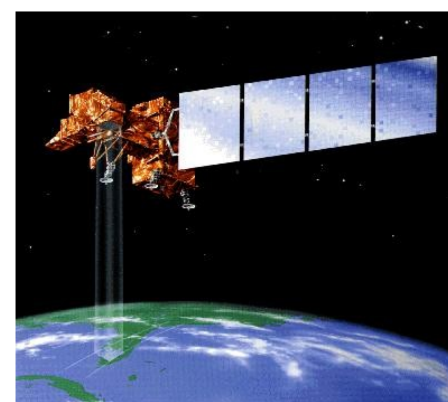



Satellite Remote Sensing
SIO 135/SIO 236

Electromagnetic Radiation and Polarization



Electromagnetic Radiation

- The first requirement for remote sensing is to have an **energy source to illuminate the target**. This energy for remote sensing instruments is in the form of electromagnetic radiation
- Remote sensing is concerned with the measurement of EM radiation returned by Earth surface features that first receive energy from (i) the sun or (ii) an artificial source e.g. a radar transmitter.
- Different objects return different types and amounts of EM radiation .
- Objective of remote sensing is to detect these differences with the appropriate instruments.
- Differences make it possible to identify and assess a broad range of surface features and their conditions

Electromagnetic Radiation (EMR)

- EM energy (radiation) is one of many forms of energy. It can be generated by changes in the energy levels of electrons, acceleration of electrical charges, decay of radioactive substances, and the thermal motion of atoms and molecules.

- All natural and synthetic substances above absolute zero (0 Kelvin, -273°C) emit a range of electromagnetic energy.

- Most remote sensing systems are passive sensors, i.e. they relying on the sun to generate all the required EM energy.

- Active sensors (like radar) transmit energy in a certain direction and records the portion reflected back by features within the signal path.

Electromagnetic Radiation Models

★ To understand the interaction that the EM radiation undergoes before it reaches the sensor, we need to understand the nature of EM radiation

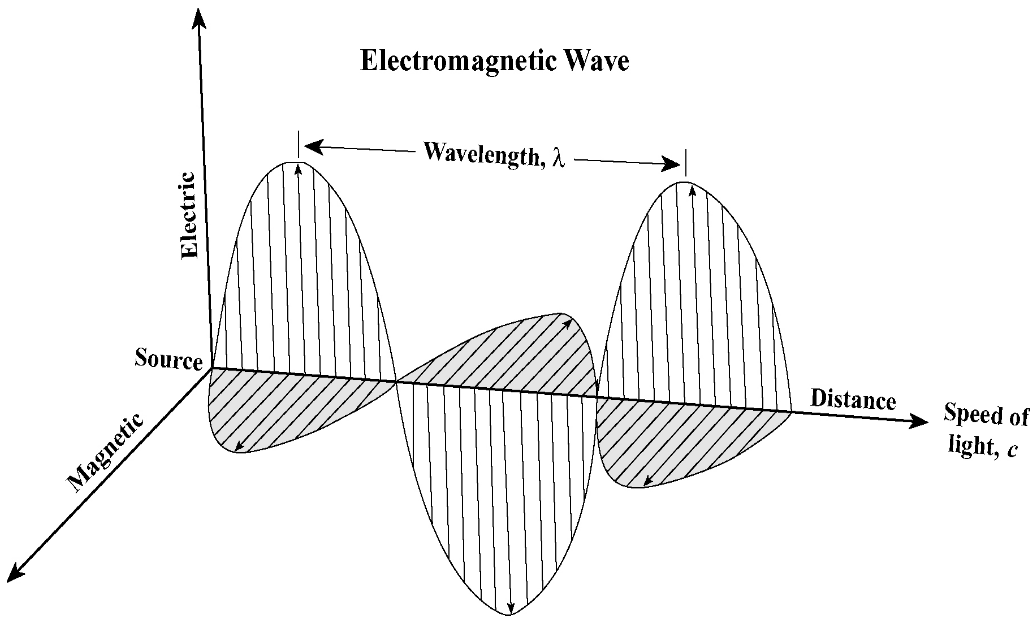
★ To understand how EM radiation is created, how it propagates through space, and how it interacts with other matter, it is useful to consider two different models:

- the *wave* model
- the *particle* model.

Wave Model of Electromagnetic Radiation

The EM wave consists of two fluctuating fields—one electric (E) and the other magnetic (B).

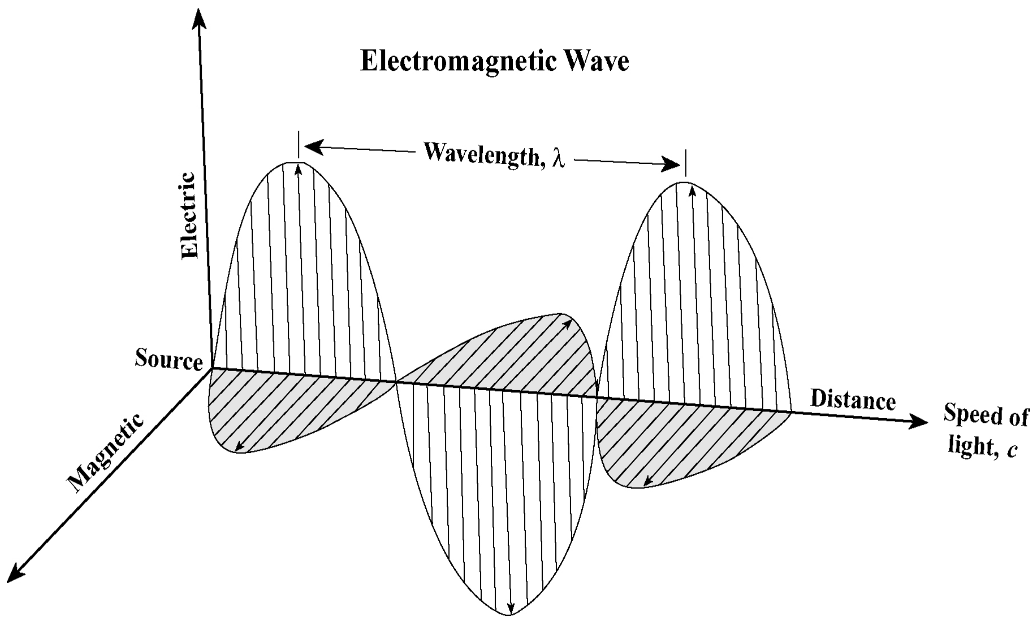
The two vectors are in phase and are at right angles (orthogonal) to one another, and both are perpendicular to the direction of travel.



Wave Model of Electromagnetic Radiation

- ★ EM waves are energy transported through space in the form of periodic disturbances of electric (E) and magnetic (B) fields

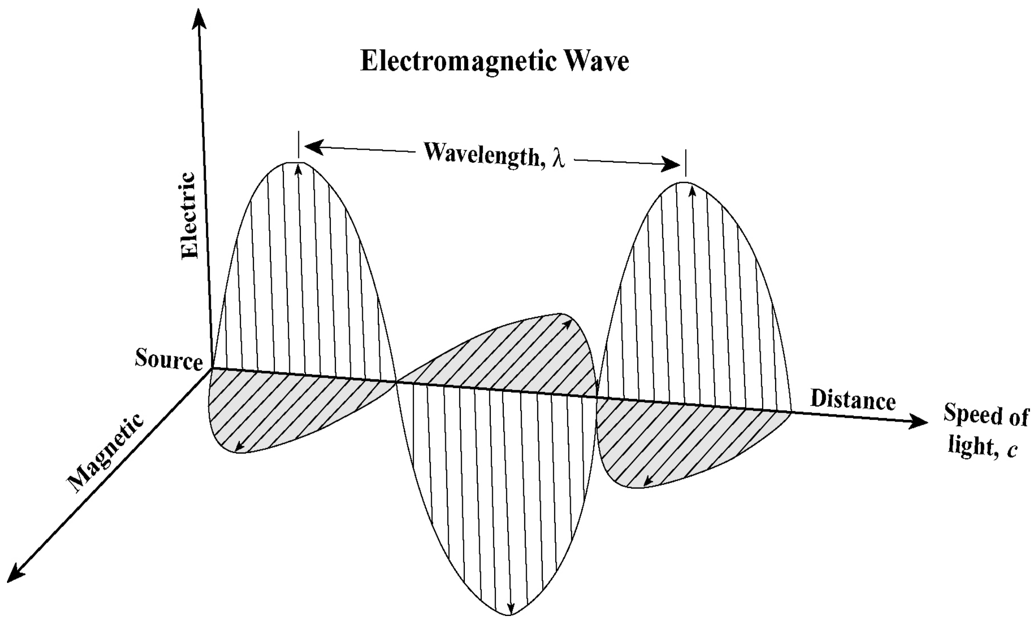
- ★ EM waves travel through space at the same speed, $c = 2.99792458 \times 10^8$ m/s, commonly known as the speed of light



