

Advanced Physics Lab - Optics

*Advanced Physics Lab, PHYS 3600
Don Heiman, Northeastern University, 2021*

This Week

1a-INTRO-a & 1b-INTRO-b: Introduction to the Course
motivation, boiler plate (syllabus/labs)
Fermi questions, exercises

2-ERRORS: Errors and Uncertainties
accuracy, precision, round off, propagation of errors

3-OPTICS: Optical Properties
EM spectrum, photo detectors, light emitters

4-SEMICOND: Semiconductors
band gap, Fermi energy, resistivity, Hall effect

5-ACOUSTICS:
sound, beats, Fourier transform, music

6-EXPERIMENTS: Intro to Lab Experiments
Virtual tour my research lab

Light, Optics and Lasers

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Labs with Optics

Photocell - RUBY, FUEL, FR, SOL

Laser - RUBY, SOL, FR



➤ Light

Electromagnetic spectrum, solar radiation

➤ Basic Optics

Lens formula, absorption, reflectivity

➤ Laser

Ruby, semiconductor, laser pointer

➤ Optical Communications

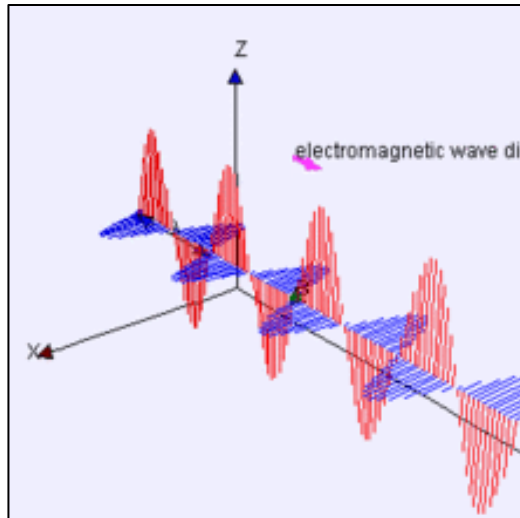
Optical fibers, laser diode

➤ Faraday Rotation

Optical polarization, electromagnet

Electromagnetic Radiation

ElectroMagnetic (EM) Waves



Electric Field

$$E = E_0 \exp[i(kx - \omega t)]$$

Magnetic Field

$$B = B_0 \exp[i(kx - \omega t)]$$

$E \perp B$ related by
Maxwell's equations

Frequency: $\omega = 2\pi f$

independent of material
(same in air, glass, water etc.)

Velocity of wave: $v = c / n$

depends on material

Index of refraction: n

depends on material

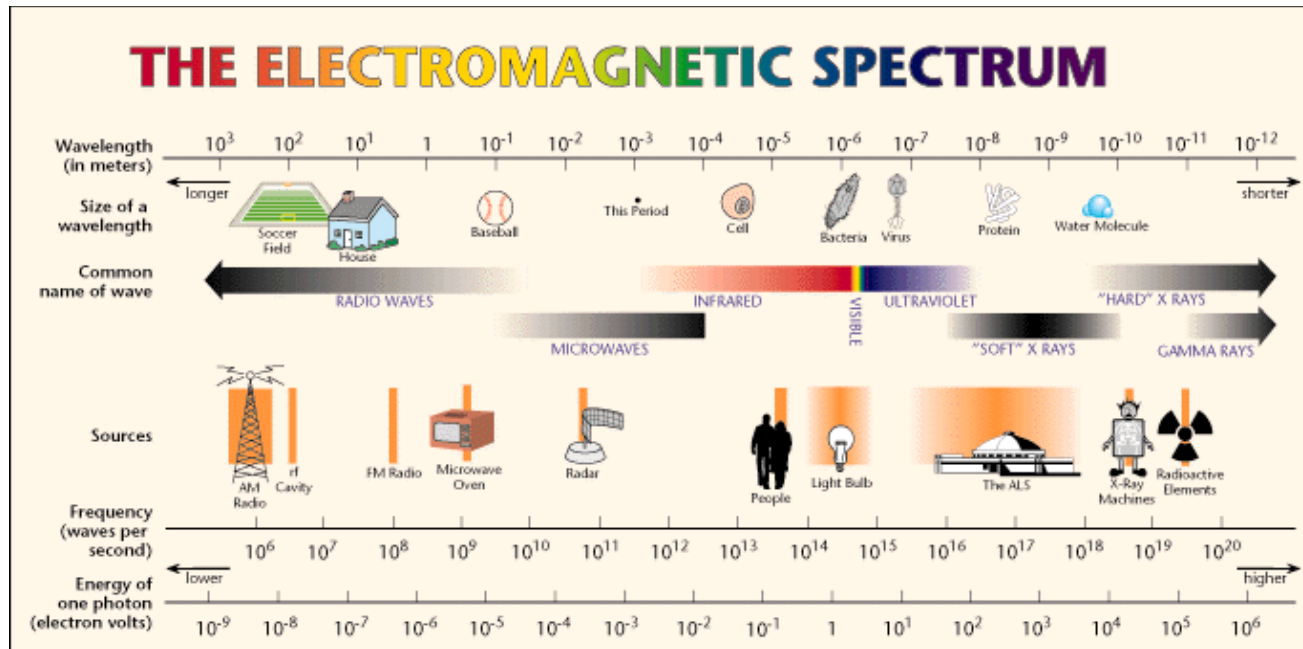
Wavelength: $\lambda = \lambda_0 / n$

depends on material

Wavevector: $k = 2\pi n / \lambda_0$

depends on material

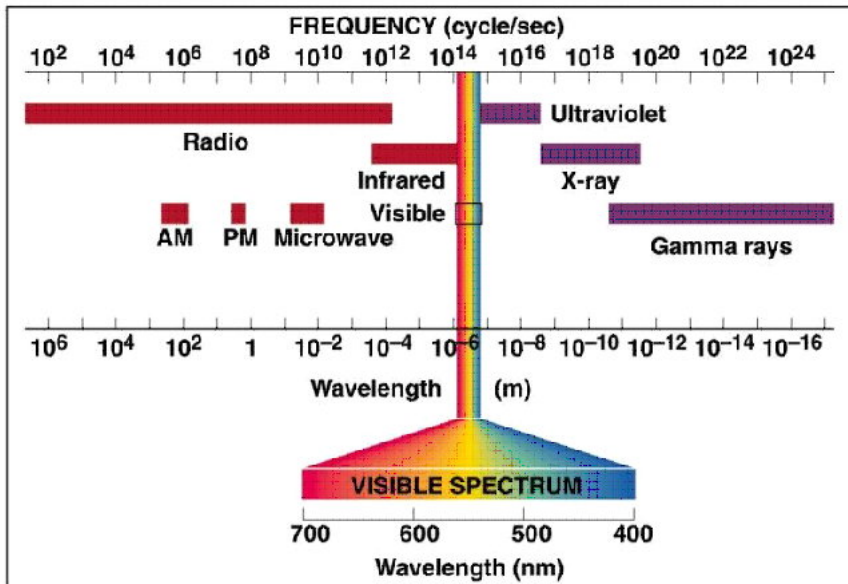
Electromagnetic Spectrum and Units



Characterize Electromagnetic Waves

- (1) Wavelength (nm, μ m)
- (2) Frequency (Hz, radians/s)
- (3) Photon energy (meV, eV, ... TeV)
- (4) Color temperature (K)

