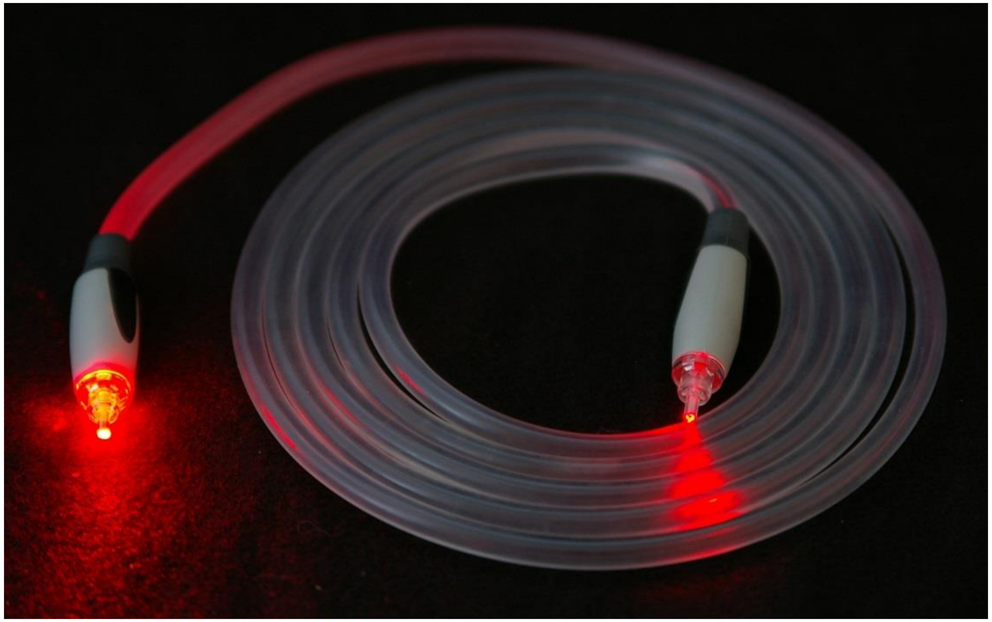
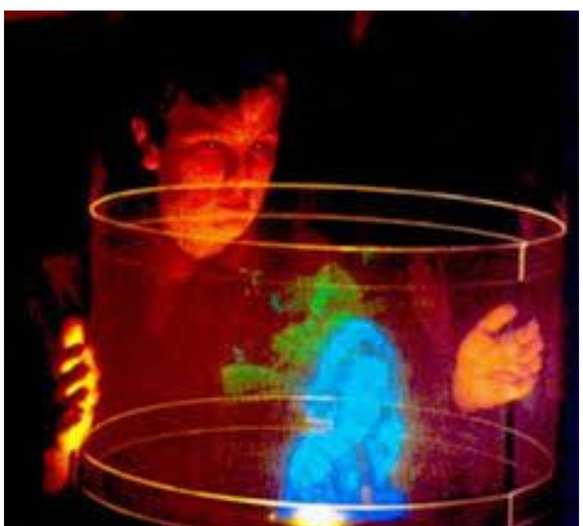


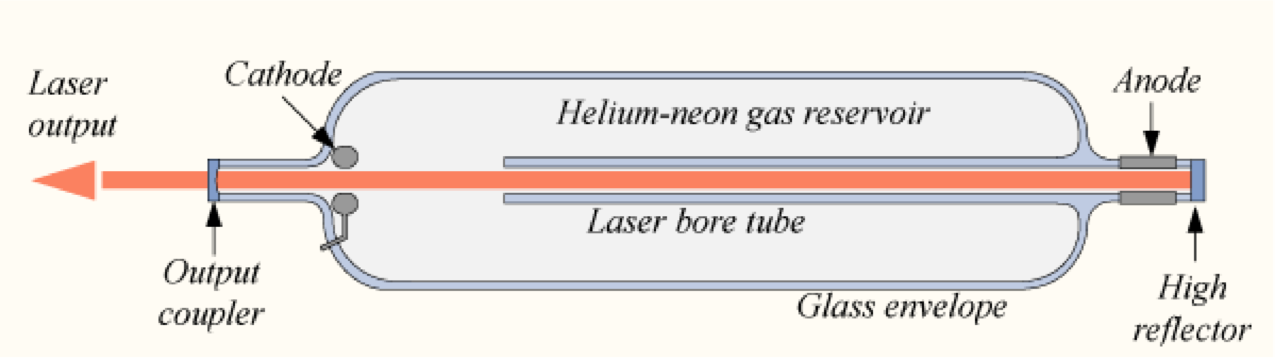
Lecture 3

Optics in everyday application: lasers, CCD cameras, optical fibers, liquid crystal displays, holography

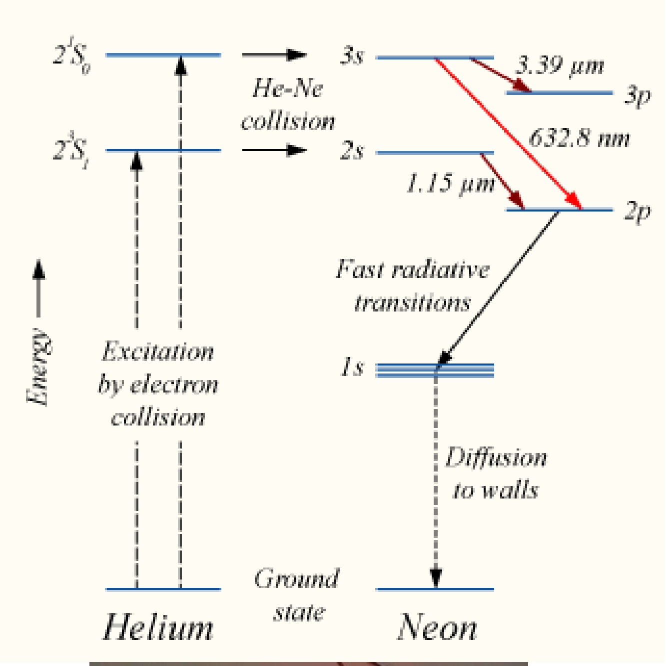


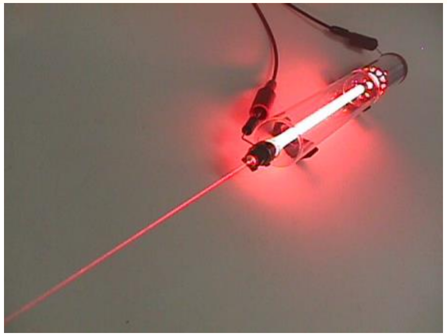
The gas laser

The He-Ne laser 1. (helium-neon)

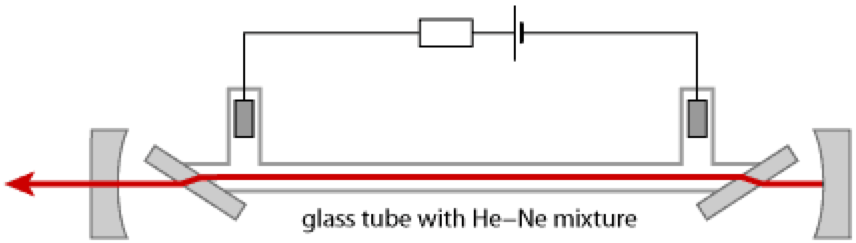


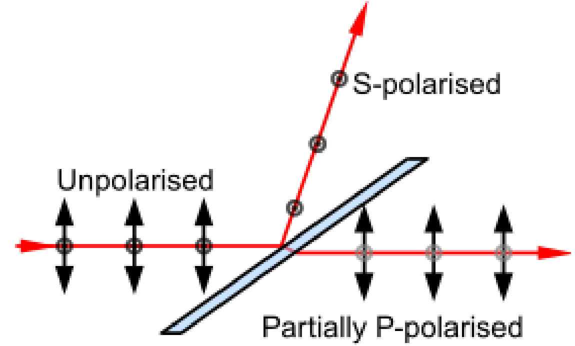
The mechanism producing population inversion and light amplification in a He-Ne laser plasma originates with inelastic collision of energetic electrons with ground state helium atoms in the gas mixture. As shown in the accompanying energy level diagram, these collisions excite helium atoms from the ground state to higher energy excited states, among them the 2^3S_1 and 2^1S_0 long-lived metastable states. Because of a fortuitous near coincidence between the energy levels of the two He metastable states, and the $3s_2$ and $2s_2$ (levels of neon, collisions between these helium metastable atoms and ground state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon.



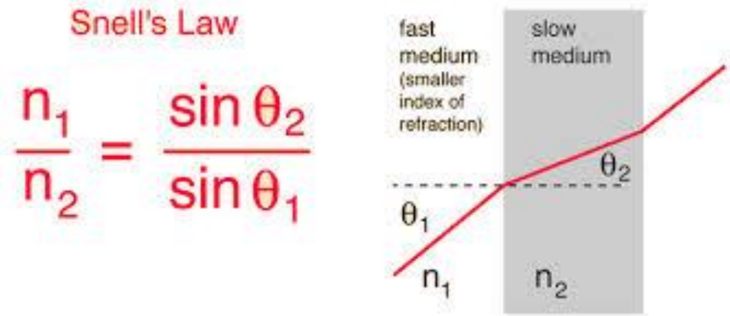


The He-Ne laser 2. (helium-neon)

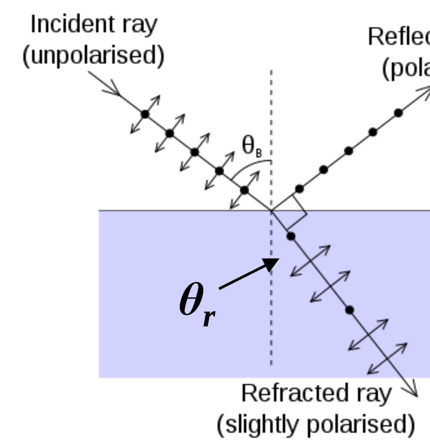




Gas lasers typically use a **window tilted at Brewster's angle** to allow the beam to leave the laser tube. Since the window reflects some *s*-polarized light but no *p*-polarized light, the gain for the *s* polarization is reduced, but that for the *p* polarization is not affected. This causes the laser's output to be *p* polarized, and allows lasing with no loss due to the window.



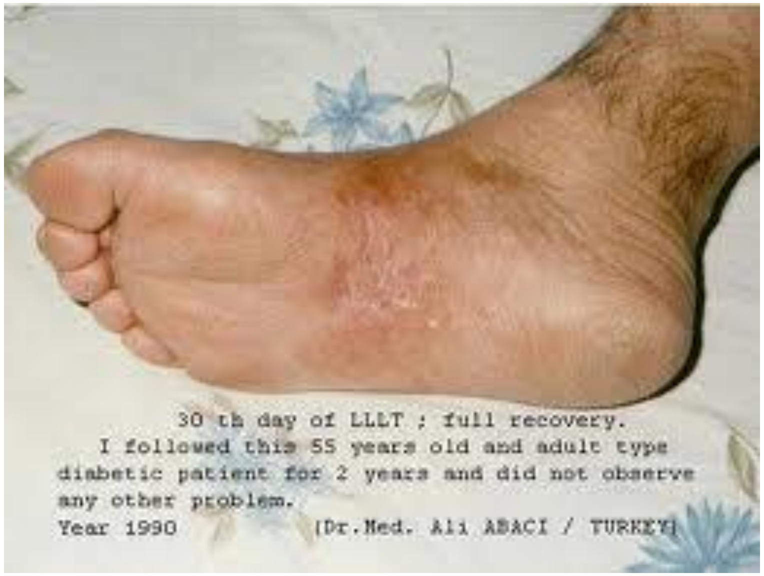
The physical mechanism for this can be qualitatively understood from the manner in which electric dipoles in the media respond to *p*-polarized light. One can imagine that light incident on the surface is absorbed, and then re-radiated by oscillating electric dipoles at the interface between the two media. The refracted light is emitted perpendicular to the direction of the dipole moment; no energy can be radiated in the direction of the dipole moment. That is, if the oscillating dipoles are aligned along the supposed direction of the reflection, no light is reflected at all.



$$\theta_r + \theta_B = 90^\circ \longrightarrow \boxed{tg\,\theta_B = \frac{n_2}{n_1}}$$

The He-Ne laser 3. (helium-neon)

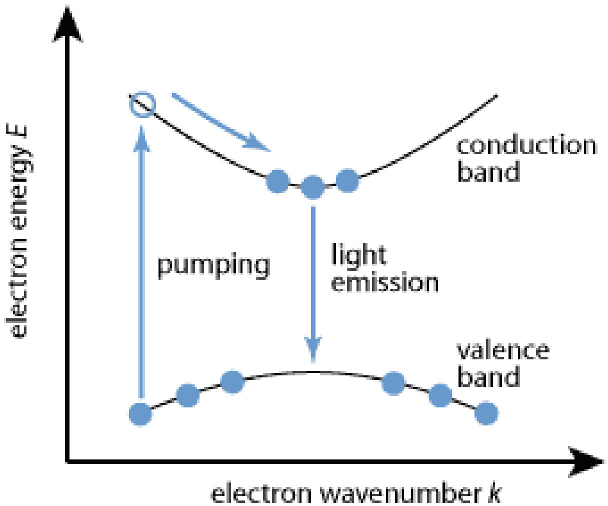
Medical treatment

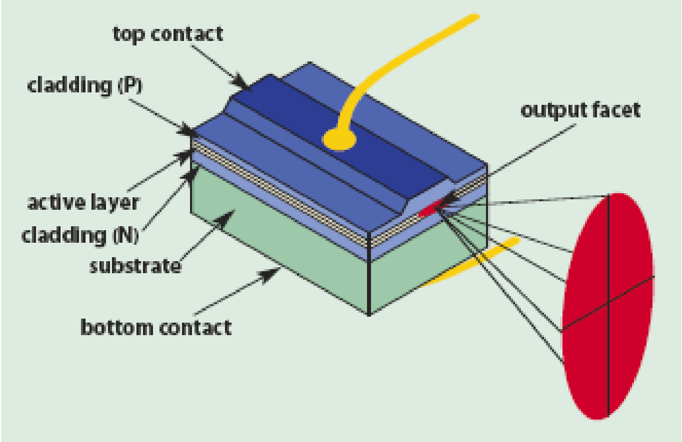


Cosmetic laser treatment

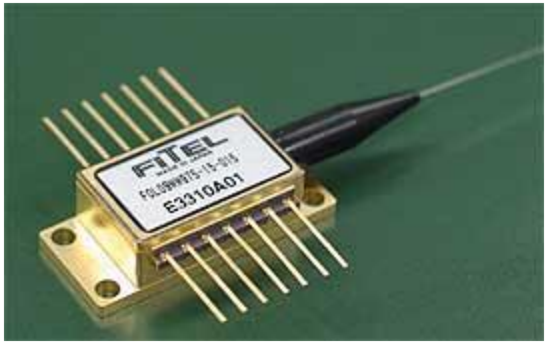
The semiconductor laser

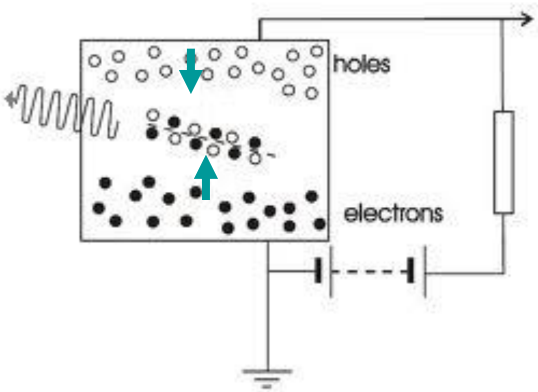
A **laser diode** is an electrically pumped semiconductor laser in which the active medium is formed by a p-n junction of a semiconductor diode similar to that found in a light-emitting diode. The laser diode is distinct from the optically pumped semiconductor laser, in which, while also semiconductor based, the medium is pumped by a light beam rather than electric current.