Wave Model of Electromagnetic Radiation

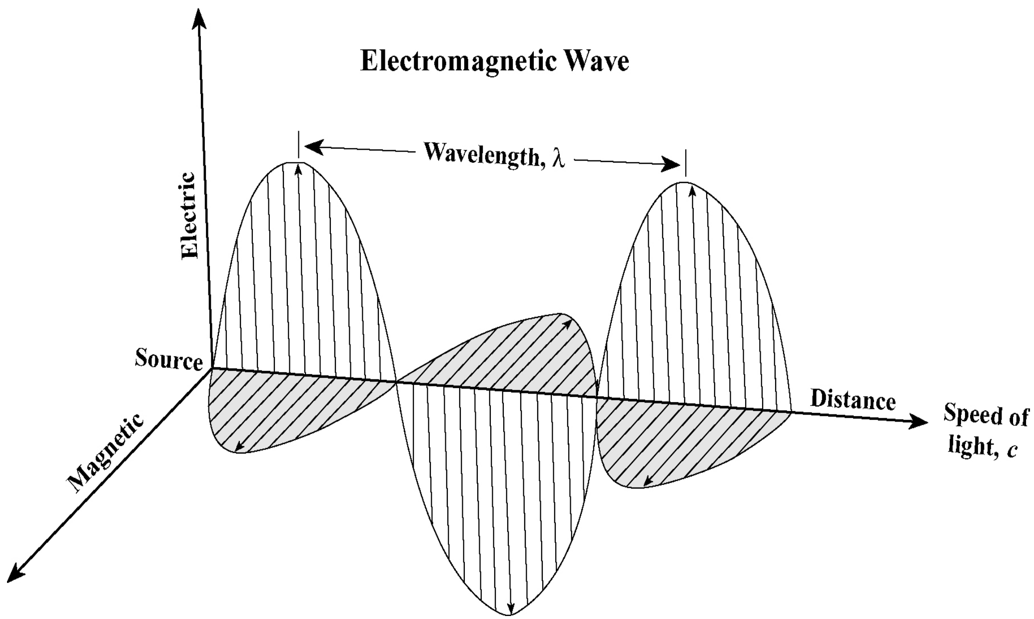
- An EM wave is characterized by a **frequency** and a **wavelength**

- These two quantities are related to the speed of light by the equation **speed of light = frequency x wavelength**



Wave Model of Electromagnetic Radiation

E is perpendicular to direction of propagation
B is perpendicular to direction of propagation
E and B are in phase
E is perpendicular to B
E x B is in direction of propagation
|B| = |E|/c



Electromagnetic (EM) Theory

Electric Field (E)

E is the effect produced by the existence of an electric charge, e.g. an electron, ion, or proton, in the volume of space or medium that surrounds it.

E=F/q F = is the electric force experienced by the particle

q= particle charge

E= is the electric field where the particle is located

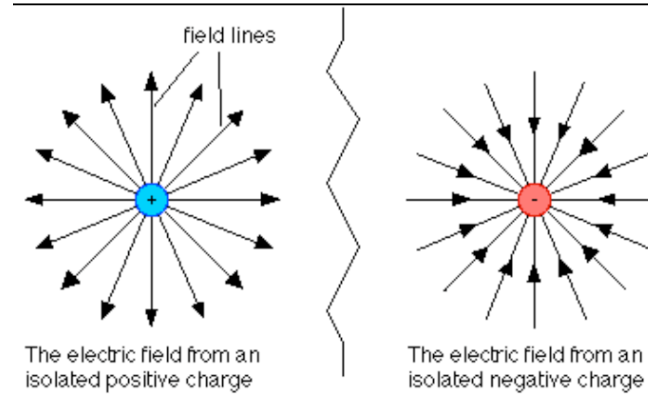
Magnetic Field (B)

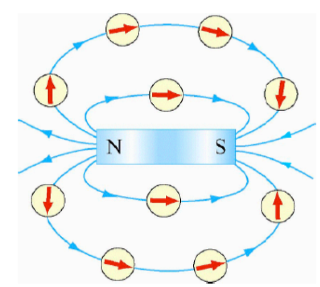
B is the effect produced by a change in velocity of an electric charge q

In a major intellectual breakthroughs in the history of physics (in the 1800s), James Clerk Maxwell came up with the four equations which described all EM phenomena:

➔ MAXWELL'S EQUATIONS

Representation of the electric and magnetic field





A convenient way to represent the magnetic field is with a drawing of "magnetic field lines."
The direction of the lines shows the direction of the magnetic field, while the density of lines shows the strength of the field.

Maxwell's Equations

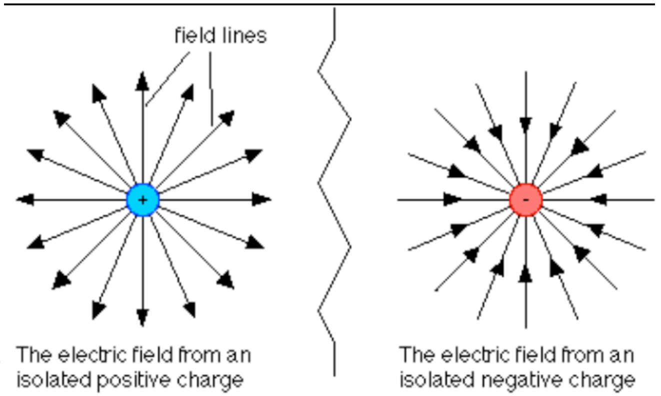
Gauss's law — $\oint \mathbf{E}\cdot d\mathbf{A} = q / \varepsilon_0$

Gauss's law for magnetism: — $\oint \mathbf{B}\cdot d\mathbf{A} = 0$

Maxwell's Faraday rotation: — $\oint \mathbf{E}\cdot d\mathbf{S} = -d\Phi_{\mathrm{B}} / dt$

Ampere's circuital law: — $\oint \mathbf{B}\cdot d\mathbf{S} = \mu_0 i + \mu_0 \varepsilon_0 d\Phi_{\mathrm{E}} / dt$

Representation of the electric and magnetic field



E = electric field (vector)

B = magnetic field (vector)

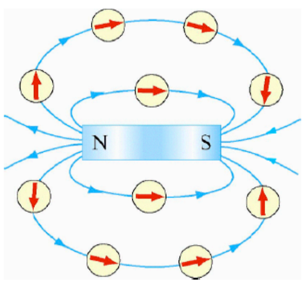
q = electric charge density,

μ_o = magnetic permeability of free space,

ε_o = electric permittivity of free space
(dielectric constant),

i = electric current,

c =1 /sqrt($\mu_o\varepsilon_o$) ~$3\mathrm{x}10^8$ ms^{-1} (speed of light)



A convenient way to represent the magnetic field is with a drawing of "magnetic field lines."
The direction of the lines shows the direction of the magnetic field, while the density of lines shows the strength of the field.

Maxwell's Equations

In the absence of charges or currents:

1 Gauss's law: $\oint \mathbf{E} \cdot d\mathbf{A} = q / \varepsilon_0$

2 Gauss's law for magnetism: $\oint \mathbf{B} \cdot d\mathbf{A} = 0$

3 Maxwell's Faraday rotation: $\oint \mathbf{E} \cdot d\mathbf{S} = -d\Phi_{\mathbf{B}} / dt$

4 Ampere's circuital law: $\oint \mathbf{B} \cdot d\mathbf{S} = \mu_0 i + \mu_0 \varepsilon_0 d\Phi_{\mathbf{E}} / dt$

1: Charges create E, in specific "patterns". Or also that E field lines "emanate" from charges

2: B field lines aren't created (there are no magnetic monopoles), but they form loops, with no start or stop.

3: Changing B makes E

4: Electric currents create magnetic fields; changing electric fields create magnetic fields.

Maxwell's Equations

Differential form in the absence of magnetic or polarizable media:

1 Gauss's law:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} = 4\pi k \rho$$

2 Gauss's law for magnetism:

$$\nabla \cdot B = 0$$

3 Maxwell's Faraday rotation:

$$\nabla x\, E = -\frac{\partial B}{\partial t}$$

4 Ampere's circuital law:

$$\nabla\ x\ B = \frac{4\pi k}{c^2} J + \frac{1}{c^2}\frac{\partial E}{\partial t}$$

$$= \frac{J}{\varepsilon_0 c^2} + \frac{1}{c^2}\frac{\partial E}{\partial t}$$

$$k = \frac{1}{4\pi\varepsilon_0} = \text{Coulomb's constant} \qquad c^2 = \frac{1}{\mu_0 \varepsilon_0}$$

Maxwell's Equations

Differential form in free space:

1 Gauss's law: $\nabla \cdot E = 0$

2 Gauss's law for magnetism: $\nabla \cdot B = 0$

3 Maxwell's Faraday rotation: $\nabla \times E = -\partial B/\partial t$

4 Ampere's circuital law: $\nabla \times B = \mu_o \varepsilon_o \, \partial E/\partial t$

Solution to Maxwell's equations

The harmonic plane wave $E_x = E_o \cos(\omega t - kz)$; $E_y = 0$; $E_z = 0$

$B_x = 0$; $B_y = E_o/c \cos(\omega t - kz)$; $B_z = 0$

satisfies Maxwell's equations

wave speed $c = \omega/k = 1/\mathrm{sqrt}(\varepsilon_o \mu_o)$

ω is the angular frequency, k is the wave number

$\omega = 2\pi f$

$k = 2\pi/\lambda$

Wave Model of Electromagnetic Radiation

- ★ EM waves propagate at the speed of light, c, and consists of an electric field E and a magnetic field B.
- ★ E varies in magnitude in the direction perpendicular to the traveling direction; B is perpendicular to E.
- ★ E is characterized by: frequency (wavelength), amplitude, polarization, phase.

