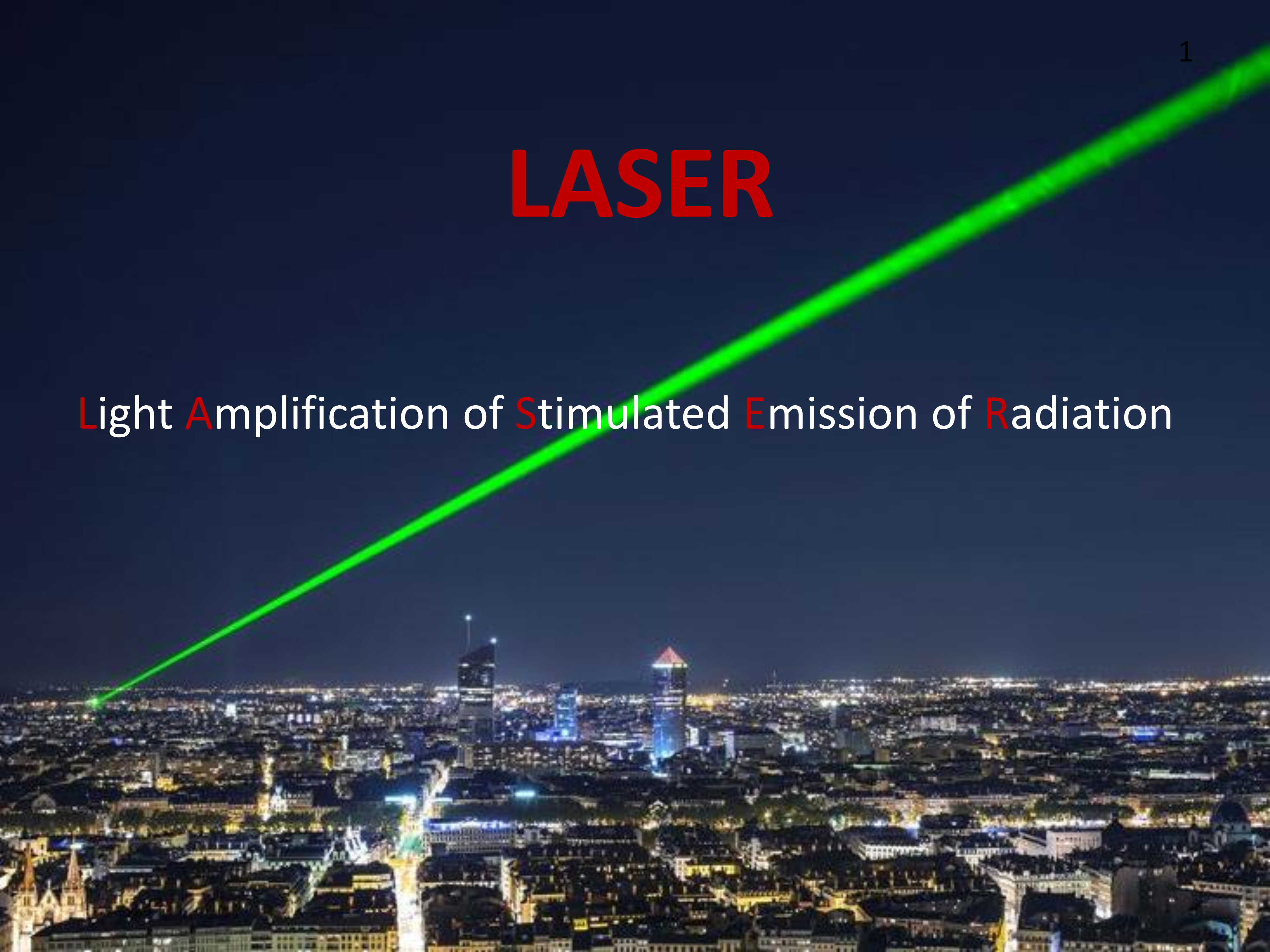
LASER

Light Amplification of Stimulated Emission of Radiation



Semiconductor Optoelectronics and Dynamics Lab

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- Research field:
  - ✓ Quantum structured semiconductor lasers
  - ✓ High-speed optical communications
  - ✓ Advanced Lidar
  - ✓ Gas spectroscopy
- Courses:
  - ✓ Principles of Lasers (undergraduate)
  - ✓ Optoelectronics Devices (graduate)

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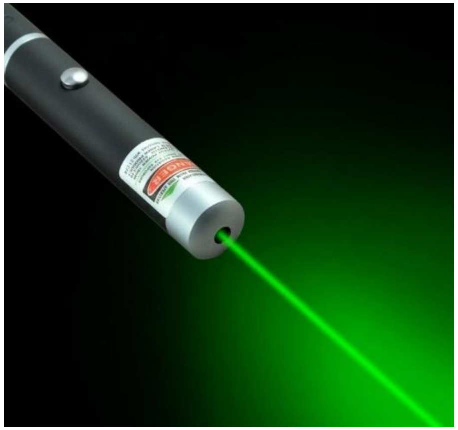
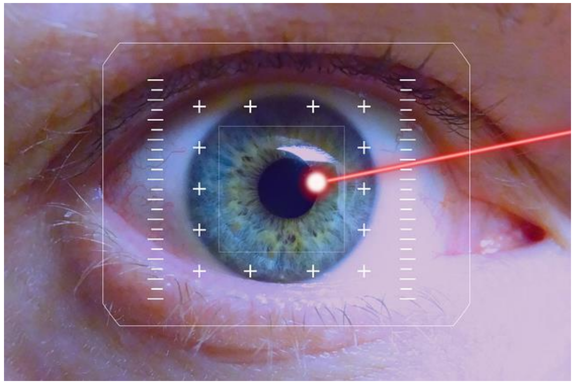
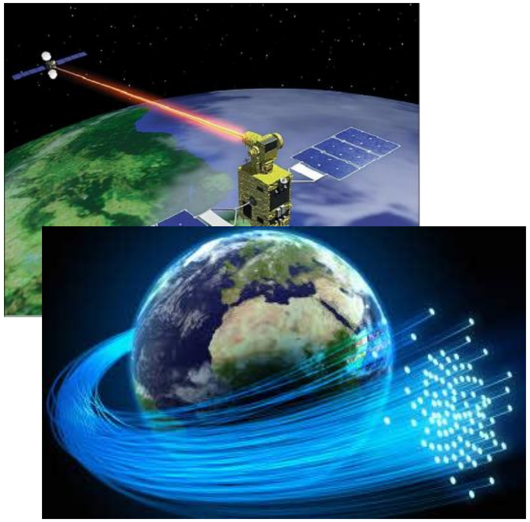
Lasers