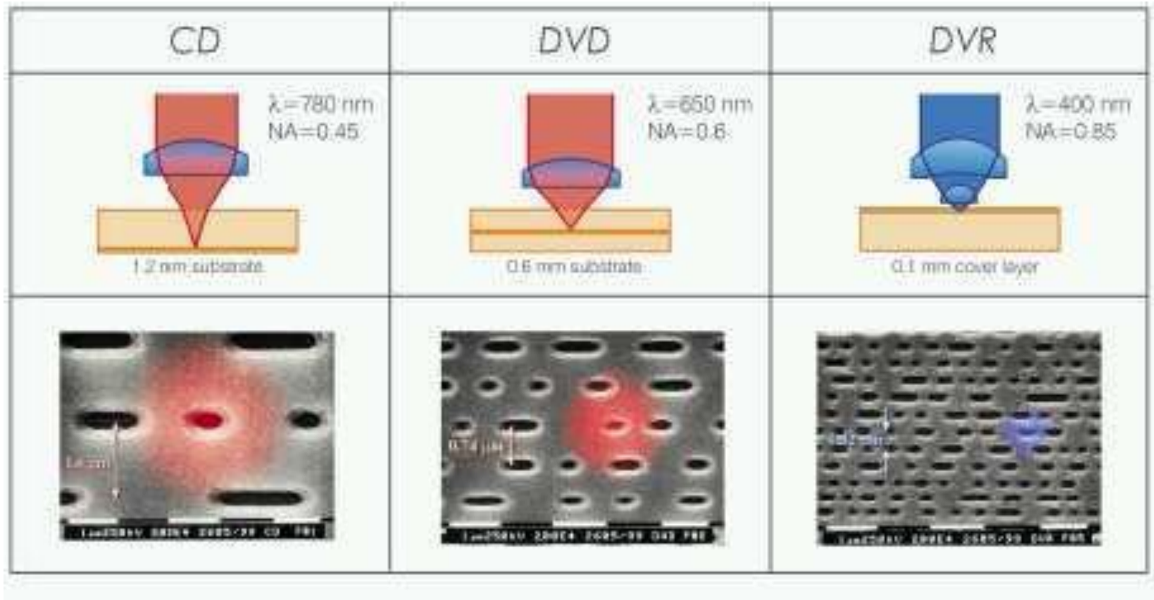
Light source in fiber-optic communication. High efficiency!

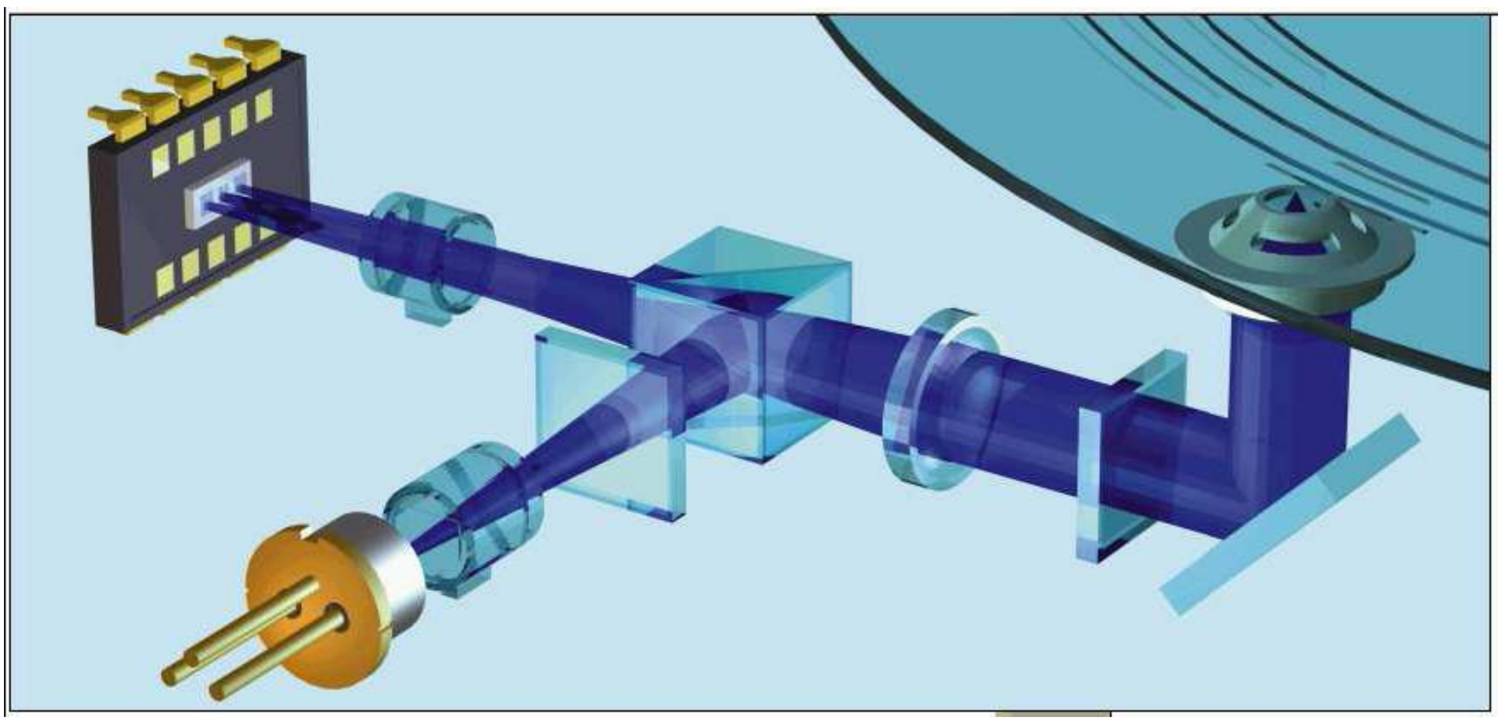




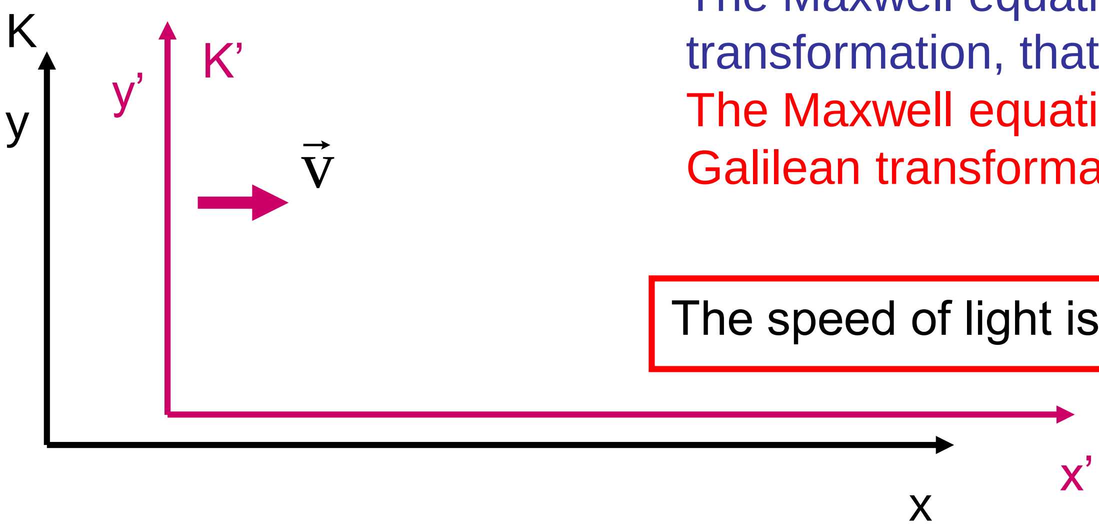
A semiconductor laser application

CD (or DVD) reader & writer (head)





The Lorentz-transformation



The transformation describe how measurements of space and time by two observers are related. The Maxwell equations are invariant to Lorentz transformation, that is a linear transformation. The Maxwell equations are not invariant to Galilean transformation (t=t', x=x'+vt).

The speed of light is the same in K and K': $c = c'$

The Lorentz-transformation:

$$x = \gamma(x' + vt') \quad \& \quad t = \gamma\left(t' + \frac{v}{c^2}x'\right)$$

$$x' = \gamma(x - vt) \quad \& \quad t' = \gamma\left(t - \frac{v}{c^2}x\right)$$

K → K' : v → -v

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The Doppler-effect 1.

The electromagnetic wave in K (traveling along the x axis):

$$E(x,t) = E_0 \cos(\omega t - kx) = A\cos\left(2\pi f t - \frac{2\pi}{\lambda} x\right)$$

The electromagnetic wave in K' (traveling along the x' axis):

$$E(x,t) = A\cos\left[2\pi f \gamma\left(t' + \frac{v}{c^2} x'\right) - \frac{2\pi}{\lambda}\gamma\left(x' + vt'\right)\right] \qquad \frac{1}{\lambda} = \frac{f}{c}$$

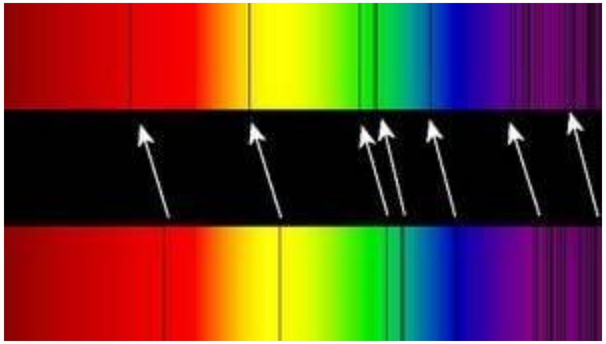
$$E(x,t) = A\cos\left[2\pi f \frac{1-\frac{v}{c}}{\sqrt{1-\frac{v^2}{c^2}}} t' - \frac{2\pi}{\lambda} \frac{1-\frac{v}{c}}{\sqrt{1-\frac{v^2}{c^2}}} x'\right] = A\cos\left[2\pi \underbrace{f\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}} t' - 2\pi \underbrace{\frac{1}{\lambda}\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}} x'\right]$$

$$f' = f\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} \qquad \lambda' = \lambda\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$

The Doppler-effect 2.

Parsec: 1pc = 3,26 light-year

The **parsec** is a unit of length used in astronomy.



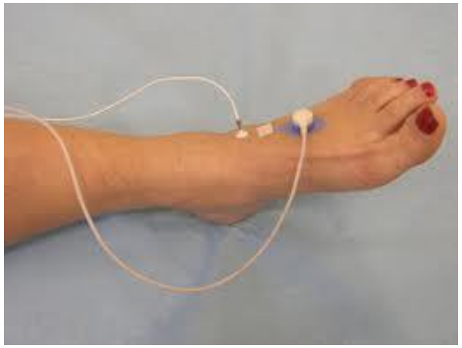
Hubble's law: $v = H_o s$

The Hubble-constant:

$H_0 = 67.0 \pm 3.2$ (km/s)/Mpc

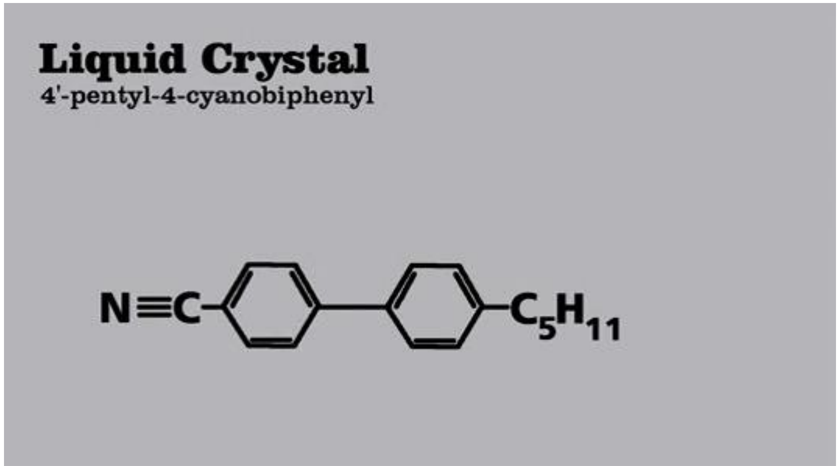
All the objects observed in deep space (intergalactic space) are found to have a Doppler shift observable relative velocity to Earth, *and* to each other. The Doppler-shift-measured velocity, of various **galaxies receding from the Earth**, is proportional to their distance from the Earth and all other interstellar bodies. In effect, the space-time volume of the observable universe is expanding and Hubble's law is the direct physical observation of this process. The motion of astronomical objects due solely to this expansion is known as the **Hubble flow**. Hubble's law is considered the first observational basis for the expanding space paradigm and today serves as one of the pieces of evidence most often cited in support of the **Big Bang model**.

