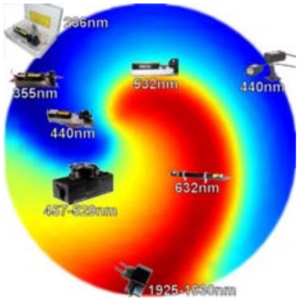
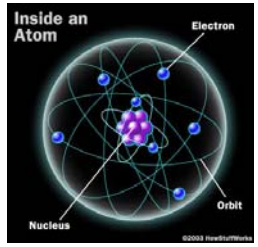


Welcome to



Phys 402:
High-power Lasers

Spring 2008

Instructor:

Andrei Sirenko
Associate Professor at the Dept. of Physics, NJIT
http://web.njit.edu/~sirenko

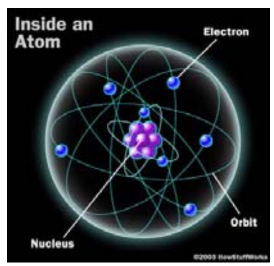
476 Tiernan

Office hours: Before the classes on Mo or Fr.
or by appointment
973-596-5342

Class Schedule:

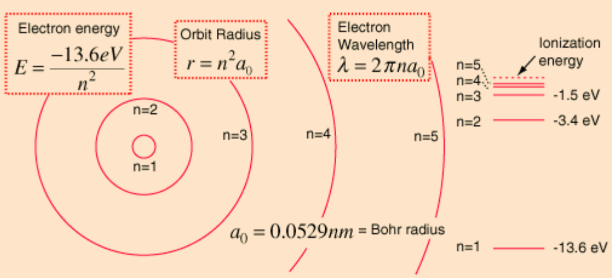
Monday 2:30 pm | OPSE Lab - Faculty 403

Light and Atoms

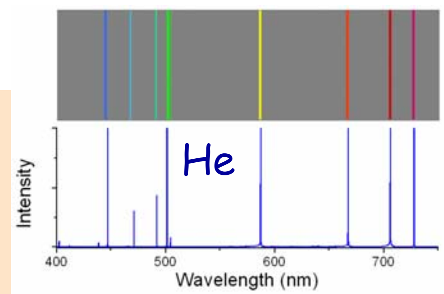


Hydrogen Energy Levels

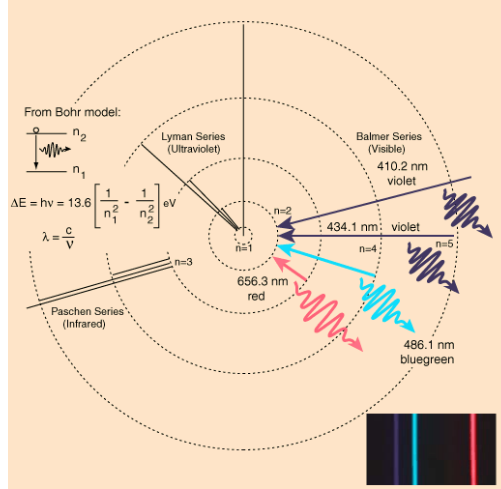
The basic hydrogen energy level structure is in agreement with the Bohr model. Common pictures are those of a shell structure with each main shell associated with a value of the principal quantum number n.



Light and Atoms



Hydrogen Spectrum



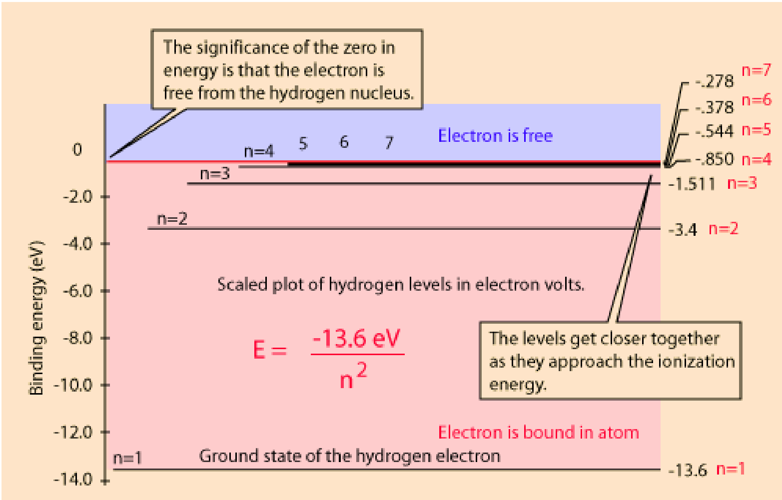
Measured Hydrogen Spectrum

The measured lines of the Balmer series of hydrogen in the nominal visible region are:

Wavelength (nm)	Relative Intensity	Transition	Color
383.5384	5	9 -> 2	Violet
388.9049	6	8 -> 2	Violet
397.0072	8	7 -> 2	Violet
410.174	15	6 -> 2	Violet
434.047	30	5 -> 2	Violet
486.133	80	4 -> 2	Bluegreen (cyan)
656.272	120	3 -> 2	Red
656.2852	180	3 -> 2	Red

The red line of deuterium is measurably different at 656.1065 (.1787 nm difference).

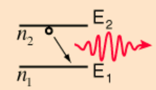
Light and Atoms



Light and Atoms

Electron Transitions

The Bohr model for an electron transition in hydrogen between quantized energy levels with different quantum numbers n yields a photon by emission with quantum energy:



A downward transition involves emission of a photon of energy:

$$E_{photon} = h\upsilon = E_2 - E_1$$

Given the expression for the energies of the hydrogen electron states:

$$h\upsilon = \frac{2\pi^2 me^4}{h^2}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] = -13.6\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]\text{eV}$$

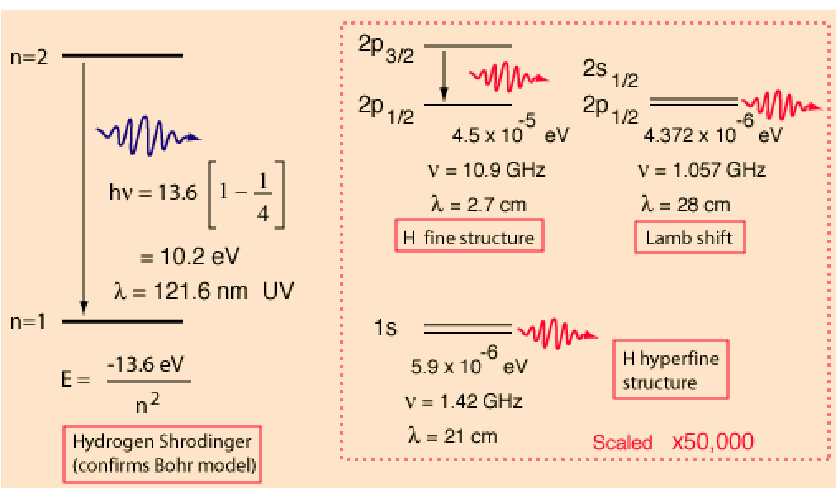
This is often expressed in terms of the inverse wavelength or "wave number" as follows:

$$\frac{1}{\lambda} = R_H\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] \quad \text{where} \quad R_H = \frac{2\pi^2 me^4}{h^2} \quad \text{is called the Rydberg constant.}$$

$$R_H = 1.0973731 x 10^7 m^{-1}$$

Lymann Series			
93.782	...	6 -> 1	UV
94.976	...	5 -> 1	UV
97.254	...	4 -> 1	UV
102.583	...	3 -> 1	UV
121.566	...	2 -> 1	UV
Balmer Series			
383.5384	5	9 -> 2	Violet
388.9049	6	8 -> 2	Violet
397.0072	8	7 -> 2	Violet
410.174	15	6 -> 2	Violet
434.047	30	5 -> 2	Violet
486.133	80	4 -> 2	Bluegreen (cyan)
656.272	120	3 -> 2	Red
656.2852	180	3 -> 2	Red
Paschen Series			
954.62	...	8 -> 3	IR
1004.98	...	7 -> 3	IR
1093.8	...	6 -> 3	IR
1281.81	...	5 -> 3	IR
1875.01	...	4 -> 3	IR
Brackett Series			
2630	...	6 -> 4	IR
4050	...	5 -> 4	IR
Pfund Series			
7400	...	6 -> 5	IR

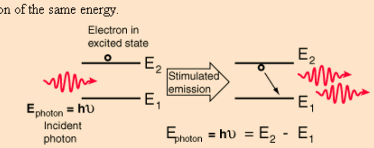
Light and Atoms



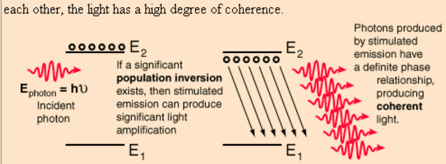
The interaction of radiation with matter

Stimulated Emission

If an electron is already in an excited state (an upper energy level, in contrast to its lowest possible level or "ground state"), then an incoming photon for which the quantum energy is equal to the energy difference between its present level and a lower level can "stimulate" a transition to that lower level, producing a second photon of the same energy.

