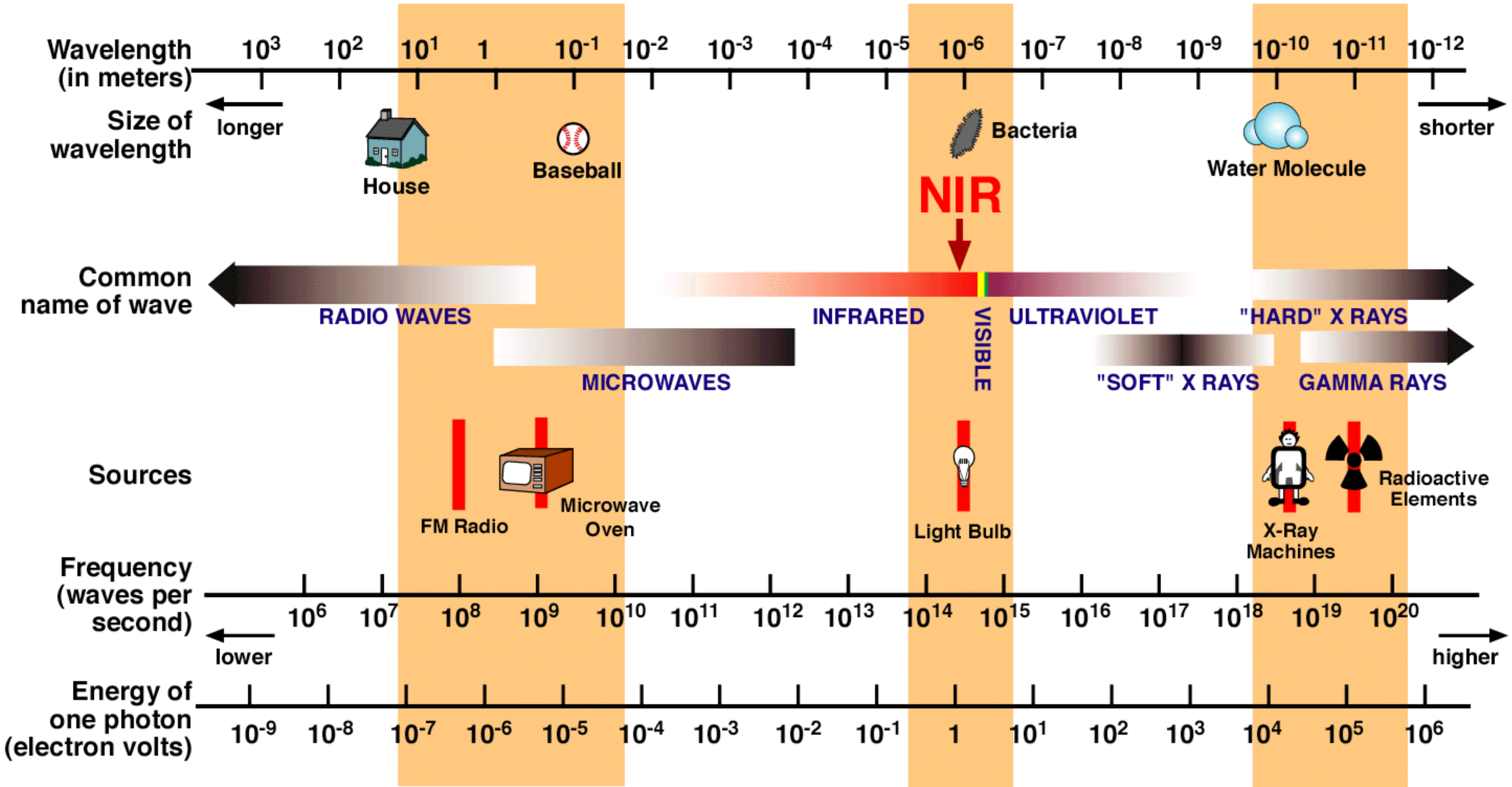
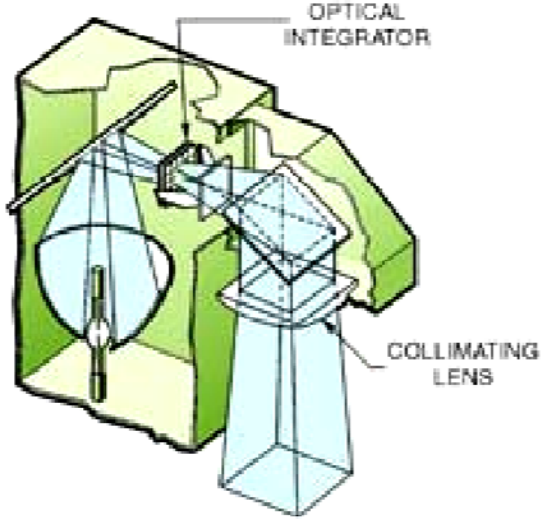
Light Sources, Detectors, and Irradiation Guidelines

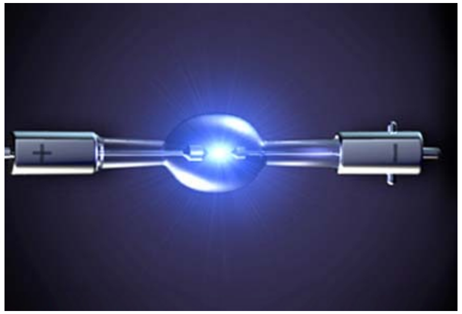
Introduction

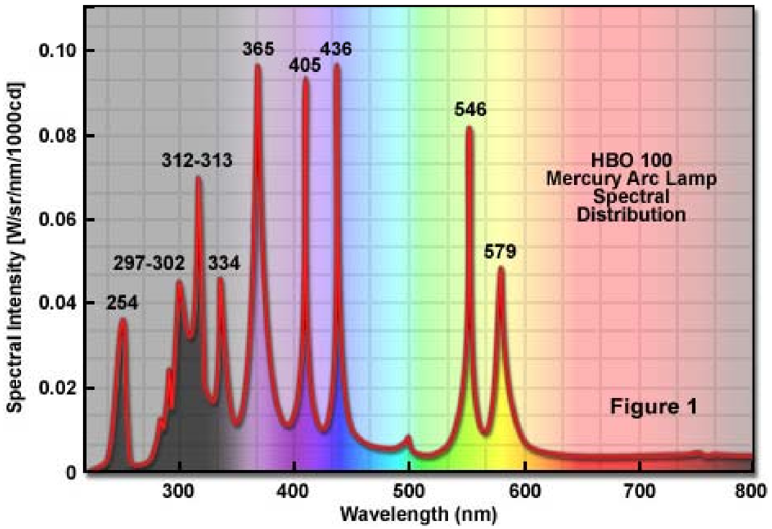


Non-laser Light Sources

- **High-Pressure Arc Lamps**
  - High intensity quasi-continuum spectra ranging from the ultraviolet to near-infrared.
  - A gas (typically xenon, mercury, or a mixture of these) in a quartz envelope with two tungsten electrodes.
  - A voltage ionizes the gas → a bright arc between the electrodes.
  - A few watts to several kilowatts.
  - Xenon arc lamp widely used in spectroscopy
    - smooth spectral profile between 250 and 700 nm.
    - Filters to choose wavelength
  - Isotropic source → omnidirectional.
  - Parabolic and ellipsoidal reflectors to collect and focus

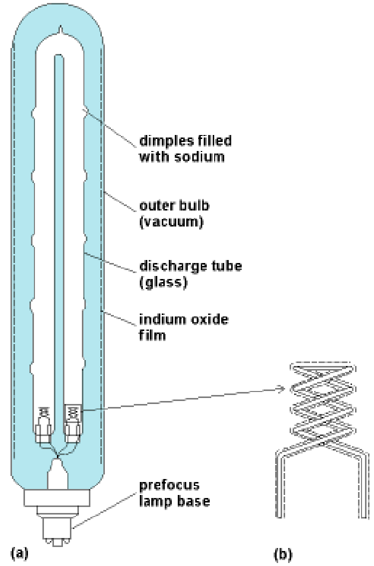


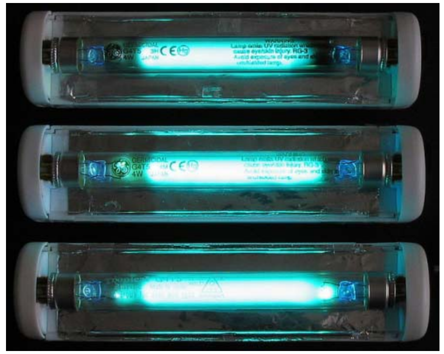




Non-laser Light Sources

- **Low-Pressure Vapor Lamps**
  - Gas discharge similar to high-pressure arc lamps
  - Less complex
  - High-intensity stable spectral lines (each elemental gas generates a known set of characteristic lines.)
    - For example, a low-pressure mercury lamp → a dominant peak at 253.7 nm as well as a prominent triplet at 365.0/365.5/366.3 nm.
  - Discrete lines
    - Simple filter type spectrometers
    - Calibration light sources.





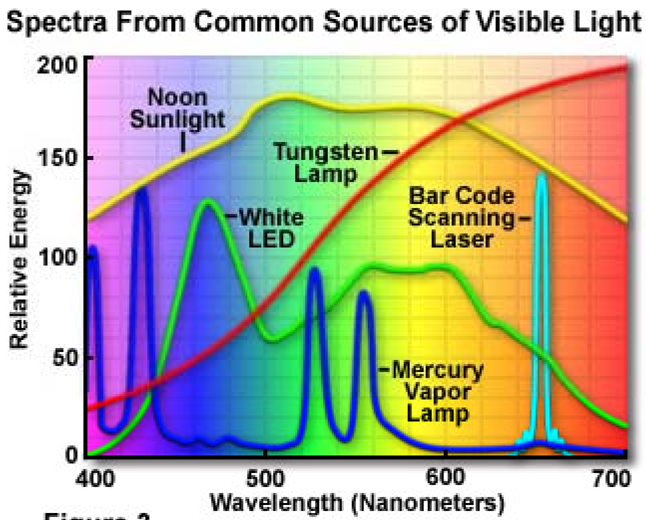
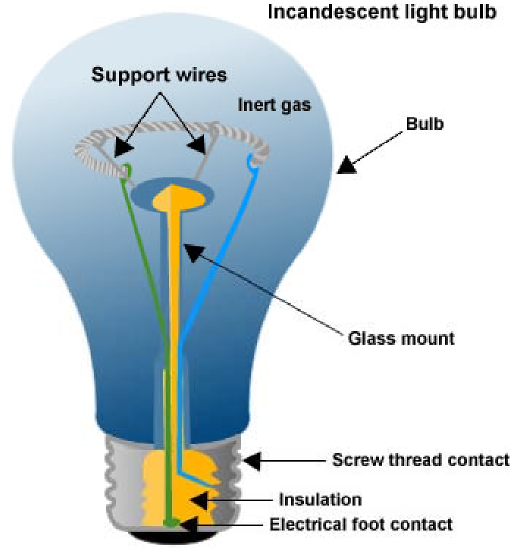


Figure 3

Non-laser Light Sources

- **Incandescent Lamps**
  - Generate light by heating a metal filament (typically tungsten.)
  - Inexpensive and very simple
  - Continuous blackbody radiation spectrum
    - Intensity calibration of various types of detectors including spectrometers.
  - However, ultraviolet output from these lamps is usually very low.