Wave equation:

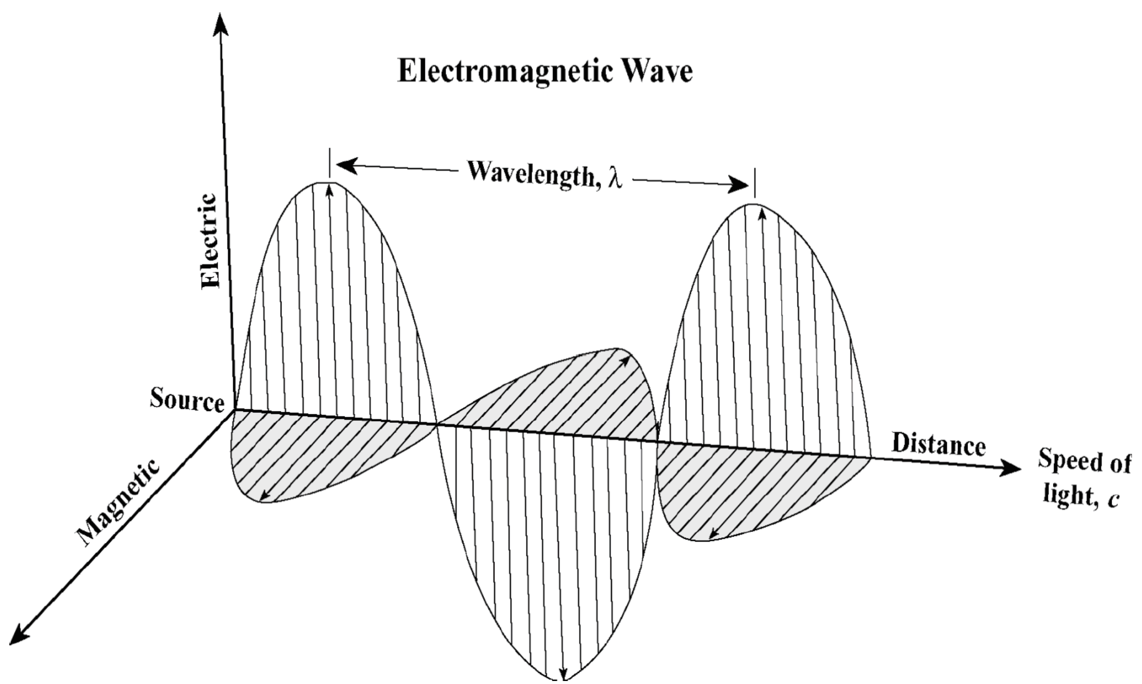
$$E_x = E_o \exp i(\omega t - kz)$$

$k = 2\pi/\lambda$ = wave number

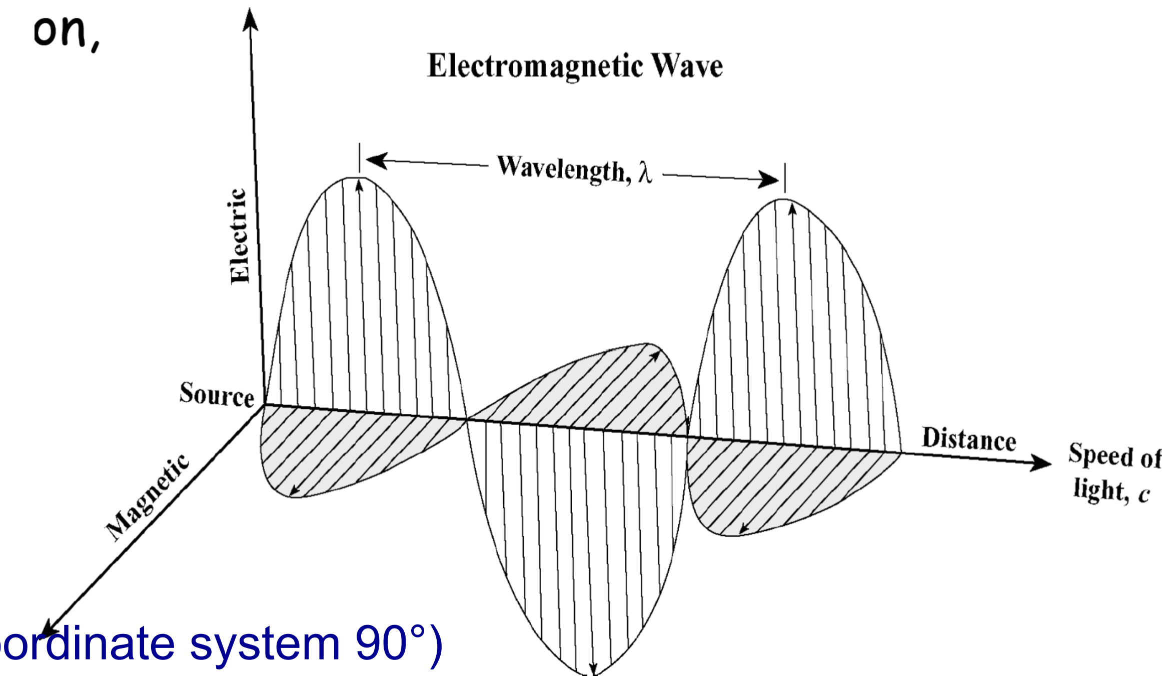
$\omega = 2\pi f$ =angular frequency

f = frequency

Φ =phase



Wave Model of Electromagnetic Radiation



Wave equation:

$$E_x = E_o \cos(\omega t - kz)$$

$k = 2\pi/\lambda$ = wave number

$\omega = 2\pi f$ =angular frequency

f = frequency

Φ =phase

Consider a second wave (rotate coordinate system 90°)

$E_y = E_o \cos(\omega t - kz)$

Now add these two waves & give them different amplitudes & phases:

$E_x = E_{ox} \cos(\omega t - kz - \Phi_x)$

$E_y = E_{oy} \cos(\omega t - kz - \Phi_y)$

$E_z = 0$

Values of E_x , E_x. Φ_x *and* Φ_y determine how the E field varies with time (polarization)

Light is a traveling EM wave

So…Maxwell's equations tell us that the velocity of EM wave is equal to the speed of light ⇨ i.e. light travels as an EM wave.

$\lambda = c / f$

λ = wavelength (m)

c = speed of light (m/s)

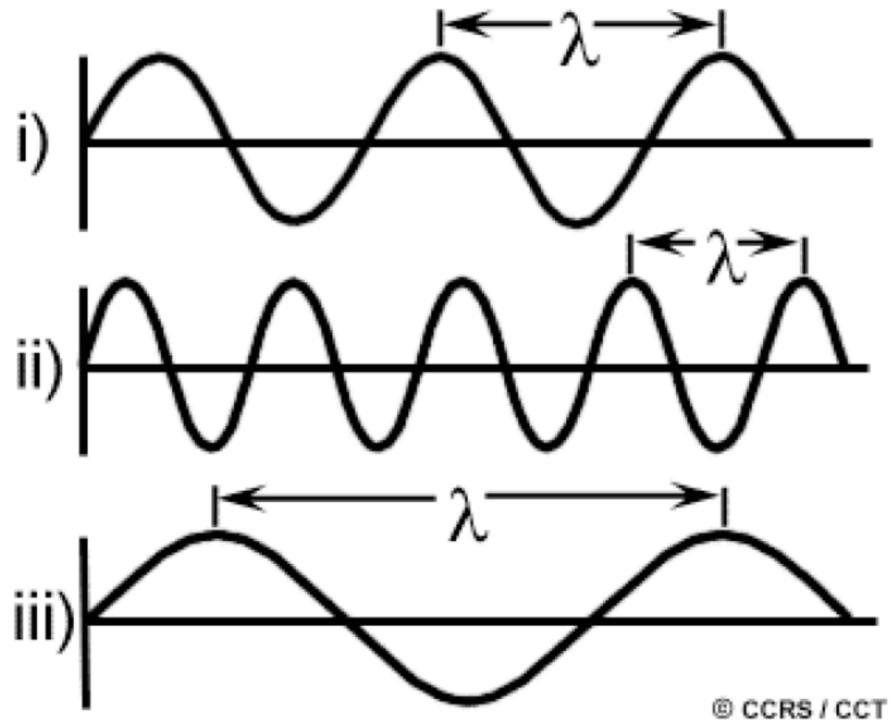
f = frequency (hz or s-1)

c = 300,000 km/s

f = 5.6 GHz; λ = 5.6 cm

f = 1.2 GHz; λ = 24 cm.

