1 4 9 5 UNIVERSITY OF ABERDEEN

THE NATURE OF LIGHT

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EG 40GC Optical Engineering

LECTURE NOTES

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The Nature of Light

- If the laser is at the focus of optical engineering,
  - ➢ **then light is at its heart**
- The basis of optical engineering is
  - ➢ **that light is the prime carrier of information**
- The optical engineer must be familiar with, and have an intuitive understanding of,
  - ➢ **the unique character of light**
  - ➢ **its origins in the atomic structure of matter.**
- We need to outline the nature of light
  - ➢ **to enable us to understand principal optical phenomena**
  - ➢ **to appreciate the unique properties of the laser.**

Waves & Photons

- Light is not the easiest of natural phenomena to describe.
- Light has an ambivalent nature that requires
  - ***two models of behaviour*** **for a satisfactory description of its properties.**
- The **electromagnetic wave** model
- The **quantum electrodynamic (photon)** model
- These models, although seemingly contradictory, are complementary
  - **Both models are needed to give a complete picture of the nature of light and to emphasise its role as an information carrier.**

The **electromagnetic wave** model

- Describes light as
  - **a continuous transfer of energy through space**
    - **→by a combination of waves of electric & magnetic fields**
  - **describes propagation of light**
  - **helps to describe phenomenon like**
    - **→black-body radiation**
    - **→diffraction**
    - **→interference**
    - **→polarisation**

The **quantum electrodynamic (photon)** model

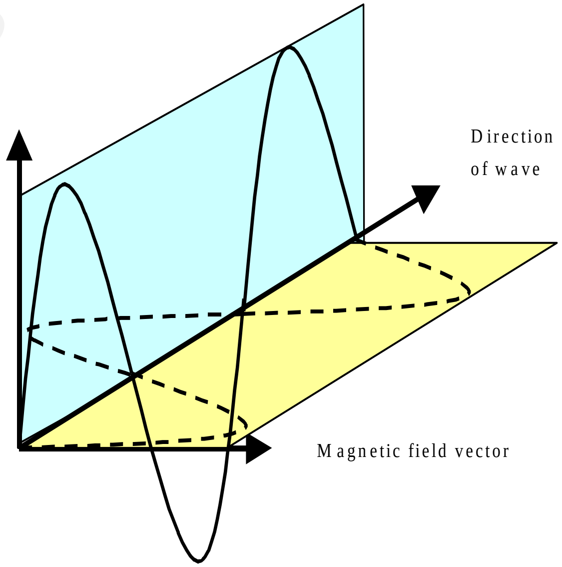
- Describes light in terms of massless elementary particles,
  - **known as** photons
  - can be thought of as localised pulses of energy
- Model is needed to describe interactions between light & matter
  - **helps us to describe absorption and emission of light from materials**

The Electromagnetic Wave Model of Light

- The *theory of electromagnetic radiation* was proposed by Scottish scientist James Clerk Maxwell
- It describes the continuous transfer of energy through space by the propagation of electro-magnetic waves.
  - **Mutual interaction of two vector fields, an electric field ξ and a magnetic field $\mathcal{H}$**
- In any dynamic situation, a propagating ξ -field will be accompanied by a corresponding $\mathcal{H}$-field propagating everywhere at right angles to it
  - **Radiation propagates in a direction that is mutually perpendicular to both ξ - and $\mathcal{H}$ -fields.**

