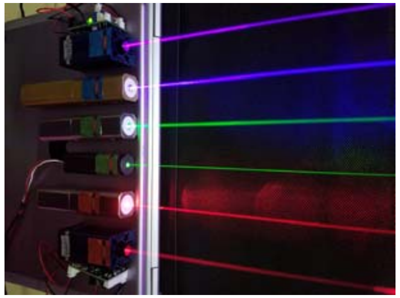
# LASER Light Amplification by Stimulated Emission of Radiation

Luminescent light source based on light amplification.



5 mW diode laser, few mms

Terawatt NOVA laser - Lawrence Livermore Laboratories. Size of a football field

13.11.2019 András Kaposi, using lecture notes of Miklós Kellermayer

# History


- 1917 - Albert Einstein: theoretical prediction of stimulated emission.
- 1946 - G. Meyer-Schwickerather: first eye surgery with light.
- 1950 - Arthur Schawlow and Charles Townes: emitted photons may be in the visible range.
- 1954 - N.G. Basow, A.M. Prochorow, and C. Townes: ammonia maser
- 1960 - Theodore Maiman: **first laser** (ruby laser)
- 1964 - Basow, Prochorow, Townes (Nobel-prize): quantum electronics
- 1970 - Arthur Ashkin: laser tweezers
- 1971 - Dénes Gábor (Nobel-prize): holography, 1947
- 1997 - S. Chu, W.D. Phillips and C. Cohen-Tanoudji (Nobel-prize): atom cooling with laser.
- 2013, october 8: NIF (National Ignition Facility, USA): launching nuclear fusion with 192 laser beams, positive energy balance.
- 2017 - ELI (Extreme Light Infrastructure), Szeged, Hungary. generation of attosecond ($10^{-18}$ s) light pulses.
- 2018 - Nobel-prize in physics: Arthur Ashkin (laser tweezers), Gérard Mourou and Donna Strickland (ultrashort laser pulses)

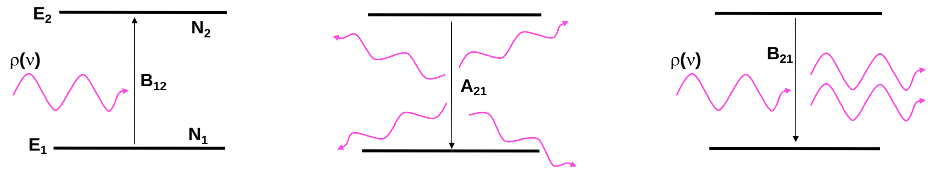


# Principles of laser. Stimulated emission

Energy

Elementary processes in Einstein's two energy state model

1. Absorption | 2. Spontaneous emission | 3. Stimulated emission




**1. Absorption**

Frequency of transition: $n_{12}=N_1B_{12}\rho(\nu)$

$\Delta E= E_2-E_1=h\nu$ energy quantum is absorbed.

**2. Spontaneous emission**

Frequency of transition: $n_{21}=N_2A_{21}$

$E_2$-$E_1$ photons travel independently in all directions.

**3. Stimulated emission**

Frequency of transition: $n_{21}=N_2B_{21}\rho(\nu)$

In the presence of exernal field. Field energy is increased. Phase, direction and frequency of emitted and external photons are identical.

*Explanation:* two-state atomic or molecular system
$E_1$, $E_2$ : energy levels, $E_2>E_1$
$\rho(\nu)$ : spectral energy density of external field
$N_1$, $N_2$ : number of atoms or molecules on the given energy level
$B_{12}$, $A_{21}$, $B_{21}$: transition probabilities (Einstein coefficients), $B_{12} = B_{21}$

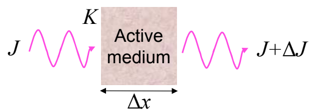
Cf. Textbook Fig. II.31



# Principles of laser. Population inversion

Energy

Light amplification depends on the relative population of energy levels.



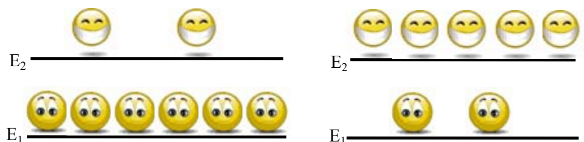

$$\Delta J=JK(N_2-N_1)\Delta x$$

$J$ = intensity
$K$ = constant
$\Delta x$ = distance travelled within medium
$N_1$, $N_2$ = number of atoms on the E level

N.B.: If $\Delta J$ is positive, more light exits the medium, than has entered!