λ = 0.4 mm; f = 750 GHz.



Light is a traveling EM wave

Maxwell's equations also tell us that EM waves don't carry any material with them. They only transport **energy**:

$E = h f = h c / \lambda$

c = speed of light (m/s)

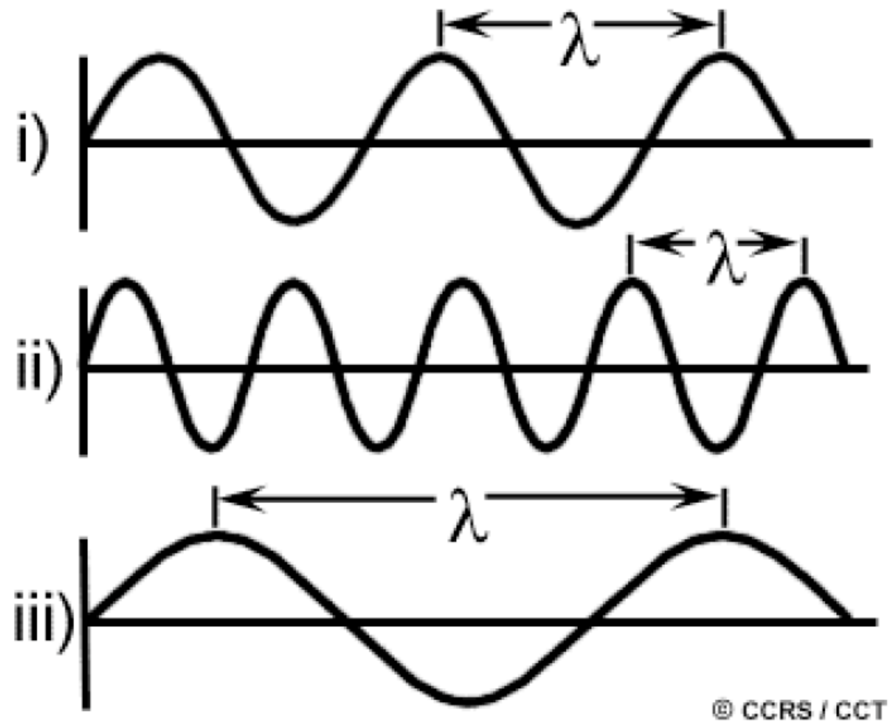
h = Planck's constant.

f = frequency (hz or s^{-1})

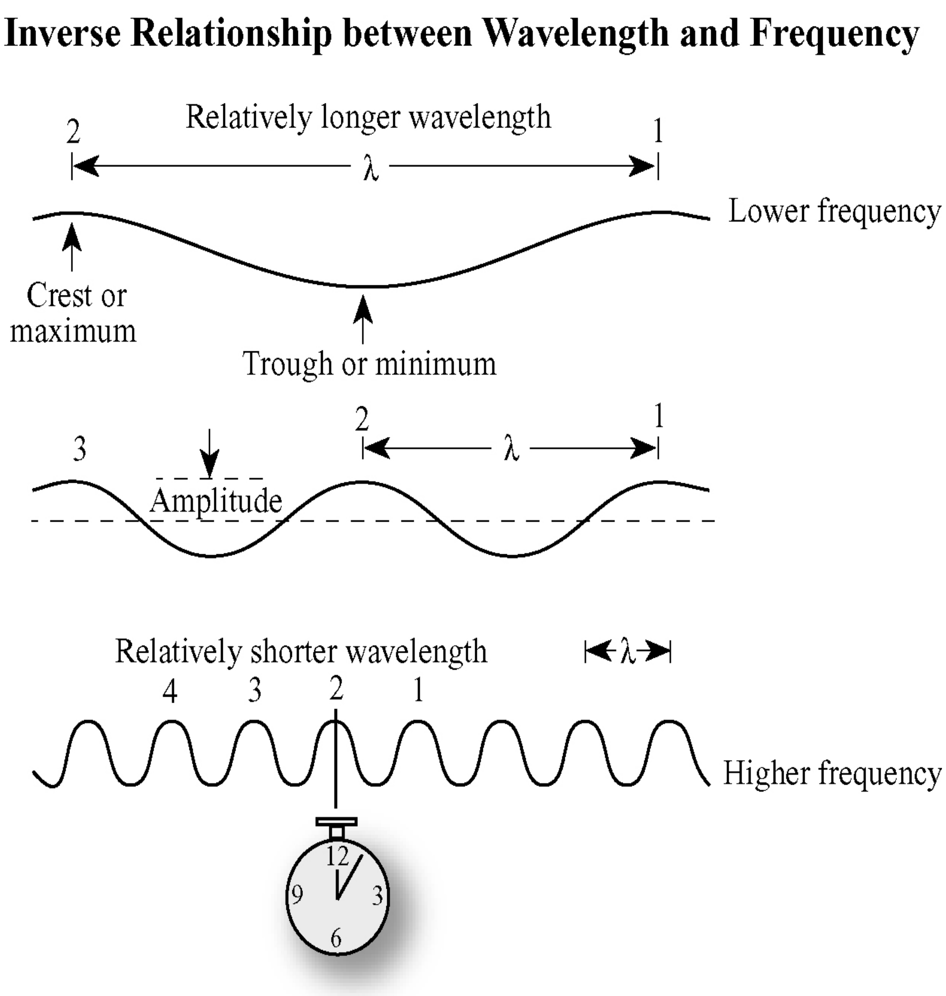
λ=wavelength

High-frequency electromagnetic waves have a short wavelength and high energy;

Low-frequency waves have a long wavelength and low energy



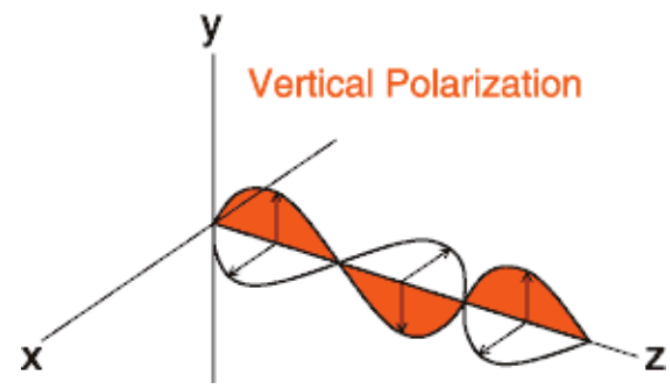
Wave Model of Electromagnetic Radiation



- This cross-section of an EM wave illustrates the inverse relationship between wavelength (λ) & frequency (ν). The longer the wavelength the lower the frequency; the shorter the wavelength, the higher the frequency.
- The amplitude of an EM wave is the height of the wave crest above the undisturbed position.
- Frequency is measured in cycles per second, or hertz (Hz).

Polarization

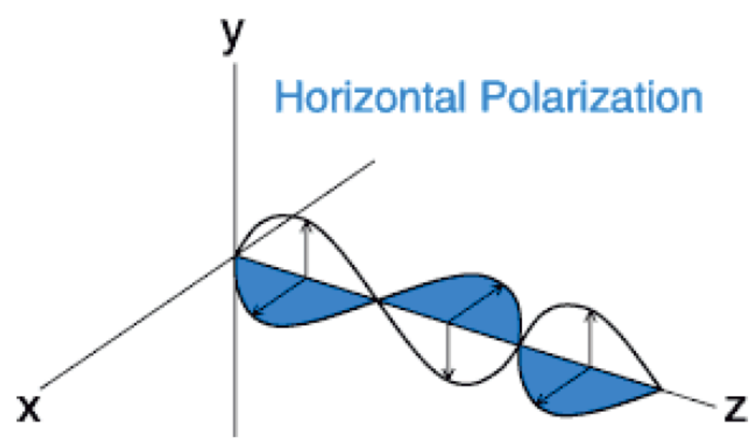
Refers to orientation of the electric field **E**



E

If both **E** and **B** remain in their respective planes, the radiation is called "**plane or linearly polarized**":

Vertically polarized (E is parallel to the plane of incidence)



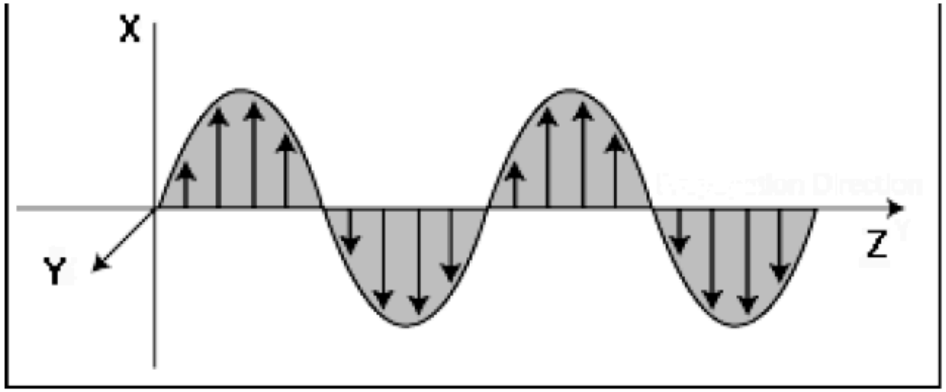
Horizontally polarized (E is perpendicular to the plane of incidence)