Visible Spectrum



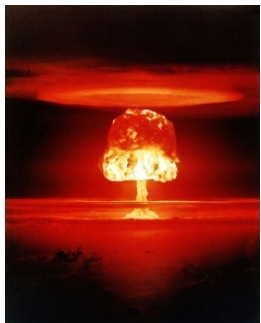
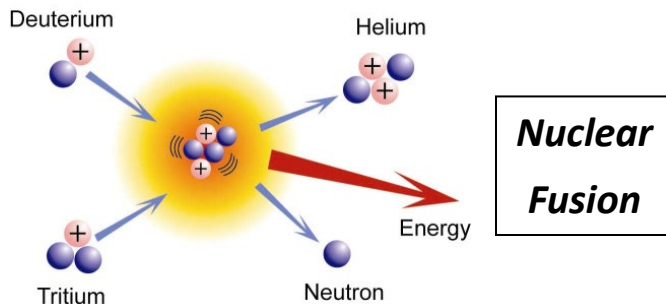
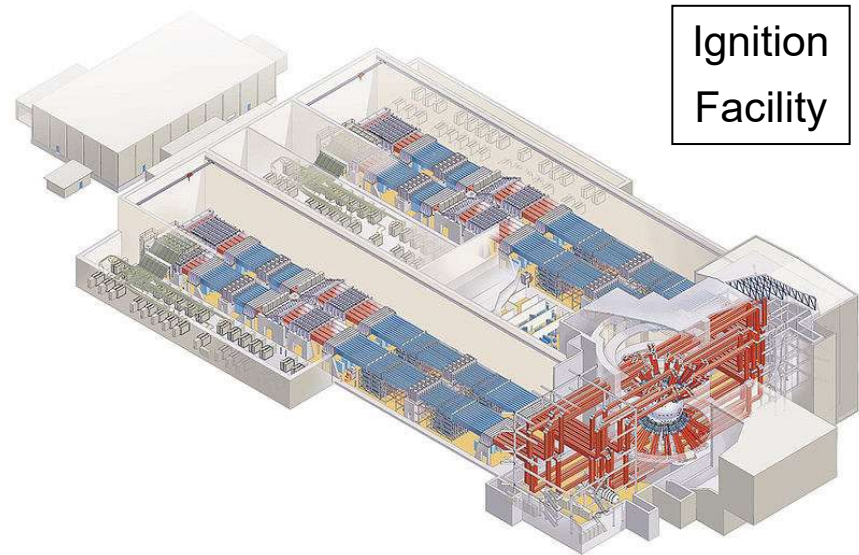
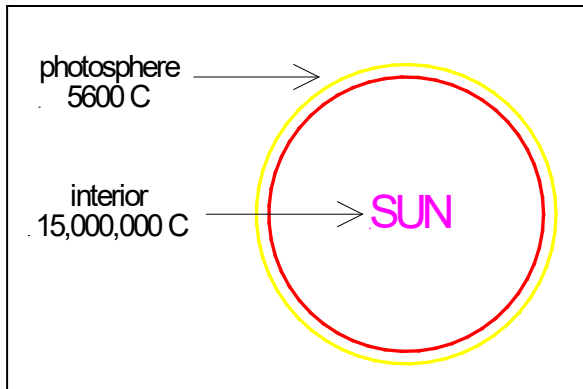
Visible Spectrum

Wavelength: $\lambda = 400 - 700 \text{ nm}$,
 $0.4 - 0.7 \mu\text{m}$

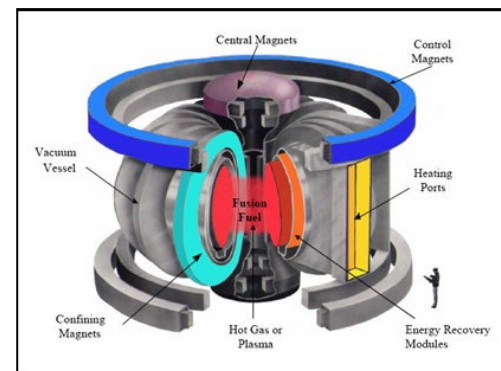
Photon Energy: $hc/\lambda = 3 - 1.8 \text{ eV}$

Color Temperature: $T = 9,300 - 1,700 \text{ K}$

Nuclear Fusion

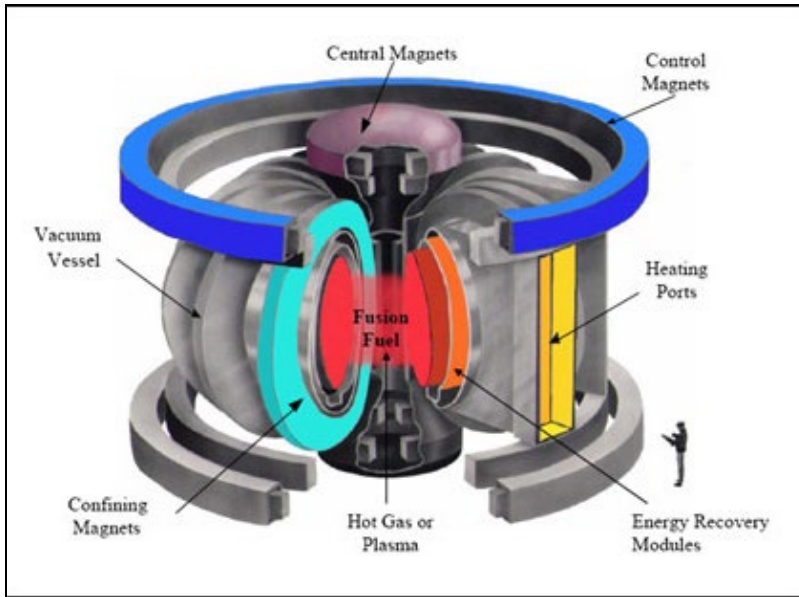


**Uncontrolled
Fusion**



Tokamak - Controlled Fusion

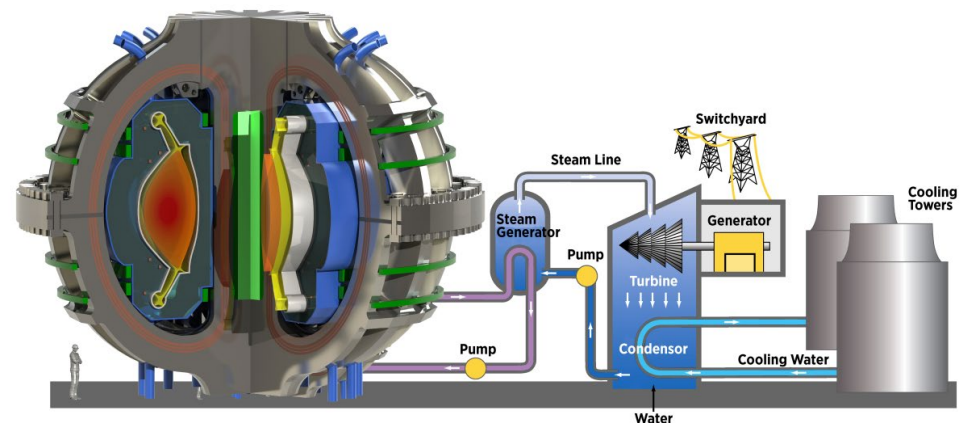
Fusion Tokamak – SPARC @MIT



SPARC Tokamak at MIT

- *Much smaller than other tokamaks*
- *High-temperature superconductors*
 - cool only with liquid nitrogen (90K)
- *Higher magnetic field coils, 12 tesla*
 - much smaller $\sim 1/8$ volume
- *Privately funded*

