CHAPTER 3: THE BASIC THEORY OF THE POLARIZATION OF LIGHT

3.1 Introduction

Interference and diffraction phenomena proved that light is a wave motion and enabled the determination of the wavelength. However, they do not give any indication regarding the character of the waves. Whether the light waves are longitudinal or transverse, or whether the vibrations are linear or circular cannot be deduced from the above two phenomena, as all kinds of waves under suitable conditions exhibit interference and diffraction. In 1816, Arago and Fresnel showed that light waves vibrating in mutually perpendicular planes do not interfere. In 1817, Thomas Young explained the absence of interference by postulating that light waves are transverse waves. About fifty years later, Maxwell developed electromagnetic theory and suggested that light waves are electromagnetic waves. As electromagnetic waves are transverse waves, it is obvious that light waves too are transverse waves. The concept of transverse nature leads to the concept of polarization. Light coming from common light sources is unpolarized. The state of polarization cannot be detected by unaided human eye. An understanding of polarization is essential for understanding the propagation of electromagnetic waves guided through waveguides and optical fibres. Polarized light has many important applications in industry and engineering. One of the most important applications is in liquid crystal displays (LCDs) which are widely used in wristwatches, calculators, TV screens etc. Polarization also plays an important role in the interaction of light with matter, as attested by the following examples:

(i) the amount of light reflected at the boundary between two materials depends on the polarization of the incident wave

(ii) the amount of light absorbed by certain materials is polarization dependent

(iii) light scattering from matter is generally polarization sensitive

(iv) the refractive index of anisotropic materials depends on the polarization. Waves with different polarizations travel at different velocities and undergo different phase shifts, so that the polarization ellipse is modified as the wave advances. This property is used in the design of many optical devices.

(v) the polarization plane of linearly polarized light is rotated by passage through certain media, including those that are optically active, liquid crystals and certain substances in the presence of an external magnetic field.

3.2 Light Propagation and Maxwell's Equations

Propagation of light is an electromagnetic phenomenon. Light waves are known to behave like any other electromagnetic wave. The physical laws describing propagation, reflection, refraction, attenuation of electromagnetic waves accurately describe the behaviour of light waves. In the electromagnetic theory of light, the mechanical displacement of the medium is replaced by a variation of the electric field at the corresponding point. The light wave consists of varying electric and magnetic fields and can be described by two vectors – the amplitude of electric field strength, **E**, and the amplitude of the magnetic field strength, **B**. These vectors oscillate at right angles to each other and to the direction of propagation. They cannot be separated. Thus a beam of light is a travelling configuration of electric and magnetic fields. The electromagnetic theory was developed by James Clerk Maxwell in 1873. The first and foremost outcome of Maxwell's equations was the prediction of existence of electromagnetic waves and the brilliant prediction that light waves are electromagnetic waves. Starting from Maxwell's equations, the propagation of light waves in space and materials can be easily explained and all the fundamental laws of optics can be derived. Expressions to calculate the reflectivity, transmissivity and absorptivity of material media can be obtained from these equations. Furthermore, the electromagnetic theory explains the origin of refractive index and the dispersion properties of optical media.

In all, there are four Maxwell’s equations. These equations cannot be derived since they are the fundamental axioms or postulates of electrodynamics, obtained with the help of generalization of experimental results.

The Maxwell’s equations are expressed in differential form and integral form in the following Table 3.1:

Table 3.1: Maxwell's Equations and their respective differential and integral forms.

Law	**Differential Form**	**Integral Form**
Gauss’s law	$\nabla.\mathbf{D} = \rho$	$\oint \mathbf{D}.\, d\mathbf{S} = \int \rho \, dV$
Faraday’s law	$\nabla \text{ x } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint \mathbf{E}.\, d\mathbf{l} = -\int_S \frac{\partial \mathbf{B}}{\partial t}.\, \mathbf{dS}$
Gauss’s law for magnetism	$\nabla.\mathbf{B} = 0$	$\oint \mathbf{B}.\mathbf{dS} = 0$
Ampere’s law	$\nabla.\mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint \mathbf{H}.\mathbf{dl} = \int [\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}] \,.\, \mathbf{dS}$

Maxwell showed that by combining the four equations, a wave equation was obtained which described the propagation of waves. The time variation of a magnetic field induces an electric field, while the variation of an electric field induces a magnetic field and electromagnetic fields can exist independently without electric charges and current. The continuous interconversion of the fields preserves them and an electromagnetic perturbation propagates in free space. Such fields are called **electromagnetic waves**. The generation of electromagnetic wave does not require any medium. The electromagnetic waves propagate through space entirely on their own. Maxwell’s theory placed no restriction on possible wavelengths for the electromagnetic radiation.