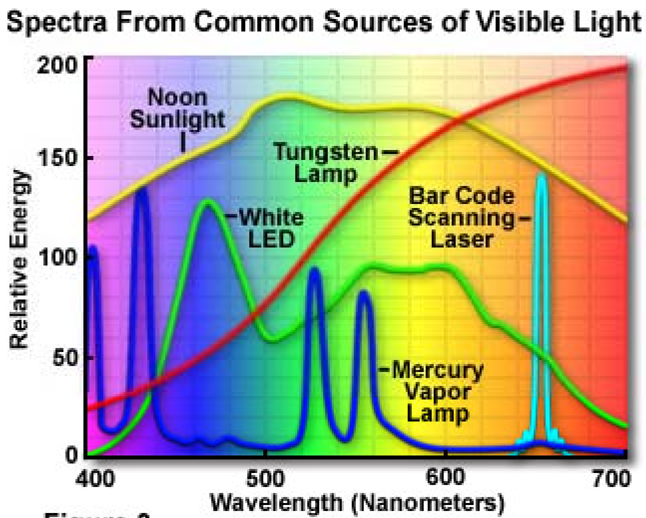
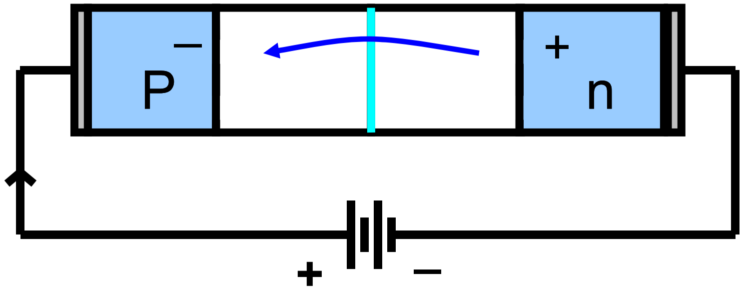
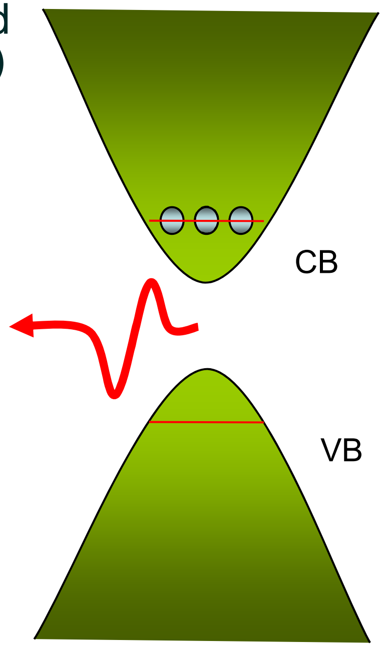


Figure 3

Non-laser Light Sources

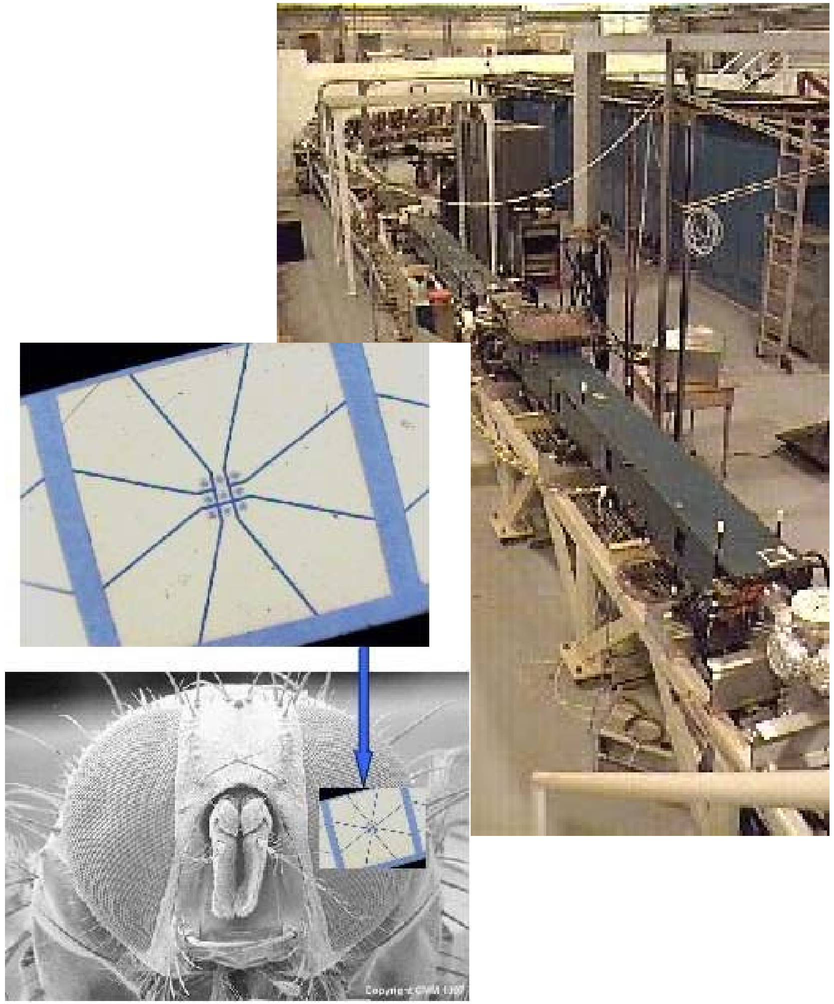
- **Light-Emitting Diodes**
  - Solid-state, semiconductor-based light sources
  - Electroluminescence when positive and negative charge carriers recombine at a semiconductor junction.
  - Close to monochromatic
  - Wavelength determined by the characteristic energy bandgap of the semiconductor or semiconductor alloy used.
  - Available wavelengths from the near-infrared (~1050 nm) to the ultraviolet (UV) (~250 nm) and expanding
  - Addition of phosphors and integration of multiple emitters in single devices → broadband and white-light LEDs
  - Output of LEDs can be modulated at high frequencies (>100 MHz)
  - Additional advantages
    - Compact size
    - Low level of heat generated
  - Lower output powers of incandescent lamps and arc lamps.





Lasers

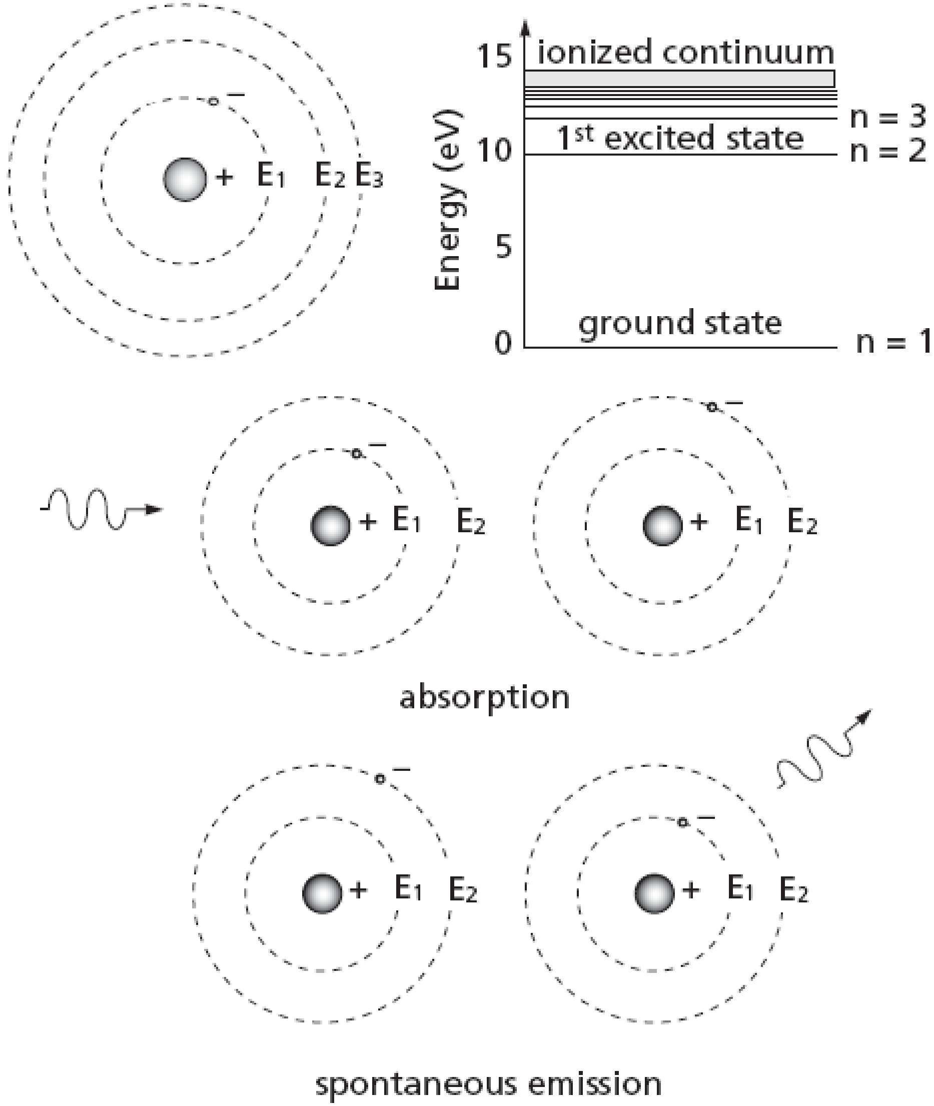
- **Characteristics**
  - High intensity, Monochromatic, Coherent, Collimated, Polarized
- **Einstein, 1917**
- **Basic operating principles → Charles Townes and Arthur Schalow, Bell Telephone Laboratories in 1958 (Nobel Prize)**
- **G. Gould → patent, 1970**
- **First actual laser**
  - Ruby crystal
  - Theodor Maiman, Hughes Research Laboratories, 1960T
- **Thousands of lasers have been invented**
  - Including the edible "Jello" laser
- **"laser" = (L)ight (A)mplification by (S)timulated (E)mission of (R)adiation.**



Lasers

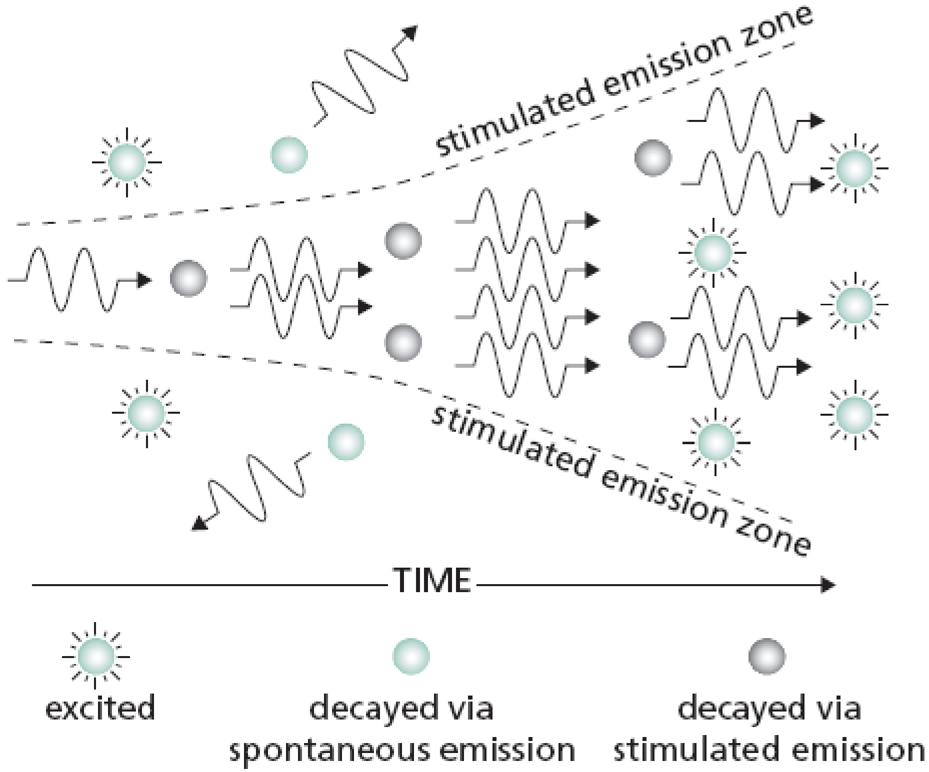
- **The Bohr atom**
  - Electrons orbit the nucleus
  - A limited number of fixed orbits are available to the electrons.
  - Under the right circumstances an electron
    - Can go from its ground state (lowest-energy orbit) to a higher (excited) state → absorb energy
    - Can decay from a higher state to a lower state → emit energy
    - but it cannot remain between these states.
  - The allowed energy states are called “quantum” states

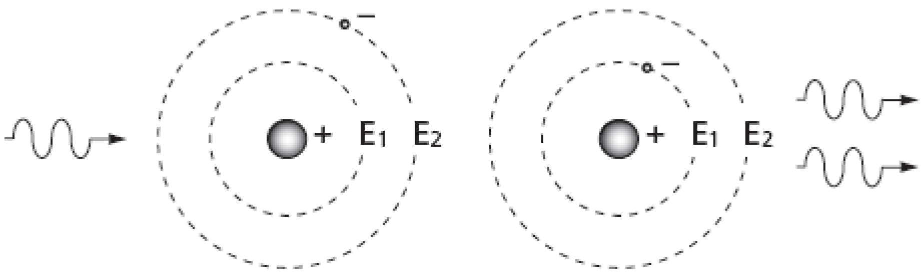
$$\lambda = \frac{hc}{\Delta E} \qquad \Delta E = E_m - E_n.$$



