

Principles, types and medical applications of lasers

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Laser

light **a**mplification by **s**timulated **e**mission of **r**adiation



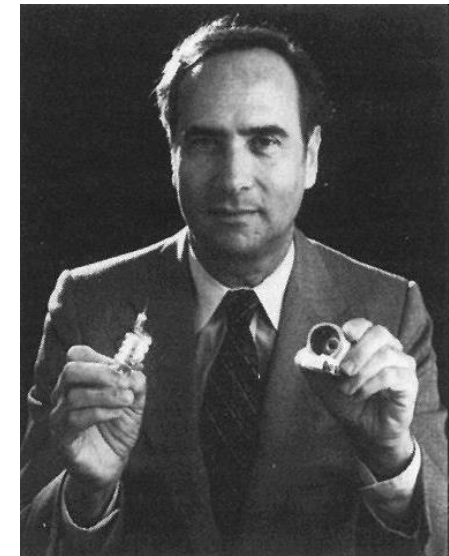
History of lasers in a nutshell...

1917 - Albert Einstein: theoretical prediction of stimulated emission

1954 - N.G. Basow, A.M. Prochorow, C. Townes: ammonia maser
(Microwave Amplification by Stimulated Emission of Radiation)

1960 - Theodore Maiman:
first laser in the visible spectral range
(ruby laser)

a flashlamp-pumped synthetic ruby crystal to
produce red laser light at 694 nm wavelength



Theodore Maiman

Nobel prize in Physics 1964

for work in quantum electronics leading to lasers and masers



Alexander Prochorow



Charles H. Townes



Nicolay Basow

Nobel prize in Physics 1971

For invention of holography



XI. kerület, Magyar tudósok körútja 2.



Gábor Dénes



Steven Chu



William D. Phillips



Claude Cohen-Tannoudji

Nobel prize in Physics 1997
for development of methods to cool and trap atoms with laser light



Zhores Ivanovich Alferov



Herbert Kroemer

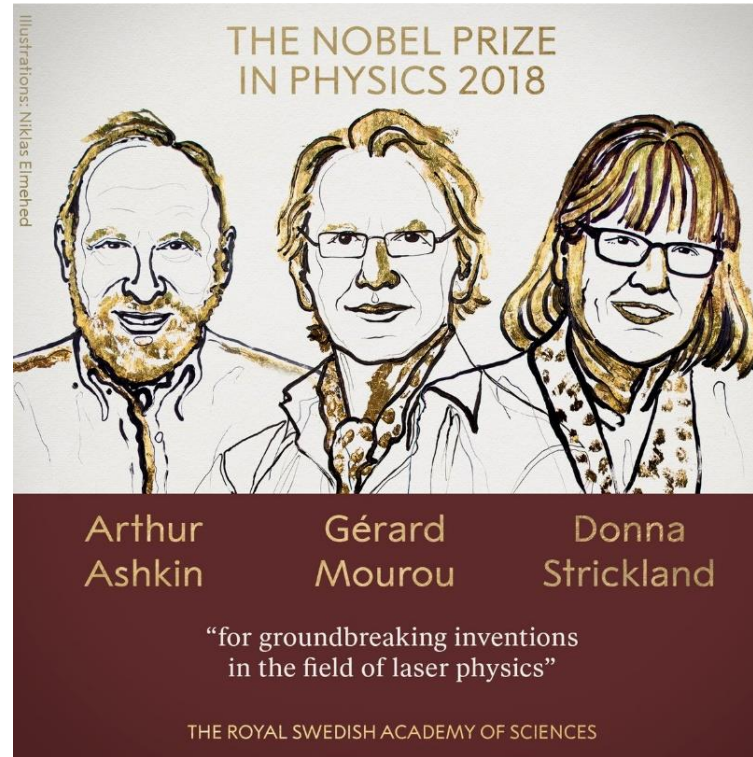
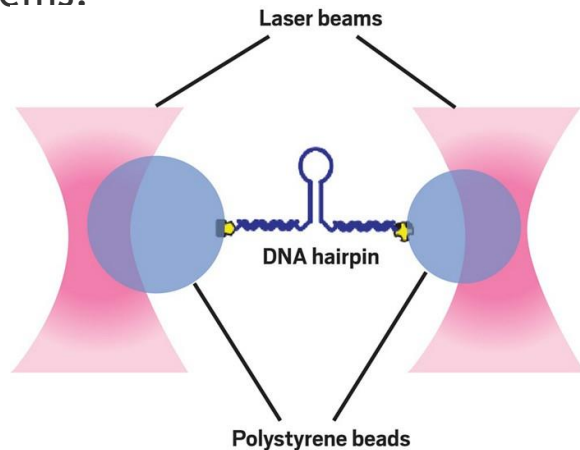
Nobel prize in Physics 2000
Semiconducting laser diode

Nobel prize in Physics 2018

"for groundbreaking inventions in the field of laser physics"

Ashkin,

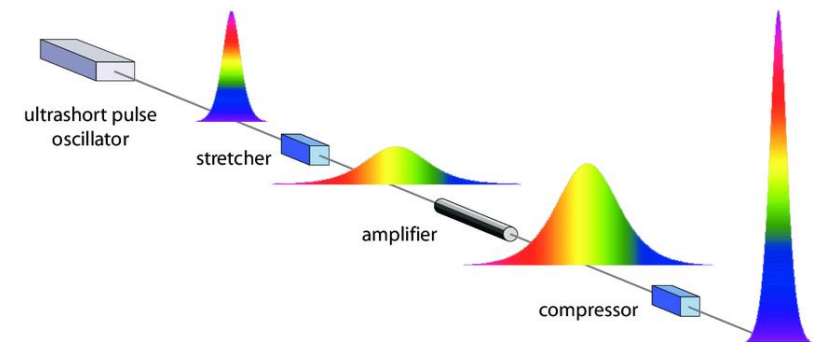
Arthur Ashkin invented optical tweezers that grab particles, atoms, molecules, and living cells with their laser beam fingers. The tweezers use laser light to push small particles towards the centre of the beam and to hold them there. In 1987, Ashkin succeeded in capturing living bacteria without harming them. Optical tweezers are now widely used to investigate biological systems.



Mourou and Strickland

paved the way towards the shortest and most intense laser pulses ever created by mankind

First they stretched the laser pulses in time to reduce their peak power, then amplified them, and finally compressed them. If a pulse is compressed in time and becomes shorter, then more light is packed together in the same tiny space - the intensity of the pulse increases dramatically. The innumerable areas of application have not yet been completely explored...



