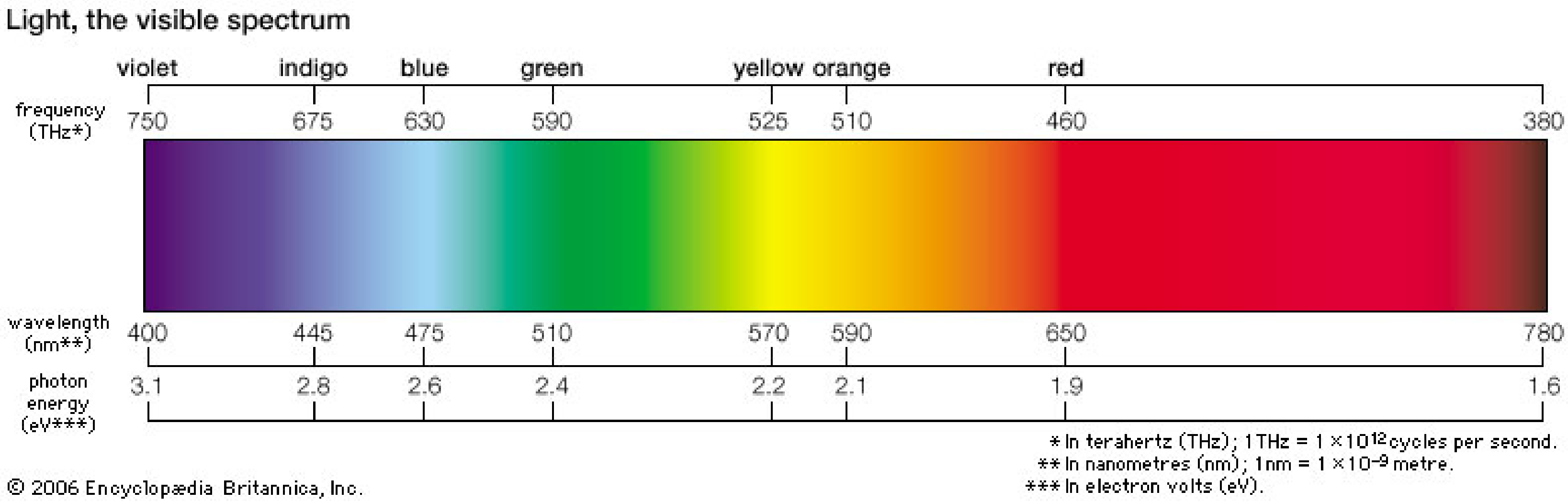
Introduction to Photonics

REU in Photonics – Summer 2012

Boston University

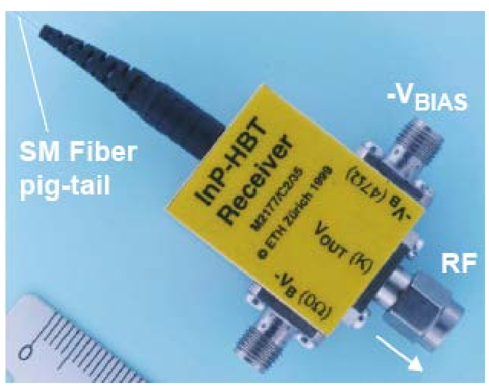
Welcome !!



Where do we use optics/photonics?

Optical Engineers work in:

- Optical communications
- Information and computing
- Medical imaging
- Biology and bio-chemical sensing
- Defense applications
- Navigation and control systems
- Image processing
- Data storage / memory



PHOTONICS/OPTICS

1- What is light?

2- How can we generate light?

3- How does light interacts with materials or itself?

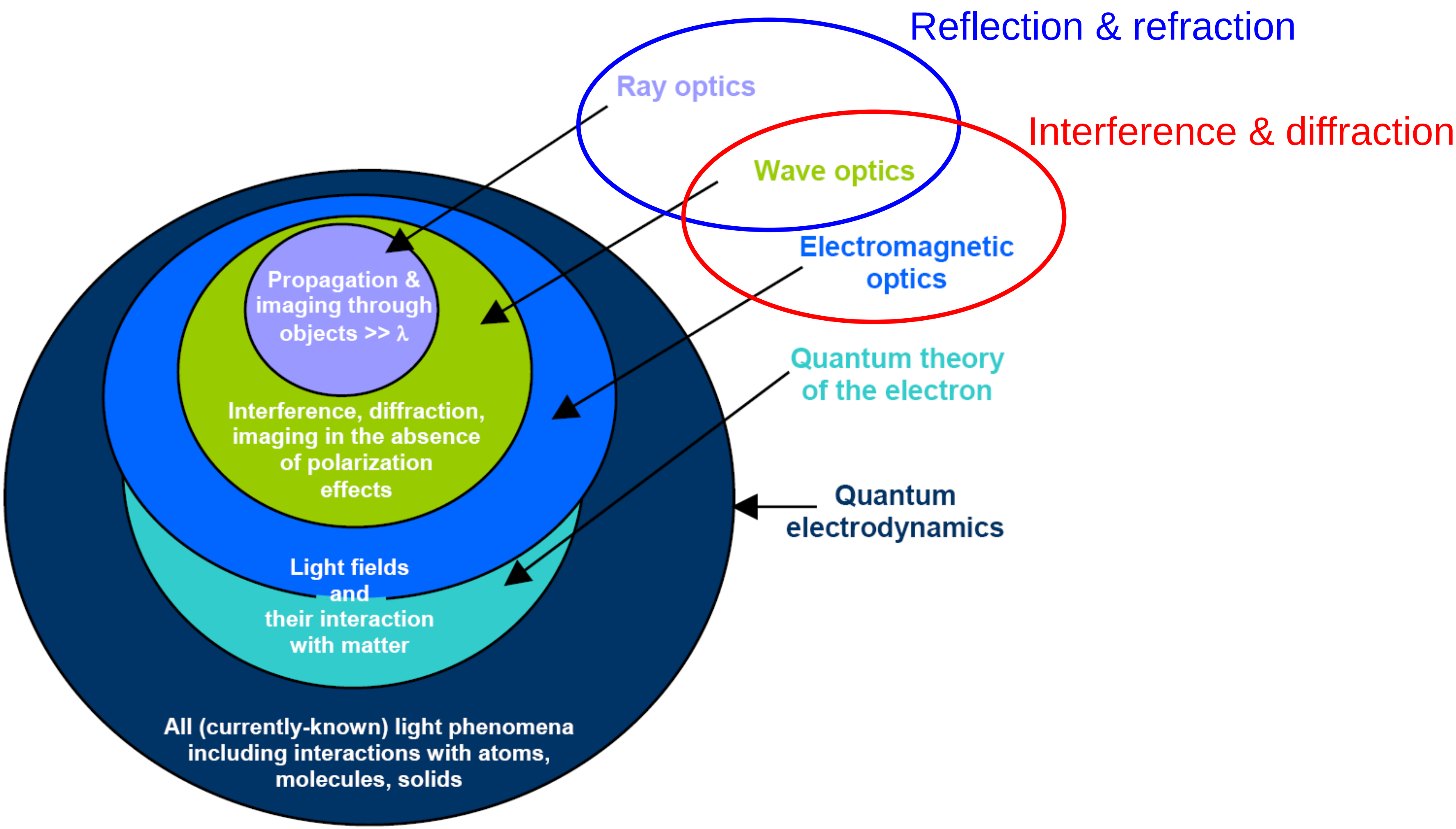
4- How can we manipulate light?

