Lecture 2

The nature of electromagnetic radiation.

Objectives:

1. Basic introduction to the electromagnetic field:
   - Definitions
   - Dual nature of electromagnetic radiation
   - Electromagnetic spectrum
2. Main radiometric quantities: energy, flux , and intensity.
3. Concepts of extinction (scattering + absorption) and emission.
4. Polarization. Stokes' parameters.

APPENDIX 2.1 Coordinate systems. Solid angle

Required reading:

G: 2.1, 2.2.1, 2.2.2, 2.3, 2.4, 4.1, Appendix 1.

Additional/advanced reading:

G: 4.2;

Online tutorial: Chapter 1, Sections 1.2 – 1.3

http://www.ccrs.nrcan.gc.ca/ccrs/eduref/tutorial/indexe.html

1. Basic introduction to electromagnetic field.

Electromagnetic radiation is a form of transmitted energy**. *Electromagnetic radiation*** is so-named because it has electric and magnetic fields that simultaneously oscillate in planes mutually perpendicular to each other and to the direction of propagation through space.

- Electromagnetic radiation has the **dual nature**:

  its exhibits **wave properties** and **particulate properties**.

Wave nature of radiation:

Radiation can be thought of as **a traveling wave.**

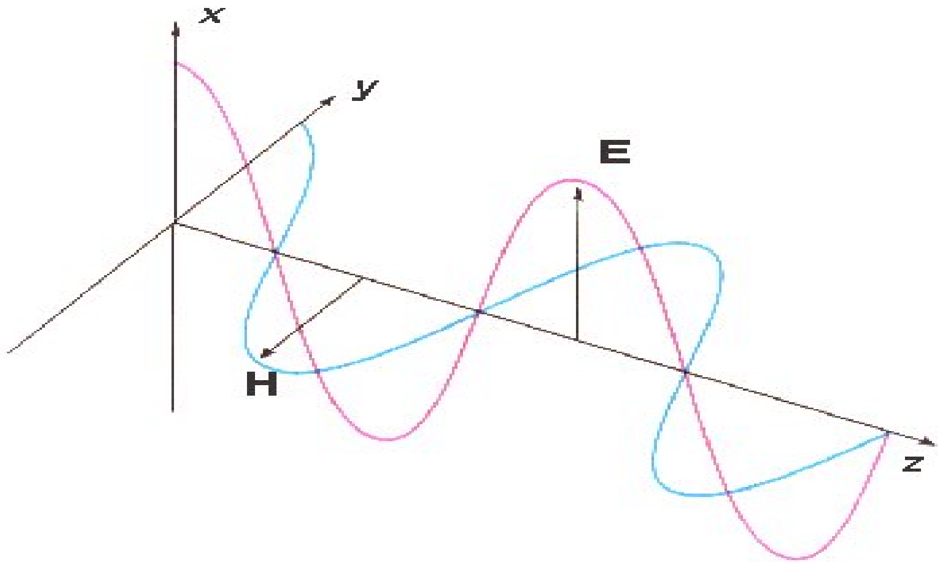


Figure 2.1 A schematic view of an electromagnetic wave propagating along the $\vec{z}$ axis. The electric $\vec{E}$ and magnetic $\vec{H}$ fields oscillate in the x-y plane and perpendicular to the direction of propagation.

Poynting vector gives the flow of radiant energy and the direction of propagation as

$$\vec{S} = c^2 \varepsilon_0 \vec{E} \times \vec{H}$$

here c is the speed of light in vacuum (c = 2.9979×10^8 m/s $\cong$ 3.00×10^8 m/s) and ε_0 is vacuum permittivity (or dielectric constant). $\vec{S}$ is in units of energy per unit time per unit area (e.g., W m^{-2})

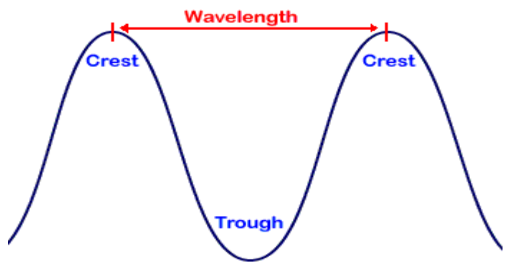
NOTE: $\vec{E} \times \vec{H}$ means a **vector product** of two vectors.