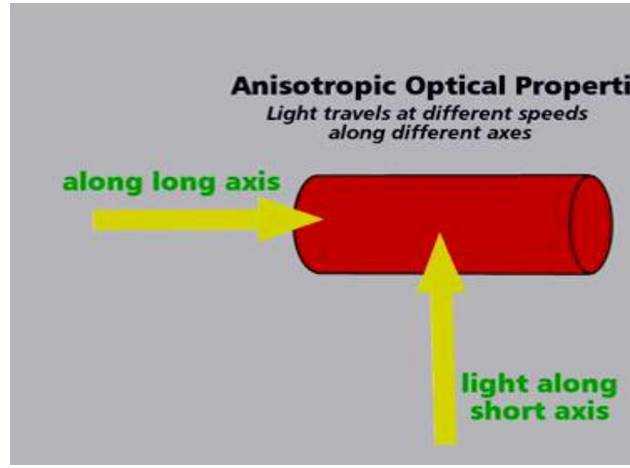
The laser "radar". (LDV)



LDV is used to measure blood flow in human tissues.

Optical activity



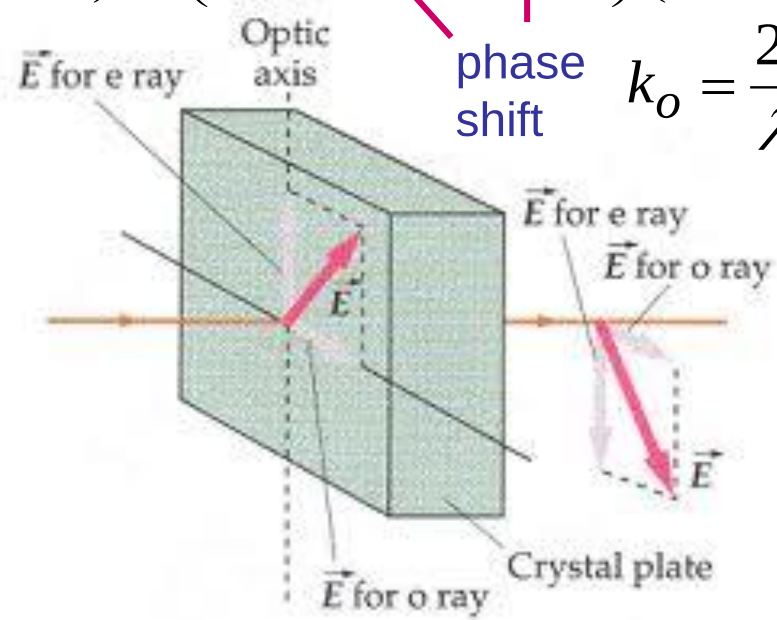


$$n_x \neq n_y$$

$$\begin{pmatrix} E_x(\ell) \\ E_y(\ell) \end{pmatrix} = \begin{pmatrix} e^{in_x k_o \ell} & 0 \\ 0 & e^{in_y k_o \ell} \end{pmatrix} \begin{pmatrix} E_x(0) \\ E_y(0) \end{pmatrix}$$

phase shift

$$k_o = \frac{2\pi}{\lambda_o}$$



Optical rotation (optical activity) is the turning of the plane of linearly polarized light about the direction of motion as the light travels through certain materials. It occurs in solutions of chiral molecules such as sucrose (sugar), solids with rotated crystal planes such as quartz. It is used in the sugar industry to measure syrup concentration, in optics to manipulate polarization, in chemistry to characterize substances in solution. It is being developed as a method to measure blood sugar concentration in diabetic people.

The liquid-crystal 1.

Each pixel of an LCD typically consists of a layer of molecules aligned between two transparent electrodes, and two polarizing filters, the axes of transmission of which are (in most of the cases) perpendicular to each other. Without the liquid crystal between the polarizing filters, light passing through the first filter would be blocked by the second (crossed) polarizer.

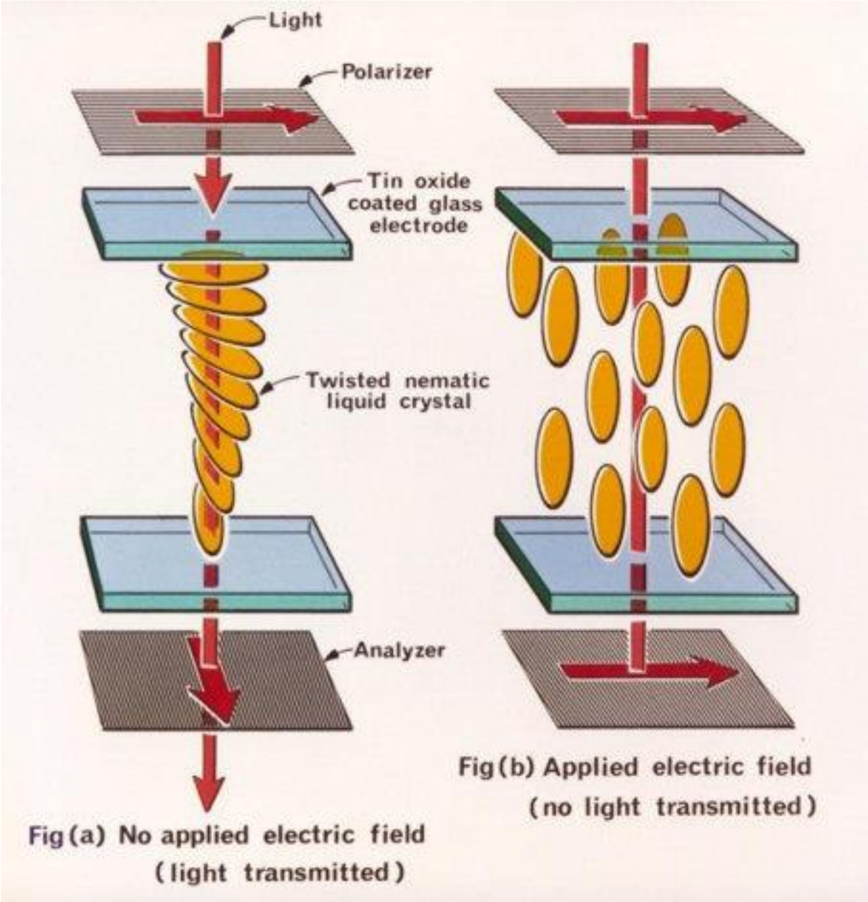
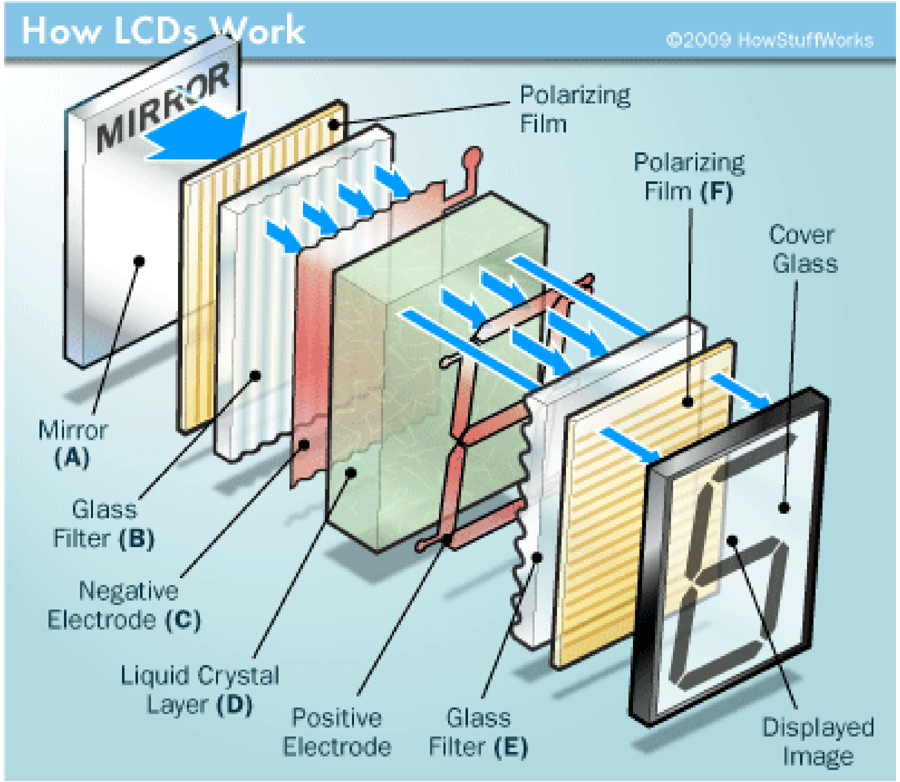


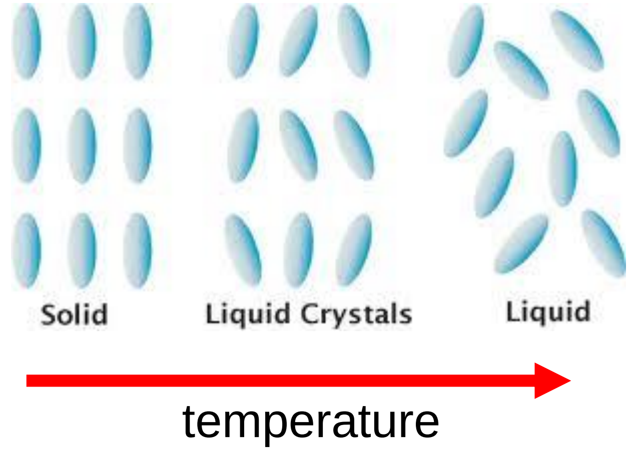
Fig (a) No applied electric field (light transmitted)

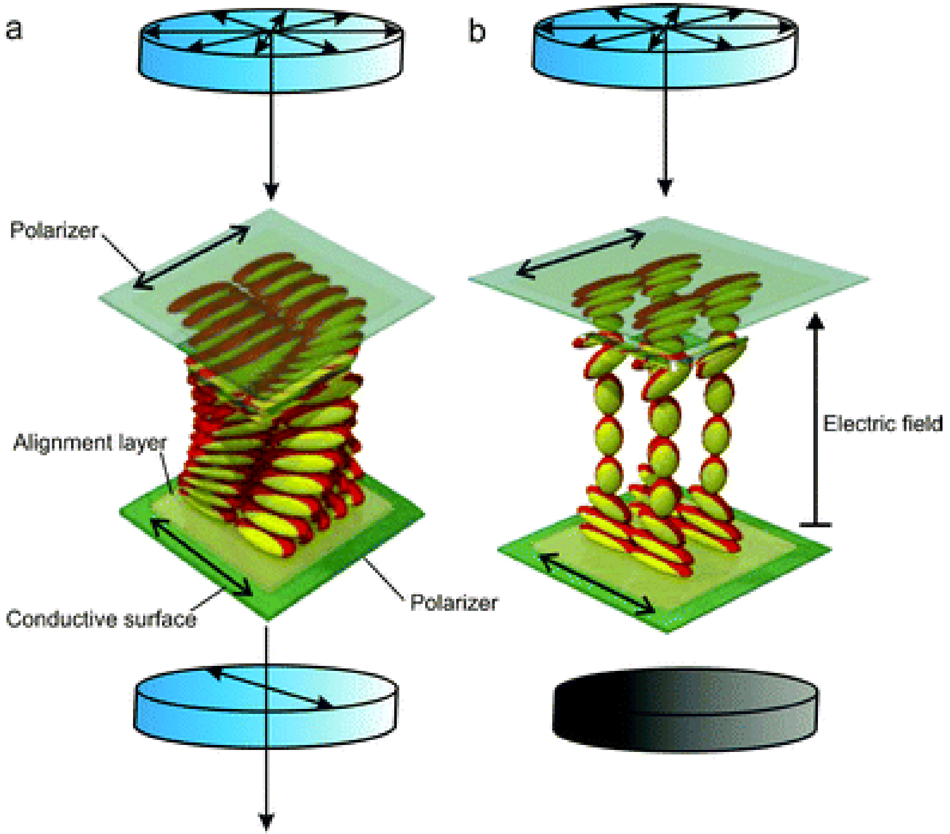
Fig (b) Applied electric field (no light transmitted)



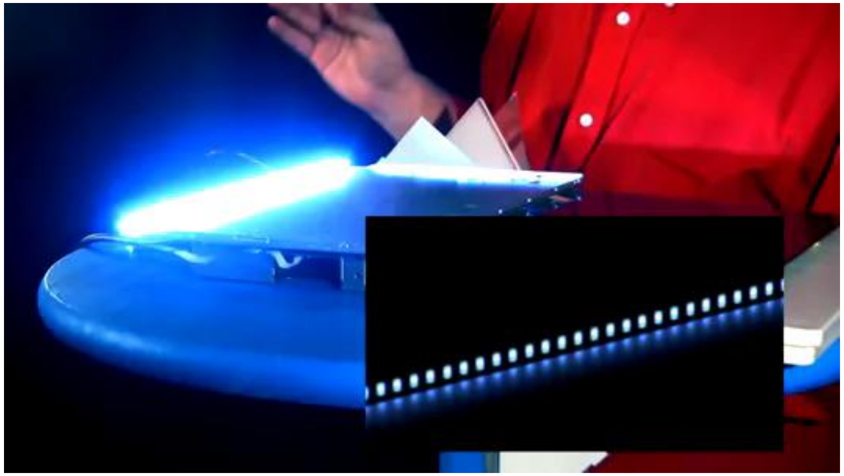
The liquid-crystal 2.