In some types of electromagnetic waves, the electric field vector **E** is at right angles to the ray while the magnetic vector **B** is not. Waves of this type are called **transverse electric waves** or **TE** waves. Since **B** vector is not normal to the ray, it must have a component along the ray direction. In another type of waves, the magnetic vector is at right angles to the ray while the electric vector **E** is not. Waves of this type are called **transverse magnetic waves** or **TM** waves. If both the **E** and **B** are at right angles to the ray, the waves are called **transverse electromagnetic waves** or **TEM** waves.

3.3 Unpolarized Light

An ordinary light consists of a very large number of atomic emitters. Each atom radiates a plane-polarized wave train. As time progresses, the orientation of the plane of polarization changes randomly and rapidly. Human eyes cannot respond to such rapid changes. In the time that the eye responds to light, millions of wave trains are emitted by the source. Furthermore, the frequencies of the wave trains are not exactly identical. Thus, ordinary light comprises of a heterogeneous group of wave trains having different wavelengths and vibrating in different planes perpendicular to the direction in which the ray is propagating (Figure 3.1). The random orientation of the planes of polarization leads to equal probability of all directions about the propagation direction, as shown in Figure 3.2. Therefore, in natural light, the optical vector has no specific favoured orientation. Light in which the planes of vibration are symmetrically distributed about the propagation direction of the wave is known as the unpolarized light.

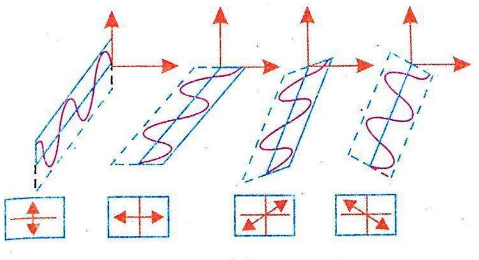

Figure 3.1: Unpolarized light with component waves having different planes of polarization.

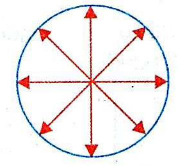

Figure 3.2: A schematic representation of unpolarized light in all directions.

Each optical vector in unpolarized light may be resolved into two rectangular components lying parallel and perpendicular to a chosen direction (Figure 3.3). In the case here, only two vectors are use, as shown in Figure 3.3, for representing unpolarized light. Due to the random distribution of the optical vectors, the amplitude of the component vectors will be equal. Therefore, if the intensity of the incident unpolarized light is I_o, the intensity of each component will be $\frac{1}{2}$ I_o. Thus, the intensity of unpolarized light ids equally distributed between the two components.

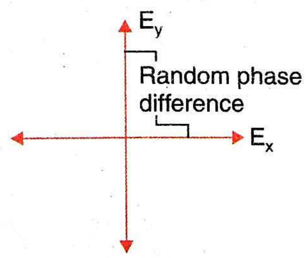

Figure 3.3: Random phase direction of unpolarized light.

3.4 Polarization of Light

A wave in which every particle of the medium oscillates up and down at right angles to the direction of wave propagation is called a transverse wave. In a transverse wave, the direction of particle displacement occurs perpendicular to the wave propagation. Hence, the direction normal to the wave propagation is the preferential direction in a transverse wave.

The existence of a preferential direction leads to the characteristic phenomenon known as **polarization** of transverse waves.

An electromagnetic wave is a transverse wave consisting of electric and magnetic fields vibrating perpendicular to each other and to the direction of propagation. The vibrating electric vector **E** and the direction of wave propagation form a plane. This plane was called the plane of vibration. It has become common nowadays to refer to it as the **plane of polarization**. The same notation is adopted and the plane of polarization of the wave is defined as the plane which contains the optical vector **E** and the direction of propagation.