- $\vec{S}$ is often called **instantaneous Poynting vector**. Because it oscillates at rapid rates, a detector measures its average value $<S>$ over some tome interval that is a characteristic of the detector.

= > Waves are characterized by **frequency, wavelength,** and **speed**.

Frequency is defined as the number of waves (*cycles*) per second that pass a given point in space (symbolized by $\tilde{\nu}$).

Wavelength is the distance between two consecutive peaks or troughs in a wave (symbolized by the λ).



Relation between λ and $\tilde{\nu}$: $\lambda \tilde{\nu} = c$ [2.1]

- Since all types of **electromagnetic radiation** travel at the speed of light, short-wavelength radiation must have a high frequency.
- Unlike speed of light and wavelength, which change as electromagnetic energy is propagated through media of different densities, frequency remains constant and is therefore a more fundamental property.

Wavenumber is defined as a count of the number of wave crests (or troughs) in a given unit of length (symbolized by ν):

$$\nu = \tilde{\nu}/c = 1/\lambda \qquad [2.2]$$

UNITS:
Wavelength units: unit length,
Angstrom (A) : 1 A = 1×10^{-10} m;
Nanometer (nm): 1 nm=1×10^{-9} m;
Micrometer (μm): 1 μm = 1×10^{-6} m;
Wavenumber units: inverse length (often in cm^{-1})

Frequency units: unit cycles per second 1/s (or s^{-1}) is called hertz (abbreviated Hz)

Table 2.1 Frequency units

Unit	Frequency, (cycles/sec)
Hertz, Hz	1
Kilohertz, KHz	10^3
Megahertz, MHz	10^6
Gigahertz, GHz	10^9

Particulate nature of radiation:

Radiation can be also described in terms of particles of energy, called **photons**.

The energy of a **photon** is given by the expression:

$$E_{photon} = h\,\tilde{\nu} = h\,c/\lambda = h\,c\nu \qquad [2.3],$$

where ***h*** is Plank's constant (h = 6.6256x10^{-34} J s).

- Eq. [2.3] relates energy of each photon of the radiation to the electromagnetic wave characteristics ($\tilde{\nu}$ and λ).
- Photon has energy but it has no mass and no charge.

Problem: A light bulb of 100 W emits at 0.5 μm. How many photons are emitted per second?

Solution:

Energy of one photon is $E_{photon} = hc/\lambda$, thus, using that 100 W = 100 J/s, the number of photons per second, N, is

$$N(s^{-1}) = \frac{100\,(Js^{-1})\;\lambda(m)}{h(Js)\;c(ms^{-1})} = \frac{100\;\times 0.5\times 10^{-6}}{6.6256\times 10^{-34}\times 2.9979\times 10^{8}} = 2.517\times 10^{20}$$

NOTE: Large number of photons is required because Plank's constant ***h*** is very small!!!

➢ Spectrum of electromagnetic radiation:

The electromagnetic **spectrum** is the distribution of electromagnetic radiation according to energy or, equivalently, according wavelength or frequency.