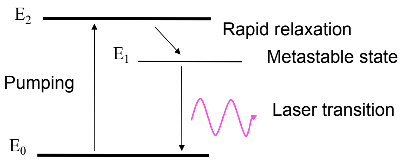
Excited state

Ground state

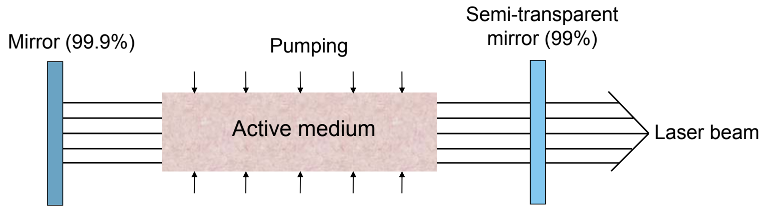



Thermal equilibrium | Population inversion

- Population inversion only in multiple-state systems
- Pumping: optical, electrical, chemical, … energy



# Principles of laser. Optical resonance




$d = m\lambda/2$ $\quad m$ = 1, 2, 3, ....

Resonator:

- two parallel (or concave) mirrors
- part of the exciting light is coupled back into the medium
- positive feedback -> self-excitation -> resonance

- Optical switch in the resonator: Q-switch, pulsed mode



# Properties of laser light

1. Small divergence
   Parallel (collimated) beam

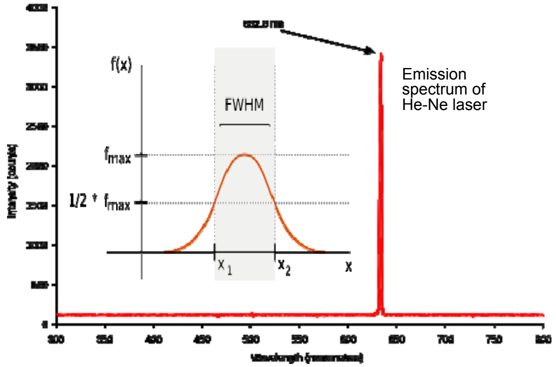
2. Large power/power density
   In continuous (CW) mode, tens, hundreds of W (e.g., $CO_2$ laser)
   In Q-switched mode, momentary power is enormous (GW)
   Because of small divergence, large spatial power density.

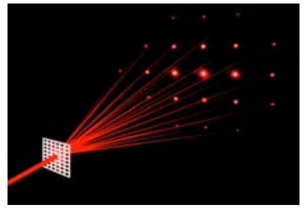
3. Small spectral bandwidth
   "Monochromaticity"
   Large spectral energy density

4. Often polarized

5. Possibility of extremely short pulses (ps, fs)

6. Coherence
   phase identity, interference tendency;
   temporal coherence (phase identity of photons emitted at different times);
   spatial coherence
   (phase identity across beam diameter).
   Application: holography, optical coherence tomography

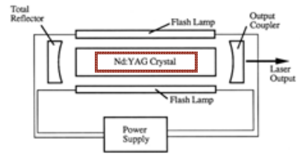


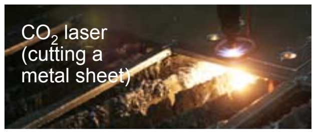


# Types of lasers based on active medium

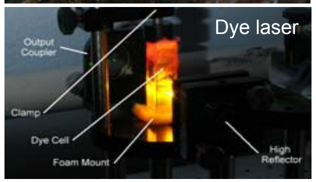
**Solid state lasers**
Metal doping in crystals or glasses; Ruby, Nd-YAG, Ti-sapphire
Red-infrared spectral range; CW, Q-switched mode, large power



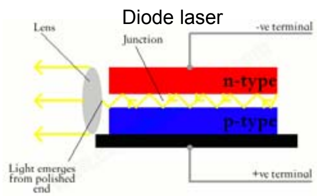

**Gas lasers**
Best known: He-Ne laser (10 He/Ne). Small energy, wide use
$CO_2$ laser: $CO_2$-$N_2$-He mixture; $\lambda$~10 μm; Huge power (100 W)