- Laser concept
- Laser properties
- Laser history

Lasers in our life







https://youtu.be/D0DbgNju2wE

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Electromagnetic spectrum

Electromagnetic spectrum			
Name	**Wavelength**	**Frequency (Hz)**	**Photon energy (eV)**
Gamma ray	< 0.02 nm	> 15 EHz	> 62.1 keV
X-ray	0.01 nm – 10 nm	30 EHz – 30 PHz	124 keV – 124 eV
Ultraviolet	10 nm – 400 nm	30 PHz – 750 THz	124 eV – 3 eV
Visible light	390 nm – 750 nm	770 THz – 400 THz	3.2 eV – 1.7 eV
Infrared	750 nm – 1 mm	400 THz – 300 GHz	1.7 eV – 1.24 meV
Microwave	1 mm – 1 m	300 GHz – 300 MHz	1.24 meV – 1.24 µeV
Radio	1 mm – 100,000 km	300 GHz – 3 Hz	1.24 meV – 12.4 feV

Ref: Wikipedia

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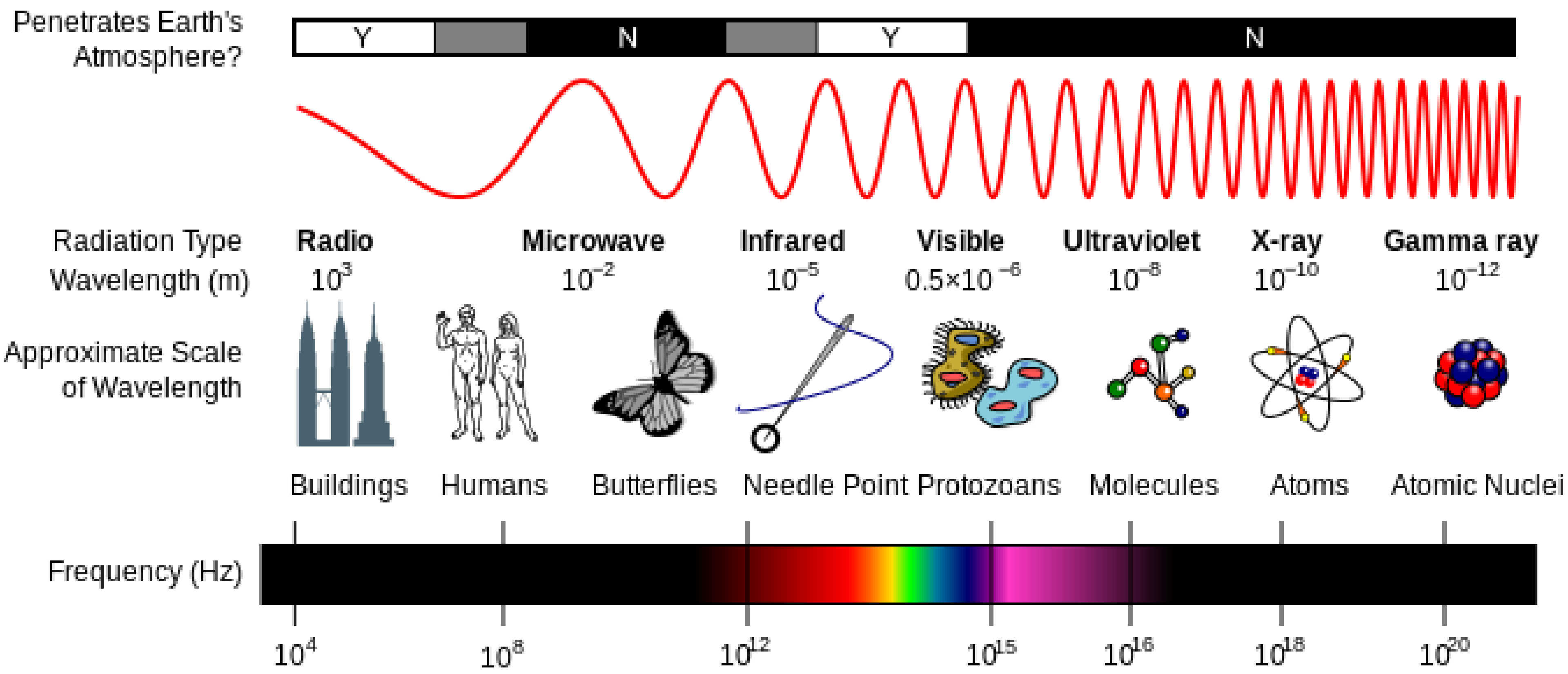
Electromagnetic spectrum



Ref: Wikipedia

Photons

- A photon is an elementary particle, the quantum form of light, it has energy, momentum, and mass.

- Photon exhibits wave-particle duality:waves and particles.

  -The nature of waves shows frequency, phase, polarization, etc.

  -The nature of particles shows energy, momentum, mass, etc.

- Photon energy is related to the frequency

$$E = hv$$

- Photon has moving mass, while the rest mass is zero

$$m = E / c^2$$

Photons

- The photon momentum is given by

$$\vec{P} = mc\vec{e} = \frac{E}{c}\vec{e} = \frac{hv}{c}\vec{e} = \frac{h}{2\pi}\frac{2\pi}{\lambda}\vec{e} = \hbar\vec{k}$$

Wave number $k = 2\pi / \lambda$

- Photon has two independent polarizations, corresponding to the two polarizations of optical waves.

- Photon has spin, and the quantum number of spin is integer.

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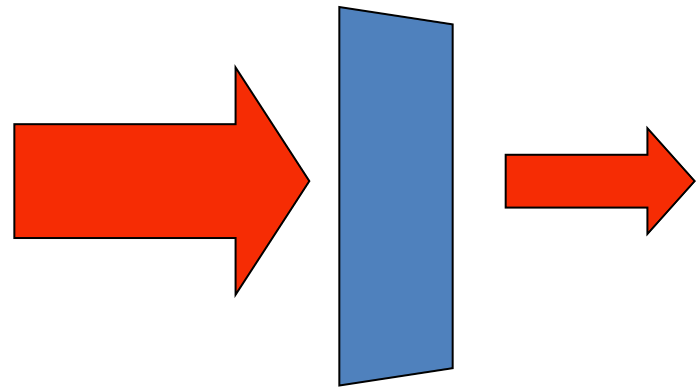
Photons

- The statistics of a large number of photons obey the Bose-Einstein statistics, that is, for a certain quantum state, there is no limitation of the photon number.

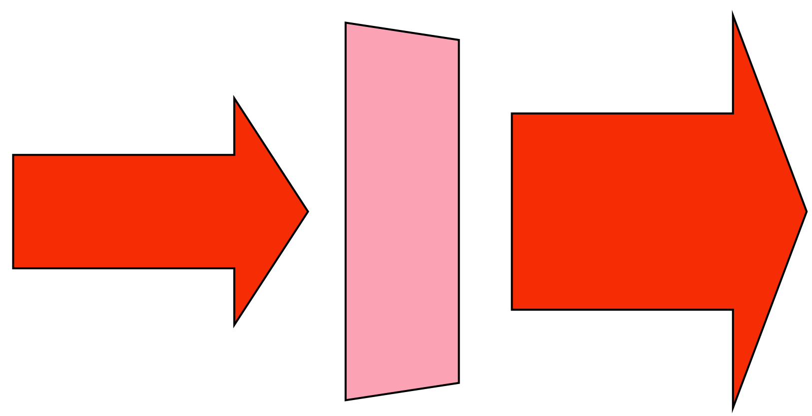
- In contrast, electrons, protons, neutrons obey the Fermi Dirac statistics, that is, one quantum state can not have two identical fermions (Pauli exclusion principle)

Interaction of light and material

When light passes through materials it is usually absorbed.



