**Speed of EM Waves in Materials**

- Speed of light is slower in materials:
  \[ c' = \frac{1}{\sqrt{\varepsilon \mu}} \]

- Materials that EM waves can move through have \( \kappa_m = 1 \), thus
  \[ c' = \sqrt{\kappa} \]

- Example: Q1 - Glass has \( \kappa = 4 \). What is the speed of light in that material?

**Energy in EM Waves**

- E and B in EM wave each carry energy
  \[ u = \frac{E^2}{2\epsilon_0} + \frac{B^2}{2\mu_0} \]

- Saw earlier that \( B_0 = E_0/c \) and that E and B follow same wave function, so
  \[ u_E = \frac{E_0^2}{2\epsilon_0} \]

- Thus: \( u_{wave} = \frac{c}{n} \)

**Wave intensity**

\[ I = \frac{dU}{dt} \]

- Unit of I: W/m²

**Poynting Vector \( \mathbf{S} \) (Intensity Vector)**

- Can also write \( I = c\epsilon_0E^2 = c^2\epsilon_0EB = \mathbf{EB}/\mu_0 \)

- Direction of power flow is \( \hat{k} = \mathbf{E} \times \mathbf{B} \)

- Can combine these with intensity vector, or Poynting vector \( \mathbf{S} \):

\[ \mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}}{\mu_0} \]

- Units of \( \mathbf{S} \): W/m²

- Gives direction and magnitude of power/unit-area carried by EM wave; varies over period of wave

- Often want average power/unit-area \( \langle S \rangle \)

**Example: TV transmitter broadcasts 50 kW of power. If power spreads over a hemisphere, what is E-field amplitude 1 km from transmitter?**

\[ \langle S \rangle = \frac{5 \times 10^4 W}{2\pi (10^3 m)^2} = \frac{E_0^2}{2\mu_0} \]

\[ E_0 = \sqrt{2\mu_0 < S >} = 2.5 V/m \]

- Q2: Earth is 1.5 x 10¹¹ m from sun. What is the total electromagnetic power output of the sun?
Antennas
- Using transmitting antenna to launch EM wave; usually a conductor of length $\lambda/4$, or a “dipole”
- Receiving antenna can be E-field or B-field based

Information via EM Wave: AM & FM
- To carry information (speech, music, digital signal on EM wave, must vary or “modulate” wave)

EM Wave Momentum and Pressure
- EM wave carries momentum $\frac{E}{c}$ similar to but less than particle carrying same energy
- From Newton’s 2nd law: $\frac{dp}{dt} \Rightarrow \text{Force}$
- Radiation Pressure: $\frac{dp}{dt} = \frac{\vec{S}}{A}$

- Optimum antenna length $\lambda/4$ (each side of dipole)
  - FM radio: $f=100$ MHz; $\lambda=c/f = 3m$; $\lambda/4=0.75$ m
  - Digital cell phone @ 1900 MHz, $\lambda/4=4 \text{ cm}=1.5$ in
- A LC circuit is used to “tune” the reception

- If light absorbed, Rad. Press. = $\frac{dp}{dt} = \frac{\vec{S}}{A}$

- Example: A 2 m$^2$ surface absorbs a $\perp$ EM wave with $E_0 = 100$ V/m. What is the force on surface?
  \[
  \left\{ \frac{dp}{dt} \right\} = A \left\{ \frac{\vec{S}}{c} \right\} = A \left( \frac{E_0^2}{c} \right) = \frac{c}{2\mu_0} \left( \frac{(2m)^2(100^2)}{7.28} \right) = 8.8 \times 10^{-8} \text{ N}
  \]