PHS 102 LECTURE NOTES

GENERAL PHYSICS II

(Part II)

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Course contents

Electromagnetic waves; basic phenomenon of physical optics for illustration (interference, diffraction, polarization); Radiation and phonon, atomic theory, radioactivity.

Suggested references:

1. University Physics W. Sears
2. Fundamentals of Physics by J. Walker
3. Advance level Physics by Nelkon and Parker
4. College Physics by Frederick, J Beuche and Eugene Hecht

ELECTROMAGNETIC WAVES

Generally, different types of fields produced by electric and magnetic fields can be categorized into two. The first includes fields that do not vary with time, these are called **ELECTROSTATIC** fields. Examples of electrostatic field include (i) distribution of charges at rest and (ii) the magnetic field of a steady state current in a conductor. The electrostatic field can vary from point to point in space, but do not vary with time at any individual point.

The 2nd category includes situation in which the **FIELDS** do vary with time. In this case we cannot treat electric and magnetic field separately. Faraday's law tells us that a time varying magnetic field produces or acts as a source of electric field. This field is manifested in the induced emf's in inductances and transformers. Hence, when **EITHER** field is changing with time, a field of the other kind is induced in adjacent regions of space.

The properties of electromagnetic waves are:

(i) The solution's of Maxwell's third and fourth equations are wavelike, where both E and B satisfy the same wave equation.

ii) Electromagnetic waves travel through empty space (i.e. vacuum) with the speed of light i.e. $c = \sqrt{\dfrac{1}{\mu_0 \varepsilon_0}}$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of free space, and $\mu_0 = 1.257 \times 10^{-6}$ H/m is the permeability of the free space

iii) The electric and magnetic field components of plane electromagnetic waves are perpendicular to each other and also perpendicular to the direction of wave propagation. i.e. e – m waves are transverse waves.

iv) The relative magnitudes of E and B in empty space is given by $c = \dfrac{E}{B}$.

v) Electromagnetic waves obey the principle of superposition.

SPEED OF ELECTROMAGNETIC WAVES

According to Faradays law electric and magnetic fields are related according to the equation:

$$E = cB \text{ -------------------------- } (1)$$

The e – m wave is consistent with Faraday's law only if E, B and c are related according to the above equation.

Ampere's law is obeyed by the e – m wave, only if the magnetic field B, speed c and the electric field E are related by the equation.

$$B = \mu\varepsilon c\, E \text{ --------------------- } (2)$$

From Eq. (1):

$$B = \frac{E}{c} \text{ ………………….. } (3)$$

By combining Eqs (2) and (3), we have

$$c = \sqrt{\frac{1}{\mu\varepsilon}} \text{ …………………. } (4)$$

ENERGY CARRIED BY E – M WAVES

Electromagnetic waves carry energy as they propagate through space. The total energy density in a region of space where E and B fields are present is given by

$$U = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

Magnetic field strength $H = \frac{B}{\mu_0}$

In terms of E and H, the energy density is

$$U = \frac{1}{2}\varepsilon_0 E^2 + \frac{\mu_0}{2}H^2$$

POYNTING VECTOR

The total energy densities (i.e. energy per unit vol.) for the electric and magnetic fields in free space are given respectively as

$$U_E = \frac{1}{2}\varepsilon_0 E^2 \text{ and } \quad U_B = \frac{1}{2\mu_0}B^2 \quad \text{---1}$$

Since $E = cB = \frac{B}{\sqrt{\mu_0 \varepsilon_0}}$ for an electromagnetic wave, the instantaneous values of these energy densities are equal. The **TOTAL ENERGY DENSITY** $U = U_E + U_B$ is therefore

$$U = \varepsilon_0 E^2 = \frac{B^2}{\mu_0}\sqrt{\frac{\varepsilon_0}{\mu_0}}EB \quad \text{---2}$$