In certain circumstances light may be amplified. This is called the material has “gain” (negative absorption), which is the basis of laser action



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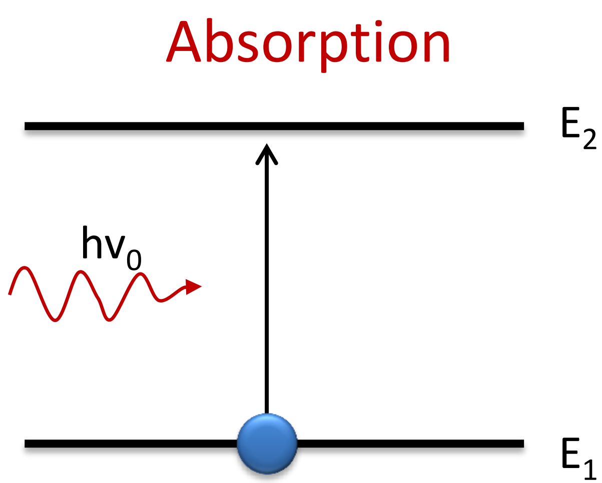
Photon absorption process

Consider two energy levels of some atom (or molecule) of a material. Assume the atom is initially in level 1.

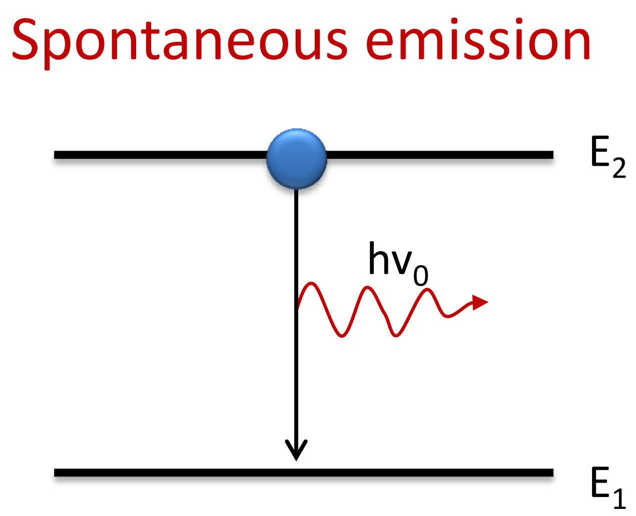


$h\nu_0=E_2-E_1$

The photon energy is the same as the energy difference between the two energy levels.

Spontaneous emission process

Assume the atom is initially in level 2.



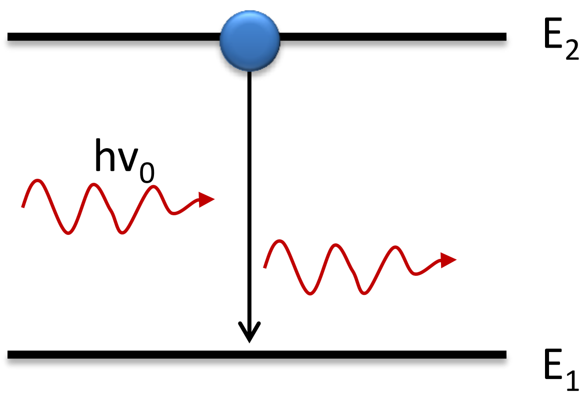
$h\nu_0 = E_2 - E_1$

The emitted photons are different from each other (in amplitude, frequency, phase, polarization, direction)

Stimulated emission process

Assume the atom is initially in level 2.

Stimulated emission

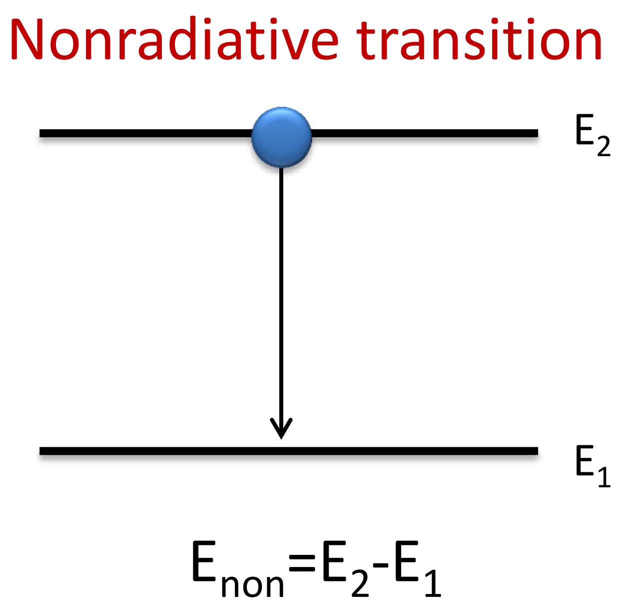


$h\nu_0 = E_2 - E_1$

The emitted photon is <u>exactly the same</u> as the incident photon (in amplitude, frequency, phase, polarization, direction)

Nonradiative transition

Assume the atom is initially in level 2.



The lost energy is delivered in some form of energy other than e.m. radiation, such as kinetic energy, thermal energy, or phonon, etc.

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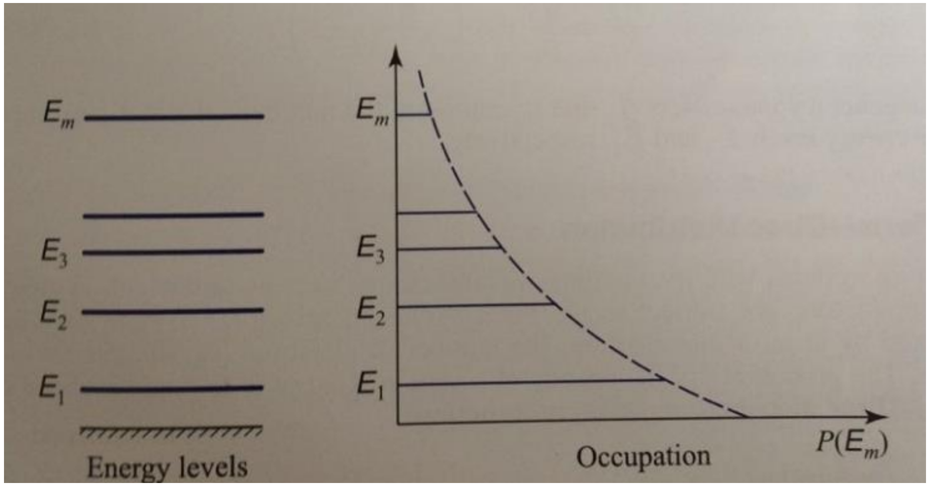
The laser idea

What is the statistics of carrier distributions in a medium, naturally?

- Thermal equilibrium: A system is said to be in thermal equilibrium if the temperature within the system is spatially and temporally uniform (constant), where the motion of atoms reach a steady state, and the atom fluctuations are, on average, invariant to time.