5- How can we measure light?

6- What can we do with light?

THEORIES of LIGHT

Understanding the nature of light and its interaction with materials



Optical waves

Light consists of coupled electric and magnetic fields that satisfy a wave equation:

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

c: speed of light (3×10^8 m/sec in free space)

which has simple sine-wave solutions: $\vec{E}(\vec{r},t) \propto \cos(\omega t - kz)$

DEFINITIONS:

$\omega=2\pi\nu$: angular frequency [rad/sec]

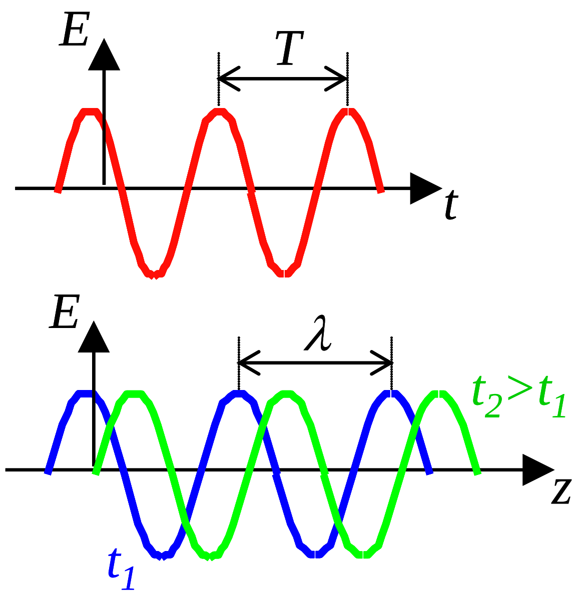
$\nu=1/T$: frequency [Hz]

T: optical period [sec]

$k=2\pi/\lambda$: wavenumber [m^{-1}]

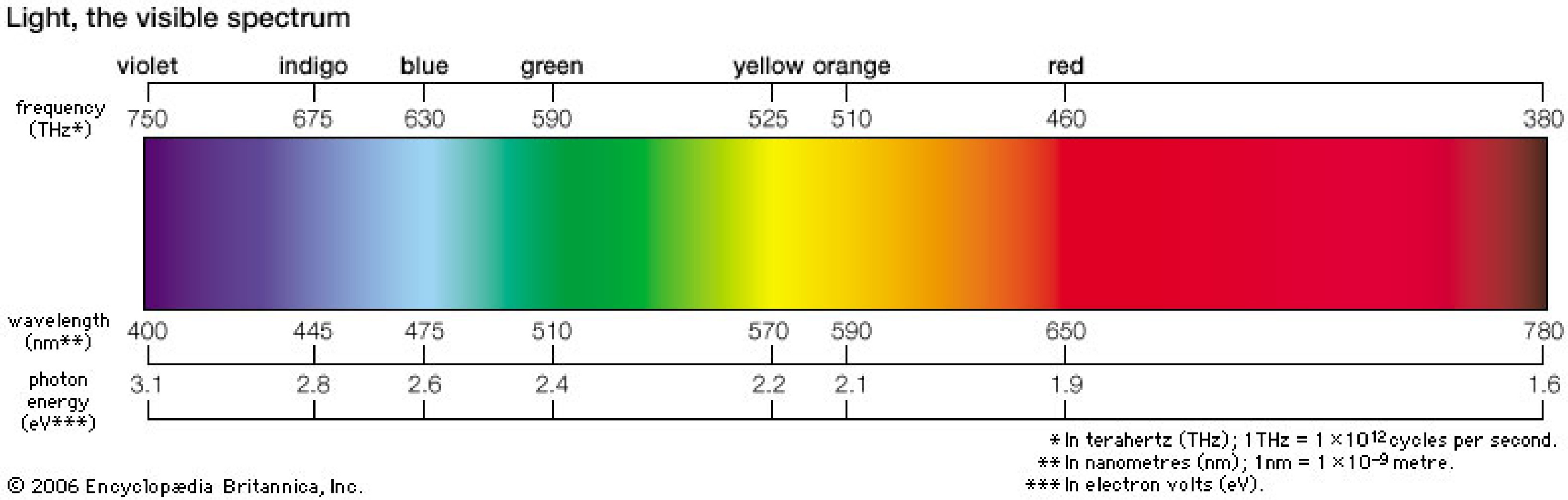
λ: wavelength [m]

HARMONIC PLANE WAVES:



From the wave equation: $\omega=ck \Leftrightarrow \nu=c/\lambda$

Wavelength and color

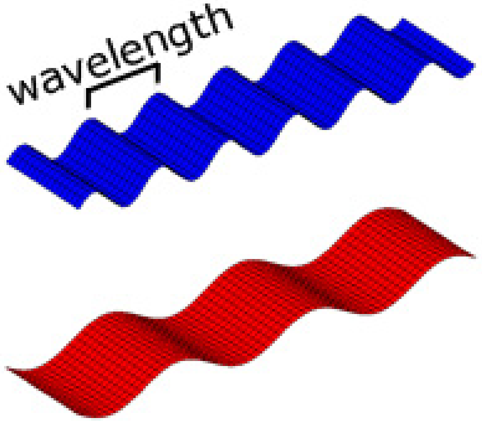


MAIN SPECTRAL REGIONS:

10 nm < λ < 400 nm: ultraviolet

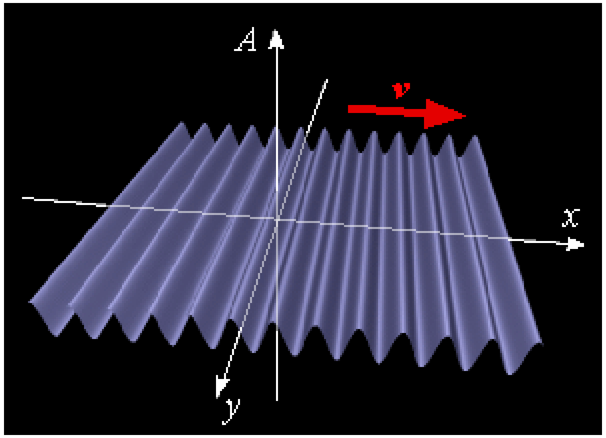
400 nm < λ < 780 nm: visible

780 nm < λ < 1 mm: infrared



Optical waves

SIMPLE TYPES:



Plane wave

Spherical wave

OTHER KEY PROPERTIES:

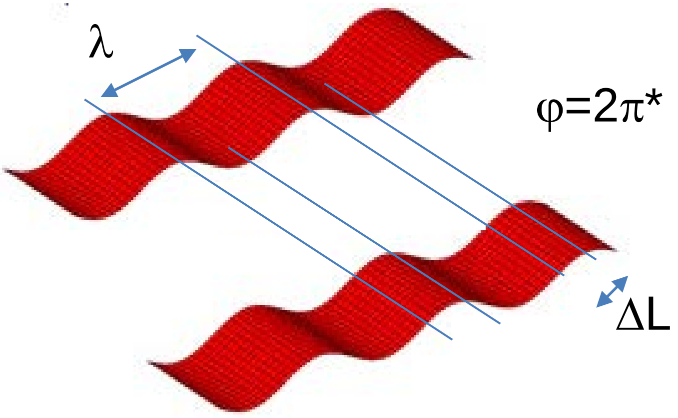
Intensity I

I: energy carried per unit area per unit time (proportional to the electric field amplitude squared)