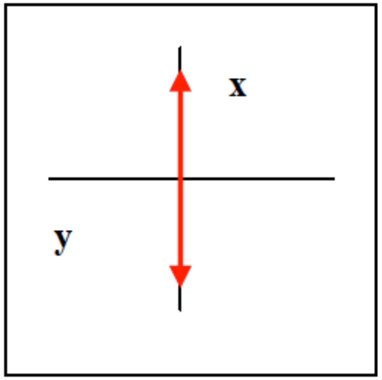
E

Plane of incidence = the plane defined by the vertical and the direction of propagation

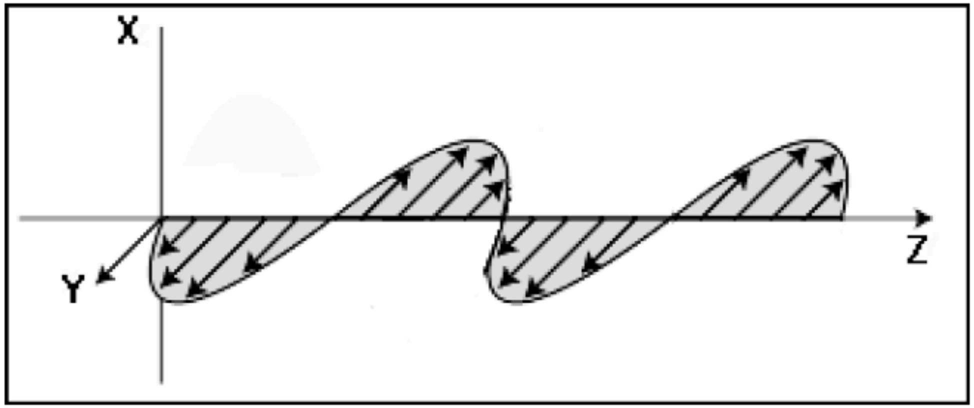
Polarization

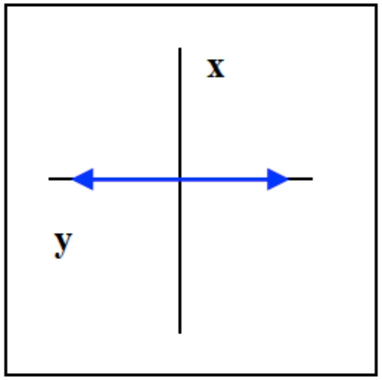
Vertically polarized wave is one for which the electric field lies only in the x-z plane.





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

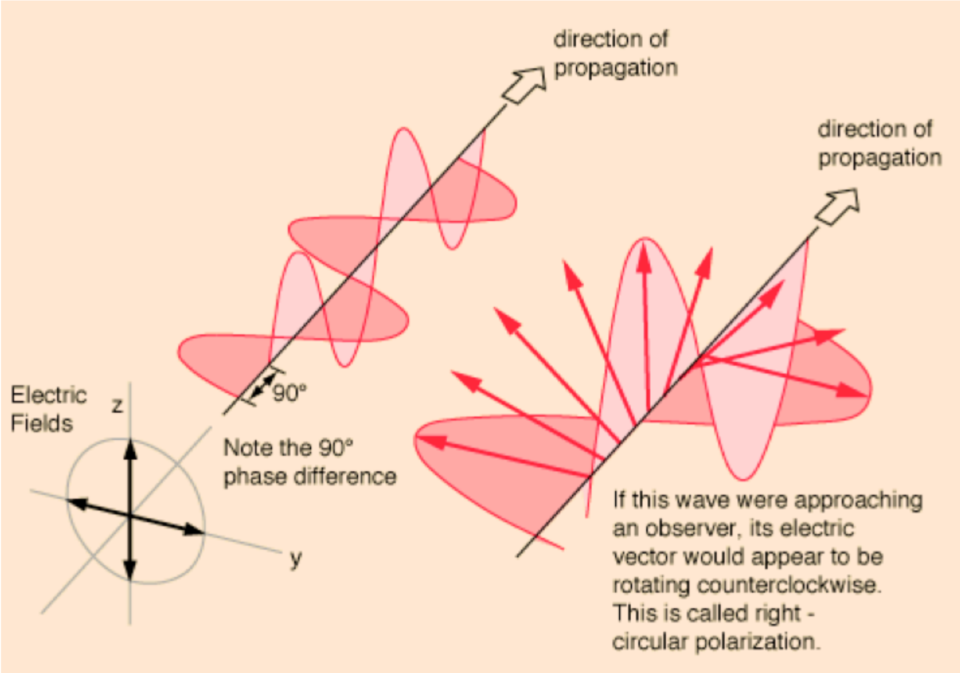




- Horizontal and vertical polarizations are an example of **linear polarization**.

Polarization

If instead of being confined to fixed direction, E rotates in the x-y plane with constant amplitude, it is said to be circularly polarized (either right- or left-hand circular (clockwise/anti-clockwise respectively)



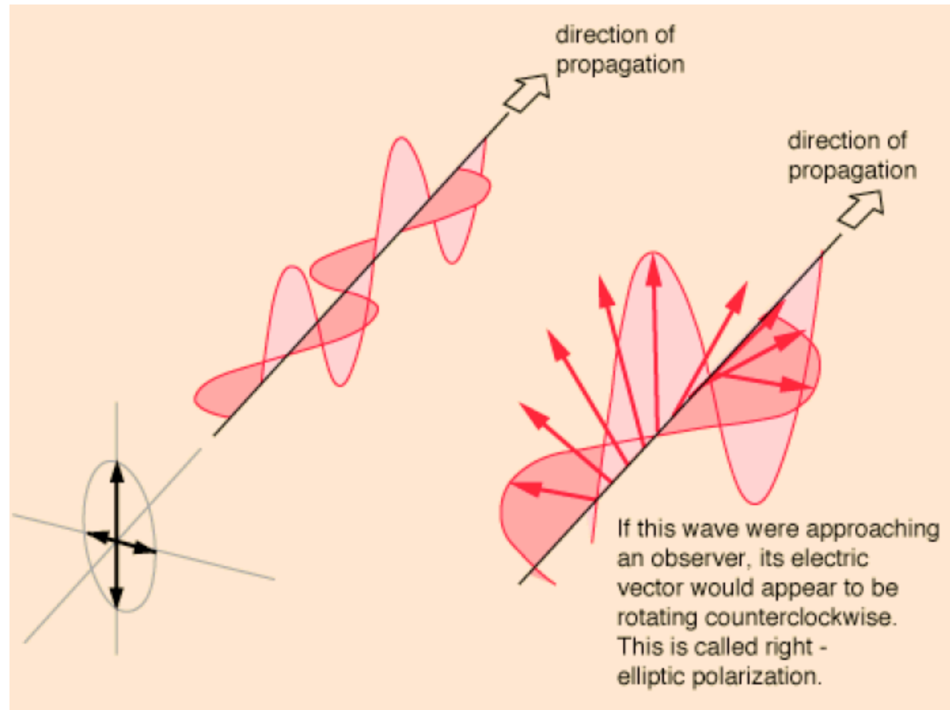
Circularly polarized light consists of two perpendicular EM plane waves of equal amplitude and 90° difference in phase. The light illustrated is right-hand circularly polarized

Radiation from the sun is unpolarized (at random angles)

Polarization

Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90°

If the thumb of your right hand were pointing in the direction of propagation of the light, the electric vector would be rotating in the direction of your fingers



Right-hand elliptically polarized light

WATCH: https://www.youtube.com/watch?v=8YkfEft4p-w

Stokes parameters

Set of four values describe the polarisation state of EM radiation:

- intensity **I – S_0**
- the degree of polarization **Q – S_1**
- the plane of polarization **U – S_2**
- the ellipticity **V** (0 for linear, 1 for circle) **S_3**

$[S_0, S_1, S_2, S_3]$ = Stokes vector

Stokes parameters expressed via amplitudes and phase shift of E_{ox} & E_{oy}

< > means time average

$$S_0 = <E_{ox}^2> + <E_{oy}^2>$$

$$S_1 = <E_{ox}^2> - <E_{oy}^2>$$

$$S_2 = 2E_{ox}E_{oy}\cos(\Delta\phi)$$

$$S_3 = 2E_{ox}E_{oy}\sin(\Delta\phi)$$

Some common Stokes vectors

Linear vertical polarization

$\boldsymbol{E_{ox}} = 0$, $\boldsymbol{E_{oy}} = 1$

$\mathbf{S_0} = \langle E_{ox}^2\rangle + \langle E_{oy}^2\rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2\rangle - \langle E_{oy}^2\rangle = -1$

$\mathbf{S_2} = 2E_{ox}E_{oy}\cos(\Delta\phi) = 0$

$\mathbf{S_3} = 2E_{ox}E_{oy}\sin(\Delta\phi) = 0$

Stokes vector is [1, -1, 0, 0]

Linear horizontal polarization

$\boldsymbol{E_{ox}} = 1$, $\boldsymbol{E_{oy}} = 0$

$\mathbf{S_0} = \langle E_{ox}^2\rangle + \langle E_{oy}^2\rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2\rangle - \langle E_{oy}^2\rangle = 1$

$\mathbf{S_2} = 2E_{ox}E_{oy}\cos(\Delta\phi) = 0$

$\mathbf{S_3} = 2E_{ox}E_{oy}\sin(\Delta\phi) = 0$

Stokes vector is [1, 1, 0, 0]

Normalized so that $S_0 = 1$.

