical paper of Kao and Hockham in 1966 that suggested that optical fibers based on silica glass could provide the necessary transmission medium. Indeed, this 1966 paper triggered the beginning of serious research in developing low-loss optical fibers. In 1970, Kapron, Keck, and Maurer (at Corning Glass in USA) were successful in producing silica fibers with a loss of about 17 dB/km at a wavelength of 633 nm. Since then, the progress in optical fibers technology has been phenomenal with routine production of optical fibers with extremely low losses (< 0.2 dB/km). Fig. 3 shows a typical optical fiber communication system. It consists of a transmitter, which could be either a laser diode or an LED, the light from which is coupled into an optical fiber. Along the path of the optical fiber are splices, which are permanent joints between sections of fibers, and repeaters that boost the signal and correct any distortion that may

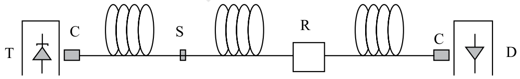

Fig. 3: A typical fiber optic communication system: T, transmitter; C, connector; S, splice; R, repeater; D, detector

have occurred along the path of the fiber. At the end of the link, the light is detected by a photodetector and electronically processed to retrieve the signal.

Total Internal Reflection (TIR) in Optical Fibers

Whenever light travels from denser to rarer medium and its angle of incidence is greater than the critical angle, it reflects back in the denser medium without any refraction as shown in Fig. 4. (a-c). This phenomenon is known as total internal reflection (TIR).

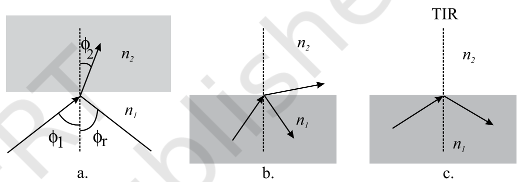

Fig. 4 (a) mA ray of light incident on a denser medium ($n_2 > n_1$). (b) A ray incident on a rarer medium ($n_2 < n_1$). (c) For $n_2 < n_1$, if the angle of incidence is greater than critical angle, it will undergo total internal reflection.

A typical optical fiber (Fig. 5a) consists of a (cylindrical) central dielectric core clad by a material of slightly lower refractive index (cladding). The refractive index of core (n_1) is greater than the refractive index of cladding (n_2). The cladding is usually pure silica while the core is usually silica doped with germanium. If a light ray enters through the end of a fiber core at the angle of incidence φ (at the internal core-cladding interface) which is greater than the critical angle φ_c [= $\sin^{-1}$ (n_2/n_1)], the ray will undergo TIR at that interface. Further, this ray will suffer TIR at the lower interface also leading to repeated total internal reflections within core (Fig. 5b). When fiber is bent, then also the light is confined in the fiber, if incident within acceptance cone. The material

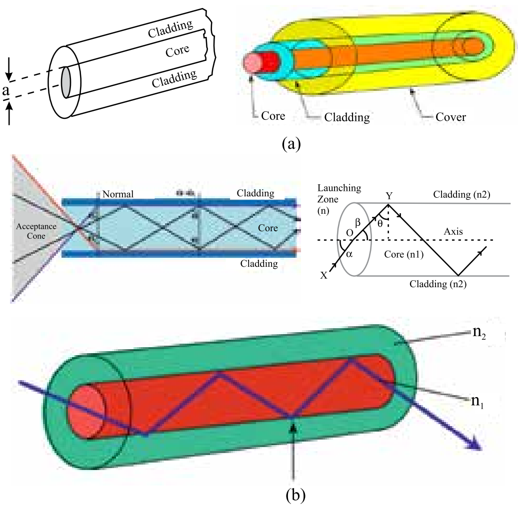

Fig. 5: A glass fiber consists of a cylindrical central core clad by a material of slightly lower refractive index. (b) Light rays impinging on the core-cladding interface at an angle greater than the critical angle are trapped inside the core of the fiber.

of the optical fiber should absorb very little amount of light, be temperature sensitive and should have considerable strength. All these requirements are fulfilled by the glass (silica). Typically, for commercially available silica fibers, if light signal is transmitted through 1 km of optical fiber, only 4% of the power is lost. This is remarkable achievement.

Optoelectronic Devices

Optoelectronics is an important field of photonics, where a useful interaction between semiconducting materials and light is explored for the origin, control and detection of light. The list of these devices is very long. We would like to discuss three important optoelectronic devices here: photo diode, solar cell and LED. In these semiconducting junction devices, either light controls the charge carriers or the light is controlled by the charge carriers.