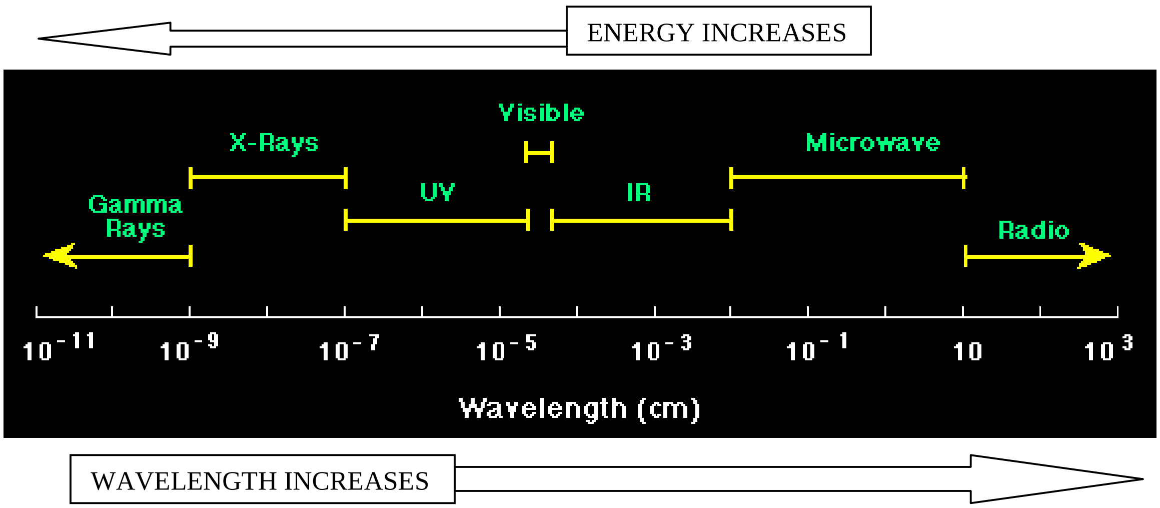


Figure 2.2 The electromagnetic spectrum.