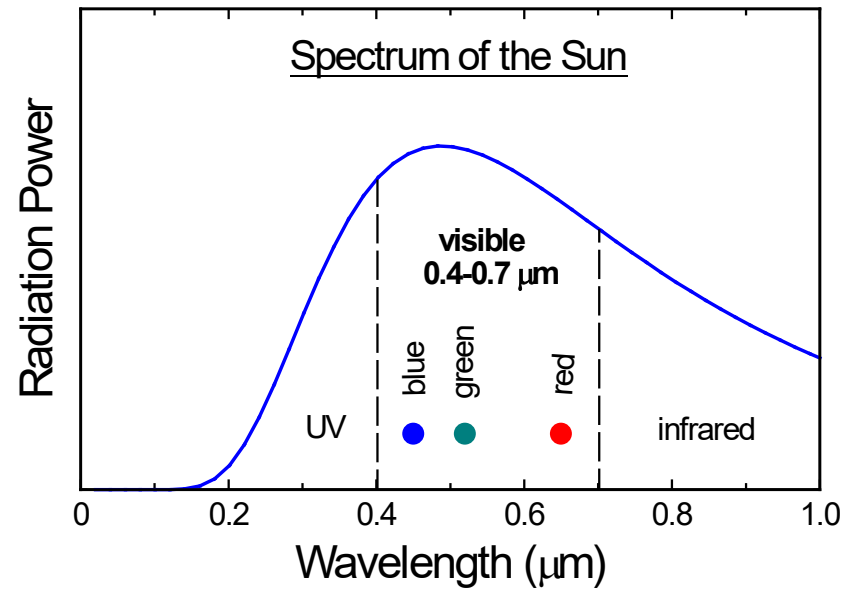
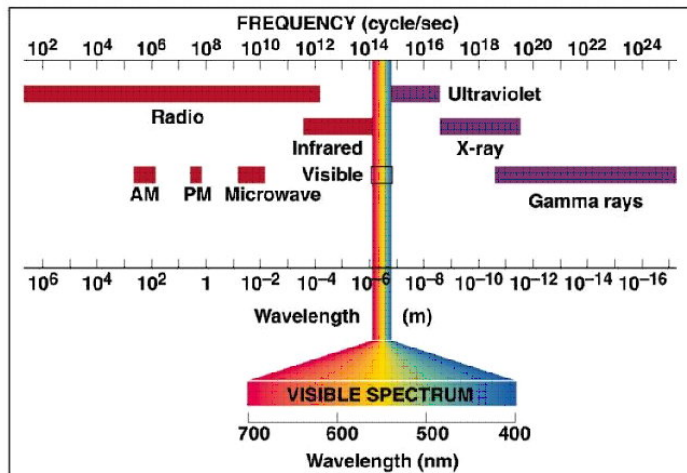
Confining magnets squeeze the hot plasma away from the walls



Solar Spectrum

The sun emits a radiation **spectrum**
according to its surface **temperature**.

Sun surface $T = 5,900 \text{ K}$



Black Body Radiation

Black Body Radiation

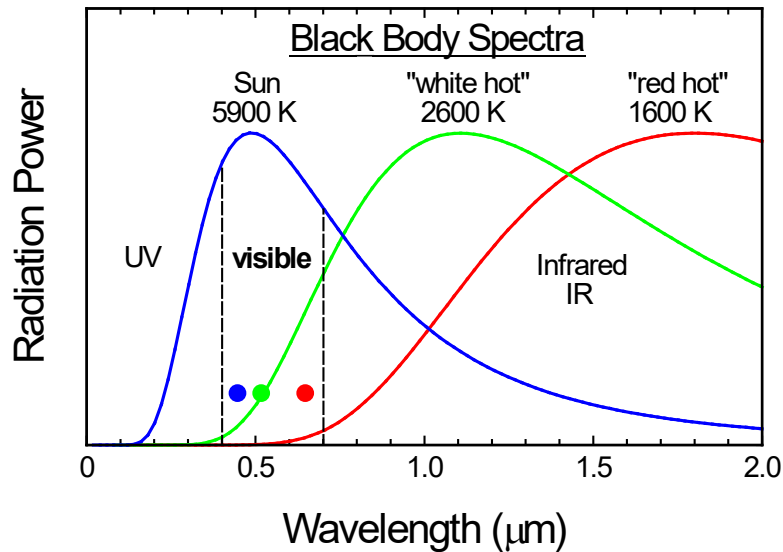
All substances emit EM radiation according to their **absolute temperature**.

Planck's Law for light power

$$P(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

$h\nu$ photon energy, kT thermal energy

Spectrum changes as the temperature changes.



How is radiation produced?

Higher temperature increases the ***motion*** of ions and charges.

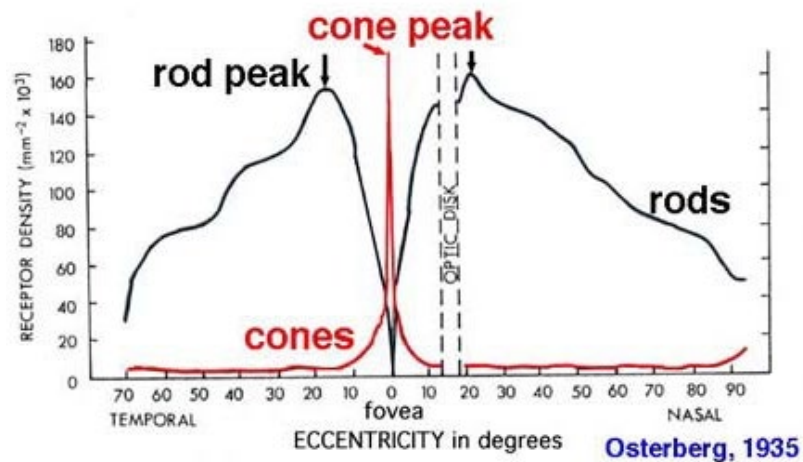
As charges accelerate/decelerate they emit radiation.