Illustrations: Niklas Elmehed

THE NOBEL PRIZE IN PHYSICS 2023



Pierre
Agostini

Ferenc
Krausz

Anne
L'Huillier

“for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter”

THE ROYAL SWEDISH ACADEMY OF SCIENCES

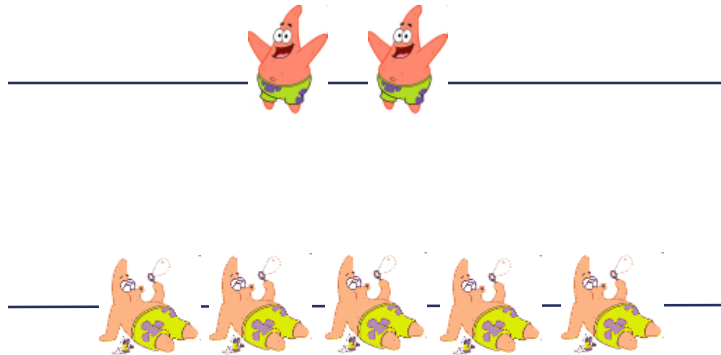
Fundamentals of laser operation

Special electronic energy states - I. at least a three-state system



Laser material: doped crystal, mixture of gases, solution of organic dyes

II: Occupancy in energy levels Population inversion

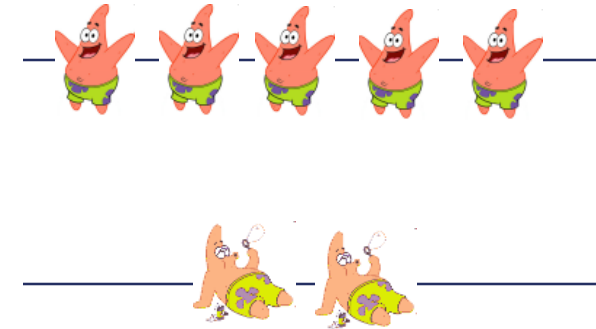


Thermal equilibrium

According to Boltzmann distribution

$$\frac{n_i}{n_0} = e^{-\frac{\epsilon_i - \epsilon_0}{k_B T}}$$

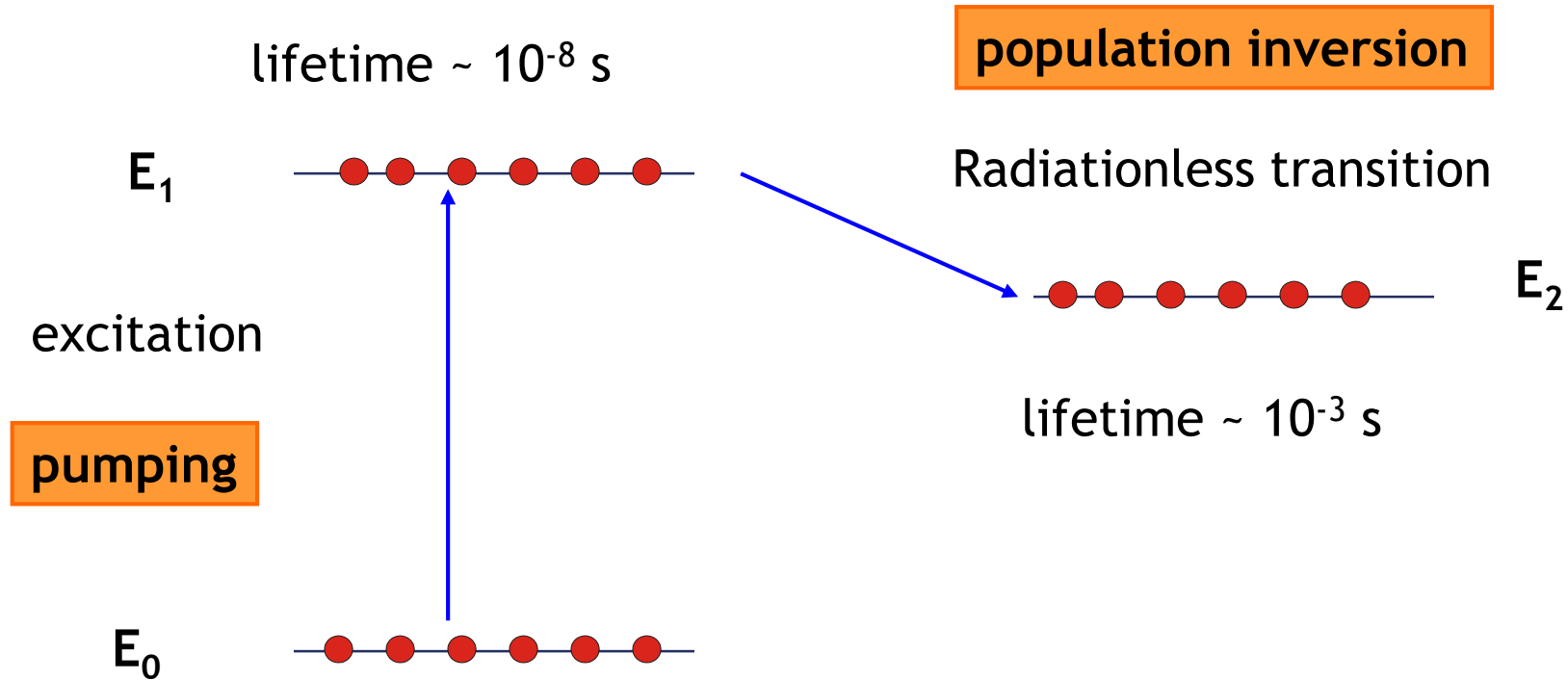
The number of atoms, n , at an energy level $\Delta\epsilon$ higher than the ground level, if the number of atoms in the ground state is n_0 in two energy levels separated by the energy difference.



Population inversion

“opposite” distribution - more electrons are in the excited state than in the ground state

