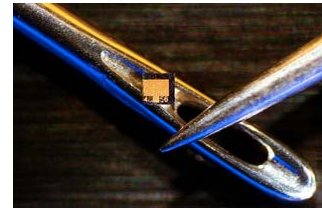


# LASER

MIKLÓS KELLERMAYER

## Lasers are everywhere



5 mW diode laser  
few mms



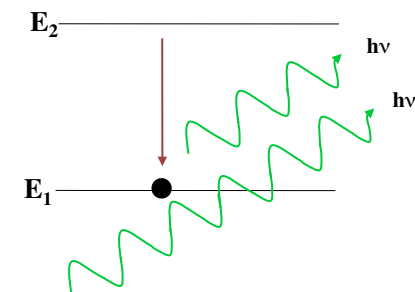
Terawatt NOVA laser - Lawrence Livermore Laboratories  
Size of a football field

## Laser

1. What is the laser?
2. Short laser history
3. Foundations of laser function
4. Properties of laser light
5. Types of lasers
6. Biomedical applications of lasers

## Laser:

“Light Amplification by Stimulated Emission of Radiation”



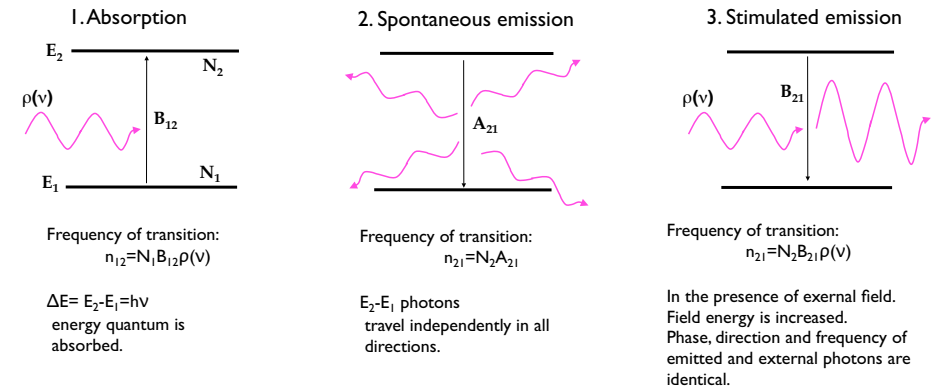
Luminescent light source based on light amplification.  
MASER: Microwave Amplification by Stimulated Emission of Radiation

# LASER HISTORY IN A NUTSHELL



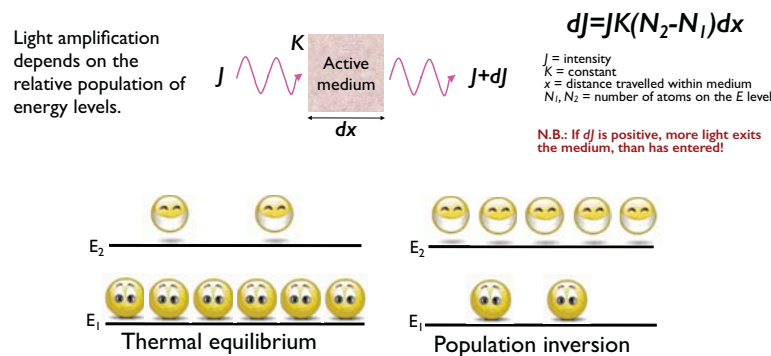
- **1917** - *Albert Einstein*: theoretical prediction of stimulated emission.
- **1946** - *G. Meyer-Schwickerath*: first eye surgery with light.
- **1950** - *Arthur Schawlow and Charles Townes*: emitted photons may be in the visible range.
- **1954** - *N.G. Basow, A.M. Prochorow, and C. Townes*: 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
- **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.

## Principles of laser I. stimulated emission

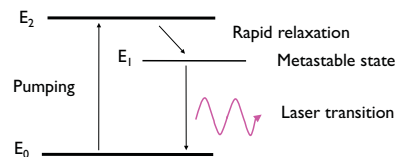


Explanation: two-state atomic or molecular system.  
 $E_1, E_2$ : energy levels,  $E_2 > E_1$   
 $\rho(\nu)$ : spectral energy density of external field.  
 $N_1, N_2$ : number of atoms or molecules on the given energy level.  
 $B_{12}, A_{21}, B_{21}$ : transition probabilities (Einstein coefficients),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