Color Vision

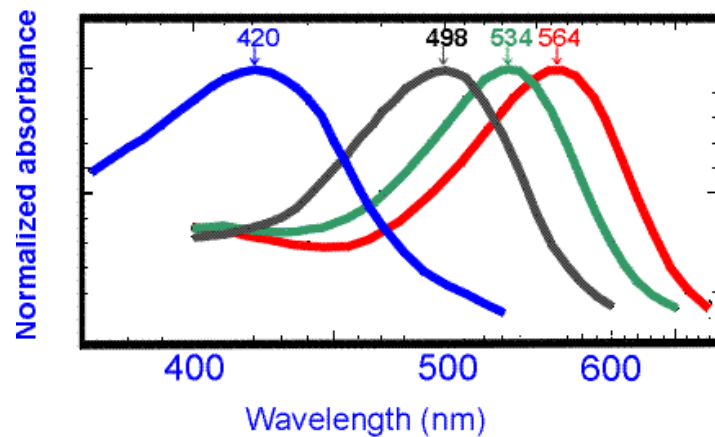
Photoreceptors in retina of eye

Rods – dark/light

Cones – color



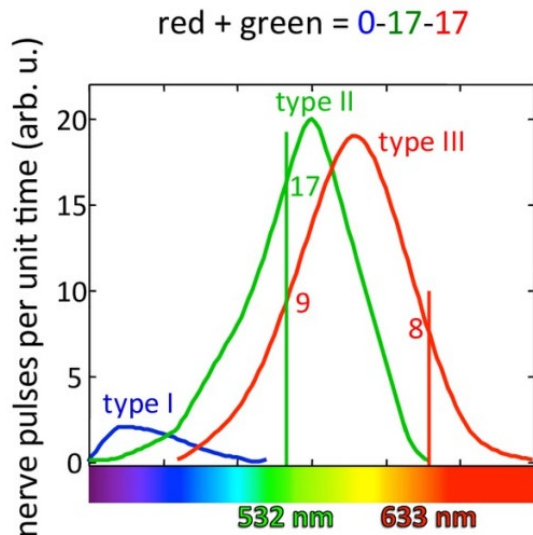
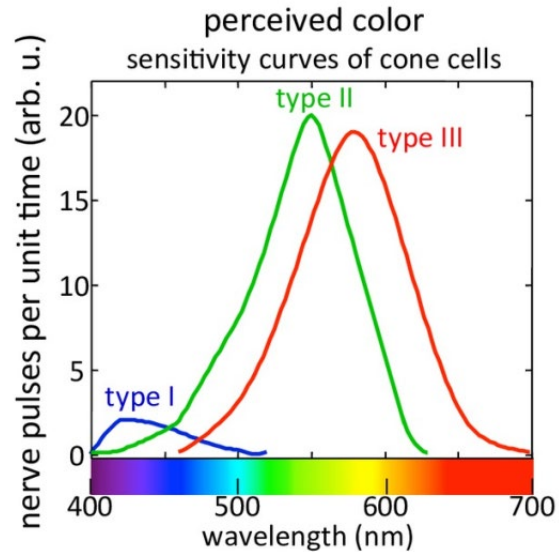
Cones have 3 different
pigments that absorb
3 different colors



After Bowmaker & Dartnall, 1980

Combining Colors

SKIP

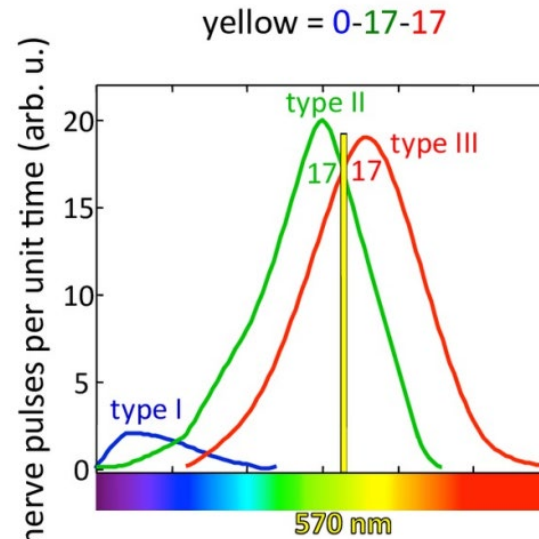


Combining (adding) Colors

Red laser pointer: 8 units

Green laser pointer: 17 + 9 units

Red + Green = Yellow = 17 + 17 units



Color: Physics and Perception

Pupa Gilbert, TEDxMadison

<http://www.youtube.com/watch?v=p6TcOYk9uS8>

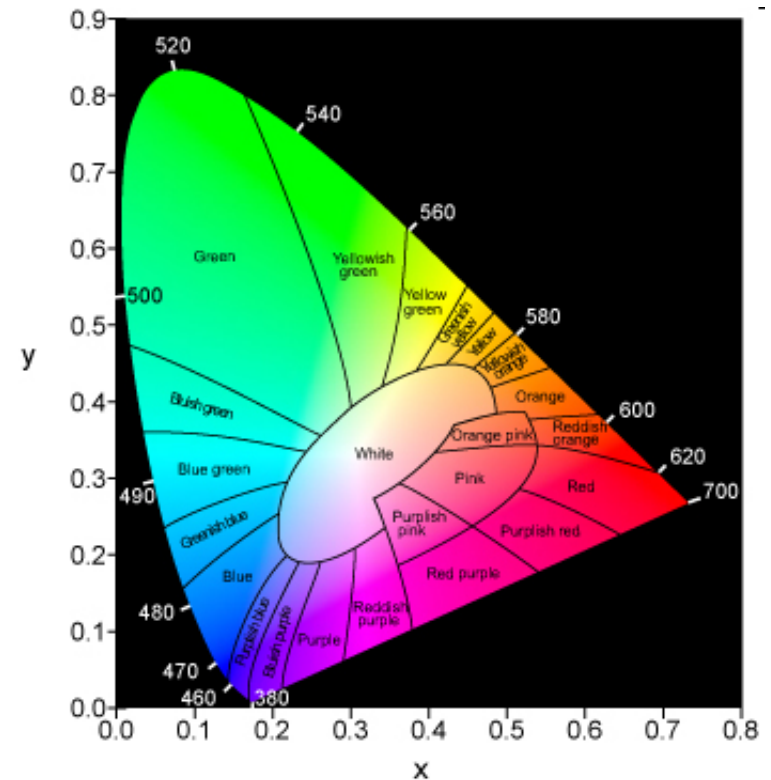
Chromaticity Diagram

Chromaticity Diagram

Requires only 3 colors

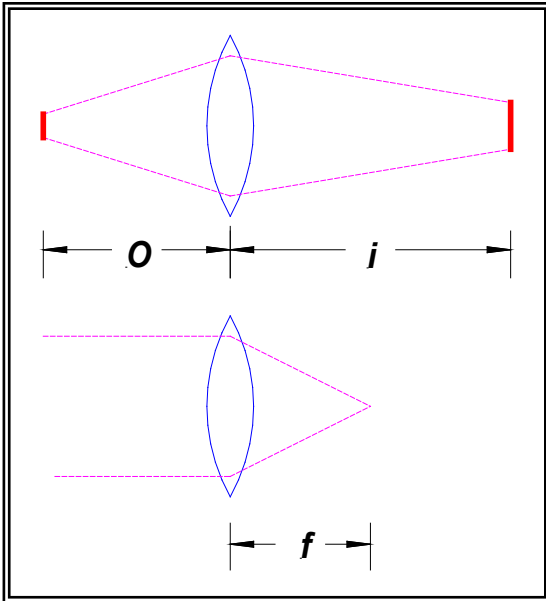
Photoreceptors (rhodopsin) in the human eye (cones) can distinguish the three additive **primary** colors: **red**, **green** and **blue**. These three colors are also used in TV and computer color monitors.

J.C. Maxwell first described a diagram, the Maxwell triangle, to quantitatively represent all possible colors using the three primary colors, which has been updated into the universally accepted **CIE chromaticity diagram** (shown on the lower right). The x- and y-axis are the relative amounts of red and green light, and the amount of blue is $1-x-y$.



Basic Lens Optics

Thin Lens Formula



The lens maker's formula is used here to determine the parameters for focusing the image of the ruby fluorescence into the optical fiber.