Let us consider two planes, each of area A, a distance dx apart, and normal to the direction of propagation of the wave. The total energy in the volume between the planes is dV = UAdx). The rate at which this energy passes through a unit area normal this energy direction of propagation is

$$\vec{S} = \frac{1}{A}\frac{dV}{dt} \quad \text{--3}$$

Since the energy is carried by the fields, which moves at speed c, it is also transported at this speed. Thus,

$$\frac{dV}{dt} = \mu Ac \quad \text{---4}$$

and so

$$\vec{S} = \mu c \quad \text{---5}$$

Using the fact that $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ and eqn (2) above, we have

$$\vec{S} = \sqrt{\frac{\varepsilon_0}{\mu_0}}EB\frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

i.e.

$$\vec{S} = \frac{EB}{\mu_0} \quad \text{--6}$$

Since the energy flow in 1a to both E and B, we therefore pointing vector as

$$\vec{S} = \frac{E \times B}{\mu_0} \quad \text{---7}$$

NOTES

i. The magnitudes of $\vec{S}$ is the intensity, that is instantaneous power that crosses a unit area normal to the direction of propagation.

ii.The direction of $\vec{S}$ is the direction of energy flow. In e – m waves, the magnitude of the poynting vector, S, fluctuates rapidly in time. A more useful quantity is the average intensity of the wave, it is the average value of $\vec{S}$. Thus **AVERAGE INTENSITY** is

$$S_{ave} = U_{ave}c = \frac{E_0 B_0}{2\mu_0}$$

The quantity S_{ave} is measured in W/m^2 is the average power per unit area, normal to the direction of propagation.

iii. The average intensity of plane wave does not diminish as it propergates

THE E – M SPECTRUM

Electromagnetic waves span an immense range of frequencies, from very long wavelength radio waves, whose frequency is around 100Hz, to extremely high energy γ rays from space, with frequencies around 10^{23}Hz. The electromagnetic spectrum, shown below, covers appropriately 100 octaves. (The audible sound spectrum covers about nine octaves). There is no theoretical limit to the high end.

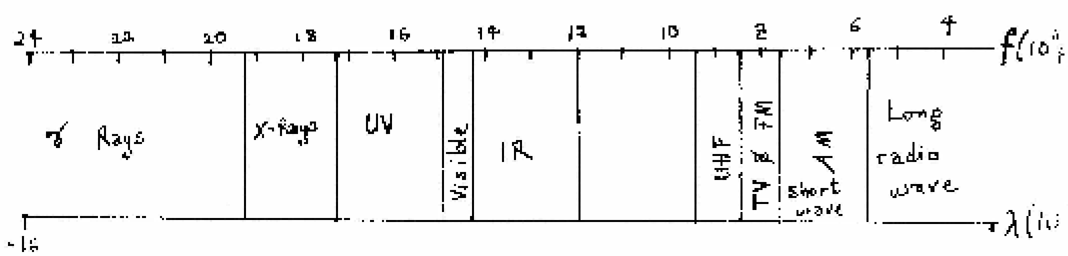

Fig.1.1: Electromagnetic spectrum

VISIBLE LIGHT

Visible light of e – m waves covers approximately one octave from 400 – 700nm. An approximate range for each colour is as follows:

Violet (400 – 450 nm), blue (450 – 520 nm), green (520 – 560 nm), yellow (560 – 600 nm), orange (600 – 625 nm) and red (625 – 700 nm). As electrons undergo transitions below energy levels in an atom, light is produced at well-defined wavelengths.

Ultraviolet Radiation

The UV region extends from 400 nm to 10 nm. It plays a role in the production of vitamin D in human skins and leads to tanning. In large or prolonged doses, UV radiation kills bacteria and can induce cancer in man. Glass absorbs UV radiation and hence can provide some protection again the sun's rays. If the ozone in the atmosphere did not absorb the UV below 300 nm, there would be a larger number of cell mutations, especially the cancerous ones, in human beings.

