Physics 116

Lecture 14
Energy and momentum of light, polarization
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• Guest lecturer today: Kevin Connolly
# Lecture Schedule

(up to exam 2)

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Today: Monday, 10/24/11 - Reflection and mirrors; ray tracing [HW 3 due]
Intensity of EM waves

- With sound waves we had intensity (watts/square meter) proportional to amplitude (pressure change) squared.
- Same is true for EM waves: amplitude = N/C or teslas.
- In time t, EM wave passing through a window of given area travels a distance ct meters.
  - All the wave energy that passed through the window lies in a volume $V = (\text{area})ct$.
  - Energy that passed through the window is $uV$.
  - Power per square meter passing through the window is $uV/t$.

\[
U(\text{Joules}) = u(\text{Joules/m}^3) V(\text{m}^3) = u [(\text{area})c \Delta t]
\]

\[
I = \frac{\Delta U}{(\text{area})\Delta t} = u \frac{(\text{area})c \Delta t}{(\text{area})\Delta t} = u c = c \left[ \varepsilon_0 E^2 \right] = c \left[ \frac{B^2}{\mu_0} \right]
\]

So intensity is again proportional to $A^2$, where amplitude $A = E$ or $B$. 

$L = ct$
Radiation pressure

- If a given area (window) absorbs energy $U$ from an EM wave, it receives a transfer of momentum given by

$$p \text{ (}kg - m/s\text{)} = \frac{U \text{ (}kg - m^2/s^2\text{)}}{c \text{ (}m/s\text{)}} \quad \text{(check units)}$$

$$\Delta p = \frac{\Delta U}{c} = \frac{u \text{ (area)} c \Delta t}{c} = \frac{I \text{ (area)} \Delta t}{c}$$

$$F_{AVG} = \frac{\Delta p}{\Delta t} = \frac{I \text{ (area)}}{c} \rightarrow p_{AVG} = \frac{F_{AVG}}{\text{(area)}} = \frac{I_{AVG}}{c}$$

- So we expect an illuminated surface to feel “radiation pressure”
- Unless $I$ is huge, this is normally a microscopic value of pressure!
**Polarization**

- Wave propagating in z direction is *plane polarized* if the E field vector has a single orientation (in the x-y plane).
- Unpolarized light is a mixture of light waves with random E field orientations.

-X and y components are in phase.
- Plane of "vibration" = x-y plane.

Linearly polarized light.
Polarized light vs natural light

- "Natural light" is *un*polarized
  - Waves from most sources have *random* polarizations
    - Light bulb filament has billions of atoms, each independently emitting *wavetrains*
  - We can *filter* natural light to get polarization
  - Example: radio wave passing through linear array of wires
    - wires *short out* the vertical component, only horizontally polarized wavetrains pass

- Edwin Land, 1928: Polaroid filter material
  - first cheap mass-market polarizing filter

  For light, 'wires' = aligned long organic molecules:
  Stretched polyvinyl alcohol
  (Idea from book by Brewster on kaleidoscopes)
“Analyzing” polarized light

- If light polarized in vertical plane encounters a Polaroid sheet oriented horizontally, light is blocked.
- If Polaroid is at angle between 0 and 90 deg, some light gets through:

\[
\vec{E} = E_y \hat{y} \\
I_0 \approx E_y^2 \\
E_\theta = E_y \cos \theta \\
I_\theta \approx E_\theta^2 \quad \Rightarrow \quad \frac{I_\theta}{I_0} = \frac{(E_y \cos \theta)^2}{E_y^2} = \cos^2 \theta \\
I_\theta = I_0 \cos^2 \theta \quad \text{(Malus, c.1800)}
\]
Example

- What is the angle $\theta$ if the final intensity is 10% of $I_0$?

\[
\frac{I}{I_0} = \frac{1}{2} \cos^2 \theta = 0.1 \rightarrow \cos^2 \theta = 0.2
\]

\[
\cos \theta = \sqrt{0.2} = 0.44 \rightarrow \theta = 63^\circ
\]
Polarization by reflection

• Next week: we’ll discuss refraction of light; for now
  – Index of refraction $n$ of a material medium = $c / \text{(speed of light in that medium)}$
  – Examples: water = 1.33, glass = 1.5

• David Brewster (1781-1868):
  Found that when $q_T - q_R = 90^\circ$
  reflected light is polarized parallel to surface
  (perpendicular to plane of incidence)
  Brewster (polarizing) angle: $\tan q_B = n_2 / n_1$
  e.g., air/glass has $q_B = \tan^{-1}(1.5) = 57^\circ$
  Reason:
  – incident light has E components parallel and perpendicular to plane of incidence
  – reflected light can only have component perpendicular to plane of incidence for $q_R = q_T + 90^\circ$
    • Parallel component would have to be along propagation direction = longitudinal wave!
  Note that $R=\text{intensity reflection coefficient} \approx 0.15$ at $q_B = 57^\circ$
  So most of light intensity is transmitted
  – Transmitted light is partially polarized
  – Degree of polarization:
    $$V = \frac{I_{\text{POLARIZED}}}{I_{\text{POLARIZED}} + I_{\text{UNPOLARIZED}}}$$
  – Stack polarizer (Arago, 1812): stack of glass plates
    • more layers = higher $V$ for transmitted beam and higher $I$ for reflected beam.
Why is the sky blue?

- Light scattered from small particles is also partially polarized.
- Blue light more readily scattered by air molecules than longer light.
  - called *Rayleigh Scattering*; *strong* function of wavelength.
  - blue light in sky has been diverted from some other path.
  - with some blue light missing, sun looks yellowish.
- Look at setting sun through smoke: it is reddened (blue removed).
Today’s quiz question

- If **natural** light passes through a Polaroid filter, it becomes

  A. Redshifted

  B. Linearly polarized

  C. unpolarized

  D. You have to tell me more to answer