College Physics B - PHY2054C

Electromagnetic Waves

10/13/2014

My Office Hours:
Tuesday 10:00 AM - Noon
206 Keen Building
1. EM Waves
   Properties of EM Waves

2. Polarization

3. The Doppler Effect
Symmetry of $\vec{E}$ and $\vec{B}$

The correct form of Ampère’s Law (due to Maxwell) says that a changing electric flux produced a magnetic field.

- Since a changing electric flux can be caused by a changing $E$, we can also say that a changing electric field produces a magnetic field.

Faraday’s Law says that a changing magnetic flux produces an induced emf; emf is always associated with an electric field.

- Since a changing magnetic flux can be caused by a changing $B$, we can say that a changing magnetic field produces an electric field.

Self-sustaining oscillations involving $E$ and $B$ are possible.

- The oscillations are an electromagnetic wave.
  (also referred to as electromagnetic radiation)
Perpendicular Fields

According to Faraday’s Law, a changing magnetic flux through a given area does produce an electric field perpendicular to the initial magnetic field.

Similarly, the magnetic field induced by a changing electric field is perpendicular to the electric field that produced it.
An electromagnetic wave involves both an electric field and a magnetic field:

- These fields are perpendicular to each other.
- The propagation direction of the wave is perpendicular to both the electric field and the magnetic field.

→ The wave is a transverse wave.
Properties of EM Waves

Maxwell found that the speed of an electromagnetic wave can be expressed in terms of two universal constants:

1. The permittivity of free space, $\epsilon_0$
2. The magnetic permeability of free space, $\mu_0$

Speed of an electromagnetic wave in vacuum is denoted by $c$:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 299,792,458 \text{ m/s} \approx 3.0 \times 10^8 \text{ m/s}$$

The value of the speed of an electromagnetic wave is the same as the speed of light.

Why?
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Maxwell answered the question of the nature of light – it is an electromagnetic wave.
Question 1

Which of these is NOT a form of electromagnetic radiation?

A. gamma rays  
B. infrared  
C. sound  
D. visible light  
E. radio
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A gamma rays
B infrared
C sound
D visible light
E radio

Sound comes from pressure waves; all others are types of EM radiation of different wavelengths.
Electromagnetic Spectrum

Penetrates Earth Atmosphere?

Wavelength (meters)

- Radio: $10^3$
- Microwave: $10^{-2}$
- Infrared: $10^{-5}$
- Visible: $0.5 \times 10^{-6}$
- Ultraviolet: $10^{-8}$
- X-ray: $10^{-10}$
- Gamma Ray: $10^{-12}$

About the size of...

- Buildings
- Humans
- Honey Bee
- Pinpoint
- Protozoans
- Molecules
- Atoms
- Atomic Nuclei

Frequency (Hz)

- $10^4$
- $10^8$
- $10^{12}$
- $10^{15}$
- $10^{16}$
- $10^{18}$
- $10^{20}$

Temperature of bodies emitting the wavelength (K)

- 1 K
- 100 K
- 10,000 K
- 10 Million K
Example

speed of light = wavelength \cdot frequency
\[ c = \lambda \cdot \nu \]

\[ c \approx 3 \cdot 10^8 \text{ m/s} \]

1. Commercial AM radio: 550 kHz – 1600 kHz

\[ \lambda = \frac{c}{\nu} = 3 \cdot 10^8 \text{ m/s} / 1000 \text{ kHz} \]
\[ = 300 \text{ m} \]

2. Microwave oven uses 2.45 GHz

\[ \lambda = \frac{c}{\nu} = 3 \cdot 10^8 \text{ m/s} / 2,450,000,000 \text{ Hz} \]
\[ \approx 12.2 \text{ cm} \]
Question 2

If an electric field wave oscillates north and south (horizontally), and the electromagnetic wave is traveling vertically straight up, then what direction does the magnetic field wave oscillate?

A  It does not oscillate: the situation is impossible.
B  East and west (horizontally)
C  North and south (horizontally)
D  Up and down (vertically)
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EM Waves in Material Substances

When an electromagnetic wave travels through a substance, its speed depends on the properties of the substance:

- The speed of the wave is always less than $c$. 