Photodiode

A photodiode is a specially designed p-n junction diode, where light is allowed to fall on the junction region through a transparent window. It is operated under reverse bias. When the photodiode is illuminated with light (photons) with energy greater than the band gap of the semiconductor, then electrons are shifted from valence band to conduction band leaving vacancies behind as holes. Thus electron-hole (e-h) pairs are generated near the depletion region of the diode. The electrons and holes are separated before they recombine because of the in-built electric field of the depletion region. The direction of the electric field is such that electrons reach n-side and holes reach p-side. Electrons are collected on n-side and holes are collected on p-side giving rise to an emf. When an external load is connected, current flows in the circuit. On increasing intensity of light, more e-h pairs are generated and higher current flows in the circuit. It is easier to observe the change in the current with change in the light intensity, when a reverse bias is applied. Thus photodiode can be used as a photodetector to detect optical signals. The circuit diagram used for the measurement of *I-V* characteristics of a photodiode is shown in Fig. 6(a) and a typical *I-V* characteristic is shown in Fig. 6(b).

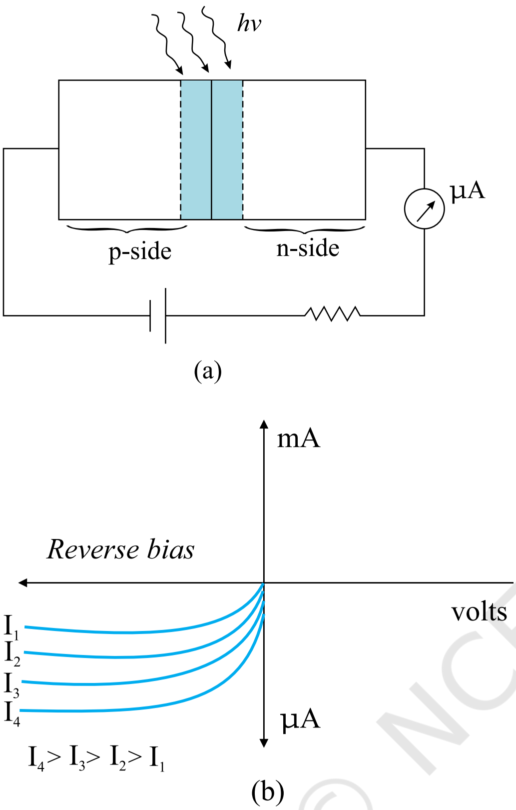

Fig. 6 (a) An illuminated photodiode under reverse bias, (b) *I-V* characteristics of a photodiode for different illumination intensity $I_4 > I_3 > I_2 > I_1$.

Solar Cell

Solar cell (also known as photovoltaic cell) is a device, which converts sunlight into electricity. However, it should be noted that apart from sunlight, other types of light can also be used for a solar cell. Solar cell is basically a p-n junction diode working in the same way as photodiode, but solar cell has no external bias and it has more area to be exposed by sunlight. The material used for solar cell should have its band gap less than the energy of incident light. In order to reach the sufficient light to the junction area, the material should be of high optical absorption. Electrical conductivity, availability of the material and cost are another important factors behind the selection of materials for solar cell. Semiconductors with band gap E_g close to 1.5 eV are ideal materials for solar cell fabrication. Solar cells are made with semiconductors like Si (E_g= 1.1 eV), GaAs (E_g = 1.43 eV), CdTe (E_g= 1.45 eV), $CuInSe_2$ (E_g = 1.04 eV), etc.

A typical solar cell is shown in Fig. 7. A p-Si wafer of about 300 µm is taken, over which a thin layer (~0.3 µm) of n-Si is grown on one-side by diffusion process. The other side of p-Si is coated with a metal (back contact). On the top of n-Si layer, metal finger electrode (or metallic grid) is deposited. This acts as a front contact. The metallic grid occupies only a very small fraction of the cell area (<15%) so that light can be incident on the cell from the top.

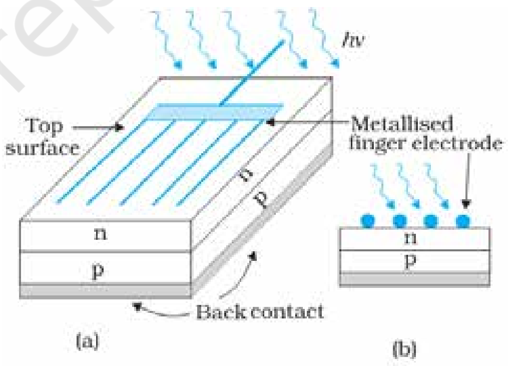

Fig.7 (a) Typical p-n junction solar cell; (b) Cross-sectional view.