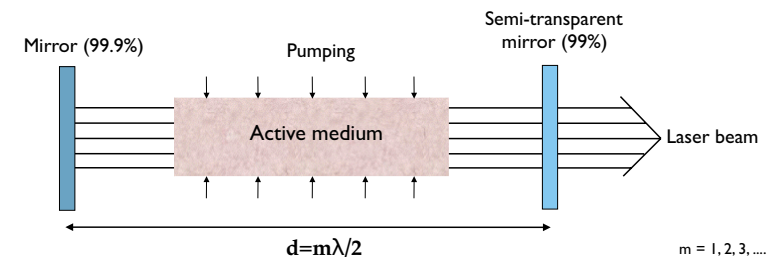
## Principles of laser II. Population inversion



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



## Principles of laser III. Optical resonance



### Resonator:

- two parallel (or concave) mirrors
- part of the exiting light is coupled back into the medium
- positive feedback  $\rightarrow$  self-excitation  $\rightarrow$  resonance

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

# Properties of laser light I.

## 1. Small divergence

Parallel (collimated) beam

## 2. Large power

In continuous (CW) mode, tens, hundreds of W (e.g., CO<sub>2</sub> laser)

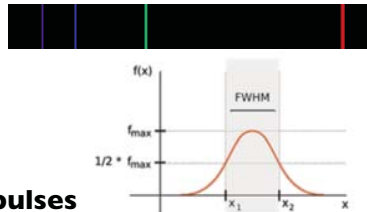
In Q-switched mode, momentary power is enormous (GW)

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

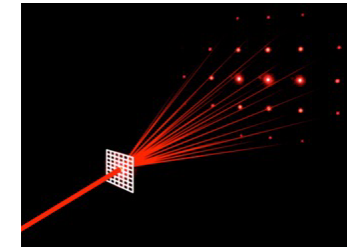
# Properties of laser light II.

## 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:

### 1. Solid state lasers

Metal doping in crystals or glasses; Ruby, Nd-YAG, Ti-sapphire

Red-infrared spectral range; CW, Q-switched mode, large power

### 2. Gas lasers

Best known: He-Ne laser (10 He/Ne). Small energy, wide use

CO<sub>2</sub> laser: CO<sub>2</sub>-N<sub>2</sub>-He mixture;  $\lambda \sim 10 \mu\text{m}$ ; Huge power (100 W)

### 3. Dye lasers

Dilute solution of organic dyes (e.g., rhodamine, coumarine); Pumped by another laser.

Large power (Q-switched mode); Tunable

### 4. Semiconductor lasers

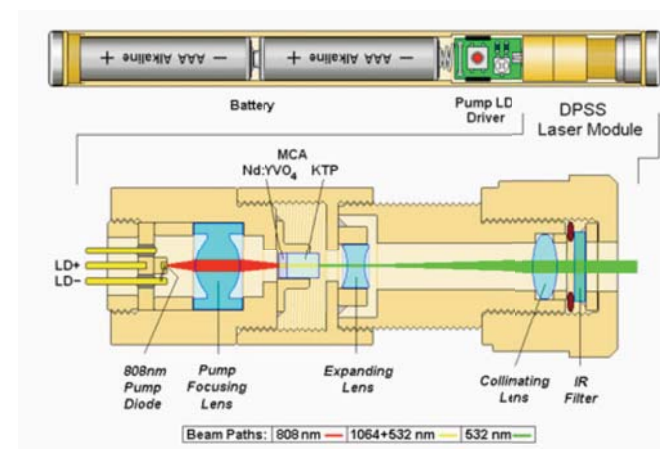
On the boundary of p- and n-type doped semiconductors.

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.

# The green laser pointer



## Steps:

1. Diode laser (808 nm) pumps
2. Solid state laser (neodimium-yttrium-vanadate) generates 1064 nm light
3. KTP (potassium titanyl phosphate) crystal doubles frequency (halves wavelength): 532 nm (green)

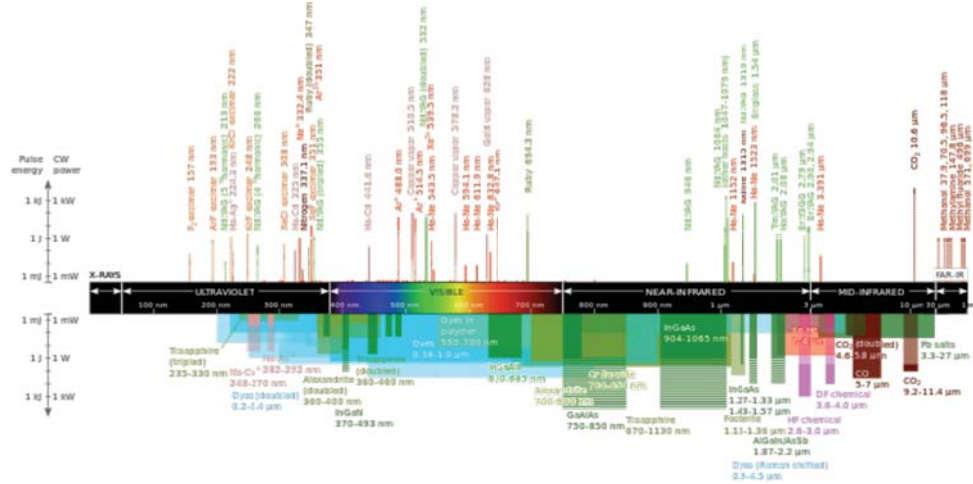
## \*Notes:

DPSS: diode-pumped solid state

MCA: multiple crystal assembly

LD: laser diode

# Lasers, spectral lines and bands



Laser lines are available from X-rays to infrared light.

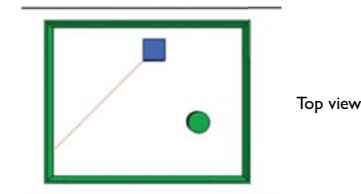
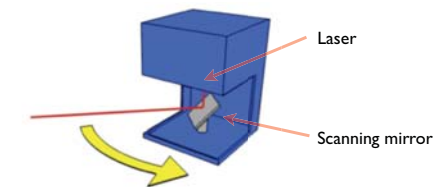
# Application of lasers based on power

- 5 mW – CD-ROM drive
- 5–10 mW – DVD player or DVD-ROM drive
- 100 mW – high-speed CD-RW writer
- 250 mW – DVD-R writer
- 1–20 W – solid-state laser for micromachining
- 30–100 W – surgical CO<sub>2</sub> laser
- 100–3000 W – industrial CO<sub>2</sub> laser (laser cutter)
- 1 kW – 1 cm diode laser bar

# Factors to be considered in laser applications

- Steerability
- Power
- Monochromaticity
- Coherence

# Speed measurement with laser LIDAR: “Light Detection and Ranging”

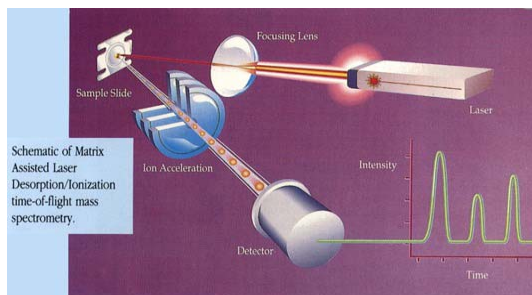


Steerability

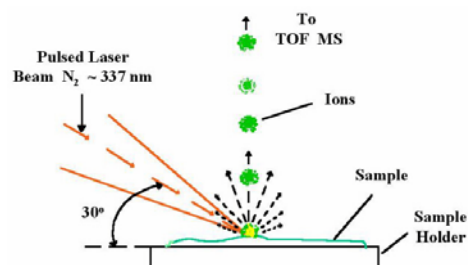
Recording:  
reconstructed spatial arrangement.  
In traffic speedometer:  
100 pulses in 0.3 s



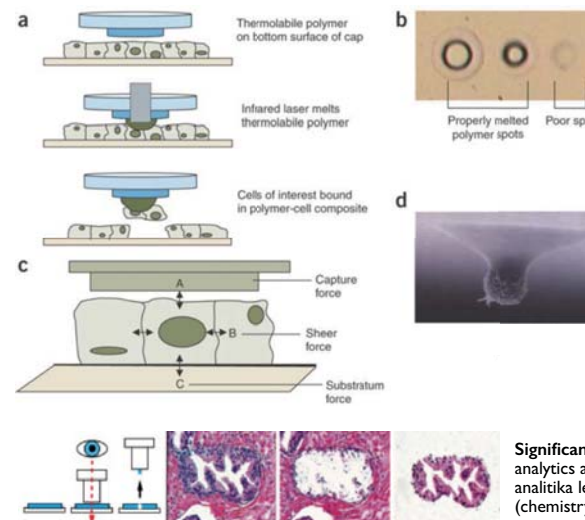
# MALDI-TOF: matrix-assisted laser desorption/ionization time of flight mass spectrometry



