Basic optics – What is light?

Biomedical Optics

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What is light?

- Waves of electromagnetic energy, therefore is one of the four fundamental forces in nature (the other three are: strong force, weak nuclear force, and gravity)
- Fundamental particles called photons that carry energy and momentum

A Brief History of Light

- 1590 – Janssen – “first optical microscope”
- 1665 – Hooke – coined the term cell
- 1673 – van Leeuwenhoek – father of microscopy and “microbiology”
- 1863 – Sorby – father of “metallurgy” and hence “materials science”
A Brief History of Light

- 1895 – Röntgen – X-ray


- It only requires a page for a Noble Prize!

Fundamentals of Optics

Ray Optics

- Light travels in the form of rays. They are emitted by light sources and can be observed when they reach an optical detector.
- An optical medium is characterized by a quantity $n > 1$ the refractive index. It is the ratio of the speed of light in free space $c_0$ to that in the medium.
- In an inhomogenous medium the refractive index $n(r)$ is a function of the position.

\[
\text{Optical pathlength} = \int_A^B n(r) ds
\]
Wave Optics

- **Definition**: That branch of optics concerned with radiant energy and related phenomena, as defined by wave characteristics.
- Thomas Young discovered the interference of light from adjacent pinholes and established the wave theory of light.
- The polarization of light by reflection had been discovered in 1808 by Malus and the polarizing angle discovered by Brewster in 1811.
- Fresnel was able to explain polarization using Young’s suggestion that light was a transverse vibration and his analyses of diffraction effects were convincing, but the final proof of the wave theory depended on the experimental proof that light traveled more slowly in denser media.

EM Optics

- **Definition**: Wave of radiation identified by individual fluctuations of electric and magnetic fields.
- Maxwell’s equations in free space
  
  \[
  \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad \text{(Gauss’s Law from Coulomb’s Law)}
  \]
  
  \[
  \nabla \cdot \mathbf{B} = 0 \quad \text{(Gauss’s Law for magnetism from Bio-Savart)}
  \]
  
  \[
  \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad \text{(Faraday’s Law)}
  \]
  
  \[
  \nabla \times \mathbf{B} - \frac{1}{\mu_0} \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J} \quad \text{(Ampere’s Law revised by Maxwell)}
  \]

Quantum Optics

- Quantum-mechanical properties of light.
- The electric and magnetic fields \( \mathbf{E} \) and \( \mathbf{H} \) are mathematically treated as operators in a vector space.

Light

- Classical (Wave) Description
  - Light is an EM wave: \( 100 \text{ nm} < \lambda < 10 \text{ microns} \)
- Quantum (Particle) Description
  - Localized, massless quanta of energy - photons
- Wave / Particle Duality
  - Appropriate description depends on experimental device examining light
**Classical Description of Light**

*EM spectrum*

Electromagnetic radiation can be considered to behave as two wave motions at right angles to each other and to the direction of propagation:

- One of these waves is electric (E) and the other is magnetic (B)
- These waves are functions of space and time

**Wave Equation** (derived from Maxwell's equations)

\[ \nabla^2 \overrightarrow{E} = \frac{1}{c^2} \frac{\partial^2 \overrightarrow{E}}{\partial t^2} \]

\[ \nabla^2 \overrightarrow{B} = \frac{1}{c^2} \frac{\partial^2 \overrightarrow{B}}{\partial t^2} \]

\( \text{Discrete propagation of light in free space.} \)

**Plane Wave Solution**

- One useful solution is for plane wave

\[ \overrightarrow{E} = \overrightarrow{E}_0 e^{i(kr - \omega t)} = \overrightarrow{E}_0 e^{i(kr + \omega t)} \]

\[ \overrightarrow{B} = \overrightarrow{B}_0 e^{i(kr - \omega t)} \]

*where,*

- \( k \) = wave number
- \( \omega \) = angular frequency

\( k = \frac{2\pi}{\lambda} \)

\( \omega = 2\pi f = 2\pi c / \lambda \)