Some common Stokes vectors

Linear at 45°

$\boldsymbol{E_{ox}} = sqrt(1/2)$, $\boldsymbol{E_{oy}} = sqrt(1/2)$

$$\Delta\phi = 0$$

$\mathbf{S_0} = \langle E_{ox}^2 \rangle + \langle E_{oy}^2 \rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2 \rangle - \langle E_{oy}^2 \rangle = 0$

$\mathbf{S_2} = 2E_{ox}E_{oy} \cos(\Delta\phi) = 1$

$\mathbf{S_3} = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, 0, 1, 0]

Linear at -45°

$\boldsymbol{E_{ox}} = sqrt(1/2)$, $\boldsymbol{E_{oy}} = -sqrt(1/2)$

$$\Delta\phi = 0$$

$\mathbf{S_0} = \langle E_{ox}^2 \rangle + \langle E_{oy}^2 \rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2 \rangle - \langle E_{oy}^2 \rangle = 0$

$\mathbf{S_2} = 2E_{ox}E_{oy} \cos(\Delta\phi) = -1$

$\mathbf{S_3} = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, 0, -1, 0]

Normalized so that $S_0 = 1$.

Some common Stokes vectors

Unpolarized Light [1, 0, 0, 0]

Linear horizontal [1, 1, 0, 0]

Linear vertical [1, -1, 0, 0]

Linear at 45 degrees [1, 0, 1, 0]

Linear at -45 degrees [1, 0, -1, 0]

Right circular [1, 0, 0, 1]

Left circular [1, 0, 0, -1]

Normalized so that $S_0 = 1$.

Stokes parameters

For **unpolarized** light:

$$Q = U = V = 0 \quad [3.7]$$

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

$$P = (Q^2 + U^2 + V^2)^{1/2} / I \quad [3.8]$$

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

$$LP = -\frac{Q}{I} \quad [3.9]$$

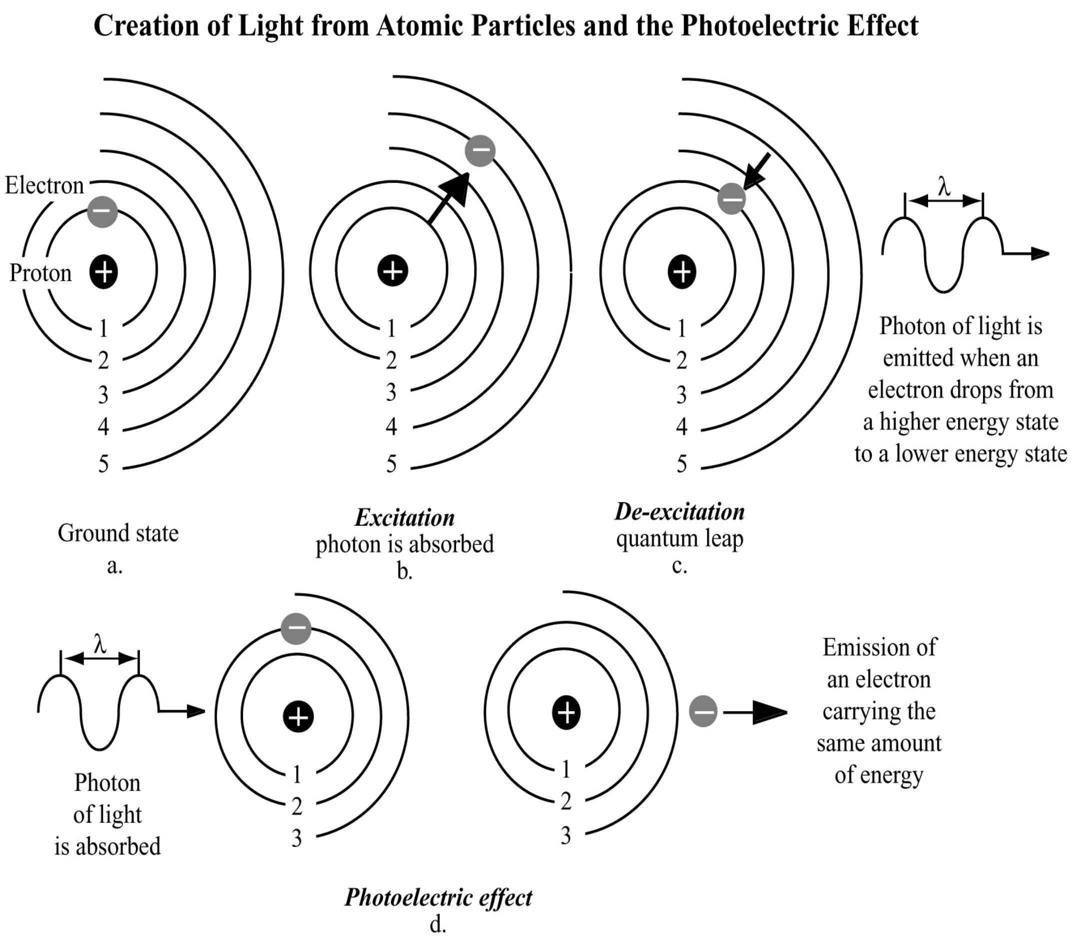
Measurements of polarization are actively used in remote sensing in the solar and microwave regions.
Polarization in the microwave – mainly due to reflection from the surface.
Polarization in the solar – reflection from the surface and scattering by molecules and particulates.
Active remote sensing (e.g., radar) commonly uses polarized radiation.

Quantum Theory of Electromagnetic Energy

- Maxwell's equations show us that light is a smooth and continuous wave, and we often describe EMR in terms of its wave-like properties. .
- Albert Einstein (1905) found that when light interacts with electrons, it has a different character -- it behaves as though it is composed of many individual bodies called *photons*, which carry such particle-like properties as energy and momentum.
- So when the energy interacts with matter it is useful to describe it as discrete packets of energy, or *quanta*.
- According to quantum physics, the energy of an EM wave is quantized, i.e. it can only exist in discrete amount.
- The basic component of energy for an EM wave is called a **photon**. The energy E of a photon is proportional to the frequency of radiation f

$\boldsymbol{E = h f}$ where h is **Planck's Constant** = 6.626×10^{-34} J s.