I=$\phi h\nu$, where h is Planck's constant and ϕ is an integer (photon flux)

PHOTON: "particle" of light

Phase φ (determines interference)



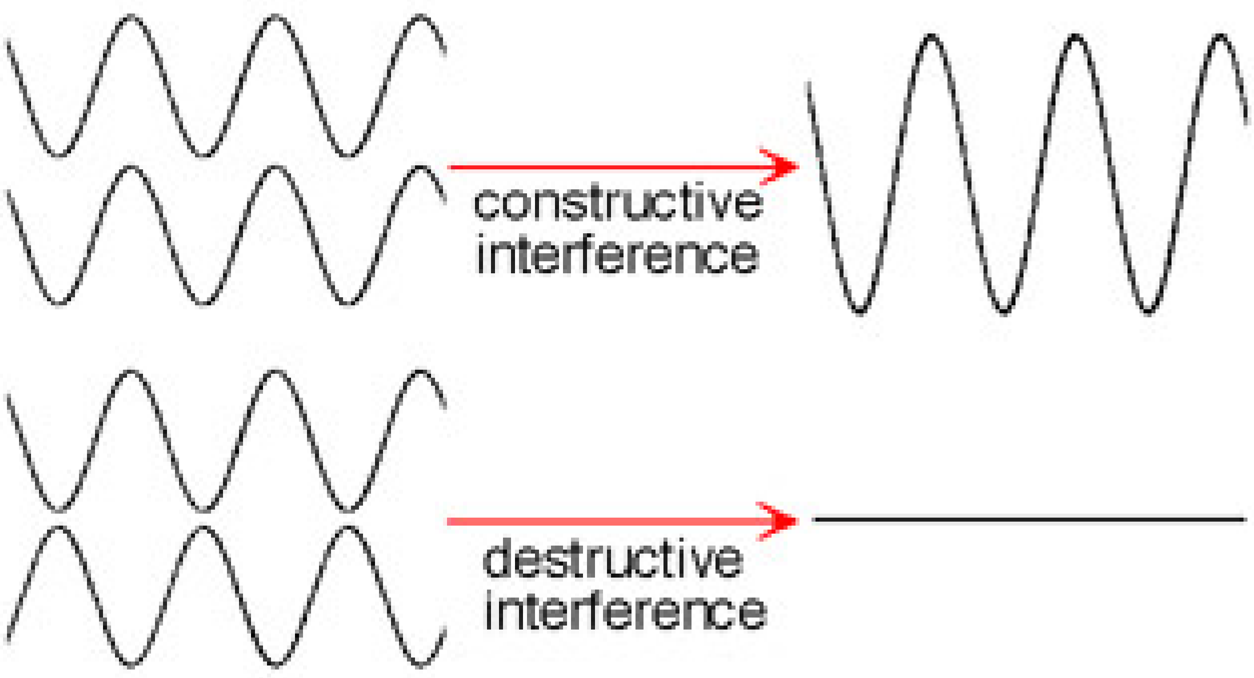
$\varphi = 2\pi * \Delta L / \lambda$

In phase when $\Delta L = n\lambda$ ($n = 0, \pm 1, \pm 2, \ldots$)

Interference conditions

$\varphi = \varphi_1 - \varphi_2 = 0$

$\varphi = \varphi_1 - \varphi_2 = \pi$



<u>Constructive Interference:</u>
➔ IN-PHASE
Phase Difference is 0, 2π, 4π, ..
Path Difference is λ, 2λ, 3λ, …

<u>Destructive Interference:</u>
➔ OUT-of-PHASE
Phase Difference is 1π, 3π,5π ..
Path Difference is 1λ/2, 3λ/2, 5λ/2, …

Interference of two waves

Intensity of wave 1: $I_1 = a_1^2$

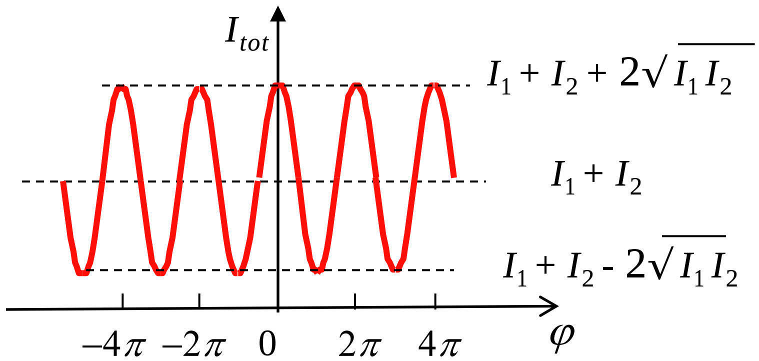
Intensity of wave 2: $I_2 = a_2^2$

Phase difference: $\varphi = \varphi_1 - \varphi_2$

$$I_{tot} = I_1 + I_2 + 2(I_1 I_2)^{1/2}\cos\varphi$$

INTERFERENCE EQUATION

Intensity of superposition depends on the intensities of the individual waves <u>and</u> on their phase difference

