Lecture 07: Technical Basis for Optical/Laser-Based Flow Diagnostics

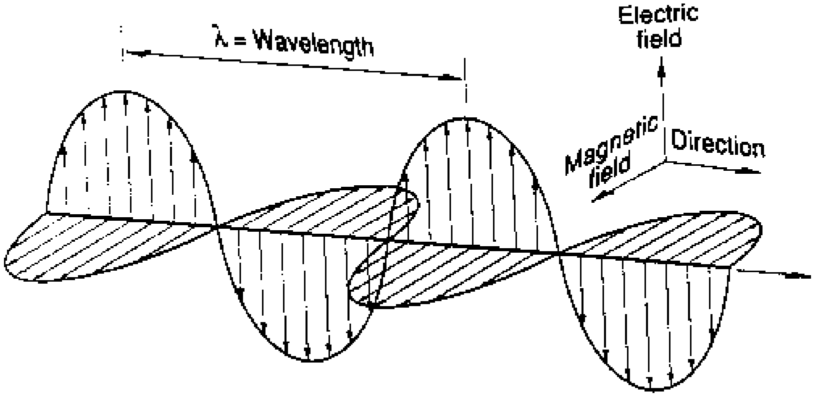
Dr. Hui Hu
Martin C. Jischke Professor in Aerospace Engineering
Dept. of Aerospace Engineering, Iowa State University
537 Bissell Road, Ames, Iowa 50011-1096, USA.
Tel: 515-294-0094 (O) / Fax: 515-294-3262 (O) / Email:
huhui@iastate.edu

❑ The Nature of Light

- *Classical electromagnetic theory: light is radiation that propagates through vacuum in free space in the form of electromagnetic waves, both oscillating transversely to the direction of wave propagation and normal to each other.*

$$E_y(x,t) = E_{y0} \sin 2\pi(\frac{x}{\lambda} - \frac{t}{T})$$

$$B_Z(x,t) = B_{z0} \sin 2\pi(\frac{x}{\lambda} - \frac{t}{T})$$



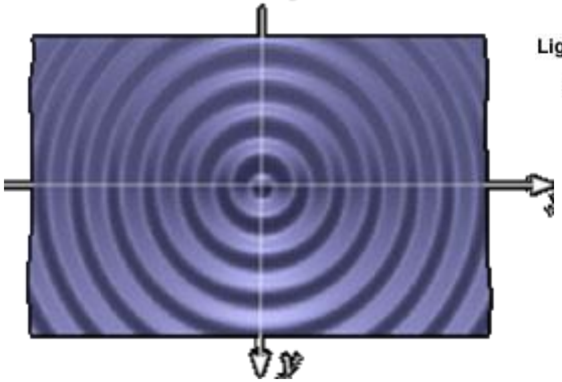
- ***λ :** **is wavelength***
- ***T :** **is the period of the oscillation***
- ***f:** **The reciprocal of the period,***

  is called frequency, f =1/T

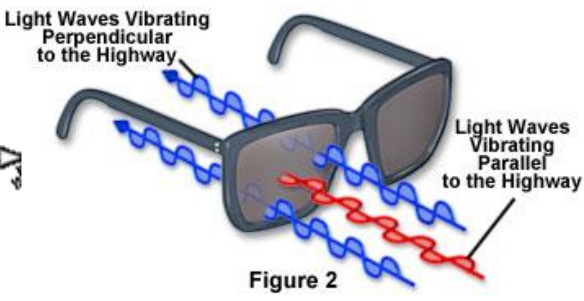
❑ The Nature of Light- as electromagnetic waves

- *Light propagation velocity, $V = f\lambda$*
- *Light propagation velocity in Vacuum,*
  $C = 2.998 \times 10^8$ m/s
- *Wave front: the locus of all points along the different paths that have the same phase.*
- *If all the wave fronts are plane, then, the light is considered to be a plane wave.*
- *If all the wave fronts are spherical or cylindrical, then, the light is considered to be a spherical or cylindrical wave.*
- *Light propagation is associated with electric and magnetic fields.*
- *The polarization is associate with the orientation of the plane of the plane of oscillation of the electric field.*
- *Concepts of linearly polarized light, elliptically polarized light and circularly polarized light, unpolarized or randomly polarized light.*

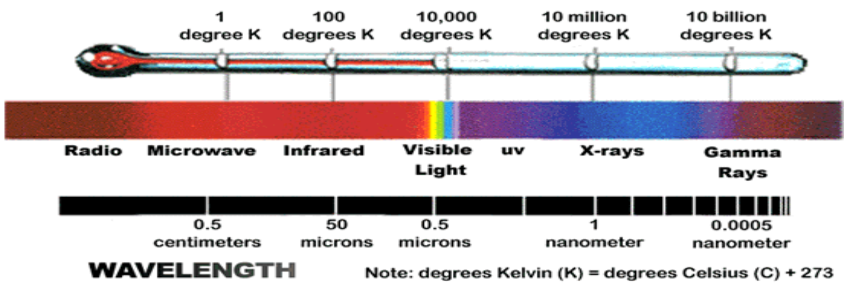
- ***wave fronts***

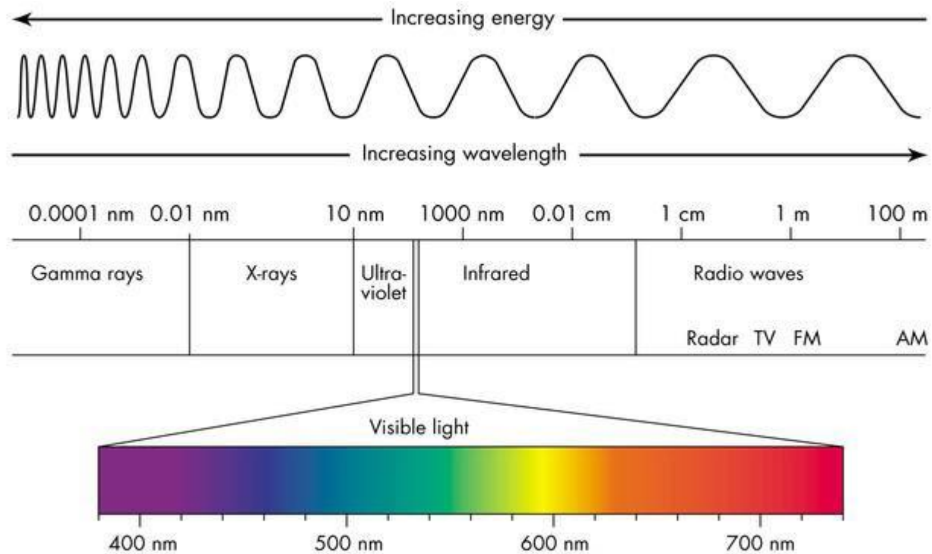


- ***Light propagation***

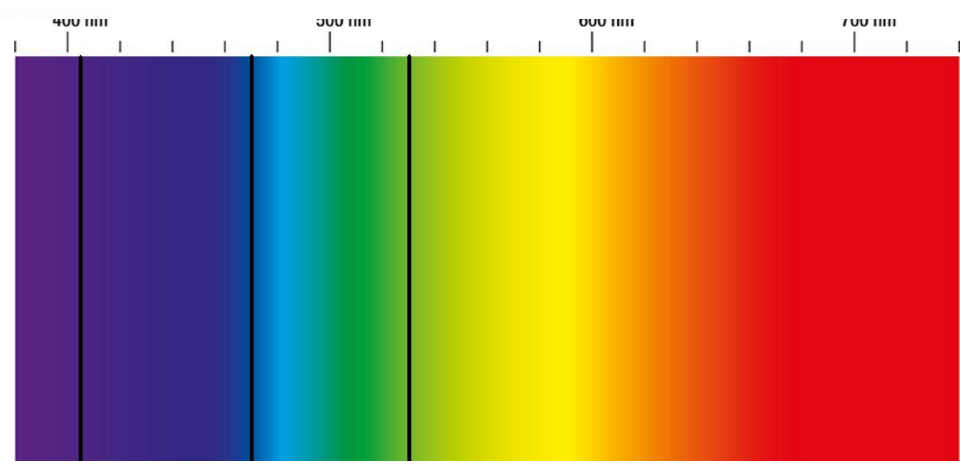


❑ THE NATURE OF LIGHT- AS ELECTROMAGNETIC WAVES



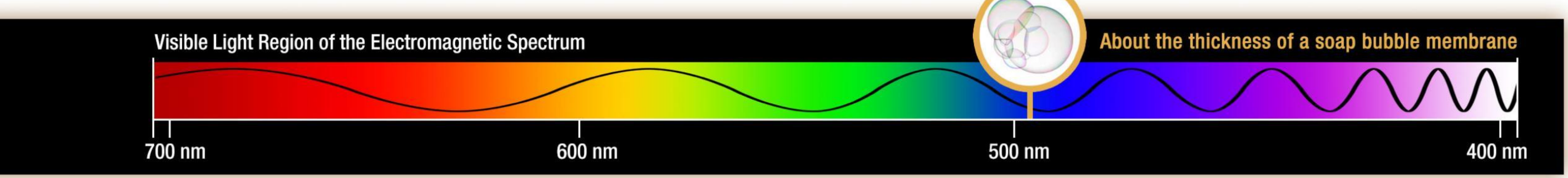


RADIATION TYPE	WAVELENGTH RANGE
Cosmic rays	$\lambda < 10^{-4}$ nm
Gamma rays	10^{-4} nm $< \lambda < 10^{-1}$ nm
X-rays	10^{-2} nm $< \lambda < 10^{2}$ nm
Disinfecting radiation	10 nm $< \lambda <$ 380 nm
Visible light	380 nm $< \lambda <$ 750 nm
Space heating	750 nm $< \lambda < 10^{7}$ nm
Microwaves	10^{6} nm $< \lambda < 10^{9}$ nm
Radar	10^{7} nm $< \lambda < 10^{9}$ nm
Radio and Television	10^{8} nm $< \lambda < 10^{13}$ nm
Electrical power waves	10^{14} nm $< \lambda < 10^{17}$ nm