The Electromagnetic Wave Model of Light

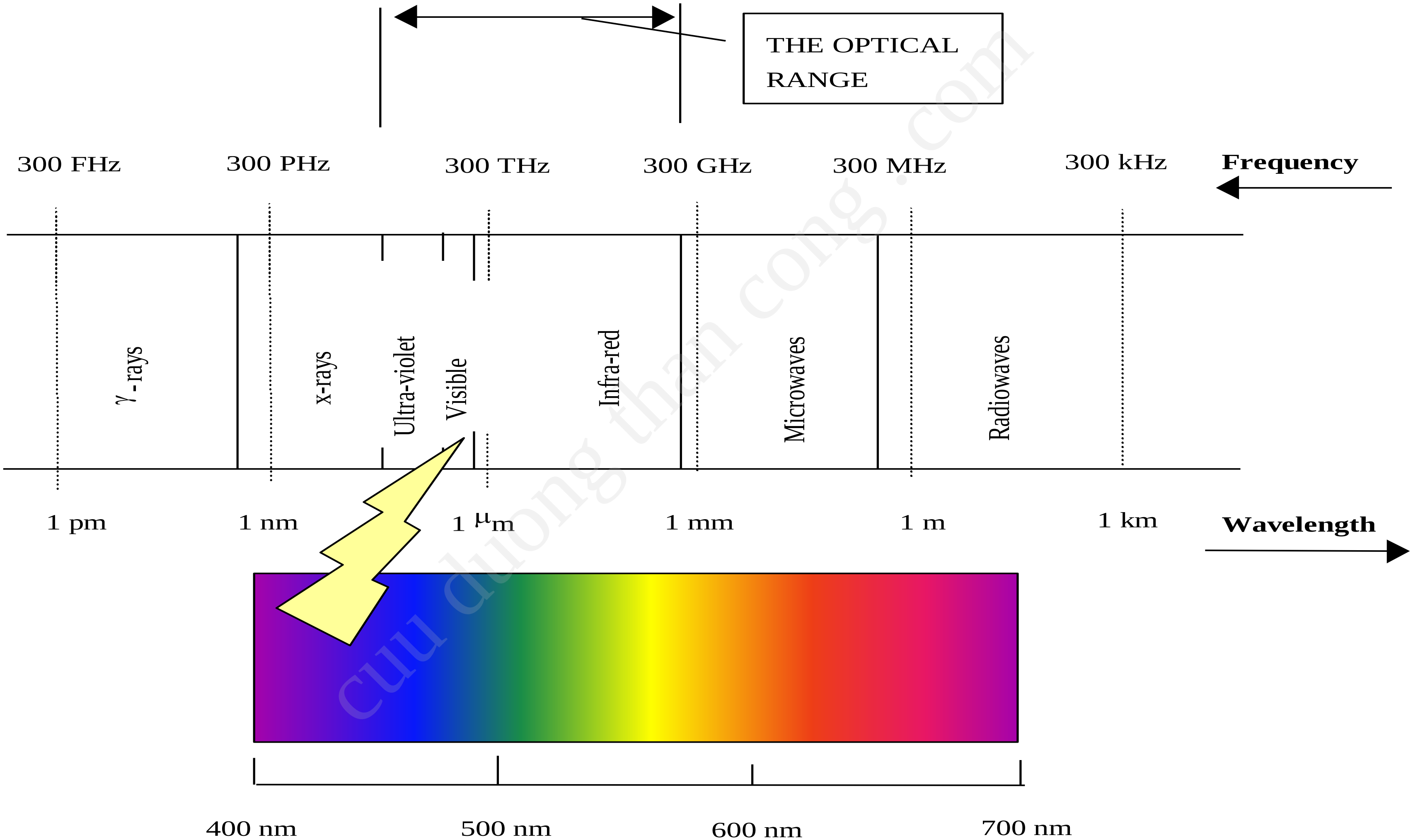
- The ξ - & $\mathcal{H}$-fields have *no component* of vibration in the direction of propagation
  - **no *longitudinal* component**
  - **exclusively transverse in nature**
- Convention in optics describes the behaviour of e-m field in terms of the oscillating electric vector
  - **ξ -field is always accompanied by an associated $\mathcal{H}$-field.**
  - **knowing one allows us to extract the other**



The Electro-Magnetic Spectrum

- Lightwaves, microwaves, radiowaves, X-rays and gamma rays are all one and the same thing
  - →**electromagnetic radiation**.
  - →**they differ only in their characteristic frequency.**
- The complete *electromagnetic spectrum* stretches continuously from γ-rays to radiowaves
- The optical range is usually considered to stretch from 200 nm (far ultra-violet) to about 20 µm (far infrared)
- Visible light, stretches from about 400 nm at the violet end to around 700 nm at the red end,
  - ➢ **forms only a small part of the *e-m spectrum.***