**Classical Description of Light**

**Properties of EM waves**

Electromagnetic radiation can be considered to behave as two wave motions at right angles to each other and to the direction of propagation:

- One of these waves is electric (E) and the other is magnetic (B)
- These waves are functions of space and time

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**Quantum Description of Light**

**Historical perspective**

- Max Planck (1858-1947) - Introduced concept of light energy or "quanta" (blackbody radiation) and the "Planck" constant
- Albert Einstein (1879-1955) - Proof for particle behavior of light came from the experiment of the photoelectric effect
Quantum Description of Light

**Energy of a photon**

\[ E_{\text{photon}} = h\nu = \frac{hc}{\lambda} \]

**Momentum of a photon**

\[ p_{\text{photon}} = \frac{E_{\text{photon}}}{c} = \frac{h}{\lambda} \]
\[ m_{\text{photon}} = 0 \]

Wave / Particle Duality

**Photons versus EM waves**

- Light is composed of small parcels called photons.
- Depending on their interactions with other matter, light either has particle or wavelike behavior.
- This duality in the nature of photons is a key aspect of Quantum theory.
- Light is a particle and has wave like behavior.
- The photon concept and the wave theory of light complement each other.
- Depends on the specific phenomenon being observed.

Wave / Particle Duality

- High frequency (X-rays)
  - Momentum and energy of photon increase
  - Photon description dominates

- Low Frequency (radio waves)
  - Interference/diffraction easily observable
  - Wave description dominates

A Photon is

- A mass-less “particle” with energy given by
  - \[ E = hv = \frac{hc}{\lambda} \text{ since } \nu = c/\lambda \text{ (wave properties)} \]
  - \[ P = \frac{h}{\lambda} \text{ and } E = cP \text{ (particle nature)} \]

Where

- \( h = \text{Planck's constant} (=0.6626\times10^{-34} \text{ Js}) \)
- \( \nu = \text{frequency} \)
- \( c = \text{speed of light} (=0.2998\times10^9 \text{ m/s}) \)
- \( \lambda = \text{wavelength (wave-particle duality)} \)
- \( P = \text{momentum (wave-particle duality)} \)
A Photon is not

- A particle having a mass (such as proton, neutron or electron)
- But photon can behave like waves
  - where \( \lambda = \frac{h}{mv} \)
  - \( m \) = mass
  - \( v \) = velocity
- The wavelength is called de Broglie wavelength

Properties of Light

- carries electric and magnetic field - interaction with electric charges
- frequency - wavelength – energy
- momentum
- polarization
- coherence
- interact with gravity
- photon-photon interactions
- obey bose-einstein statistics (more then one photon can occupy a given state)
Light is very versatile!

Poynting’s theorem

- We observe energy rather than the field amplitude!
- Relation between propagating electromagnetic fields and the energy transported.

\[
\nabla \cdot S + \frac{\partial u_{\text{field}}}{\partial t} = -\frac{\partial u_{\text{medium}}}{\partial t}
\]

\[
S \equiv E \times \frac{B}{\mu_0}
\]

S is the Poynting vector
The speed of light is $c = \omega / (nk_0)$. Since $k_0$ becomes $k = nk_0$ in a medium,

$$c = \frac{\omega}{(nk_0)} = \frac{\omega}{k_0} \frac{1}{n} \quad \Rightarrow \quad c = c_0 / n$$

where $c_0$ is the speed of light in vacuum.

The refractive index, $n$, of a medium is thus the ratio of the speed of light in vacuum to the speed of light in the medium. It can be defined as the ratio:

$$n \equiv \frac{c_0}{c}$$

The refractive index is usually $> 1$. But it can be $< 1$.

**The Refractive Index $n$**

- The dimensionless quantity $n(\omega)$, index of refraction, is the ratio of the speed of the light in vacuum to the speed of the wave in the material.

$$n(\omega) = \sqrt{1 + \chi(\omega)}$$

if absorption negligible

$$N = (n + i\kappa)$$

if absorption plays a roll

$$k = \frac{\omega}{c} n(\omega) = \frac{\omega}{c} \sqrt{1 + \chi(\omega)}$$

$$v = \left( \frac{c}{n(\omega)} \right)$$

**A light wave in a medium**

- The speed of light, the wavelength (and $k$), and the amplitude change, but the frequency, $\omega$, doesn’t change.