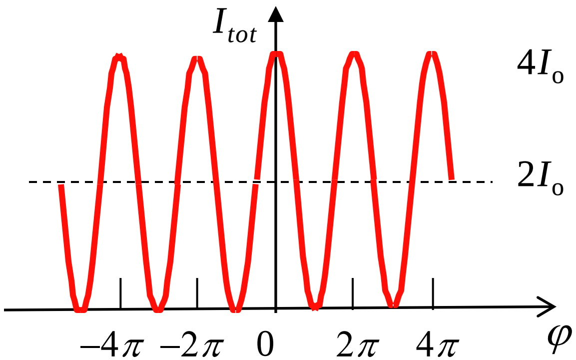


Max Intensity → **Constructive Interference**
Occurs when waves are **IN-PHASE**

Min Intensity → **Destructive Interference**
Occurs when waves are **OUT-PHASE**

Special Case

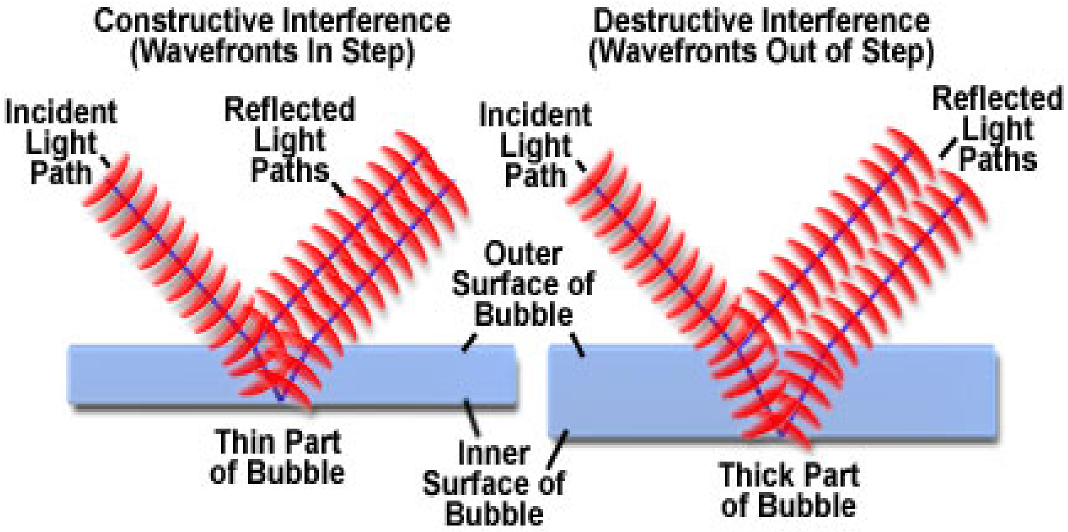
$I_1 = I_2 = I_0$



Thin film interference: science of soap bubbles

Soap Film Interference Patterns

Reflected Light Pathways Through Soap Bubbles

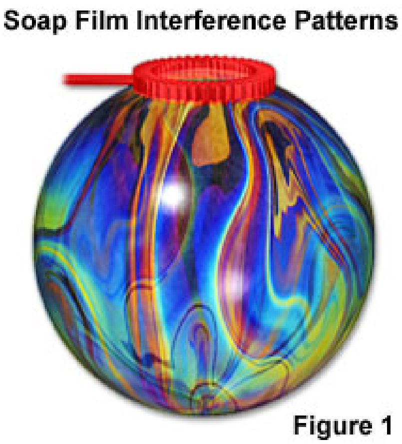


Thickness variations and angle of incident light changes color

The phase difference between the two reflected waves depends on the difference in their path length and on the wavelength

