

# Electromagnetic Waves

## 1 – Maxwell's Predictions

During the early stages of studies of electric and magnetic phenomena, they were thought to be unrelated. In 1865, **James Clark Maxwell** provided a mathematical theory that showed a close relation between electric and magnetic phenomena.

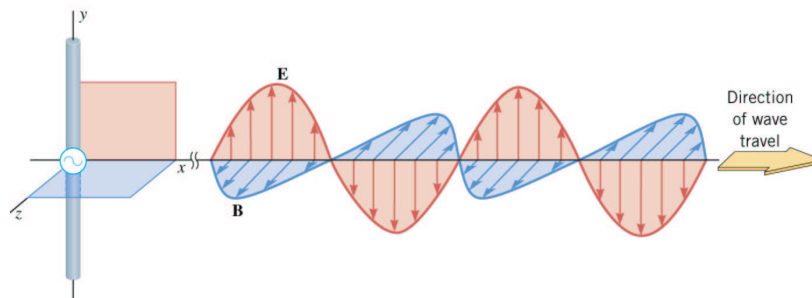
His theory is based upon the following 4 pieces of information:

1. Electric fields originate on positive charges and terminate on negative charges.
2. Magnetic field lines always form closed loops.
3. A varying magnetic field induces an emf and hence an electric field (Faraday's law of induction).
4. Magnetic fields are generated by moving charges.

# Electromagnetic Waves

Maxwell's theory also predicted that electric and magnetic fields can move through space as waves. He calculated their speed to be equal to the speed of light  $c = 3 \times 10^8 \text{ m/s}$  and concluded that *light waves are electromagnetic in nature*.

In other words, light consists of fluctuating electric and magnetic fields that travel through space as transverse waves.

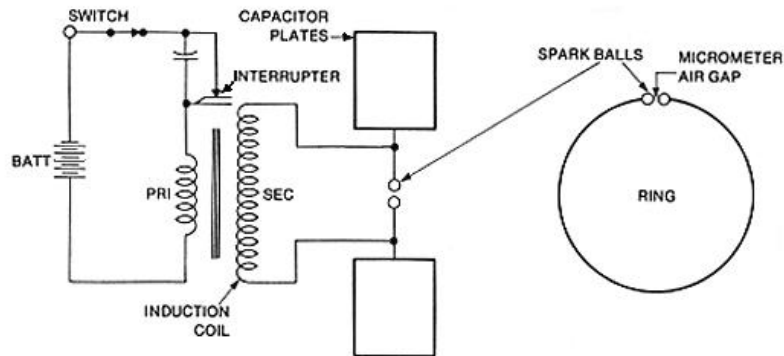


# Electromagnetic Waves

## 2 – Hertz's Discoveries

In 1887, Heinrich Hertz was the first to generate and detect electromagnetic waves in a laboratory experiment.

Schematic of Heinrich Hertz's first transmitter and receiver of electromagnetic waves:

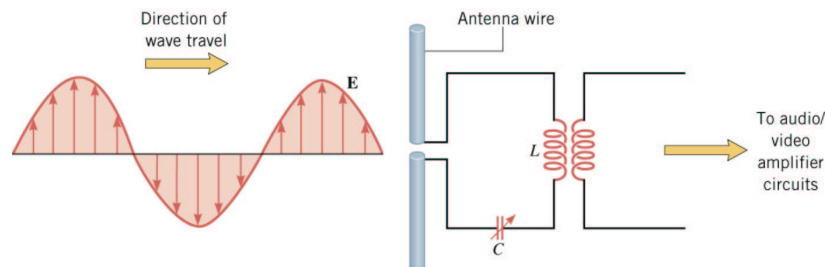


He also measured the speed of the electromagnetic waves, verifying that Maxwell's prediction that they travel at the speed of light was correct.

# Electromagnetic Waves

A radio wave can be detected using an LC circuit. The resonance frequency of oscillation of an LC circuit is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$



When the frequency of the wave matches the resonance frequency of the LC circuit, a maximum voltage is induced in the secondary circuit which is then further amplified and processed (not shown). The frequency of the waves that are received can be selected by varying  $C$ .

# Electromagnetic Waves

## 3 – Properties of Electromagnetic Waves

- The electric and magnetic fields in an electromagnetic wave are in phase.
- The electric and magnetic fields are perpendicular to each other.
- The electric and magnetic fields are in planes perpendicular to the direction of travel of the wave. They are transverse waves.
- Electromagnetic waves travel at the speed of light:

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (1)$$

where  $\mu_0 = 4\pi \times 10^{-7} \text{ N} \cdot \text{s}^2/\text{C}^2$  is the permeability of free space and  $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2)$  is the permittivity of free space. Numerically,  $c = 2.99792 \times 10^8 \text{ m/s}$ .