The simplest type of an electromagnetic wave is a wave in which the direction of vibrations of electric vector **E** is strictly confined to a single direction in the plane perpendicular to the direction of propagation of the wave. Such a light is said to be *plane-polarized* light. If the wave is coming towards the eye, the electric vector appears executing a linear vibration normal to the ray direction. Hence, a plane-polarized wave is also known as a linearly polarized wave. The following definitions are offered:

A **plane-polarized** light is a wave in which the electric vector is everywhere confined to a single plane.

A **linearly polarized** light wave is a wave in which the electric vector oscillates in a given, constant orientation.

As discussed before, the polarization of an electromagnetic wave is taken as the direction of the **E** vector. It describes the shape and locus of the tip of the **E** vector in the plane orthogonal to the direction of propagation at a given point in space as a function of time. The direction of the field vector at some point in space and time lies along a line in a plane perpendicular to the direction of propagation.

If a cross-sectional view of the wave in the xy-plane at $z = 0$ is taken, the magnitude of the field vectors is observed to vary sinusoidally (Figure 3.4). The field vectors reverse direction with each half-cycle but this variation is always along a line (the $\pm y$ direction for **E** and the $\pm x$ direction for **B**). Since the direction of the field vectors at some point in space and every point in time lies along a line in a plane perpendicular to the direction of propagation, the wave is said to be **linearly polarized**. Thus, the uniform plane waves are **linearly polarized**.

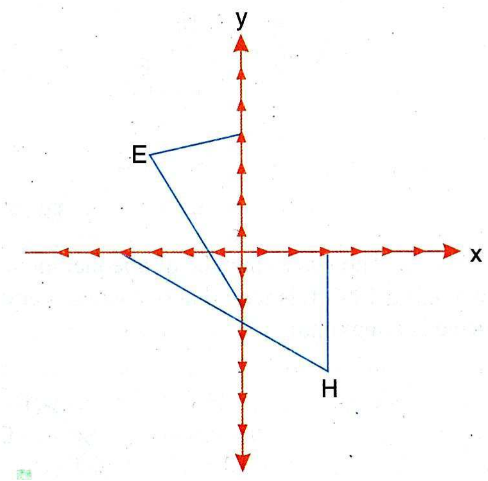

Figure 3.4: The linearly-polarized uniform plane wave as a function of time at $z = 0$.

In general, waves can either have E_y or E_x components when travelling in z-direction. If a wave has E_y component, the wave is polarized along y-direction and if the wave has E_x component, it is polarized along x-direction. If two coherent and linearly polarized waves polarized in mutually perpendicular directions propagate in the same direction, they combine to give a resultant wave whose state of polarization depends on their phase difference.

If the waves are of equal or of unequal intensity ($E_y = E_x$ or $E_y \neq E_x$) and are in phase, they may be represented by

$$E_1 = E_y \sin(\omega t - kz) \quad \ldots.. \ (3.1)$$

and

$$E_2 = E_x \sin(\omega t - kz) \quad \ldots.. \ (3.2)$$

These two waves may be considered as the rectangular components of a wave. The waves are shown in Figure 3.5.

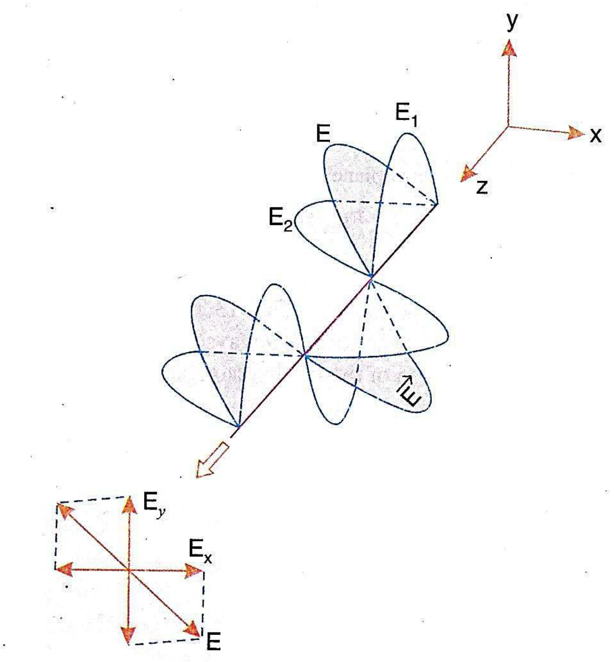

Figure 3.5: Rectangular components of a wave and when combined, yields a linearly polarized wave.