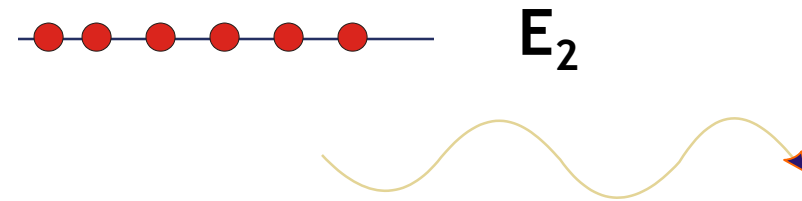
III: Excitation Optical pumping



Spontaneous photon emission

E_1 _____

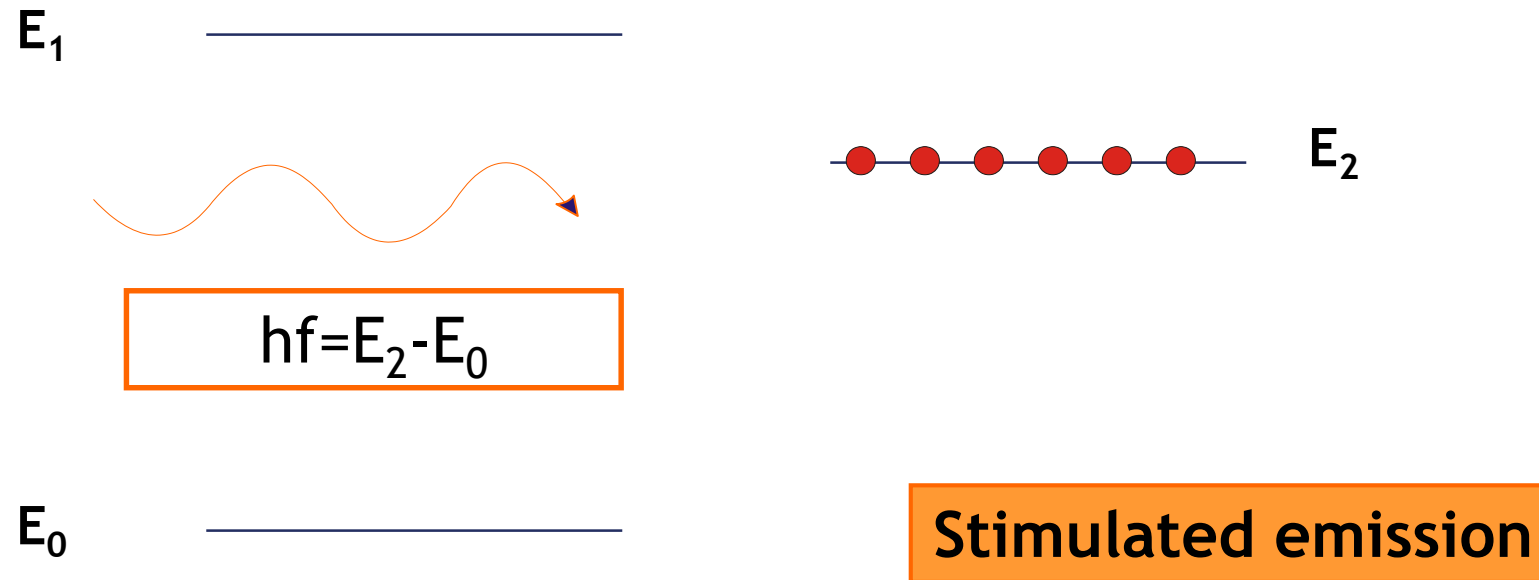
E_0 _____ ●



Spontaneous light emission

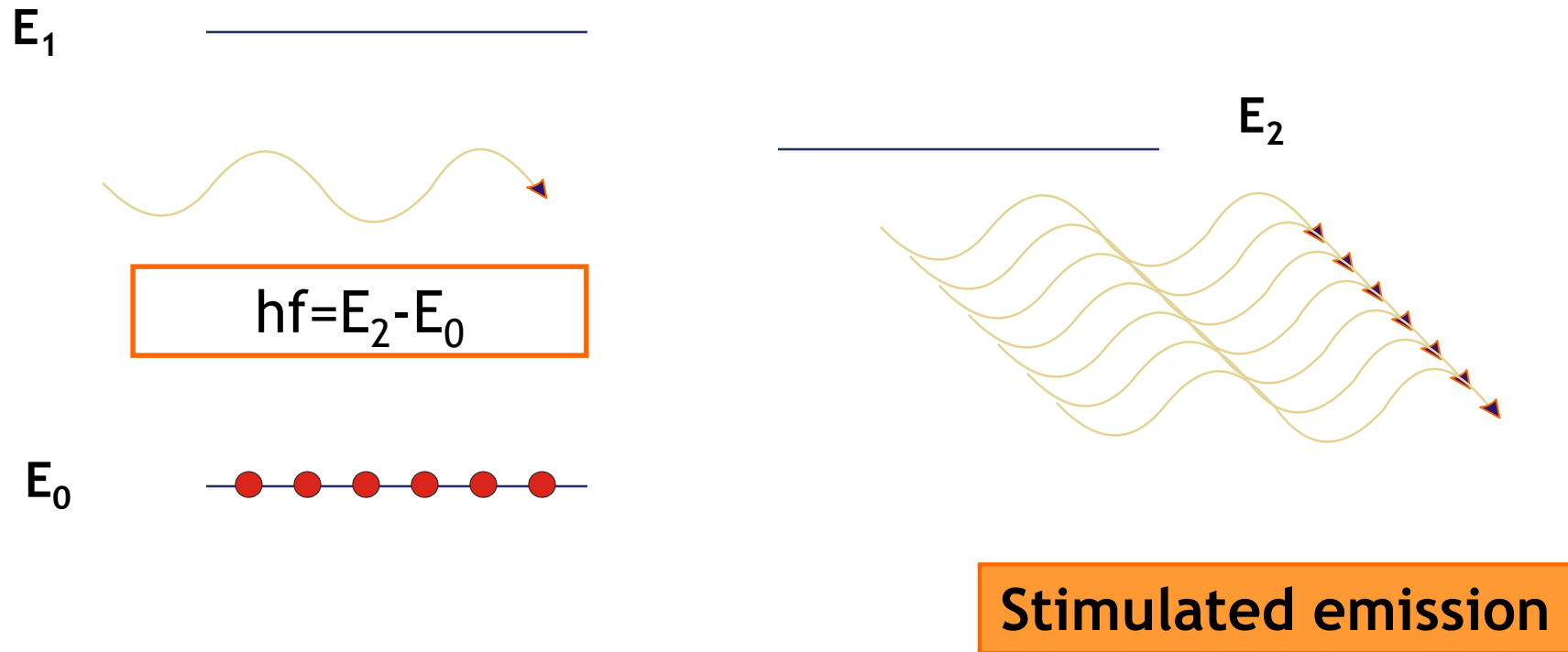
Low probability

Induction of atomic transition - relaxation of electrons from metastable state



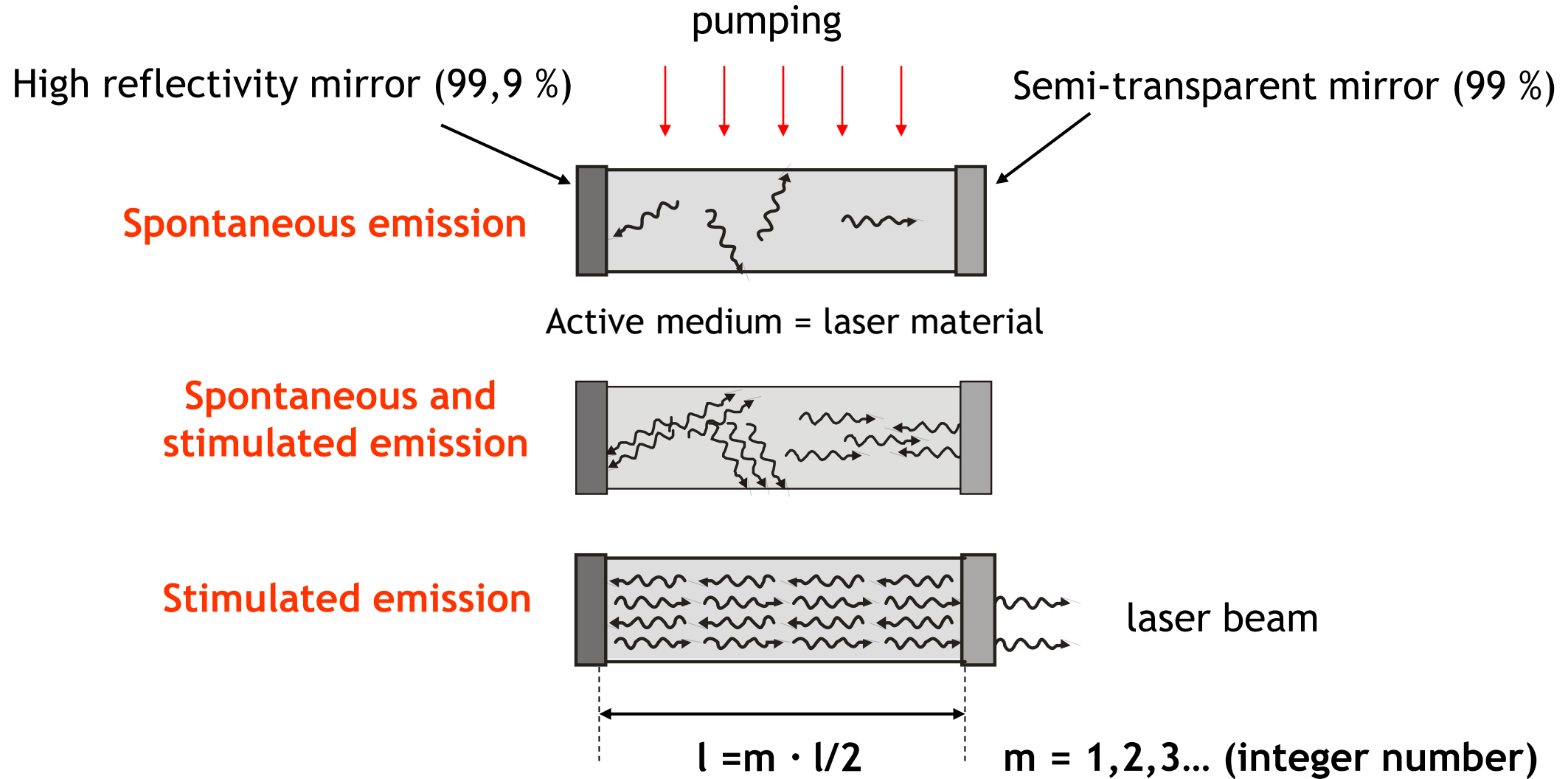