Convex focusing lens are useful for projecting an image of an object from one side of a lens onto the other side. See the diagrams. The distance of an image from the lens is related to the distance of the object from the lens by the *thin lens formula*,

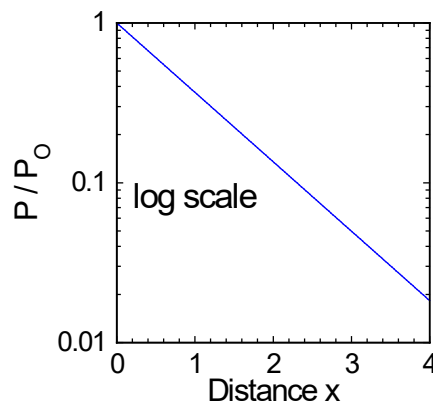
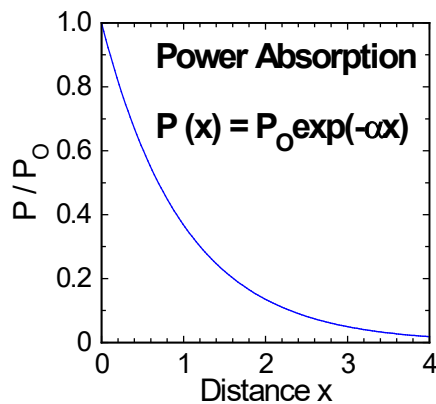
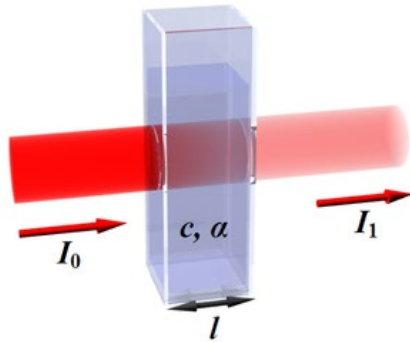
$$1/i + 1/o = 1/f,$$

where *i* is the image distance, *o* the object distance, and *f* the focal length of the lens. The magnification of the lens is $M = i/o$.

A special case of this formula is the focusing of a collimated laser beam. There the object distance is infinite, so the laser beam is focused to a small diameter spot at a distance $i = f$ from the lens, shown in the lower diagram.

Basic Transmission Optics

Light Absorption



The light intensity I (or power P) passing through a material decreases as a function of increasing distance x into the material given by

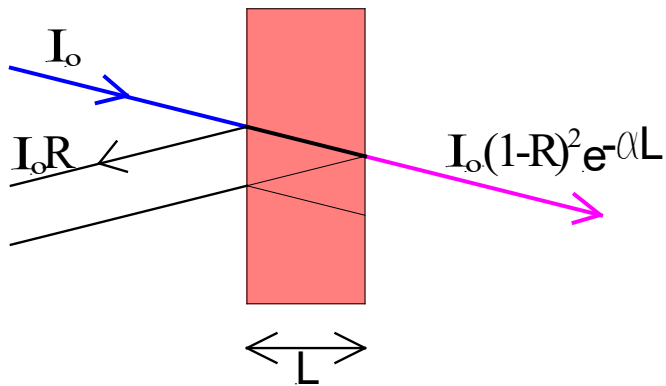
$$I(x) = I_0 \exp(-\alpha x),$$

where I_0 is the initial intensity at $x=0$. The **absorption coefficient is α** . The **absorption length, $1/\alpha$** , characterizes the penetration depth of the light. Light energy absorbed in a ruby crystal is converted into energy stored in the excited Cr ions (plus some energy lost which goes into heating the crystal).

Note that light **intensity** is the light **power** divided by the cross sectional area of the light beam, $I = P / A$.

Basic Reflection Optics

Reflectivity



Light is reflected at interfaces where the index of refraction changes. The reflectivity R is given by

$$R = (n_1 - n_2)^2 / (n_1 + n_2)^2,$$

where n_1 and n_2 are the refractive indices on the sides of the reflecting surface.

For air on one side of the surface $n=1$, then

$$R = (n-1)^2 / (n+1)^2.$$

The light intensity after passing through a crystal of length L is now given by

$$I = I_o (1-R)^2 \exp(-\alpha L),$$

where I_o is the initial light intensity.

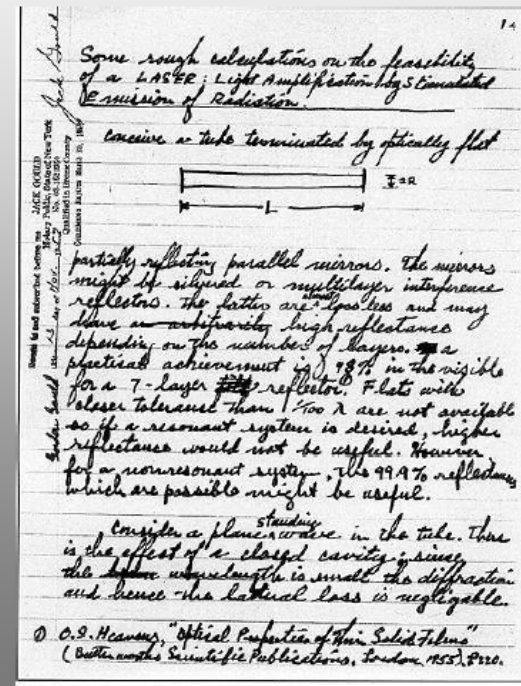
The factor $(1-R)^2$ corrects for reflection losses from the two surfaces.

History of the Laser

Laser History

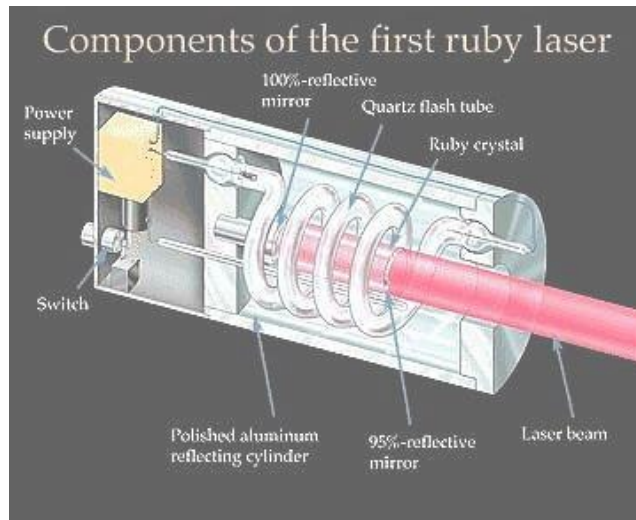
- 1917 – Einstein theorizes Stimulated Emission
- 1950 – Alfred Kastler proposes Optical Pumping
- 1957 – Gordon Gould (Columbia Univ) coins term LASER
- 1960 -- First working laser at Hughes Laboratory (pulsed ruby)
- 1960 – First gas laser
- 1962 – First idea of semiconductor laser
- 1970 – Room Temperature continuous semiconductor laser

Pehr Hovey / pehrhovey.net



First Laser

World's first laser: the Ruby Laser



The first LASER was developed at Hughes Research Lab in Malibu, California, by Theodor Maiman. However,

- (1) the Cr lifetime was predicted to be too short and
- (2) Hughes was not interested laser research!

Bell Labs in New Jersey stole the credit for 2 years.