**Dye lasers**
Dilute solution of organic dyes (e.g., rhodamine, coumarine); Pumped by another laser.
Large power (Q-switched mode); Tunable

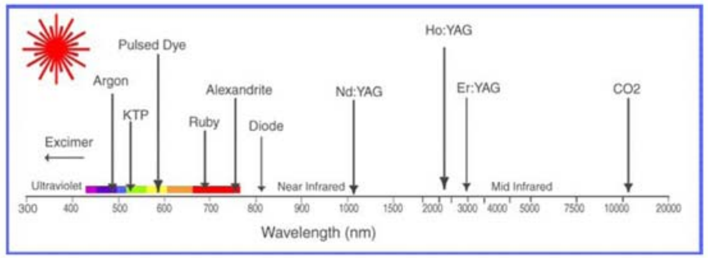



**Semiconductor (diode) lasers**
On the boundary of p- and n-type doped semiconductors. No need for resonator mirrors (total internal reflection), Red, IR spectral range. Huge CW power (up to 100W). Beam characteristics are not very good. Wide use because of small size.






# Types of lasers based on wavelength




laser lines (wavelengths) are available from X-rays to infrared light!

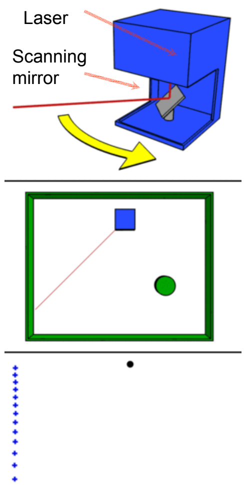
# Factors to be considered in laser applications

- Steerability (small divergence)
- Monochromaticity
- Coherence
- Possibility of short pulses
- Power:

| | |
|---|---|
| 10 mW | DVD player |
| 200 mW | DVD burner |
| 20 W | solid-state laser for micromachining |
| 100 W | surgical $CO_2$ laser |
| 3 kW | industrial $CO_2$ laser (laser cutter) |
| 1 kW | 1 cm diode laser bar |

**Distance/speed measurement with laser. LIDAR: "Light Detection and Ranging"**

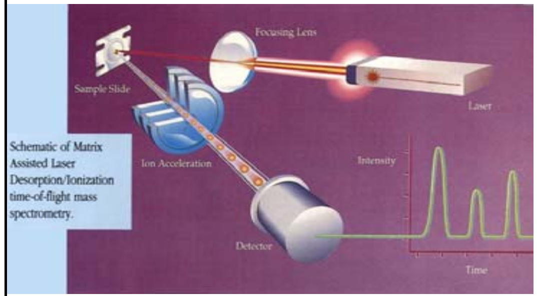
laser property utilized: steerability, short pulses

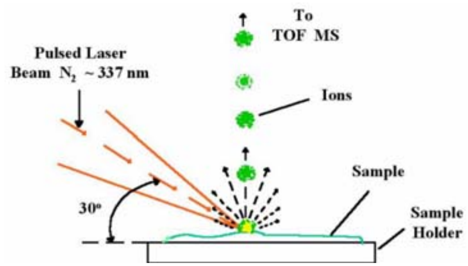



Recording: reconstructed spatial arrangement. In traffic speedometer: 100 pulses in 0.3 s