The incoming photon of $hf = E_2 - E_0$ can interact with electrons on metastable state causing them to drop to the lower energy level

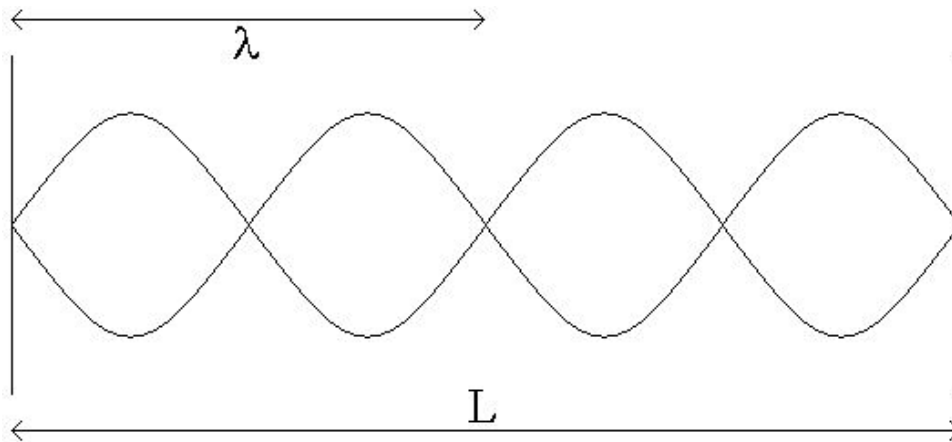
Induction of atomic transition - relaxation of electrons from metastable state



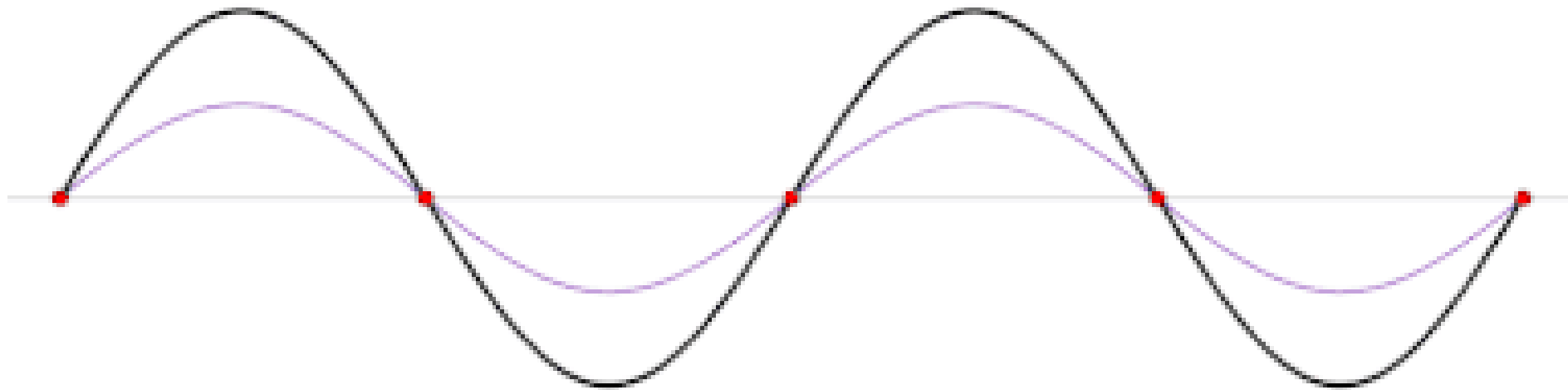
Phase, frequency, polarization, and direction of the photons emitted with the stimulated emission are identical with that of induced the stimulation.