They combine to yield a linearly polarized wave, shown in Figure 3.5 also.

3.5 Generation of Polarized Light

Linearly polarized light may be produced from unpolarized light using one of the following five optical phenomena:

(i) reflection

(ii) refraction

(iii) scattering

(iv) selective absorption

(v) double refraction

In the work here, only polarization by selective absorption will be discussed as the broadband polarizer works by selective absorption.

3.5.1 Polarization by Selective Absorption

In 1815, Biot discovered that certain mineral crystals absorb light selectively. When natural light passes through a crystal such as tourmaline, it is split into two components, which are polarized in mutually perpendicular planes. The crystal strongly absorbs light that is polarized in a direction parallel to a particular plane in the crystal but freely transmits the light component polarized in a perpendicular direction. This difference in the absorption for the rays is known as selective absorption. If the crystal is of proper thickness, one of the components is totally absorbed and the other component emerging from the crystal is linearly polarized. Selective absorption is illustrated in Figure 3.6.

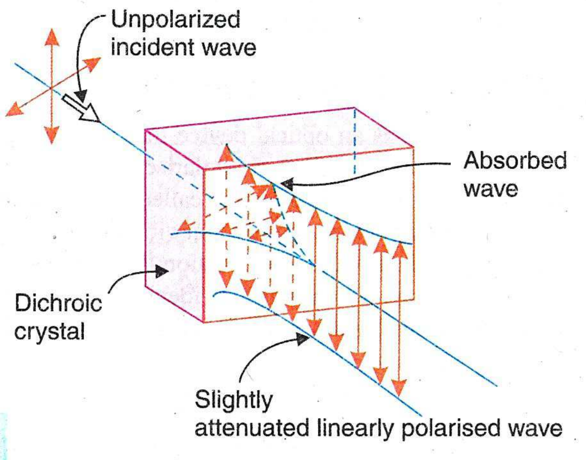

Figure 3.6: Schematic illustration of selective absorption of waves in a dichroic crystal.

The difference in absorption in different directions may be understood from the electron theory. When the frequency of the incident light wave is close to the natural frequency of the electron cloud, the light waves are absorbed strongly. Crystals that exhibit selective absorption are anisotropic. The crystal splits the incident wave into two waves. If the light wave frequency is close to the natural frequency of the electron cloud, the component having its vibrations perpendicular to the principle plane of the crystal gets absorbed. The component with parallel vibrations is less absorbed and transmitted. The transmitted light is linearly polarized.

3.6 Anisotropic Dielectric Property

Dielectric medium is said to be anisotropic if its macroscopic optical properties depend on direction. The macroscopic properties of a material are eventually governed by its microscopic properties: the shape and orientation of the individual molecules and the organization of their centres in space. Optical materials have different kinds of positional and orientational types of order, which may be described as follows:

isotropic – the molecules are located at totally random directions. Some examples of isotropic materials are gases, liquids and amorphous solids.

polycrystalline – the structure takes the form of disjointed crystalline grains that are randomly oriented with respect to each other. The individual grains are in general anisotropic but their averaged macroscopic behaviour is isotropic.

anisotropic – the molecules are organized in space according to a regular periodic pattern and they are oriented in the same direction. An example of anisotropic material would be crystals. If the molecules are anisotropic and their orientations are not totally random, the medium is anisotropic even if their positions are totally random. An example for this would be liquid crystals, which have orientational order but lack complete positional order.

When a light beam is incident on a isotropic medium, it refracts as a single ray. An optically isotropic material is one in which the index of refraction is the same in all directions. The atoms in a crystal are arranged in a regular periodic manner. If the arrangement of atoms differs in different directions within a crystal, the physical properties vary with the direction. The refractive index hence depends on the crystallographic direction along which the property is measured. The crystal is said to be *anisotropic*.

