Physics 1214 — Chapter 23: Electromagnetic Waves — 03/01

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1 Introduction to Electromagnetic Waves

electromagnetic wave: time-varying electric and magnetic field propagating through space from one region to another even when there is no matter in the intervening region (versus water waves, sound waves)

Maxwell's Equations (one form):

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

2 Speed of an Electromagnetic Wave

wave front: the boundary of a wave

$$\boxed{E = cB, \text{only in SI units}}$$

$$\boxed{c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}}$$

Characteristics of electromagnetic waves in vacuum:

- the wave is transverse; both $\vec{E}$ and $\vec{B}$ are perpendicular to the direction of propagation of the wave and to each other
- there is a definite ratio between the magnitudes of $\vec{E}$ and $\vec{B}$; $E = cB$
- the wave travels in vacuum with a definite and unchanging speed c
- electromagnetic waves require no medium

3 The Electromagnetic Spectrum

electromagnetic spectrum: the broad spectrum of wavelengths covered by electromagnetic waves including radio, TV, and cellular phone transmission, microwaves, visible light, infrared and ultraviolet light, radiation, x rays and gamma rays.

speed of electromagnetic waves in vacuum:

$$\boxed{c = \lambda f}$$

where λ is the wavelength and f is the frequency of the wave

monochromatic: single-color light

4 Sinusoidal Waves

plane wave: at any instant the fields are uniform over any plane perpendicular to the direction of propagation. One form of the wave function for a transverse wave traveling to the right along a stretched string:

$$\boxed{y(x,t) = A\sin(\omega t - kx)}$$

where y is the transverse **displacement** from its equilibrium position at
time t of a point with
coordinate x on the string where
A is the maximum displacement or **amplitude** of the wave
ω is the **angular frequency** (2π times the **frequency** f
k is the **wave number** or *propagation constant* ($2\pi/\lambda$) where
λ is the **wavelength**

Where E and B are the instantaneous values of the electric and magnetic fields respectively, and E_{max} and B_{max} are the amplitudes of those fields

$$E = E_{max}\sin(\omega t - kx)$$

$$B = B_{max}\sin(\omega t - kx)$$

thus the sinusoidal oscillations of $\vec{E}$ and $\vec{B}$ are *in phase* and the amplitudes are related by

$$E_{max} = cB_{max}$$

linearly polarized: a wave whose $\vec{E}$ field always lies along the same line.

5 Energy in Electromagnetic Waves

energy density: energy per unit volume.

Energy density in electric and magnetic fields:

The energy density u (energy per unit volume) in a region of empty space where electric and magnetic fields are present is

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0}B^2.$$

The two field magnitudes are related by

$$B = \frac{E}{c} = \sqrt{\epsilon_0\mu_0}E.$$

Thus the energy density u can also be expressed as

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

and the energy density associated with the $\vec{E}$ field is equal to the that of the $\vec{B}$.

intensity: I, the average power per unit area in an electromagnetic wave; $I = S_{average}$.

$$\boxed{I = S_{av} = \frac{1}{2}\sqrt{\frac{\epsilon_0}{\mu_0}}E_{max}^2 = \frac{1}{2}\epsilon_0 c E_{max}^2 = \frac{E_{max}B_{max}}{2\mu_0}.}$$

radiation pressure: the force due to the absorbtion of an electromagnetic wave on a surface perpendicular to the direction of the propagation of the wave; the rate of change of the momentum p per unit area or I/c where c is the speed of light.

6 Nature of Light

"What's in a name? that which we call a rose
By any other name would smell as sweet;" Sir William Shakespeare

but can a rose be something else entirely?

Light–both wave and particle

- wave (continuous) best for understanding propagation (path)
- *photons* or *quanta* (discrete bundles of energy) best for understanding absorption by atoms and nuclei (energy)
- quantum electrodynamics: a comprehensive theory that includes both wave and particles properties

fundamental sources of all electromagnetic radiation (EMR) are electric charges in accelerated motion

all objects emit EMR as a result of thermal motion of their molecules (*thermal radiation*)

wave front: the locus of all adjacent points at which the phase of vibration of the wave is the same.
ray: an imaginary line along the direction of travel of the wave.
geometric optics: branch of optics using the ray behavior of light
physical optics: branch of optics using wave behavior

7 Reflection and Refraction

reflection: light that scattered off of the incident material.
refraction: light that is transmitted through the incident material.
specular reflection: reflection at a definite angle from a very smooth surface.
diffuse reflection: scattered reflection from a rough surface.

index of refraction

The index of refraction of an optical material, denoted as n, is the ratio of the speed of light in vacuum (c) to the speed of light in the material (v):

$$n = \frac{c}{v}.$$

Light always travels more slowly in a material than in vacuum, so n for any material is always greater than one. For vacuum, n=1 by definition.