**Interference**

- constructive interference

- destructive interference

- by $\pi$ out of phase
Absorption Coefficient and the Irradiance

The irradiance is proportional to the (average) square of the field. Since \( E(z) \propto \exp(-\alpha z) \), the irradiance is then:

\[
I(z) = I(0) \exp(-\alpha z) = I(0) \exp(-N\sigma z)
\]

where \( I(0) \) is the irradiance at \( z = 0 \), and \( I(z) \) is the irradiance at \( z \).

Thus, due to absorption, a beam’s irradiance exponentially decreases as it propagates through a medium.

The 1/e distance, \( 1/\alpha \), is a rough measure of the distance light can propagate into a medium (the penetration depth).

Dispersion is the tendency of optical properties to depend on frequency

- Dispersion of the refractive index allows prisms to separate white light into its components and to measure the wavelength of light.

Refractive Index vs. Wavelength

- Since resonance frequencies exist in many spectral ranges, the refractive index varies in a complex manner.

Because the refractive index depends on wavelength, the refraction angle also depends on wavelength: this is called angular dispersion.

\[
\cos(\theta) = \frac{d\theta}{d\lambda} = \frac{dn}{d\lambda} \sin(\theta^{\text{out}})
\]

We obtain the prism dispersion:

\[
D = \frac{d\theta}{d\lambda} = \frac{dn}{d\lambda} \cos(\theta)
\]
Angle of Incidence = Angle of Reflection

The electric field wave-fronts are continuous at a boundary. The speed of light is the same in the incident and reflected media (because they're the same). Let $\theta_r$ be the reflected-beam propagation angle.

\[
\begin{align*}
AD &= BD / \sin(\theta) & AD &= AE / \sin(\theta) & BD \sin(\theta) &= AE / \sin(\theta) \\
\text{But:} & & BD &= v_i \Delta t = (c_0 / n_i) \Delta t & \Rightarrow & AE &= v_i \Delta t = (c_0 / n_i) \Delta t \\
\text{So:} & & (c_0 / n_i) \Delta t / \sin(\theta) &= (c_0 / n_i) \Delta t / \sin(\theta) \\
\text{Or:} & & \sin(\theta) &= \sin(\theta) & \Rightarrow & \theta_i = \theta_r
\end{align*}
\]

Snell's Law causes things to look bent in water.

Reflection Differences

Specular

Diffuse

Spread

Refraction and Snell's Law

The electric field (and its wave-fronts) are continuous at a boundary. But the speed of light will be different in the two media.

\[
\begin{align*}
AD &= BD / \sin(\theta) & AD &= AE / \sin(\theta) \\
\text{So:} & & BD / \sin(\theta) &= AE / \sin(\theta) \\
\text{But:} & & BD &= v_i \Delta t = (c_0 / n_i) \Delta t & \Rightarrow & AE &= v_i \Delta t = (c_0 / n_i) \Delta t \\
\text{So:} & & (c_0 / n_i) \Delta t / \sin(\theta) &= (c_0 / n_i) \Delta t / \sin(\theta) \\
\text{Or:} & & n_i \sin(\theta_i) &= n_i \sin(\theta_t)
\end{align*}
\]
Snell's Law for many parallel layers

If the layers are parallel, then these angles are always equal.

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) = n_3 \sin(\theta_3) = \ldots = n_m \sin(\theta_m) \]

So we can ignore the intermediate layers if we’re only interested in the output angle!

Snell’s Law explains why stars twinkle

- The atmosphere has non-uniform temperature and hence non-uniform refractive index.
- And these regions move about in time.

Refraction and reflection

Fresnel Equations

We would like to compute the fraction of a light wave reflected and transmitted by a flat interface between two media with different refractive indices.

\[ r_\perp = \frac{E_{0r}}{E_{0i}} \]
\[ t_\perp = \frac{E_{00}}{E_{0i}} \]

for the perpendicular polarization

where \( E_{0r} \), \( E_{0p} \), and \( E_{00} \) are the field complex amplitudes.