Color via interference

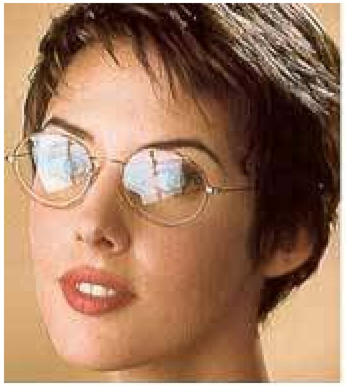


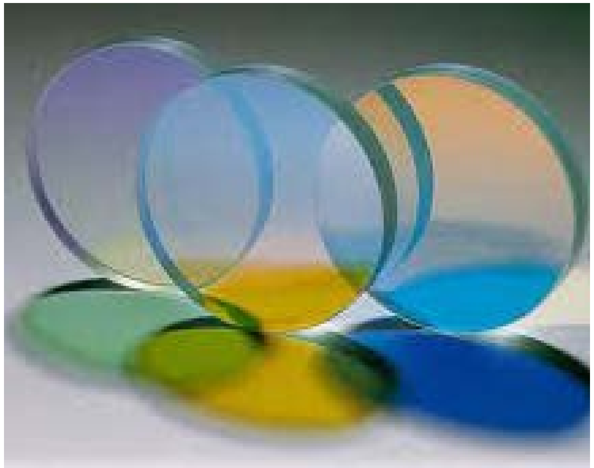


Interference based displays

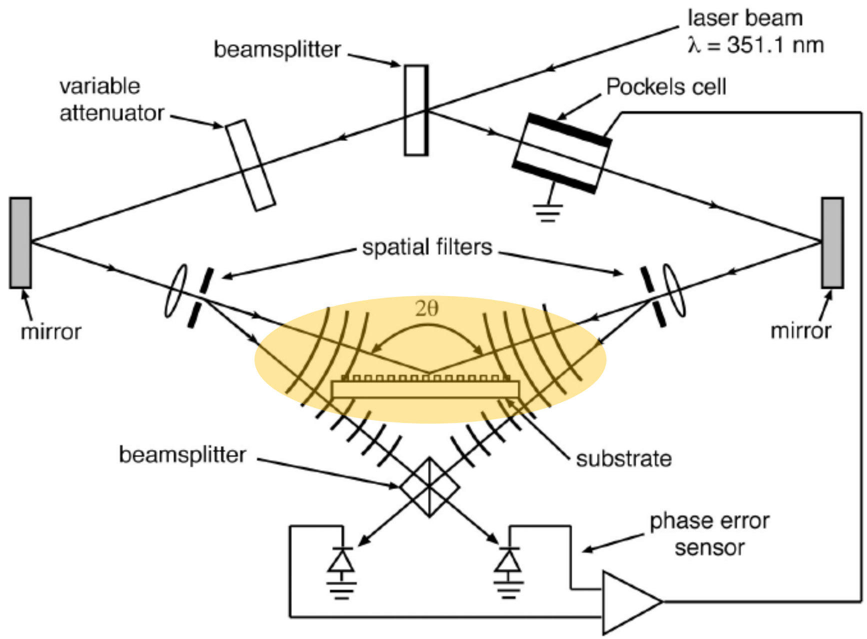
Anti-reflection coating

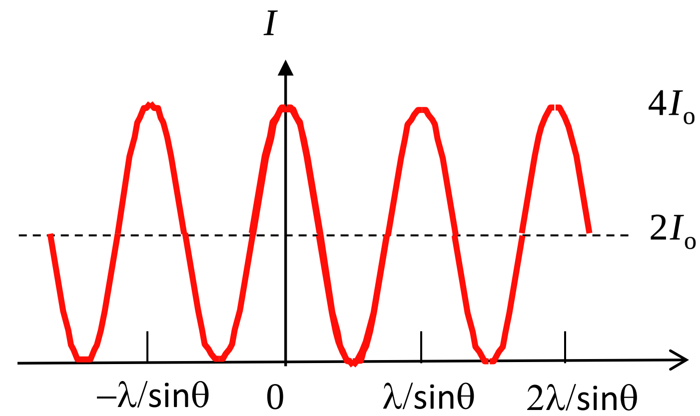
Interference filters

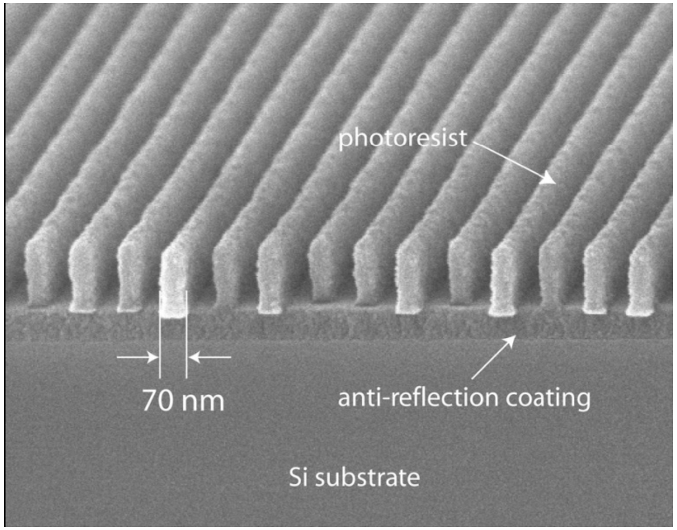


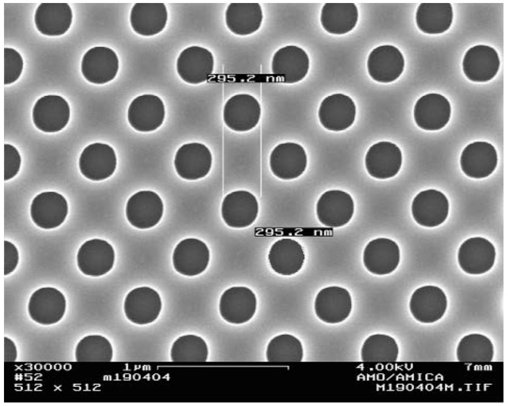


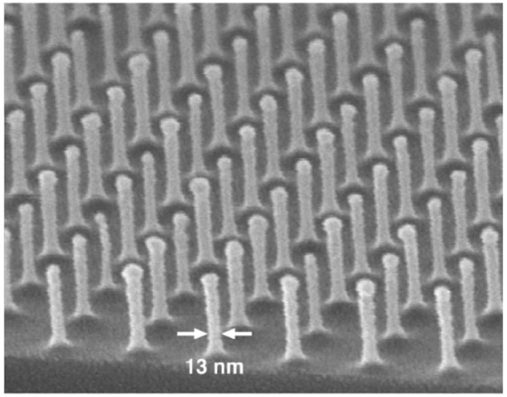
Interference lithography









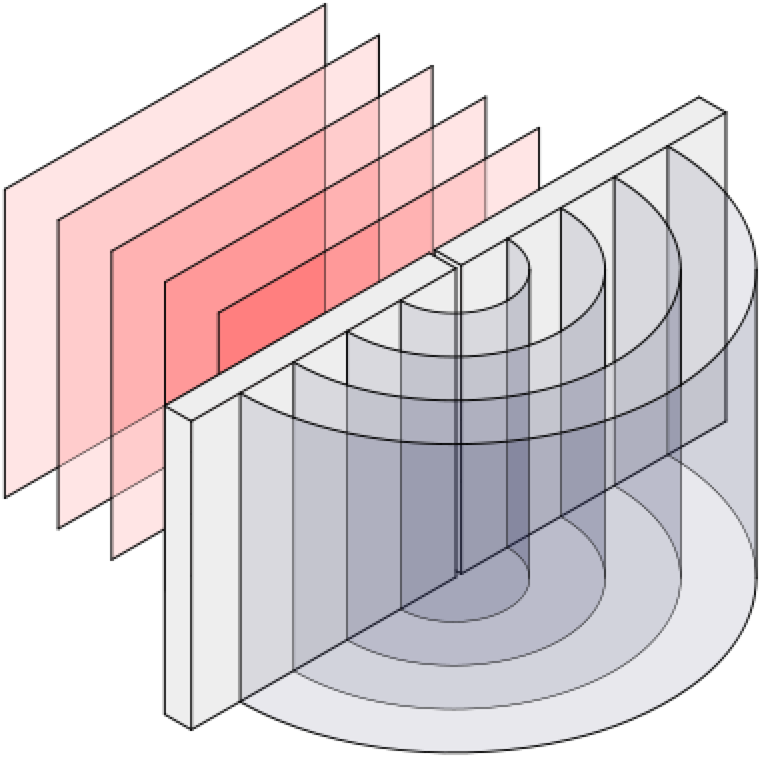


100nm-period posts in Si

Single exposure ➔ lines
Multiple exposure ➔ 2D patterns

Diffraction

Diffraction: “ A modification which light undergoes especially in passing by the edges of opaque bodies or through narrow openings and in which the rays appear to be deflected”



Diffraction of water waves

Diffraction occurs for all waves

Ocean waves passing through slits in Tel Aviv, Israel

Diffraction: wave phenomenon

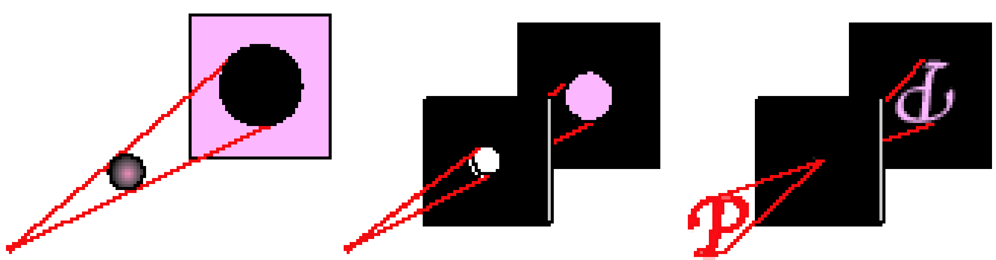
Diffraction: **Wave phenomenon**

Occurs whenever a portion of a wavefront (light, sound, water) is obscured

* wave encounters the edges of an opaque body
* wave encounters an aperture in an opaque film

Deviation of light from rectilinear propagation

RAY OPTICS



Perfect Shadow

Perfect Image

WAVE OPTICS

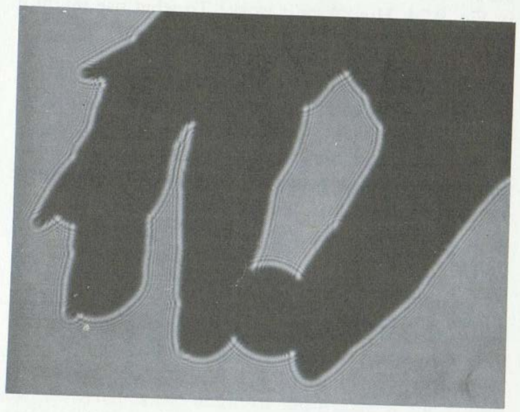


Figure 10.1 The shadow of a hand holding a dime, cast directly on 4 × 5 Polaroid A.S.A. 3000 film using a He–Ne beam and no lenses. (Photo by E.H.)

Fuzzy Image
(Best: Diffraction Limited)

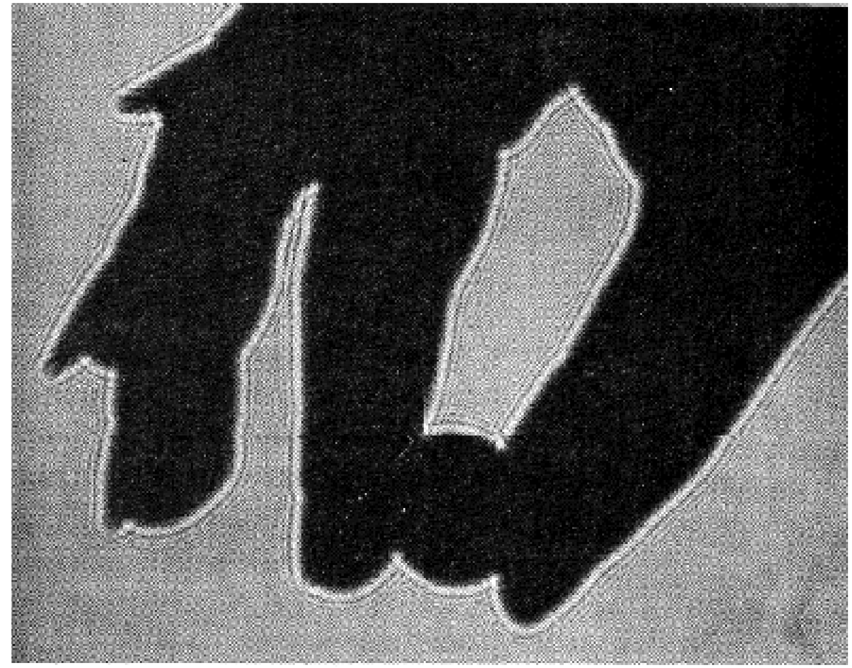
Diffraction: wave phenomenon

1) Light does not always travel in a straight line.