Infrared radiation

The IR region starts from 700 nm and extends to about 1 mm, just beyond the red end of visible spectrum. IR radiation is associated with the vibration and rotation of molecules and is perceived by man as heat. IR – sensitive film is used in satellites for geophysical surveying and in the detection of the hot exhaust gases of a rocket launch. IR is used in the detection of tumors – which are warmer than the surrounding tissue.

Microwaves

Microwaves cover wavelength from 1mm to 15cm. microwaves up to 30GHz (1cm) may be generated by the oscillations of elections in a device called **KLYSTRON**. In the microwaves ovens used in kitchens, the radiation has frequency of 2450MHz modern intensity communication, such as numerical data, phone conversations and TV programs are often carried via antennae.

Radio and TV signals

These signals span the range from 15cm to 2000m. dipoles are used for both transmission and reception. For AM radio, a coil is usually used for reception because the wavelength is so much larger than is practical for an electric dipole. For UHF TV, the cell is used because wavelengths are so small.

X-Rays

X-rays was discovered in 1895 by W. Roentgen. It extends from to 0.01 nm adjacent to the UV. X-ray machines produce these waves. This type of radiation passes a range of frequencies and is called **BREMSSTRAHLUNG** or "braking radiation". X-rays are used to study the atomic structure of crystals or molecules, such as DNA. Besides their diagnostic and therapeutic use in medicine, X-rays are used to detect tiny faults in machinery.

γ-Rays

γ -Rays were part of radiative emission. Whereas X-rays are produced by electrons, r-rays are usually produced within the nucleus of an atom and are extremely energetic. They cover the range from 0.01nm downward, or equivalently from 10^{20} Hz up.

HUYGENS' PRINCIPLE

In 1678, C. Huygens proposed a principle that is useful in predicting the propagation of wavefronts. He proposed that when a light pulse is emitted by a source, the nearby particles of "ether" are set into motion. The light propagates because this motion is communicated to the nearby particles. Thereby each particle acts as secondary **WAVELETS.** In order to explain the rectilinear propagation of rays, he asserted that only the wavelets in forward direction is strong. The wavelets that are spread to the sides were quietly ignored as being "too feeble" to be seen.

Huygens' principle states that "Each point on a wavefront acts as secondary wavelets". At a later time, the envelope of the leading edges of the wavelets form the new wavefronts.

The figure below shows plane wavefronts approaching a flat surface at angle θ to the surface and being reflected at angle θ' to the surface. Since the rays are far to the wavefronts, the angles θ and θ' are also the angles made by the rays to the **NORMAL** to the surface. When the edge A of wavefront AB meets the surface, it starts to produce its secondary wavelet. The same happens as each successive point of AB strikes the surface. The line DC forms the reflected wavefront. Since the speeds of the incident and reflected waves an identical AD = BC. Triangles ACD and ACB are both right angled and have a common hypotenuse. We conclude that $\theta = \theta'$ which is the law of reflection.

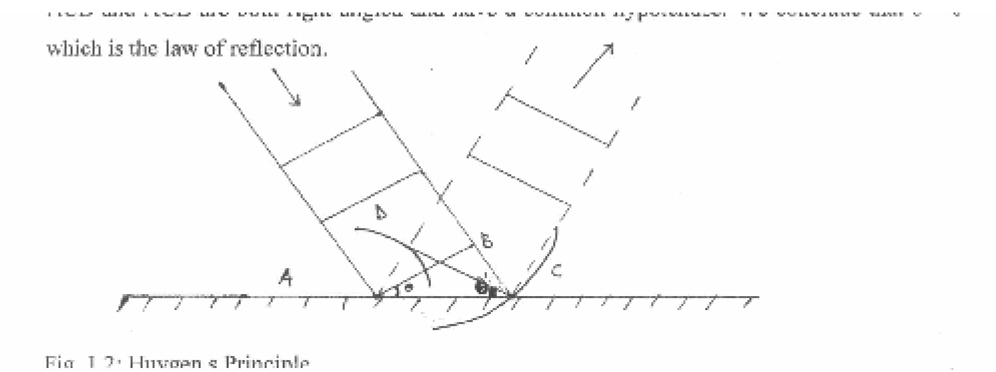

Fig. 1.2: Huygen.s Principle

From the geometry of the triangles ABC and ADC we conclude that $\theta = \theta'$