We consider the boundary conditions at the interface for the electric and magnetic fields of the light waves.
Fresnel’s reflection coefficients

\[ r_s = \frac{E_{rs}^{(s)}}{E_s^{(s)}} = \frac{\sin(q_s \cos(q_s) - \sin(q_s \cos(q_s))}{\sin(q_s \cos(q_s) + \sin(q_s \cos(q_s))} = \frac{n_1 \cos(q_s) - n_2 \cos(q_s)}{n_1 \cos(q_s) + n_2 \cos(q_s)} \]

\[ t_s = \frac{E_{ts}^{(s)}}{E_s^{(s)}} = \frac{2 \sin(q_s \cos(q_s))}{\sin(q_s \cos(q_s) + \sin(q_s \cos(q_s))} = \frac{2n_1 \cos(q_s)}{n_1 \cos(q_s) + n_2 \cos(q_s)} \]

\[ r_p = \frac{E_{rp}^{(p)}}{E_p^{(p)}} = \frac{\cos(q_p \sin(q_p) - \cos(q_p \sin(q_p))}{\cos(q_p \sin(q_p) + \cos(q_p \sin(q_p))} = \frac{n_1 \cos(q_p) - n_2 \cos(q_p)}{n_1 \cos(q_p) + n_2 \cos(q_p)} \]

\[ t_p = \frac{E_{tp}^{(p)}}{E_p^{(p)}} = \frac{2 \cos(q_p \sin(q_p))}{\cos(q_p \sin(q_p) + \cos(q_p \sin(q_p))} = \frac{2n_1 \cos(q_p)}{n_1 \cos(q_p) + n_2 \cos(q_p)} \]

Reflectance (R)

\[ R = \frac{\text{Reflected Power}}{\text{Incident Power}} = \frac{I_r A}{I_i A} \]

\[ A = \text{Area} \]

Because the angle of incidence = the angle of reflection, the beam area doesn’t change on reflection.

Also, \( n \) is the same for both incident and reflected beams.

So: \[ R = r^2 \]
Polarisation

- Consider the superposition of two plane polarized waves:
  \[ \psi_x = E_x \sin(kz - \omega t) \]
  \[ \psi_y = E_y \sin(kz - \omega t + \epsilon) \]
  \[ E = \sqrt{E_x^2 + E_y^2} \]
  \[ \tan \theta = \frac{E_y}{E_x} \]

Right Circularly Polarized Light:
- If \( \epsilon = (2m-1/2)\pi \), \( m \) being an integer
  \[ E_x = E_y = E_i \]
  \[ \psi = \sqrt{\psi_x^2 + \psi_y^2} = \sqrt{E_x^2 + E_y^2} = E_i \]
  \[ \tan \theta = \frac{\epsilon}{\sqrt{\psi_x^2 + \psi_y^2}} \]
  \[ \theta = \pi/2 + \alpha \text{ at } z = 0 \]

Left Circularly Polarized Light:
- If \( \epsilon = (2m+1/2)\pi \), \( m \) being an integer
  \[ E_x = E_y = E_i \]
  \[ \psi = \sqrt{\psi_x^2 + \psi_y^2} = \sqrt{E_x^2 + E_y^2} = E_i \]
  \[ \tan \theta = \frac{\psi_y}{\psi_x} \]
  \[ \theta = \pi/2 + \alpha \text{ at } z = 0 \]

Right and left circular light can be written as,
\[ E_{\pm}(z,t) = E_i [\sin(kz - \omega t) \pm j\cos(kz - \omega t)] \]
\[ E_{\pm}(z,t) = E_i [\sin(kz - \omega t) \pm j\cos(kz - \omega t)] \]
Their superposition becomes
\[ E(z,t) = 2E_i \sin(kz - \omega t) \]

Dichroism – Polarization by Absorption

- Selective absorption of one of the two orthogonal P-state in incident natural light.