Lasers

- **Stimulated emission**
  - Photon happens with energy ~ E2-E1
  - Cause the electron to decay → photon is emitted at exactly the same wavelength, in exactly the same direction, and with exactly the same phase → amplification





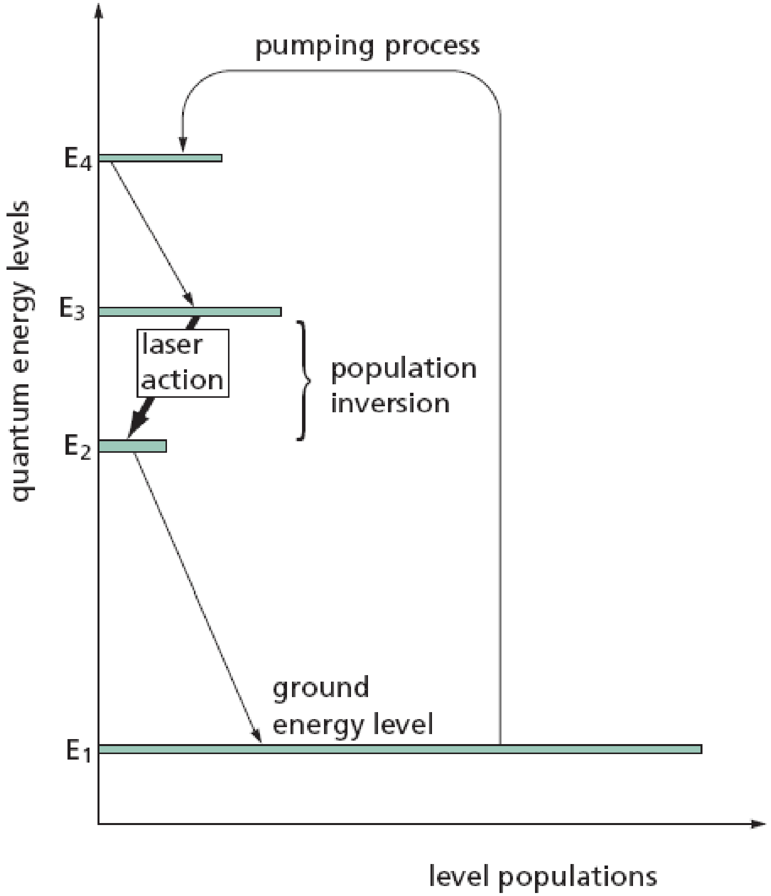
stimulated emission

Lasers

- **Population Inversion**
  - Probability for stimulated emission is quite small
  - Few atoms are usually in an excited state
  - Boltzmann's principle
    - A fundamental law of thermodynamics
    - When a collection of atoms is at thermal equilibrium, the relative population of any two energy levels is given by
  - Many more energy levels each has its own time constants for decay.
  - The electron is pumped (excited) into an upper level (e.g E4)
  - Decays to E3, then to E2, and finally to the ground state E1.
  - if the time it takes to decay from E3 to E2 is much longer than the time it takes to decay from E4 to E3 or E2 to E1, with continuous pumping process → "population inversion" between the E3 and E2 energy states
  - A photon entering the population will be amplified coherently.

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

$$\Delta N \equiv N_1 - N_2 = \left(1 - e^{-h\nu/kT}\right) N_1$$

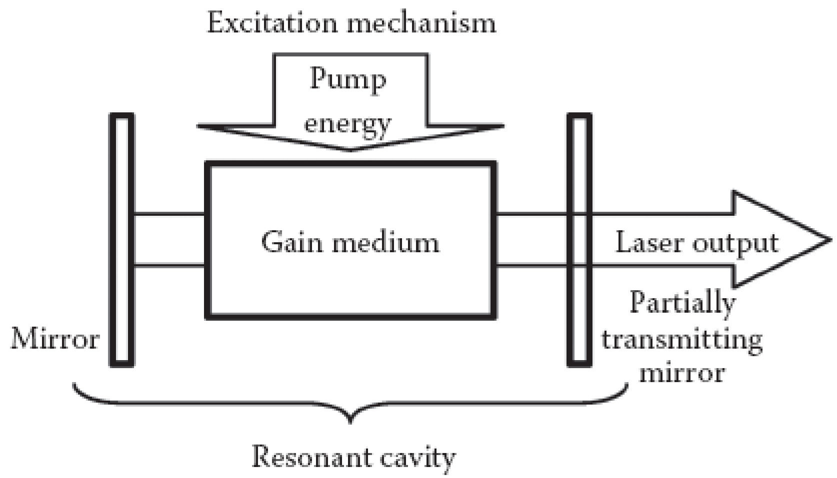


Lasers

• Laser Resonators

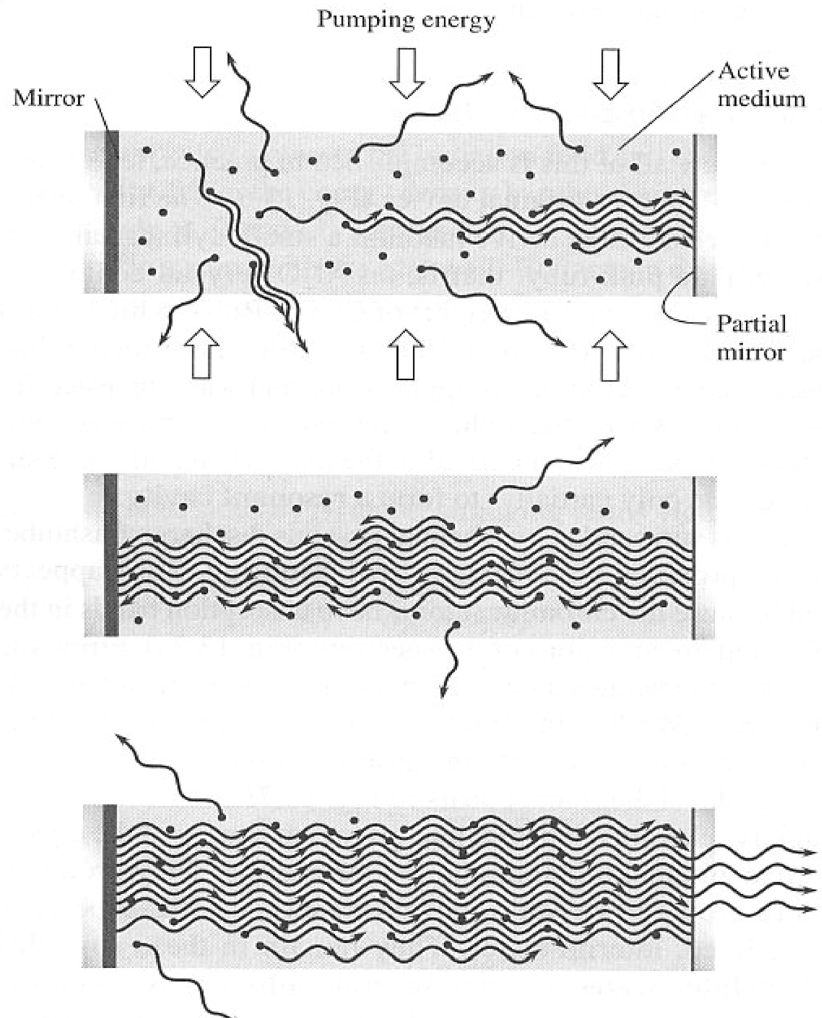
- Gain Medium
  - Where light amplification takes place.
  - Solid, liquid, or gas
  - The electronic energy-level structure of a material determines its emission wavelengths and bandwidths
    - **Gain (G) = $e^{\sigma(N_2-N_1)b}$**
    - b = length of active medium
    - s = transition cross-section
- Oscillation begins when:
  - gain in medium = losses of system
  - **$\rho_1\rho_2G^2 = 1$**
    - ρ = loss fraction
- Threshold population inversion:

$$(N_2 - N_1)_{th} = \frac{\ln(1/\rho_1\rho_2)}{2\sigma b}$$



Lasers

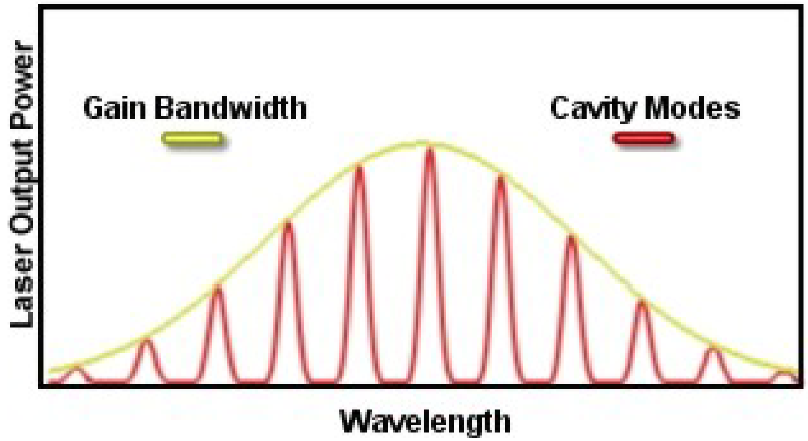
- **Suitable excitation (“pumping”)**
  - Excitation mechanism
  - Excitation may be through
    - Electrical pumping (injecting an electrical current into a semiconductor or gaseous gain medium)
    - Optical pumping (the gain medium absorbs light, either from a flash lamp or another laser) → convert it to a different wavelength for emission.
  - Energy stored by atoms in their excited state
  - Energy released via either spontaneous or stimulated emission as the atoms relax back to their original ground state



(b)

Lasers

- **Achieving Resonance**
  - Stimulated emission is coherent (all light waves in phase)
    - If the cavity is an integer multiple of the wavelength, each wave will be at the same phase when it reflects from one of the cavity mirrors (recall that a photon make many round trips in a laser cavity before it is emitted).
    - This allows constructive interference between all photons.
    - Want: $m\lambda = 2nL$
  - Other wavelengths will not be strongly amplified, and thus, will die out.
  - In practice, laser transitions have gain over a range of wavelengths – the gain bandwidth… so that resonance cavity lengths are not impossible to achieve.



Laser cavity:
$L = m\lambda/2n$

Estimate amplification factor:
$Amp = (1+Gain)^L$

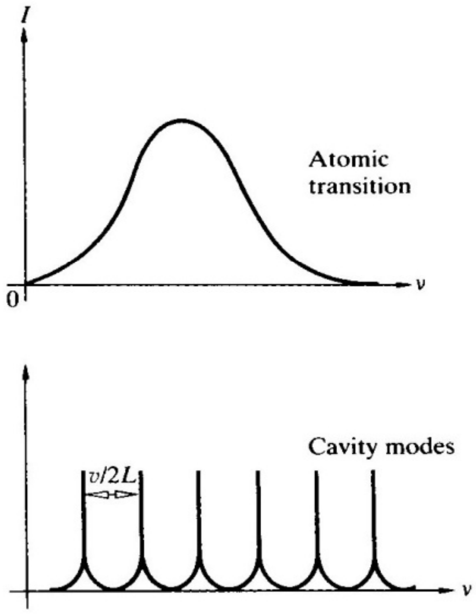
Longitudinal Modes

- A longitudinal mode of a resonant cavity is a particular standing wave pattern formed by waves confined in the cavity.
- The longitudinal modes correspond to the wavelengths of the wave which are reinforced by constructive interference

$$L = m\frac{\lambda}{2n} \qquad f = m\frac{c}{2nL}$$

$$f_{m+1} - f_m = \frac{c}{2nL}$$

- Actual f is the convolution of the transition bandwidth and the f of the longitudinal modes.