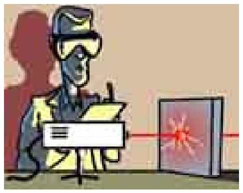


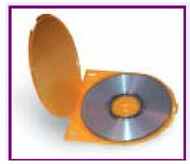
When a sizable population of electrons resides in upper levels, this condition is called a "population inversion", and it sets the stage for stimulated emission of multiple photons. This is the precondition for the light amplification which occurs in a laser, and since the emitted photons have a definite time and phase relation to each other, the light has a high degree of coherence.



Like absorption and emission, stimulated emission requires that the photon energy given by the Planck relationship be equal to the energy separation of the participating pair of quantum energy states.

Application of Lasers



TELECOMMUNICATION

Types of Lasers

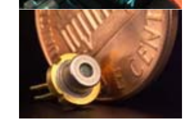
The laser medium can be a solid, gas, liquid or semiconductor.

Solid-state lasers have lasing material distributed in a solid matrix (such as the ruby or neodymium:yttrium-aluminum garnet "YAG" lasers). The neodymium-YAG laser emits infrared light at 1064 nanometers (nm).

Gas lasers (helium and helium-neon, HeNe, are the most common gas lasers) have a primary output of visible red light. CO2 lasers emit energy in the far-infrared, and are used for cutting hard materials.

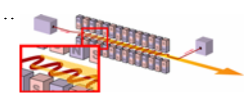
Excimer lasers (the name is derived from the terms *excited* and *dimers*) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range.

Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

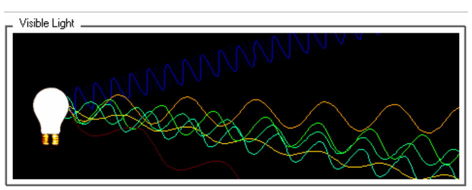


Semiconductor lasers, sometimes called diode lasers, are not solid-state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, such as the writing source in some laser printers or CD players.

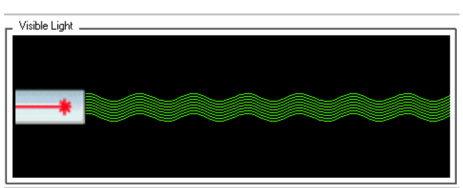
And more: Ring lasers, Disk lasers, Free electron lasers, …




Regular Light



Laser Light

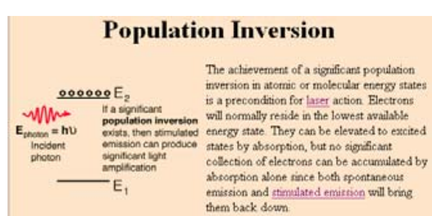


What is the difference ?

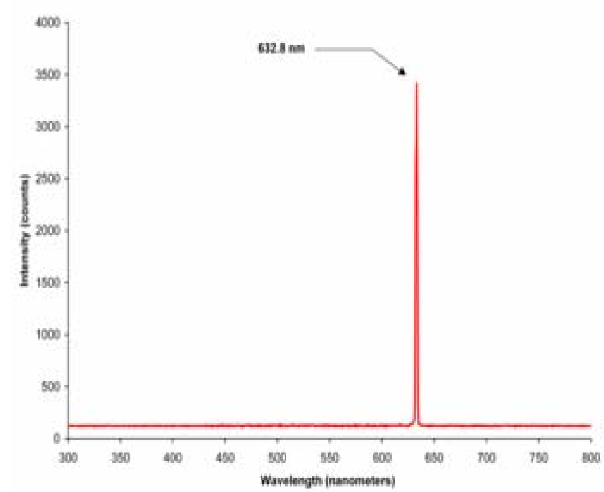
Properties of laser radiation:

- **Monochromatic**
- **Coherent**
- **Directional**

- **Stimulated emission and gain**



Laser Wavelength



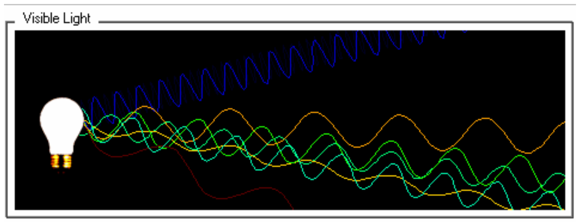
Properties of laser radiation:

- **Monochromatic**
- **Coherent**
- **Directional**

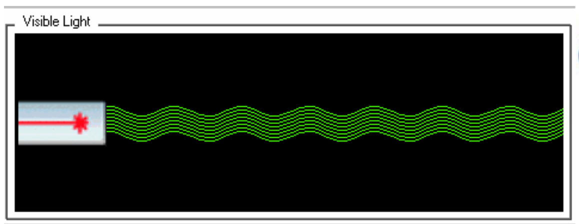
- **Stimulated emission and gain**

Regular Light

Like rain



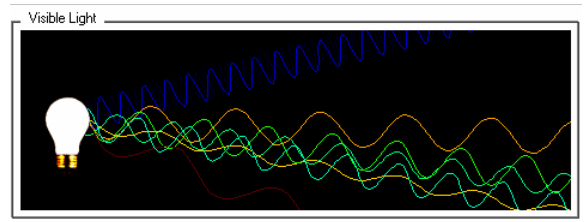
Laser Light



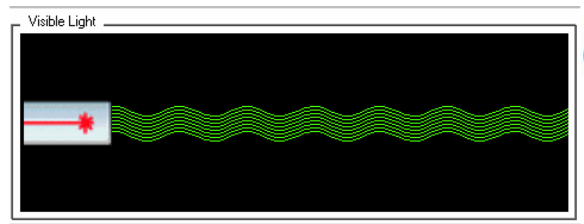
Regular Light

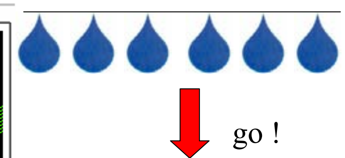
COHERENCE:

Like rain



Laser Light

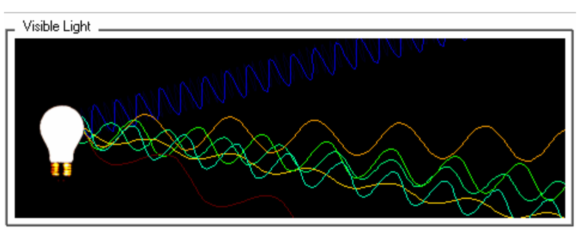




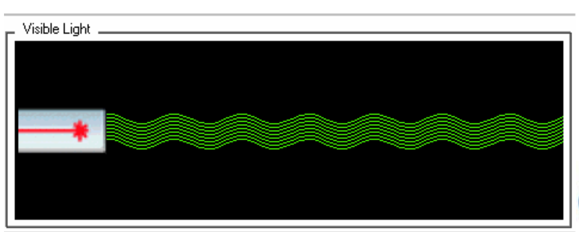
go !

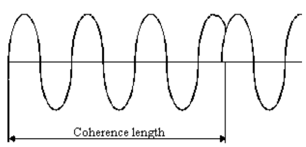
Regular Light

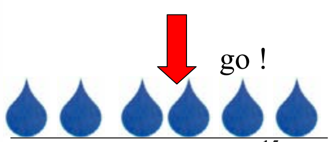
COHERENCE:



Laser Light







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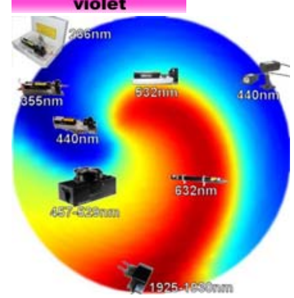
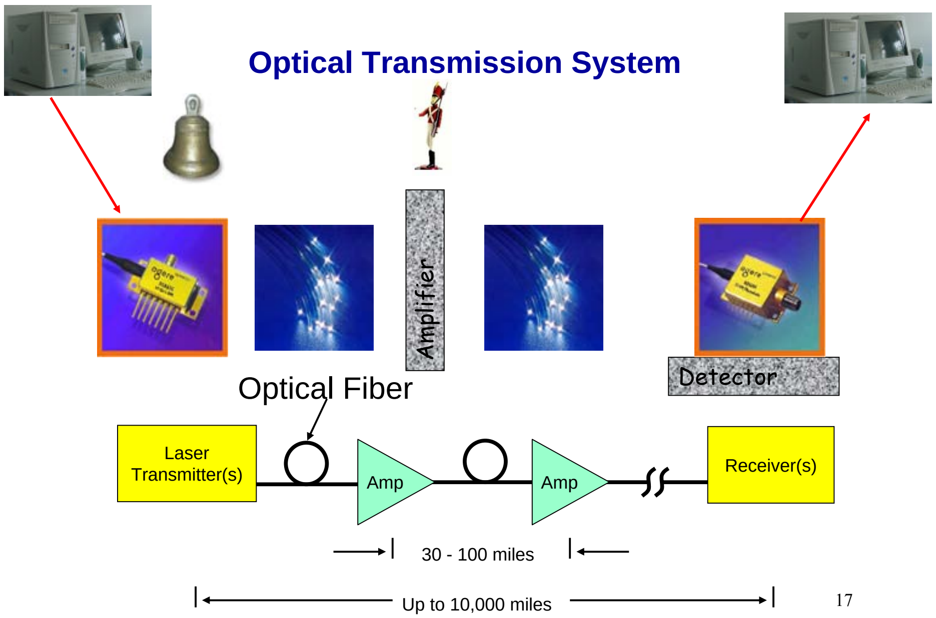


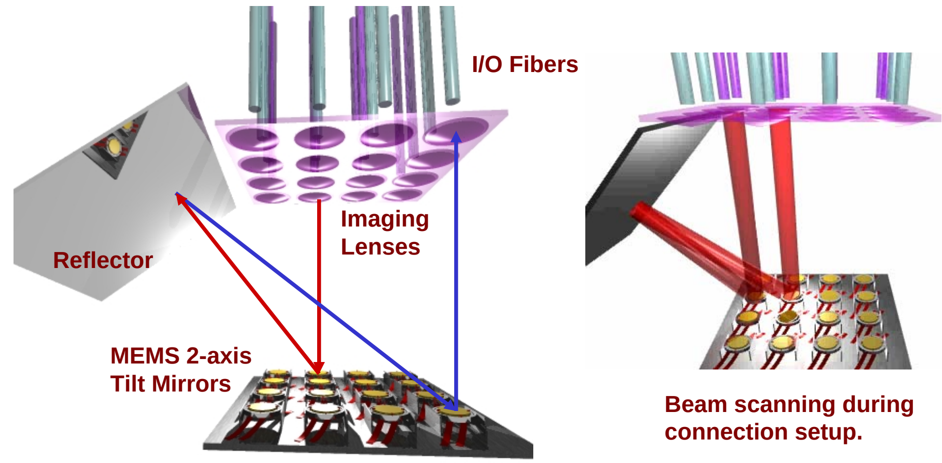
Typical Laser Wavelengths:

Laser Type	Wavelength (nm)
Argon fluoride (UV)	193
Krypton fluoride (UV)	248
Xenon chloride (UV)	308
Nitrogen (UV)	337
Argon (blue)	488
Argon (green)	514
Helium neon (green)	543
Helium neon (red)	633
Rhodamine 6G dye (tunable)	570-650
Ruby ($CrAlO_3$) (red)	694
Nd:Yag (NIR)	1064
Carbon dioxide (FIR)	10600

Optical Transmission System



MEMS OXC-- 2N Mirror Design

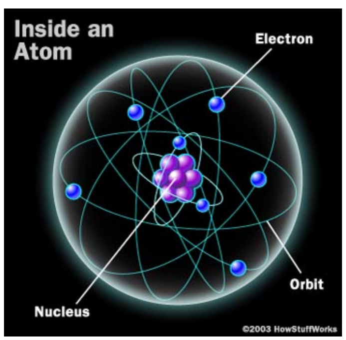


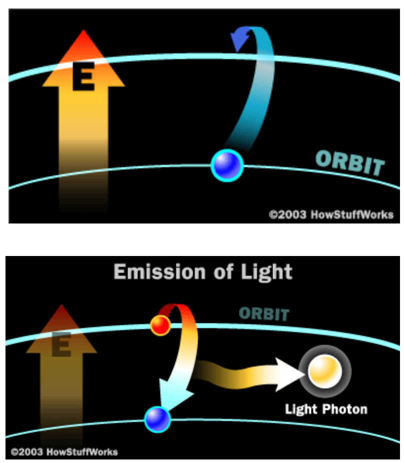
Beam scanning during connection setup.