Ruby – $\text{Al}_2\text{O}_3:\text{Cr}$

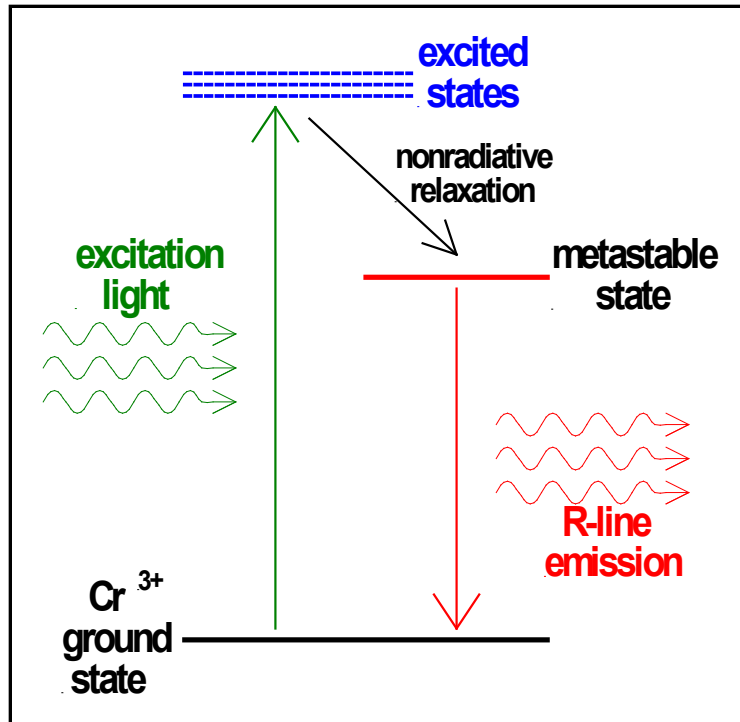
Crystalline sapphire doped with Cr

The first laser was made in May 1960 by Theodor Maiman. It was constructed with a cylindrical ruby crystal surrounded by a photographic flash lamp, all contained in a polished aluminum cylinder (on left). The flash lamp was used to excite the chromium ions in the sapphire (Al_2O_3) host crystal. As the **excited Cr(3+)** ions de-excite they emit light as individual photons. Then as these photons travel back and forth in the optical cavity between the mirror-coated ends on the crystal, they induce other excited Cr ions to de-excite causing "stimulated emission." Rapidly, all of the ions become de-excited and generate a lasing light pulse. The light beam is **coherent** in the sense that the photons all travel in the same **direction** and have the same **phase**.

Lasers

Optical Excitation in Ruby

Energy Diagram



A photon absorbed by a ruby crystal raises the energy of a Cr ion to an excited state. This state rapidly relaxes to the long-lived **metastable** state having a lifetime τ . After turning on an excitation source, the number of excited ions increases in time by

$$N(t) = N_0 [1 - \exp(-t/\tau)],$$

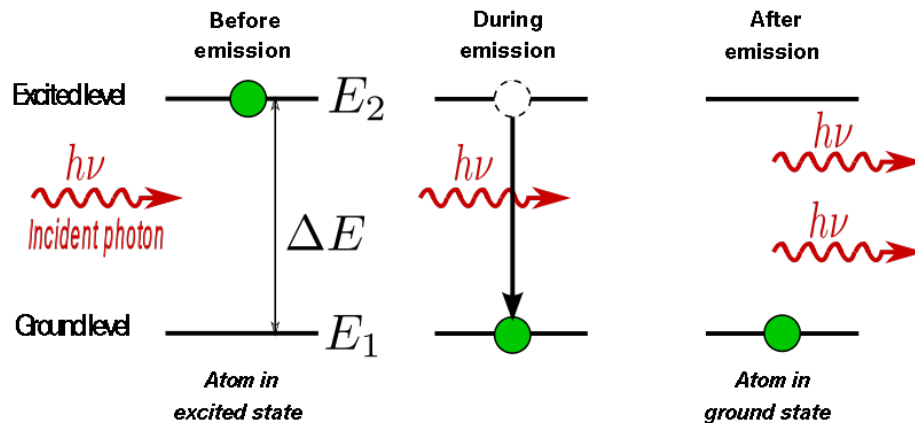
where N_0 is the number of ions illuminated. Before stimulated emission occurs, the excitation process comes to equilibrium when the rate of excitation equals the rate of decay ($1/\tau$) from the metastable state. This produces a **population inversion**. After the exciting light is removed, the number of excited Cr ions can decrease by **spontaneous emission** as

$$N(t) = N_0 \exp(-t/\tau).$$

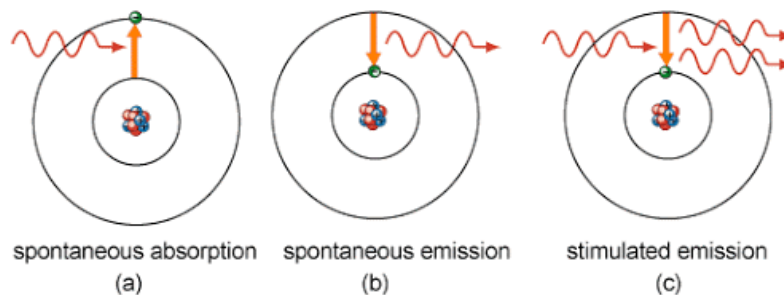
However, **stimulated emission** can make the excited Cr ions de-excite coherently (in phase and in the same direction).

Lasers

Stimulated Emission in a Laser



$$E_2 - E_1 = \Delta E = h\nu$$



Stimulated Emission

After a photon is produced by a de-excited Cr ion, it generates an oscillating electric field that is in resonance with an excited Cr ion. The excited Cr ion de-excites and emits a photon that is in the same direction and in phase with the original stimulating photon.

Exponential Growth

$$1 \rightarrow 2 \rightarrow 4 \rightarrow 8 \rightarrow 16 \rightarrow \dots$$

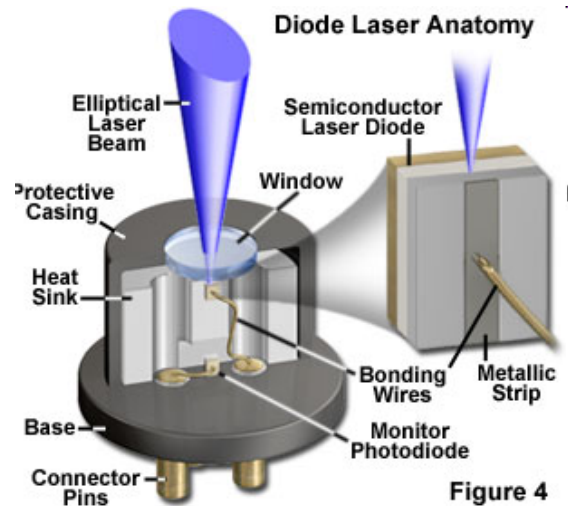
$$N(n) = N_0 \beta^n \quad n=1,2,3,\dots \quad \beta > 1.0$$

Semiconductor Diode Laser

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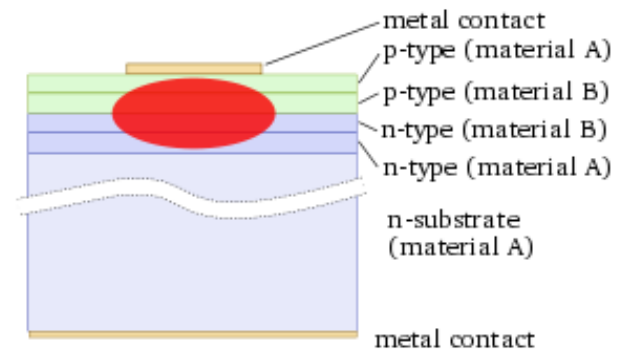
1970 - first CW IR LD