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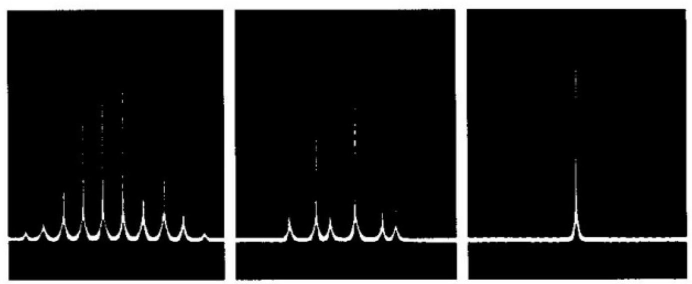
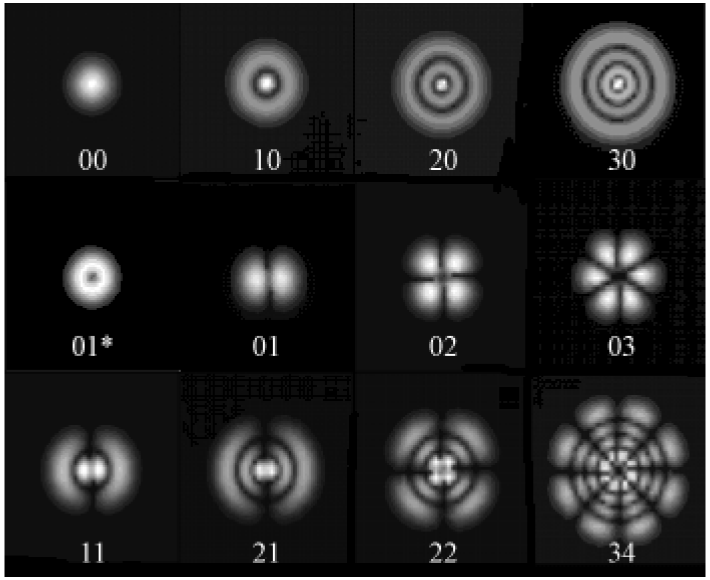
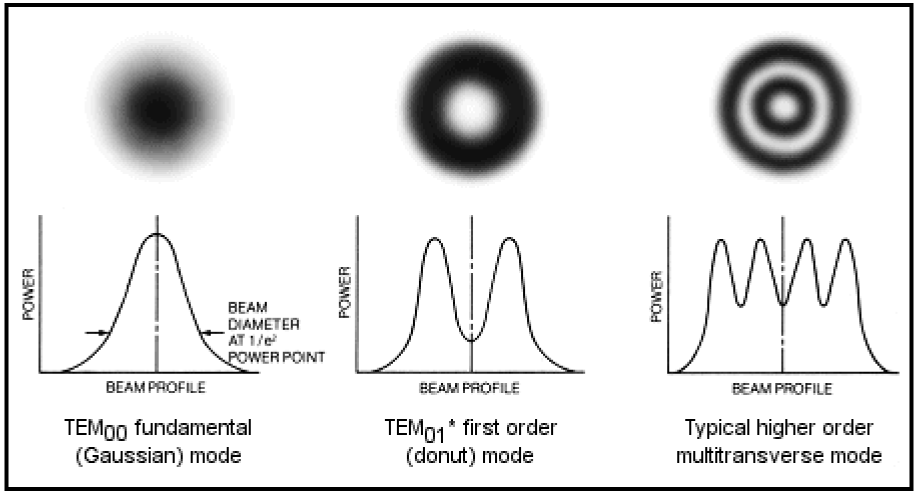


Transverse Modes

- Transverse modes determine the pattern of intensity distribution across the width of the beam.
- TEM_{00} has a Gaussian distribution and is the most commonly used.
- The resonator geometry of many commercial lasers is designed to obtain "single transverse mode" operation.



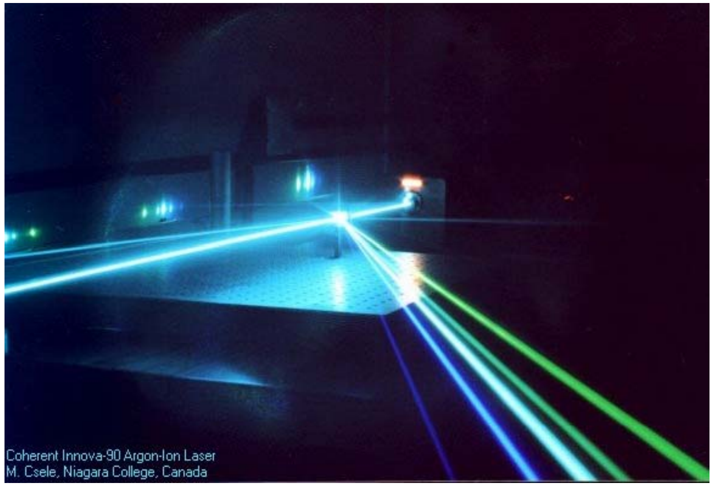


$$I(\mathrm{r}) = \frac{2\mathrm{P}}{\pi \mathrm{d}^2} e^{-2r^2/d^2}$$

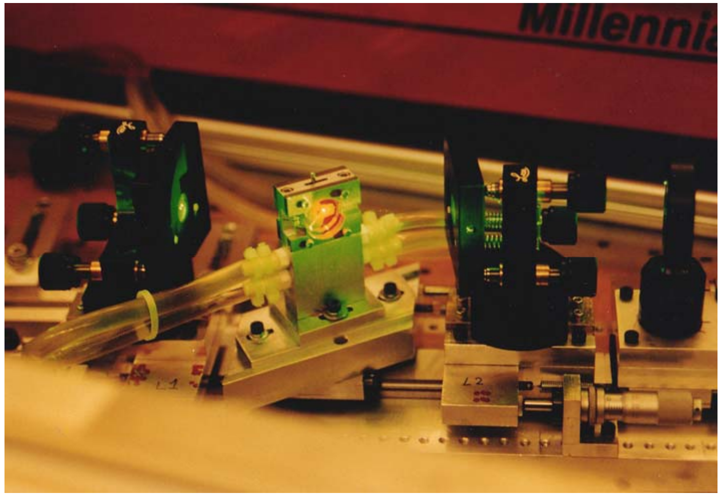
www.wikipedia.org
www.lexellaser.com

Gain Medium Materials

- **Gas**
  - Have been the “workhorse” for many years
  - Narrow linewidth properties have allowed tremendous advances in physics and engineering
  - Are declining as solid state and semiconductor lasers become cheaper, more powerful, and more versatile

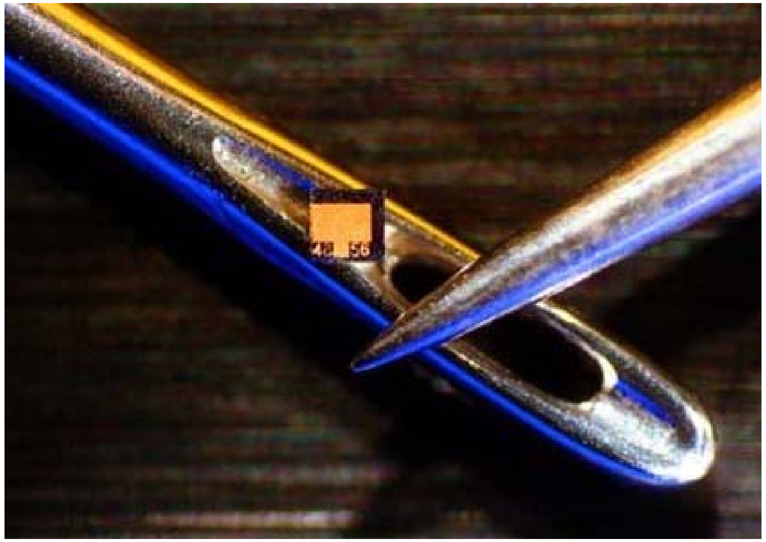


- **Solid State (Crystal)**
  - Generally a few milimeters in size
  - Can generate high powers
  - Susceptible to non-linear effects
  - First visible light laser was a ruby laser
  - Broad gain bandwidth, capable of narrow linewidths, VERY versatile!

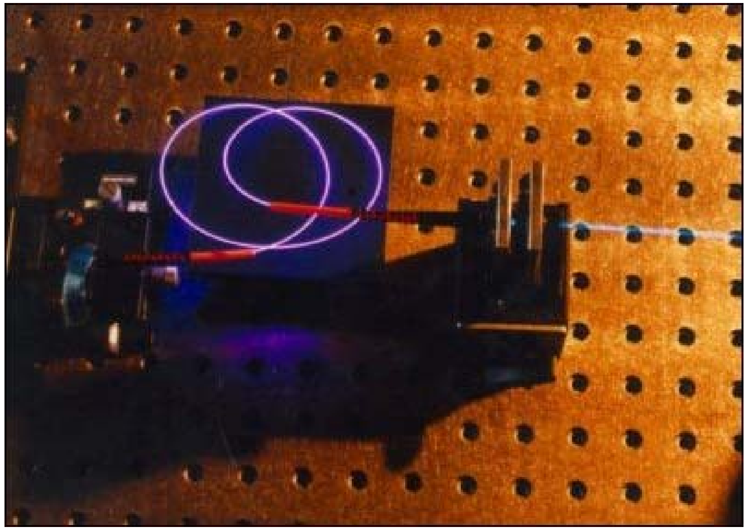


Gain Medium Materials

- **Semiconductor diodes**
  - Can be on the order of a hundred microns in size
  - Generally produce low powers, however there are exceptions; can be “stacked” in arrays to produce high powers; used as “pump” for many solid-state lasers
  - Narrow gain bandwidth
  - Inexpensive compared to other materials

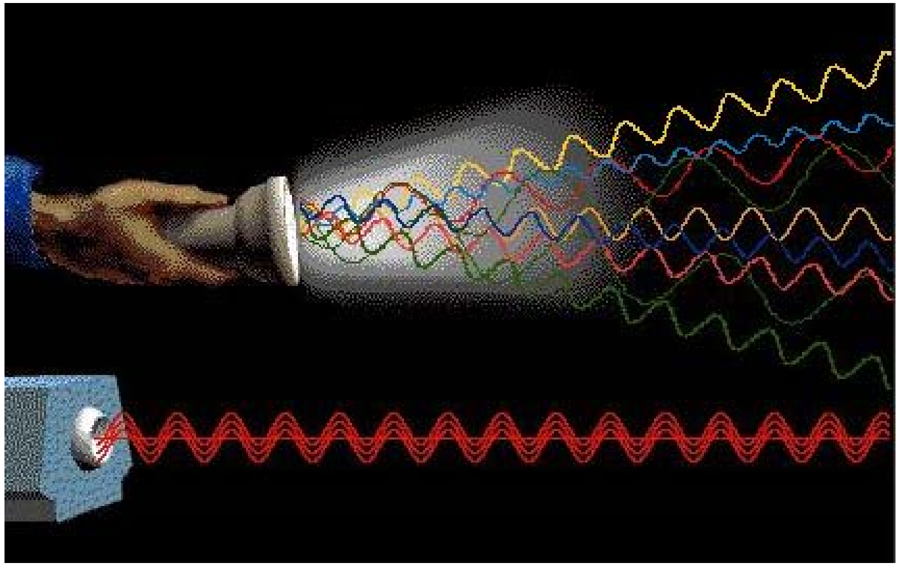


- **Fiber Lasers**
  - Can have broad bandwidths and high powers, but are limited to fiber-optic wavelengths and susceptible to nonlinear effects
  - Remarkably stable, but not versatile
  - Can demonstrate narrow linewidths
  - Compact size



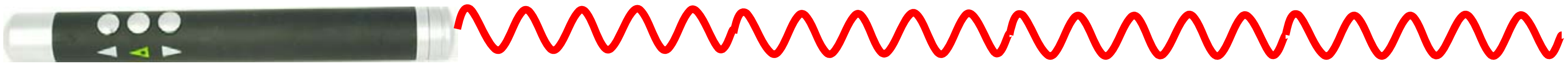
Lasers

- **Laser light characteristics**
  - High intensity
  - Monochromatic
  - Coherent
  - Collimated
  - Polarized



Lasers

- **Continuous Wave**
  - Output power is constant with no temporal "breaks"
  - Mathematically characterized by a single frequency



- **Pulsed**
  - Output power comes in short bursts; short pulses can have enormous peak intensities but generally have low average power
  - Mathematically characterized by a coherent superposition of many frequencies