In anisotropic crystals, the force of interaction between the electron cloud and the lattice is different in different crystallographic directions. The natural frequency of the electron cloud is likewise dependent on the direction in which the electrons are caused to vibrate by the incident light wave. This results in different velocities in different directions and the index of refraction is different in different directions within the crystal.

3.7 Light Polarizer

Basically, a polarizer is a device that converts a beam of light with undefined or mixed polarization into a beam with well-defined polarization. The principal of integrated polariser is to make one polarization mode lossier than the other, either by leakage or absorption loss, thereby achieving a large difference in propagation loss between the two orthogonally polarised modes. As a consequence, a large extinction ratio – defined as the ratio of the power in the desired polarisation to the power in the undesired polarisation can be achieved. A previous approach has used the strong polarisation dependence of plasmonic modes in metal-dielectric waveguides to suppress one of the polarisations [1]. High extinction ratio between orthogonally polarised modes can be achieved using metal-cladding based integrated waveguide polarisers. The effect is wavelength dependent, requires complex structures and the incorporation of resonant buffer layers in order to produce broadband polarisation response, thus increasing the complexity of PIC fabrication.

For graphene, its conductance is defined by the fine structure constant and is independent of frequency over a wide range. Bao *et. al*. have demonstrated a broadband fibre polariser by replacing the metal thin film in the polarising waveguide with a graphene layer [2]. Later, Kim *et. al*. demonstrated a planar waveguide using graphene core waveguides [3] and subsequently the polarization-dependent coupling of plasmonic modes at the waveguide-graphene interface of polymer waveguides [4].

GO typically exhibits a strongly isotropic complex dielectric function [5]. This property was demonstrated in FET-type electronic devices. At optical frequencies, such dielectric anisotropy may be expected to lead to differences in the propagation loss for different polarisation states, which can be used to provide the function of polarisation selection in an optical waveguide.

The polarization mechanism is attributed to the differential attenuation of two polarization modes. In conventional two-dimensional electron systems, the local dynamic conductivity is described by the Drude model. In this model, only the transverse-magnetic (TM) mode can propagate in such structures. The transverse-electric (TE) mode is forbidden at a single interface between a metal and a dielectric according to boundary conditions [6]. The spectra of electromagnetic modes are sensitive to the electron (hole) mass. However, the situation in graphene is quite different because of its massless Dirac fermions. The dynamic conductivity of graphene can be determined from the Kubo formalism, consisting of intraband and interband contributions. In Kubo formalism, the imaginary part plays an important role in the propagation of surface waves in a graphene sheet. The imaginary part is always positive so that the TM mode can be supported. The contribution of interband optical transition gives rise to the negative imaginary part, which supports the conditions for TE mode existence. This TE mode has a weakly damped wave propagating along the graphene sheet at close to the velocity of light [6]. It is this that underpins the basis for the development of a broadband graphene TE-pass polarizer.

Conduction in GO occurs via hopping of electrons between localized states [7, 8]. The hopping probability diminishes rapidly with the separation between the hopping sites. Since the GO sheets are separated by the functional groups and intercalating molecules, interlayer hopping conduction is strongly suppressed compared to in-plane conductivity. Due to giant conductivity anisotropy, GO behaves as a semiconductor for in-plane conduction but as a dielectric for electric field applied in the out-of-plane direction. In the work of Eda *et. al*. [5], where a field effect transistor was fabricated, having GO as the gate dielectric, the leakage current measured at the gate electrode was consistently below 1 nA. The conduction was found to be *p*-type, suggesting hole doping by adsorbed water and oxygen molecules as what is commonly observed in GO and other forms of carbon nanostructures [9].

3.8 Review of the Development of Graphene Material based Polarizer

The massless Dirac fermions in graphene modify the plasmon and plasmon polariton spectra and introduce some new features. This makes graphene able to selectively support either the TM or TE electromagnetic modes depending on its Fermi level and incident energy. This provides the basis for the development of graphene/silica hybrid waveguide, which supports either a TM or TE surface wave selectively, thus transforming unpolarized incident light into polarized light.