Creation of Light from Atomic Particles

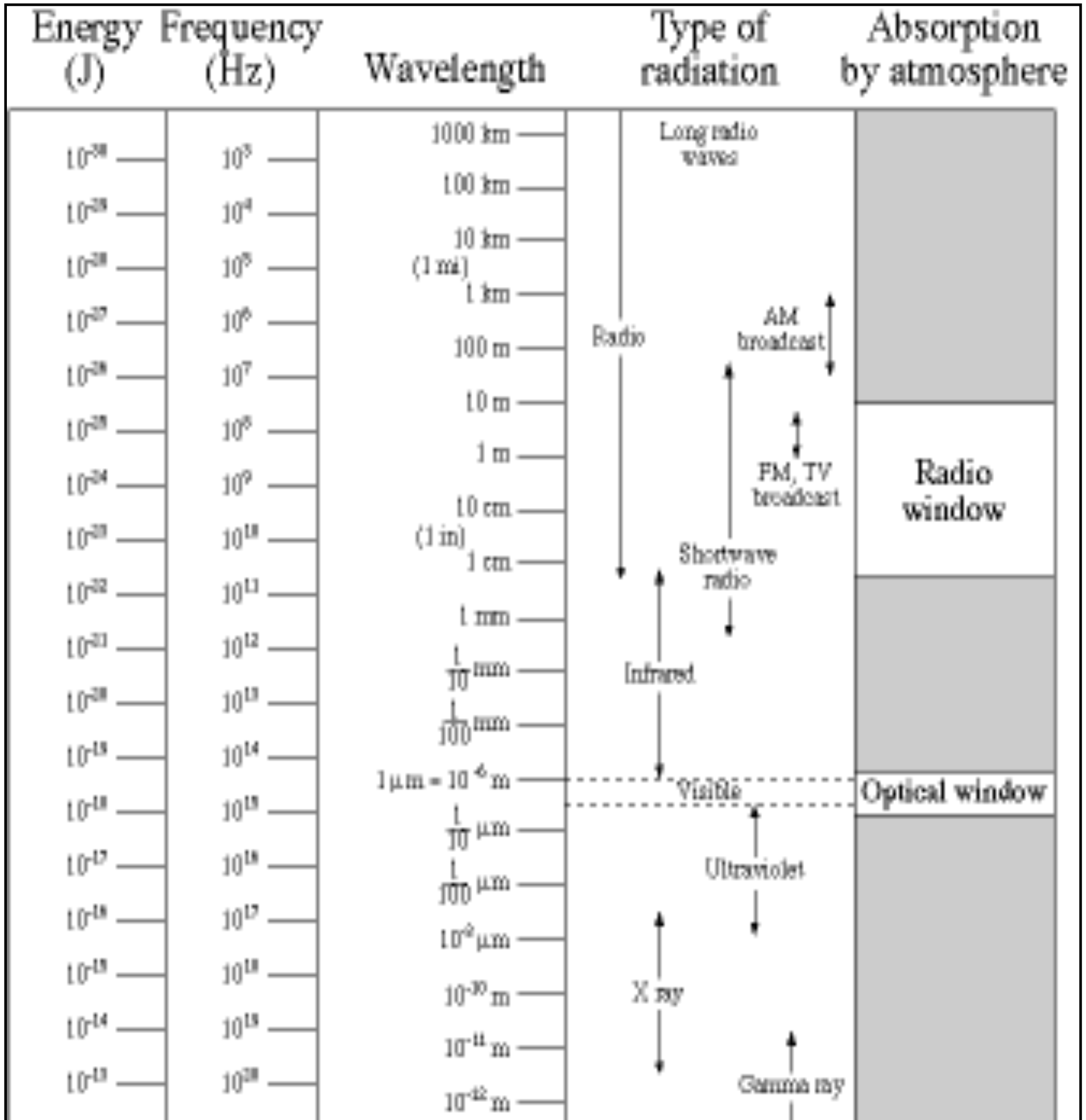


A **photon** of light is emitted when an electron in an atom or molecule drops from a higher-energy state to a lower-energy state. The light emitted (i.e., its wavelength) is a function of the changes in the energy levels of the outer, valence electro, e.g., yellow light may be produced from a sodium vapor lamp.

Matter can also be subjected to such high temperatures that electrons, which normally move in captured, non-radiating orbits, are broken free. When this happens, the atom is left with a positive charge equal to the negatively charged electron that escaped.

The electron becomes a free electron, and the atom is now an ion. If another free electron fills the vacant energy level created by the free electron, then radiation from all wavelengths is produced, i.e., a continuous spectrum of energy. The intense heat at the surface of the Sun produces a *continuous spectrum* in this manner.

Energy of Quanta (Photons)



The energy of quanta (photons) ranging from gamma rays to radio waves in the EM spectrum.

Electromagnetic Spectrum

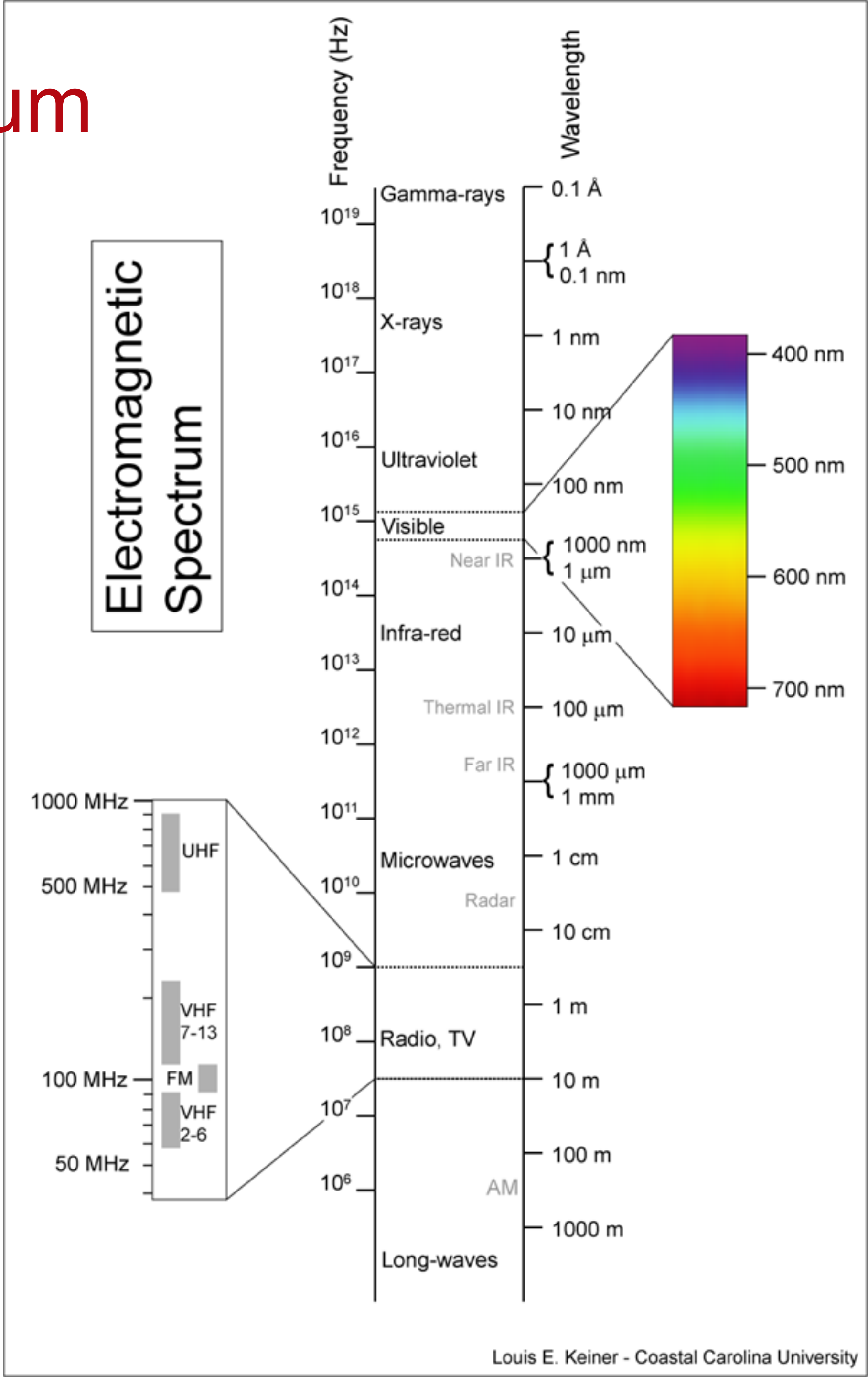
- ★ Frequency (or wavelength) of an EM wave depends on its source.
- ★ There is a wide range of frequency encountered in our physical world, ranging from the low frequency of the electric waves generated by the power transmission lines to the very high frequency of the gamma rays originating from the atomic nuclei.
- ★ This wide frequency range of electromagnetic waves make up the **Electromagnetic Spectrum**.

Electromagnetic Spectrum

- Represents the continuum of electromagnetic energy from extremely short wavelengths (cosmic and gamma rays) to extremely long wavelengths (microwaves).

- No natural breaks in the EMS -- it is artificially separated and named as various spectral bands (divisions) for the description convenience.

- Common bands in remote sensing are visible, infra-red & microwave.

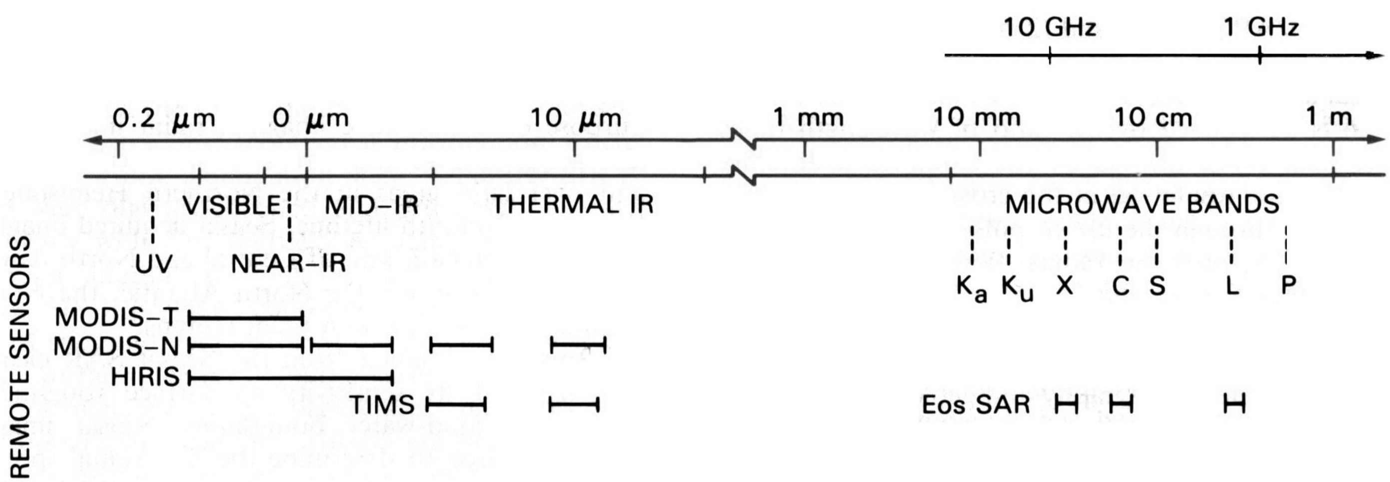


Spectral bands

Three important spectral bands in remote sensing:

- visible light
- infrared radiation
- microwave radiation

Image from NASA 1987. SAR: Synthetic Aperture Radar.
Earth Observing System, Vol. IIf.