- **Pulses longer than a few microseconds (10^{-6} s) are easily produced by directly modulating the CW output of a laser**
  - mechanical, electro-optic, or acousto-optic shutter mechanisms
- **Shorter pulse durations, in the order of nanoseconds (10^{-9} s) or less, require more specialized laser designs.**
  - Q-switching
  - Modelocking

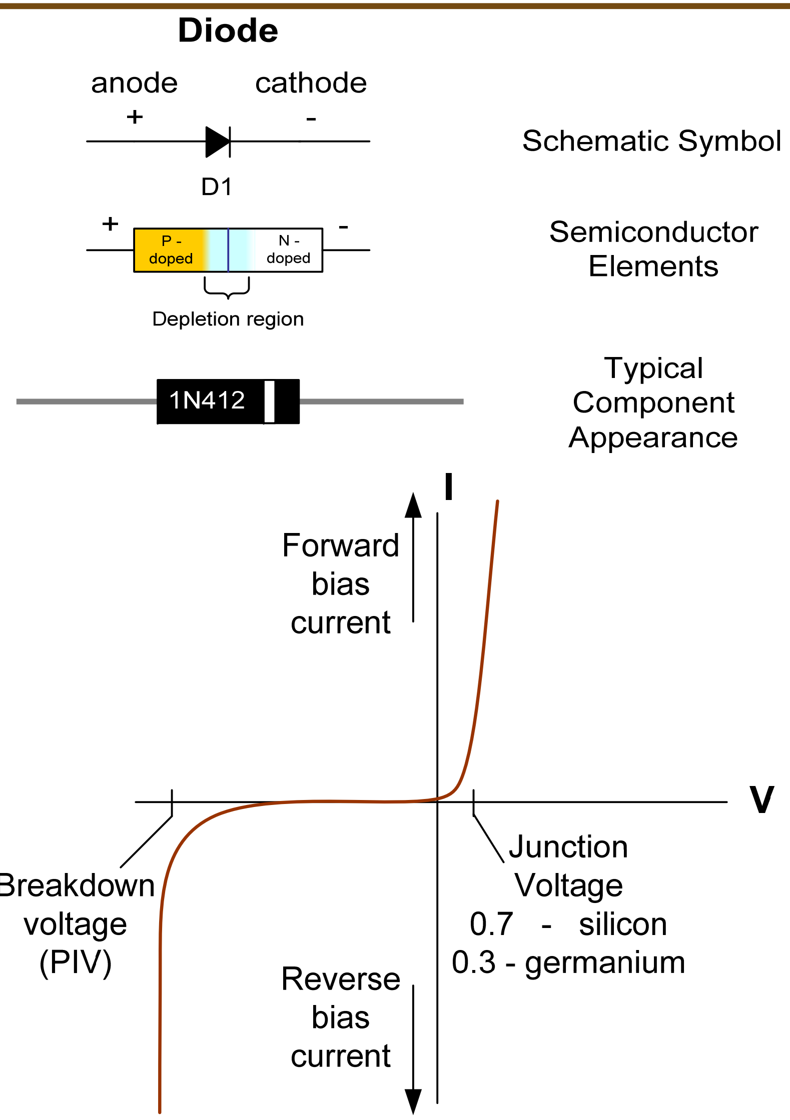
Lasers

- **Q-switching**
  - Light pulses with extremely high (gigawatt) peak power, much higher than CW
  - Lower pulse repetition rates than mode-locking
  - Method
  - Variable attenuator inside the laser's optical resonator
  - Laser medium pumped while the Q-switch is set to prevent feedback of light
  - Population inversion but no lasing yet
  - Energy stored in the gain medium increases as the medium is pumped → gain saturated
  - Q-switch device quickly changed from low to high Q → feedback
  - Net result: a short pulse of light (“giant pulse”) which may have very high peak intensity.
- **Mode-locking**
  - Mode-locking produces of extremely short duration, on the order of picoseconds (10^{-12} s) or femtoseconds (10^{-15} s).
  - Induce a fixed phase relationship between the modes of the laser's resonant cavity. Very large bandwidth.
  - Interference between these modes causes the laser light to be produced as a train of pulses.

Photodiodes

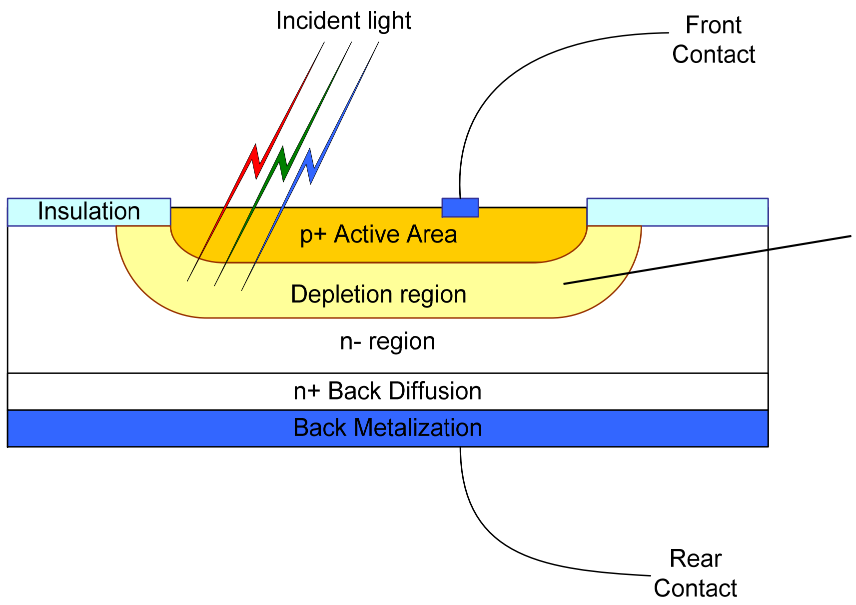
Diode devices

- **Check valve behavior**
  - Diffusion at the PN junction of P into N and N into P causes a depleted non-conductive region
  - Depletion is enhanced by reverse bias
  - Depletion is broken down by forward bias
- **When forward biased**
  - High current flow junction voltage
- **When reverse biased**
  - Very low current flow unless above peak inverse voltage (PIV) (damaging to rectifying diodes, OK for zeners)



Photodiodes

- **Photodiode structure**

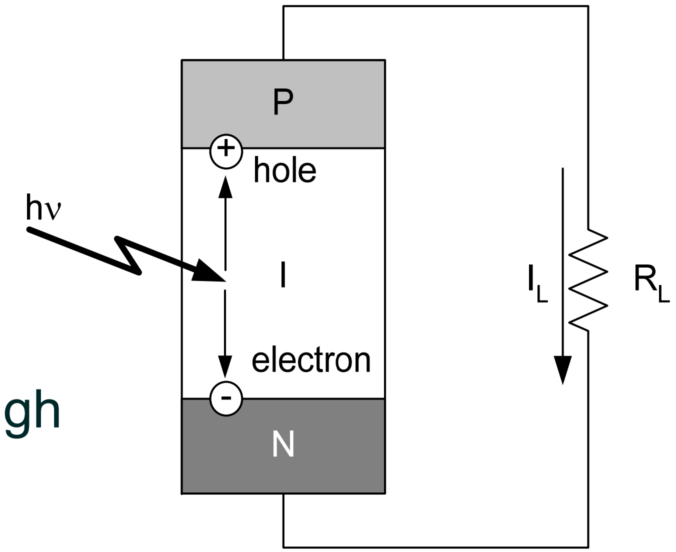


Absorbtion in the depletion layer causses current to flow across the photodiode and if the diode is reverse biased considerable current flow will be induced

Photodiodes

Photodiode fundamentals

- **Based on PN or PIN junction diode**
  - photon absorption in the depletion region induces current flow
  - Depletion layer must be exposed optically to source light and thick enough to interact with the light

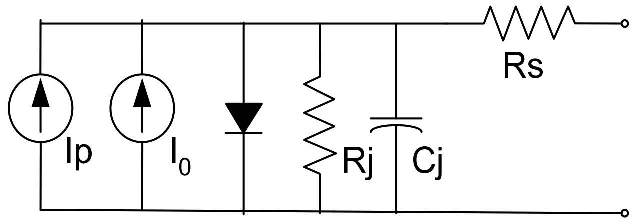


- **Spectral sensitivity**

Material	Band gap (eV)	Spectral sensitivity
silicon (Si)	1.12	250 to 1100 nm
indium arsenide (InGaAs)	~0.35	1000 to 2200 nm
Germanium (Ge)	.67	900 to 1600 nm

Photodiodes

Photodiode characteristics



- **Circuit model**
  - I_0 Dark current (thermal)
  - I_p Photon flux related current
- **Noise characterization**
  - Shot noise (signal current related)
    - q = 1.602 x 10–19 coulombs
    - I = bias (or signal) current (A)
    - i_s = noise current (A rms)
  - Johnson noise (Temperature related)
    - k = Boltzman's constant = 1.38 x 10–23 J/K
    - T = temperature (°K)
    - B = noise bandwidth (Hz)
    - R = feedback resistor (W)
    - e_{OUT} = noise voltage (Vrms)

$$i_s = \sqrt{2qi}$$

$$e_{out} = \sqrt{4kTBR}$$

Photodiodes

For the photovoltaic mode

- I = thermal component + photon flux related current

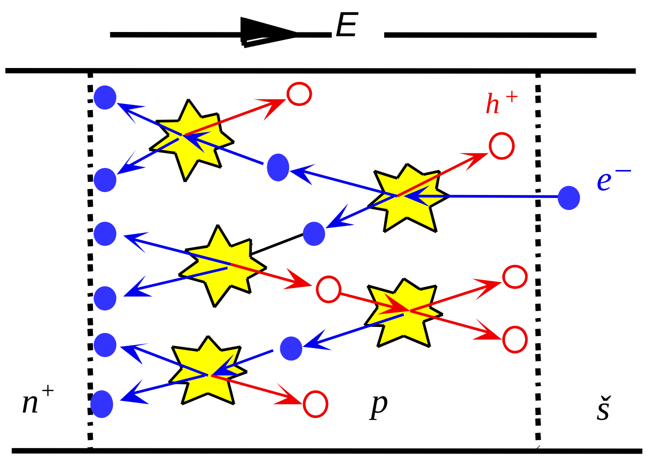
$$I = I_0\left(e^{\frac{eV}{kT}} - 1\right) - \frac{\eta eP}{hf}$$

- where

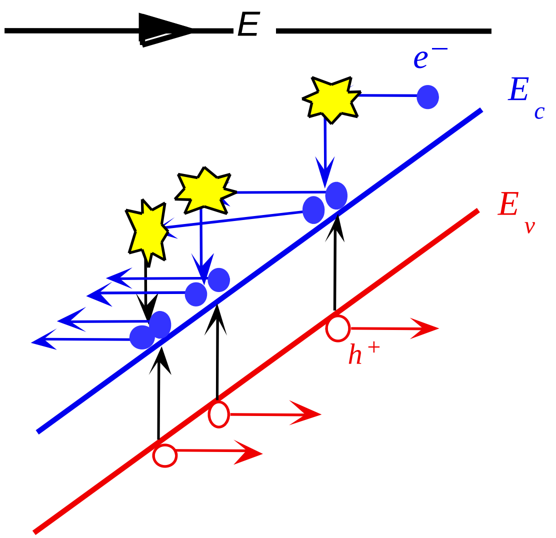
I = photodiode current
V = photodiode voltage
I_0 = reverse saturation current of diode
e = electron charge
k = Boltzman's constant
T = temperature (K)
f = frequency of light
h = Plank's constant
P = optical power
η = probability that hv will elevate an electron across the band gap

Avalanche Photodiodes

- **Designed for operation at a high reverse bias (usually 50–300 V)**
  - Reverse bias → high electric field inside the photodiode
  - Accelerates the photo-generated charges
  - Collision of these accelerated (primary) charges with the crystal lattice leads to ionization, which in turn generates secondary electron-hole pairs → chain reaction (avalanche process) → additional charge by further ionization processes.
- **Gain or multiplication factor of the APD**
  - Depends on the reverse bias
  - 50 to several 100 times
- **High gain factors → useful when measuring small optical signals not detected with conventional photodiodes**



Avalanche region

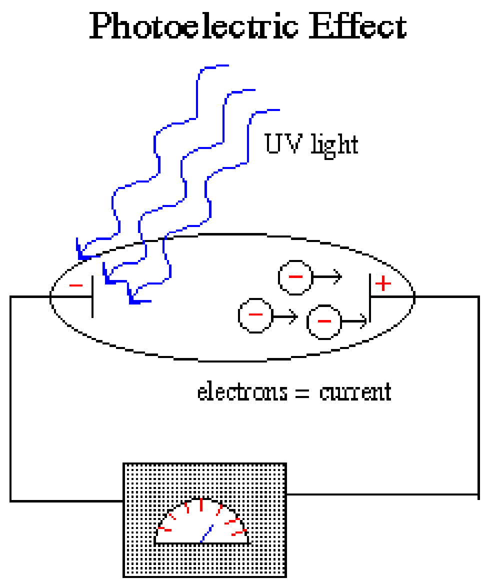


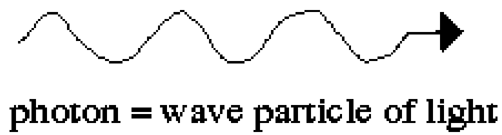
Avalanche Photodiodes

- **Advantage**
  - Increased sensitivity
- **Limitations:**
  - operation close to the breakdown voltage results in nonlinear response
  - the active area of APDs is very limited in size since defects in the crystal structure and strain must be avoided to achieve the high breakdown voltages required for an efficient avalanche process
  - the noise level is often higher than in conventional photodiodes since amplification noise constitutes an additional source of noise
  - the readout circuit is generally more complex due to the need for a high operating voltage.