Optical resonator





Standing waves: superposition of two waves, which have equal frequencies and amplitudes and propagate in opposite direction.



$$l = m \cdot \lambda/2 \quad m = 1, 2, 3... \text{ (integer number)}$$

General properties of laser light

Photons emitted by stimulated emission and the inducing photons are identical:

- energy
- phase
- polarization
- direction



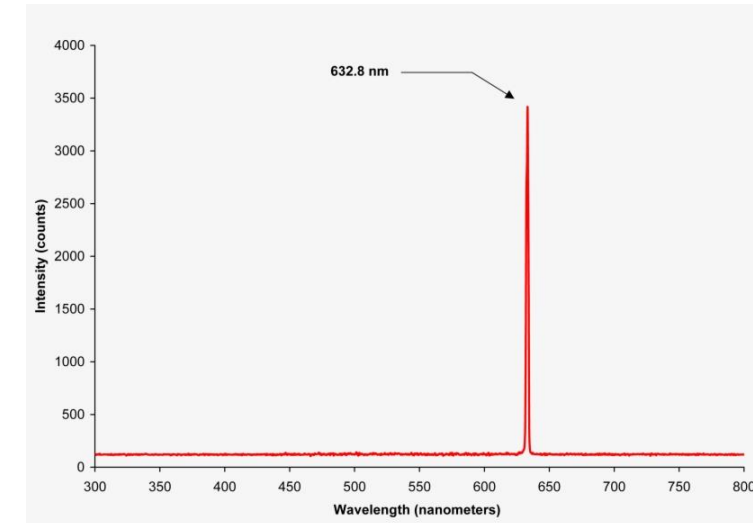
Consequently laser light is

- monochromatic
- coherent
- polarized
- parallel beam

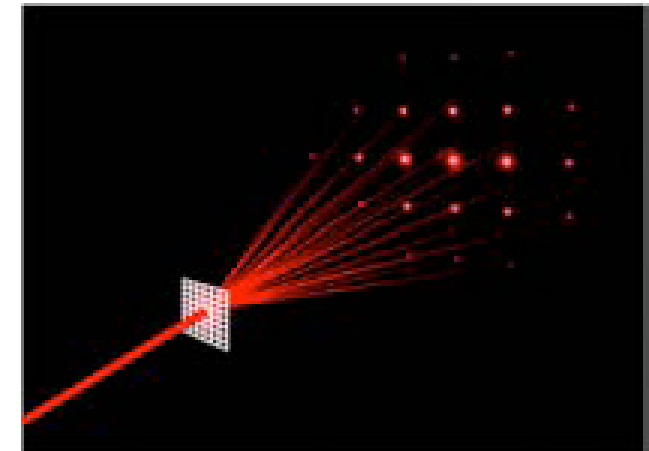


Light generated by stimulated emission

1. monochromatic - narrow spectral width
2. coherent - phase identity
 - temporal coherence: (phase identity of photons emitted at different times)
 - spatial coherence: (phase identity across beam diameter)
1. Small divergence: parallel beam
2. Polarized: electric field vector oscillates in a single plane
3. Extremely short pulses: fs, ps, as
4. High power (kW-GW): large spatial power density, e.g.:
Nd-YAG laser pulse energy 2 J, 20 ns, 10 Hz \rightarrow emitted average power: 2 J/0,1 s = 20 W, power of single pulse: $2 \text{ J}/20 \text{ ns} = 10^8 \text{ W}$
5. Continuous wave or pulsed lasers