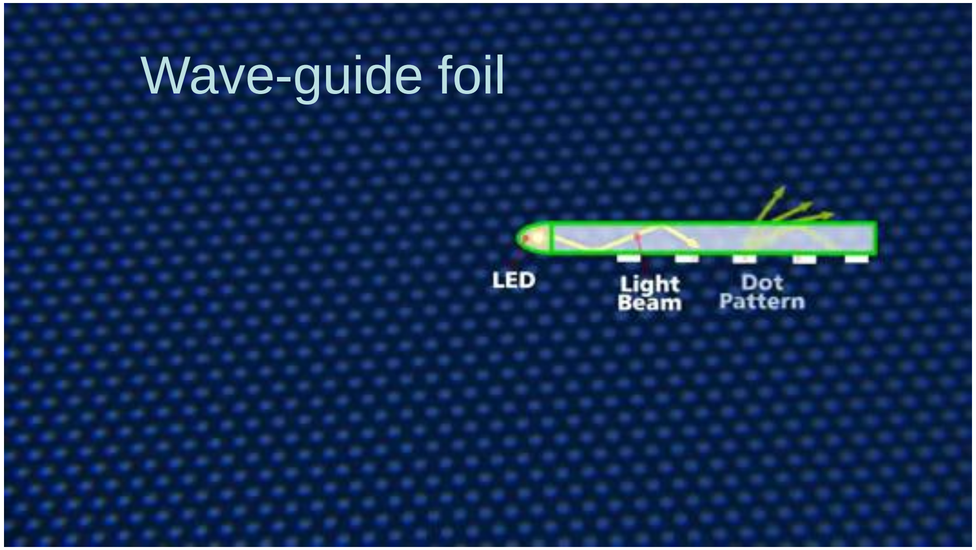
The twisted nematic effect is based on the precisely controlled realignment of liquid crystal molecules between different ordered molecular configurations under the action of an applied electric field. This is achieved with little power consumption and at low operating voltages.

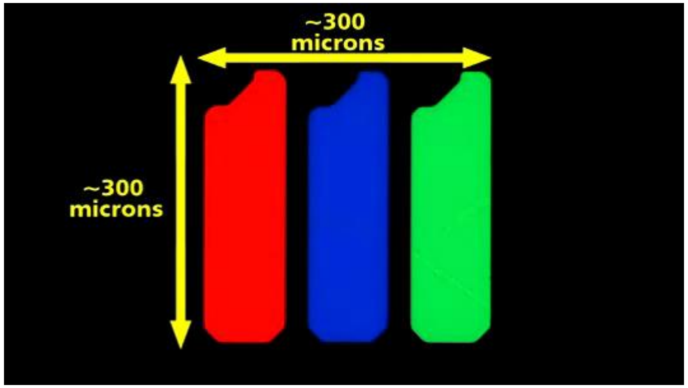


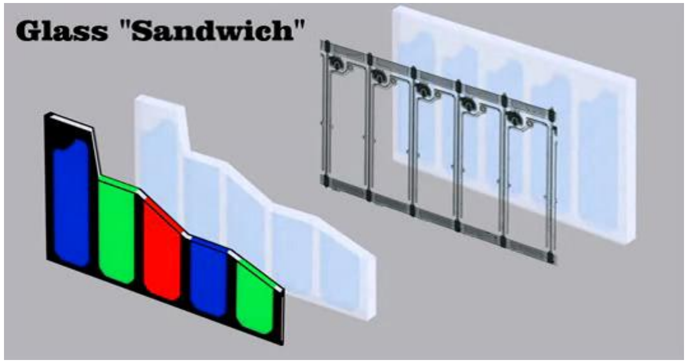


The liquid-crystal 3.

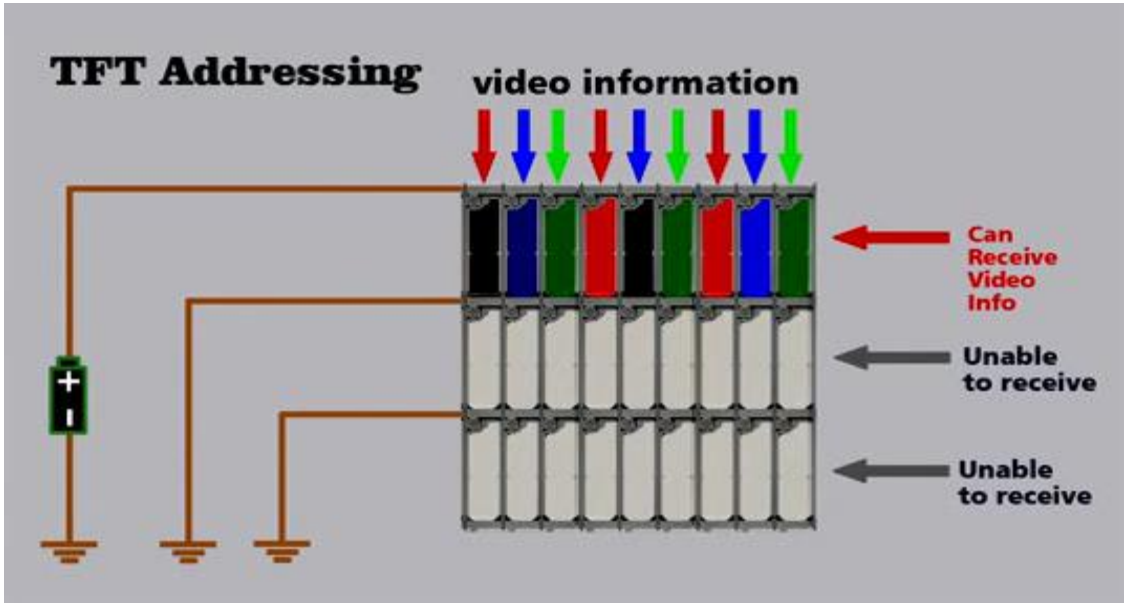




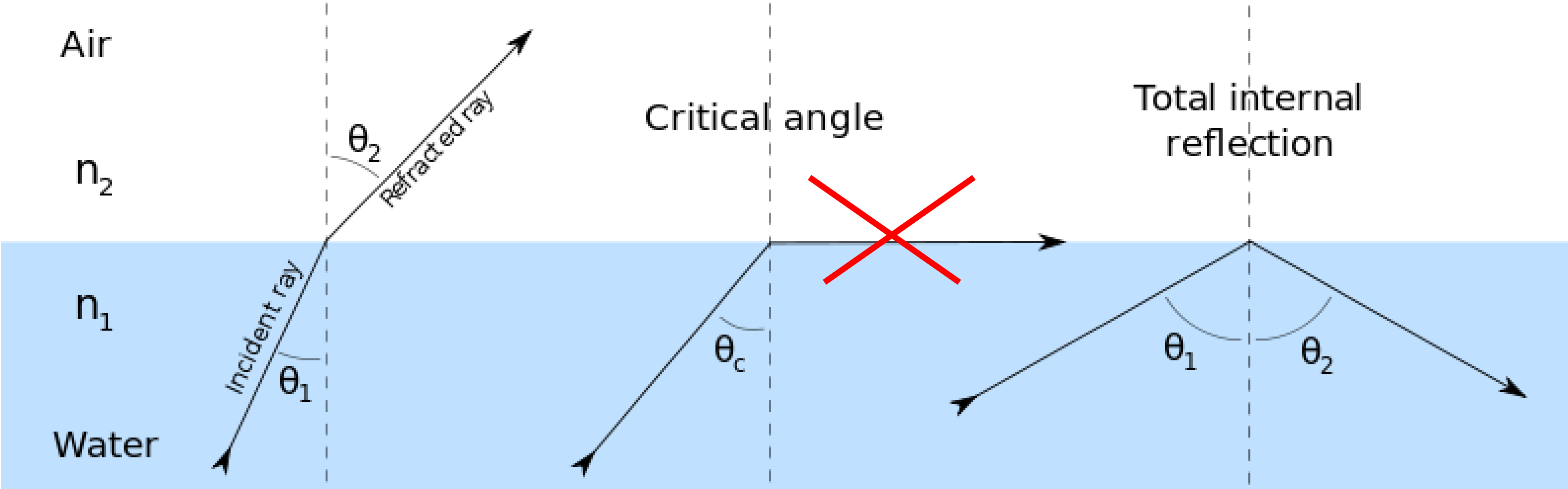




The structure of LCD monitor

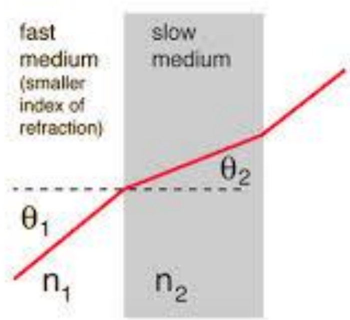


Optical fibers 1.



Snell's Law

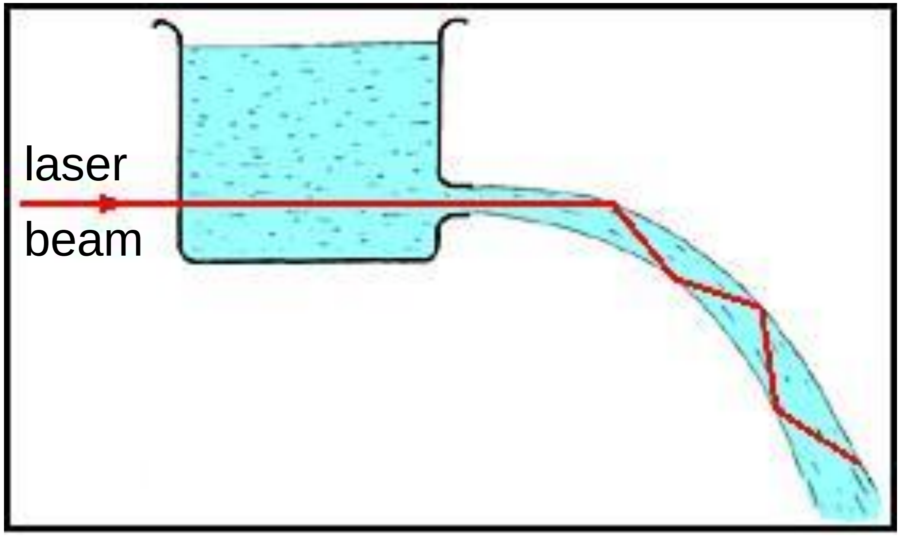
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

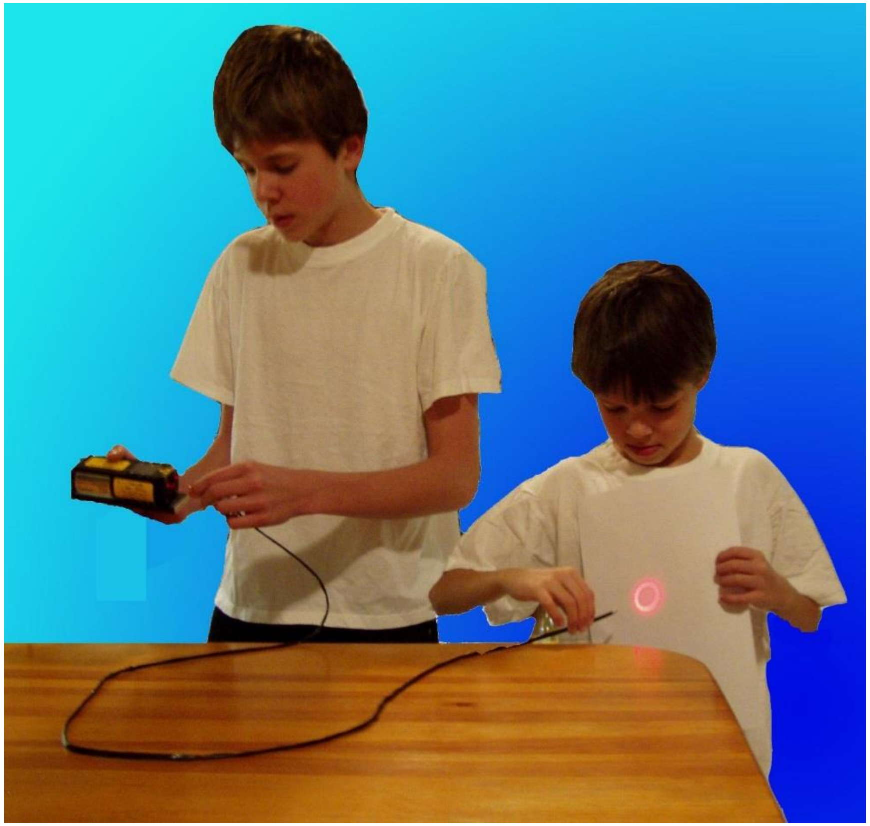


Total internal reflection: the wave cannot pass through and is entirely reflected. This can only occur where the wave travels from a medium with a higher refractive index (n_1) to one with a lower refractive index (n_2). For example, it will occur with light when passing from glass to air, but not when passing from air to glass.

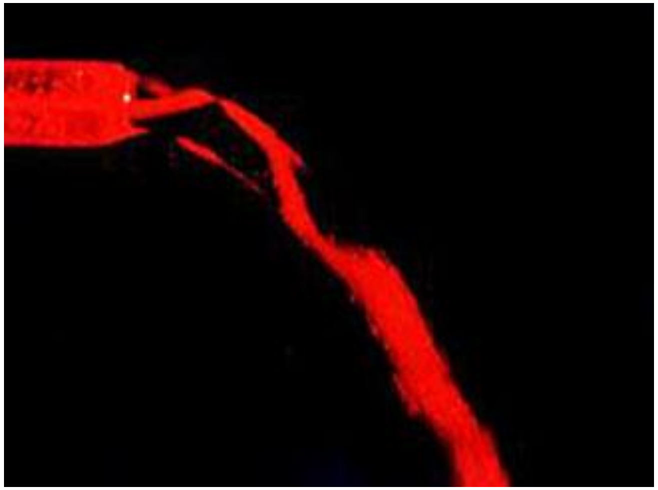
The critical angle: $$\sin\theta_c = \frac{n_1}{n_2}$$

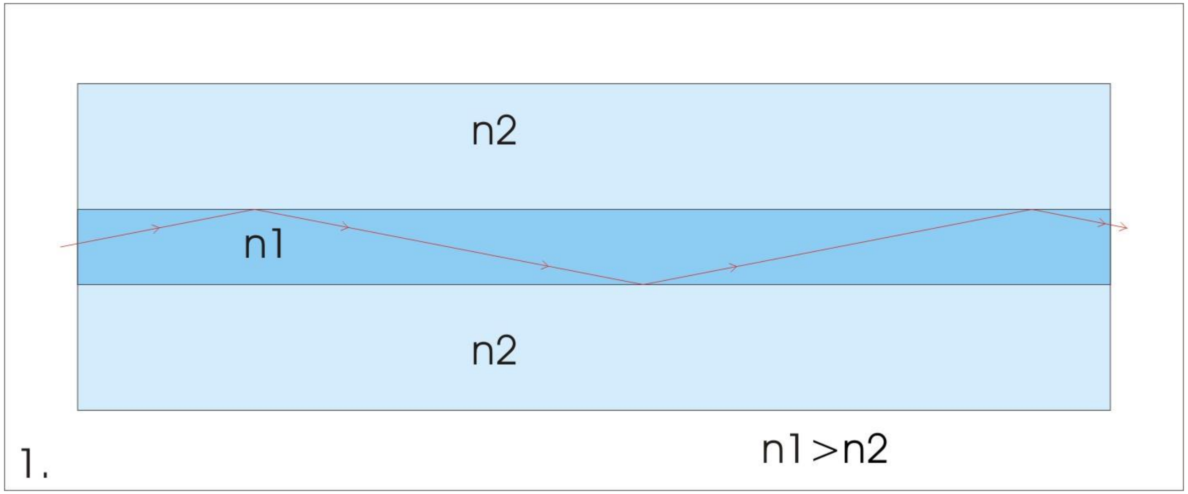
Optical fibers 2.