Photomultiplier Tubes

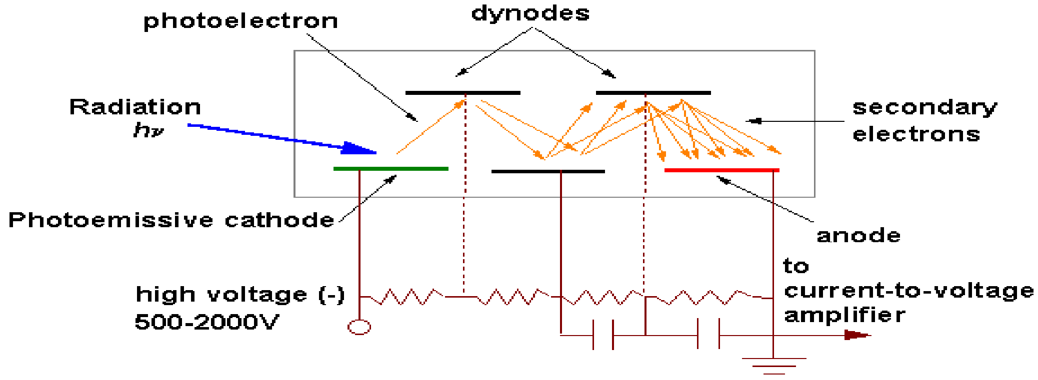
- **Photomultiplier Tubes (PMTS**
  - light detectors for low intensity applications
    - E.g. fluorescence spectroscopy.
  - High internal gain → very sensitive
- **Photoelectric effect.**
  - The effect was discovered by Heinrich Hertz in 1887 and explained by Albert Einstein in 1905.
  - Explanation
    - Light is composed of discrete particles of energy, or quanta, called PHOTONS.
    - When photons with enough energy strike the photocathode, they liberate electrons that have a kinetic energy equal to the energy of the photons less the “work function” (the energy required to free the electrons from a particular material).
  - Einstein received the Nobel Prize for his 1905 paper explaining the photoelectric effect.
  - What were the other two famous Einstein papers from 1905?
    - Theory of special relativity
    - Explanation of Brownian motion





Photomultiplier Tubes

- **Operation**
  - Evacuated glass enclosure
  - Photocathode
    - Photons strikes the cathode and emits electrons due to the photoelectric effect (very small signal)
  - A series of dynodes
    - Electrons are accelerated towards a series of additional electrodes called dynodes.
    - Additional electrons are generated at each dynode.
    - Cascading effect → 10^5 to 10^7 electrons for each photon hitting the first cathode
      - Depends on the number of dynodes and the accelerating voltage.
  - Anode
    - Collects the amplified signal where it can be measured.



- **Vacuum inside tube body**
  - Purpose -- minimize collisions of electrons with gas molecules during transit
  - Requires strong tube body
    - Pins for electrical connections pierce through glass at bottom of tube (leak-tight)
  - Damage to tube by helium or hydrogen
    - "Small" gas molecules can leak into tube, even through glass

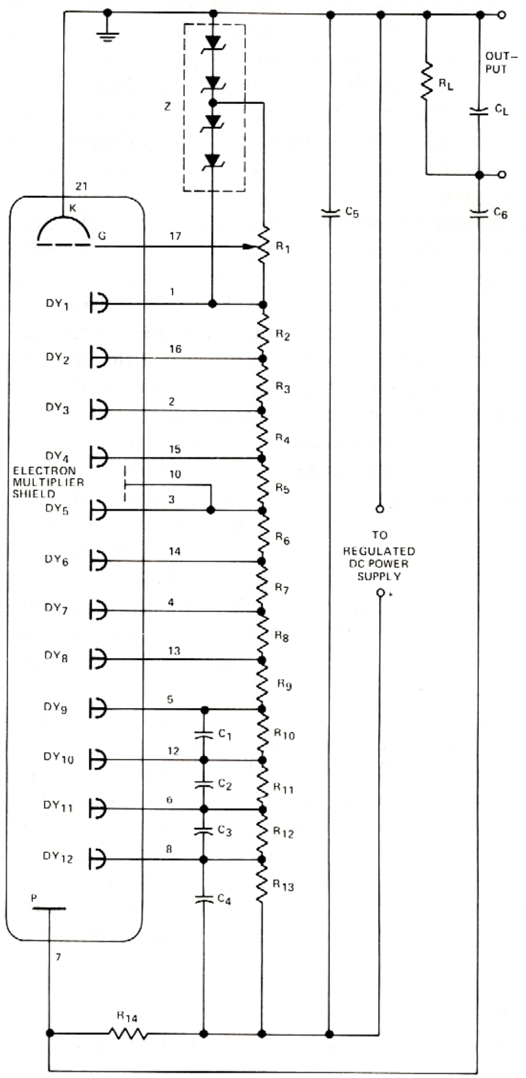
Photomultiplier Tubes

- **Photocathode**
  - Photocathode composition
    - Semiconductor material made of antimony (Sb) and one or more alkalai metals (Cs, Na, K)
    - Thin, so ejected electrons can escape
  - Definition of photocathode quantum efficiency, h(l)

$$\eta(\lambda) = \frac{\text{Number of photoelectrons released}}{\text{Number of incident photons (l) on cathode}}$$

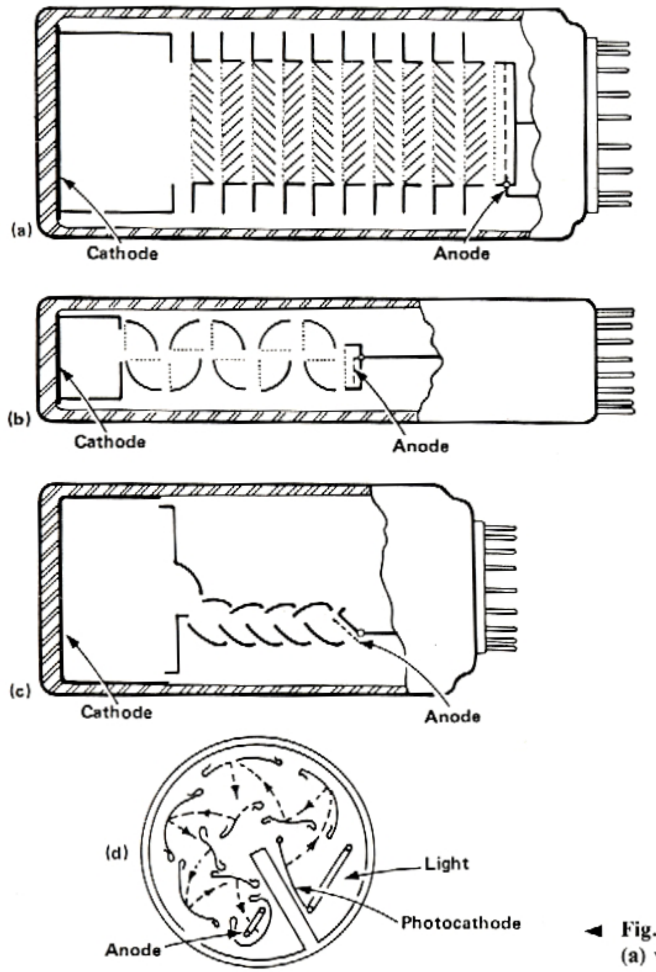
    - Typical photocathode quantum efficiency is 10 - 30%
  - Photocathode response spectrum
    - Need for matching incident light spectrum with photocathode response spectrum
- **The dynode chain**
  - High voltage applied to dynodes creates electric fields which guide electrons between from stage to stage
  - Purpose -- provide an electric field between photocathode and first dynode successive dynodes to accelerate electrons from stage to stage
  - About 100 V voltage difference needed between stages
  - Chain of resistors forms voltage divider to split up high voltage into small steps
  - Capacitors store readily-available charge for electron multiplication
  - Typical base draws 1 - 2 milliamperes of current
  - Composition of dynodes
    - Ag - Mg
    - Cu - Be
    - Cs - Sb

Deposited in thin layer on conducting support



Photomultiplier Tubes

- **Photomultiplier Tube Gain**
  - δ = average number of electrons generated at each dynode stage
    - Typically, δ = 4 , but this depends on dynode material and the voltage difference between dynodes
  - n = number of multiplication stages
  - Photomultiplier tube **gain = δ^n**
    - For n = 10 stages and δ = 4 , gain = $4^{10} = 1x10^7$
    - This means that one electron emitted from the photocathode (these are called "photoelectrons") yields 10^7 electrons at the signal output



◄ Fig.
(a)

Image Sensors

CCD and CMOS

- Both CCD and CMOS sensors work by employing photosensitive circuitry that reacts to light and stores the analog signals as digital data, namely an image.
- They both use different methods to achieve this.

- **CCD**
  - Charge Coupled Device
- **CMOS**
  - Complementary Metal Oxide Semiconductor
- **Array of Diodes (photosites) that produce a voltage:**
  - Linearly Proportional to the AMOUNT incident light.
  - Non-linearly Depending on the WAVELENGTH
- **Built out of layers of Silicone**
  - Silicone is sensitive to light
  - Layers add functionality – different layers perform different functions. (called 'die')

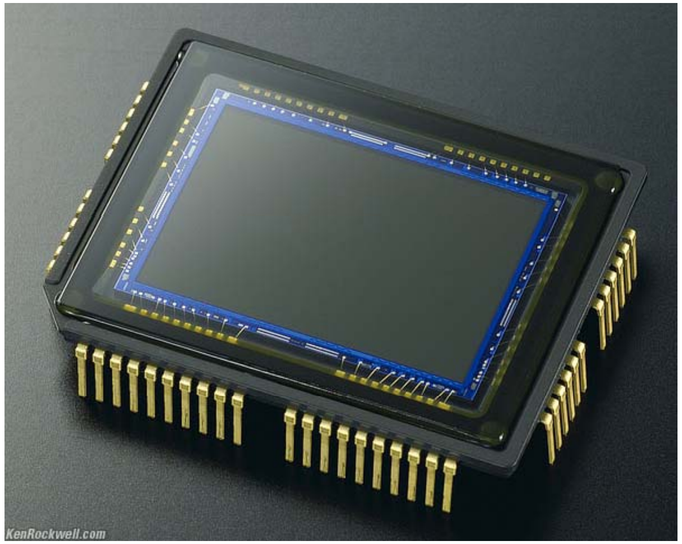


Image Sensors

- **CCD (Charged-Coupled Device)**
  - Photosensitive analog device
    - Records light as a small electrical charge in each of its pixels or cells. (In essence a CCD is an collection of CCD cells.)
  - Light strikes a CCD → cells acquire electrical charge proportional to how much light has hit the particular CCD cell
  - CCD captured signal requires additional circuitry
    - Convert the analog light data into a readable digital signal.
    - Mainly layers of capacitors called "Stages" → Transport the analog signal to an array of flip-flops which store the data
    - Each CCD cell transfers its charge to its neighboring cell and then off to external circuitry.
    - Charge is then read off by an analog-to-digital converter
      - Integer on a range of 0 to 4095 for most modern DSLR cameras.
      - Lower ranges exist, such as 0-255, for lower quality cameras.
    - All controlled by a clock signal.
    - This is the definition of an Analog Shift Register.