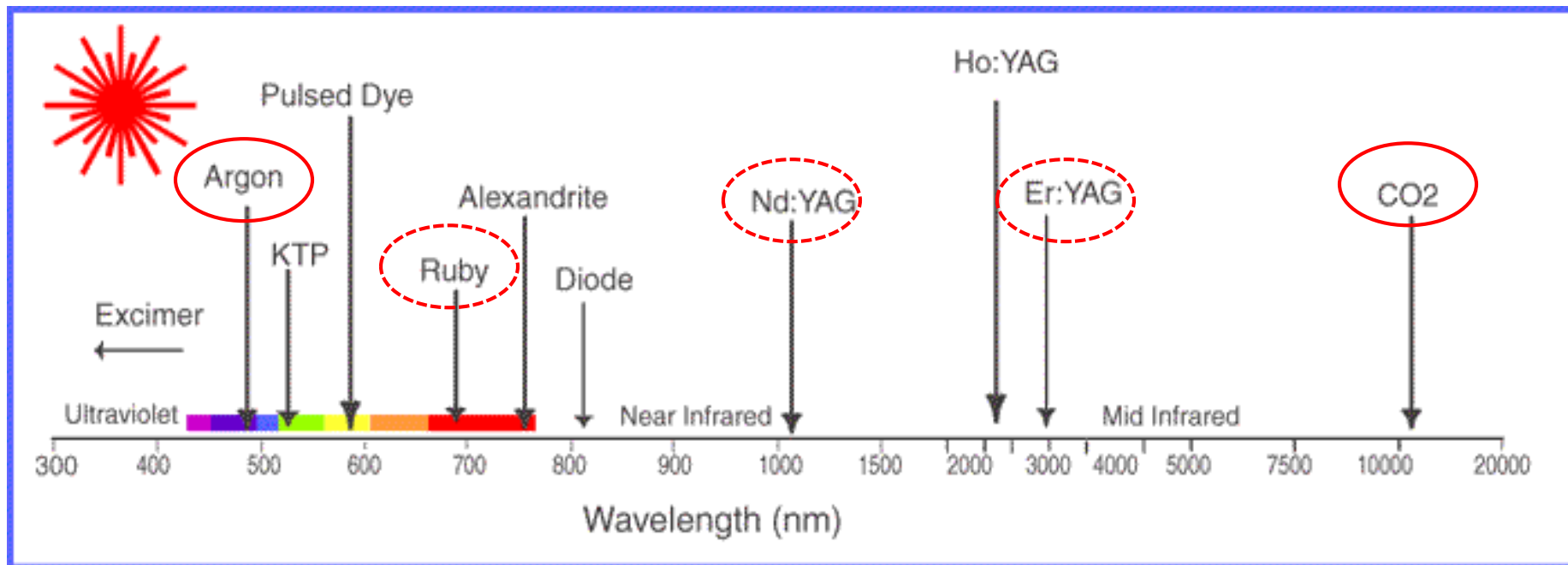
He-Ne laser emission spectrum



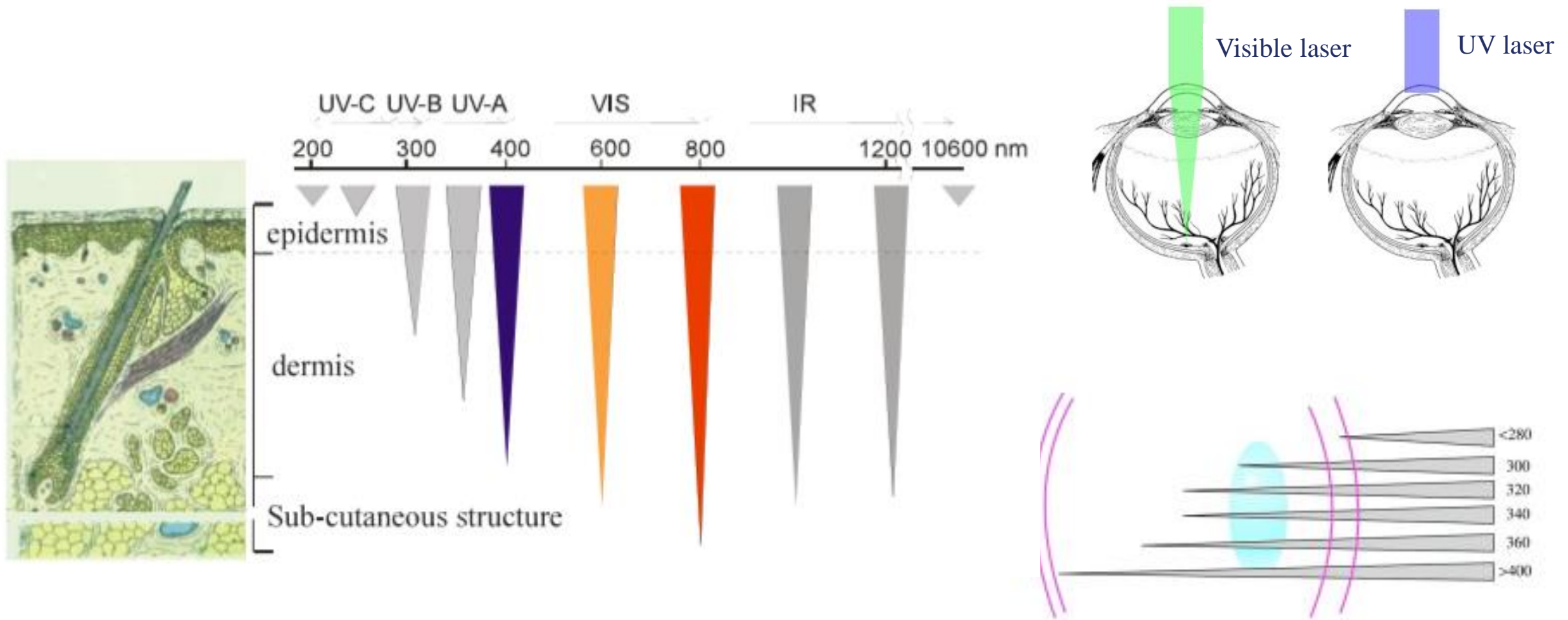
Interference pattern of laser beam

Types of lasers - *based on material (active medium)*

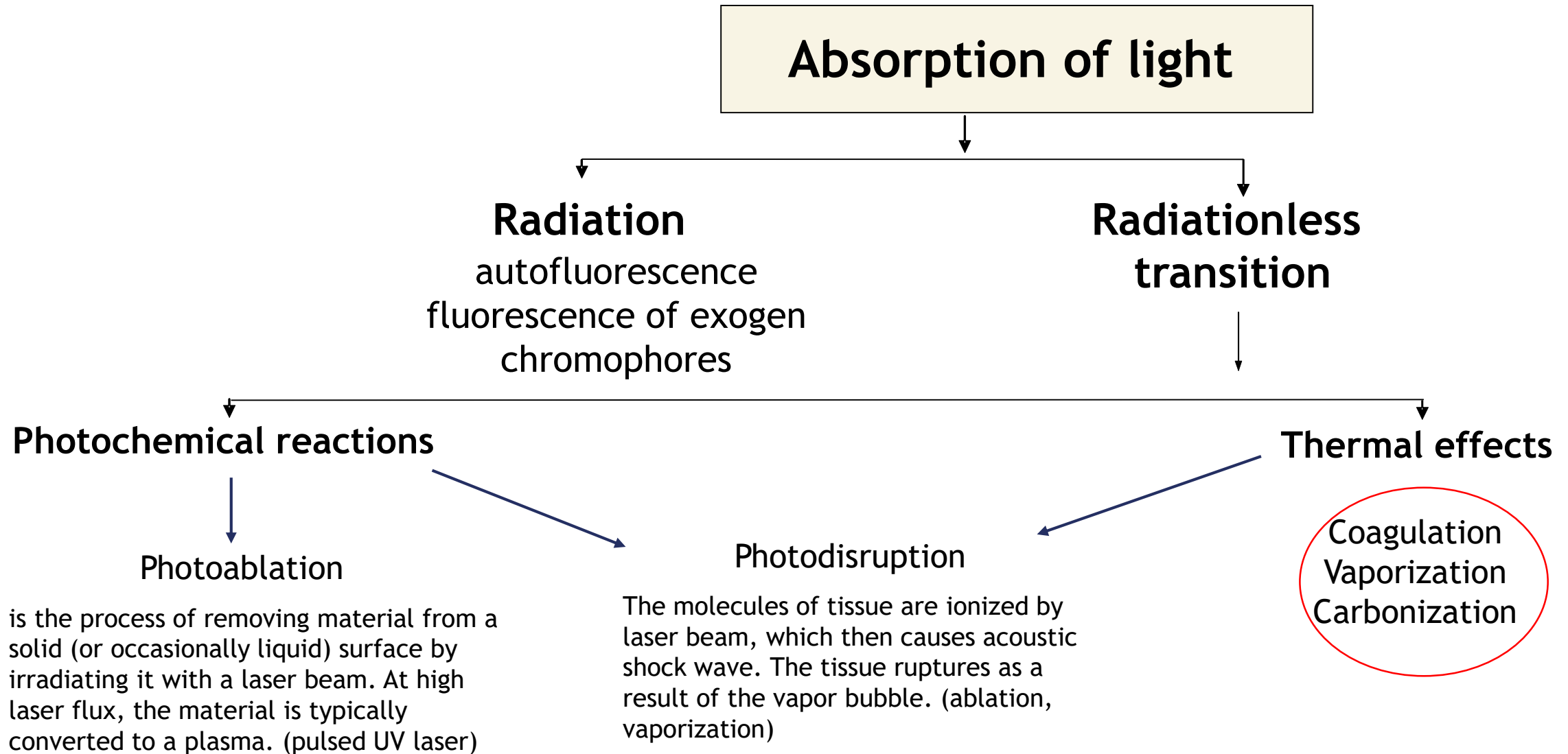
1. Solid state lasers: Metal doping crystals (Ruby, Nd-YAG ittrium-aluminium-garnet, Ti-sapphire)
2. Gas lasers: He-Ne, CO₂, Ar, Kr
3. Dye lasers: dilute solution of organic dyes (rhodamine, coumarin)
4. Semiconductor (diode) lasers: combination of p- and n-type dopes semiconductors



Penetration ability of light in tissue highly depends on its wavelength!