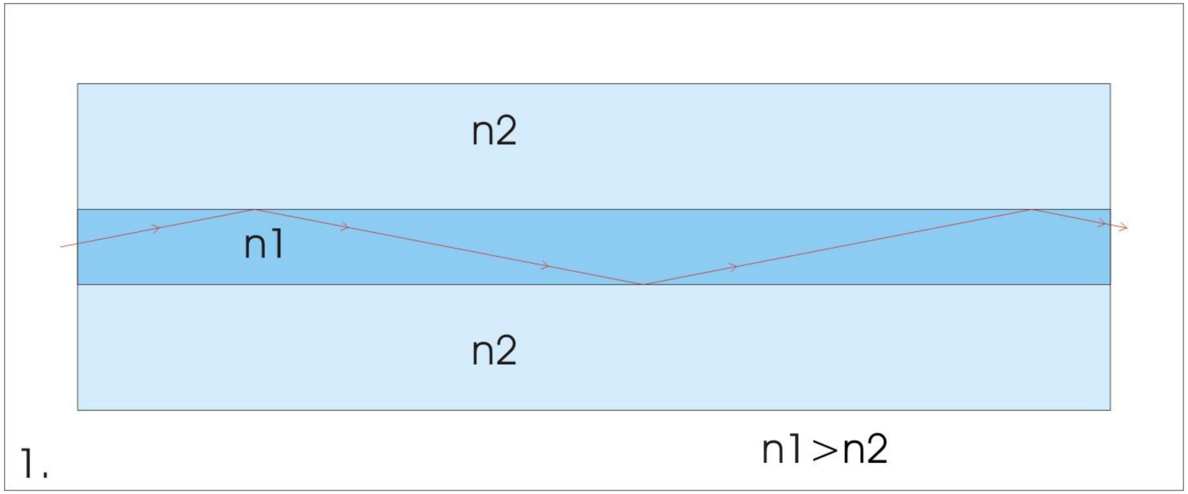


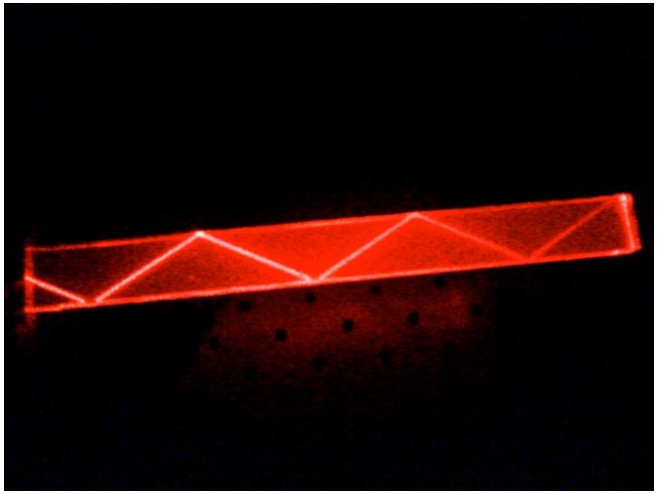
Total internal reflection





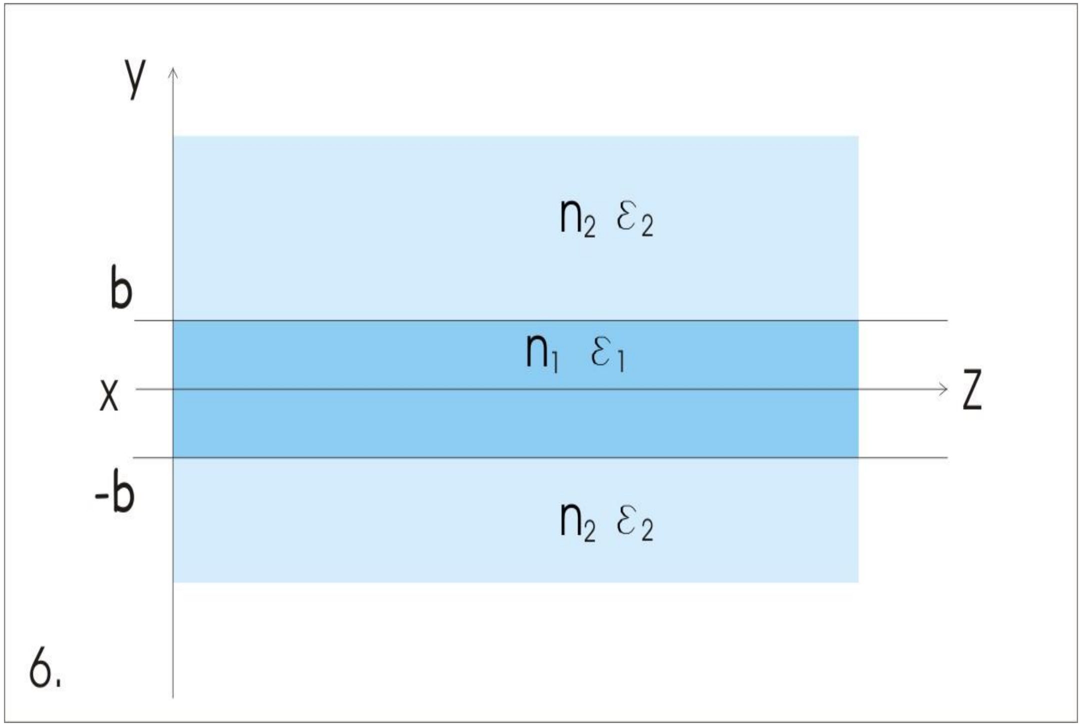
Optical fibers 3.





Fiber with a core diameter less than about ten times the wavelength of the propagating light cannot be modeled using geometric optics. Instead, it must be analyzed as an electromagnetic structure, by solution of Maxwell's equations as reduced to the electromagnetic wave equation. As an optical waveguide, the fiber supports one or more confined transverse modes by which light can propagate along the fiber.
The waveguide analysis shows that **the light energy in the fiber is not completely confined in the core**. Instead, especially in single-mode fibers, a significant fraction of the energy in the bound mode travels in the cladding as an evanescent wave.

Symmetric waveguide



Conditions:

x: $\longrightarrow \infty$: $\frac{\partial}{\partial x} = 0$

z: direction of traveling

$$\varepsilon_1 > \varepsilon_2$$

Time dependance:
exp[i(ωt-βz)]

Maxwell eq.-s:

(j=1, 2)

$$\frac{\partial H_z}{\partial y} + i\beta H_y = i\omega\varepsilon_o\varepsilon_j E_x$$

$$-i\beta H_x = i\omega\varepsilon_o\varepsilon_j E_y$$

$$-\frac{\partial H_x}{\partial y} = i\omega\varepsilon_o\varepsilon_j E_z$$

T.M.

T.E.

$$\frac{\partial E_z}{\partial y} + i\beta E_y = -i\omega\mu_o H_x$$

$$-i\beta E_x = -i\omega\mu_o H_y$$

$$-\frac{\partial E_x}{\partial y} = -i\omega\mu_o H_z$$

T.E. (5), (6) →(1) : $\dfrac{\partial^2 E_x}{\partial y^2} + \left(k_o^2\varepsilon_j - \beta^2\right)E_x = 0$ $\qquad \left(k_o = \omega\sqrt{\varepsilon_o\omega_o}\right)$

Traveling modes: $k_o^2\varepsilon_2 < \beta^2 < k_o^2\varepsilon_1$

New variables:

$$k_1^2 = k_o^2\varepsilon_1 - \beta^2$$

$$\kappa_2^2 = \beta^2 - k_o^2\varepsilon_2$$

Substance 1: $\frac{d^2E_x}{dy^2} + k_1^2 E_x = 0 \longrightarrow$

(n_1)

$$E_x = A\cos(k_1 y)$$

$$H_y = A\frac{\beta}{\omega\mu_o}\cos(k_1 y)$$

$$H_z = -A\frac{k_1}{i\omega\mu_o}\sin(k_1 y)$$

Solution(s): sin , <u>cos</u>

Substance 2 : $\frac{d^2E_x}{dy^2} - \kappa_2^2 E_x = 0 \longrightarrow$

(n_2)

$$E_x = Be^{-\kappa_2|y|}$$

$$H_y = B\frac{\beta}{\omega\mu_o}e^{-\kappa_2|y|}$$

$$H_z = \mp B\frac{\kappa_2}{i\omega\mu_o}e^{-\kappa_2|y|}$$

Boundary conditions: $A\cos(k_1 b) = Be^{-\kappa_2 b}$

$$-A\frac{k_1}{i\omega\mu_o}\sin(k_1 b) = -B\frac{\kappa_2}{i\omega\mu_o}e^{-\kappa_2 b} \longrightarrow \text{det.=0} \longrightarrow \boxed{tg(k_1 b) = \frac{\kappa_2}{k_1}}$$

$$k_1^2 + \kappa_2^2 = k_o^2(\varepsilon_1 - \varepsilon_2)$$

$$\kappa_2 = \sqrt{k_o^2(\varepsilon_1 - \varepsilon_2) - k_1^2}$$

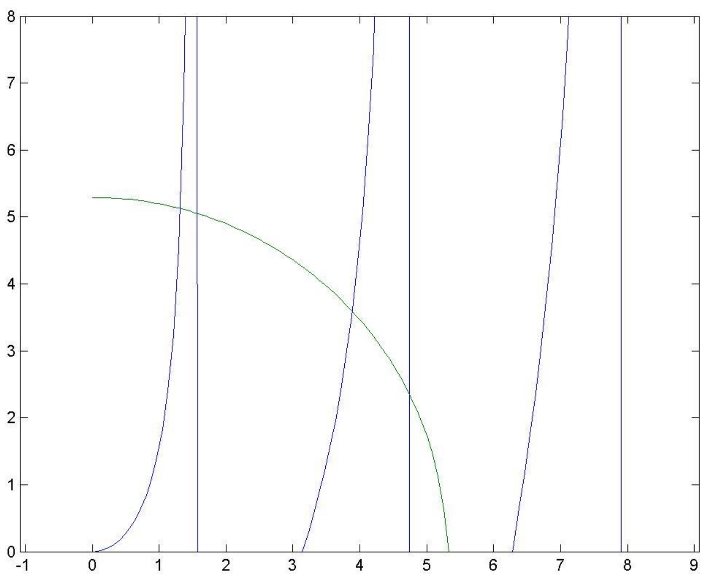
$$k_1 tg(k_1 b) = \sqrt{k_o^2(\varepsilon_1 - \varepsilon_2) - k_1^2}$$

Intr.:

$$u = k_1 b$$
$$w = \kappa_2 b$$
$$V = b k_o \sqrt{\varepsilon_1 - \varepsilon_2}$$

$$u tg(u) = \sqrt{V^2 - u^2}$$
$$u^2 + w^2 = V^2$$

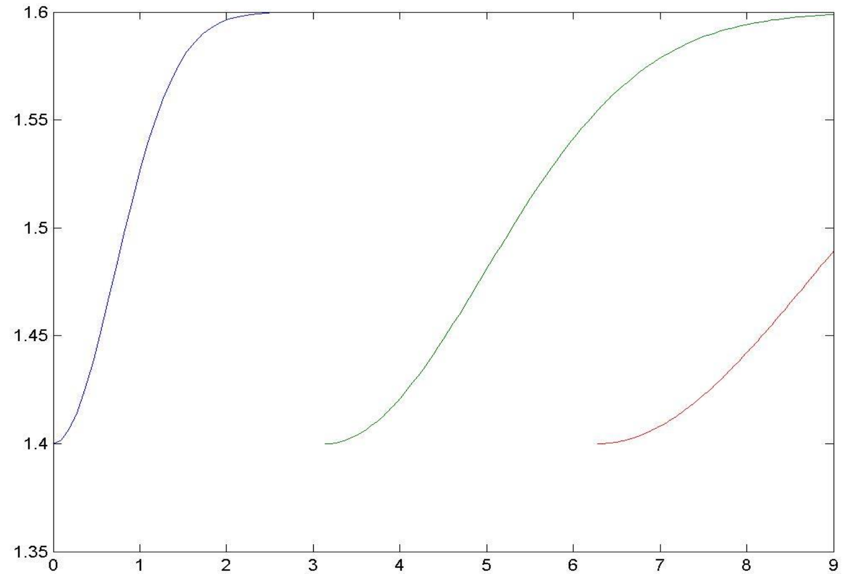
$\boldsymbol{w}$



$\boldsymbol{u}$

π 2π

$\dfrac{\beta}{k_0}$



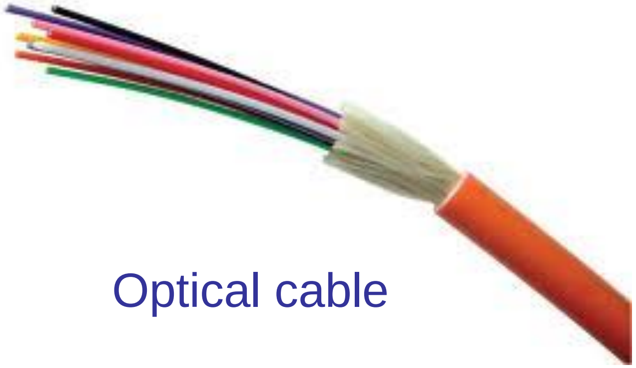
n_1

n_2

π 2π

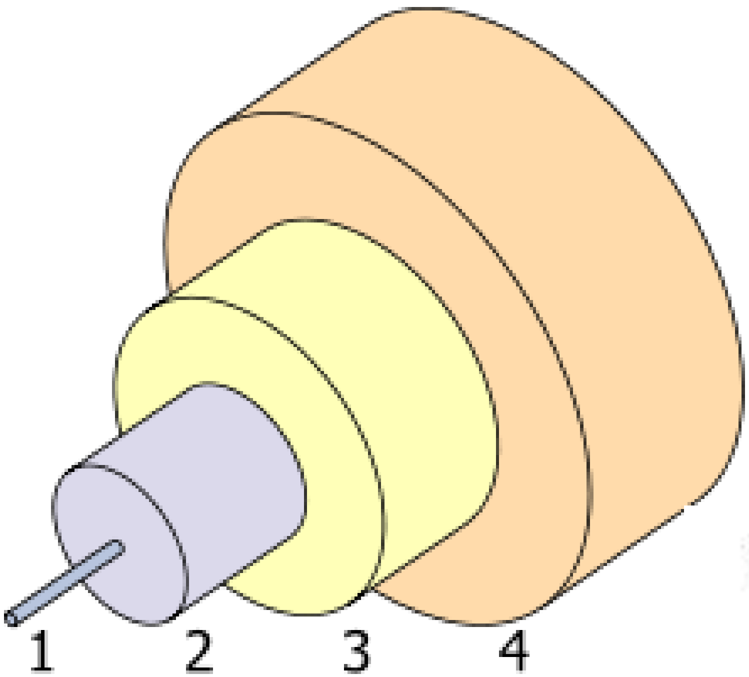
V

Optical fibers 4.