Power density

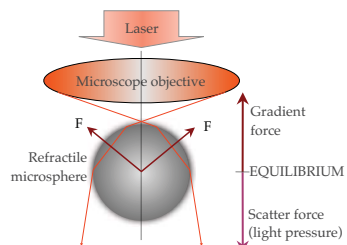


# “Laser capture microdissection”



# Laser tweezers

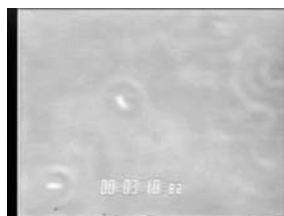
Power density



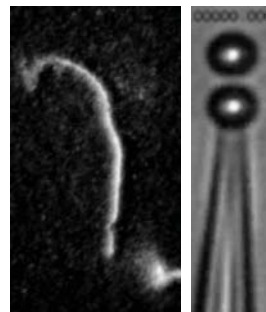
In the laser tweezer momentum change occurs between the photons and the trapped particle:



Trapping bacterial cells with laser tweezers



Manipulating molecules with laser tweezers



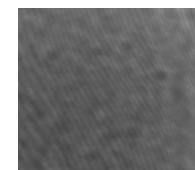
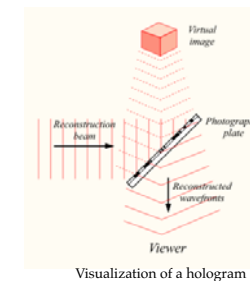
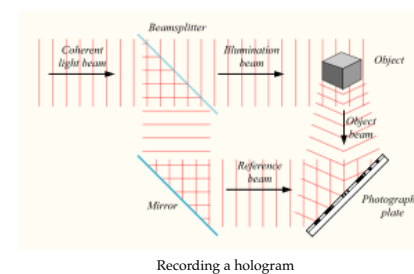
Molecular force measurement!

# Holography

Coherence



Dénes Gábor  
(1900-1979)

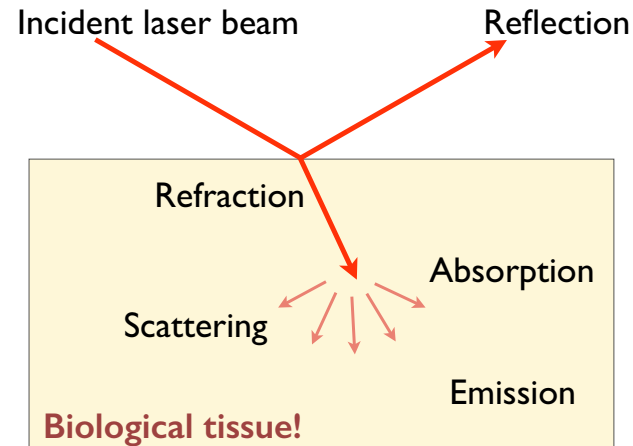


Surface of a hologram recording



Holograms

# Biomedical applications of lasers I.



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

# Biomedical applications of lasers II.

**Surgical disciplines:** “laser knife”, coagulation, blood-less surgery. Tumor removal, tattoo removal. CO<sub>2</sub> and Nd:YAG lasers, holmium laser lithotripsy (urology).

**Dermatology:** wide-spread uses (tattoo removal, naevus removal, etc.)

**Dentistry:** caries absorbs preferentially.

**Photodynamic tumor therapy:** laser activation of photosensitive chemicals preferentially taken up by the tumor.

**Ophthalmology:** Retina lesions, photocoagulation, glaucoma, photorefractive keratectomy (PRK).

## Dermatological applications: I. Considerations

### 1. Employed wavelengths:

- Argon: 488 or 514.5 nm
- Ruby: 694 nm
- Alexandrite: 755 nm
- Pulsed diode array: 810 nm
- Nd:YAG: 1064 nm

### 2. Pulse width

### 3. Size of illuminated area (8-10 mm diameter)

### 4. Energy flux (J/cm<sup>2</sup>)

### 5. Repetition rate (accumulation effects)

### 6. Epidermal cooling (gels, liquids, sprays, air)

## Dermatological applications: 2. Hair removal

Phototricholysis, photoepilation

Basis: selective photothermolysis  
selective absorption by chromophores

Employed chromophores:

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



Before treatment

After treatment

## Dermatological applications:

### 3. Tattoo removal

Q-switched Nd:YAG laser (1064 nm)