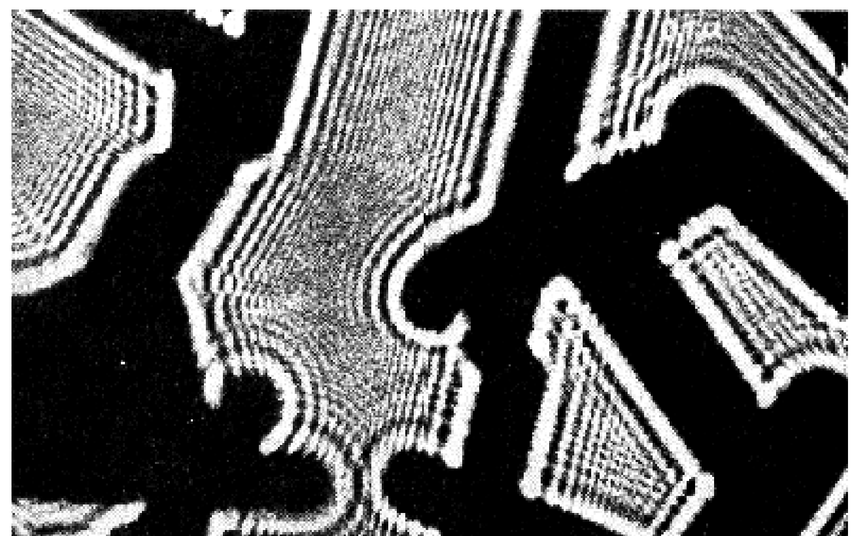
2) It tends to bend around objects. This tendency is called **diffraction**.

3) Any wave will do this, including matter waves and acoustic waves.

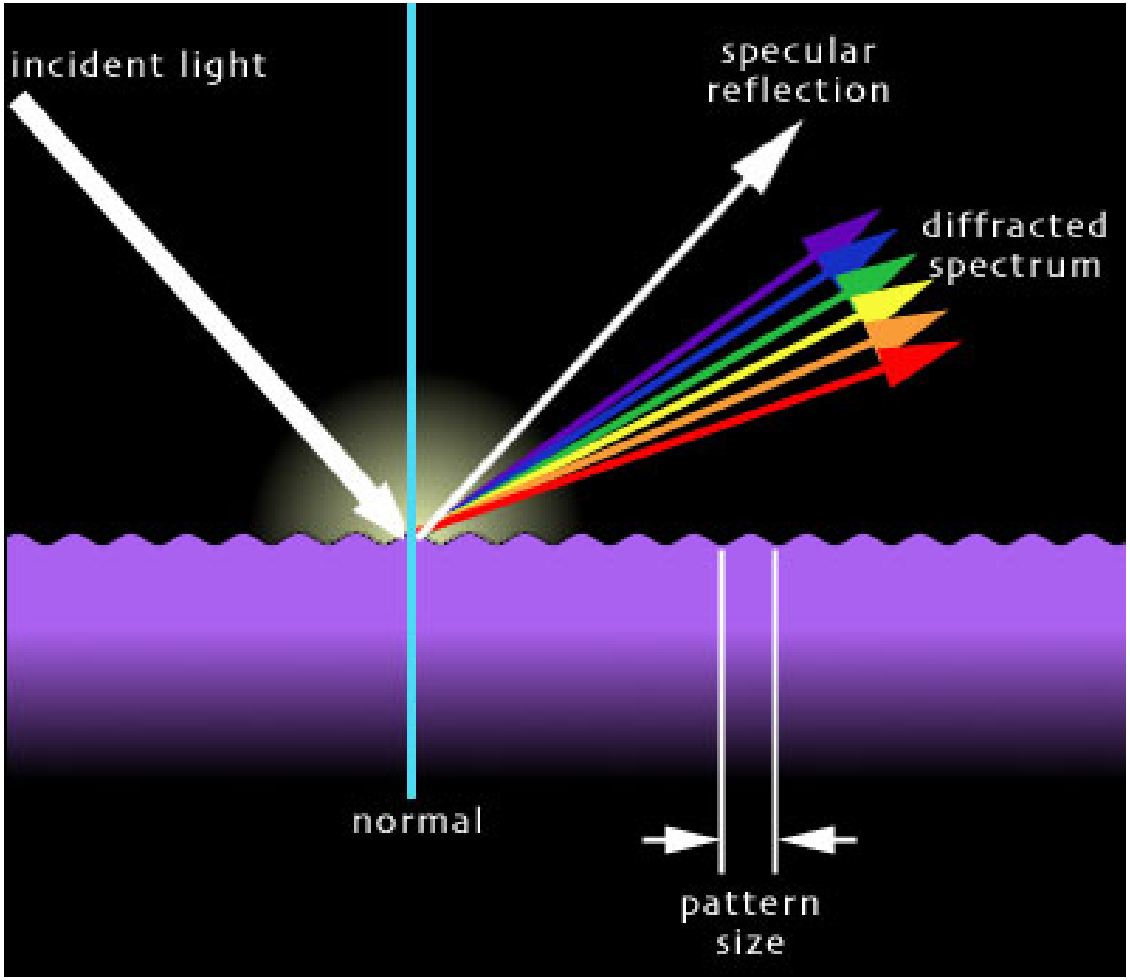
Shadow of a hand illuminated by a **Helium-Neon laser**

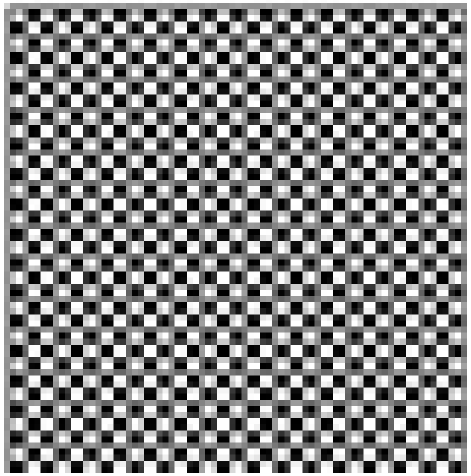


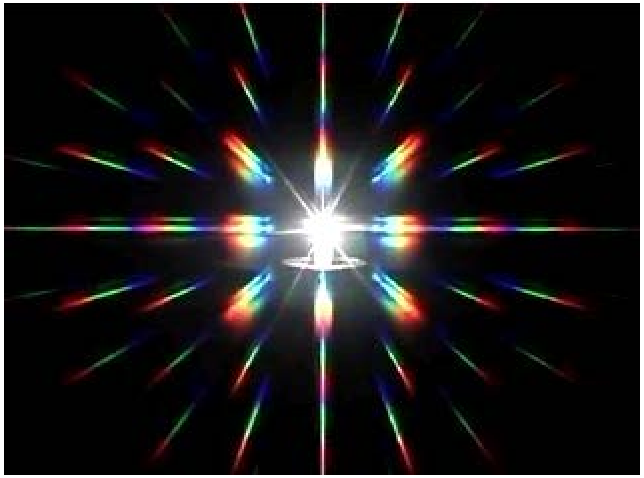
Shadow of a zinc oxide crystal illuminated by a **electrons**