The laser idea

- In thermal equilibrium, the populations in energy levels is determined by Boltzmann statistics.



$$P(E_m) = \frac{N_m}{N_T} \propto \exp(-E_m / kT)$$

$$\Rightarrow \frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

***kT* = 25.7 meV @298 K**

- Under thermal equilibrium, the material gain is always negative, as an absorber.

$$N_2 < N_1 \Rightarrow g = \sigma\left(N_2 - N_1\right) < 0$$

The laser idea

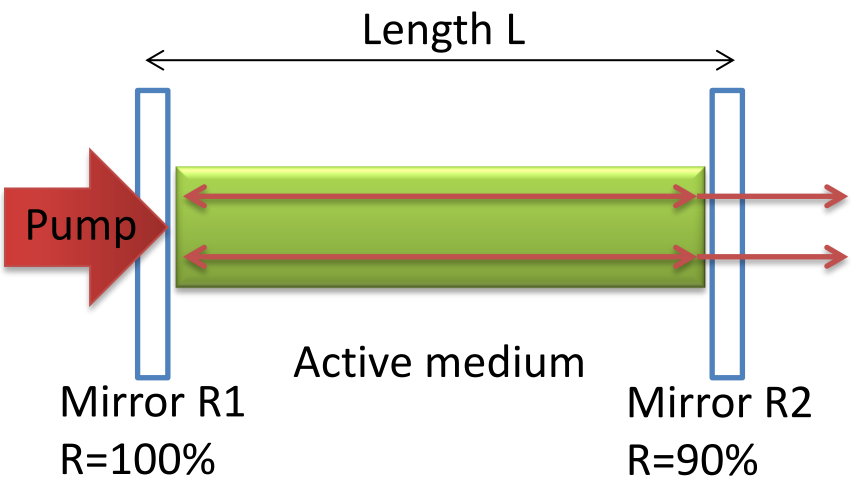
How to have a positive gain?

Active medium

- In the non-equilibrium condition, it is possible to achieve a positive gain, then the material will act as an amplifier.
- In this case, $N_2>N_1$, it is said there is population inversion in the material.
- The material with population inversion is called active material/medium.
- The population inversion can be achieved by the pumping process, either using electrical pumping scheme or the optical pumping scheme.

The laser idea

How to make a laser oscillator?



Laser components:

- ✓ Active medium
- ✓ Resonant cavity (mirrors)
- ✓ Pump source

❑ In order to achieve a laser oscillator from an amplifier, a suitable positive feedback is required. This feedback is usually achieved by placing the active medium between two highly parallel reflecting mirrors.

The way to laser

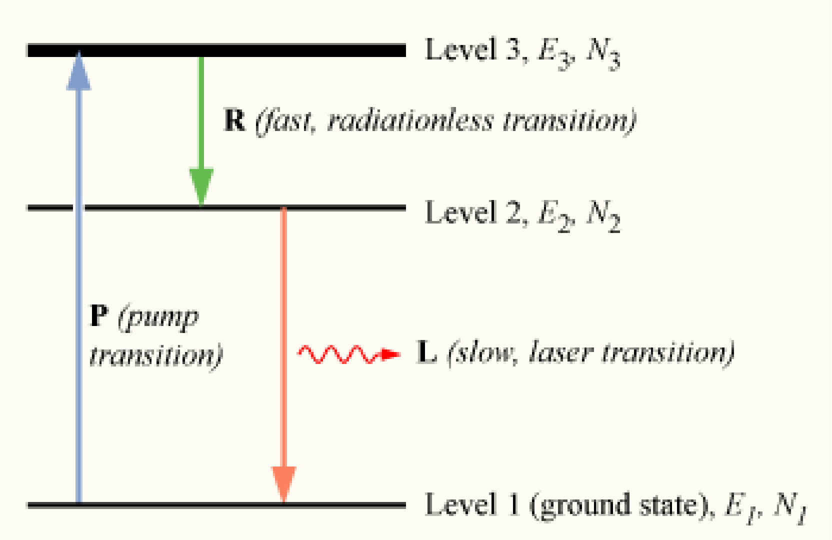
How to get laser emission from a laser oscillator?

- To achieve laser emission, the gain g of the medium has to overcome the loss α in the cavity (coupling, scattering loss, etc.)
- The critical pumping condition for g reaches g= α is called laser threshold.
- The critical population inversion condition is called critical inversion.

Once the critical inversion is achieved, oscillation will build up from spontaneous emission.

Three-level laser

For three-level laser, population inversion is achieved at level 2 and level 1.

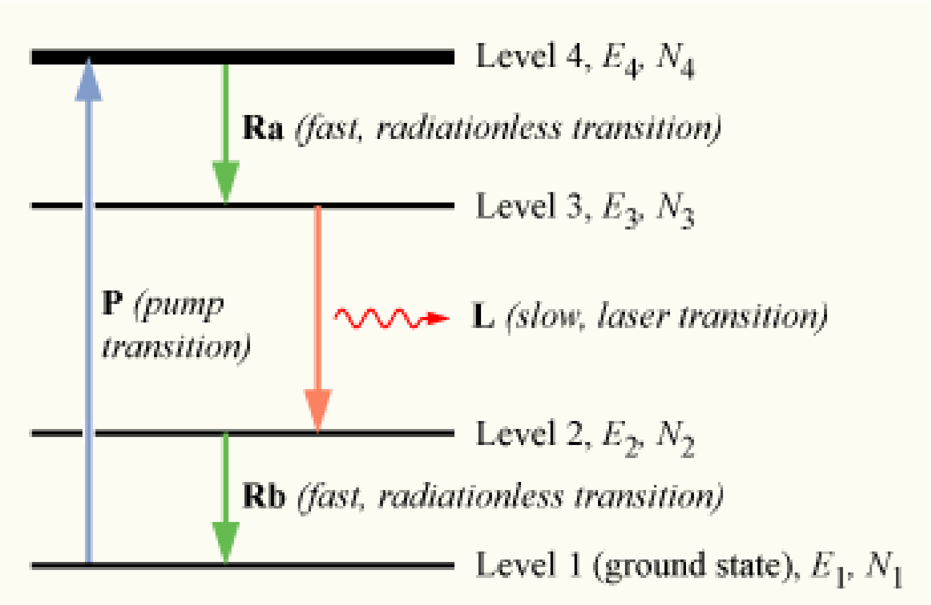


E_2-E_1>> kT

- Because the energy difference between levels are >>kT, thus most all carriers are initially (at equilibrium) in the ground level (level 1).
- Assume the total carrier number is N_t, the transparency is achieved when N_2=N_1=N_t/2, that is, to realize population inversion, at least half of the total carriers in the ground state must be pumped up.

Four-level laser

For four-level laser, population inversion is achieved at level 3 and level 2.