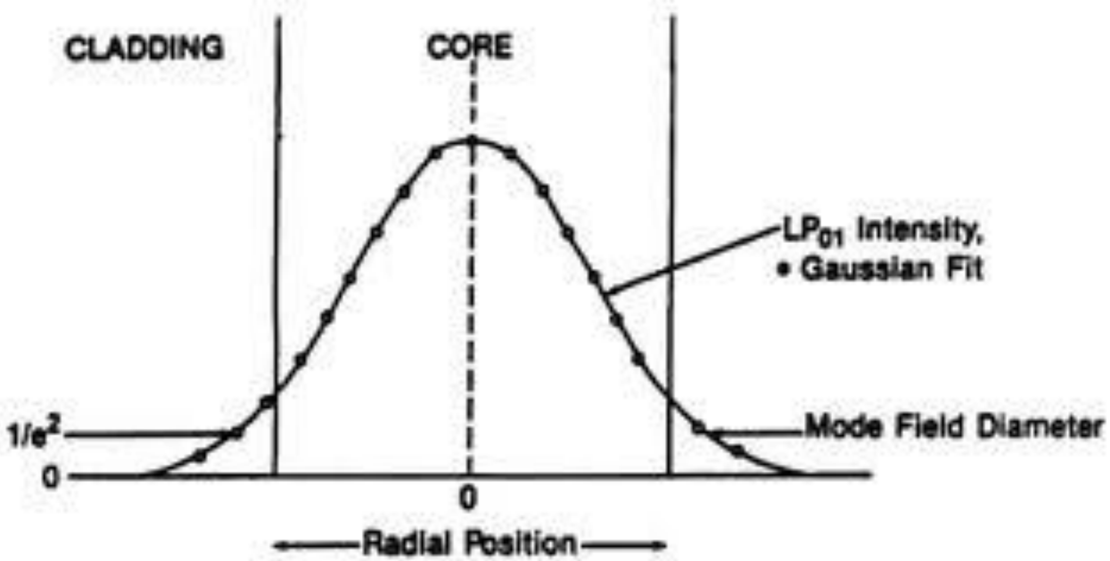
Optical cable

Connectors of multimode fibres



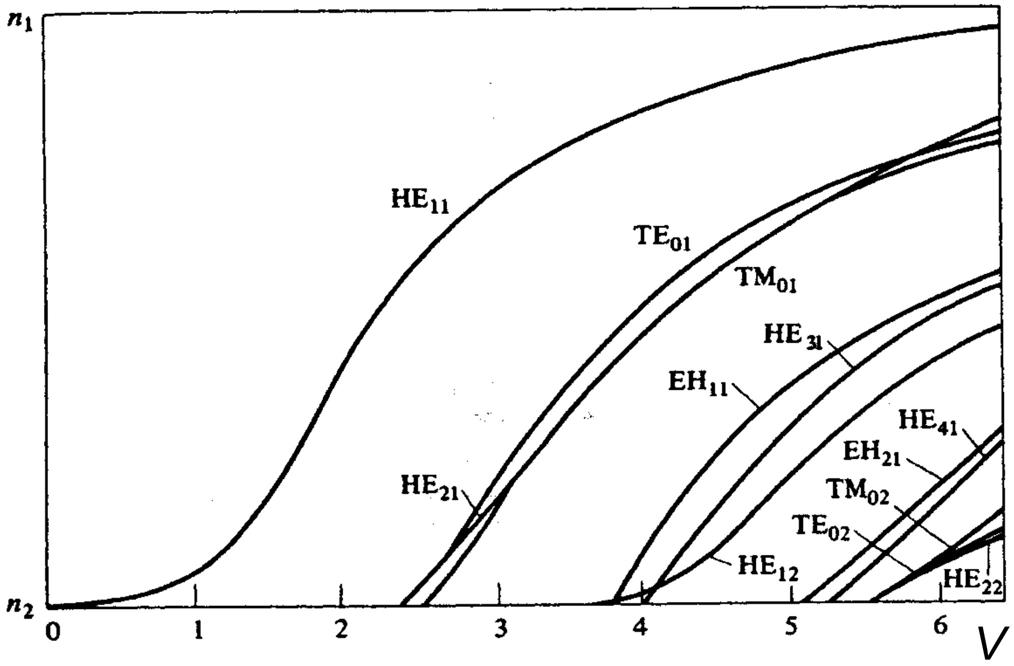
The structure of a typical single-mode fiber.

1. Core: 8 μm diameter
2. Cladding: 125 μm dia.
3. Buffer: 250 μm dia.
4. Jacket: 400 μm dia.

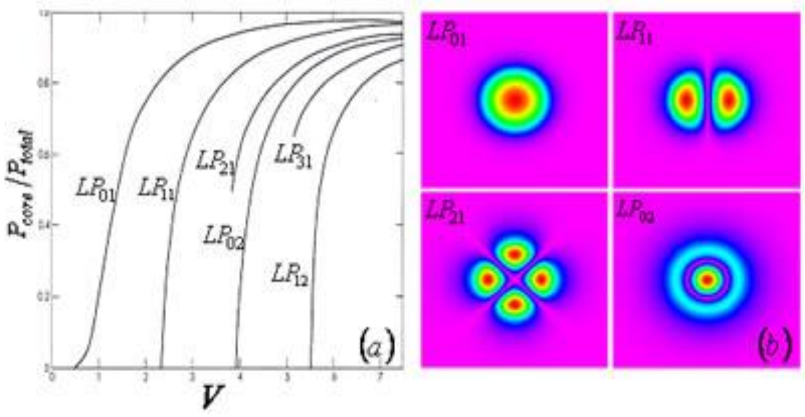


Intensity distribution

Optical fibers 5.



V ~ ***a***, where ***a*** is the radius of the core. $\boldsymbol{n_1}$ and $\boldsymbol{n_2}$ are the refractive indexes of the core and the cladding.



Modes of EMW in optical fibre

The electromagnetic structure can be described by solution of Maxwell's equations as it reduced to the electromagnetic wave equation. The electromagnetic analysis may also be require to understand behaviors such as speckle that occur when coherent light propagates in multi-mode fiber. As an optical waveguide, the fiber supports one or more confined transverse modes by which light can propagate along the fiber. Fiber supporting only one mode is called *single-mode* or *mono-mode fiber*.

The most common type of single-mode fiber has a core diameter of 8–10 μm and is designed for use in the near infrared; wavelength: λ = 1550 nm.

The ***advantages of optical fiber communication*** with respect to copper wire systems are:-

1. **Broad Bandwidth**

Broadband communication is very much possible over fiber optics which means that audio signal, video signal, microwave signal, text and data from computers can be modulated over light carrier wave and demodulated by optical receiver at the other end. It is possible to transmit around 3,000,000 full-duplex voice or 90,000 TV channels over one optical fiber.

2. **Immunity to Electromagnetic Interference**

Optical fiber cables carry the information over light waves which travel in the fibers due to the properties of the fiber materials, similar to the light traveling in free space. The light waves (EMW) are unaffected by other electromagnetic radiation nearby. The optical fiber is electrically non-conductive, so it does not act as an antenna to pick up electromagnetic signals which may be present nearby. So the information traveling inside the optical fiber cables is immune to electromagnetic interference e.g. radio transmitters, power cables adjacent to the fiber cables, or even electromagnetic pulses generated by nuclear devices.

3. **Low attenuation loss over long distances**

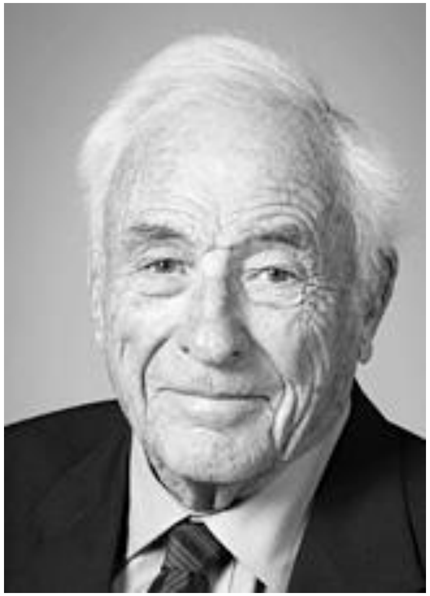
There are various optical windows in the optical fiber cable at which the attenuation loss is found to be comparatively low and so transmitter and receiver devices are developed and used in these low attenuation region. Due to low attenuation of 0.2dB/km in optical fiber cables, it is possible to achieve long distance communication efficiently over information capacity rate of 1 Tbit/s.

4 **Electrical Insulator**

Optical fibers are made and drawn from silica glass which is nonconductor of electricity and so there are no ground loops and leakage of any type of current. Optical fibers are thus laid down along with high voltage cables on the electricity poles due to its electrical insulator behavior.

Optical fibers 7.

The Nobel Prize in Physics 2009

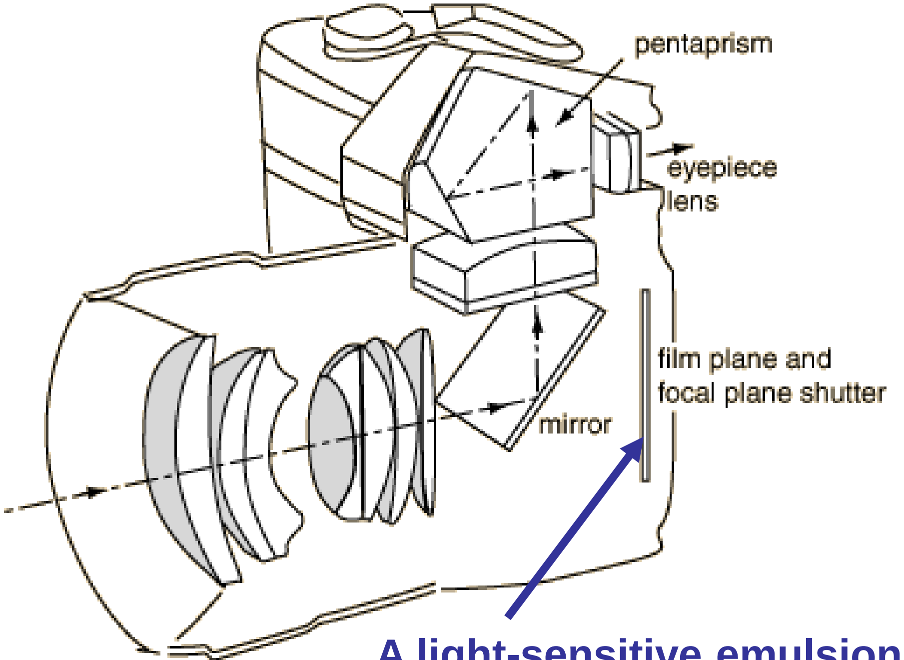

Charles Kuen Kao **Willard S. Boyle** **George E. Smith**

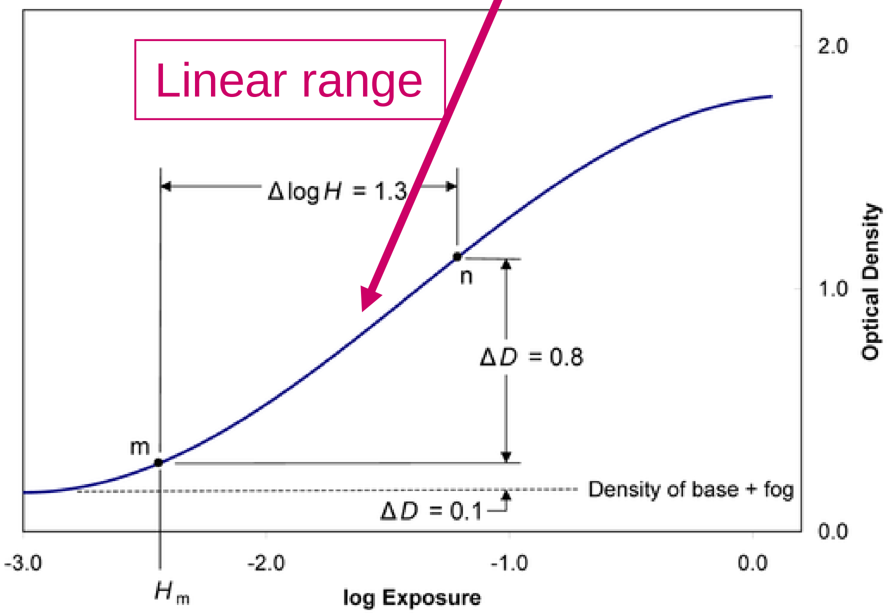
The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit - the CCD sensor"*.