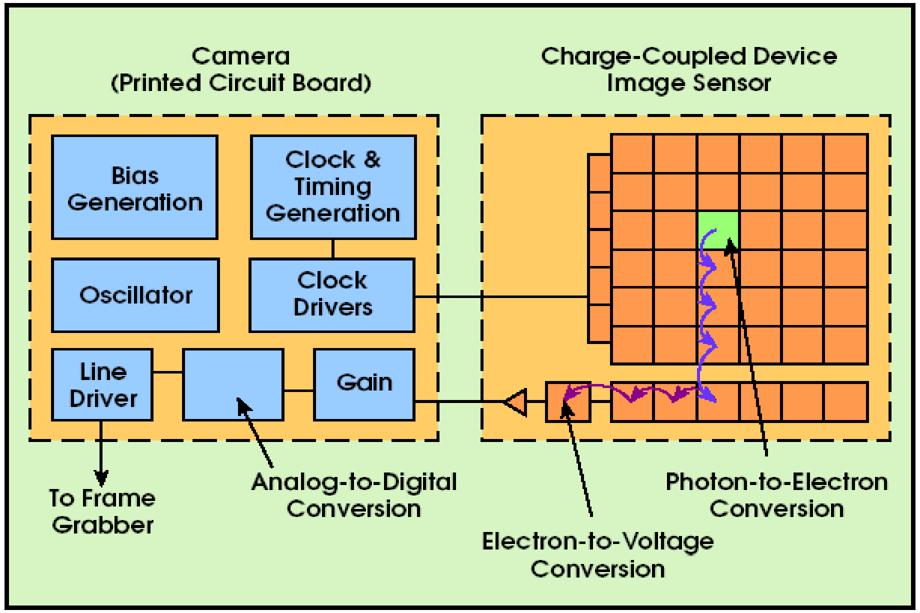


Image Sensors

- **How CCDs Record Color**
  - Each CCD cell in the CCD array produces a single value independent of color.
  - Color images
    - CCD cells organized in groups of four cells (making one pixel)
    - A Bayer Filter is placed on top of the group
      - only red light hits one of the four cells, blue light hits another and green light hits the remaining two.
    - Reasoning behind the two green cells
      - The human eye is more sensitive to green light
      - It is more convenient to use a 4 pixel filter than a 3 pixel filter (harder to implement)
      - Can be compensated after image capture with something called white balance.

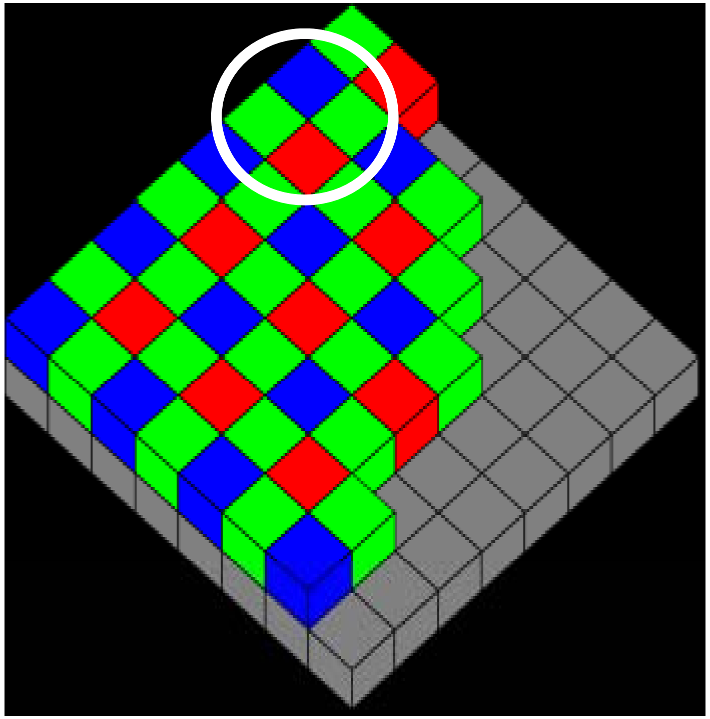
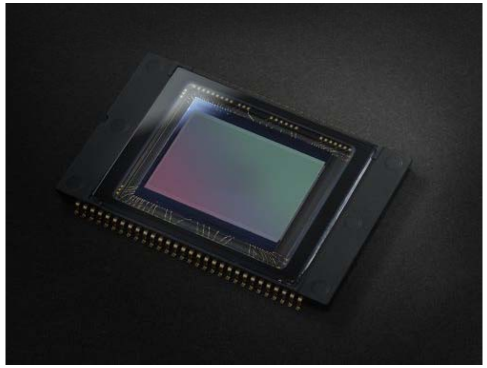


Image Sensors

- **CMOS (Complementary Metal Oxide Semiconductor)**
  - Each pixel has neighboring transistors
    - Analog to digital conversion locally performed
  - Each one of these pixel sensors are called an Active Pixel Sensor (APS).
  - Difference in readout vs. CCD
- **Many implications in the overall organization and capability of a camera.**
  - The imaging logic is integrated on a CMOS chip, where a CCD is a modular imager that can be replaced
    - Design of a new CMOS chip is more expensive
  - However, APSs are transistor-based,
    - CMOS chips can be cheaply manufactured on any standard silicon production line



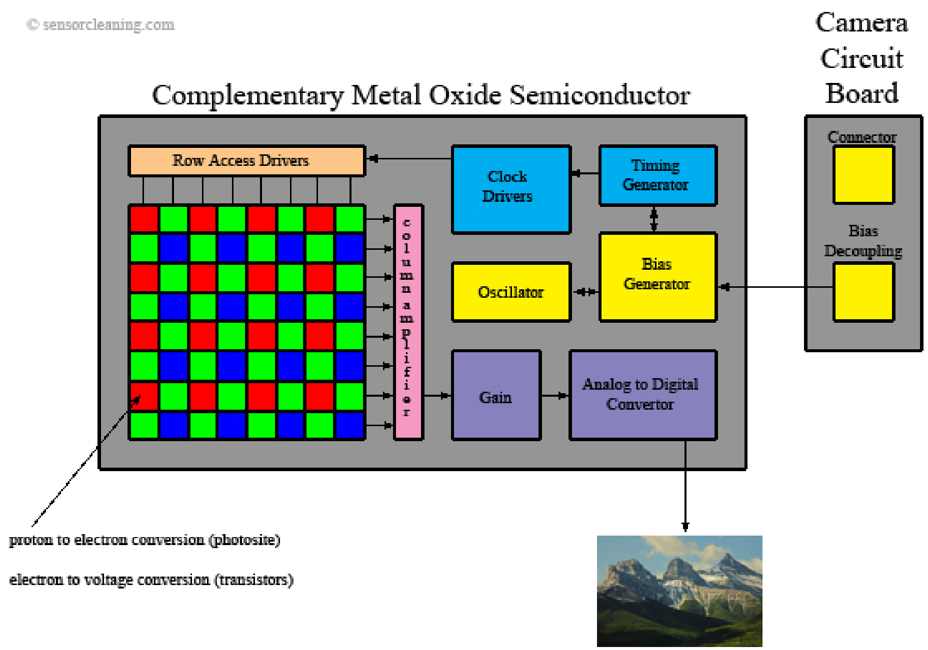


Image Sensors

CCD	vs	CMOS

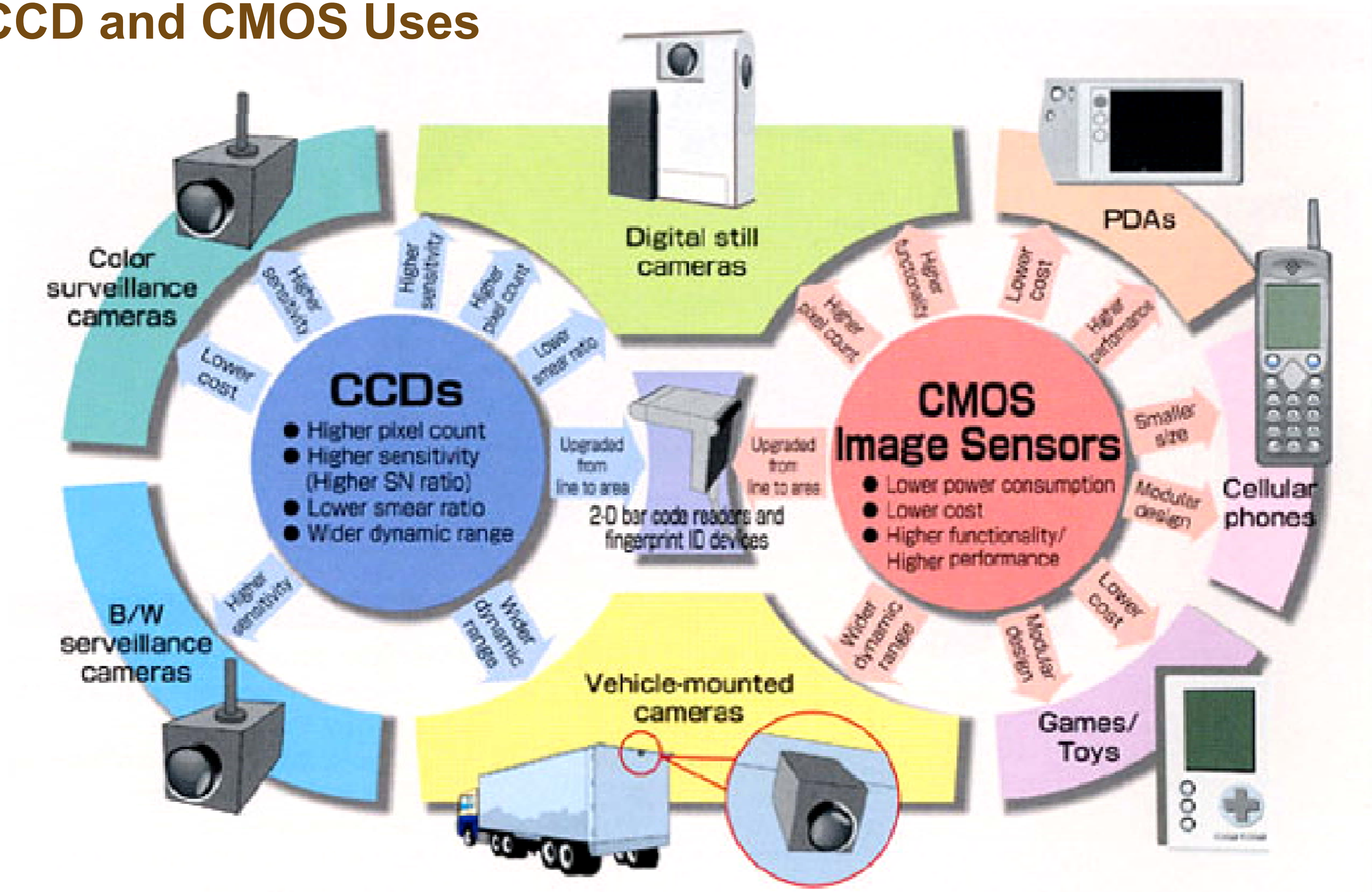
- Create high-quality, low-noise images.
- Greater sensitivity and fidelity
- 100 times more power
- Require specialized assembly lines
- Older and more developed technology

- More susceptible to noise
- Light sensitivity is lower
- Consume little power
- Easy to Manufacture
- Cheaper

Picture quality, sensitivity and cost	vs.	Cost and battery life.