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Electromagnetic Waves Carry Energy

Electromagnetic waves carry energy in the electric and magnetic fields associated with the waves.

Assume a wave interacts with a charged particle: the particle will experience an electric force.
EM Waves Carry Energy

As the electric field oscillates, so will the force:
- The electric force will do work on the charge.
- The charge’s kinetic energy will increase.
- Energy is transferred from the wave to the particle.

The total energy (of a wave) per unit volume is the sum of its electric and magnetic energies:

$$ u_{\text{total}} = u_{\text{elec}} + u_{\text{mag}} $$

As the wave propagates, the energies per unit volume oscillate. The electric and magnetic energies are equal:

$$ \frac{1}{2} \epsilon_0 E_0^2 = \frac{1}{2\mu_0} B_0^2 $$

$$ E_0^2 = \frac{1}{(\epsilon_0 \mu_0)} B_0^2 $$
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\[ E_0 = c B_0 \]
Synchrotron Radiation

Synchrotron radiation

Magnetic field accelerates electron by curving its path. Electron radiates as a result.

Synchrotronstrahlung:
Intensity of an EM Wave

The strength of an electromagnetic wave is usually measured in terms of its intensity:

- Unit is W/m².
- Intensity is the amount of energy transported per unit time across a surface of unit area.
- Intensity also equals the energy density multiplied by the speed of the wave:

\[
I_{\text{total}} = u_{\text{total}} \times c = \left( \frac{1}{2} \varepsilon_0 E_0^2 + \frac{1}{2\mu_0} B_0^2 \right) c = \varepsilon_0 c E_0^2
\]

\[
I_{\text{avg}} = \frac{1}{2} \varepsilon_0 c E_0^2
\]

The intensity is thus proportional to the square of the electric field amplitude. Since \( E = c B \), the intensity is also proportional to the square of the magnetic field amplitude.
Example

On a typical summer day, the intensity of sunlight at the Earth’s surface is approximately $I = 1000 \, \text{W/m}^2$. What is the amplitude of the electric field associated with this electromagnetic wave?
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The electric field amplitude and the intensity are related by (previous slide):

$$I_{\text{avg}} = \frac{1}{2} \epsilon_0 c E_0^2 \quad \rightarrow \quad E_0 = \sqrt{\frac{2I}{\epsilon_0 c}}$$

Solve:

$$E_0 = \sqrt{\frac{2 (1000) \text{ W/m}^2}{(8.85 \cdot 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2))(3.0 \cdot 10^8 \text{ m/s})}} = 870 \text{ V/m}$$

The electric field is very large!
An electromagnetic wave has no mass, but it does carry momentum.
EM Waves Carry Momentum

The momentum is carried by the wave before the collision and by the particle after the collision:

- When the charge absorbs an electromagnetic wave, there is a magnetic force on the charge in the direction of propagation of the original wave: \( F = q \nu B \).
- Charge’s velocity originates from its oscillation due to the wave’s electric field.
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- When the charge absorbs an electromagnetic wave, there is a magnetic force on the charge in the direction of propagation of the original wave: \( F = q \mathbf{v} \times \mathbf{B} \).
- Force on charge is related to charge’s change in momentum:

\[
F_B = \frac{\Delta p}{\Delta t}
\]

\[
p_{\text{wave}} = \frac{E_{\text{total}}}{c}
\]
The momentum is carried by the wave before the collision and by the particle after the collision:

- When the charge absorbs an electromagnetic wave, there is a magnetic force on the charge in the direction of propagation of the original wave: \( F = q \nu B \).
- Radiation pressure is the force of the electromagnetic force divided by the exposed area:

\[
P_{\text{radiation}} = \frac{F}{A} = \frac{I}{c}
\]
Example

A spacecraft designer wants to use radiation pressure to propel a spacecraft as sketched. Near the Earth, the intensity of sunlight is about 1000 W/m$^2$ and the exposed area of the spacecraft is 500 m$^2$. If the sunlight is completely absorbed, what is the force on the spacecraft?