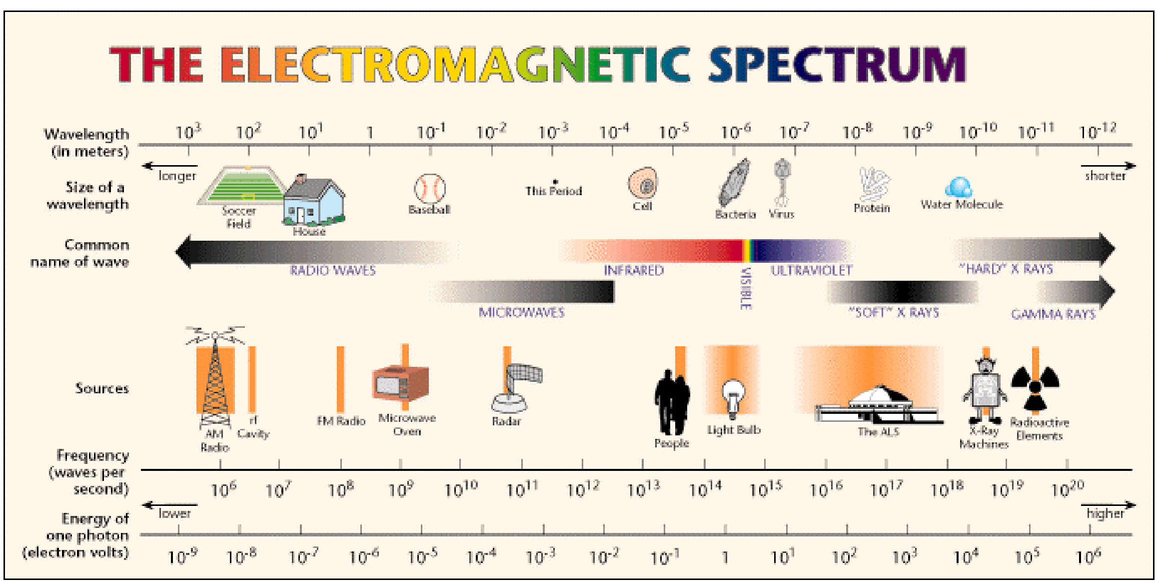


Figure from http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

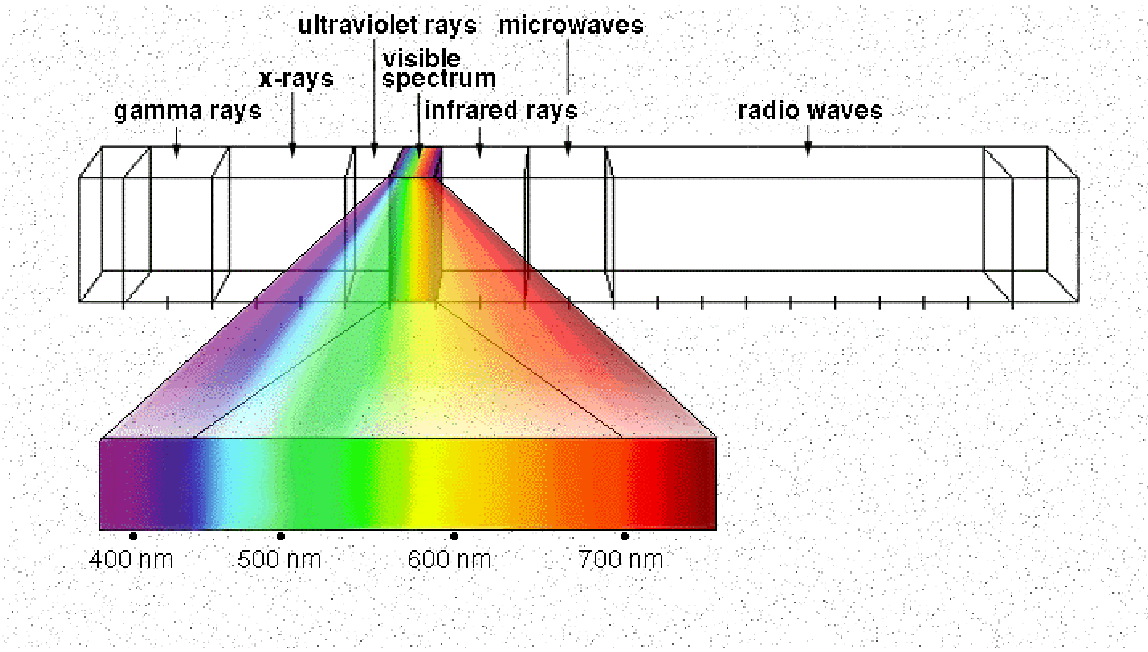


Figure 2.3 Visible spectrum

Effect of atmospheric gases (will be discussed in Lecture 6-7)

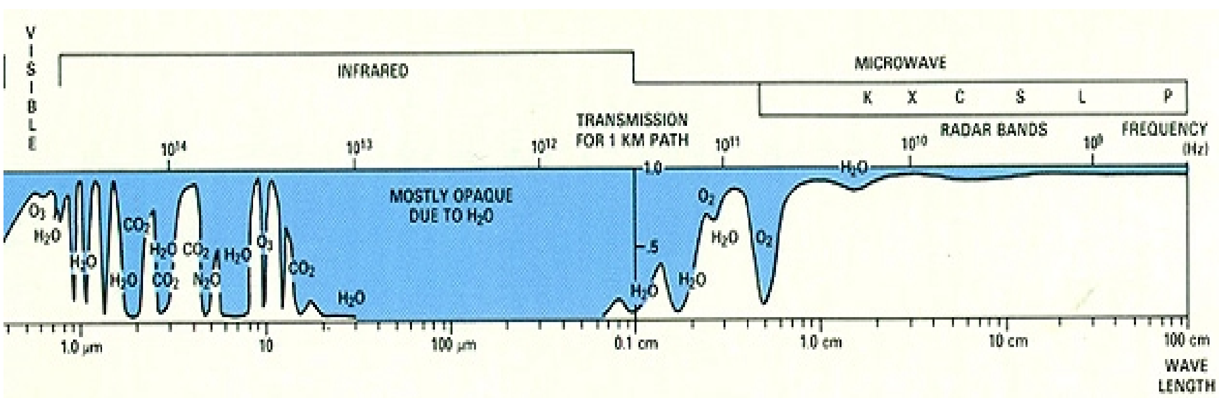


Figure 2.4 A generalized diagram showing relative atmospheric radiation **transmission** at different wavelengths. Blue zones show low passage of incoming and/or outgoing radiation and white areas denote atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't absorbed.

- In this course we study the UV, visible, infrared and microwave radiation.

Table 2.2 Relationships between radiation components.

Name of spectral region	**Wavelength region, μm**	**Spectral equivalence**
Solar	0.1 - 4	Ultraviolet + Visible + Near infrared = Shortwave
Terrestrial	4 - 100	Far infrared = Longwave
Infrared	0.75 - 100	Near infrared + Far infrared
Ultraviolet	0.1 - 0.38	Near ultraviolet + Far ultraviolet = UV-A + UV-B + UV-C + Far ultraviolet
Shortwave	0.1 - 4	Solar = Near infrared + Visible + Ultraviolet
Longwave	4 - 100	Terrestrial = Far infrared
Visible	0.38 - 0.75	Shortwave - Near infrared - Ultraviolet
Near infrared	0.75 - 4	Solar - Visible - Ultraviolet = Infrared - Far infrared
Far infrared	4 - 100	Terrestrial = Longwave = Infrared - Near infrared
Thermal	4 - 100 (up to 1000)	Terrestrial = Longwave = Far infrared
Microwave	10^3 - 10^6	Microwave
Radio	> 10^6	Radio