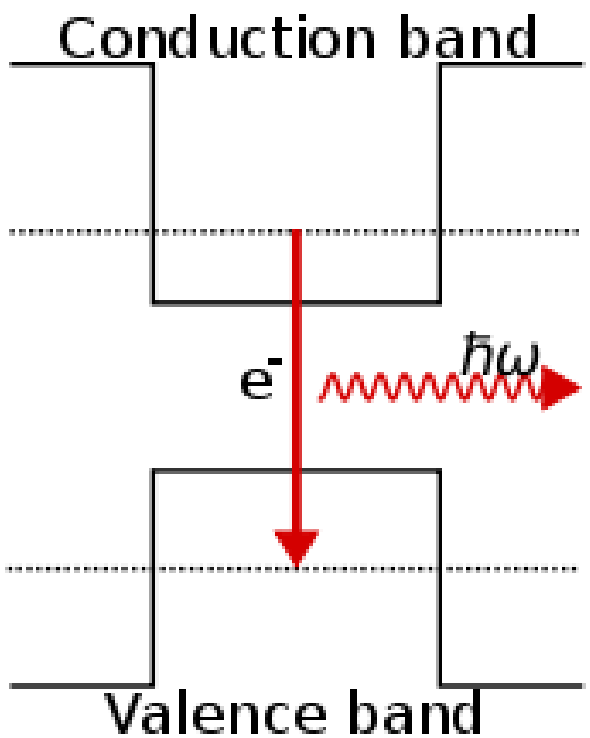


E_2-E_1>> kT

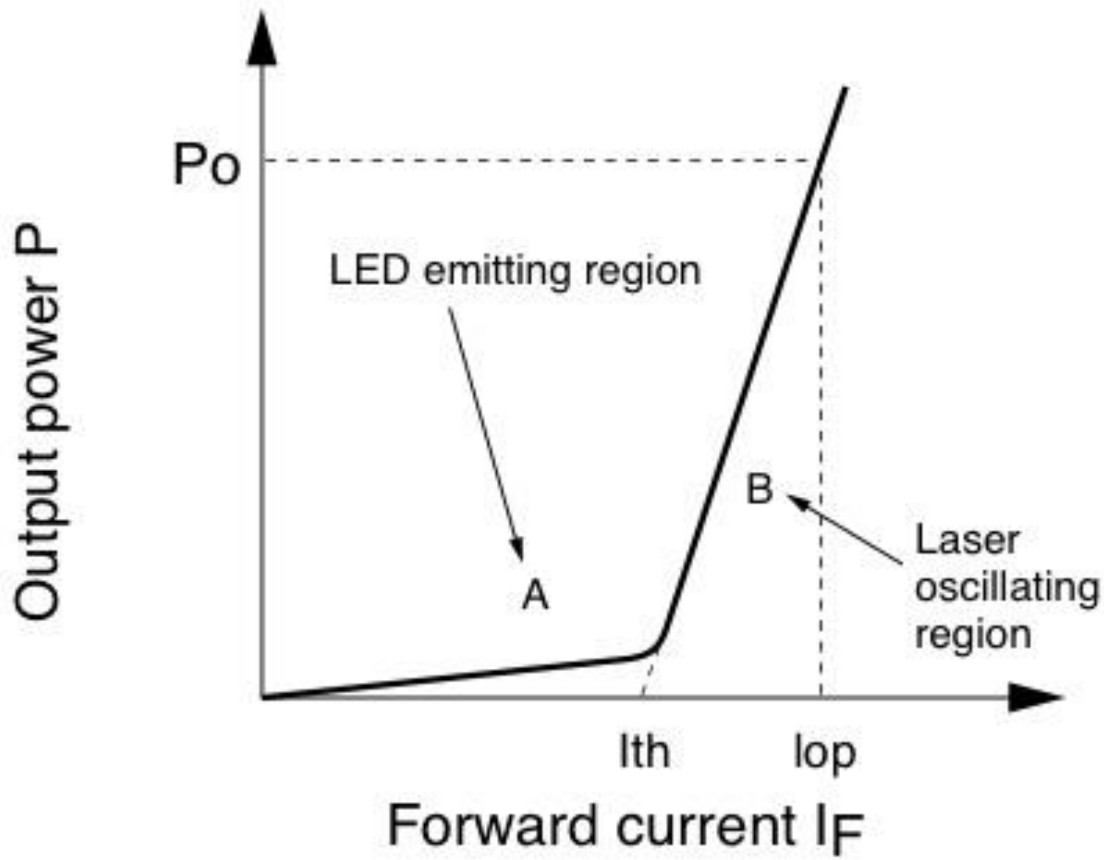
- Since level 2 is almost empty, any atom raised to level 3 will contribute to the population inversion.
- Note that materials have many energy levels, “three” or “four” only refers to those related to the laser emission.

Semiconductor laser

For semiconductor lasers, population inversion is achieved by higher occupation probability of electrons in the conduction band than in the valence band.



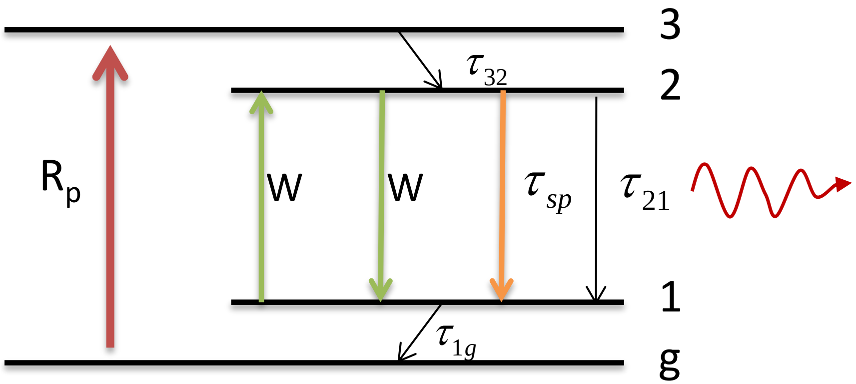
L-I curve



There is always a threshold in any lasers.

Theory: rate equations

The carrier and the photon dynamics can be theoretically described by a set of coupled equations named rate equations.



$$\boxed{v_g g N_P = W(N_2 - N_1)}$$

$$\frac{dN_3}{dt} = R_p - \frac{N_3}{\tau_{32}}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - v_g g N_P - \frac{N_2}{\tau_{21}} - \frac{N_2}{\tau_{sp}}$$

$$\frac{dN_1}{dt} = v_g g N_P + \frac{N_2}{\tau_{21}} + \frac{N_2}{\tau_{sp}} - \frac{N_1}{\tau_{1g}}$$

$$\frac{dN_g}{dt} = \frac{N_1}{\tau_{1g}} - R_p$$

$$\frac{dN_P}{dt} = v_g g N_P - \frac{N_P}{\tau_P} + \beta \frac{N_2}{\tau_{sp}}$$