REFRACTION

A drinking straw appears to be bent when it is partially immersed in H_2O; a magnifying lens can focus the sun's rays or make the objects x cm larger. These and many other optical effects are caused by **REFRACTION.** An important phenomenon associated with refraction of light is termed **REFRACTIVE INDEX,** n; it is defined as the ratio of the speed of light in a vacuum, c, to the speed of light, v, in the medium.

i.e.

$$n = \frac{c}{v} \quad \text{--1}$$

Let us consider the figure below wherein light travel from air (vacuum) into a medium of refractive index n_2. If the angle made by the incoming ray with the normal is θ_i while the angle of refraction is θ_r. Then we obtain a very important law of refraction called Snell's law of refraction as follows.

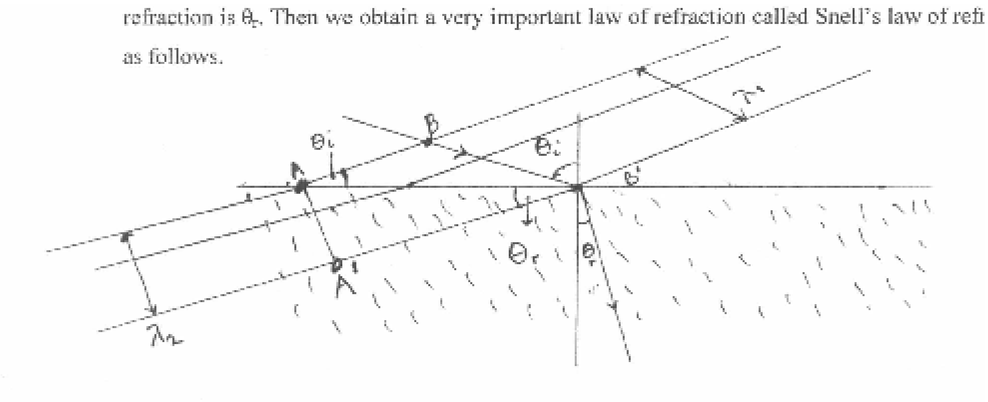

Fig 1.3: Using Huygen's principle to explains refraction.

In a short time interval Δt, the wavelet from point B of wavefront AB travels a distance.

$$S_1 = V_1\Delta t \quad \text{---}2$$

to Point B', where

$$BB' = V_1\Delta t = AB' \sin\theta. \quad \text{-----------------------------}3$$

In this time, the wavelet from A travels a distance

$$S_2 = V_2\,\Delta t \quad \text{---}4$$

to point A' in the 2^{nd} medium, where

$$AA' = V_2\,\Delta t = AB' \,\text{Sin}\,\theta_r \quad \text{---}5$$

The new wavefront, A'B' is tangent to the wavelets from wavefront AB. The ratio BB^1/AA^1 yield,

$$\frac{V_1\,\Delta t}{V_2\,\Delta t} = \frac{AB'\,\text{Sin}\,\theta_i}{AB'\,\text{Sin}\,\theta_r}$$

i.e

$$\frac{v_1}{v_2} = \frac{\sin\theta_i}{\sin\theta_r} \quad \text{---}6$$

where V_1 and V_2 and the velocities of light from the 1^{st} and 2^{nd} medium respectively (with $v_1 > v_2$). Equation (6) is the Snell's law of refraction. In terms of refractive index, Eq. (6) can be written as:

$$\frac{n_1}{n_2} = \frac{\sin\theta_i}{\sin\theta_r} \quad \text{---}6$$

When $n_2 > n_1$, it follows that $\theta_r < \theta_i$ i.e, on entering a medium with a "higher refractive index the RAY BENDS TOWARDS the NORMAL, otherwise the ray moves away from the normal.