**MALDI-TOF: matrix-assisted laser desorption/ionization time of flight mass spectrometry**

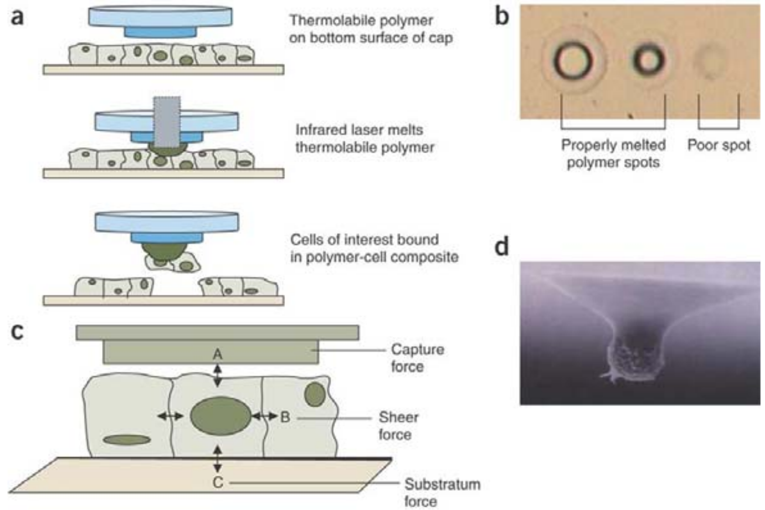
laser property utilized: power density



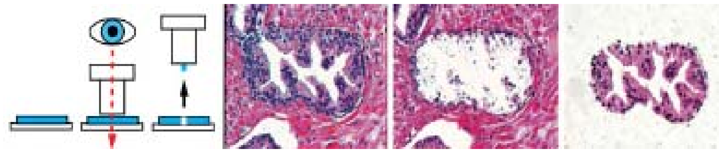






# "Laser capture microdissection"




laser property utilized: power density, steerability

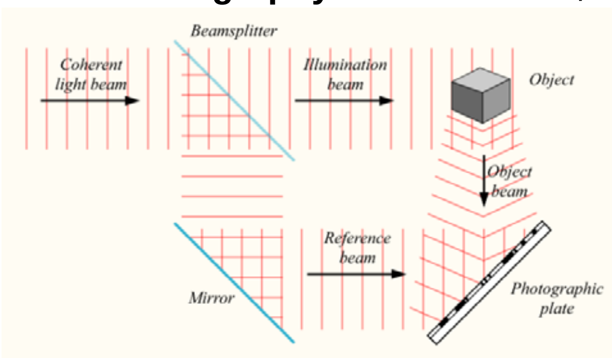


Significance: local analytics are possible (chemistry, genetics)

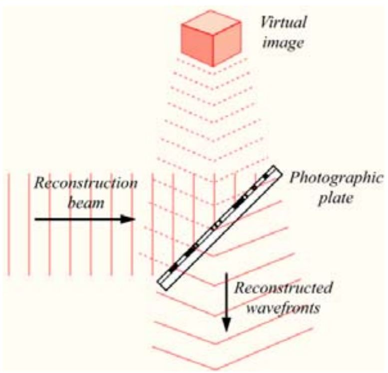


# Holography

Laser property utilized: coherence

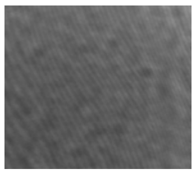



Recording a hologram

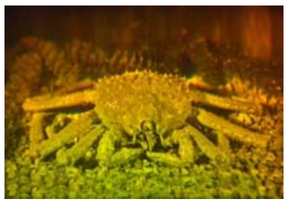



Visualization of a hologram

Dénes Gábor (1900-1979)



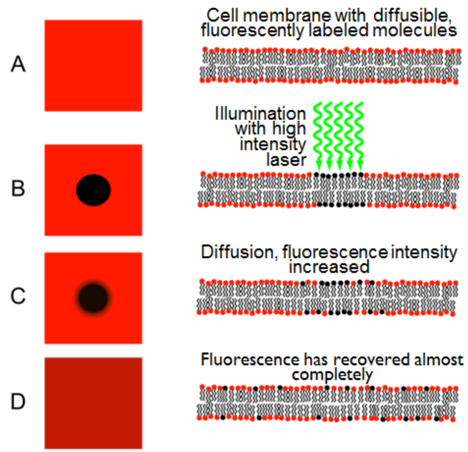
Surface of a hologram recording

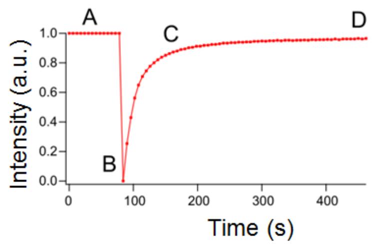



Holograms



# Fluorescence Recovery After Photobleaching (FRAP)



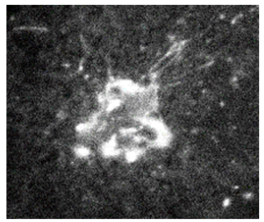
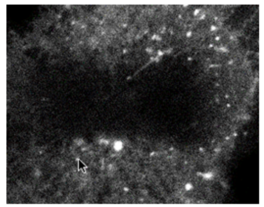
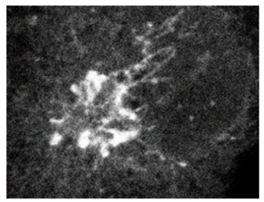