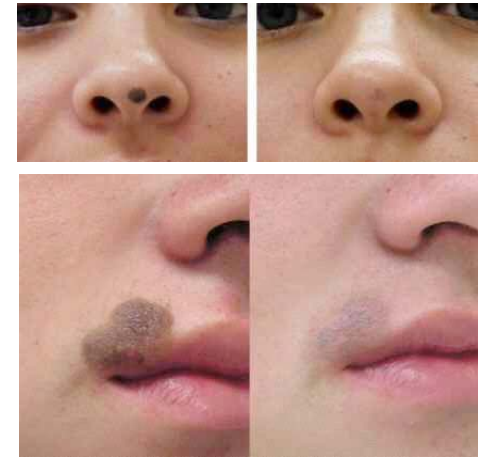


Before treatment

After treatment

## Dermatological applications:

### 4. Naevus removal

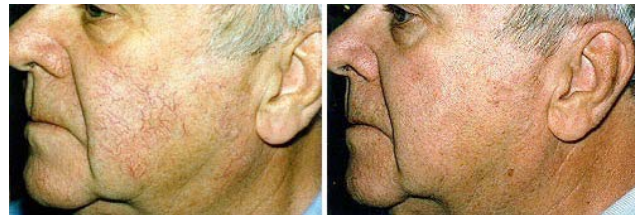


Before treatment

After treatment

## Dermatological applications:

### 5. Removal of superficial blood vessels, veins



Before treatment

After treatment



Before treatment

2 years after treatment

## Dermatological applications:

### 6. Resurfacing

1993. Adrian  
CO<sub>2</sub>, Erbium:YAG laser



Wrinkle removal



Sun damage



Rhinophyma (sebaceous gland hypertrophy, fibrosis)



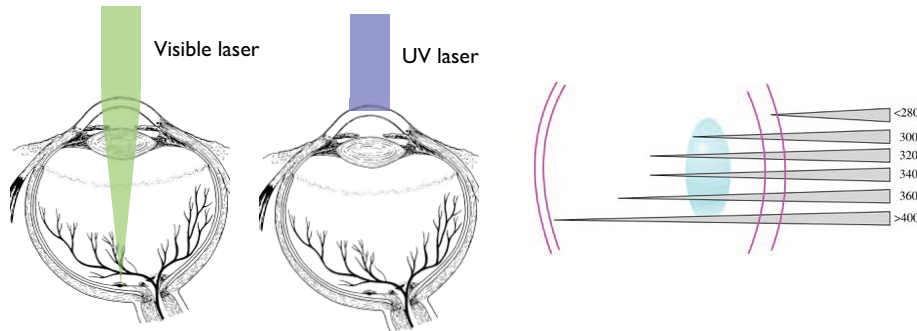
Systemic epidermal naevus



# Ophthalmologic applications:

## I. Principles

Transmittivity of optical media is wavelength-dependent



# Ophthalmologic applications:

## 2. LASIK

“Laser-assisted In Situ Keratomileusis”  
One 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).

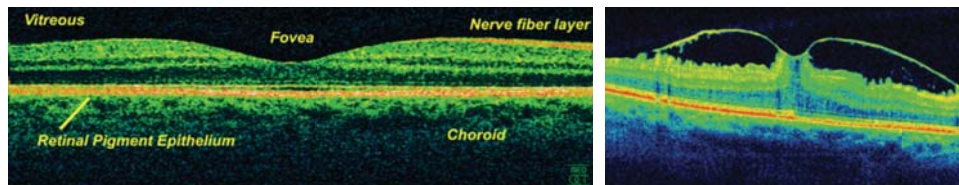
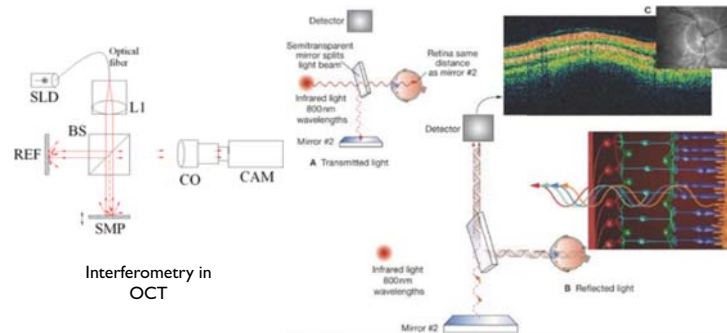


# OCT

**Optical Coherence Tomography**

- 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

# Photodynamic therapy

**Photodynamic therapy (PDT):**

Roswell Park Cancer Institute 1970's.

**Three-component tumor therapeutic method:**

1. Photosensitizing agent, 2. Light, 3. Oxygen.

Steps:

1. Administration of photosensitizing agent (aminolevulinic 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  $\rightarrow$  excited singlet state  $\rightarrow$  triplet state  $\rightarrow$  energy transfer with triplet oxygen  $\rightarrow$  excited, reactive oxygen  $\rightarrow$  tissue reaction
5. The illuminated area necrotizes in a few days.