The e-m Spectrum



Plane Waves - 1

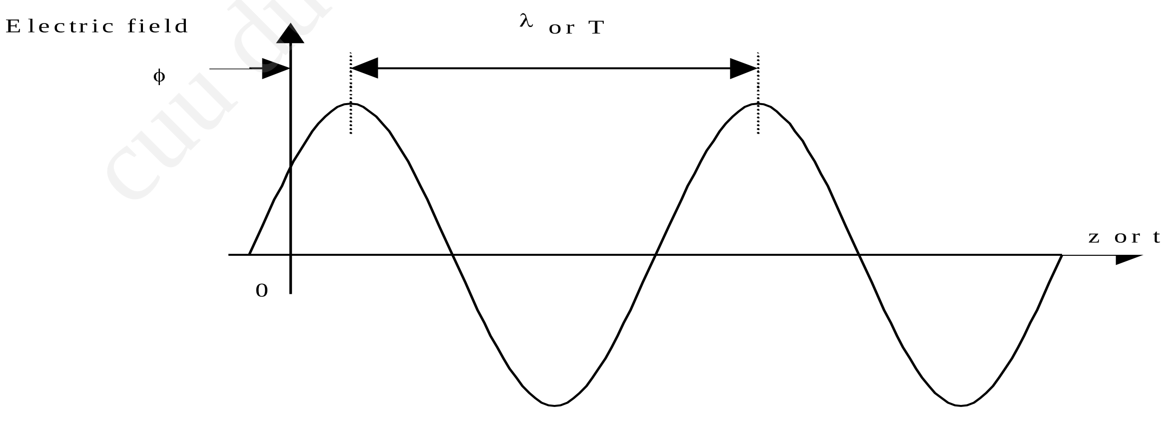
- A complete, formalised description of the propagation of light through free space and the energy transferred by it, requires that
  - **we treat electro-magnetic (e-m) radiation as a *vector* field**
  - **specify in 3-d space, in terms of its magnitude and direction.**

- For most purposes we may represent a travelling light wave as
  - **a** *one-dimensional, scalar wave***, propagating in a given direction.**
  - **Such a wave is known as a** plane wave
  - **all the surfaces upon which the wave has equal phase are parallel to each other and perpendicular to the direction of propagation.**
  - **The planes can be considered as the wavefronts of the wave and usually represent the peak amplitude of the wave**
  - **separated by the wavelength**

- We need only describe such a wave in terms of either the electric field or the magnetic field.
  - **Both are not necessary, since we can always extract one from the other.**

Plane Waves - 2

- Conventionally, amplitude of electric field vector, ξ, describes a plane wave of angular frequency ω and wave vector, k, propagating in the +z direction
  - $\xi = \xi_0 \cos(\omega t - kz - \phi)$
  - **ϕ is the initial phase of the wave which depends on the chosen location of the origin**
  - **t and z are the respective time and space co-ordinates**
  - **ξ_0 is the peak amplitude of the wave**
  - **ω is angular frequency**
  - **$\omega = 2\pi\nu$ [rad s^{-1}] ν is linear frequency of light**
- **Wavefronts** correspond to the peaks of the sine wave
  - **They are perpendicular (normal) to direction of propagation**

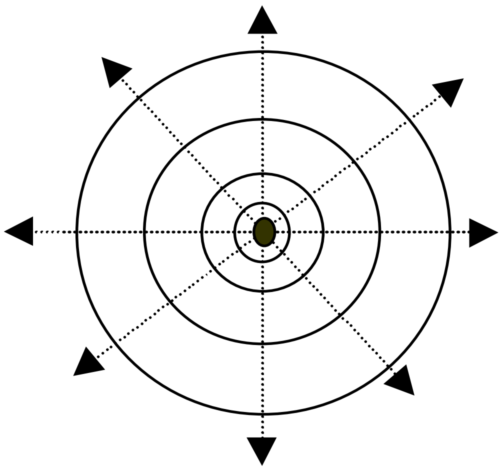


Plane Waves - 3

- The propagation constant is
  - $k = 2\pi/\lambda$ **[m^{-1}]**
  - λ is the wavelength.
- The velocity of propagation of the light wave in a vacuum,
  - $c = \nu\lambda$ **[$m\ s^{-1}$]**
- The velocity of the wave in any medium is related to its free-space velocity
  - $v = c/n = \nu(\lambda/n)$
- The refractive index itself is related to the relative magnetic and electric constants, ε_r and μ_r
  - $n = c/v = \sqrt{(\varepsilon_r.\mu_r)/(\varepsilon_0.\mu_0)}$
- The constants, ε_0 and μ_0 are:
  - **$\varepsilon_0 = 8.87 \times 10^{-12}\ F\ m^{-1}$** **primary electric constant of free space**
  - **$\mu_0 = 4 \times 10^{-7}\ H\ m^{-1}$** **primary magnetic constant of free space**
- The velocity of propagation of an electromagnetic wave in free space (i.e. a vacuum)
  - $c = \sqrt{(\varepsilon_0\mu_0)}$ **$= 2.998\times10^8\ m\ s^{-1} \approx 3\times10^8\ m\ s^{-1}$**