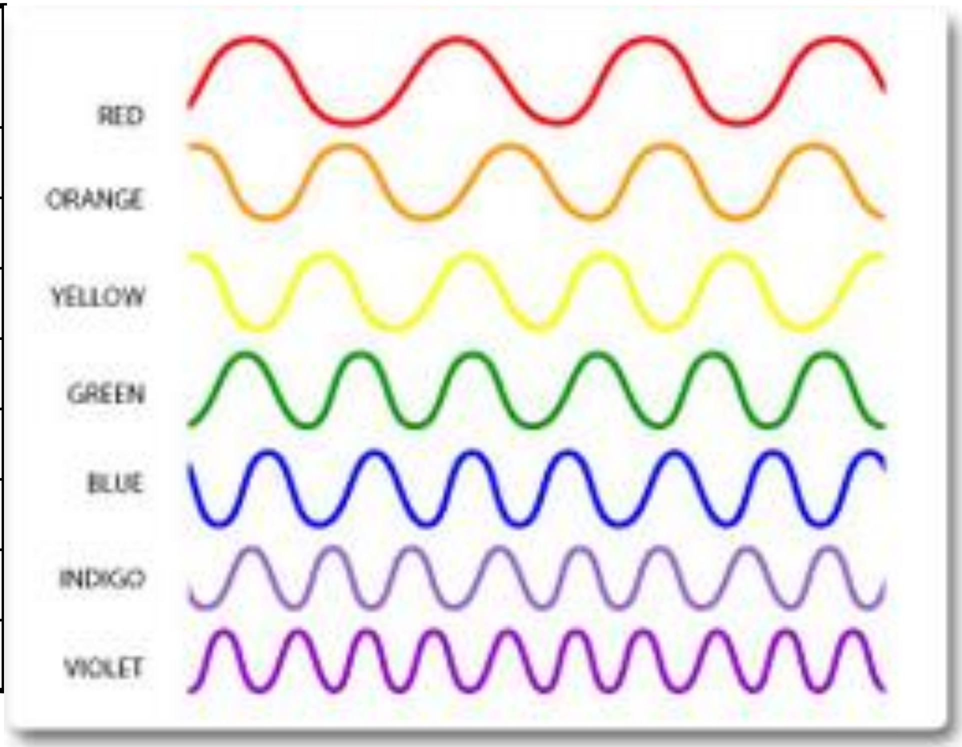


❑ THE NATURE OF LIGHT- AS ELECTROMAGNETIC WAVES

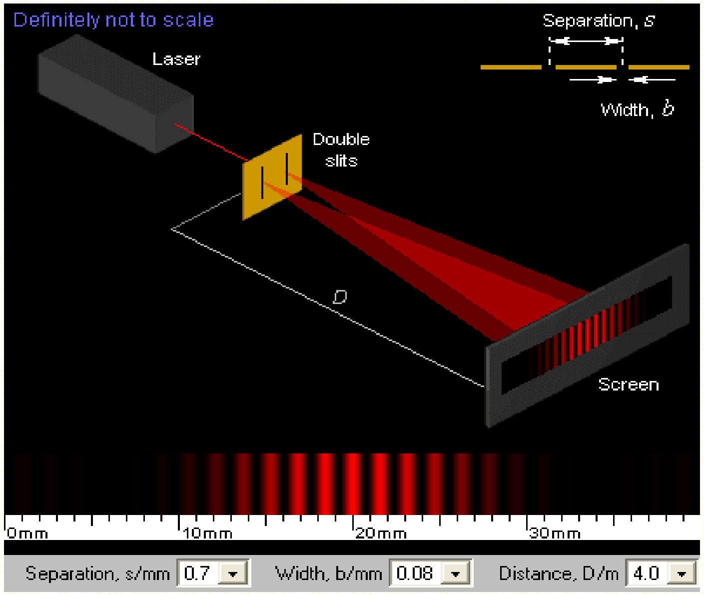
- *The colors: visible light consists of radiation with wavelength in the range of 380~750nm (1nm=10^{-9}m) which corresponds to the frequency range between 4.0 $\times 10^{15}$ to 7.9 $\times 10^{15}$ Hz.*

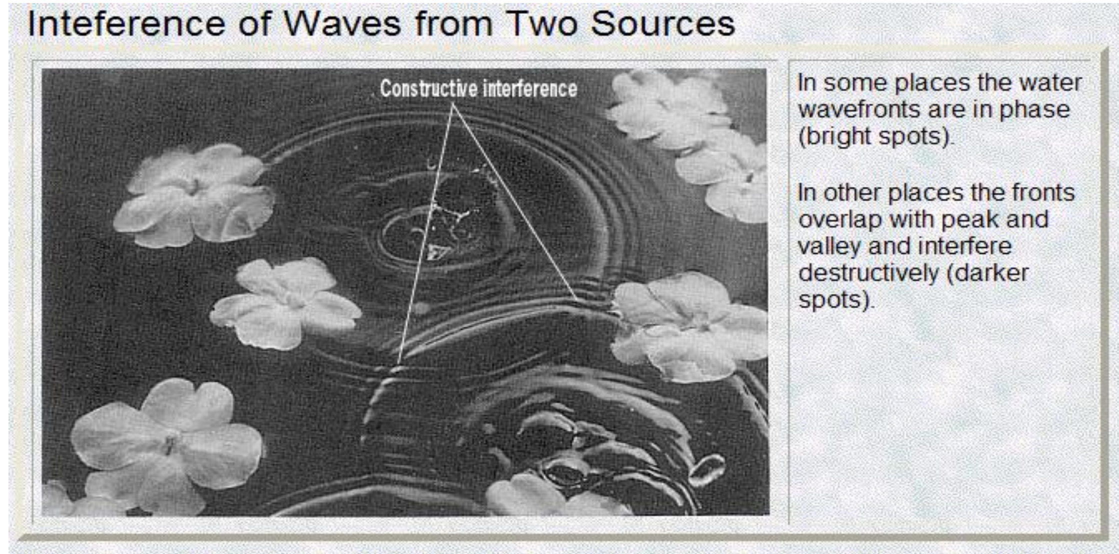


COLOR	***WAVELENGTH RANGE***
Ultraviolet (UV)	***0.85 nm < λ < 380 nm***
Violet	***380 nm < λ < 424 nm***
Blue	***424 nm < λ < 491 nm***
Green	***491 nm < λ < 575 nm***
Yellow	***575 nm < λ < 585 nm***
Orange	***585 nm < λ < 647 nm***
Red	***647 nm < λ < 750 nm***
infrared	***750 nm < λ < 1000 nm***

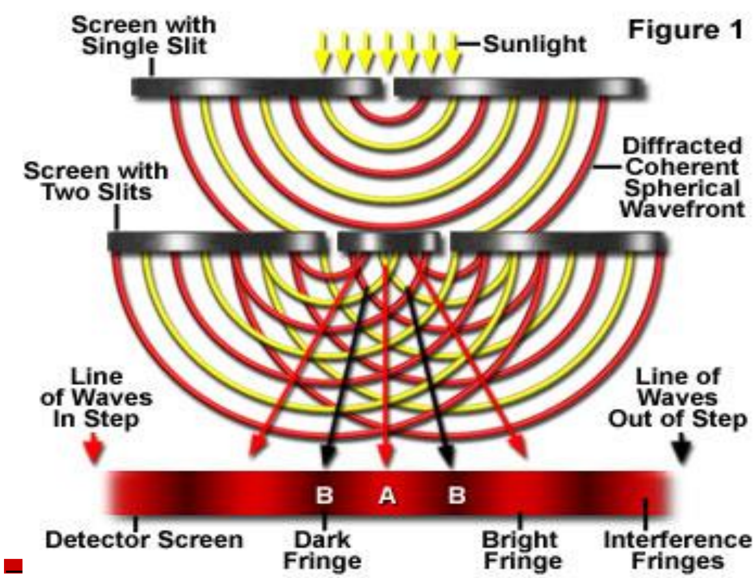


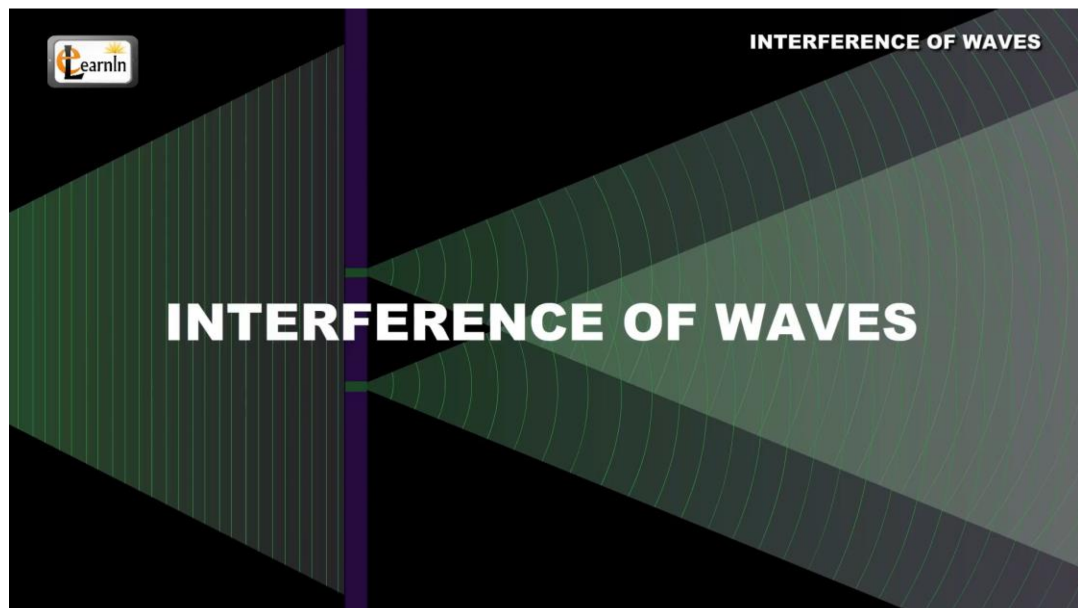
❑ Light as Waves - Interference of light waves





Thomas Young's Double Slit Experiment

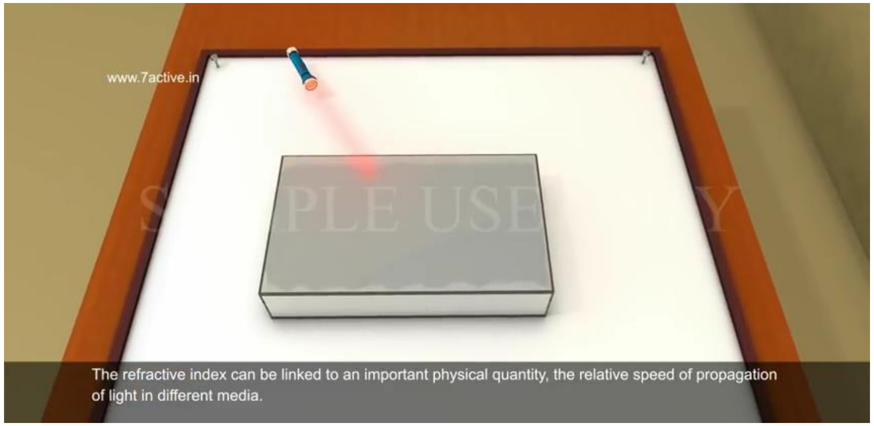




❑ LIGHT PROPAGATION THROUGH MEDIA

- ***Refractive index***:

$$n = c / v = \frac{\lambda_0}{\lambda} > 1$$



Index of refraction of a material generally increasing slightly with decreasing wavelength of the light. Such phenomena is called dispersion.