Table 2.3 Microwave frequency bands used in remote sensing

Band	**Frequency [GHz}**	**Wavelength [cm]**
P-band	0.225-0.39	133-77
L-band	0.39-1.55	77-19
S-band	1.55-3.90	19-7.7
C-band	3.9-6.2	7.7-4.8
X-band	5.75-10.9	5.2-2.8
Ku-band	10.9-18.0	2.8-1.7
Ka-band	18.0-36.0	1.7-0.8

2. Basic radiometric quantities.

Intensity (or radiance) is defined as radiant energy in a given direction per unit time per unit wavelength (or frequency) range per unit solid angle per unit area perpendicular to the given direction:

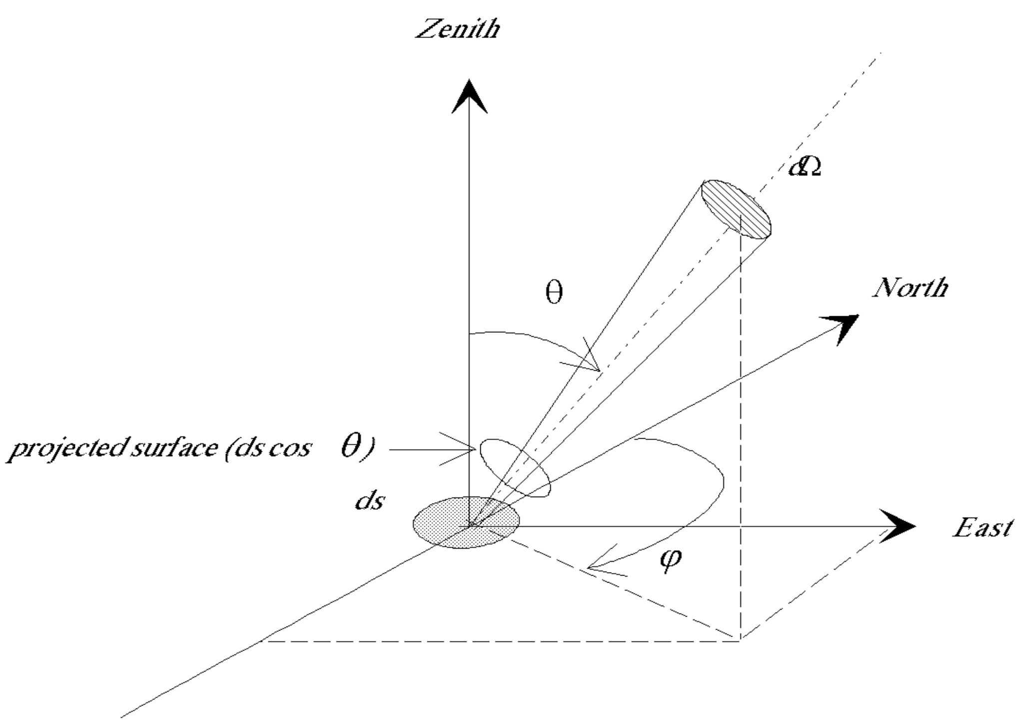
$$I_{\lambda} = \frac{dE_{\lambda}}{\cos(\theta) d\Omega dt dA d\lambda} \qquad [2.4]$$

I_{λ} is referred to as **monochromatic** intensity.

UNITS: from Eq.[2.4]: (J sec^{-1} m^{-2} sr^{-1} μm^{-1}) = (W m^{-2} sr^{-1} μm^{-1})

- Monochromatic does not mean at a single wavelengths λ, but in a very narrow (infinitesimal) range of wavelength Δλ centered at λ.

NOTE: *same name*: intensity = specific intensity = radiance



Properties of intensity:

a) In general, intensity is a function of the coordinates ($\vec{r}$), direction ($\vec{\Omega}$), wavelength (or frequency), and time. Thus it depends on seven independent variables: three in space, two in angle, one in wavelength (or frequency) and one in time.

b) Intensity, as a function of position and direction, gives a complete description of the electromagnetic field.