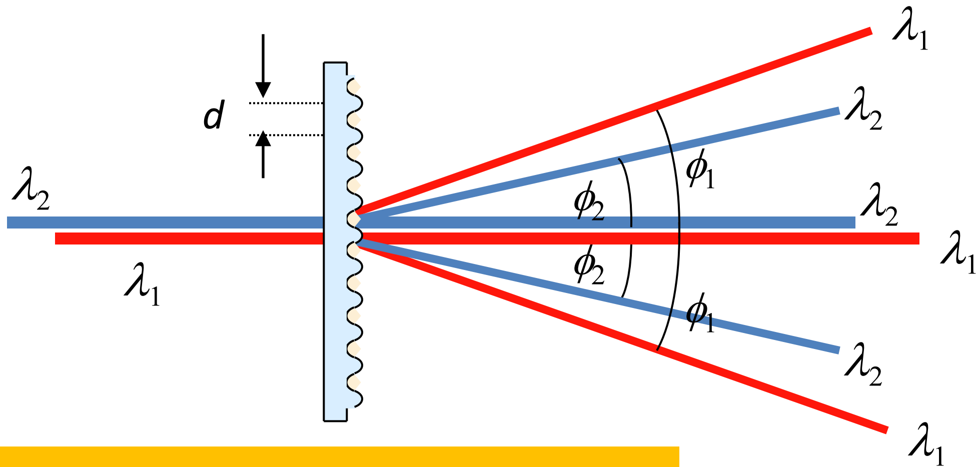
Diffraction gratings







Grating spectrometers



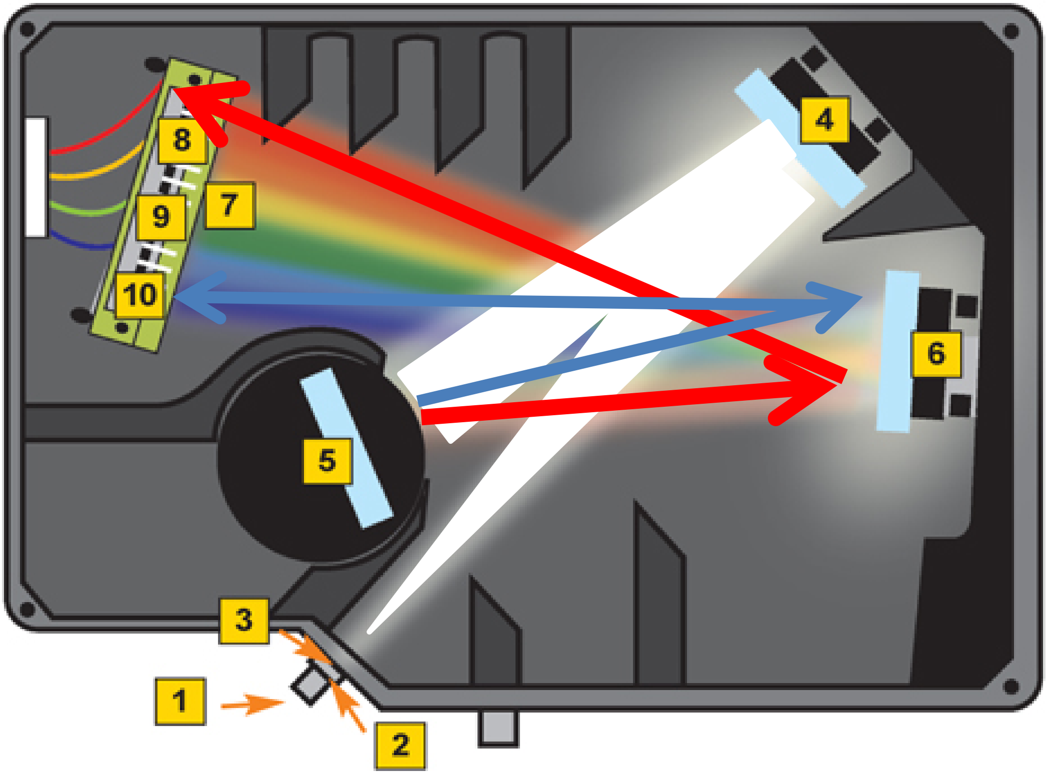
$$d \sin(\phi) = m\lambda$$
$$m=0, \pm1, \pm2, \ldots$$

for $\lambda \ll d$, $m=1$: $\begin{cases} \phi_1 \approx \lambda_1/d \\ \phi_2 \approx \lambda_2/d \end{cases}$

We can make objects such as gasses glow by heating them up in a flame, or by passing electricity through them.

Different elements emit light with different colors when they glow.

Spectroscopy works by taking light and splitting it up into its component colors.
➔we can identify the elements by the bright lines we see in the spectroscope.



Light sources

SEVERAL DIFFERENT LIGHT EMISSION MECHANISMS:

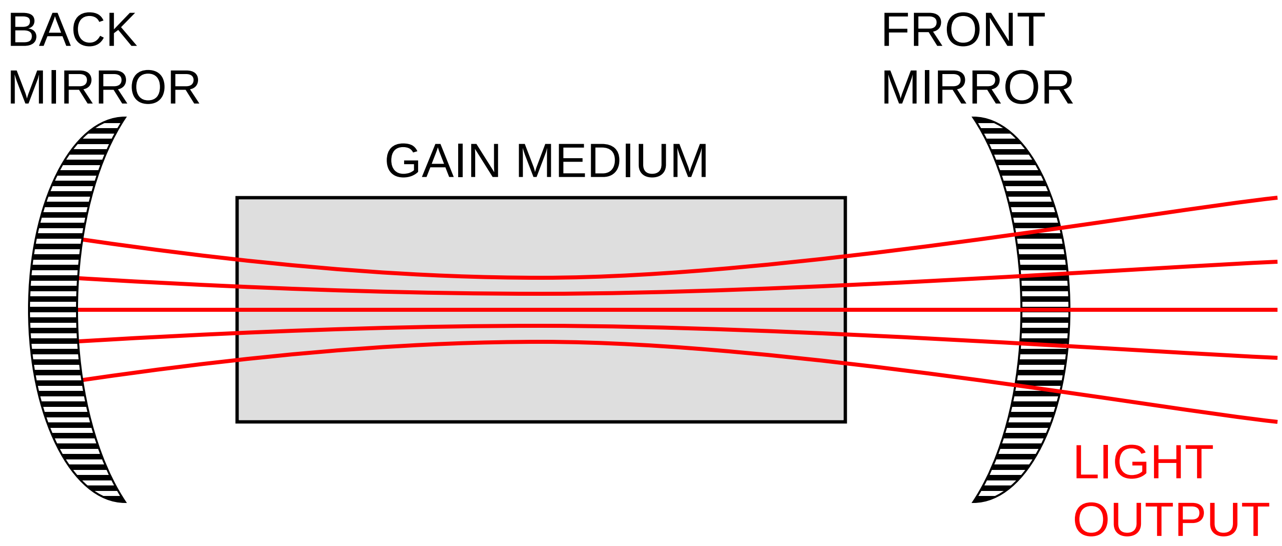
INCANDESCENCE: light emission from a hot medium due to its temperature [Examples: the sun, incandescent light bulbs]