Birefringence

A material which displays two different speeds of propagation in fixed and orthogonal directions, and therefore displays two refractive indices, is known as birefringent.

Distinction: A dichroic material absorbs one of the orthogonal P-states is dichroic while in birefringent material we usually neglect the absorption.

Atomic structure of a CaCO\(_3\) tetrahedron.

\[ n_\parallel = \frac{c}{v_\parallel} \]
\[ n_\perp = \frac{c}{v_\perp} \]
\[ \Delta n = n_\parallel - n_\perp \]

- uniaxial positive
- uniaxial negative

\[ \Delta n = n_\parallel - n_\perp \] is called birefringence.
Retarders

Retarders are devices that cause one orthogonal P-state component to lag behind the other on emerging from the retarders.

The path difference is \[ \text{OPD} = (n_x - n_y) \theta \]

Full wave plate:
\[ \text{OPD} = (n_x - n_y) \theta = m \lambda \quad m = 1, 2, 3... \]

Half-wave plate:
\[ \text{OPD} = (n_x - n_y) \theta = \left( m + \frac{1}{2} \right) \lambda \quad m = 1, 2, 3... \]

Quart-wave plate:
\[ \text{OPD} = (n_x - n_y) \theta = \left( m + \frac{1}{4} \right) \lambda \quad m = 1, 2, 3... \]

The component \( E_{\parallel} \) and \( E_{\perp} \) that travels faster defines the fast axis of the plate.

What is Light?

Coherence

- Study of the correlation properties between the phases of monochromatic wave components in radiation
- Temporal coherence (longitudinal coherence) spectral purity of the source
- Spatial coherence (lateral coherence) size of the source

In point \( P \):
\[ E_p = E_1(r_1, t) + E_2(r_2, t) \]

Square-law detector:
\[ I_p = \langle E_p \ast E_p \rangle = \langle (E_1 + E_2) \ast (E_1 + E_2) \ast \rangle \]
\[ = I_1 + I_2 + 2\text{Re}(E_1E_2^*) \]

Assume \( S \) to be stationary:
\[ t_1 = t \quad \text{and} \quad t_2 = t + \tau \]
Radiometry vs Photometry

- Radiometry is the science of measuring light in any portion of the electromagnetic spectrum.
- Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye.

Scopitic vs Photopic

- Colour vision is provided by the cones, of which there are three distinct classes each containing a different photosensitive pigment. The cones therefore provide us with colour vision (photopic vision).
- The three pigments have maximum absorptions at about 430, 530, and 560 nm and the cones are often called blue, green, and red. The cones are not named after the appearance of the cone pigments but are named after the colour of light to which the cones are optimally sensitive. This terminology is unfortunate since monochromatic lights at 430, 530, and 560 nm are not blue, green, and red respectively but violet, blue-green, and yellow-green. The use of short-, medium-, and long-wavelength cones is a more logical nomenclature.

Photometric measurements

Visual Sensitivity:

- The eye is not equally sensitive to the different colors of light in the visible spectrum.
Eye sensitivity

Radiant Power $P$
- Power emitted, transferred or received as radiation [W]
- Some examples of radiant sources:
  - sun $4 \times 10^{26}$ W
  - light bulb 100 W
  - medical CO$_2$ laser 20 W
  - flashlight 0.1 W
  - HeNe laser $1 \times 10^{-3}$ W

Radiant energy $Q$
- Energy emitted, transferred or received as radiation [J]
- $Q = P \times t = \text{power}\times\text{time}$

Radiant intensity $I$
- In a given direction from a source, the radiant energy flux (or power) leaving the source, or an element of the source, in an solid angle containing the given direction, divided by that element of solid angle [W/sr]
- $I = P/\Omega$
  - $\Omega$
  - $I = \frac{P}{W}$
Luminous Flux and Intensity

Luminous flux $\Phi$: the rate at which light energy flows. Unit: lumen
One lumen is the luminous flux emitted into a unit solid angle (1 steradian) from a point source of intensity 1 candela. $\Phi = I \omega$