Medical applications of lasers - interactions...



Thermal effects

Biostimulation

Faster healing process,
mobilize the immun system



Orthopedics

Coagulation

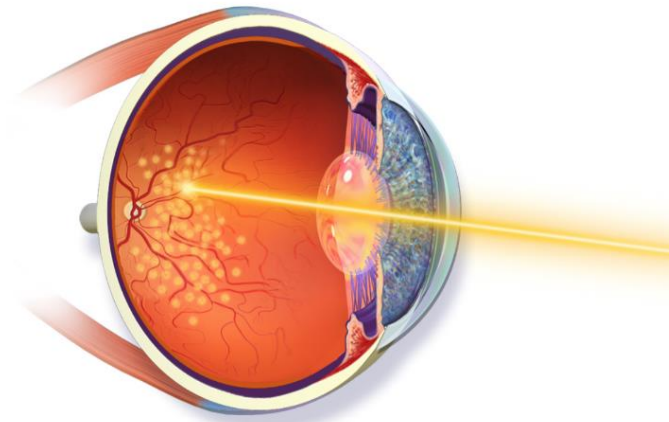
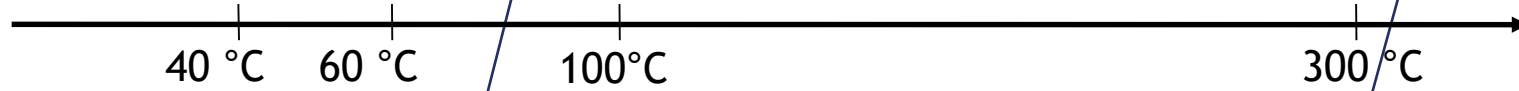
(denaturation of proteins)

Carbonization

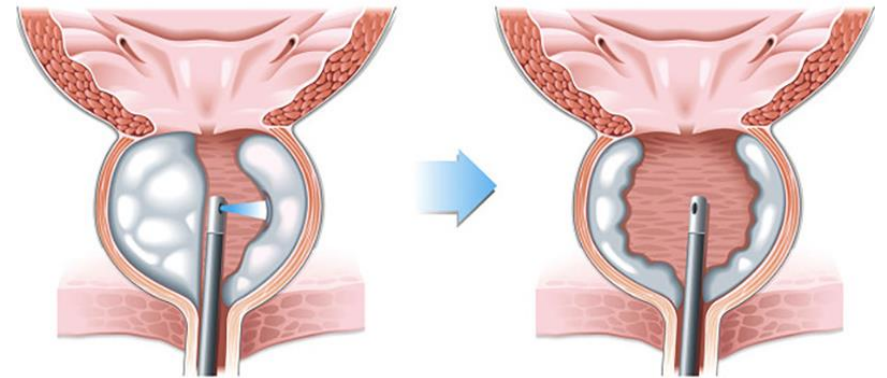
conversion of an organic
substance into carbon

Vaporization

conversion of an organic substance
into vapor phase (gas)



Retina treatment



Laser surgery of benign
prostatic hyperplasia

Medical applications of lasers - DENTISTRY

Soft laser therapy (SLT)

- **Biostimulation**
- Low power: 100-150 mW
- Two wavelength ranges applied:
650-660 nm - 3 cm depth
780-980 nm - 8-10 cm depth
- Faster wound healing
- Antimicrobial effect
- Bone restoring, implantology



Caries removal

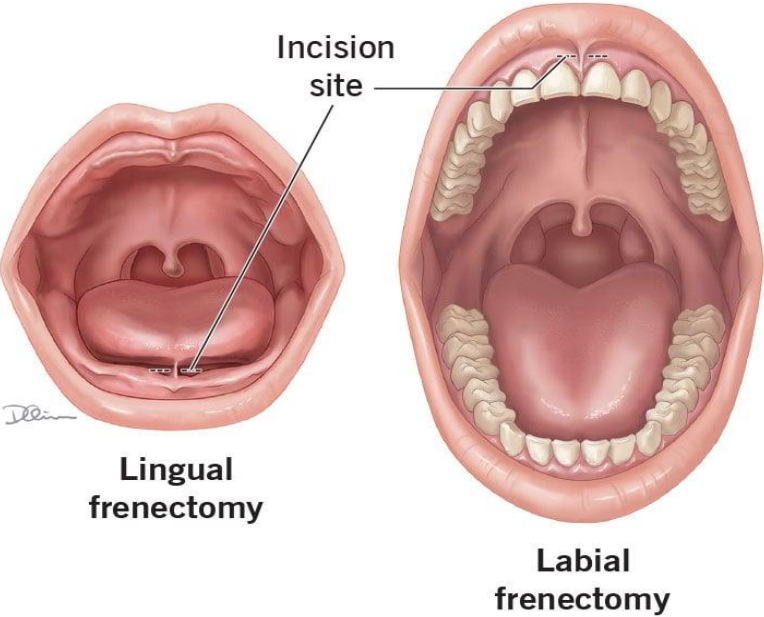
- Vaporization and mechanical shockwave
- ErYAG
- 2940 nm
- Absorption in water and hydroxyapatite
- No carbonization, no heat formation
- Superficial layer is treated