Image prior to bleaching





Laser property utilized: power density, steerability

The diffusion coefficient can be determined from the time-dependent recovery of fluorescence as:

$$D = \frac{w^2}{4t_D}$$

$D$ = diffusion coefficient

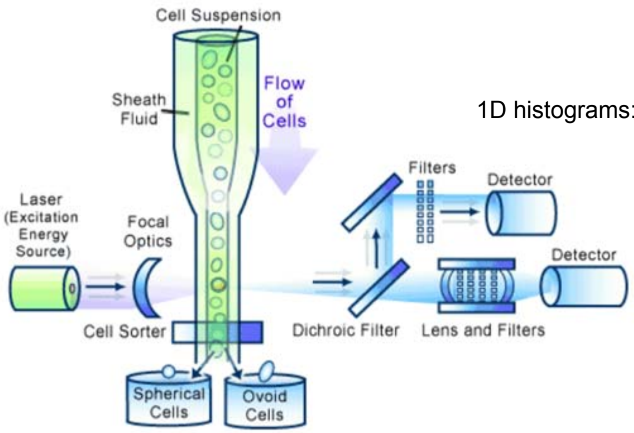
$w$ = width of bleached area

$t_D$ = time constant

# **Fluorescence activated cell sorter (FACS).** Flow cytometry

- A cell suspension, fluorescently labeled by using specific antibodies, is analyzed cell-by-cell
- Numerous parameters are measured simultaneously (fluorescence intensity at several wavelengths, small- and large-angle scatter)
- Statistical analysis
- If needed, cells can be separated according to their fluorescence

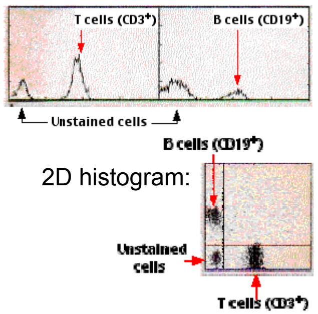
Laser property utilized: monochromaticity, small spot size




Cytometry statistics

1D histograms:

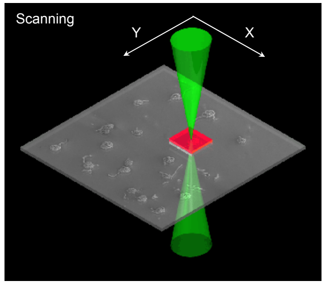
2D histogram:



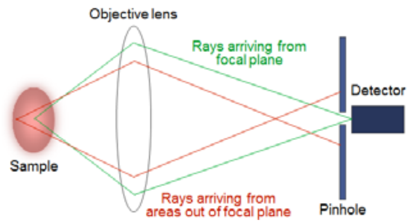


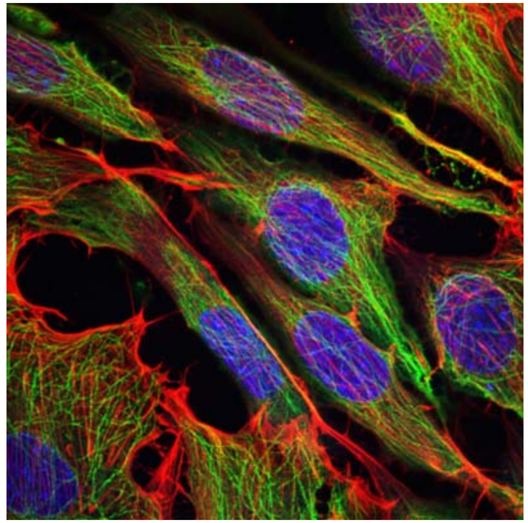

# **Laser scanning confocal microscopy**

Laser property utilized: monochromaticity, steerability




"Confocal principle"



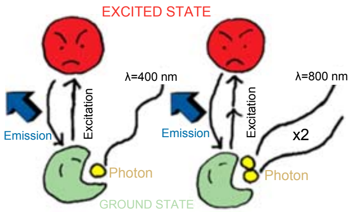
*Green: microtubules; Red: actin; Blue: nuclei*