Photography

The transmission of the photoplate (or film):

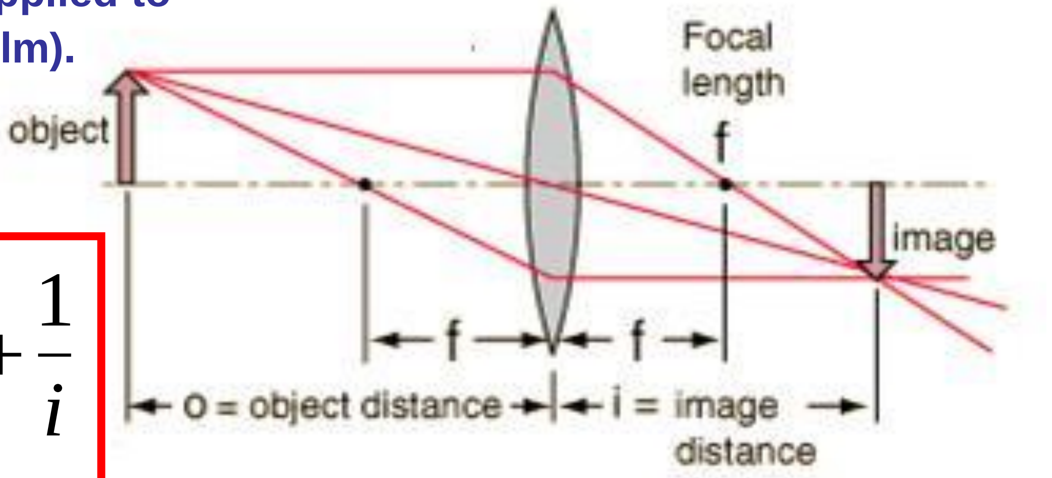
$$h(x, y) = h_o + t \cdot I(x, y)$$





A light-sensitive emulsion of silver salts is applied to a glass plate (or film).

$$\boxed{\frac{1}{f} = \frac{1}{o} + \frac{1}{i}}$$



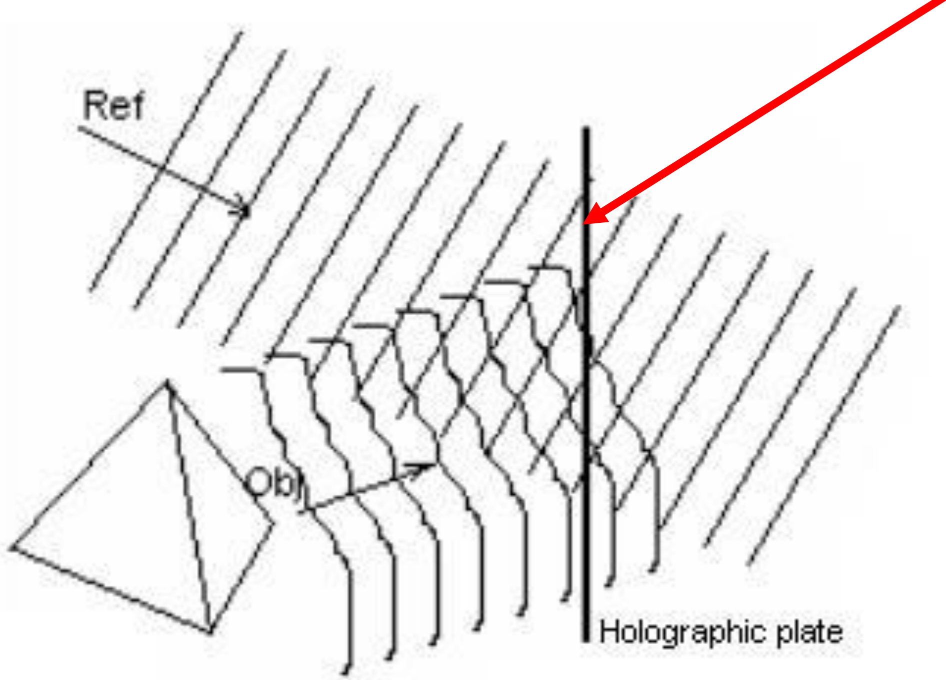
Holography 1.

Holography: lensless photography

1st step: **Exposition**

Interference pattern (on holoplate):

$$I = I_o + I_r + E_o E_r^* + E_r E_o^*$$



2nd step: **developement**
(chemical process)

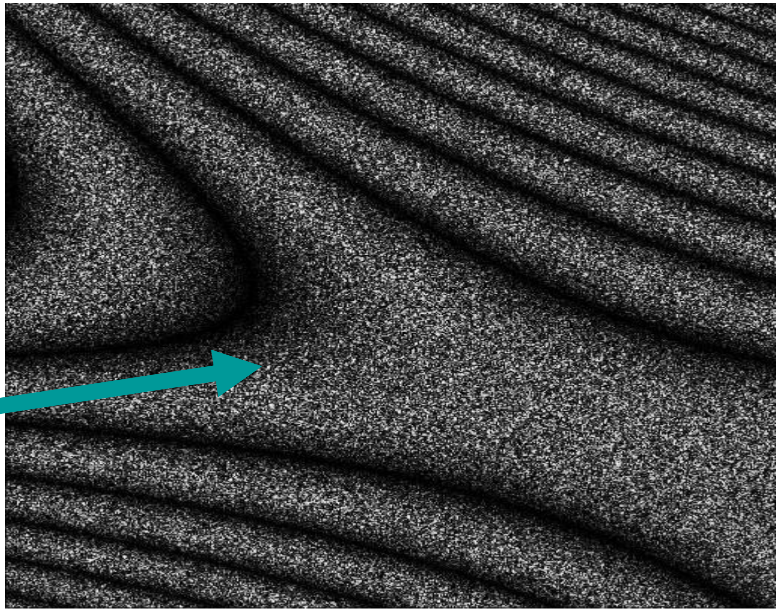
The transmission of the hologram:

$$h(x, y) = h_o + t \cdot I(x, y)$$

Ref: reference beam
(plane wave of spherical wave)

Obj: object wave
(reflected from the 3D object)

Hologram:
the recorded
interference
pattern



Holography 2.

3rd step: **Reconstruction**

Interference pattern (on holoplate):

$$I = I_o + I_r + E_o E_r^* + E_r E_o^*$$

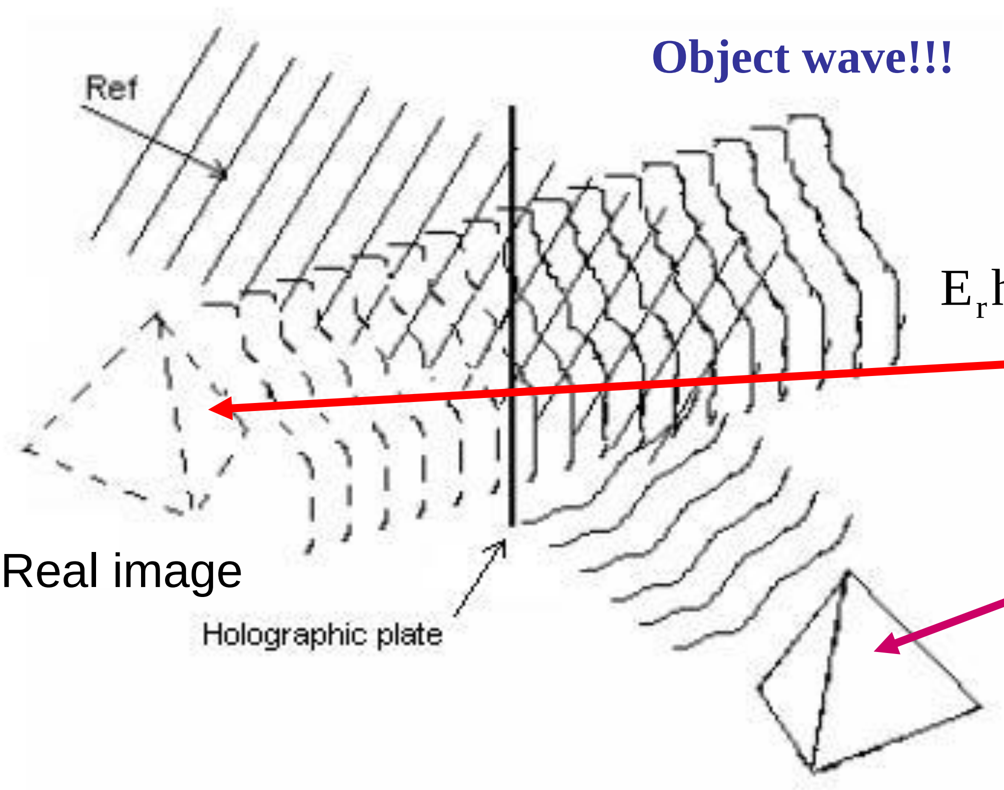
Amplitude transmission:

$$h(x, y) = h_o + t \cdot I(x, y)$$

Object wave!!!

Reconstruction:

$$E_r h = h_o E_r + E_r t(I_o + I_r) + E_o |E_r|^2 + E_r^2 E_o^*$$



Real image

Virtual image

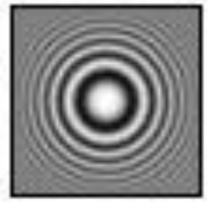
Off axis holography:

Real, virtual, undiffracted waves are spatially separated

Holography 3.

Digital holography 1.

+



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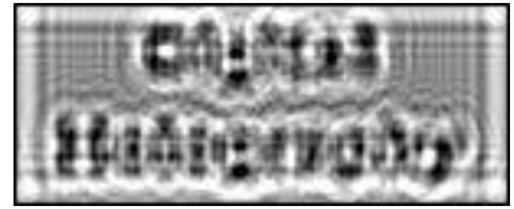


The resolution of a holographic plate: 5000 lines/mm

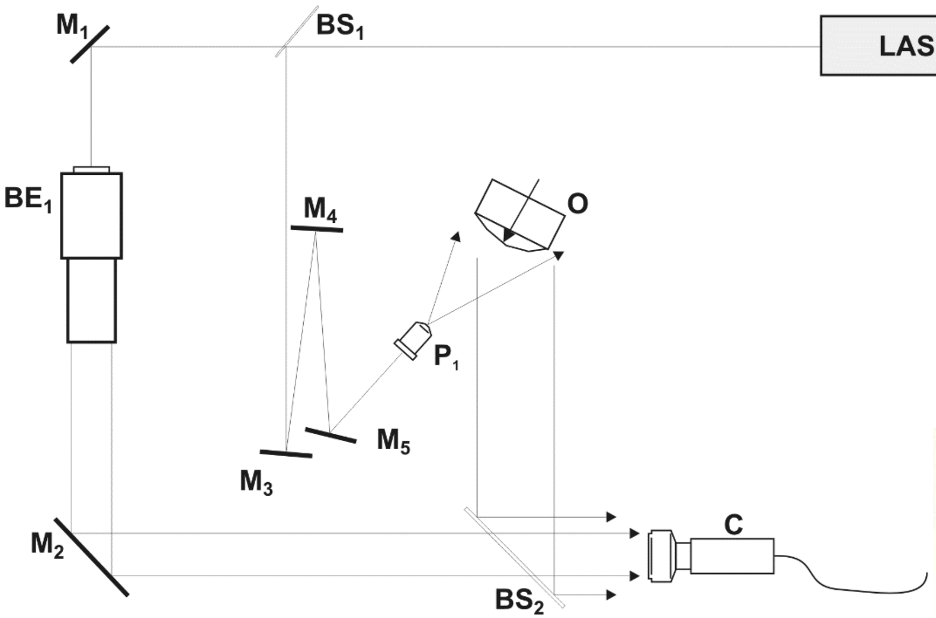
Camera	Chip type	Number of pixels	Pixel size [μm^2]	Frames per second	Dynamic range	Θmax for λ=633nm
Roper Sci. MegaPlus 1.4i	FT	1017* 1035	6.8 * 6.8	6.9	8 bit	2.7°
Roper Sci. Megaplus 16.8i	FT	4096* 4096	9 * 9	0.47	8 bit	2.0°
Roper Sci. Megaplus ES 1.0	IT	1008* 1018	9 * 9	30	8 or 10 bit	2.0°
Roper Sci. Megaplus 4.0	IT	2048* 2048	7.4 * 7.4	30	8 or 12 bit	2.45°
Hamamatsu C8484-01	PSI	1344* 1024	6.45 * 6.45	8.3	12 bit	2.81°
Duncan DT1100	PS	1392* 1040	4.65 * 4.65	12	8 or 12 bit	3.9°

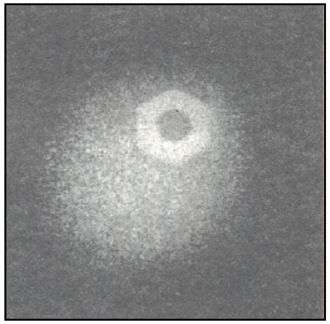
FT: full frame: interline transfer, PSI: progressive scan interline, PS: progressive scan

Holography 4.

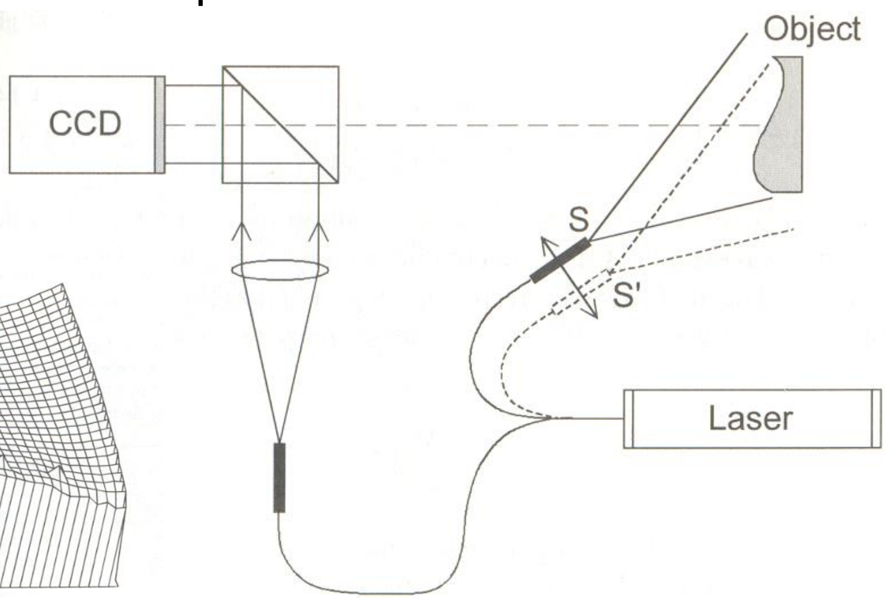
Digital holography 2.