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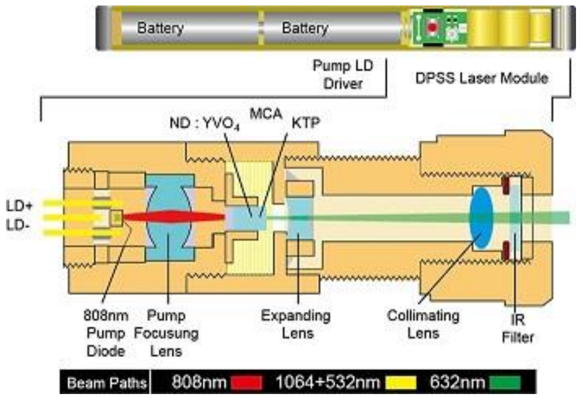
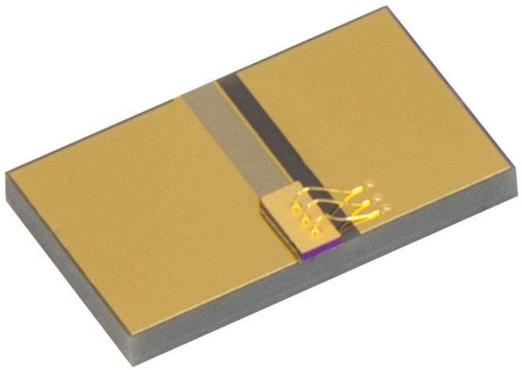
Pumping schemes

- Pumping is the process by which atoms are raised from level 1 to level 3 (in three-level laser) or from level 1 to level 4 (in four level laser).
- Pumping can use high intensity lamp, diode lasers, or electrical discharge in the active medium.



Diode pumped solid-state laser

Gas laser



Semiconductor laser

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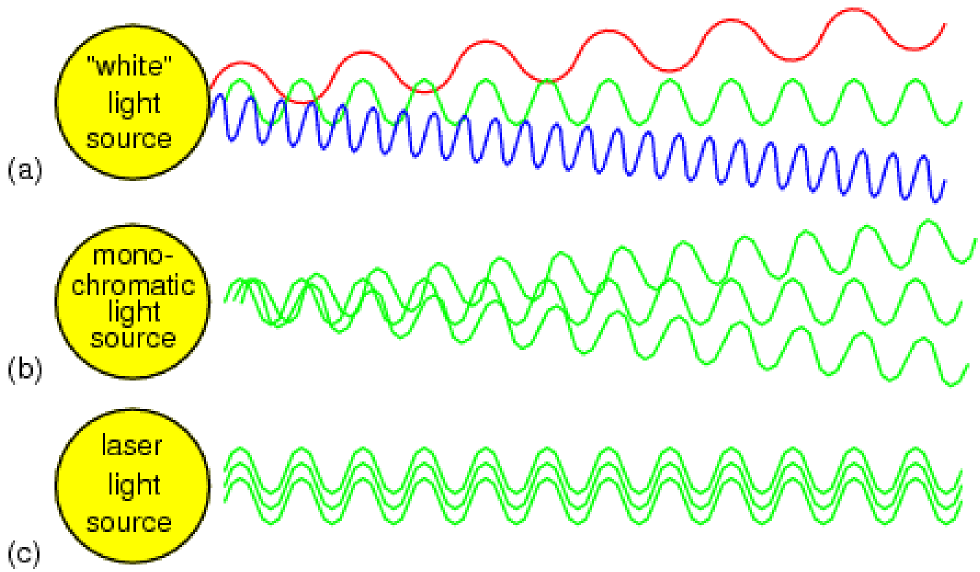
Lasers

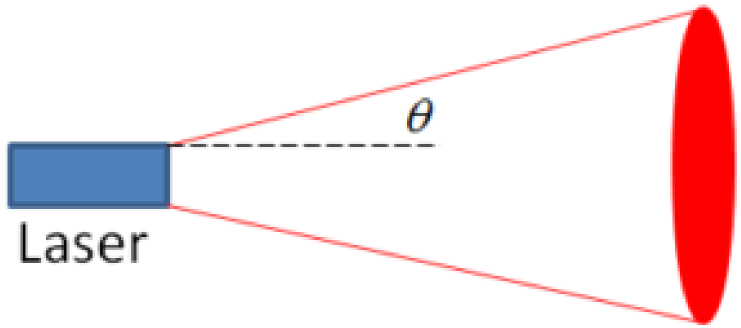
- Laser concept
- Laser properties
- Laser history

Properties of laser beams



- ❑ Directionality
- ❑ Monochromaticity
- ❑ Coherence
- ❑ Brightness
- ❑ short time duration (maybe not)

Directionality



- The directionality is described by the beam divergence, which is determined by the diffraction limit, assume the cavity mirror diameter is D,

$$\boxed{\theta_d \approx \frac{\lambda}{D}}$$

For a He-Ne laser at 0.63 μm, and a mirror of D=3 mm, θ_d=2e-4 rad=0.02°

- The directionality is related to the cavity type, cavity length, laser medium etc.
- Gas laser is better than solid state laser, better than laser diode

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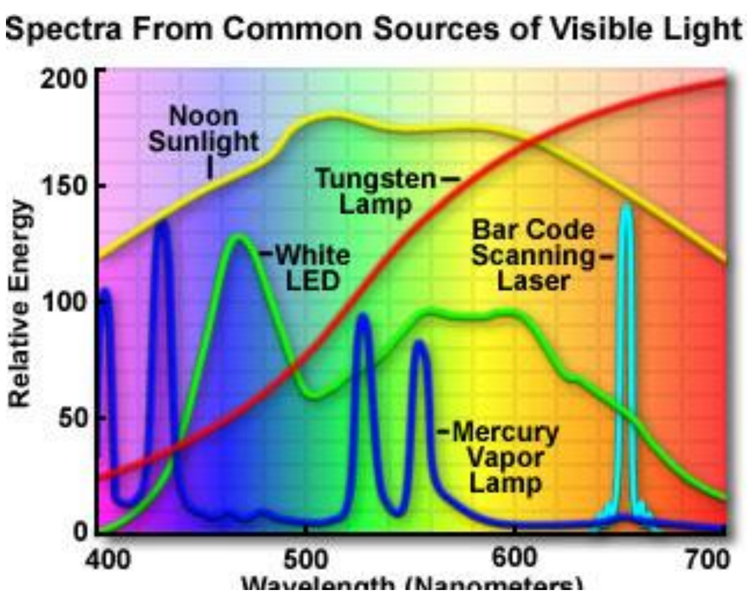
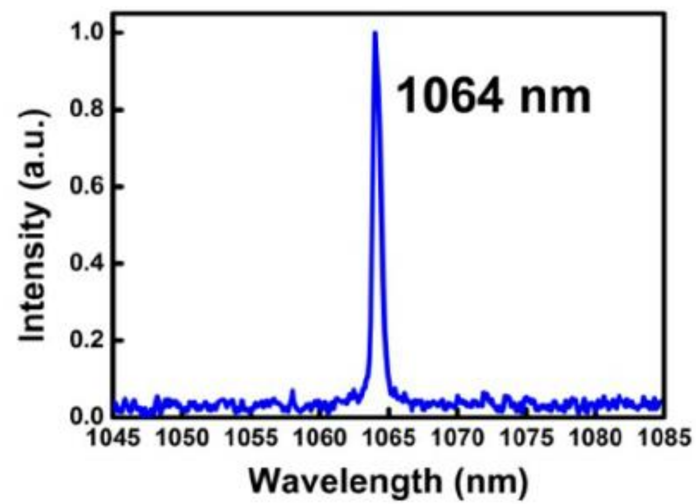
Monochromaticity