$$n = \sqrt{\frac{1+2K_L\rho}{1-K_L\rho}}$$

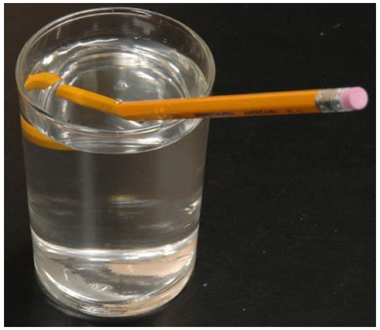
Gas	n	Liquid	n	Solid	n
Air	1.00029	Water	1.333	Fused quartz	1.46
He	1.00036	Ethyl alcohol	1.361	Pyrex glass	1.47
CO_2	1.00045	Turpentine	1.472	Crown glass	1.52
H_2	1.00013	Benzene	1.501	Flint glass	1.57~1.89
				Plexiglas	1.51
				Lexan	1.58
				Polystyrene	1.59
	589nm			sapphire	1.77
				zircon	1.92
				Diamond	2.42

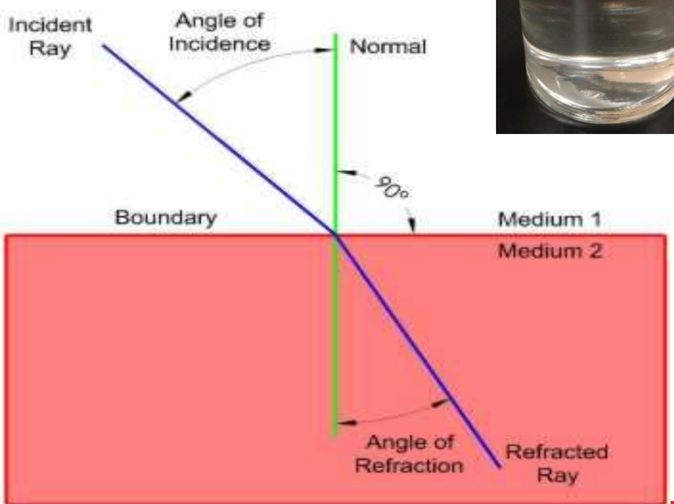
❑ Light propagation through media

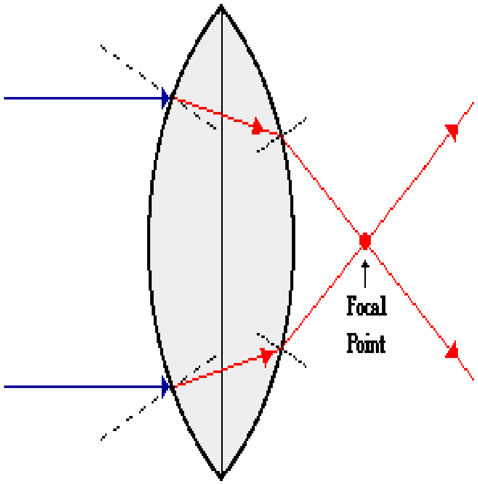
- ***Refraction:***
  - *When light propagates through a homogenous medium, its path would be straight, whereas, if the medium is non-homogeneous or if the light across from one medium to another, the path may change direction gradually or abruptly. The change of light propagation direction is called refraction.*

$$n = c / v = \frac{\lambda_0}{\lambda} > 1 \qquad \frac{\sin \varphi_1}{\sin \varphi_2} = \frac{n_2}{n_1}$$

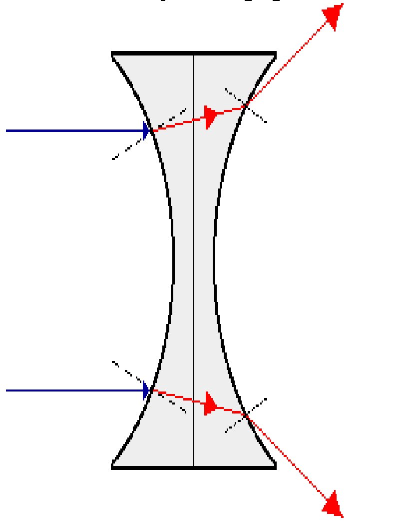
  - *Optically denser medium ($n_1 < n_2$)*
  - *Snell's Law:*







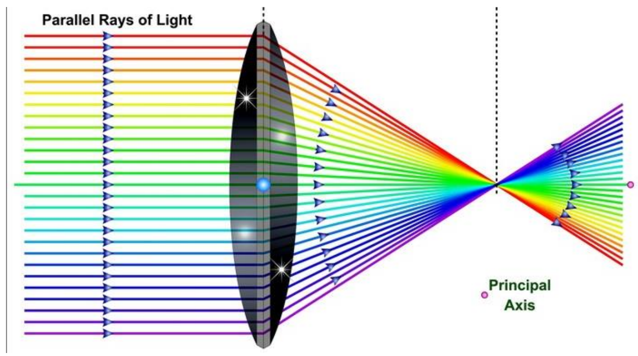
Incident rays which travel parallel to the principal axis will refract through the lens and converge to a point.

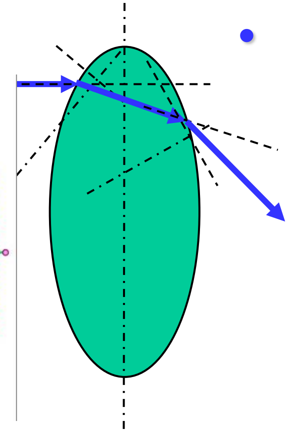


Incident rays traveling parallel to the principal axis will refract through the lens and diverge, never intersecting