In the work of Bao *et. al*., a graphene TE-pass polarizer with an extinction ratio up to 27 dB in the telecommunications band has been demonstrated [10]. The polarizing effect is found to originate from the different attenuation of the TE and TM modes. The broadband (visible to near-infrared) polarizing effect of graphene enables ultra-broadband light modulation. Furthermore, the polarizer is low cost and comes with simple fabrication. This graphene polarizer also has chemical tunability, which will allow the fabrication of environment-sensitive polarizers.

Kim *et. al*. demonstrated a graphene-based plasmonic waveguide for photonic integrated circuits [4]. This waveguide uses surface plasmon polaritons coupling, where the collective excitations of electrons are supported at metal-dielectric surface. The plasmonic waveguide is a metal-like material, fabricated by embedding chemical vapor deposited (CVD) graphene strip in a photoactive UV curable perfluorinated acrylate polymer with a low refractive index and material loss. It serves as a light signal guiding medium for high-speed optical data transmission. This waveguide supports the TM polarization modes with a average extinction ratio of 19 dB at a wavelength of 1.31 μm. Optical signals of 2.5 Gbps were successfully transmitted via 6 mm long waveguide.

The same author also demonstrated another type of graphene-based polymer waveguide polarizer by using CVD-grown graphene film having 1 to ~10 layers of graphene [3]. The graphene strips were carefully transferred mechanically to the polymer waveguide, fabricated using a UV-curable polymer. With a graphene strip placed on the waveguide core, the waveguide polarizer serves as a TE-pass poalrizer, with a extinction ratio of ~10 dB. Unlike the previous plasmonic waveguide, the electrical properties of the graphene strip can be tuned by using a UV-curable polymer resin, and this makes the polarizer supports also TM-mode surface waves, with a extinction ratio of 19 dB. Thus, this graphene polarizer could serve alternatively as a TE-pass or TM-pass polarizer.

Another group has demonstrated a tunable graphene-based polarizer on a attenuated total reflection (ATR) structure [11]. The structure, with a single graphene layer on it, works well as a tunable polarizer in the terahertz frequency domain, in a broad range of gate potential differences. The polarization of the reflected electromagnetic wave is controlled by adjusting the voltage applied to graphene. The near-complete absorption of the TM mode of unpolarized incident radiation at resonance yields a high polarization ratio of the reflected waves. The mechanism is based on the resonant coupling of *p*-polarized waves to the surface plasmon-polaritons in graphene. The authors indicate the possibility of using the same principle for filtering out the *s*-polarized component of the incident wave. It would allow to extend the operation frequency range to the infrared domain.

On the latest development and a follow-up, Zhu *et*. *al*. showed that an electrically tunable polarizer can be obtained using a periodic array of graphene ribbons supported on a dielectric film on top of a thick piece of metal [12]. The polarizing mechanism originates from anisotropic absorption of the graphene ribbons. The results of their simulations show that absorption of 0.0075 for one polarization and 0.9986 for another polarization can be obtained at normal incidence in the THz range. For circular incidence polarization, the corresponding polarizing extinction ratio increases to 65 dB. In addition, the polarizing effect can be turned on and off or for activity at different frequencies via electrostatic doping of graphene.

Table 3.2 presents a selection of demonstrations of several types of graphene material based polarizers and their respective performance comparison.

Table 3.2: A brief summary of various graphene material based polarizers and their respective performance.

Polarizer type	**Graphene material deposition method**	**Wavelength**	**Selected mode**	**Extinction ratio**	**Ref.**
Optical fibre	Immersion of optical fibre beneath water/graphene interface followed by scooping	488 nm – 1550 nm	TE-pass	13.9 dB – 23.6 dB	[2]
Polymer waveguide	-	1310 nm	TM-pass	19 dB	[4]
Polymer waveguide	Mechanical	1310 nm	TE- and TM-pass	10 dB (for TE-pass) and 19 dB (for TM-pass)	[3]
Attenuated total reflection (ATR) structure	'Sandwiched' between two dielectric media	-	TE-pass with *s*-polarization	-	[11]
Metal material	Graphene ribbons on a dielectric film	-	TM-pass	65 dB	[12]

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