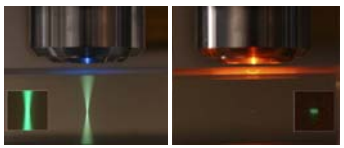


# **Multiphoton fluorescence microscopy**

Laser property utilized: monochromaticity, steerability, short pulses

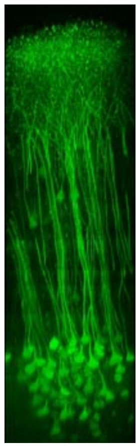
- Energy of two (or more) photons are added during excitation
- Excitation (hence emission) only in the focal point (limited photodamage)
- Excitation with long wavelength (near-IR), short (fs) light pulses
- Large (up to 2 mm) penetration due to long wavelength



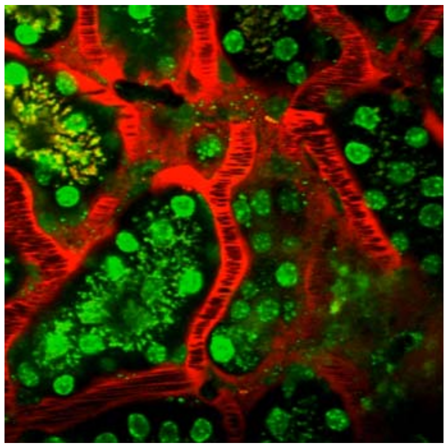



Single-photon fluorescence

Two-photon fluorescence



*Cortical pyramidal cells*

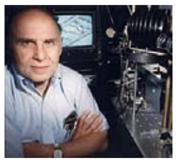


*Green: proximal kidney tubules; Red: albumin (plasma)*

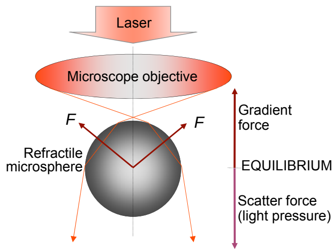


# **Laser tweezers**

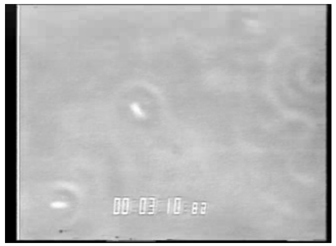
Laser property utilized: power density, steerability



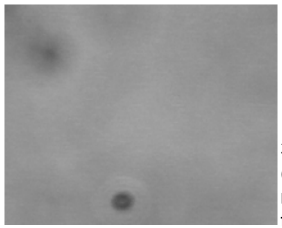
Arthur Ashkin (1970)




In the laser tweezer, momentum change occurs between the photons and the trapped particle.