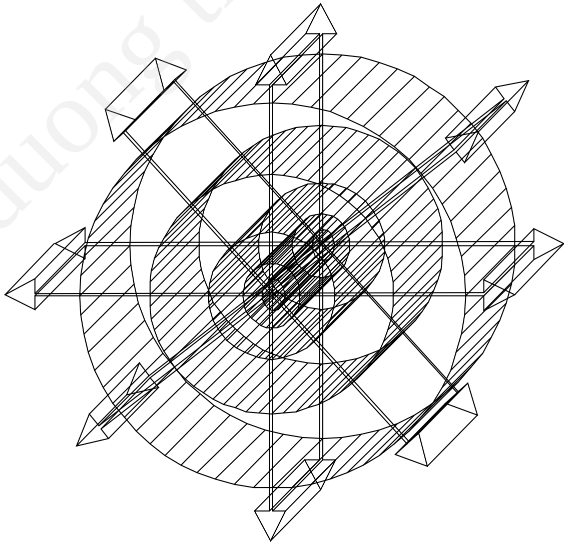
Spherical Waves

- Some sources of light generate waves that spread radially outwards equally in all directions from a common point of emission.
  - **wavefronts expand outwards in concentric spheres with ever increasing diameters**
  - **known as** isotropic point sources
- The spherical wave decreases in amplitude as it propagates
  - $\xi = (\xi_0/r)\cos(\omega t - kr)$
  - **at large distances from the point source, the spherical wave can be approximated by a plane wave.**



Cylindrical Waves

- The electric field distribution of a cylindrical wave is given as
  - $\xi = (\xi_0 / r^{1/2}) \cos(\omega t - kr)$
- Cylindrical waves are good approximations to the source profile emitted when a plane wave is incident on a long slit or the radiation profile from a linear flashtube.

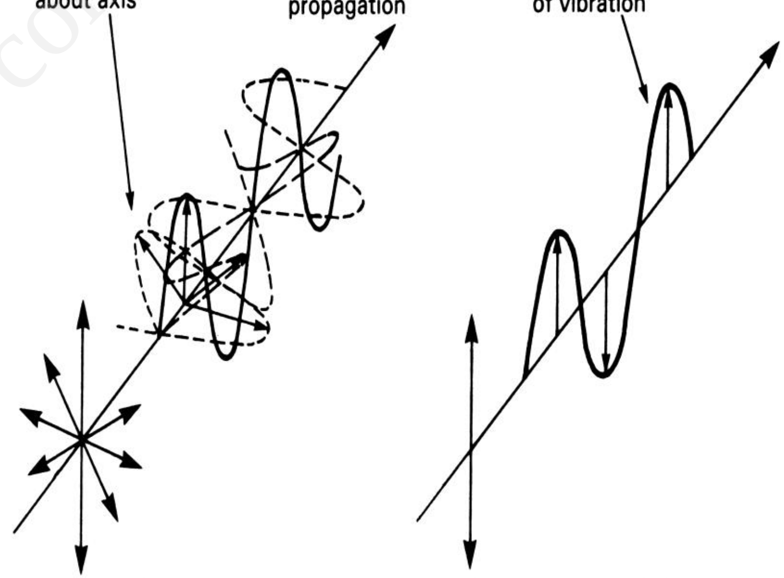


Irradiance of Light

- The **irradiance** of an e-m wave is the *power per unit area* that is incident on a surface
  - $E = \rho c = \langle \xi^2 \rangle / Z_0$ **[W m^{-2}]**
  - **ρ is the radiation density (energy per unit volume)**
  - **Z_0 is the characteristic impedance of free space,**
  - $Z_0 = \xi_x / \mathcal{H}_y = (\mu_0/\varepsilon_0)^{1/2}$ **= 377 Ω**
- Light can also exert pressure on a surface
  - **Average radiation pressure is defined in terms of irradiance**
  - $P_{rad} = E/c$ **[J m^{-3}]**