# Electromagnetic Waves

- The ratio of the electric to the magnetic field in an electromagnetic field is given by

$$\frac{E}{B} = c \quad (2)$$

- Electromagnetic waves carry energy. Energy can be transferred to objects placed in their path. The total energy density,  $u$ , carried by an electromagnetic wave is

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0} B^2 \quad (3)$$

Note: For the average energy density,  $\bar{u}$ , replace  $E, B$  by  $E_{rms}, B_{rms}$ . To describe the energy transport by an electromagnetic wave we introduce *intensity*, which is the power passing through an unit area perpendicular to the travel direction per unit area: ( $S = P/A$ ):

$$S = cu \quad (4)$$

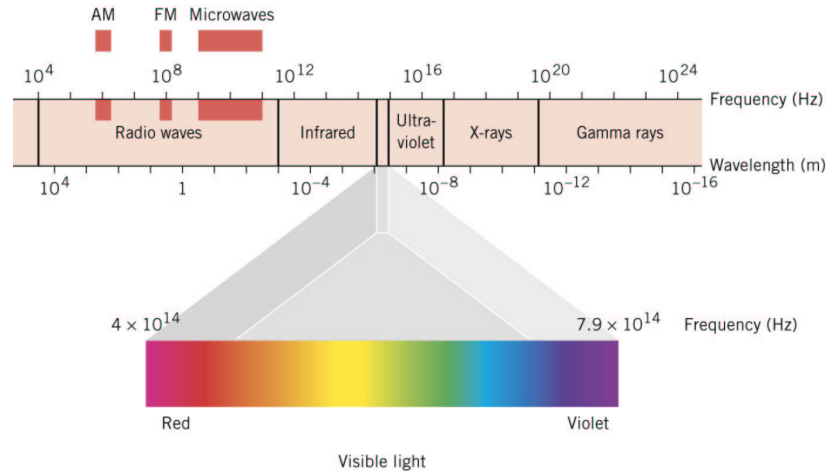
# Electromagnetic Waves

## 4 – The Spectrum of Electromagnetic Waves

The frequency,  $f$ , and wavelength  $\lambda$  of electromagnetic waves is related by

$$c = f\lambda \quad (5)$$

The types of electromagnetic waves are



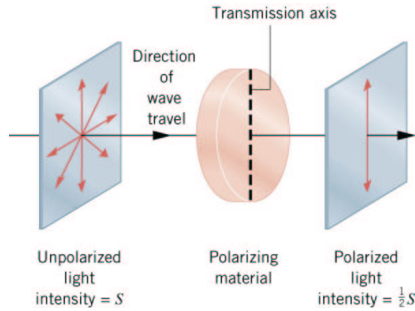
# Electromagnetic Waves

## 5 – Polarization of Electromagnetic Waves

The phenomenon of polarization is firm evidence for the transverse nature of electromagnetic waves.

- Electromagnetic waves emitted by an ordinary source are **unpolarized**, *ie* the electric field vector,  $\mathbf{E}$ , points randomly in the plane perpendicular to the direction of wave travel.
- A wave is said to be **linearly polarized** if  $\mathbf{E}$  oscillates in the same direction at all times.
- The most common technique to produce polarized light is to use a material that
  1. transmits waves whose electric field vectors oscillate in a plane parallel to a certain direction and
  2. absorbs those waves whose electric field vectors oscillate in directions perpendicular to that direction.

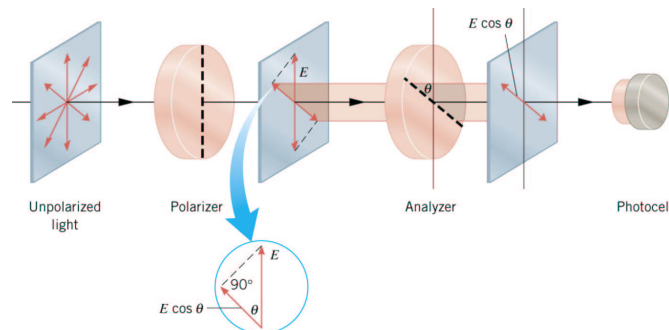
# Electromagnetic Waves



**Example:** *polaroid*. A long chain hydrocarbon, stretched such that the molecules align.

- Suppose an unpolarized light beam is incident on the first on a polarizing sheet (called **polarizer**). The light that is passing through is polarized vertically. Its intensity is reduced to half its original value.
- A 2nd polarizing sheet (called **analyzer**) intercepts this beam with its transmission axis at an angle  $\theta$  with respect to the axis of the polarizer.

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- The component of  $\mathbf{E}$  perpendicular to the axis of the analyzer is completely absorbed, while the component parallel to the axis passes through. The average transmitted intensity varies as the *square* of the transmitted amplitude:

$$\overline{S} = \overline{S}_0 \cos^2 \theta \quad (6)$$

where  $\overline{S}_0$  is the average intensity of the polarized wave incident on the analyzer (**Malus's law**).

# Electromagnetic Waves

## 6 – The Doppler Effect

Sound waves exhibit the Doppler effect, i.e. when the source and/or the observer of a sound wave are moving with respect to the medium of propagation of the sound wave the frequency of the sound wave heard by the observer is different from the frequency emitted by the source (see Chapter 16).

When electromagnetic waves, the source and the observer all travel in vacuum (or air) the observed frequency,  $f_o$ , compared to the frequency emitted by the source,  $f_s$ , of the electromagnetic wave will depend on the relative speed of the source and the observer (for  $v_{rel} \ll c$ ):

$$f_o = f_s \left( 1 \pm \frac{v_{rel}}{c} \right) \quad (7)$$

+: source and observer come together, -: source and observer move apart

Application: *redshift* (<http://cfa-www.harvard.edu/seuforum/galSpeed>)