- If intensity does not depend on the direction, the electromagnetic field is said to be **isotropic.** If intensity does not depend on position the field is said to be **homogeneous**.

Flux (or irradiance) is defined as radiant energy in a given direction per unit time per unit wavelength (or frequency) range per unit area perpendicular to the given direction:

$$F_\lambda = \frac{dE_\lambda}{dt dA d\lambda} \qquad [2.5]$$

From Eqs. [2.4]-[2.5]:

$$F_\lambda = \int_\Omega I_\lambda \cos(\theta) d\Omega \qquad [2.6]$$

Thus monochromatic **flux** is the integration of normal component of monochromatic **intensity** over the all solid angles over the hemisphere.

Eq. [2.6] in spherical coordinates:

$$F_\lambda = \int_0^{2\pi} \int_0^{\pi/2} I_\lambda(\theta, \varphi) \cos(\theta) \sin(\theta) d\theta d\varphi$$

NOTE: For isotropic radiation the hemispherical flux is $\boldsymbol{F_\lambda = \pi I_\lambda}$

- Each detector measures electromagnetic radiation in a particular wavelength range, $\Delta\lambda$. The intensity $\boldsymbol{I_{\Delta\lambda}}$ and flux $\boldsymbol{F_{\Delta\lambda}}$ in this range are determined by integrating over the wavelength the monochromatic intensity and flux, respectively:

$$I_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \qquad\qquad F_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda$$

- Using measured time-averaged Poynting vector, intensity and flux can be expressed as

$$F = \langle S \rangle \qquad\qquad I = \langle S \rangle / d\Omega$$

3. The concepts of extinction (scattering + absorption) and emission.

Electromagnetic radiation in the atmosphere interacts with gases, aerosol particles, and cloud particles.

- **Extinction** and **emission** are two main types of the interactions between an electromagnetic radiation field and a medium (e.g., the atmosphere).

General definition:

Extinction is a process that decreases the radiant **intensity**, while **emission** increases it.

NOTE: "same name": **extinction = attenuation**

Radiation is **emitted** by **all** bodies that have a temperature above absolute zero (^{O} K) (often referred to as **thermal emission**).

- **Extinction** is due to **absorption** and **scattering**.

Absorption is a process that removes the radiant energy from an electromagnetic field and transfers it to other forms of energy.

Scattering is a process that **does not** remove energy from the radiation field, but may redirect it.

NOTE: Scattering can be thought of as **absorption** of radiant energy followed by **re-emission** back to the electromagnetic field with negligible conversion of energy. Thus, scattering can remove radiant energy of a light beam traveling in one direction, but can be a "source" of radiant energy for the light beams traveling in other directions.

- **Elastic scattering** is the case when the scattered radiation has the same frequency as that of the incident field. **Inelastic (Raman)** scattering results in scattered light with a frequency different from that of the incident light.

4. Polarization. Stokes parameters.

Polarization is a phenomenon peculiar to **transverse** waves.

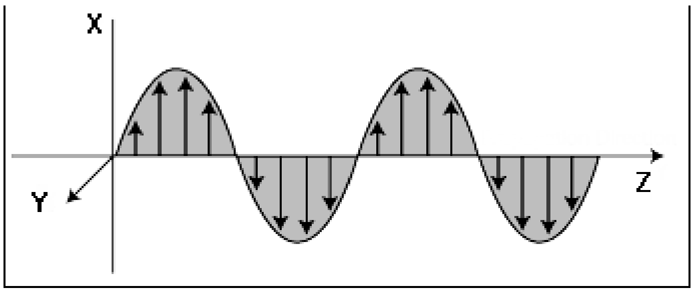
- Electromagnetic radiation travels as **transverse** waves, i.e., waves that vibrate in a direction perpendicular to their direction of propagation

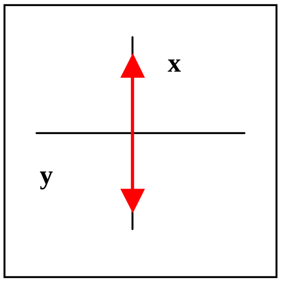
NOTE: In contrast to electromagnetic waves, sound is a **longitudinal** wave that travels through media by alternatively forcing the molecules of the medium closer together, then spreading them apart.