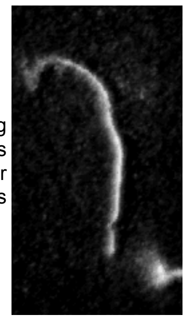



Trapping bacterial cells with laser tweezers

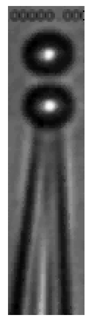


3 µm latex (polystyrene) microspheres in the optical trap

Manipulating molecules with laser tweezers



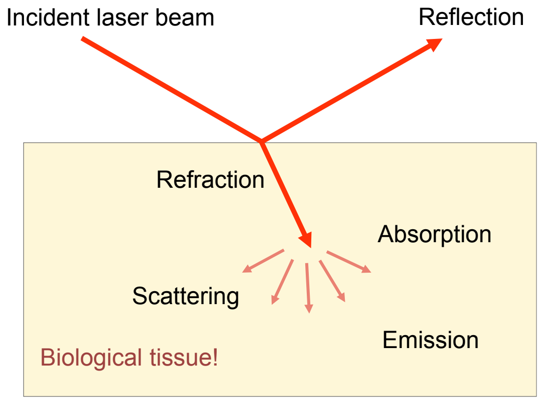
Actin filament



dsDNA

Molecular force measurement

# Medical applications of lasers



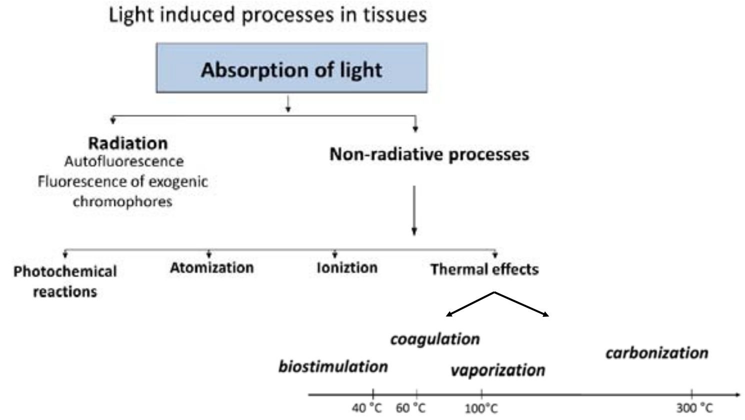

Laser properties to consider:

- Steerability (small divergence, surgeries)
- Power (surgical applications)
- Monochromaticity (tissue absorbance)
- Coherence (interference, image formation)

The effects depend not only on the properties of the laser, but also on those of the biological tissue: absorbance, transmittivity, light-induced reactions.



# Medical applications of lasers




- Surgical disciplines: “laser knife”, coagulation, blood-less surgery.
- Tumor removal, tattoo removal: $CO_2$ and Nd:YAG lasers, holmium laser lithotripsy (urology).
- Dermatology: wide-spread uses (tattoo removal, naevus removal, etc.)
- Dentistry: caries treatment (caries absorbs preferentially).
- Photodynamic tumor therapy: laser acivation of photosensitive chemicals preferentially taken up by the tumor.
- Opthalmology: Retina lesions, photocoagulation, glaucoma, photorefractive keratektomy (PRK).



# Dermatological applications. Hair/ tattoo/ naevus removal

Phototricholysis, photoepilation

Mechanism: selective photothermolysis, selective absorption by chromophores

Employed chromophores:

1. Carbon (exogenous, carbon or graphite-containing creams)
2. Hemoglobin (endogenous)
3. Melanin (endogenous)






# Dermatological applications

Removal of superficial blood vessels


Resurfacing

Wrinkle removal

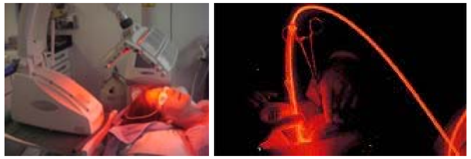


Rhinophyma (sebaceous gland hypertrophy, fibrosis)

# Oncological applications: Photodynamic therapy

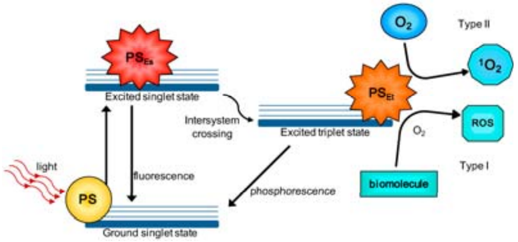
Photodynamic therapy (PDT):
Roswell Park Cancer Institute 1970's.

Three-component tumor therapeutic method:
1) photosensitizing agent, 2) light, 3) oxygen
Steps:



Delivery of light into the patient:
surface exposure, optical fiber

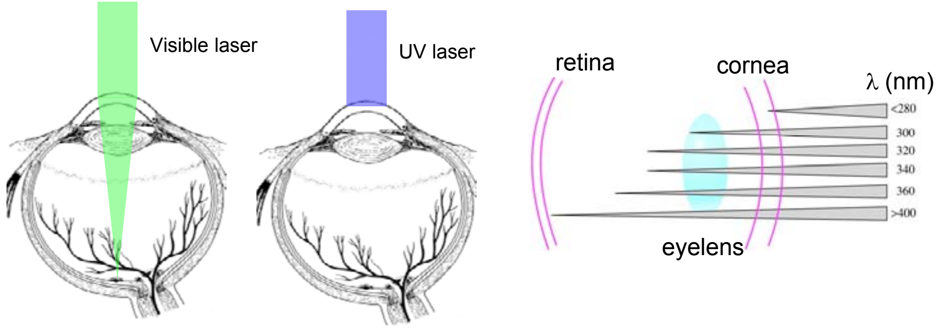

1. Administration of photosensitizing agent (aminolevulic acid, ALA).
2. Incubation for few hours. ALA is transformed into protoporphyrin IX.
3. Illumination of target area with diode laser (few minutes).
4. Protoporphyrin absorbs ➛ excited singlet state ➛ triplet state ➛ energy transfer with triplet oxygen ➛ excited, reactive oxygen ➛ tissue reaction. The illuminated area necrotizes in a few days.