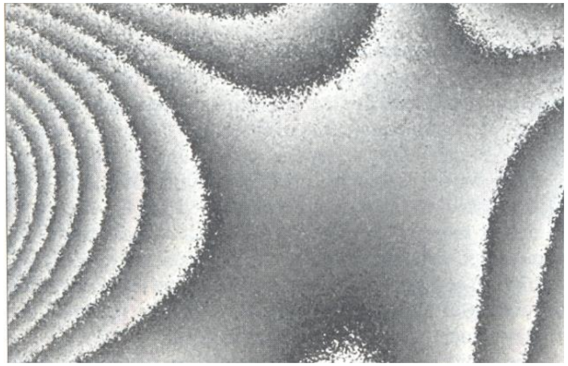
"In-line" arrangement

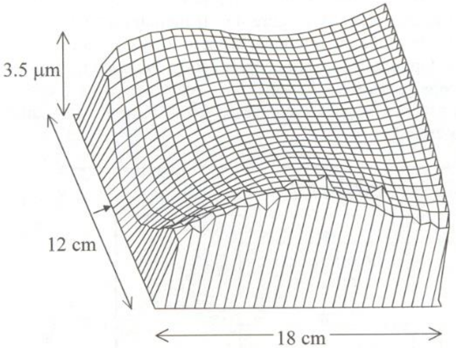




3D shape measurement:

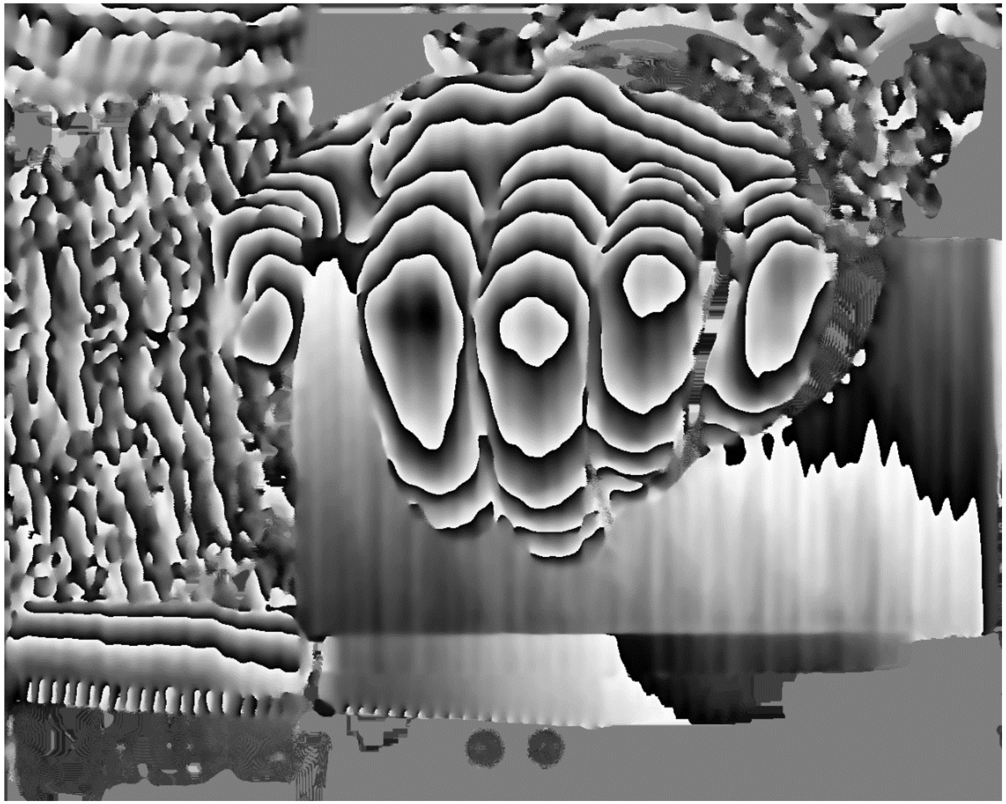


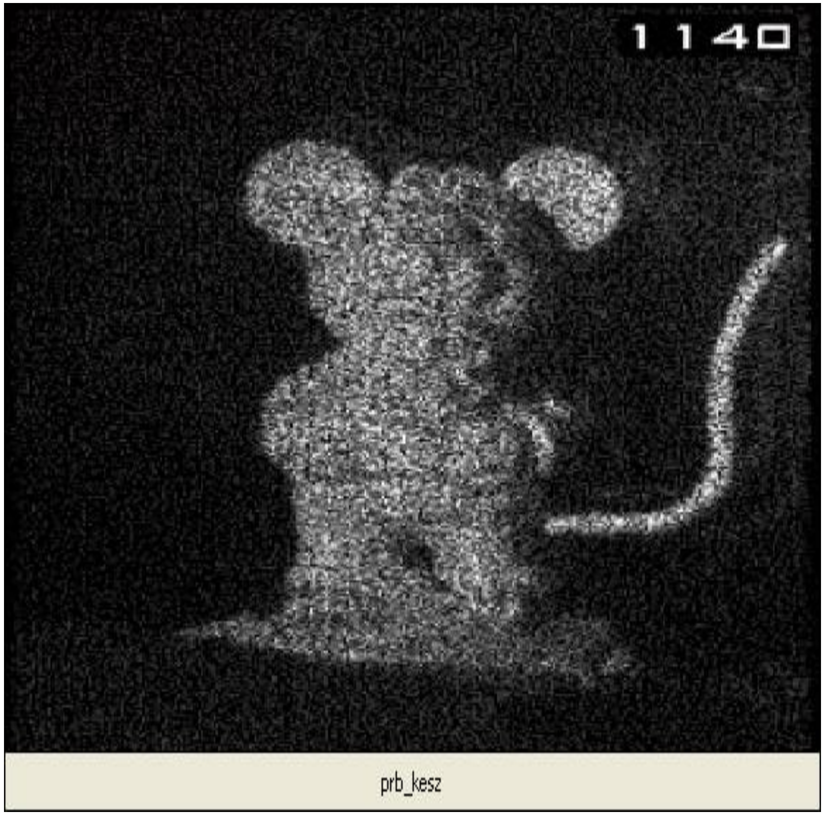


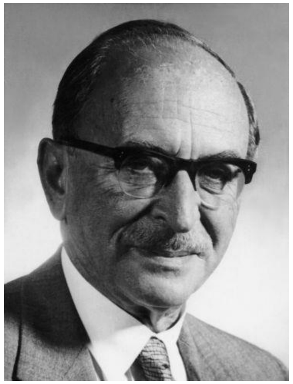


Holography 5.

Digital holography 3.







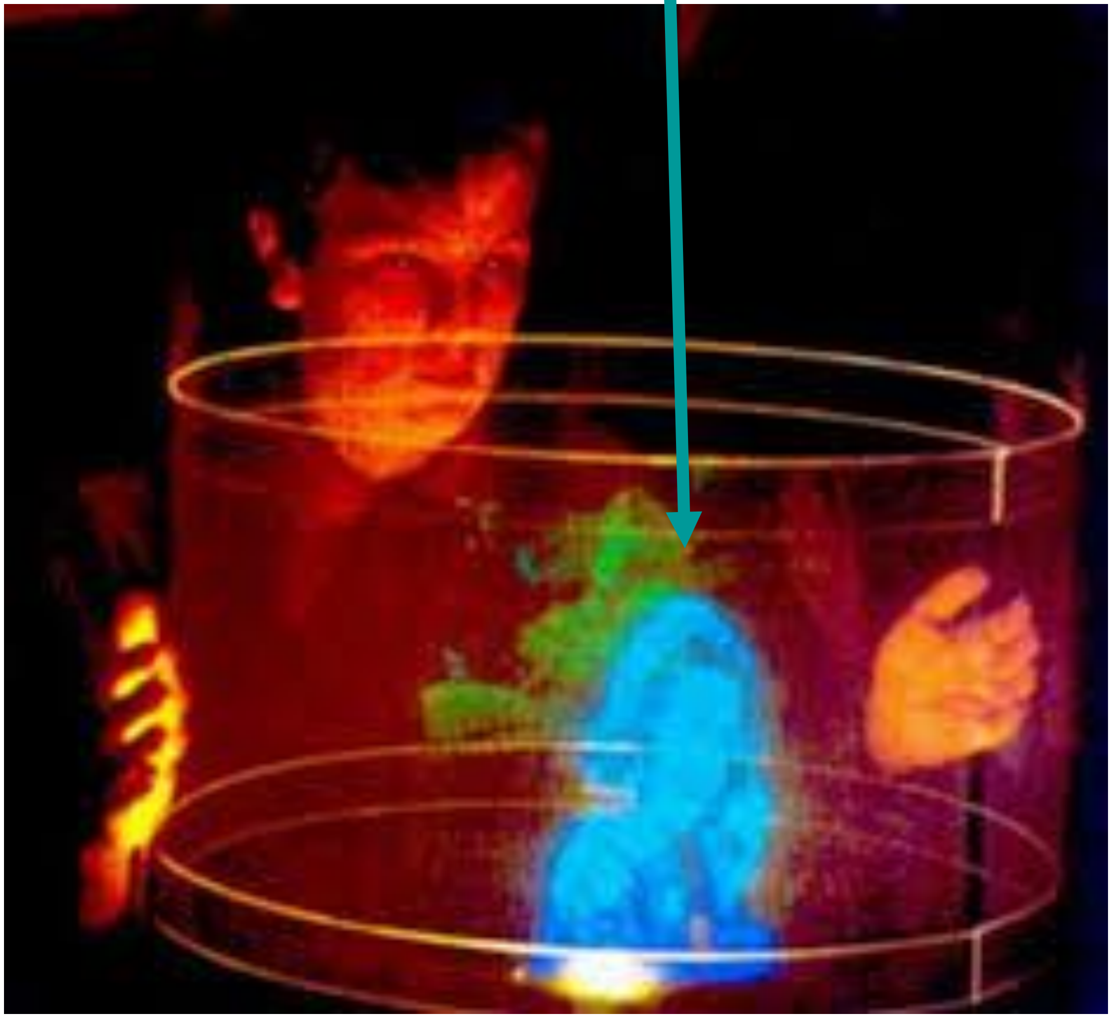
Gábor Dénes (Dennis Gabor): a Hungarian electrical engineer and physicist, he invented the holography.

He received the 1971 Nobel Prize in Physics.

Holography 6.

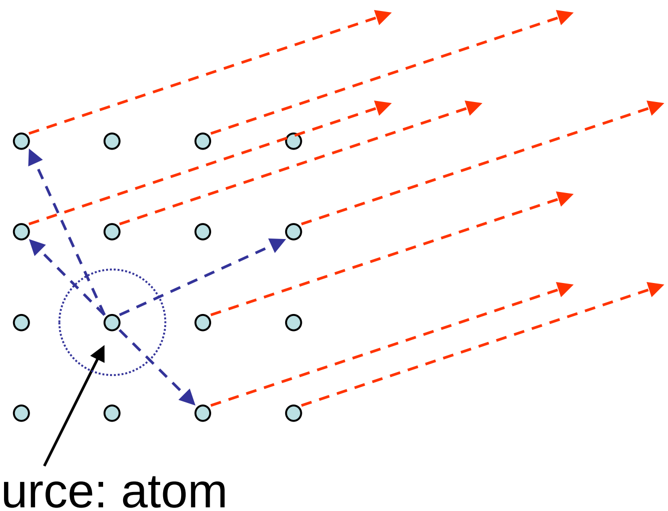
Digital holography 4.

A computer-generated hologram:



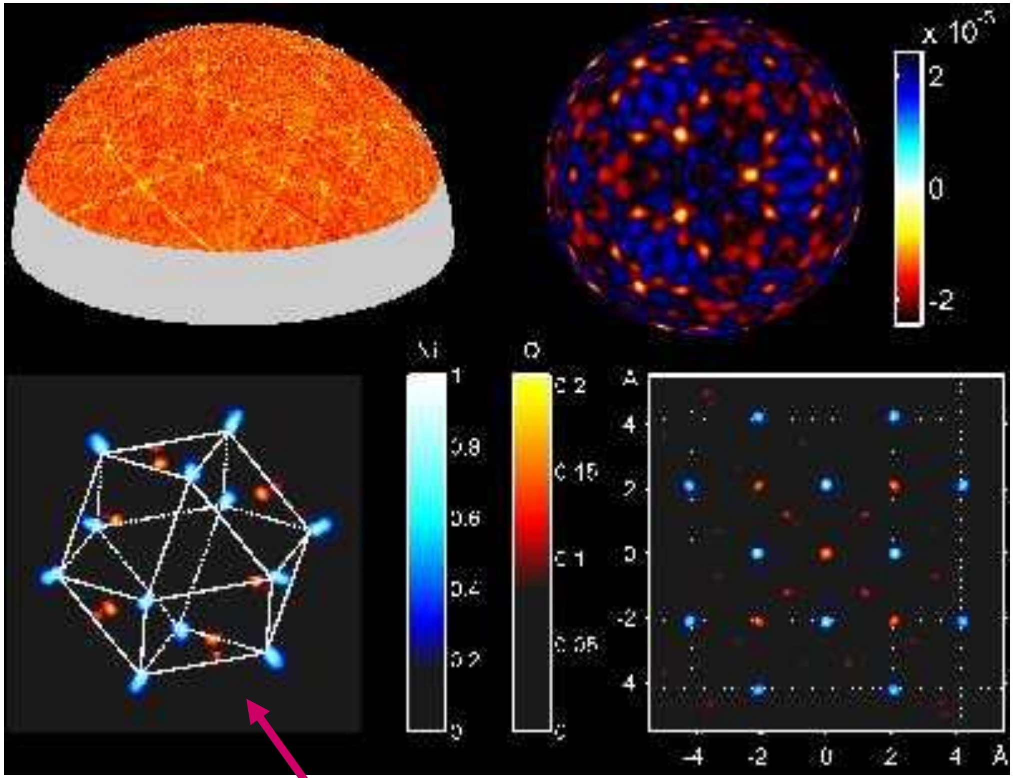
Holography 7.

X-ray, neutron, electron holography
Source: an atom



Reference wave: primary wave
(the original wave)

Object wave: secondary waves
scattered from the neighbor atoms



Computer generated reconstruction