**Physics 202, Lecture 20**

**Today’s Topics**
- Electromagnetic Waves (EM Waves)
- The Hertz Experiment
- Review of the Laws of Electro-Magnetism
- Maxwell’s equation
- Speed of EM Waves
- EM Wave Spectrum, Wavelength and Frequency
- Antenna
- How to make a “HDTV” Antenna?

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**Review: General Waves (Ch. 16)**

- **Wave:**
  - Propagation of a physical quantity in space over time
  - \( q = q(x, t) \)
- **Wave function for a running wave:**
  - \( y(x, t) = f(x-vt) \)
- **Linear Wave equation and harmonic wave**
  - \[
  \frac{\partial^2 y}{\partial x^2} - \frac{1}{v^2} \frac{\partial^2 y}{\partial t^2} = 0
  \]
  - \( y = A \sin\left(\frac{2\pi}{\lambda} x - 2\pi ft + \phi\right) \)

- **Wavelength frequency relationship:**
  - \( v = \lambda f \)

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**Review: Gauss’s Law / Coulomb’s Law**

- The relation between the electric flux through a closed surface and the net charge \( q \) enclosed within that surface is given by the Gauss’s Law

\[
\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q_{\text{enclosed}}}{\varepsilon_0}
\]

- \( \varepsilon_0 \): permittivity of free space (a constant)

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**Gauss’s Law for Magnetism**

- The Gauss’s Law for the electric flux is a reflection of the existence of electric charge. In nature we have not found the equivalent, a magnetic charge, or monopole
- We can express this result differently: if any closed surface as many lines enter the enclosed volume as they leave it

\[
\oint \mathbf{B} \cdot d\mathbf{A} = 0
\]
Review: Faraday's Law

- The emf induced in a "circuit" is proportional to the time rate of change of magnetic flux through the "circuit" or closed path.

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

- Since \( \mathcal{E} = \oint \mathbf{E} \cdot d\mathbf{l} \)
- Then \( \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \)

\[ \Phi_B = \int \mathbf{B} \cdot d\mathbf{A} \]

Review: Ampere's Law

- A magnetic field is produced by an electric current is given by the Ampere's Law

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I \]

- A changing electric field will also produce a magnetic field

Finally:

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

\[ \Phi_E = \int \mathbf{E} \cdot d\mathbf{A} \]

\( \varepsilon_0 \): permittivity of free space (a constant)

\( \mu_0 \): permeability of free space (also a constant)

Maxwell Equations

- Gauss's Law/ Coulomb's Law

\[ \oint \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_0} \]

- Gauss's Law of Magnetism, no magnetic charge

\[ \oint \mathbf{B} \cdot d\mathbf{A} = 0 \]

- Faraday's Law

\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \]

- Ampere Maxwell Law

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

Also, Lotentz force Law \( \mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B} \)

These are the foundations of the electromagnetism

Sources of \( \mathbf{E} \) and \( \mathbf{B} \) Fields

- Sources for the electric field:
  - Electric charges (Coulomb's Law, static)
  - Subjects of past several weeks
  - Change of \( \mathbf{B} \) field (Faraday's Law, varying in time)

- Sources for the magnetic field:
  - Electric current (Biot-Savart Law/Ampere's Law, static)
  - Change of \( \mathbf{E} \) field (Ampere-Maxwell Law, varying)

All these features are summarized in Maxwell Equations.

Thinking machine:
A varying \( \mathbf{E} \) can produce a (varying) \( \mathbf{B} \), a varying \( \mathbf{B} \) can produce a varying \( \mathbf{E} \).... (looks like no charge is necessary)
**EM Fields in Space**

- Maxwell equations when there is no charge and current:

\[
\oint \mathbf{E} \cdot d\mathbf{A} = 0 \\
\oint \mathbf{B} \cdot d\mathbf{A} = 0
\]

\[
\oint \mathbf{E} \cdot dl = -\frac{d\Phi}{dt} \\
\oint \mathbf{B} \cdot dl = \varepsilon_0 \mu_0 \frac{d\Phi}{dt}
\]

differential forms:

(single polarization)

\[
\frac{\partial E_x}{\partial x} = -\frac{\partial B_z}{\partial t} \\
\frac{\partial B_z}{\partial x} = -\mu_0 \varepsilon_0 \frac{\partial E_x}{\partial t}
\]

**Electromagnetic Waves**

- EM wave equations:

\[
\frac{\partial^2 E_x}{\partial x^2} = \mu_\varepsilon_0 \frac{\partial^2 E_x}{\partial t^2} \\
\frac{\partial^2 B_z}{\partial x^2} = \varepsilon_\mu_0 \frac{\partial^2 B_z}{\partial t^2}
\]

- Plane wave solutions:

\[
E = E_{\text{max}} \cos(kx - \omega t + \phi) \\
B = B_{\text{max}} \cos(kx - \omega t + \phi)
\]

- Speed of EM wave:

\[
c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 2.9972 \times 10^8 \text{ m/s}
\]

In vacuum

- Wavelength and Frequency Relationship:

\[
\lambda f = c = 3 \cdot 10^8 \text{ m/s}
\]

- EM wave can transmit in vacuum

**Demo: Hertz Experiment**

In 1887, Heinrich Hertz first demonstrated that EM fields can transmit over space.

**The EM Wave**

Two polarizations possible (showing one)
Spectrum of EM Waves

- **VHF**: 30-300 MHz
- **UHF**: 300 MHz - 3.0 GHz
- **Cell phone**: 800/900/1800/1900 MHz
- **Wifi**: 2.4/5 GHz
- **Microwave Oven**: 2.4 GHz
- **Cordless phone**: 0.9/2.4/5.8 GHz

**Wavelength For TV Signals**

- Wavelength and frequency relationship for EM wave
  \[ \lambda f = c = 3 \cdot 10^8 \text{ m/s} \quad \text{In vacuum} \]
- Example: Determine the wavelength (in air) of an EM wave of frequency 687 MHz (HDTV channel 3, CBS = UHF ch. 50)
  \[ \lambda = \frac{c}{f} = \frac{3 \cdot 10^8 \text{ m/s}}{687 \text{ MHz}} = \frac{3 \cdot 10^8 \text{ m/s}}{6.87 \cdot 10^8 \text{ s}^{-1}} = 0.44 \text{ m} \]

- **VHF**: \(\lambda = 1 - 10 \text{ m}\)
- **UHF**: \(\lambda = 0.1 - 1 \text{ m}\)

- Over-The-Air (OTA) DTV channels:
  - 90% of them in UHF band \(\lambda \sim 0.4 - 0.6 \text{ m}\)

**Demo: Receiving HDTV Signals**

- **Functional flow of a HDTV (or in general a digital TV)**
  - Signal Reception \(\Rightarrow\) Tuning & Amplification \(\Rightarrow\) Decoding & Image Processing \(\Rightarrow\) Display (LCD/Plasma)

- **Antennas**: Specially shaped/configured conductors for receiving radio frequency (RF) EM waves (via induction).

- **Keywords for antennas**: gain, impedance, bandwidth, orientation, polarization, impedance matching, velocity factor, ...

**Half-Wave Antenna**

- Standing Wave Condition (ch. 18)
- A special configuration \(\frac{1}{4}\)-wave antenna
Various RF Antennas

- Beverage
- rhombic
- yagis
- horizontal
- vertical
- loop
- mecrapstrip
- log-periodic