# Ophthalmologic applications: Considerations

Transmittivity of optical media is wavelength-dependent



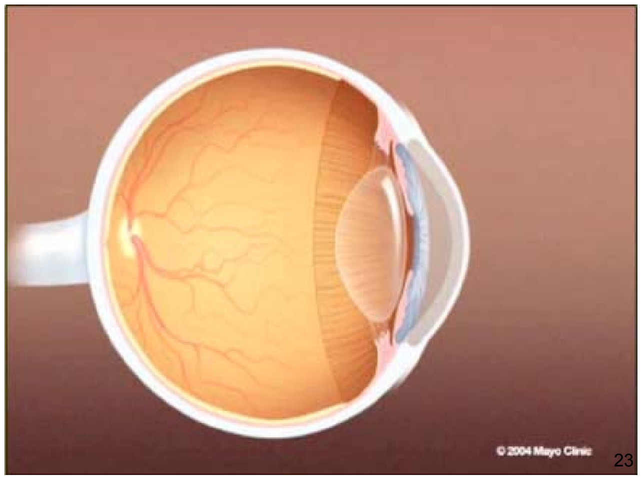



# Ophthalmologic applications, LASIK

"Laser-assisted In Situ Keratomileusis". type of refractive laser eye surgery

History:
Jose Barraquer, 1970: construction of a microkeratome, with which he was able to cut lines and lobes in the cornea with laser (keratomileusis).
Lucio Buratto (Italian) and Ioannis Pallikaris (Greek), 1990: combination of keratomileusis photorefractive keratectomy.
Thomas and Tobias Neuhann (Germany), 1991: automated microkeratome.

Steps:
1. Removal of contact lens (7-10 days prior to treatment)
2. Scanning the topography of the cornea with low-power laser.
3. Cutting and lifting a layer of the cornea with femtosecond laser.
4. Removal of material from the corneal stroma (few tens of microns). Excimer laser (193 nm).

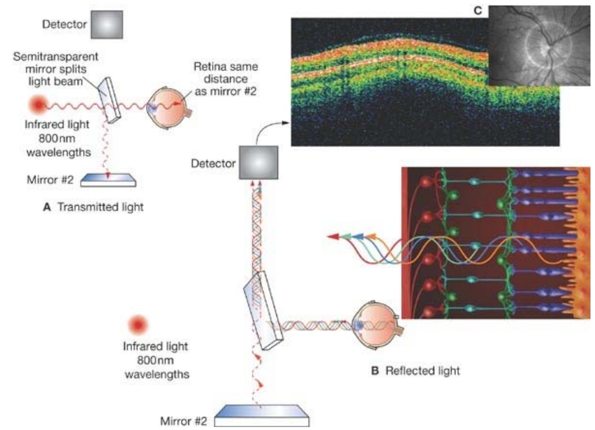


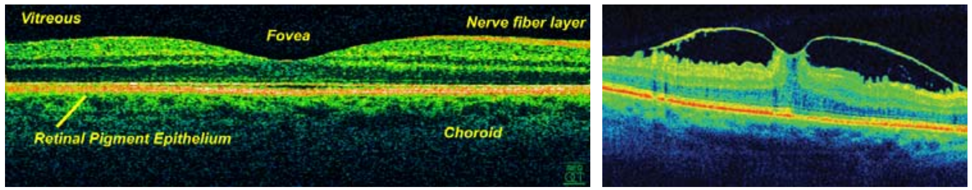



# Ophthalmologic applications
# Optical Coherence Tomography (OCT)

- Non-invasive
- Contrast-agent free
- Near microscopic resolution

Principles:
light rays reflected in deeper tissue layers can be separated from scatter by using interferometry. The spatial position of the reflecting layers can be determined. The structure of the illuminated sample can be resolved within 1-2 mm depth.




Normal retina

Macula degeneration