The mechanism of solar cell involves three basic processes to produce the electricity, which are: (1) Formation of electron-hole pairs due to solar light close to the junction,

(2) Separation of electrons and holes due to electric field of the depletion region, and (3) Collection of the electrons reaching the n-side by the front contact and collection of holes reaching to p-side by the back contact. In this way, p-side of the cell becomes positive and n-side becomes negative giving rise to photo-voltage. When solar cell is connected through an external load, a photocurrent I_L flows through it as shown in Fig. 8a. Photocurrent depends upon the intensity of light falling on the cell. A typical I-V characteristic of a solar cell is shown in the Fig. 8b drawn in the fourth quadrant of the coordinate axes. This is because a solar cell does not draw current but supplies the current to the load.

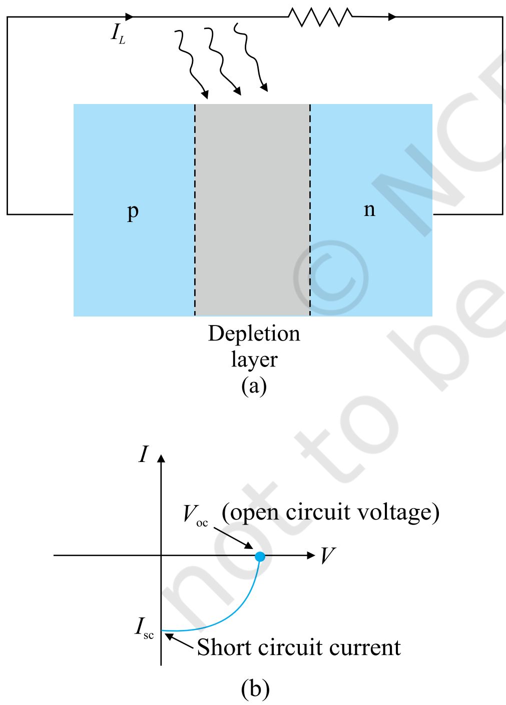

Fig. 8 (a) A typical illuminated p-n junction solar cell; (b) I-V characteristics of a solar cell.

Apart from its general use in daily life for the electricity, Solar cells are particularly used to power electronic devices in satellites and space vehicles and also as power supply to some calculators. The future challenge in the solar cell technology is to reduce the cost and increase the efficiency.

Light emitting diode

You would be familiar with the bright and colourful light of LED. The word LED is an acronym for Light Emitting Diode, which converts electrical energy into light. LED is a heavily doped p-n junction which under forward bias emits spontaneous radiation. The diode is encapsulated with a transparent cover to allow the emitted light to come out. When a voltage is applied across the junction in forward bias, electrons are able to move from n-side to p-side where they are minority carriers. In the same way holes are also injected from p-side to n-side, but less in number. The current is primarily due to the flow of electrons into the p-side. The electrons injected into the p-side recombine with the holes and the holes injected into the n-side recombine with the electrons. The recombination of e-h pairs results in spontaneous emission of photons (light) as shown in Fig. 9. The wavelength or colour of the emitted light depends on the band gap of the material. The semiconductor used for fabrication of visible LEDs must at least have a band gap of 1.8 eV (spectral range of visible light is from about 0.4 μm to 0.7 μm, i.e., from about 3 eV to 1.8 eV). LEDs are available in different colours of red, yellow, orange, green and blue. The compound semiconductor Gallium Arsenide – Phosphide ($GaAs_{1-x}P_x$) is used for making LEDs of different colours. $GaAs_{0.6}P_{0.4}$ (E_g ~ 1.9 eV) is used for red LED.

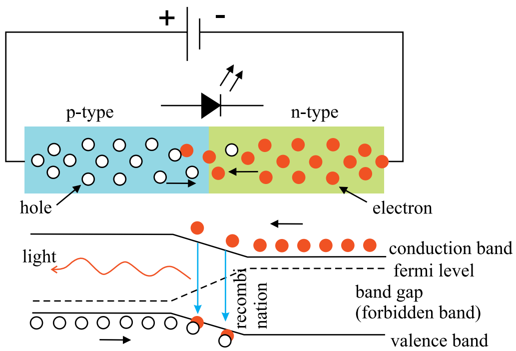

Fig. 9: The inner workings of an LED, showing circuit (top) and band diagram (bottom) (adopted from Wikipedia)

GaAs (E_g~ 1.4 eV) is used for making infrared LED.