Visible LD Al-Ga-In-P



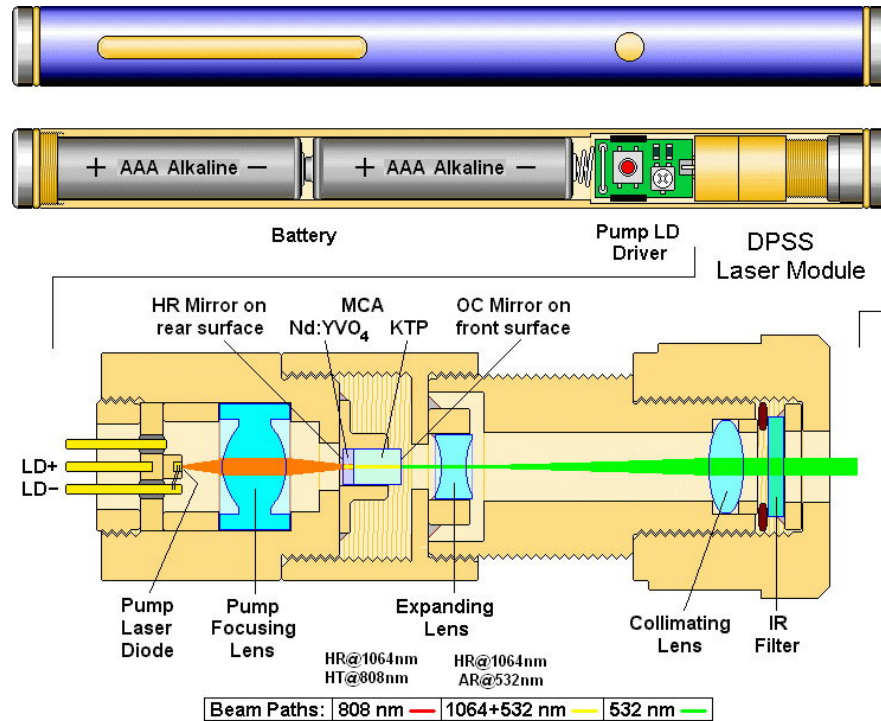
Aluminium gallium indium phosphide

AlGaInP



Green Laser Pointer

SKIP



0.9 μm



1.06 μm

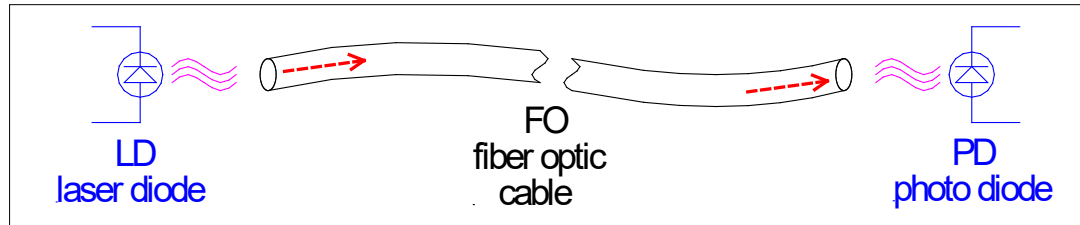


energy
doubled
to
0.53 μm

- (1) Infrared GaAs semiconductor diode laser, $\lambda = 900 \text{ nm}$
- (2) This pumps a Nd:YVO crystal to produce light at $\lambda = 1064 \text{ nm}$
- (3) Finally, this IR light is frequency-doubled in KTP to $\lambda = 532 \text{ nm}$

Optical Communications

Fiber Optics



Fiberoptic (FO) systems are used for long distance telephone and internet communications. A FO communication system contains:

- (1) a laser diode (LD) is electrically modulated (on/off) to encode digital information;
- (2) a FO cable for transmitting the light pulses; and
- (3) a photodiode to convert the light pulses back into electrical pulses.

Most long-haul FO systems use **picosecond** light pulses generated by a GaInAsP semiconductor laser diode operating at **1.55 μm wavelength** where the optical absorption in the glass FO is minimum.

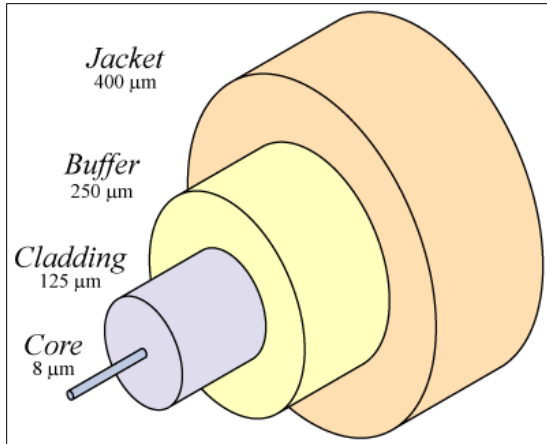
In a 10 GHz system the pulses are only a few cm in length. These pulses are transmitted through single-mode fibers of optical glass (SiO_2 =silica=quartz) having a **core diameter** of about **6-8 μm** .

At the receiving end of the optical fiber the pulses are detected by a high-speed InGaAs photodiode which converts the encoded light pulsed back into electrical pulses.