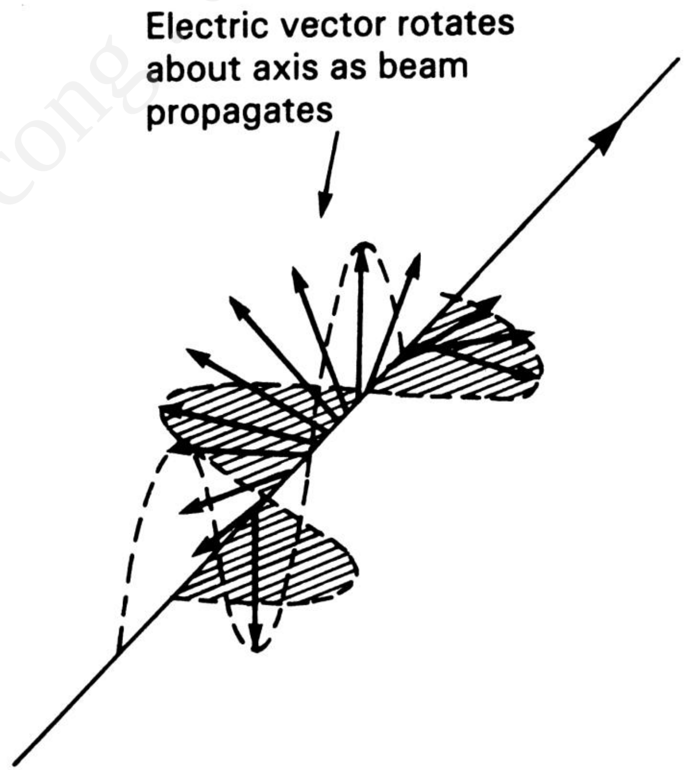
Polarisation of Light Waves - Linear

- A propagating light wave may be expressed uniquely in terms of its ξ-vector.
  - **For most sources of light,**
    - → **the radiant emission will be composed of many waves**
    - → **each with their ξ- vectors randon orientated wrt each other.**
  - **Beam is** unpolarised **or** randomly polarised**.**
- In some cases waves are constrain to oscillate in preferential planes
  - **Beam is polarised**
- When the light wave oscillates in a single plane of the electric vector
  - **Beam is** linearly **or** plane polarised
  - **Normally the plane of vibration of ξ-vector will be specified e.g. vertical**



Polarisation of Light Waves – Circular & Elliptical

- More complex situation occurs when the plane of polarisation continually rotates perpendicularly to the direction of propagation as the wave propagates.
    - **Beam is** circularly polarised
    - **Two senses: *left* and *right* polarisation, denote the direction of rotation of the polarisation plane.**
- In some cases, the amplitude of the polarisation vector also changes with the rotation as the wave propagates
    - **Beam is** elliptically **polarised**



Circularly polarized light

The Photon Model of Light

- The propagation of light through space may be described in terms of a travelling wave motion
  - **emission & absorption of light by materials is not easy to describe on this basis**
- Whether or not light existed as a stream of particles or as a wave motion was the subject of heated debate for hundreds of years
- There are some phenomena which defy all attempts to describe them on the basis of a classical wave model of light propagation
  - **emission of light from gases and solids**
  - **black body radiation**
  - **the photoelectric effect**
- It is necessary to invoke the idea of light being emitted in tiny pulses, or ***quanta*** of energy
  - **not as a continuous distribution of energy.**
  - **the pulses of light are known as photons**
  - **the amount of energy carried by a photon is proportional to the frequency of the radiation**

Energy Imparted by a Photon

- Light can be considered to propagate through space as a stream of vast numbers of “particles”.
  - **This particle is not a “hard” lump of well-defined mass, but a massless, quantum of energy**
- Each photon carries with it a precisely defined amount of energy which depends only on its characteristic frequency or wavelength
  - **The energy of a single photon is**
  - **$W_{ph} = h\nu_{ph} = hc/\lambda_{ph}$**
    - **→h = 663 x 10^{-36} J s** **Planck's constant**
    - **→c is the velocity of propagation of the photon in free space**

Energy of a Photon

- A particular photon has a wavelength of 600 nm. This photon would be in the red part of the spectrum.
- The energy of a single photon is,
- $W_{ph} = h\nu_{ph} = hc/\lambda_{ph}$
- $= (663 \times 10^{-36}\ \text{J s} \times 300 \times 10^{6}\ \text{m s}^{-1})/(600 \times 10^{-9}\ \text{m})$
- $= 332 \times 10^{-21}\ \text{J}$
  - **This is a tiny amount of energy!**
- An **electronvolt** (**eV**) is defined as the energy obtained by an electron when it is accelerated through a potential difference of 1 volt.
  - $1\ \text{eV} = 160 \times 10^{-21}\ \text{J}$
- Therefore, the energy of the 600 nm photon, in electronvolts, is
  - $\mathbf{W_{ph} = 332 \times 10^{-21}\ J / 160 \times 10^{-21}\ J\ eV^{-1} = 2.07\ eV}$
- Visible photons range in energy from 1.74 eV (700 nm) to 3.34 eV (400 nm).

Number of Photons in a Beam of Light

- For a parallel beam of light of 0.5 J energy and 600 nm wavelength, the number of photons contained in this beam is given by
  - **$N_{ph} = Q/W_{ph}$**
- The energy of a 600 nm photon is 332×10^{-21} J. Thus the number of photons is
- $N_{ph} = Q/W_{ph}$
- $= 0.5\ J/332 \times 10^{-21}\ J$
- $= 1.5 \times 10^{18}$
- Total energy or radiant power of a beam of light defines the total number of photons contained within the beam.
- Photon energy gives us the energy of an individual photon.