The intensity of the light produced by LED is function of forward current of the diode. It first increases with the increase in forward current and then decreases after further increase in the forward current. LEDs are biased such that the light emitting efficiency is maximum. The I-V characteristic of an LED is similar to that of a Si junction diode. But the threshold voltages are much higher and slightly different for each colour. The reverse breakdown voltages of LEDs are very low, typically around 5 V. LEDs have the following advantages over conventional incandescent low power lamps:

(i) Low operational voltage and less power.

(ii) Fast action and no warm-up time required.

(iii) The bandwidth of emitted light is 100 Å to 500 Å or in other words it is nearly (but not exactly) monochromatic.

(iv) Long life, light weight, smaller size and ruggedness.

(v) Fast on-off switching capability.

(vi) Do not contain toxic material like mercury.

The LEDs are extensively used in remote controls, burglar alarm systems, optical communication, traffic signals, digital computers, camera flashes, aviation lighting, etc. Extensive research is being done for developing white LEDs which can replace incandescent lamps.

Application of Photonics

Photonics finds its use almost in all spheres of the life. It has contributed remarkably in the advancement of various technologies. Information technology and telecommunications have benefitted a lot by photonics. Transport and processing of information became fast, optical storage has increased manifold and displays became better. Photonics offers new and unique solutions where today's conventional technologies are approaching their limits in terms of speed, capacity and accuracy. It is very difficult to imagine the world today without photonics. It has tremendous applications in various fields and many more are yet to come. Let us have a glimpse of these:

Photonics in our daily life

Whatever comes to us in daily life is linked to photonics in direct or indirect way. Few examples are— Infrared remote controls, TV flat panel or large screen, compact disc players, Laser light shows, IR motion sensors for home security, video disk players, alarm clock radio with LED display, IR noncontact "ear" thermometers, and infrared remote headphones. In offices, the frequently used tools such as optical scanners, fax machines, optical data storage, laser printers, photocopiers, overhead slide projectors, video teleconferences, laser pointers, computer active matrix displays, computer displays, and infrared remote connections are all because of photonics. In cars, the comfort and control provided by the Infrared security systems, optical monitors for antilock brakes, optical fiber dashboard displays, LED traffic signals, laser traffic radar, and solar-powered emergency services are manifestation of photonics. In stores, supermarket bar-code scanners and credit card holograms include photonics.

Photonics in Healthcare and Life Sciences

With the ability of light to detect and measure in a fast, sensitive and accurate way, photonics has an extensive role in health care and life sciences. It can detect diseases at an early stage with non-invasive imaging techniques or point-of-care applications. From diagnosis to therapy, photonics finds an indispensable role to play in the sector of healthcare. One can find the success stories of cataract treatment with CPA laser technology by LASIK (Fig. 10) very frequently in newspapers. Ultrafast lasers (femtosecond lasers) can be employed for the treatment of Glaucoma as well. Lasers are useful for cancer treatment also by killing the ill cells selectively. New avenues are being explored in cardiovascular medicine by the use of photonics technology in the form of intracoronary imaging and sensing, laser ablation and optical pacing. Lasers can be used for analysis of blood flow inside the tooth for painless laser tooth pulp vitality check.

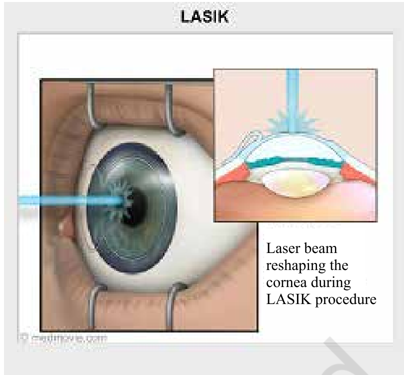

Fig. 10: LASIK procedure

Dermatological conditions can be monitored and cared by the use of phototherapy. In general surgery such as endovascular surgery and gastro intestinal surgery, lasers are used extensively. Fig. 11 shows a schematic diagram of non-invasive treatment for brain tumours with Cyberknife system which works by delivering beams of high dose radiation to tumours with extreme accuracy. A laser scalpel is extremely useful in surgery, cutting and ablating living biological tissue with tremendous light energy. Photonics is also used in the manufacturing of medical devices, for example stents and catheters. It is an important tool in genomic research, microbiology (viral and bacterial analysis) and drug discovery because analysis of