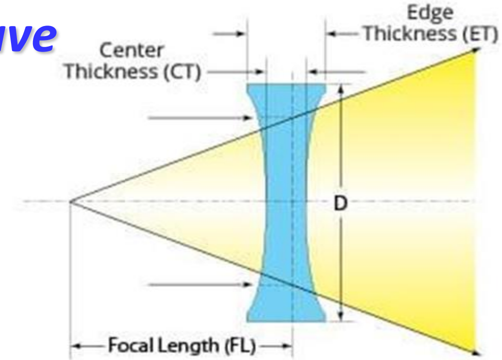
❑ LIGHT PROPAGATE THROUGH MEDIA

- *Convex lens*

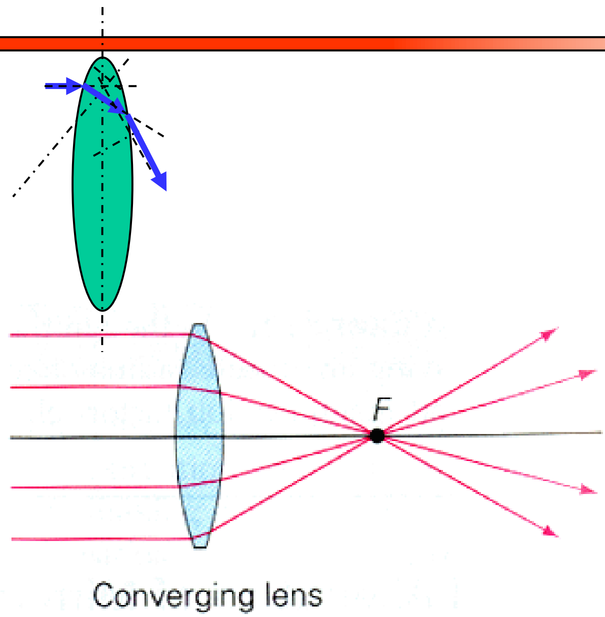




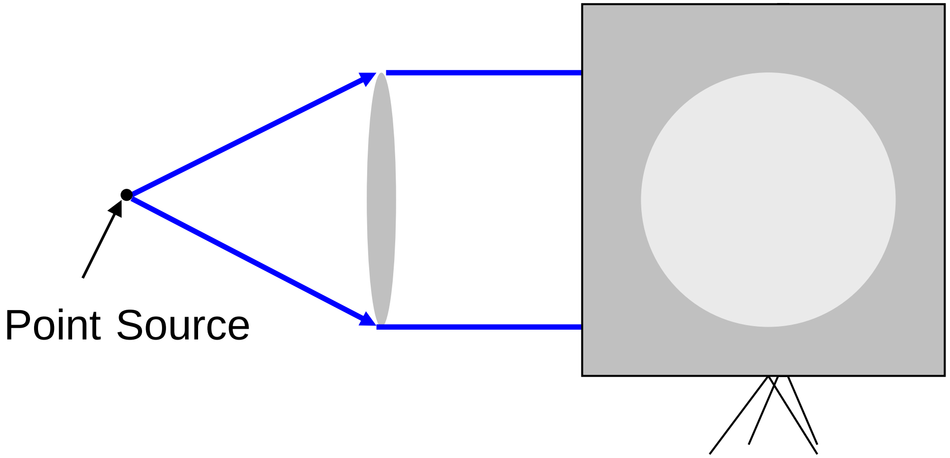
- *Concave lens*

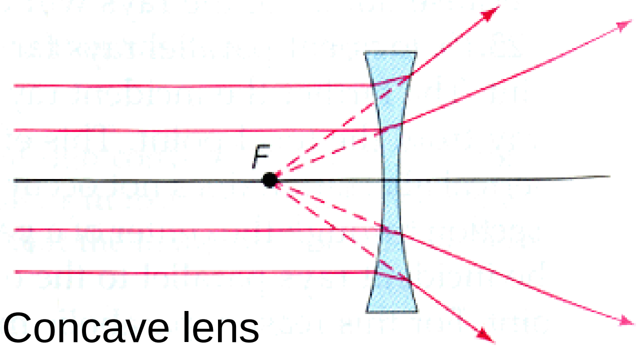


Optical Lenses

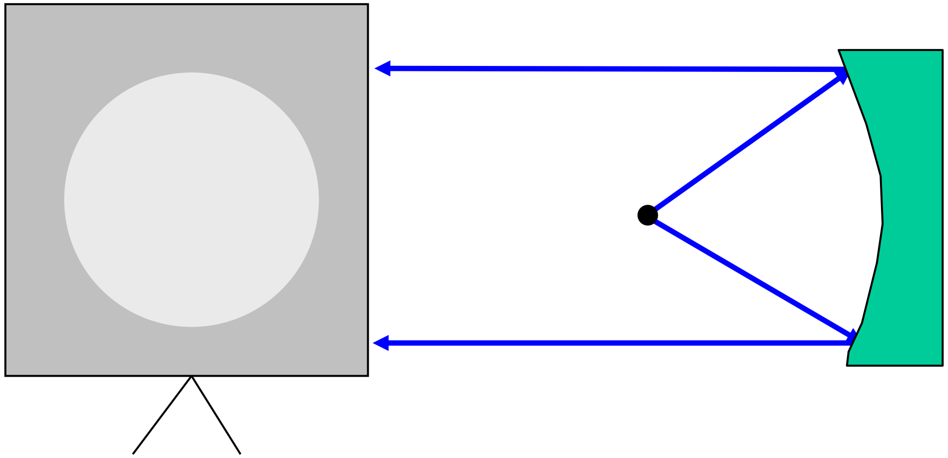


Convex lens





Concave lens



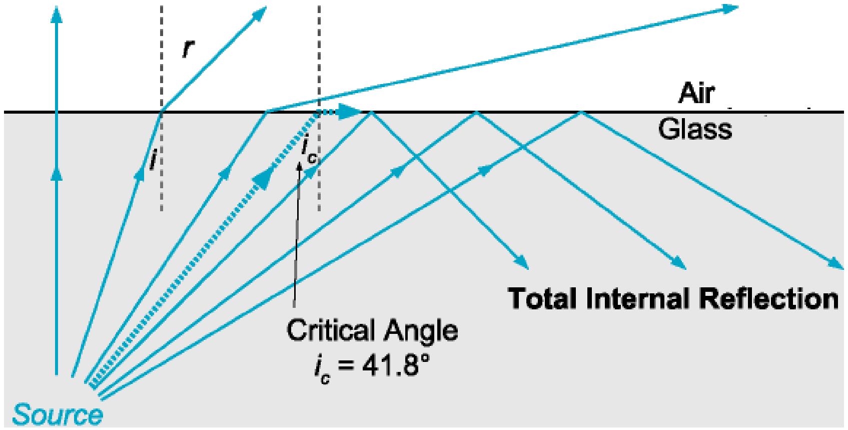
❑ LIGHT PROPAGATION THROUGH MEDIA

- ***Total refraction***

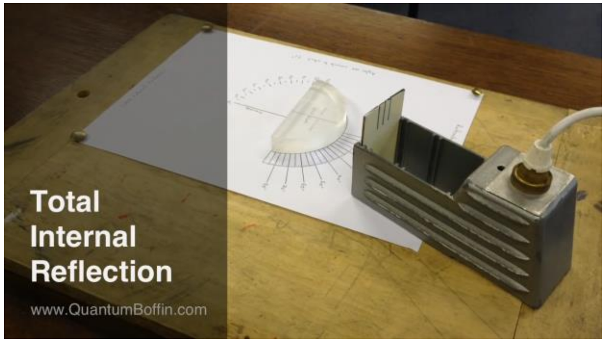
$$\frac{\sin \varphi_1}{\sin \varphi_2} = \frac{n_2}{n_1}$$

$$n_1 > n_2 \Rightarrow \varphi_2 > \varphi_1$$

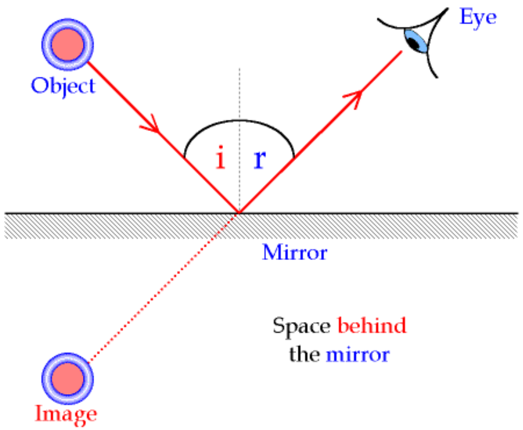
$$\varphi_{2\max} > \pi/2 \Rightarrow \varphi_{1cri} = \sin^{-1}(n_2/n_1)$$

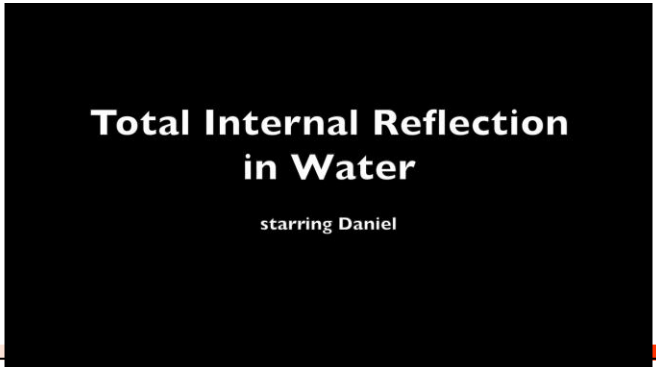


Refraction and total internal reflection.



- ***Reflection***



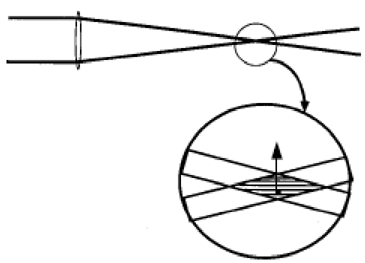


❑ Light Propagation Through Media

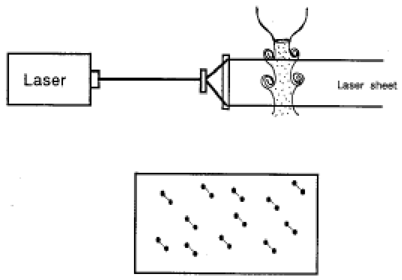
How does refractive-index-matching help?

- Optical techniques avoid disturbing the flow to be measured
- Typical approaches are LDV, PIV, PTV, flow visualization, PLIF, etc.

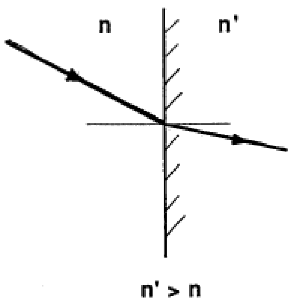
Laser Doppler Velocimetry



Particle Image Velocimetry

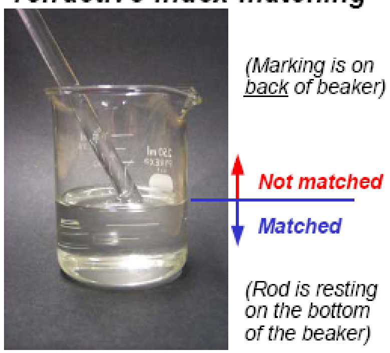


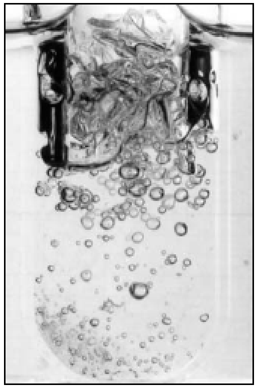
Snell's Law



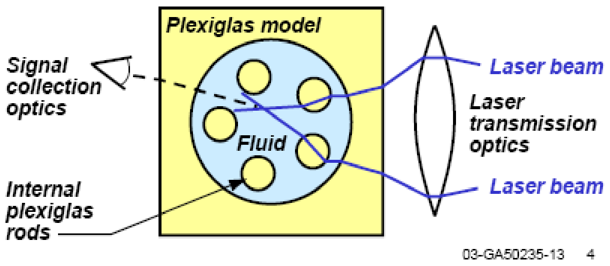
- Unless the refractive indices are matched, the view may be distorted or impossible even with "transparent" materials and position measurements may be incorrect