Also see Figure 2.2 in Rees

Electromagnetic Spectrum

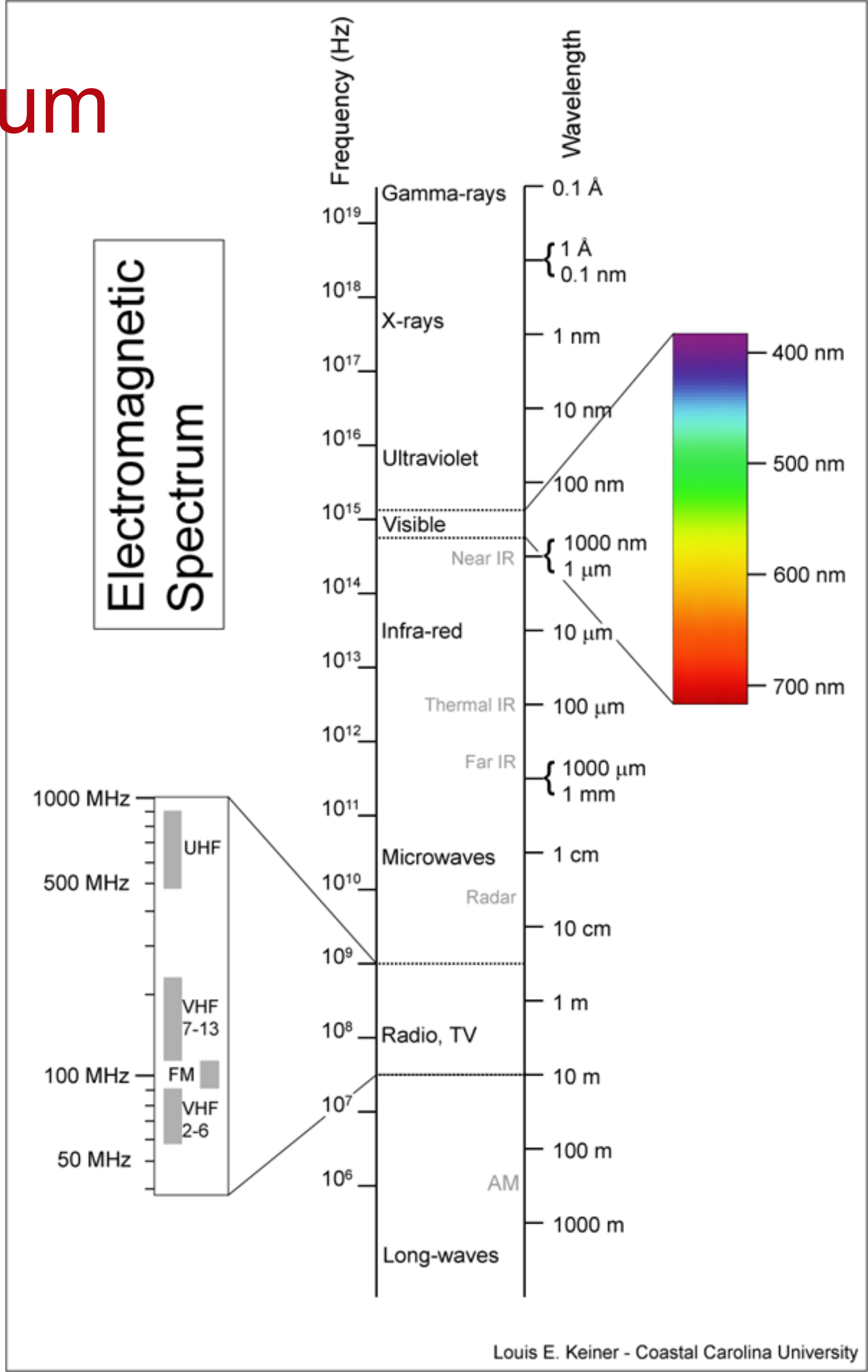
Visible: Small portion of the EMS that humans are sensitive to:
blue (0.4-0.5 μm); green (0.5-0.6 μm); red (0.6-0.73 μm)

Infrared: Three logical zones:

1. Near IR: reflected, can be recorded on film emulsions (0.7 - 1.3μm).
2. Mid infrared: reflected, can be detected using electro-optical sensors (1.3 - 3.0μm).
3. Thermal infrared: emitted, can only be detected using electro-optical sensors (3.0 - 5.0 and 8 - 14 μm).

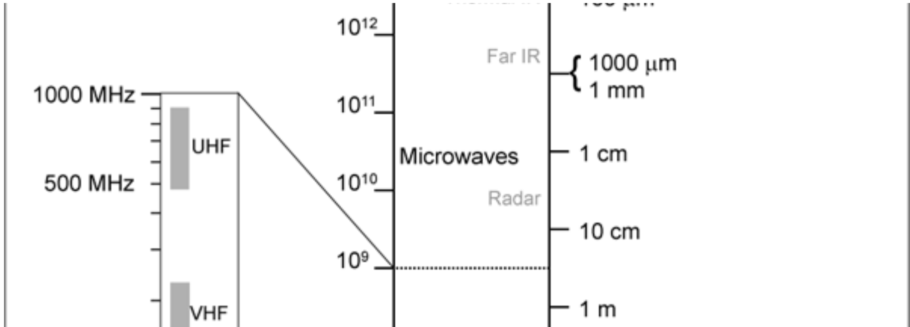
Microwave

Radar sensors, wavelengths range from 1mm - 1m (K_a, K_u, X, C, S, L & P)



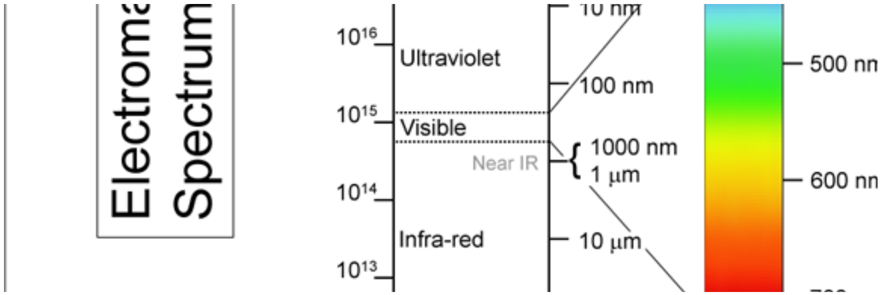
Wavelengths of microwave

- **Microwaves**: 1 mm to 1 m wavelength.
- Further divided into different frequency bands:**(1 GHz = 10^9 Hz)**
- **P band**: 0.3 - 1 GHz (30 - 100 cm)
- **L band**: 1 - 2 GHz (15 - 30 cm)
- **S band**: 2 - 4 GHz (7.5 - 15 cm)
- **C band**: 4 - 8 GHz (3.8 - 7.5 cm)
- **X band**: 8 - 12.5 GHz (2.4 - 3.8 cm)
- **Ku band**: 12.5 - 18 GHz (1.7 - 2.4 cm)
- **K band**: 18 - 26.5 GHz (1.1 - 1.7 cm)
- **Ka band**: 26.5 - 40 GHz (0.75 - 1.1 cm)



Wavelengths of Infrared

- **Infrared**: 0.7 to 300 μm wavelength. This region is further divided into the following bands:
- **Near Infrared (NIR)**: 0.7 to 1.5 μm.
- **Short Wavelength Infrared (SWIR)**: 1.5 to 3 μm.
- **Mid Wavelength Infrared (MWIR)**: 3 to 8 μm.
- **Long Wavelength Infrared (LWIR)**: 8 to 15 μm.
- **Far Infrared (FIR)**: longer than 15 μm.
- The NIR and SWIR are also known as the **Reflected Infrared**, referring to the main infrared component of the solar radiation reflected from the earth's surface. The MWIR and LWIR are the **Thermal Infrared**.



Wavelengths of visible light

- **Red**: 610 - 700 nm
- **Orange**: 590 - 610 nm
- **Yellow**: 570 - 590 nm
- **Green**: 500 - 570 nm
- **Blue**: 450 - 500 nm
- **Indigo**: 430 - 450 nm
- **Violet**: 400 - 430 nm