Nd:YAG laser

- The monochromaticity is described by the spectral linewidth.
- The spectral purity of lasers come from:

1. The laser medium only emits light of frequency around $h\nu_0=E_2-E_1$.

2. The laser cavity only allows light oscillation at the resonance frequencies of this cavity.

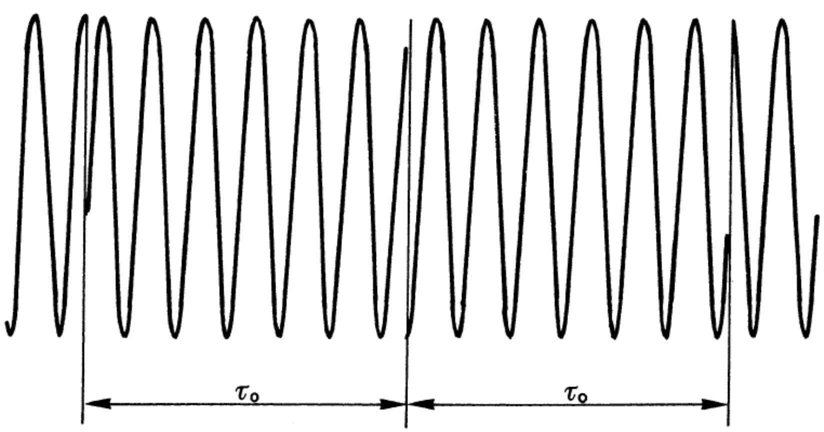
Coherence

- Coherence means the phase correlation relation in the spatial or temporal dimension.

  --- The spatial coherence is linked with the directionality

  --- The temporal coherence is linked with the monochromaticity

- The coherence is degraded by the discontinuity of the phase



Coherence time vs. spectral linewidth

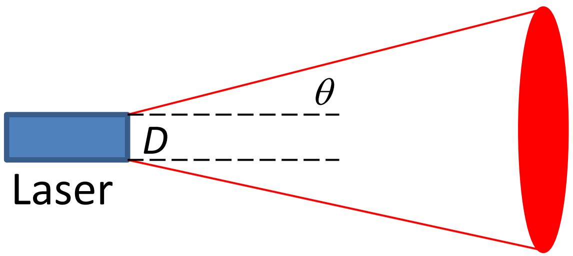
$$\boxed{\Delta\nu \approx 1/\tau_c}$$

Coherence time vs. coherence length

$$L_c = c\tau_c$$

Brightness of laser

❑ **Brightness:** The light power per unit surface area of the light source per unit solid angle.



When normal to the emission surface, the solid angle (unit is steradian 球面度) is

$$\Omega = \pi \sin^2 \theta$$

$$B \equiv \frac{P}{S\Omega} \qquad \text{unit: W}/\left(cm^2 sr\right)$$

$$= \frac{P}{\left(\pi R^2\right)\left(\pi \sin^2 \theta\right)}$$

$$\approx \frac{P}{\left(\pi \theta D/2\right)^2}$$

❑ The brightness at difraction limit

$$\boxed{B_d \approx \left(\frac{2}{\pi\lambda}\right)^2 P}$$

Short time duration

- Q-switch technique produces short pulses width duration of ~ ns
- Mode locking technique produces ultrashot pulses with duration of fs to ps
- Not all the lasers can be used to produce short pulses

Types of lasers

- Physical state: solid state, liquid, and gas lasers. (free electron lasers)
- Wavelength: infrared, visible, UV, and X-ray lasers. (1 mm---1 nm)
- Power: CW laser from nW to a few MW; Pulsed laser peak power up to PW (10^{15} W)
- Pulse duration: from ms down to fs (10^{-15} s)
- Cavity length: from nm up to km

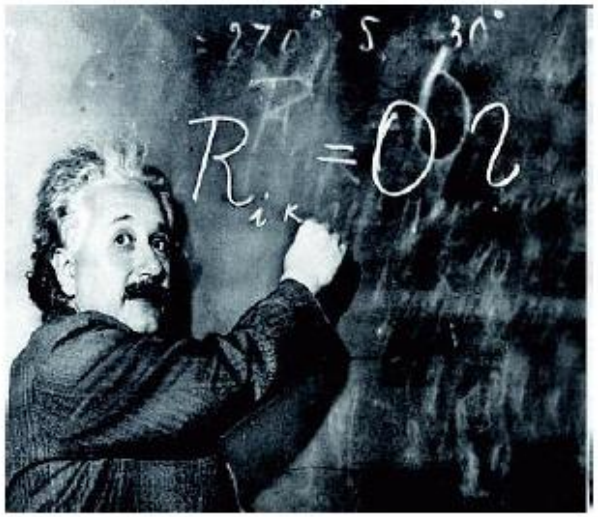
Lasers

- ❑ Laser concept
- ❑ Laser properties
- ❑ Laser history

Discovery of stimulated emission in 1917

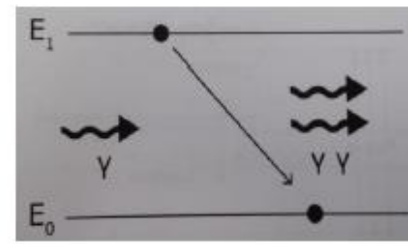
Albert Einstein

* 14.3.1879 (Ulm, Germany) † 18.4.1955, (Princeton, USA)




Zur Quantentheorie der Strahlung

Von A. Einstein.