If the wavelength in the vacuum is λ_0 and that in the medium is λ_n, then

$V = \lambda_n$ --7

And

$C = \lambda_0$ --8

Using (7) and (8) in (1)

$$n = \frac{\lambda_0}{\lambda_n} \quad \text{--9}$$

Worked example:

1) Light of wavelength 600 nm in air is incident at an angle of 35^0 to the normal of a plate of heavy fling glass of refractive index 1. 6. Assume that the refractive index of air is 1. Find (a) the angle of refraction, (b) the wavelength of the light in the glass, (c) the speed of light in the glass.

Solution

$\theta_i = 35^0$, θ_r=?, $n_1 = 1$, $n_2 = 1.6$

(a) We know that

$$n_1 \text{ Sin}\theta_i = n_2 \sin\theta_r$$

(b) In terms of wavelength, the refractive index, n is given by

$$n = \frac{\lambda_0}{\lambda_n}$$

λ_0=600 nm = 600 x 10^{-9}m, n = 1.6

hence

$$\lambda_n=355 \text{ nm}$$

(c) The speed of light in the glass is obtained from the definition of refraction i.e.

$$n = \frac{c}{v_2}$$

n=1.6, c=3.0 X 10^8 m/s, hence

v2=1.88X10^8m/s

TOTAL INTERNAL REFLECTION

The figure below shows the boundary between two media with refractive . index n_1 and n_2, where $n_2 > n_1$. A ray approaching the boundary forms the medium of higher refractive index is refracted away from the normal. For a small angle of incident, there is both reflected and refracted ray. However, at some critical angle of incidence, θ_c the refracted ray emerges parallel to the surface. For any angle of incidence greater that θ_c the light is totally reflected back into the medium of higher refractive index. This is called TOTAL INTERNAL REFLECTION and way first reprinted by Kepler in 1604. The value of θ_c it can be found from Snells law by setting $\theta_r = \theta_c$ and $\theta_i = 90^0$.

n_2 Sinθ_c = n_1 ------------------------- (1)

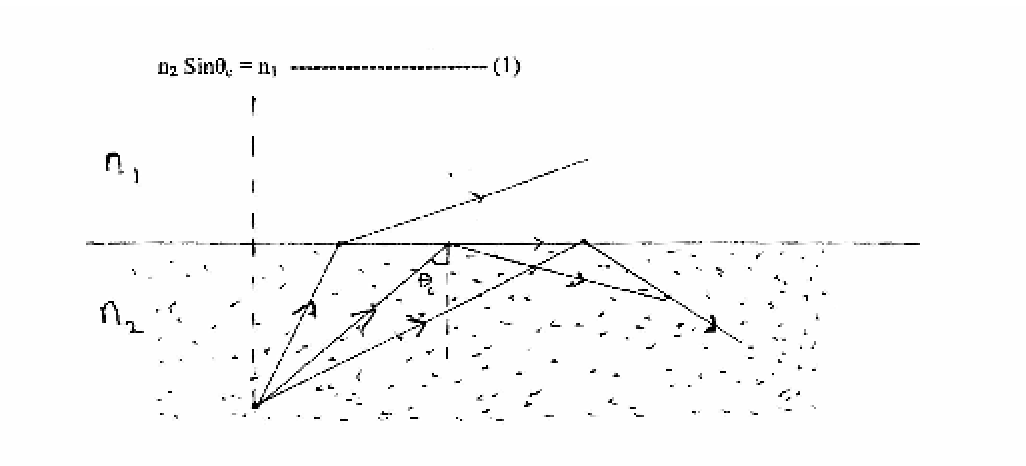

Fig.1.3: Total internal reflection

If the medium with the lower refractive index is air, we may take $n_1 = 1$. Then, for water where $n_2 = 1.33$, the θ_c will be = 48.5^0; on the other hand if n2 = 1.55 i.e. for glass, $\theta_c = 42^0$.