Definition:

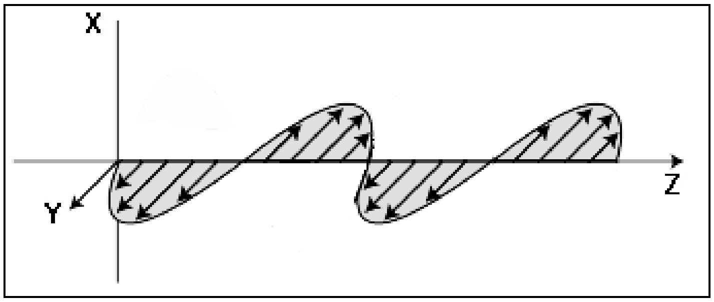
Polarization is the distribution of the electric field in the plane normal to the propagation direction.

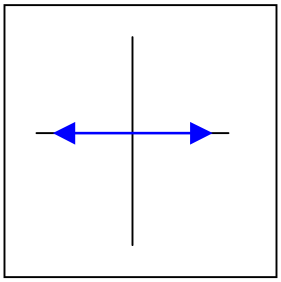
Vertically polarized wave is one for which the electric field lies only in the x-z plane.





Horizontally polarized wave is one for which the electric field lies only in the y-z plane.





- Horizontal and vertical polarization are an example of **linear polarization**.

> Any polarization state of the electromagnetic field can be considered as a superposition of two linearly polarized waves oscillating at 90^o angles to each other (called orthogonal linear polarizations).

Mathematical representation of a plane wave propagating in the direction z is

$$E = E_0 \cos(kz - \omega t + \varphi_0) \qquad [2.7]$$

where E_0 is the **amplitude;**

$\boldsymbol{k}$ is the propagation (or wave) constant, $\boldsymbol{k = 2\pi/\lambda}$

ω is the circular frequency, $\omega = \boldsymbol{kc = 2\pi c/\lambda}$

φ_0 is the constant (or initial phase)

$\varphi = (kz - \omega t + \varphi_0)$ is **the phase of the wave**

Introducing complex variables, Eq.[2.7] can be expressed as

$$E = E_0 \exp(i\varphi) \qquad [2.8]$$

NOTE: In Eq.[2.8], we use $\exp(\pm i\varphi) = \cos(\varphi) \pm i\sin(\varphi)$

The electric vector $\vec{E}$ may be decomposed into the parallel E_l and perpendicular E_r components as

$$\vec{E} = E_l \vec{l} + E_r \vec{r}$$

According to Eq.[2.8], we can express E_l and E_r in the form

$$E_l = E_{l0} \cos(kz - \omega t + \varphi_{l0})$$

$$E_r = E_{r0} \cos(kz - \omega t + \varphi_{r0})$$

Then we have

$$E_l / E_{l0} = \cos(\zeta)\cos(\varphi_{l0}) - \sin(\zeta)\sin(\varphi_{l0})$$

$$E_r / E_{r0} = \cos(\zeta)\cos(\varphi_{r0}) - \sin(\zeta)\sin(\varphi_{r0})$$

where $\zeta = kz - \omega t$.

Performing simple mathematical manipulation, we obtain

$$(E_l / E_{l0})^2 + (E_r / E_{r0})^2 - 2(E_l / E_{l0})(E_r / E_{r0})\cos(\Delta\varphi) = \sin^2(\Delta\varphi) \quad [2.9]$$

where $\Delta\varphi = \varphi_{lo} - \varphi_{r0}$ called the **phase shift**.

Eq.[2.9] defines an ellipse => **elliptically polarized wave**.

If the phase shift $\Delta\varphi$ = n π (n=0, +/-1, +/-2,…), then

$\sin(\Delta\varphi) = 0$ and $\cos(\Delta\varphi) = \pm 1$, and Eq.[2.9] becomes

$$\left(\frac{E_l}{E_{l0}} \pm \frac{E_r}{E_{r0}}\right)^2 = 0 \quad \text{or} \quad E_r = \pm\frac{E_{ro}}{E_{lo}} E_l \qquad [2.10]$$

Eq.[2.10] defines a straight lines => **linearly polarized wave**

If the phase shift $\Delta\varphi$ = n π /2 (n= +/-1, +/-3,…) and $E_{l0} = E_{r0} = E_0$, then

$\sin(\Delta\varphi) = \pm 1$ and $\cos(\Delta\varphi) = 0$, and Eq.[2.9] becomes

$$E_l^2 + E_r^2 = E_0^{\ 2} \qquad [2.11]$$

Eq.[2.11] defines a circle => **circular polarized wave**

- The sign of the phase shift gives **handedness**: right-handed and left-handed polarization

Unpolarized radiation **(**or randomly polarized) is electromagnetic wave in which the orientation of the electrical vector changes randomly.