Example of application of refractive-index-matching





Refractive index not matched



❑ The Optical Index of Refection Matching Approach

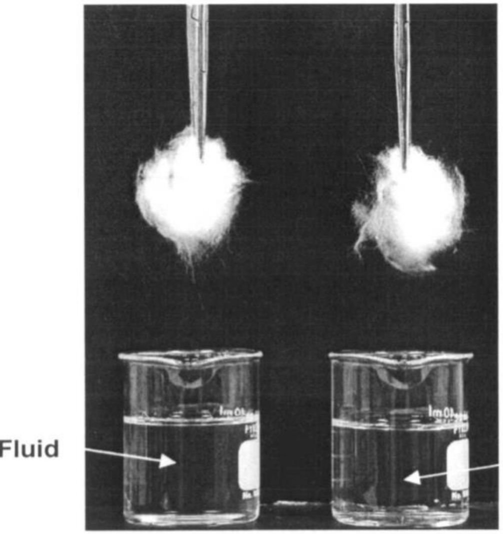


Figure 3. Wool in air

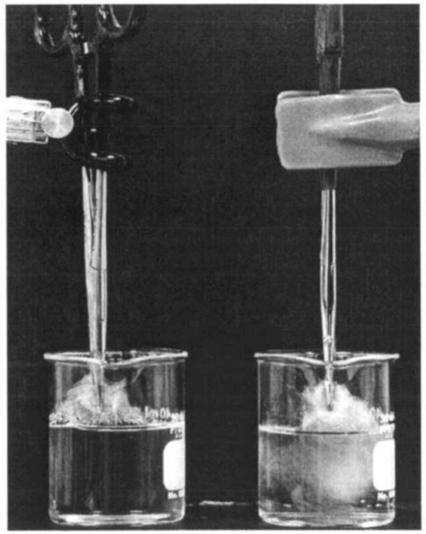


Figure 4. Half submerged

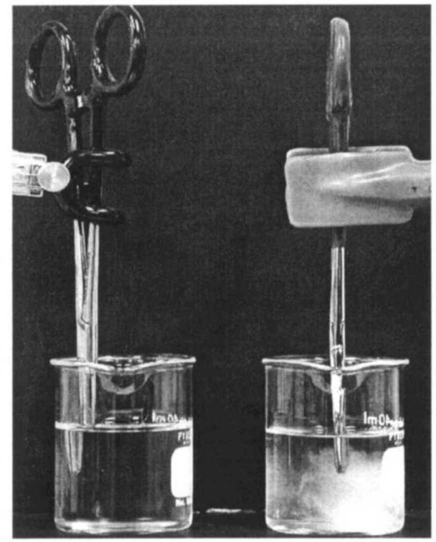
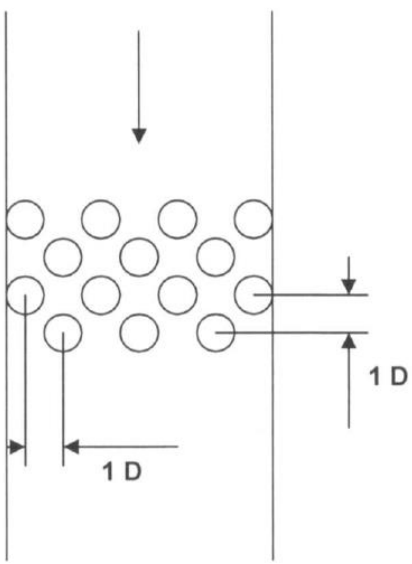
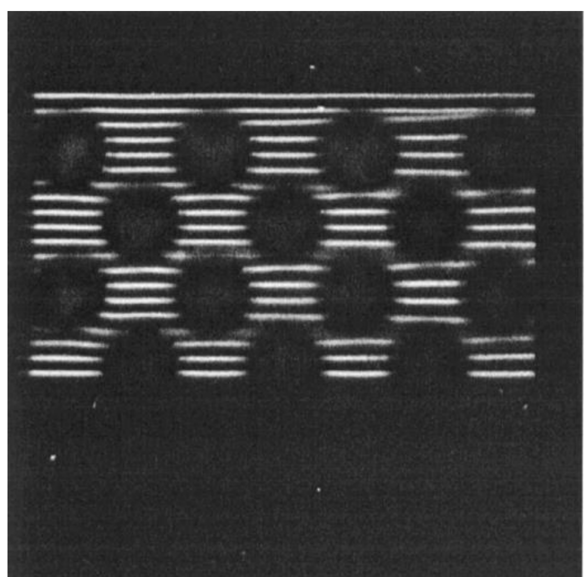
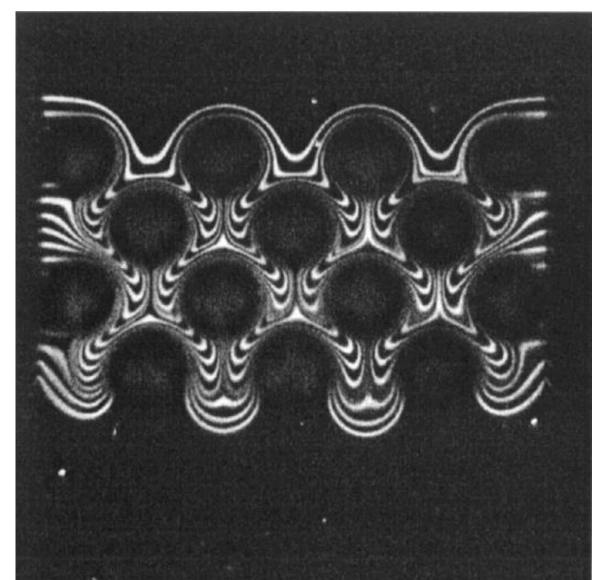


Figure 5. Totally submerged



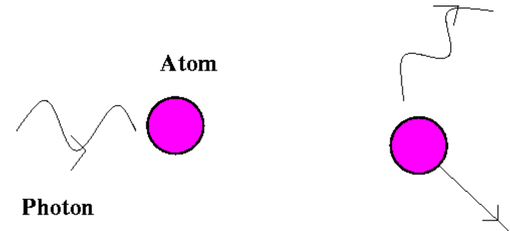




❑ THE NATURE OF LIGHT – AS PHOTONS

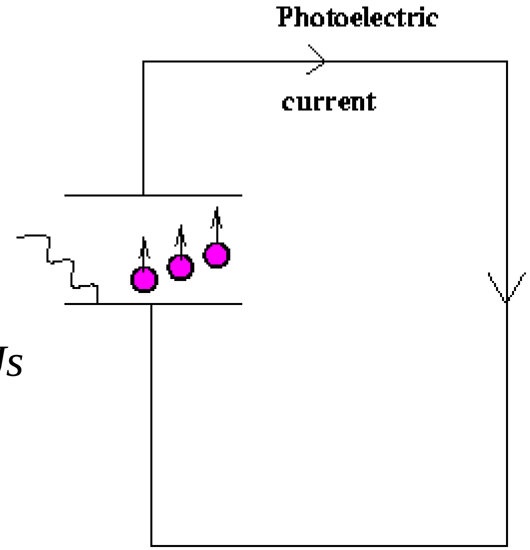
Photon scattering:

- *one finds experimentally that the frequency of the scattered wave is changed, which does not come out of a wave picture of light. However, when the light is viewed as a photon with energy proportional to the associated light wave, excellent agreement with experiment is found.*



$$\varepsilon = h\nu$$

$$Planck\,const = 6.624 \times 10^{-34}\,Js$$

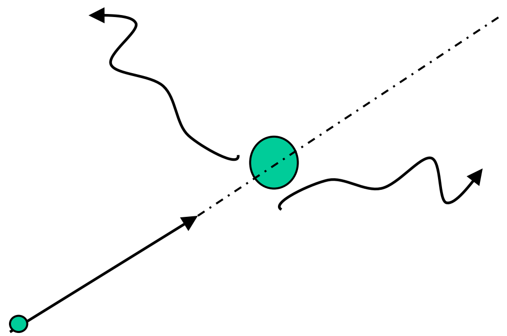


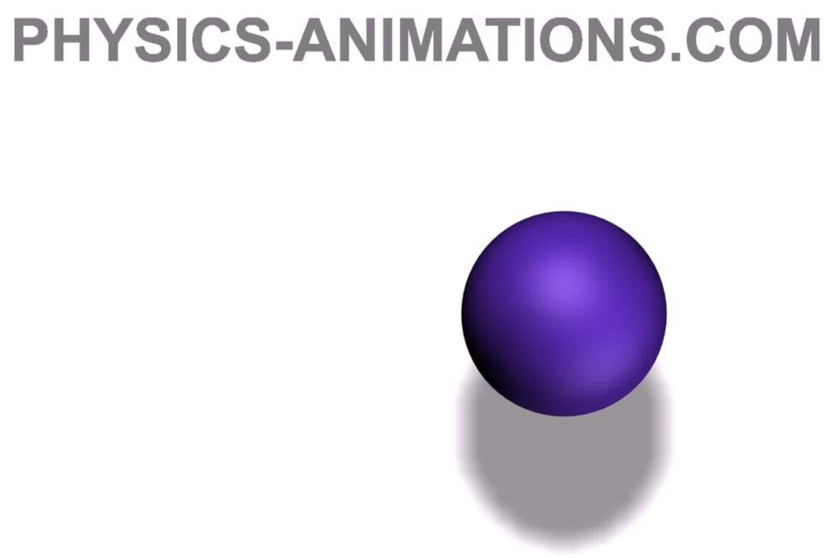
The photoelectric effect:

- *When light shines on a metal plate, electrons are ejected. These electrons are accelerated to a nearby plate by an external potential difference, and a photoelectric current is established, as below*
- *The photons hit an electron in the metal, giving up energy. If photon energy is sufficient to free the electron, it is accelerated towards the other side; hence, a flow of charges (current).*
- *The photoelectric current depends critically on the frequency of the light. This is a feature of the energy that the electrons gain when struck by the light.*
- ***The explanation was first given by Einstein and won him the Nobel Prize**.*

❑ Light Scattering

- *Scattering*
  - *Scattering is a general physical process whereby some forms of radiation, such as light, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which it passes.*
- *Elastic Scattering*
  - *Excited electron or atoms emits a photon with exact the same frequency as the incident one.*
- *Inelastic scattering*
  - *Excited electron or atoms emits a photon with a frequency different from the incident one.*





❑ Elastic Scattering

Rayleigh Scattering

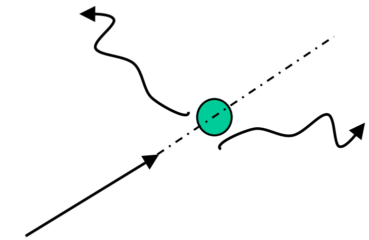
–*Light scattering from particles that are smaller than 1/15 of the incident light wavelength (d< λ/15).*

–*Efficiency of the scattering from a particle is expressed in terms of scattering cross section.*

$$\sigma_R = \sigma_T \left(\frac{\lambda_0}{\lambda}\right)^2$$

$$\sigma_T = 6.65 \times 10^{-29} m^2$$

λ_0 *is the charateristic wavelength of the atom.*



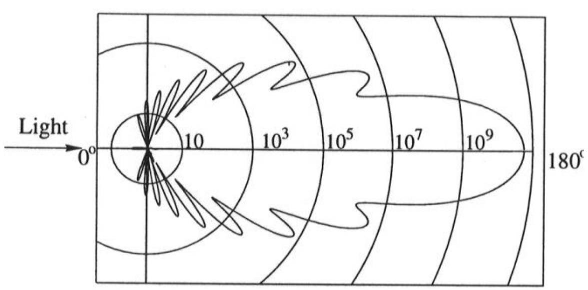
Mie Scattering

–*Light scattering from a particles with its size close on bigger than the incident light wavelength (d > λ).*

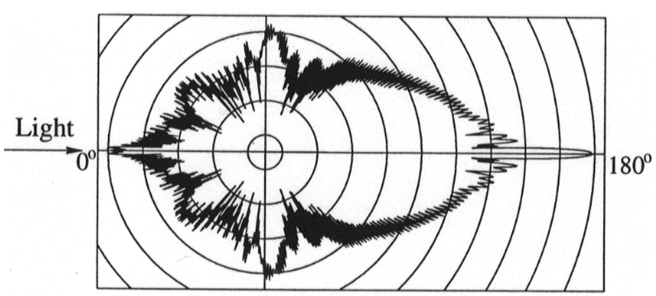
–*Conservation of polarization direction*