Principles of geometric optics

1. The incident, reflected, and refracted rays, and the normal to the surface, all lie in the same plane.
2. The angle of reflection Θ_r is equal to the angle of incidence Θ_a for all wavelengths and for any pair of substances; $\Theta_r = \Theta_a$. **Law of reflection**.
3. With qualifiers, the ratio of the sines of the angles Θ_a and Θ_b, where both angles are measured from the normal to the surface, is equal to the inverse ratio of the two indexes of refraction:

$$\boxed{\frac{\sin\Theta_a}{\sin\Theta_b} = \frac{n_b}{n_a} \quad \text{or } n_a \sin\Theta_a = n_b \sin\Theta_b.}$$

Law of refraction or **Snell's law**.

The wavelength λ of the light in a material is less than its wavelength λ_0 in a vacuum by the factor n:

$$\lambda = \frac{\lambda_0}{n}.$$

8 Total Internal Reflection

critical angle: the angle of incidence from which the refracted ray emerges tangent to the surface.

Total internal reflection

When a ray traveling in a material a with index of refraction n_a reaches an interface with a material b having index n_b, where $n_b < n_a$, it is totally reflected back into material a if the angle incidence is greater than the critical angle given by

$$\sin\Theta_{critical} = \frac{n_b}{n_a}.$$

9 Dispersion

dispersion: the dependence of wave speed and index of refraction on wavelength

10 Polarization

linearly polarized: a wave with displacement in only one plane
polarizing filter or polarizer: a filter that polarizes a wave in a certain direction
dichroism: the selective absorption of one of the polarized components much more strongly than the other
polarizing axis: the axis in which the light is polarized parallel to

Light transmitted by polarizing filter

When linearly polarized light strikes a polarizing filter with its axis at an angle ϕ to the direction of polarization, the intensity of the transmitted light is

$$I = I_{max}\cos^2\phi,$$

where I_{max} is the maximum intensity of the light transmitted (at $\phi = 0$) and I is the amount transmitted at angle ϕ. This is known as **Malus's Law.**

plane of incidence: the plane containing the incident and reflected rays and the normal to the surface.
polarizing angle: the angle for which $\vec{E}$ is perpendicular to the plane of incidence (and parallel to the reflecting surface), thus the reflected light is linearly polarized perpendicular to the plane of incidence.
Brewster's law:

$$\frac{\sin\Theta_p}{\cos\Theta_p} = \tan\Theta_p = \frac{n_b}{n_a}$$

photoelasticity: the property of certain materials, when placed under mechanical stress, to have their index of refraction different for different planes of polarization.

11 Huygens Principle

Huygen's Principle

Every point of a wave front may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the wave.

12 Scattering of Light

scattering:

13 Links

Poster of EM spectrum pdf right click and download; extensive
Berkeley EM scale pdf
Mathematica Demonstrations: Electromagnetic Wave

EM radiation in the news:
Supermassive Black holes and from Muse Supermassive Black hole

14 Greek

alpha	α	A
beta	β	B
gamma	γ	Γ
delta	δ	Δ
epsilon	ϵ or ε	E
zeta	ζ	Z
eta	η	H
theta	θ or ϑ	Θ
iota	ι	I
kappa	κ	K
lambda	λ	Λ
mu	μ	M
nu	ν	N
xi	ξ	Ξ
omicron	o	O
pi	π or ϖ	Π
rho	ρ or ϱ	P
sigma	σ or ς	Γ
tau	τ	T
upsilon	υ	Υ
phi	ϕ or φ	Φ
chi	χ	X
psi	ψ	Ψ
omega	ω	Ω

15 Constants

speed of light in a vacuum	$c = 2.99792458 \times 10^{8}$ m s^{1}
mass of the electron	$m_e = 9.1093826(16) \times 10^{-31}$ kg
mass of the proton	$m_p = 1.67262171(29) \times 10^{-27}$ kg
mass of the neutron	$m_n = 1.67492728(29) \times 10^{-27}$ kg
electric force constant or electrostatic constant	$k = 8.987551789 \times 10^{9} \mathrm{N} \cdot \mathrm{m}^2/\mathrm{C}^2$ $k = \frac{1}{4\pi\epsilon_0}$
vacuum permittivity	$\epsilon_0 = 8.854 \times 10^{-12} \mathrm{C}^2/(\mathrm{N} \cdot \mathrm{m}^2)$
fundamental unit of charge	$e = 1.602176565(35) \times 10^{-19} \mathrm{C}$
vacuum permeability	$\mu_0 = 4\pi \times 10^{-7} \mathrm{N}/\mathrm{A}^2$