If there is a definite relation of phases between different scatterers => radiation is called **coherent.** If there is no relations in phase shift => light is called **incoherent**

- **Natural light is incoherent.**
- **Natural light is unpolarized.**

The state of polarization is completely defined by the four parameters: two amplitudes, the magnitude and the sign of the phase shift (see Eq.[2.9]). Because the phase difference is hard to measure, the alternative description called a **Stoke vector** is often used.

Stokes Vector consists of four parameters **(called Stokes parameters)**:

intensity *I*,

the degree of polarization *Q*,

the plane of polarization *U*,

the ellipticity *V*.

Notation

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad \text{or} \quad \{I, Q, U, V\}$$

- **Stokes parameters** are defined via the intensities which can be measured:

I = total intensity

$Q = I_0 - I_{90}$ = *differences in intensities between horizontal and vertical linearly polarized components;*

$U = I_{+45} - I_{-45}$ = *differences in intensities between linearly polarized components oriented at* $+45^0$ *and* -45^0

$V = I_{rcl} - I_{lcr}$ = *differences in intensities between right and left circular polarized components.*

It can be shown that for a light beam we have

$$I^2 \geq Q^2 + U^2 + V^2$$

For **unpolarized** light:

$$Q = U = V = 0$$

The **degree of polarization** ***P*** of a light beam is defined as

$$P = (Q^2 + U^2 + V^2)^{1/2} / I$$

The **degree of linear polarization** ***LP*** of a light beam is defined by neglecting U and V

$$LP = -\frac{Q}{I}$$

NOTE: Computer Lab 1 deals with polarization and Stoke parameters.

APPENDIX 2.1 Coordinate systems. Solid angle.

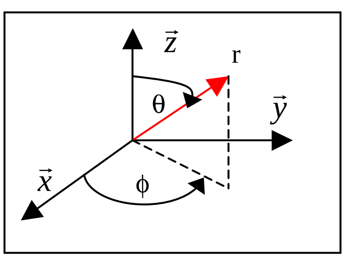
- Both the Cartesian coordinate system and spherical coordinate system are used to characterize the propagation of electromagnetic radiation.

Cartesian (rectangular) coordinate system: three orthogonal unit vectors $\vec{x}, \vec{y}, \vec{z}$

Any vector $\vec{A}$ can be expressed as $\vec{A} = A_x\vec{x} + A_y\vec{y} + A_z\vec{z}$,

and its magnitude is $A = |A| = \sqrt{A_x^2 + A_y^2 + A_z^2}$

Spherical coordinate system: distance r and the zenithal θ and azimuthal ϕ angles



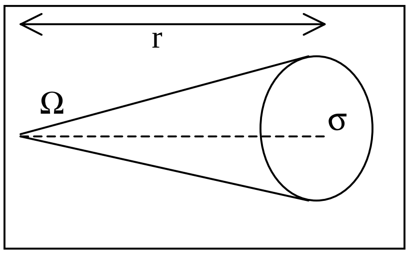
Spherical and rectangular coordinates are related as

x = r sin(θ) cos(ϕ); y = r sin(θ) sin(ϕ); z = r cos(θ)

<u>Solid angle</u> is defined as the ratio of the area σ of a spherical surface intercepted by the core to the square of the radius:

$$\Omega = \frac{\sigma}{r^2}$$

<u>UNITS:</u> of a solid angle = steradian (sr)



EXAMPLE: Solid angle of a sphere = 4π

- A differential solid angle can be expressed as

$$d\Omega = \frac{d\sigma}{r^2} = \sin(\theta)\, d\theta d\phi \ ,$$

using that a differential area is $d\sigma = (r\, d\theta)\, (r \sin(\theta)\, d\phi)$