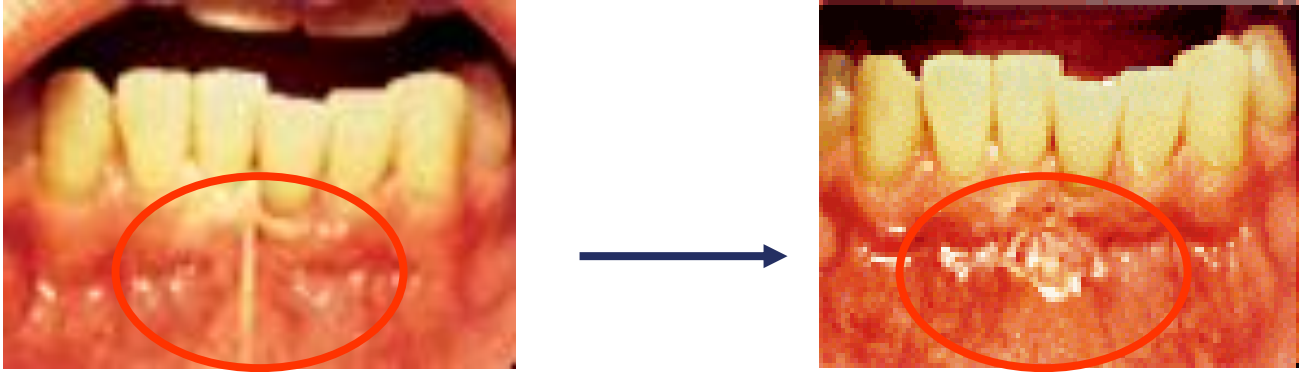
Oral surgery

Nd:YAP* laser
1340 nm

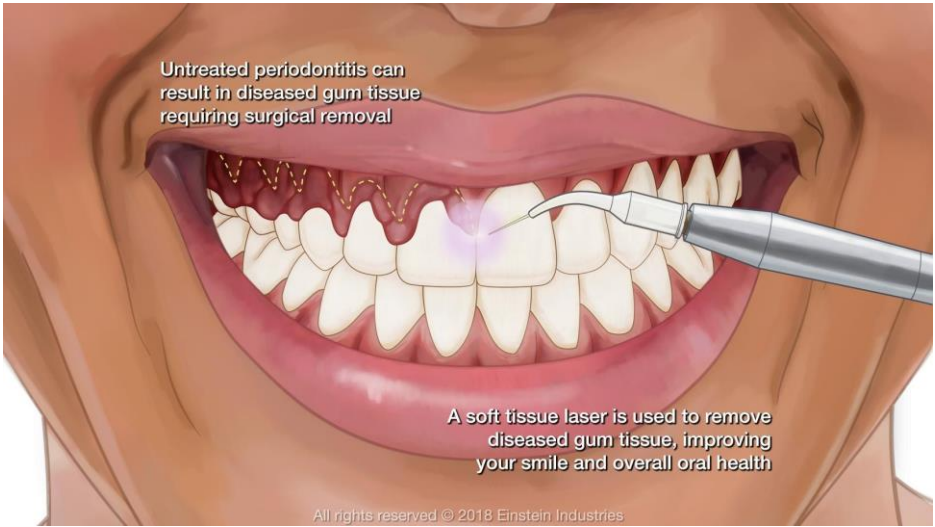
Frenectomy



Cleveland Clinic ©2022



frenectomy



gingivectomy

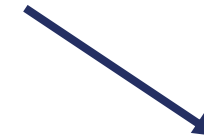
*YAlO₃:Nd Neodymium doped yttrium aluminium perovskite

Teeth whitening

- Argon laser
- 488 nm



Ad of whitening pen...



<https://www.youtube.com/watch?v=NW6XI5JvGsE>

Medical applications of lasers – DERMATOLOGY

Lasertype	Wavelength	Cutaneous application
Copper vapor/bromide (quasi-CW)	510nm 578nm	Pigment Vascular lesions
Pulsed dye	510nm 585nm	Superficial pigment, red/yellow/orange tattoos Vascular lesions, warts, hypertrophic scars, striae
Potassium titanyl phosphate (KTP)	532nm	Pigmented/vascular lesions
Neodymium:yttrium-aluminium-garnet (Nd:YAG) [frequency-doubled]	532nm	Superficial pigment, red/orange/yellow tattoos
Tunable dye argon (quasi-CW)	577/585nm	Vascular lesions
Ruby	694nm	
Q-switched		Pigment, blue/black/green tattoos
Normal mode		Hair
Alexandrite	755nm	
Q-switched		Pigment, blue/black/green tattoos
Long-pulsed		Hair
Nd:YAG	1064nm	
Q-switched		Pigment, blue-black tattoos
Long-pulsed		Hair (darker skin phototypes)
Nd:YAG	1320nm	Nonablative skin resurfacing
Erbium:YAG (pulsed)	2940nm	Skin resurfacing, epidermal lesions
Carbon dioxide (CO ₂)[CW]	10 600nm	Actinic cheilitis, verrucae, rhinophyma
CO ₂ (high-energy, pulsed)	10 600nm	Skin resurfacing, epidermal/dermal lesions

CW = continuous wave; **Q-switched** = quality-switched.

Removal of superficial blood vessels, veins

Photocoagulation

Potassium titanyl phosphate (KTP)
pulsed laser

532 nm



chromophore: oxyhemoglobin with 418, 542 and 577 nm absorption maxima
BUT! Depth of vessels, thickness, skin phototype, avoid: melanocytes, hair follicles

Aesthetic applications: hair, tattoo removal

DOES YOUR CAT NEED LASER HAIR REMOVAL?



Hair removal

Ruby: 694 nm

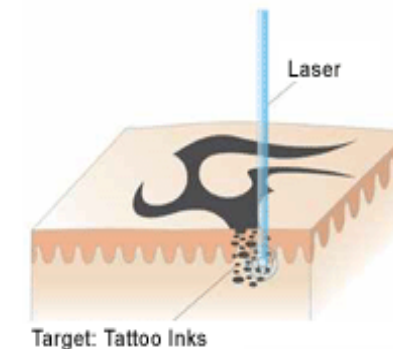
Alexandrite (BeAl_2O_4): 755 nm

NdYAG: 1064 nm



before

after

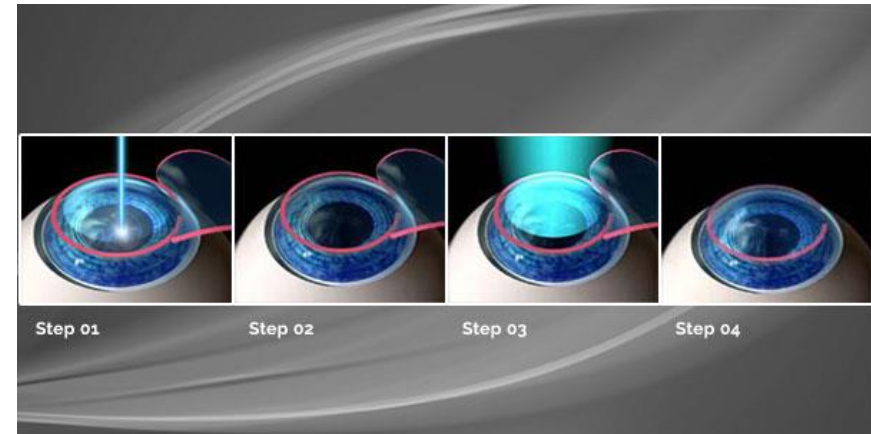


ruby laser (694 nm) is specifically absorbed by the color pigments in the tattoo - **vaporization**

Medical applications of lasers - OPHTHALMOLOGY

FEMTO-LASIK - Femtosecond-assisted Laser In Situ Keratomileusis

- is used to reshape the cornea of the eye
- correct refractive disorders
- femto laser - to create the corneal flap
- removal of material from the corneal stroma (few tens of μm)
- excimer laser at 193 nm - noble gases or the mixture of noble gas and halogen
- after surgery, the flap can be replaced without sutures, allowing for quicker healing



Checklist

- Requirements of laser operation
 - 3 energy levels (metastable)
 - Population inversion (pumping)
 - Stimulated emission
- Optical resonator
- Properties of laser light (coherence, polarized, monochromatic, high power, parallel beam)
- Types of lasers
- Laboratory and medical applications
 - Absorption in tissue
 - Thermal effects
 - Penetration depth in tissues