The radiation pressure is related to the intensity of the radiation:

$$F = P_{\text{radiation}} A = \frac{I A}{c}$$

$$= \frac{(1000 \text{ W/m}^2)(500 \text{ m}^2)}{3.0 \cdot 10^8 \text{ m/s}}$$

$$= 1.7 \cdot 10^{-3} \text{ N}$$

Equal to the weight of a penny!
Question 3

When light is absorbed by an object, the radiation pressure is \( P_{\text{radiation}} = \frac{I}{c} \). Suppose the exposed surface of an object has instead a reflective coating so that it reflects electromagnetic waves. Which of the following statements is true?

A. The force on the object due to radiation pressure is the same whether the light is absorbed or reflected.

B. The force on the object due to radiation pressure is greater by a factor of two when the light is reflected.

C. There is no force on the object due to radiation pressure when the light is reflected.
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Outline

1. **EM Waves**
   Properties of EM Waves

2. **Polarization**

3. **The Doppler Effect**
Polarization

There are many directions of the electric field of an electromagnetic wave that are perpendicular to the direction of propagation. Most light in nature is unpolarized.
Polarized light can be created using a **polarizer**. (e.g. a thin plastic film)

The polarizer absorbs radiation with electric fields that are not along the axis. When unpolarized light strikes a polarizer, the light that comes out is **linearly-polarized**.

![Diagram of a polarizer](image)
If the electric field is parallel to the polarizer’s axis:

\[ E_{\text{out}} = E_{\text{in}} \]

If the electric field is perpendicular to the polarizer’s axis:

\[ E_{\text{out}} = 0 \]

If the electric field makes an angle \( \theta \) relative to the polarizer’s axis:

\[ E_{\text{out}} = E_{\text{in}} \cos \theta \]
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If the electric field makes an angle \( \theta \) relative to the polarizer’s axis:

\[ E_{\text{out}} = E_{\text{in}} \cos \theta \]

\[ I_{\text{out}} = I_{\text{in}} \cos^2 \theta \]
Examples

Unpolarized light can be thought of as a collection of many separate light waves, each linearly-polarized in different and random directions.

A The intensity is reduced to 1/2 by the first polarizer:

\[ I_{\text{out}} = (I_{\text{in}} \cos^2 \theta)_{\text{avg}} = \frac{1}{2} I_{\text{in}} \]

B Three polarizers are used: a non-zero intensity results.
Summary

When analyzing light as it passes through several polarizers in succession, always analyze the effect of one polarizer at a time:

- The light transmitted by a polarizer is always linearly polarized.
- The transmitted wave has no “memory” of its original polarization.
Applications

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Doppler Effect

Moving (sound) source and observer at rest:
If the source is moving toward you, the wavelengths seem shorter; if moving away, they seem longer.
Doppler Effect

Similar situation for moving observer and source at rest
The Doppler Effect

$f_{\text{obs}} = f_{\text{source}} \frac{\sqrt{1 - \frac{v_{\text{rel}}}{c}}}{\sqrt{1 + \frac{v_{\text{rel}}}{c}}}$

$v_{\text{rel}}$: velocity of the source rel. to the observer
Waves from moving source tend to pile up in direction of motion (blue shift) and be stretched out on the other side (red shift).
Doppler Shift

The Doppler effect shifts an object’s entire spectrum either towards the red or towards the blue.

Example
Astronomer observes $H_\alpha$ line in spectrum of star to have a wavelength of 657 nm instead of 656.3 nm:
The Doppler effect shifts an object’s entire spectrum either towards the red or towards the blue.

Example

Astronomer observes Hα line in spectrum of star to have a wavelength of 657 nm instead of 656.3 nm:

\[
\left( \frac{657}{656.3} - 1 \right) \cdot c \approx 0.0011 \cdot \text{speed of light} \approx 320 \text{ km/s}
\]
The Doppler effect shifts an object’s entire spectrum either towards the red or towards the blue.

**Example**

Astronomer observes Hα line in spectrum of star to have a wavelength of 655 nm instead of 656.3 nm:

\[
(655 / 656.3 - 1) \cdot c \approx -0.002 \cdot \text{speed of light} \approx -594 \text{ km/s}
\]