–*Angle dependent*

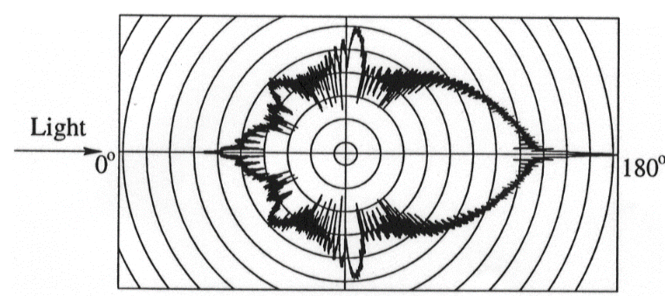
- *Forward scattering*
- *Back scattering*



(a). d=1μm



(b). d=10μm



(c). d=30μm

Inelastic Scattering

Raman Scattering

- *Inelastic scattering from molecules.*
- *Chance to occur is about 10^{-5} ~ 10^{-2} of times lower than the Rayleigh scattering*
- *Scattering cross section is several orders smaller than the Rayleigh scattering*
- *Stoke transition : the energy of the emitted photon is higher than the absorbed photo.*
- *Anti-stoke transition: the energy of the emitted photon is lower than the absorbed photo.*
- *Time between the absorption and emission: 10^{-14} s.*
- *Anti-stokes line will be stronger when the temperature is low.*

Scattering of light by molecules

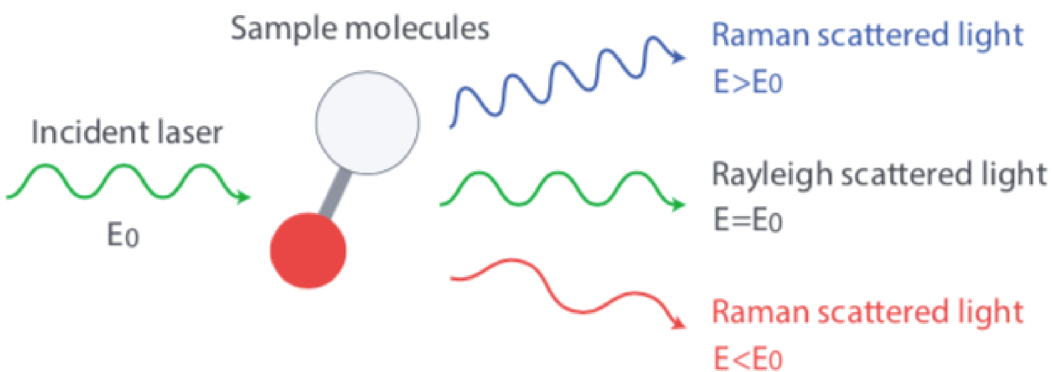


Table 5.5. Wavelengths of Raman-scattered radiation for some common molecules in air at standard atmospheric pressure and a temperature of 295 K; excitation was provided by a ruby laser

Molecule	Anti-Stokes line (nm)	Stokes line (nm)
Incident light	694.30 (Rayleigh line)	
CO_2	638.23	761.17
CO_2	637.92	762.23
CO_2	633.25	768.37
CO_2	632.42	769.61
O_2	626.57	778.44
O_2^+	615.50	796.23
NO	614.26	798.31
CO	604.34	815.73
N_2^+	603.19	817.82
N_2	597.57	828.39
CH_4	577.45	870.46
H_2	538.67	976.41

❑ Fluorescence and Phosphorescence

– Rayleigh and Raman scattering occurs essentially instantaneously. Not allowing other energy conversion phenomena to occur.

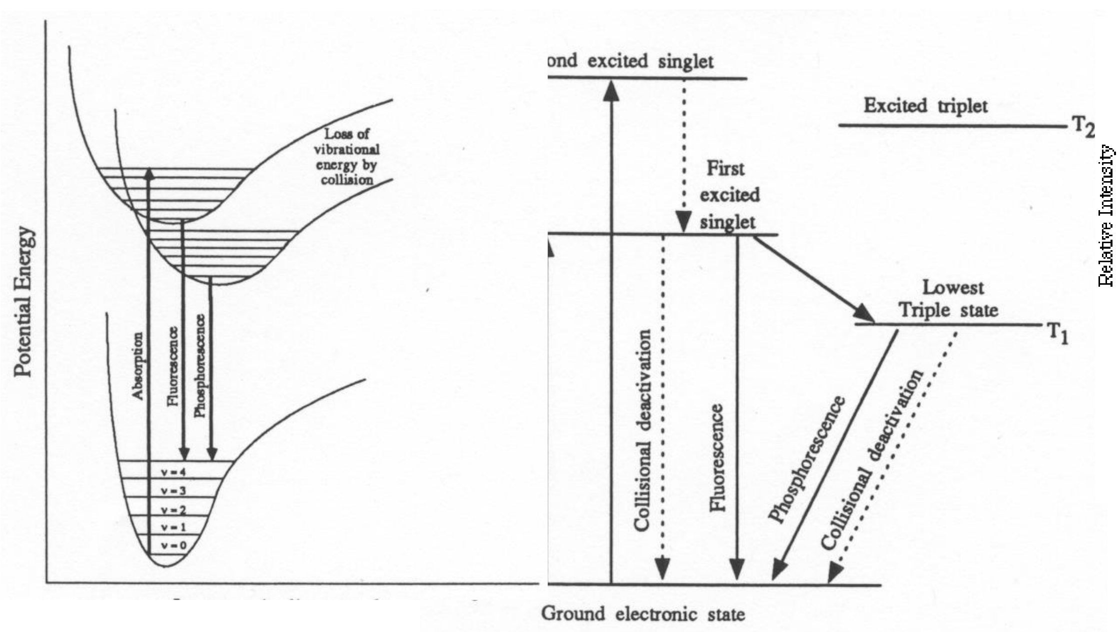
Fluorescence and phosphorescence

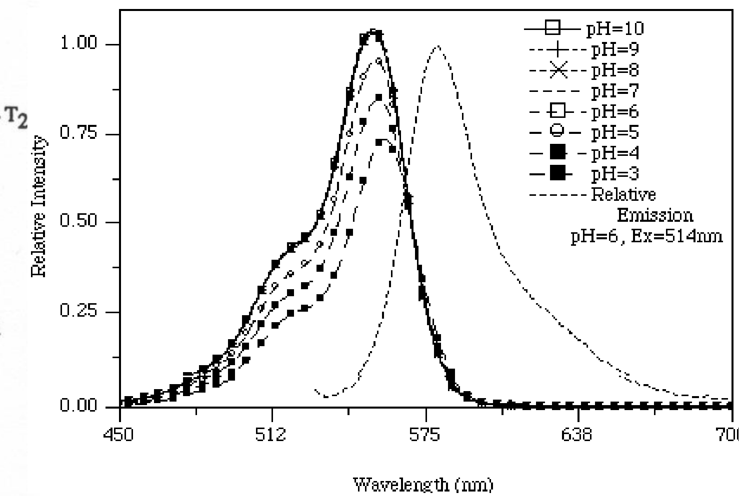
– Photoluminescence with time delay

Fluorescence

– Emission when the excited from singlet state to ground,

– lifetime is about $10^{-10} \sim 10^{-5}$ s.



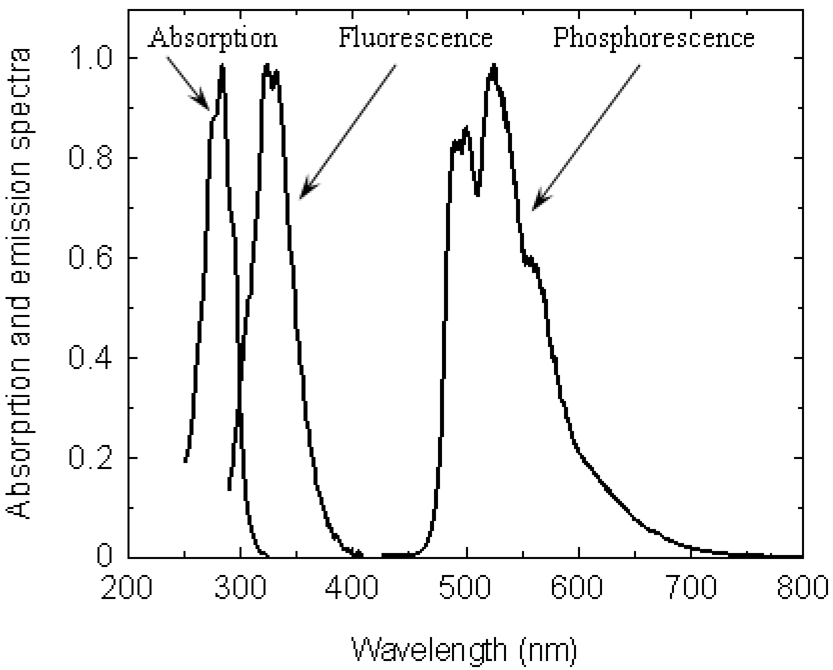


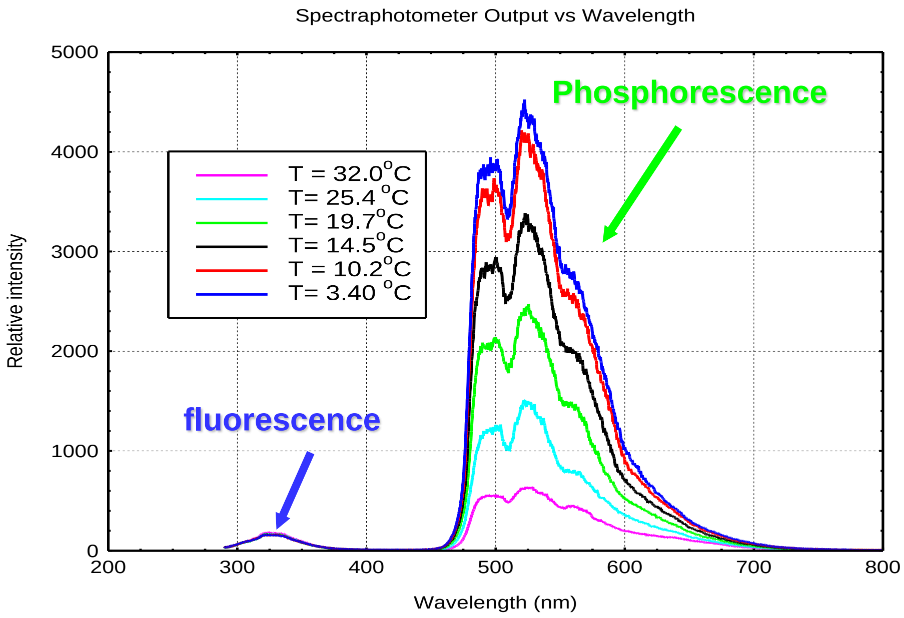
Rhodamine B

Fluorescence and phosphorescence

Phosphorescence

- Emission when the excited atom or molecule from triplet state to ground,
- lifetime is about $10^{-4} \sim 10^{-5}$ s.