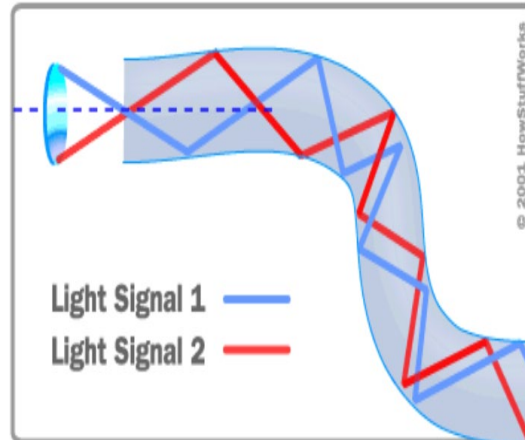
Optical Fibers

Fiber Optics

SKIP



FO cable where the light passes through the glass core region



Internal reflection inside the glass fiber

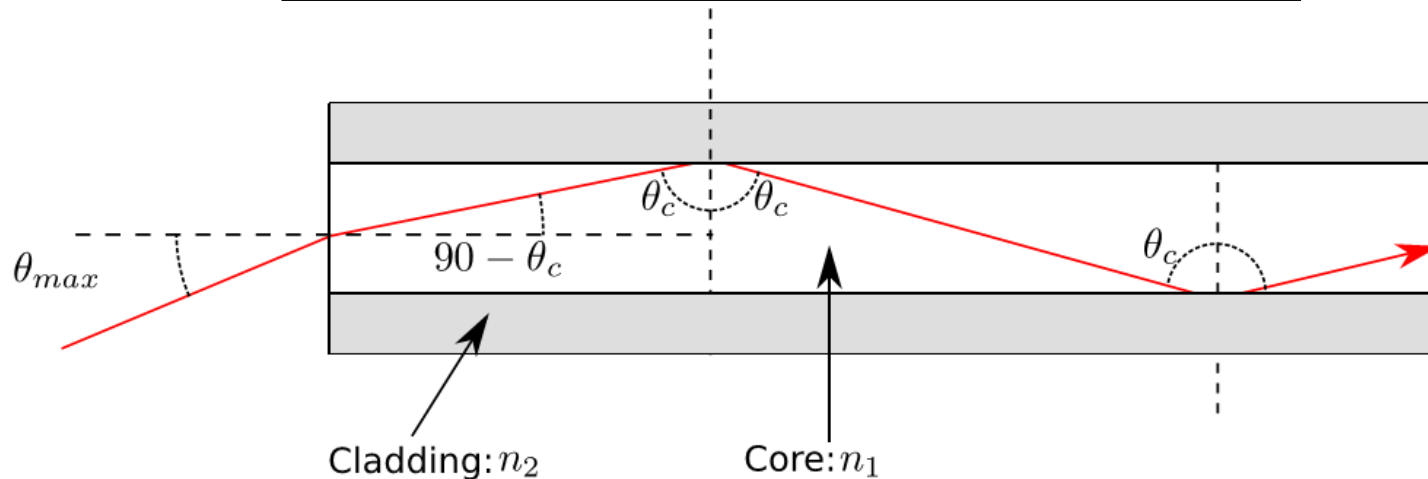


Single 8 μm FO replaces a cable with 100 copper wires

Optical Fibers

Optical fibers are light-pipes or light-waveguides

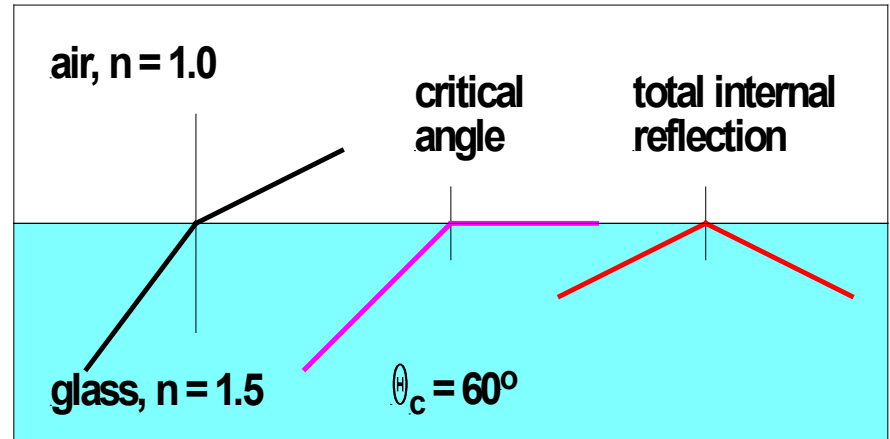
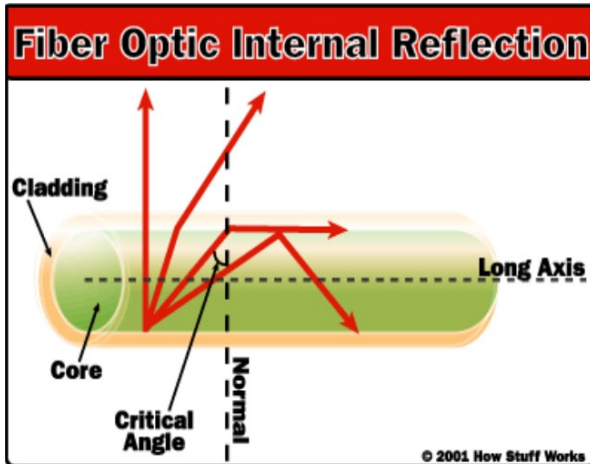
Once the light is inside, it stays inside



For light to exhibit **total internal reflection**, the cladding layer must have a smaller refractive index than the core region.

$$n_1 \text{ (core)} > n_2 \text{ (cladding)}$$

Total Internal Reflection



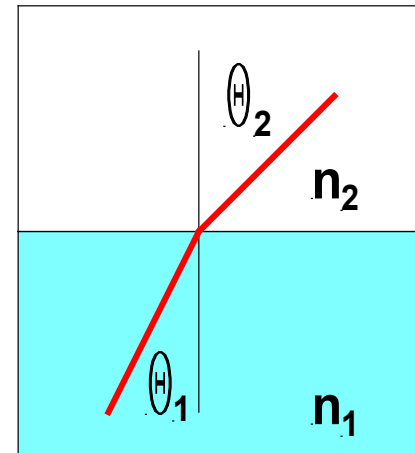
Snell's Law for Reflection at a Surface

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Set $\theta_2 = 90^\circ$, $n_2 = 1.0$ for air, $n_1 = 1.5$ for glass

$$\theta_1 = \arcsin(n_2/n_1) = 60^\circ$$

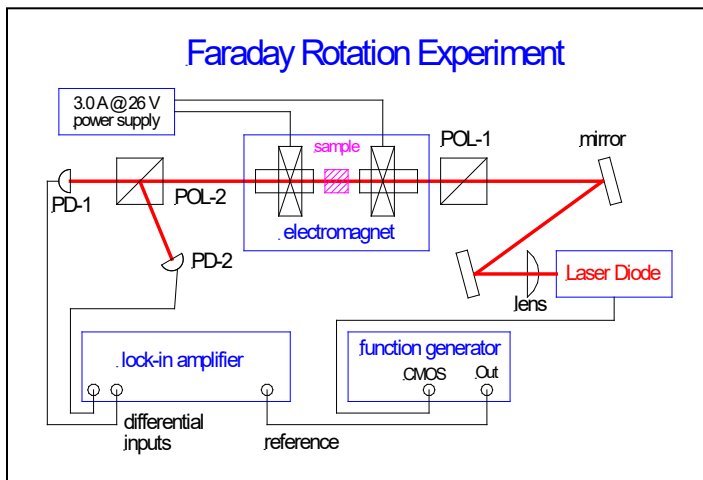
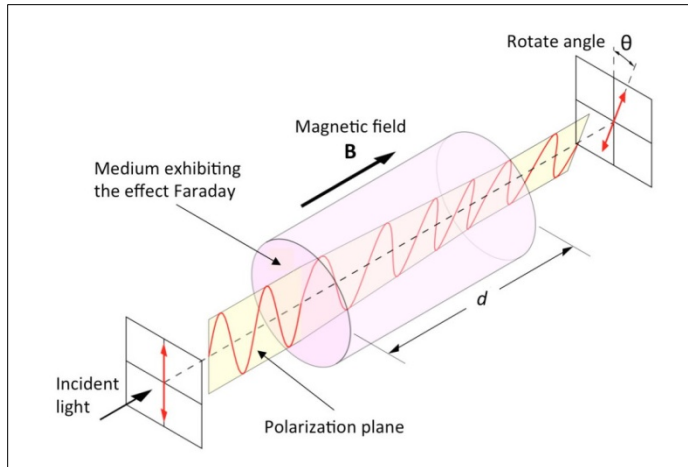
$$\theta_c = 60^\circ$$



Faraday Rotation

SKIP

Magnetic field rotates polarization



More than 150 years ago, Michael Faraday discovered that **linearly polarized** light traveling through a substance experiences a rotation when a magnetic field is applied to the material. The amount of rotation (θ) was found to be proportional to the magnitude of the magnetic field (B) and to the length of the sample (L),

$$\theta = V B L,$$

where the constant of proportionality (V) is called the Verdet constant.

A linearly polarized beam of light, one that has a unique electric field E -vector direction, can be decomposed into two circularly polarized beams of equal intensity. These right- and left-circularly polarized beams propagate simultaneously, but are independent of each other (orthogonal). An applied B -field causes the material to become *optically active* – producing different refractive indices for the two beams so that they travel at different phase velocities. Thus, when the two beams exit the material they have a different phase relationship, which is manifest in a rotation of the E -vector of the combined beams.

END