Luminous intensity of a source: $I = \frac{\Phi}{\omega}$
For a specified direction: $I = \frac{d\Phi}{d\omega}$

Solid angle

Solid angle of cone, $W$:
$W = (4\pi[\text{sr}]) \pi^2/4\pi R^2 = \pi R^2$
$W = 2\pi(1 - \cos(\phi))$

Whole sphere has steradians $4\pi[\text{sr}]$ of solid angle

Irradiance for plane wave

- In most situations we are measuring the time average of $S = <S>_t$

$I = \frac{n\epsilon_0 c}{2} E_0 \cdot E_0^* = \frac{n\epsilon_0 c}{2} \left( |E_{0x}|^2 + |E_{0y}|^2 + |E_{0z}|^2 \right)$

Irradiance $E$

- At a point of a surface, the radiant energy flux (or power) incident on an element of the surface, divided by the area of the surface [W/cm$^2$]
- $E = P/A$
- Fluence rate
- Radiant exittance, $M$
  - radiant dose rate
  - radiant emittance

Ex: Irradiance of a flashlight beam on a wall
The illuminance at a point on a surface does not depend on the nature of the surface since it is only concerned with incident light.

### Two laws:

1. **The illuminance at a point on a surface is inversely proportional to the square of the distance between the point and the source.** This law applies strictly only in the case of point sources.

   \[ E = \frac{d\Phi}{dA} \]

   \[ E = \frac{I\, d\omega}{dA} \]

   \[ d\omega = \frac{\Delta A \cos \theta}{r^2} \]

   \[ E = \frac{I}{r^2 \cos \theta} \]

2. **The second is that if the normal to an illuminated surface is at an angle \( \theta \) to the direction of the incident light, the illuminance is proportional to the cosine of \( \theta \).**

   \[ E_{\text{normal}} = I \cos \theta \]

   \[ E_{\text{incidence}} = I \]

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### Radiance L

- The power that radiates from a source within a solid angle [sr] and passes through a cross-sectional area \( A \cos \theta \) within unit area and unit solid angle.

- \( L = \frac{P}{W} A \cos \theta \)

### Luminance

The luminance \( L \) of any surface in a specified direction is defined as the luminous intensity per unit projected area in the direction concerned.

\[ L = \frac{I(\theta)}{A \cos \theta} \]

A uniformly diffusing surface obeys the Lambert’s Law of Emission.

\[ I \propto \cos \theta \]

Illuminance is concerned with the luminous flux incident on a surface and this does not depend on the nature of the surface.

Luminance is concerned the flux which is emitted (or transmitted, or reflected) in a given direction and this will be dependent on the nature of the surface.
Radiometric quantities and units

<table>
<thead>
<tr>
<th>Name</th>
<th>Concept</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant Power (of a source)</td>
<td>Electromagnetic energy emitted per time from a source</td>
<td>W = J/s</td>
</tr>
<tr>
<td>Radiant Solid-Angle Intensity (of a source)</td>
<td>Radiant power per steradian emitted from a point-like source (4π steradians in a sphere)</td>
<td>W/ sr</td>
</tr>
<tr>
<td>Radiance or Brightness (of a source)</td>
<td>Radiant solid-angle intensity per unit projected area of an extended source. The projected area foreshortens by cos θ, where θ is the observation angle relative to the surface normal.</td>
<td>W/(sr · cm²)</td>
</tr>
<tr>
<td>Radiant Emittance or Emissance (from a source)</td>
<td>Radiant Power emitted per unit surface area of an extended source (the Poynting flux leaving).</td>
<td>W/cm²</td>
</tr>
<tr>
<td>Irradiance (to a receiver), Often called intensity</td>
<td>Electromagnetic power delivered per area to a receiver; Poynting flux arriving.</td>
<td>W/cm²</td>
</tr>
</tbody>
</table>