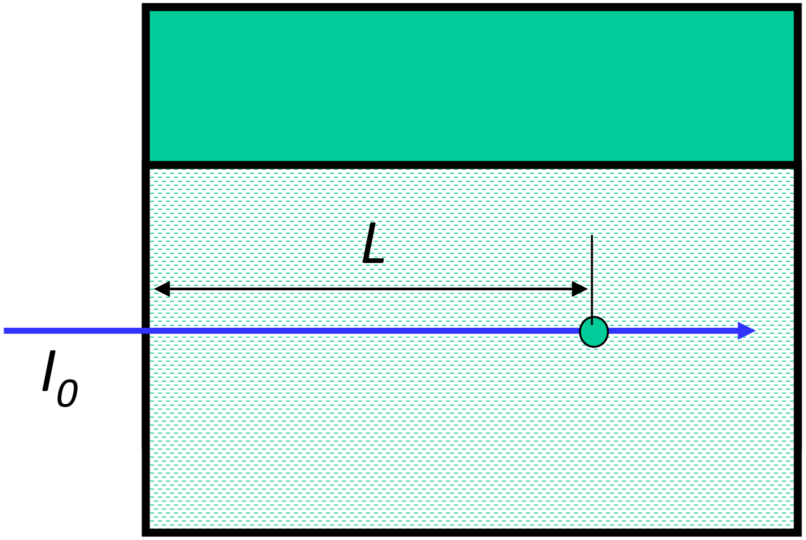




MTV chemical: 1-BrNp•Mβ-CD•ROH complex

Absorption

Light is transmitted through a material, it will be absorbed by the molecules of the material



Beer's law: $$I = I_0 \exp(-\alpha L)$$

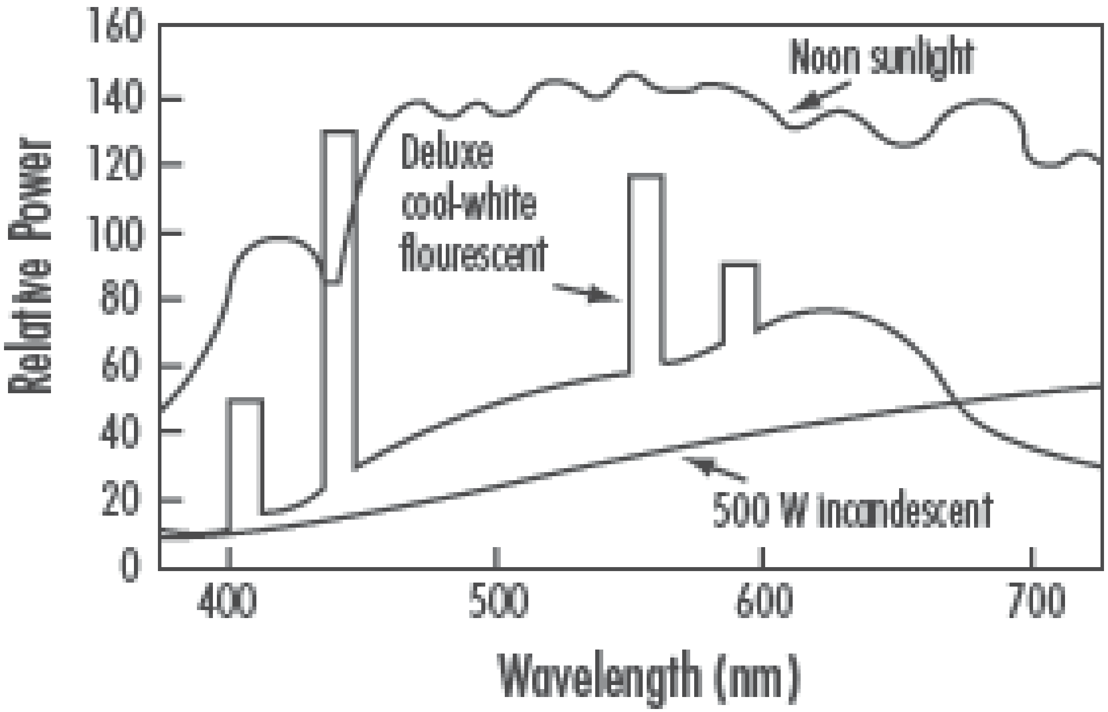
- *α is the absorption or attenuation coefficient*
- *Lc=1/α is called penetration depth.*
- *When $L=L_c$, $I/I_0=1/e=37\%$, i.e., 63% energy was absorbed*
- *Metals have very small Lc=1/α.*
  - *Copper, Lc=0.6nm for 100 nm UV light*
  - *Copper, Lc=6.0nm for 1000 nm infrared light.*
  - *2nm copper plate as a low pass filter.*

❑ ILLUMINATION

Light sources:

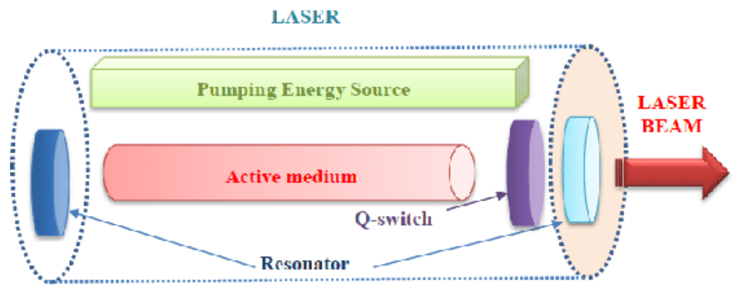
- *Thermal source:*
  - *Lamps: Continuous wave (CW)*
  - *Flash lamps (Pulsed)*
  - *Arc lamps*

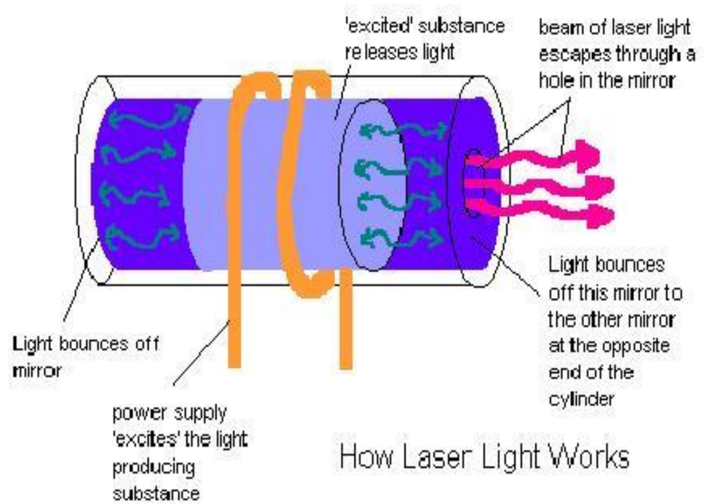
- *Laser sources*
  - *Continuous wave (CW)*
  - *Pulsed laser*
  - *Singe wavelength*



❑ Laser

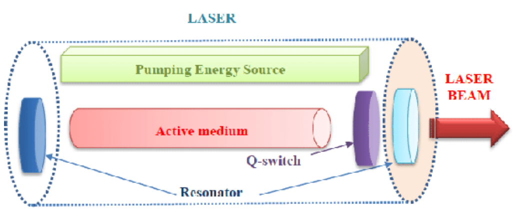
- *Laser: Light Amplification by Stimulated Emission of Radiation (LASER)*
- *How a laser works:*
  - *Radiation energy is produced by an activated medium(can be gas, crystal or semiconductor or liquid solution).*
  - *The medium consists of particles (atom, ions or molecules).*
  - *When a photo, having energy hv, approaching the particles, the photo may be absorbed cause an electron or atoms to be raised temporarily to high-energy level.*
  - *When the excited electron or molecule to return ground level, spontaneous emission or stimulated emission would take place.*

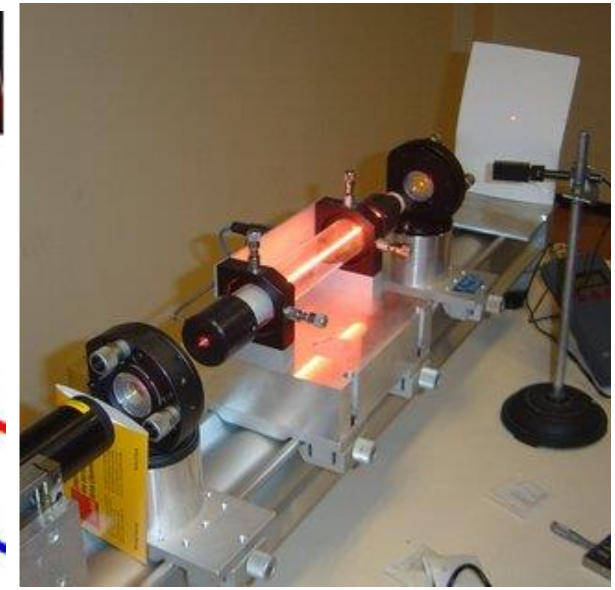




❑ Commonly used Lasers

– *Helium-neon (He-Ne) laser*
  - *Active medium is helium neon atoms*
  - *Continuous wave laser*
  - *Power 0.3 ~15 mW*
  - *λ =633nm (red)*



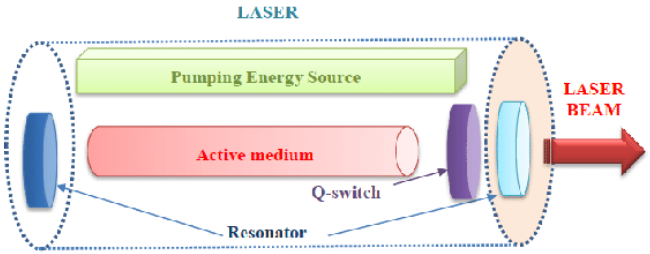


– *Argon-ion (Ar-ion) laser*
  - *Active medium is argon atoms maintained at the ion state.*
  - *Continuous wave laser*
  - *Power level: 100 mW ~10 W*
  - *Have seven wavelengths*
  - *λ =488n (blue)*
  - *λ =514.5nm (green)*
  - *LDV application*
  - *LIF in liquid flows*