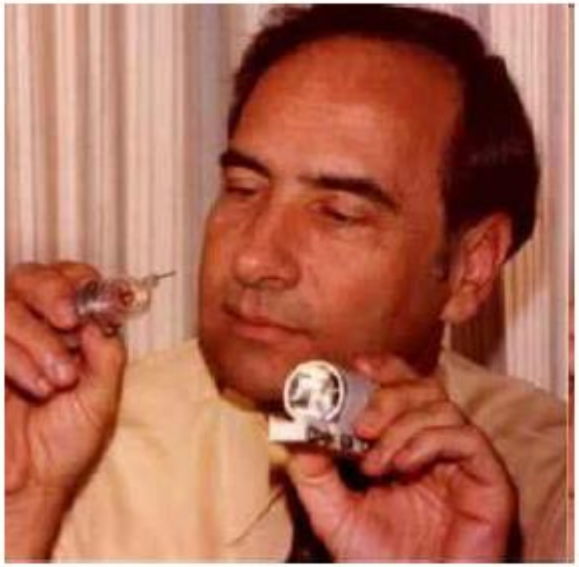


Ref: S. Domsch, *Basics of Laser Physics*, at Univeritaetsmedizin Mannheim

Maser in 1950s

C. H. Townes, *How the Laser Happened*, (Oxford, 1999).

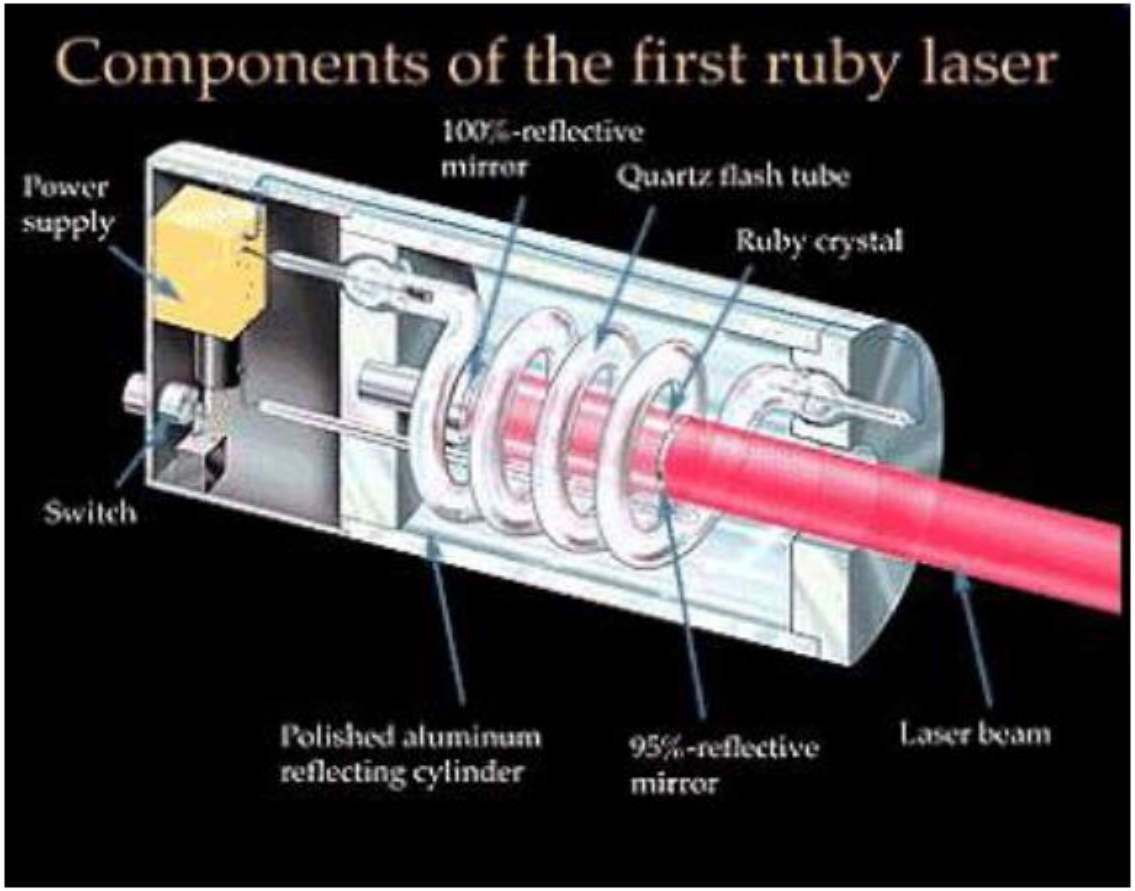
First Laser in 1960 (Ruby)



Theodore Harold Maiman

* 11.7.1927, Los Angeles, USA

† 5.5.2007, Vancouver, Canada



@694 nm

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Nobel prize in physics in 1964

„…for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle“

Charles Hard Townes

* 28.7.1915, Greenville, USA
† 27.1.2015, Oakland, USA

Nikolay Gennadiyevich Basow

* 14.12.1922, Usman, Russia
† 1.7.2001, Moscow, Russia

Aleksandr Mikhailovich Prokhorov

* 11.7.1916, Atherton, Australia
† 8.1.2002, Moscow, Russia

Theoreticl work: MASER principle -> LASER

Concept of optical pumping

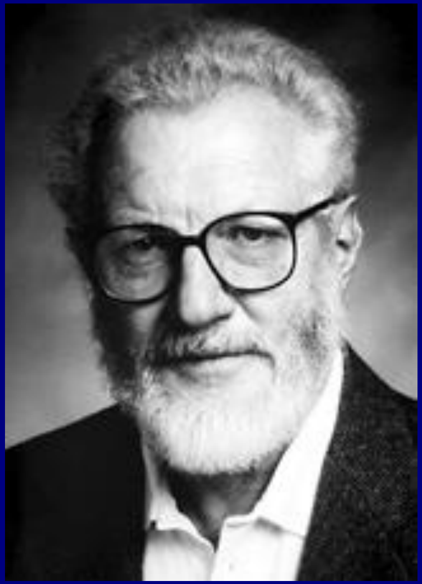
The Nobel Prize in Physics 2000

"for basic work on information and communication technology"

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

"for his part in the invention of the integrated circuit"

Zhores I. **Alferov** b. 1930



Herbert **Kroemer** b. 1928

Jack S. **Kilby** 1923–2005

Laser-related Nobel prizes in Physics

1964		Nicolay Gennadiyevich Basov	Soviet Union
		Alexander Prokhorov	Soviet Union
		Charles Hard Townes	United States

- "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle"

1981		Nicolaas Bloembergen	Netherlands United States
		Arthur Leonard Schawlow	United States

- "for their contribution to the development of laser spectroscopy"

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Laser-related Nobel prizes in Physics

1997		Steven Chu	United States
		Claude Cohen-Tannoudji	France
		William Daniel Phillips	United States

- "for development of methods to cool and trap atoms with laser light"

2000		Zhores Ivanovich Alferov	Russia
		Herbert Kroemer	Germany

- " For developing semiconductor heterostructures used in high-speed-and optoelectronics"

Laser-related Nobel prizes in Physics

2005		Roy J. Glauber	United States
		John L. Hall	United States
		Theodor W. Hänsch	Germany

- "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

2009		Charles K. Kao	Hong Kong United Kingdom United States
		Willard S. Boyle	Canada United States

- "for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

Laser-related Nobel prizes in Physics

2014		Isamu Akasaki	Japan
		Hiroshi Amano	Japan
		Shuji Nakamura	Japan United States

- "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

2017		Rainer Weiss	Germany United States
		Kip Thorne	United States
		Barry Barish	United States

- "for decisive contributions to the LIGO detector and the observation of gravitational waves"

LIGO: Laser Interferometer Gravitational-Wave Observatory

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International Year of Light

United Nations
Educational, Scientific and
Cultural Organization

International
Year of Light
2015

In proclaiming an International Year focusing on the topic of light science and its applications, the UN has recognized the importance of raising global awareness about how light-based technologies promote sustainable development and provide solutions to global challenges in energy, education, agriculture and health. Light plays a vital role in our daily lives and is an imperative cross-cutting discipline of science in the 21st century. It has revolutionized medicine, opened up international communication via the Internet, and continues to be central to linking cultural, economic and political aspects of the global society.

Homework

- State-of-the-art of Metamaterials
- State-of-the-art of LIGO
- State-of-the-art of Free Electron Lasers

Requirement:

1. Select any one of the three topics
2. In English, in PDF file
3. Template of Journal of Quantum Electronics (Exact format)
4. No less than 2 pages
5. Reference no less than 10
6. Do not plagiarize
7. Deadline: For SIST, 12/06; For others, 17/06;
8. Email to: 王星光 <wangxg@shanghaitech.edu.cn>


Making the World a Better
Place through Light!