Lecture 1

Basic Properties of Light

Light is described using 3 pictures - seemingly contradictory!

Waves - Rays - Photons

Waves

[Reading Assignment: Hecht, Chapter 2 (most of this should be review), 3.2, 3.3, 3.4.4, 3.5, 3.6]

A propagating “disturbance” in electric and magnetic field (simultaneously!)

Example:

\[ \hat{E} = E \hat{x} \cos \left( \frac{2\pi}{\lambda} z - 2\pi ft \right) \]

\[ E_x \]

\[ \lambda \]

\[ z = 0, t = 0 \]

\[ t' = \delta t \]

- At a fixed point in space, the electric field oscillates in time. At a fixed point in time, we see a wave train frozen.
- This is called a plane-wave because the field is constant everywhere in the x-y plane at a given z. Another way to draw this is

  "wave-fronts" surface of constant "phase" or "phase-fronts"

- The wavefront advances by a distance \( \lambda \), in a time \( 1/f \). So the velocity is \( v = \text{distance/time} = \lambda f \). One of the many remarkable properties of light is its universal, constant speed:

  \[ c = 2.97 \times 10^8 \text{ m/sec} \]

  \[ c = \lambda f \] in vacuum

- The physics of electromagnetic (EM) wave propagation is valid for arbitrary \( \lambda, f \). On Earth, we can generate, manipulate and/or detect EM waves with wavelength from \( \sim 100 \text{ km} \) all the way down to \( \sim 10^{-6} \text{ A}^\circ \). Usually we describe light by wavelength rather then frequency, except in the microwave and radio regions.
• The electromagnetic spectrum encompasses the complete range of frequency/wavelength. Different regions have different names. Radio, microwave, infrared, visible, ultraviolet, x-ray, γ-ray.

**Index of Refraction**
• When light travels in materials, the speed is modified:
  \[ v = \frac{c}{n} = \frac{\lambda f}{n} \]
  Usually \( n \geq 1 \). (It can be \(< 1 \))
• The reason is that the electric field shakes the electrons, which tends to drag the field.
• Plane wave still has the same form: \( \hat{E} = E \hat{x} \cos(\frac{2\pi}{\lambda} x - 2\pi ft) \), but the effective wavelength becomes modified by \( n \). If we define the vacuum wavelength, \( \lambda_{\text{vac}} = \frac{c}{f} \) then in the material \( \lambda = \frac{c}{nf} = \frac{\lambda_{\text{vac}}}{n} \). The wavelength becomes shorter, if \( n > 1 \).

**Dispersion**
The index of refraction in most materials depends on wavelength. \( n(\lambda) \). This is called dispersion.

In air – the index depends also on air pressure, humidity, and temperature which leads to many beautiful atmospheric effects.

**Wavelength units** (length)
We commonly use Angstrom units (Å) for light wavelength.

\[ 1\text{Å} = 10^{-8}\text{cm} = 0.1\text{nm} \]

This is of the order of the size of an atom. We also use standard metric units: m, cm, mm, nm

Visible light \( \sim 4000 \rightarrow 7000\text{Å} \), \( 400 \rightarrow 700 \text{ nm} \), \( 0.4 \rightarrow 0.7 \mu\text{m} \)
Spherical Waves

Another type of ideal light wave. Constant phase fronts are circular, emanating from a point source. Far away from the source, the radius of the circle becomes so large that we can approximate the wave as a plane wave.

For spherical waves, we have

\[
E = E_0 \frac{\cos\left(\frac{2\pi r}{\lambda} - 2\pi ft\right)}{r}
\]

Huygens’ Principle

Very useful model for wave propagation.

• Every point on a wavefront is regarded as a secondary point source generating a spherical wavelet.
• The advance of the wave front is found at the envelope of all these wavelets

• Generally, this seems to give parallel wavefronts. But things get interesting at edges. This leads to diffraction (more later).

Rays

• Follow a point on the wavefront. As the wavefront advances the point traces a straight line. This is a ray of light.
• For many cases, we can forget the waves and just trace rays in optical systems. This allows a vast simplification of our analysis and design processes. Virtually all optical design is done with rays. Highly sophisticated optical design CAD programs are available for ray tracing.
Photons (light “particles”)
- This picture has light represented by tiny bundles of energy (or quanta), following straight line paths along the rays.
- The coexistence of electromagnetic wave physics and photon physics is the central paradox of quantum mechanics.
- Each photon has an energy given by

\[ E = h \nu \]

\[ h = 6.62 \times 10^{-34} \text{ J-s} \]

For 2 eV visible photons, \[ 1 \text{ W} = 6.3 \times 10^{18} \text{ eV/s} \]
\[ = 3.15 \times 10^{18} \text{ photons/sec} \]

- Light power $\rightarrow$ photons/sec

Photoelectric Effect
- The electron energy is directly related to the photon energy.
- When the photon energy is below threshold value, no electrons are emitted. The threshold depends on the metal. It is called the work function.
- When the light power is low $\sim 10^2 \rightarrow 10^3$ photons/sec $\rightarrow$ each individual electron can be separated and counted. This called **photon counting** (more later).

**Atomic Radiation**

- Atoms have energy states corresponding to electron orbits.

![Energy Level Diagram](image)

$E_2 \rightarrow E_1$

$h \nu = E_2 - E_1$

- One atom “jumps” from a higher energy state to a lower energy state and emits one **photon**.
- Photons are not point particles. They have a wave-like property. A useful picture is the wave-packet.

Many photon packets can be thought of as superimposing to make up a plane wave, spherical wave or any other wave.

The typical photon energy unit is the electron-Volt. This is defined as the energy required to push one electron across a one-Volt potential,

$$1\text{eV} = 1.6 \times 10^{-19} \text{J}$$

Typical visible photon energy $\sim 1.2 \rightarrow 2.3 \text{ eV}$