Fig. 11: Non-invasive treatment for brain tumours with Cyberknife system which works by delivering beams of high dose radiation to tumours with extreme accuracy.

processes at the molecular level gives a greater understanding of the origin of diseases, and hence allowing prevention and new treatments. Sterilization of medical tools is done using light sources. There are novel biomedical materials that change their properties after light treatment. Photonics is used in in-vivo imaging techniques, such as X-ray, MRI, CT, PET, photoacoustic imaging and OCT. In-vitro diagnostics, for cell-based studies to identify diseases such as cancer and neurodegenerative diseases is done using optical microscopy and spectroscopy. Photonic technologies also play a major role in addressing the needs of our ageing society: from pace-makers to synthetic bones and from endoscopes to the micro-cameras used in in-vivo processes.

Photonics and Energy Saving

Today's world is energy driven world and in order to have a sustainable world, the need of renewable and clean energy is obvious. Solid state lighting (SSL) based on light emitting diode (LED) and organic LED (OLED) technologies are energy efficient, cost-effective and provide higher quality lighting. Apart from these, SSL lighting is robust, has more life time, has dimming and colour tenability and hence it is easy to shape and adjust the lighting environment to accommodate individual needs.

Telecommunication

It is difficult to imagine life without information and communication technology (ICT) in modern time. The whole world has become a global village, any information is at your fingertip, and access to services is as easy as never before. This is an era of easily accessible and fast internet with immediate transfer of information whether in the form of e-mail or social networking sites or e-commerce activities. Users of internet have increased substantially to remote areas. All these became possible because of the new advances in optical fiber technology which provides very large bandwidth for transmission of signals. It is now possible to send data beyond a terabit per second (>1000 Gb/s) over distances in excess of 100 km. This is equivalent to transmitting more than 10 million simultaneous phone calls through a single hair-size glass fiber. At this speed, one can transmit 100,000 books coast to coast in 1 second!

Safety and Security

Photonics can also be useful in safety and security of the people, property and environment. It can reliably detect potential hazards. Contactless sensors are possible to make with photonics. Detecting structural defects in the building sector, security applications like biometrics and border security systems, video surveillance systems and equipment to detect dangerous or illegal goods are only to name a few, where photonics has major role to play.

High Quality Manufacturing

Laser processing has become essential for high-volume, cost-effective and precision manufacturing. They are used for treatment of plastics in the automotive industry, for the manufacture of solar cells, semiconductors and miniaturised components for use in medical technology, etc.

Defense

The properties of high intensity, good spectral brightness and very less divergence of a laser beam make them very useful in warfare. Laser range finders (LRF), laser guided bombs, target trackers, and simulators of weapon training are some of the devices and equipment based on photonics technology. These devices use laser as source with optical components and electronic instrumentation for measurement and fire control. More recent in the series are beam weapons for destroying targets, thermal imaging for night viewing, surveillance (airborne and satellite platforms), and concepts of multisensory fusion and countermeasures.

The short wavelength of optical radiation compared to the microwave radar makes it possible to distinguish different specific targets at distances up to 10-20 km. These radars can range the target area at low grazing angles and the possibility of the direct interruption of the beam is considerably reduced. Laser range finders are developed for maximum range of 10-20 km with range accuracy of ±5 m. Different versions of LRFs are available for use in infantry, artillery, tanks, observation posts, and aircraft. LRFs are now available in the form of handheld binoculars. Guidance of weapons by laser assisted technology (smart bomb) is another important use of photonics in warfare. In modern low flying aircrafts used for ground attack, suitable laser instrumentation is provided for range finding and target designation capabilities for seeking the target, measuring its range, and sending the weapon onto it thereby reducing the human element to the minimum.

Tracking of spy satellites can be done by laser. The laser beam of high intensity and high directivity is sent to the satellite (or high flying airborne platforms including missile and aircraft) and return echo is used to keep the target in view. Laser-based weapon simulators have the advantage of saving ammunition during training exercise. Laser weapons are so destructive because a large quantity of energy is delivered on a small area in a short time. Heat deposited by a continuous beam, shock waves produced by a pulsed beam, or a combination of thermal and shock produced by a series of rapid pulses can penetrate the skin of the target. The intense laser beam disables the guidance system of warhead, or triggers an explosion of the fuel or warhead. Underwater TV surveillance systems based on optical fibers are already in use. In numerous applications, from infantry weapons to airborne ground attack systems, photonics provide the ability to see, detect, recognise and engage targets with speed, clarity and precision that no other systems can match.

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