LUMINESCENCE: light emission from a medium in an excited energy state when it relaxes to its ground state spontaneously [Examples: phosphors, LEDs]

STIMULATED EMISSION: light emission from a medium in an excited energy state when it relaxes to its ground state under the action of an electromagnetic wave [lasers]

Laser: Light Amplifier by Stimulated Emission of Radiation

Lasers

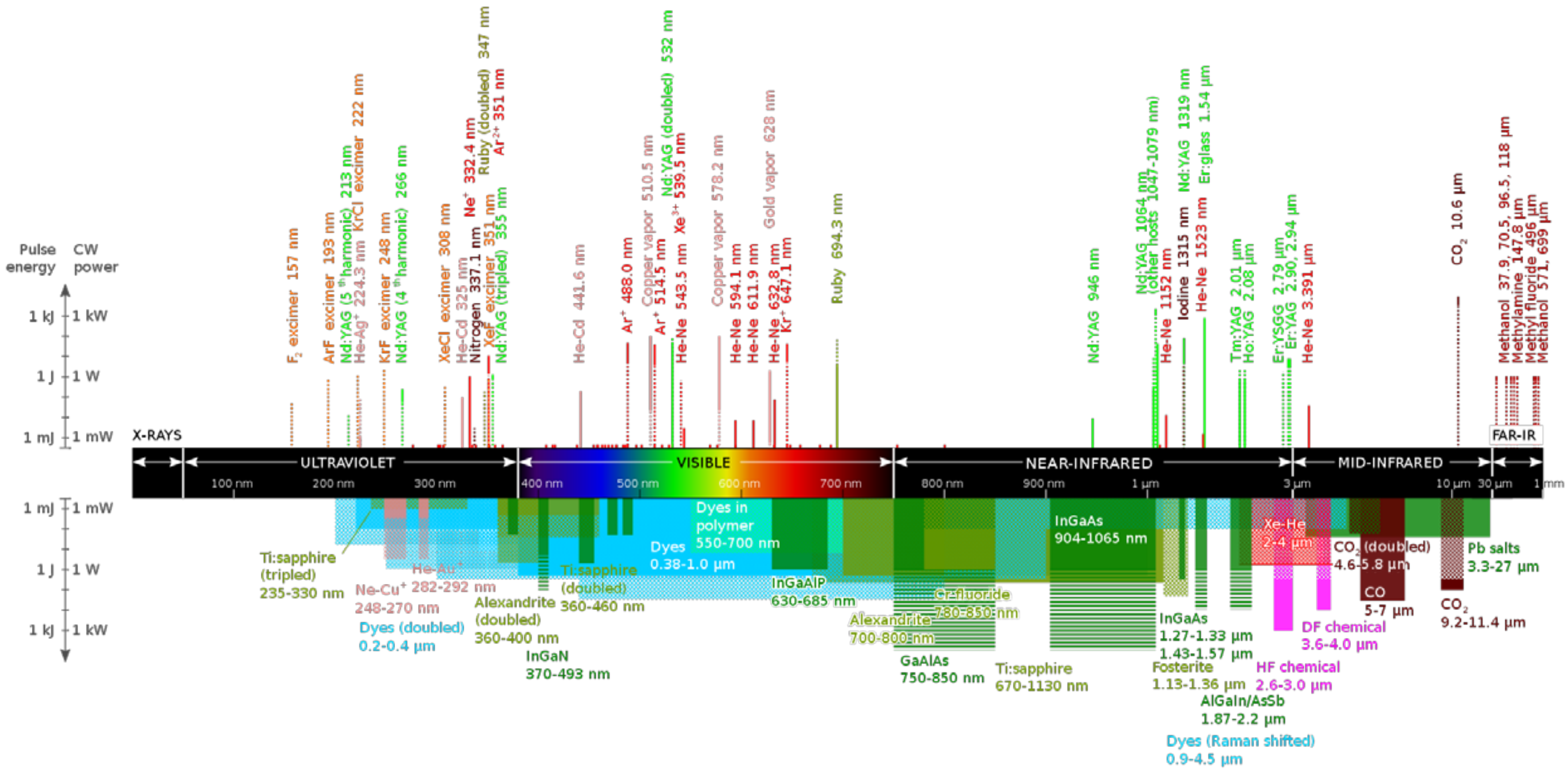


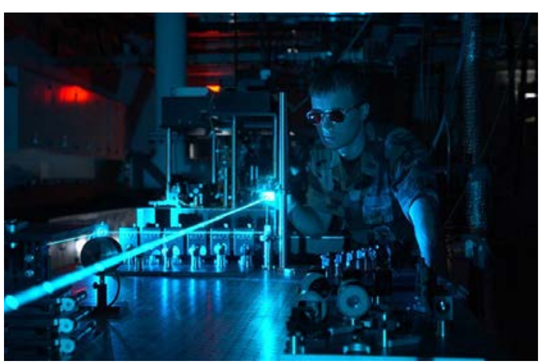
TWO MAIN INGREDIENTS:

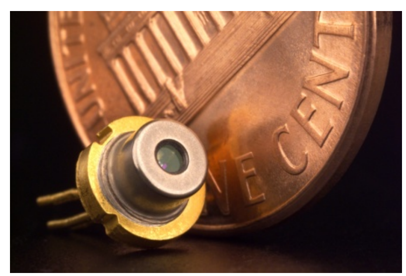
GAIN MEDIUM: a sample of some material capable of amplifying light at certain wavelengths (when suitably pumped)

OPTICAL CAVITY: two mirrors aligned about a common axis, providing optical feedback to the gain medium

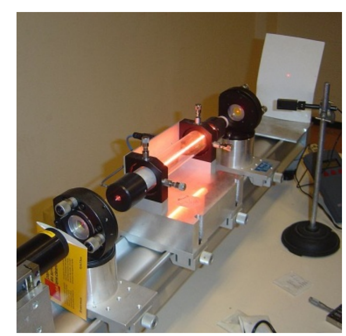
Available laser wavelengths







Diode laser

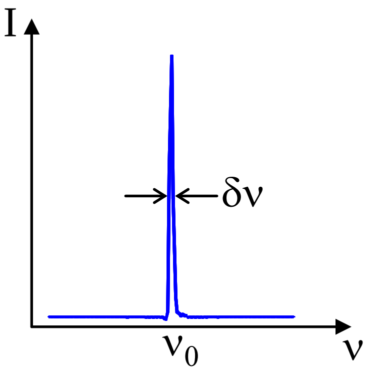


HeNe laser

Laser light

KEY PROPERTIES (for a HeNe laser as an example):

Quasi-monochromatic: very narrow spectrum with $\delta\nu/\nu$ as small as 10^{-10} (versus 10^{-1} for thermal light)



Highly directional: divergence angle as small as 10^{-4} rad

Highly coherent: phase remains constant over very long propagation distances (a few 10 km, versus μm for thermal light)

High peak intensity: over 12 orders of magnitude higher than sunlight (per unit bandwidth, per unit solid angle)