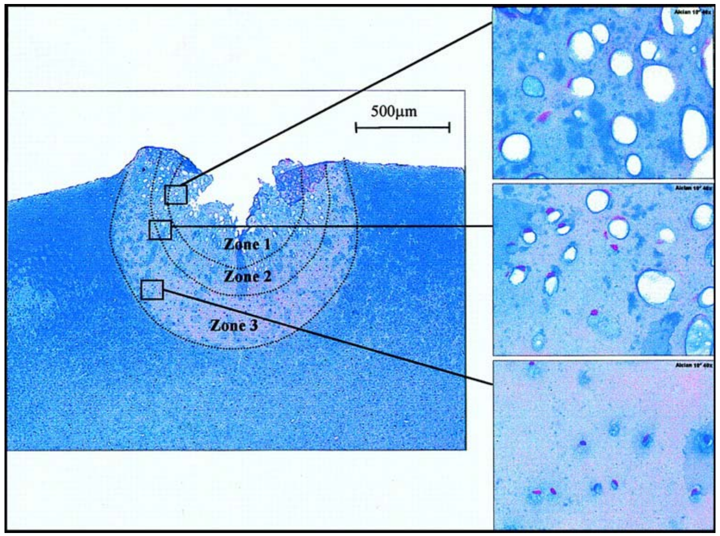
Image Sensors

- CCD and CMOS Uses



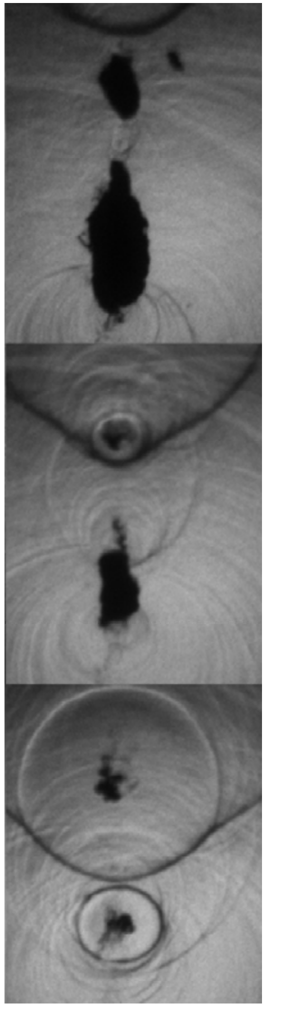
Irradiation Guidelines

- **Biological tissue or living cells exposed to optical radiation**
  - Adverse processes or responses can be triggered
    - Depending on the nature and state of cells and tissue
    - Wavelength, power, and duration of optical exposure
  - These adverse responses can also be turned into therapeutic mechanisms



Irradiation Guidelines

- **Damage mechanisms at the Tissue Level**
  - Photochemical Damage
    - At low power densities (order of 1 W/cm2) and prolonged exposure (>1 s)
    - A tissue component is excited by high-energy visible radiation
    - The energy released upon de-excitation can cause unwanted chemical reactions → damage
      - Split a bond in another molecule producing reactive oxygen species (singlet oxygen, hydrogen peroxide, hydroxyl radicals, and other free radicals.)
      - Reactive oxygen species are very aggressive and very dangerous to tissue → they can attack and break cell membranes.
  - UV-Induced Risks
    - Acute
      - Inflammation → Repair at the cellular level and by morphologic changes
    - Chronic
      - Premature aging of the skin, wrinkling, and increased skin fragility
      - Mutations in tumor suppressor genes → increased probability of developing skin cancer and suppression of immunity against infections.
  - Thermal Damage
    - Absorption of light by the tissue and subsequent conversion into thermal energy
    - Can be harmful in many circumstances, but it is also extensively used for therapeutic and aesthetic purposes
  - Thermoacoustic Damage
    - Short laser pulses, less than 1 ns → ignificant thermal transients → thermoelastic stress as the heated volume cools down → propagates outside the heated area.
    - Other phenomena
      - Surface vaporization, bubble formation and explosion, nonlinear absorption, self-focusing and laser-induced breakdown
    - Damage induced via this mechanism has found significant application in medicine
      - Laser tissue ablation in dermatology for skin rejuvenation, in ophthalmology for intraocular surgery, and in orthopedics.



Irradiation Guidelines

- **Radiation Effects at the Cellular Level**
  - Photobleaching
    - Defines a class of phenomena that cause fluorescent probes to fade permanently
    - Most common mechanism = excitation of the fluorophore to a long-lived triplet state rather than the desired singled state
    - More when discussing fluorescence
  - Photodamage
    - Physical damage to the sample
      - E.g. membrane permeability changes or DNA strand breaks
    - Most commonly by heating
  - Phototoxicity
    - Generation of harmful chemical species
      - most notably reactive oxygen species (ROS)
    - More when discussing Photodynamic Therapy

Differential Photobleaching in Multiply-Stained Tissues

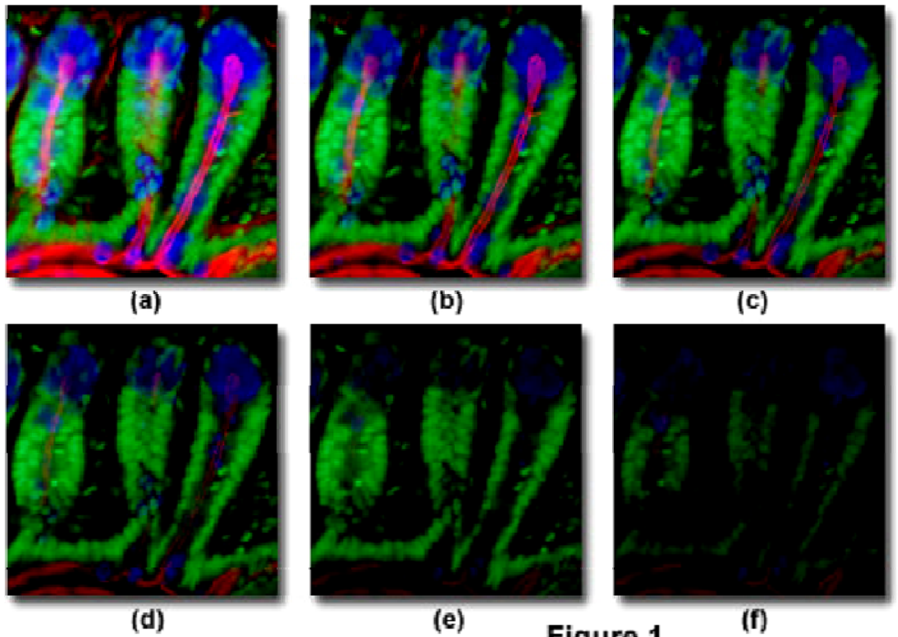
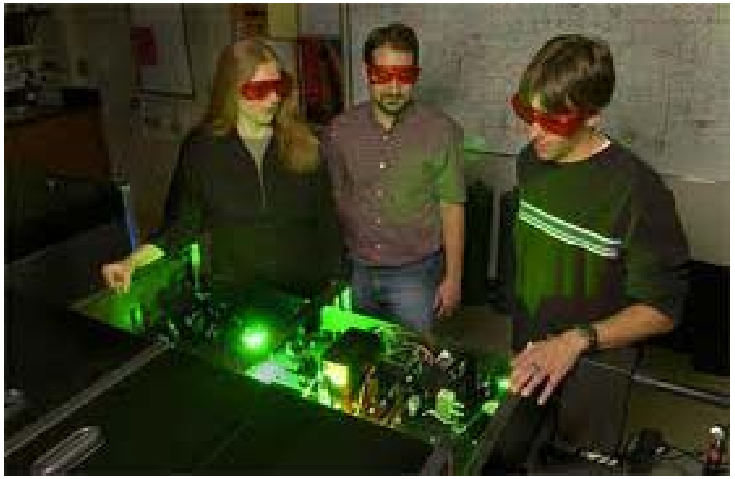


Figure 1

Irradiation Guidelines

- **Safety Practices**
  - First line of defense → aversion
    - Does not work for non-visible!
  - Laser safety guidelines
    - Never look directly at the beam or turn the beam towards others no matter how safe you think the laser is.
    - Wear protective goggles
    - Do not lean over laser systems and do not pass through the beam path
    - Confine the beams
    - Do not leave the laser on when not present
    - Only operate a laser if you are well trained
    - Post appropriate signs
  - ANSI standard (ANSI Z136)



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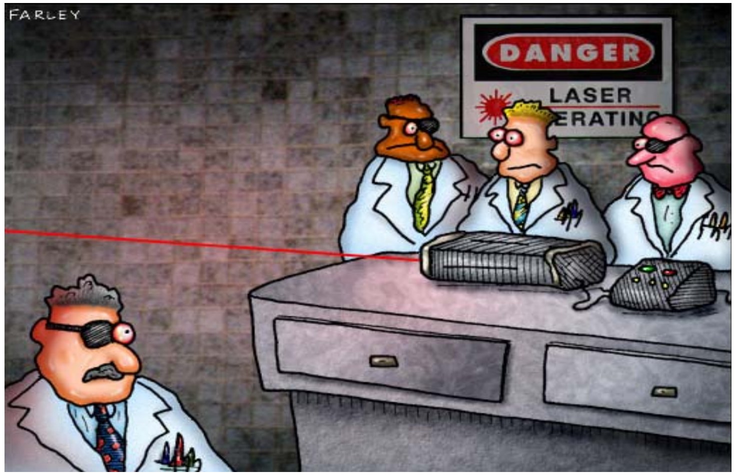

Irradiation Guidelines

- **The ANSI standard (ANSI Z136) defines the Maximum Permissible Exposure (MPE) values for eyes and skin.**

Maximum Permissible Exposure (MPE) for Skin Exposure to a Laser Beam

Wavelength (µm)	Exposure Duration t (s)	MPE ($J \cdot cm^{-2}$)	MPE ($W \cdot cm^{-2}$)	Notes
Ultraviolet				
0.180 to 0.302	10^{-9} to 3×10^4	3×10^{-3}		or $0.56\ t^{1/4}$, whichever is lower. 3.5 mm limiting aperture: (See Table 8)
0.303	10^{-9} to 3×10^4	4×10^{-3}		
0.304	10^{-9} to 3×10^4	6×10^{-3}		
0.305	10^{-9} to 3×10^4	1.0×10^{-2}		
0.306	10^{-9} to 3×10^4	1.6×10^{-2}		
0.307	10^{-9} to 3×10^4	2.5×10^{-2}		
0.308	10^{-9} to 3×10^4	4.0×10^{-2}		
0.309	10^{-9} to 3×10^4	6.3×10^{-2}		
0.310	10^{-9} to 3×10^4	1.0×10^{-1}		
0.311	10^{-9} to 3×10^4	1.6×10^{-1}		
0.312	10^{-9} to 3×10^4	2.5×10^{-1}		
0.313	10^{-9} to 3×10^4	4.0×10^{-1}		
0.314	10^{-9} to 3×10^4	6.3×10^{-1}		
0.315 to 0.400	10^{-9} to 10	$0.56 t^{1/4}$		
0.315 to 0.400	10 to 10^3	1		
0.315 to 0.400	10^3 to 3×10^4		1×10^{-3}	
Visible and Near Infrared				
0.400 to 1.400	10^{-9} to 10^{-7}	$2 C_A \times 10^{-2}$		3.5 mm limiting aperture. (See Table 8)
	10^{-7} to 10	$1.1 C_A\ t^{1/4}$		
	10 to 3×10^4		$0.2 C_A$	
Far Infrared*				
1.400 to 10^3	10^{-9} to 10^{-7}	10^{-2}		(See Table 8 for limiting apertures)
	10^{-7} to 10	$0.56\ t^{1/4}$		
	> 10		0.1	

Parameters and Correction Factors

Correction Factor	Wavelength (µm)	Figure*
$T_1 = 10 \times 10^{20(\lambda - 0.550)}$	0.550 to 0.700	9
$C_B = 1.0$	0.400 to 0.550	9
$C_B = 10^{15(\lambda - 0.550)}$	0.550 to 0.700	9
$C_A = 1.0$	0.400 to 0.700	8a
$C_A = 10^{2(\lambda - 0.700)}$	0.700 to 1.050	8a
$C_A = 5.0$	1.050 to 1.400	8a
$C_P = n^{-1/4}$ **	0.400 to 1.400	13
$C_E = 1.0 \quad \alpha < \alpha_{min}$	0.400 to 1.400	-
$C_E = \alpha / \alpha_{min} \quad \alpha_{min} < \alpha < 100$	0.400 to 1.400	-
$C_E = \alpha^2 / (100\ \alpha_{min}) \quad \alpha > 100$	0.400 to 1.400	-
$C_C = 1.0$	1.050 to 1.150	8b
$C_C = 10^{18(\lambda - 1.150)}$	1.150 to 1.200	8b
$C_C = 8$	1.200 to 1.400	8b