Commonly used Lasers

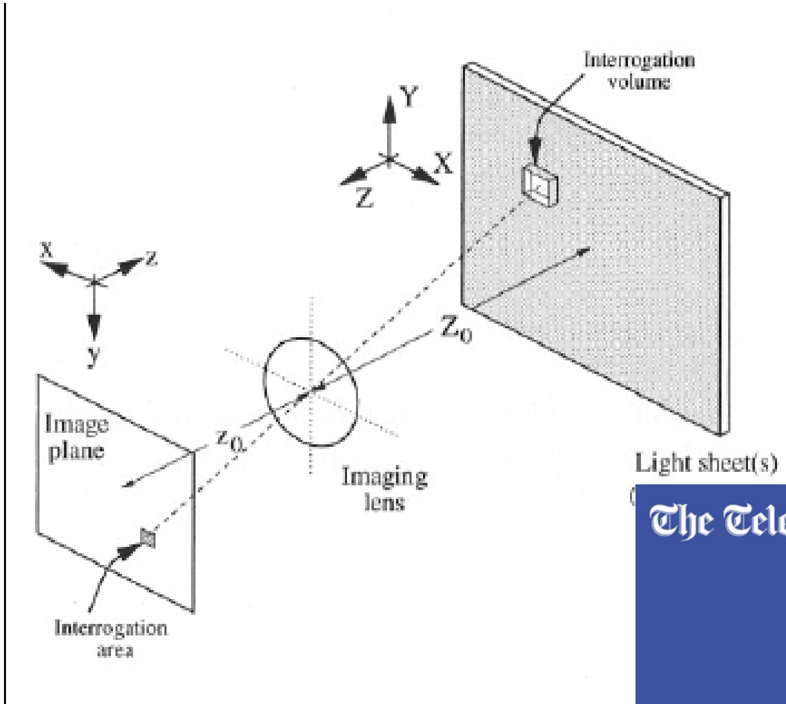
– **Nd-YAG laser**
- *Solid-state laser*
- *Active medium: neodymium (Nd+3) as active medium incorporated as an impurity into a crystal of Yattium-Aluminium-Garnet (YAG) as a host*
- *Flash lamp is used as external source*
- *pulsed laser: 10 -400mJ/pulse or more*
- *Pulse duration: 100ps ~ 10ns*
- *Wavelenght of tube λ =1064nm (infrared)*
- *SHG: λ =532nm (green), THG: λ =355nm (UV), FHG: λ =266nm (deepUV)*
- *PIV, MTV, PLIF*
- *Repetition rate can be as high as 30 Hz.*

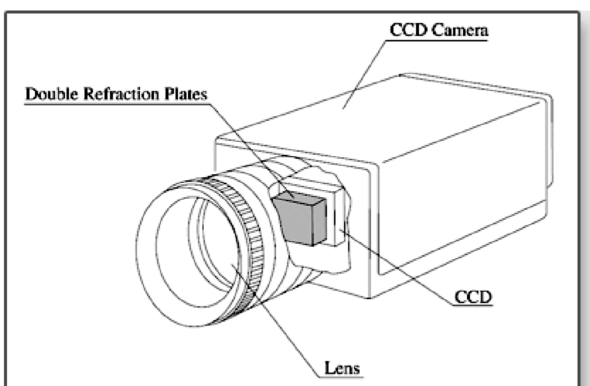
– **Dye laser**
- *Active medium: complex multi-atomic organic molecules*
- *λ =200nm ~ 1500nm*



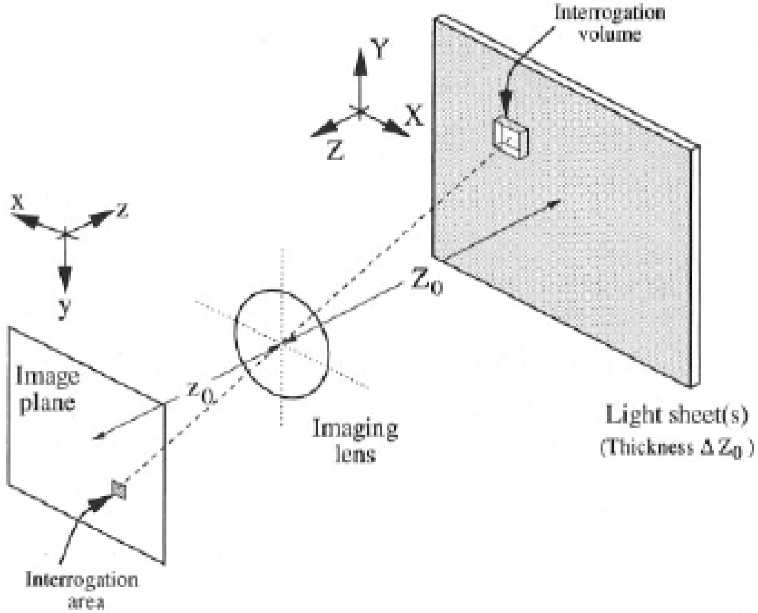
– **Excimer laser**
- *Gas laser KrF and Xecl*
- *High-energy*
- *UV wavelength*
- *Pulsed laser*
- *high repetition frequency*

❑ Light sensing and recording





❑ Lenses



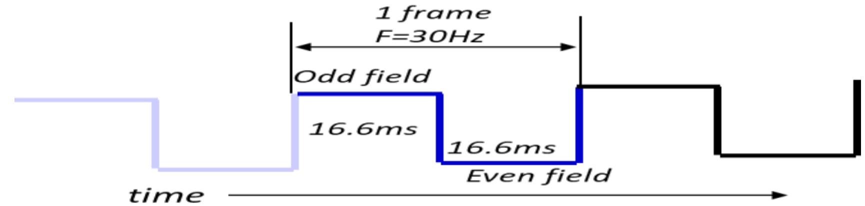
- Focal length: **f**
- **f/#** , "F-number": defined as the ratio of focal distance of the lens and its clear aperture diameter.
- Depth of focus ***H = 2 ·f/# · c · Z/f***

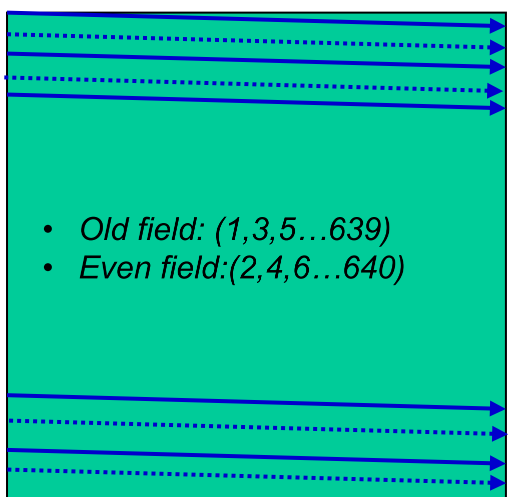
f2 F2.8	*f4 f5.6 f8 f11*	*f16 f 22*
wide aperture		*small aperture*
more light		*less light*
small number		*larger number*
		

Interlaced Cameras

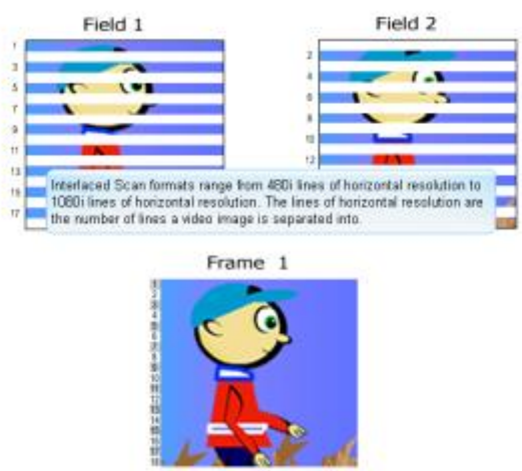
- *The fastest response time of human being for images is about* ***~ 15Hz***
- *Video format:*
  - *PAL (Phase Alternating Line) format with frame rate of f=25Hz (sometimes in 50Hz). Used by U.K., Germany, Spain, Portugal, Italy, China, India, most of Africa, and the Middle East*
  - *National Television Standards Committee (NTSC) with frame rate of f=30Hz. Used by U.S., Canada, Mexico, some parts of Central and South America, Japan, Taiwan, and Korea.*

480 pixels by 640 pixels





Interlaced camera



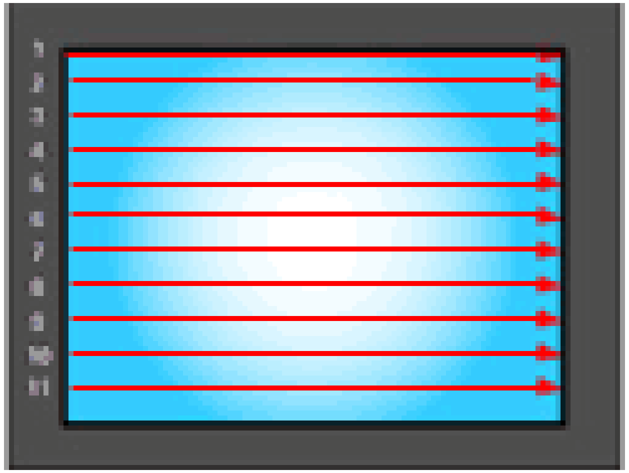
❑ Interlaced camera vs. Progressive Scan Camera

Note: In these examples, the cameras have been using the same lens. The car has been driving at 20 km/h (15 mph) using cruise control.

- *All image systems produce a clear image of the background*
- *Jagged edges from motion with interlaced scan*
- *Motion blur caused by the lack of resolution in the 2CIF sample*
- *Only progressive scan makes it possible to identify the driver*

Interlaced

Progressive Scan
(Non-interlaced)



One complete frame
using progressive scanning

Electronic shutter modes

- ***Rolling shutter:*** *The sensor is exposed line by line. Each of the pixels integrate light for the specified exposure time; however, not all pixels are exposing at the same time. The start time for each pixel's exposure is a function of sensor position. This mode is typical of large format sensors, such as digital SLR cameras.*

- ***Global shutter:*** *Each pixel integrates light for the specified exposure time simultaneously. This method is preferred for capturing highly dynamic events. This mode is typical of high-speed CMOS cameras which can operate at frame rates beyond 1 million frames per second.*

Rolling shutter
Point Grey Cameras

Gobal shutter
Point Grey Cameras

❑ Mystery of flying rods

- *WT testing @ 13:30;*
- *High-speed Imaging @29:30; 33:00; 38:20*