Photometric quantities and units

<table>
<thead>
<tr>
<th>Name</th>
<th>Concept</th>
<th>Typical Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous Power (of a source)</td>
<td>Visible light energy emitted per time from a source; lumen (lm)</td>
<td>lm = 1/683 W 6555 nm</td>
</tr>
<tr>
<td>Luminous Solid-Angle Intensity (of a source)</td>
<td>Luminous power per steradian emitted from a point-like source; candela (cd)</td>
<td>cd = lm/ sr</td>
</tr>
<tr>
<td>Luminance (of a source)</td>
<td>Luminous solid-angle intensity per projected area of an extended source. (The projected area foreshortens by cos θ, where θ is the observation angle relative to the surface normal.)</td>
<td>cd/ cm² = stilb</td>
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<tr>
<td></td>
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<td>cd/ cm² = nit</td>
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<tr>
<td></td>
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<td>ml = 1/683 lumens</td>
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<tr>
<td></td>
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<td>ml/ cm² = phot</td>
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<tr>
<td></td>
<td></td>
<td>ln/ f = footcandle</td>
</tr>
</tbody>
</table>

Collection of light: by aperture

\[ E(r) = P \frac{2}{w_0^2} \exp(-\frac{2r^2}{w_0^2}) \]

\[ P = \int_0^\infty E(r) 2\pi r \, dr \]

\[ P_{\text{collected}}(a) = \int_0^a E(r) 2\pi r \, dr = P(1 - \exp(2a^2/w_0)) \]

Collection of light: aperture at a limited solid angle of light
**Integrating sphere**

**Fiber Optics**

Optical fibers use TIR to transmit light long distances.

They play an ever-increasing role in our lives!

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**Design of optical fibers**

Core: Thin glass center of the fiber that carries the light

Cladding: Surrounds the core and reflects the light back into the core

Buffer coating: Plastic protective coating

\[ n_{\text{core}} > n_{\text{cladding}} \]
Propagation of light in an optical fiber

Light travels through the core bouncing from the reflective walls. The walls absorb very little light from the core allowing the light wave to travel large distances.

Some signal degradation occurs due to imperfectly constructed glass used in the cable. The best optical fibers show very little light loss -- less than 10%/km at 1.550 μm.

Maximum light loss occurs at the points of maximum curvature.

Absorption in optical fibers

This is why optical telecommunications occur at ~1550 nm.

Safety, the eye

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<th>Wavelength</th>
<th>Thermal Effects</th>
<th>Photochemical Effects</th>
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<tbody>
<tr>
<td>UV A</td>
<td>320-400 nm</td>
<td>Cornea, Lens</td>
</tr>
<tr>
<td>Visible</td>
<td>400-700 nm</td>
<td>Retina</td>
</tr>
<tr>
<td>IR B</td>
<td>1400-3000 nm</td>
<td>Cornea</td>
</tr>
<tr>
<td>IR C</td>
<td>3000-1000000 nm</td>
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</tr>
</tbody>
</table>

Effects of light

<table>
<thead>
<tr>
<th>Photobiological Spectral Domain (CE Band)</th>
<th>Eye Effects</th>
<th>Skin Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet C (200-280 nm)</td>
<td>Photokeratitis</td>
<td>Erythema (Sunburn) Skin Cancer</td>
</tr>
<tr>
<td>Ultraviolet B (280-315 nm)</td>
<td>Photokeratitis</td>
<td>Erythema (Sunburn) Accelerated Skin Aging Increased Pigmentation</td>
</tr>
<tr>
<td>Ultraviolet A (315-400 nm)</td>
<td>Photochemical UV Cataract</td>
<td>Pigment Darkening Skin Burn</td>
</tr>
<tr>
<td>Visible (400-780 nm)</td>
<td>Photochemical and Thermal Retinal Injury Color and Night Vision Degradation</td>
<td>Skin Burn Photosensitive Reactions</td>
</tr>
<tr>
<td>Infrared A (780-1400 nm)</td>
<td>Retinal Burns</td>
<td>Skin Burn</td>
</tr>
<tr>
<td>Infrared B (1400-3000 nm)</td>
<td>Corneal Burn</td>
<td>Skin Burn</td>
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<td>Infrared C (3000-1 million nm)</td>
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</table>
Linköping University
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