2N MEMS mirrors in an NxN single-mode fiber optical crossconnect.

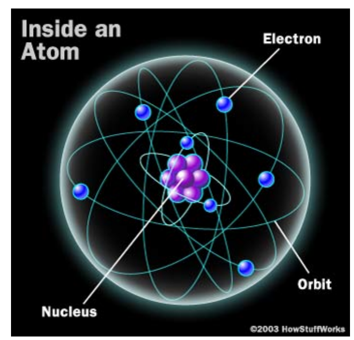
Lucent Technologies
Bell Labs Innovations

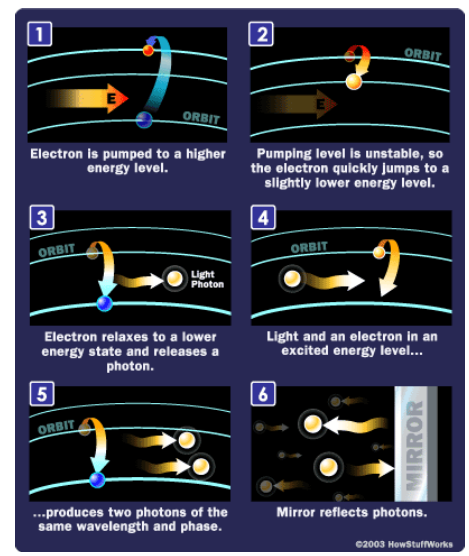
Principles of Laser Radiation



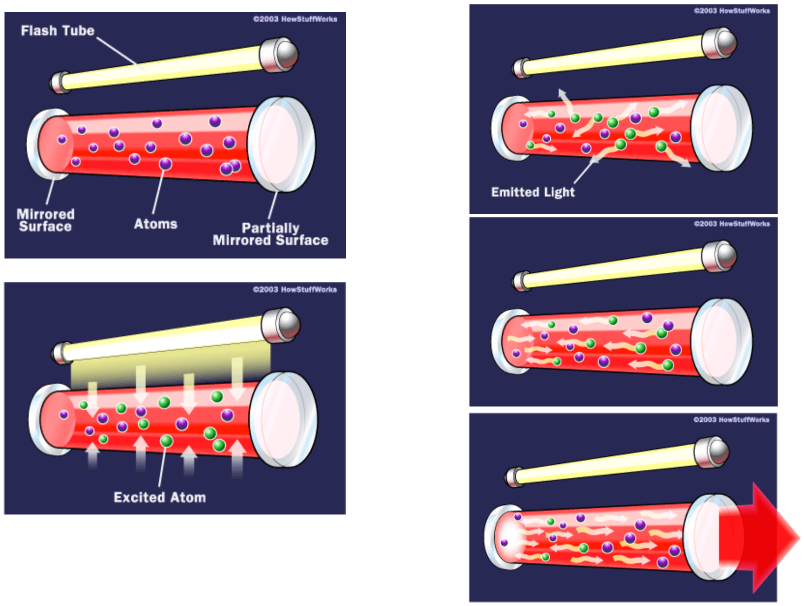


Principles of 3-level laser operation

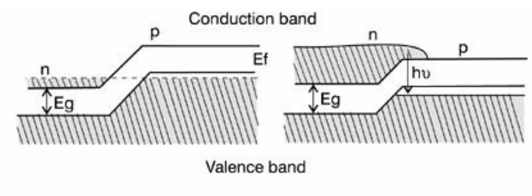




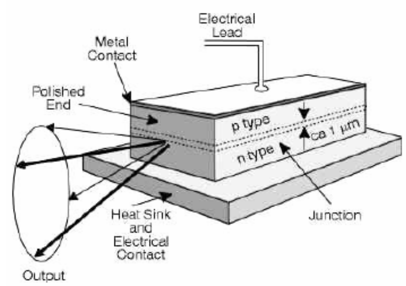
Principles of the Solid State Laser operation



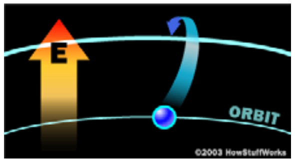
Semiconductor Lasers

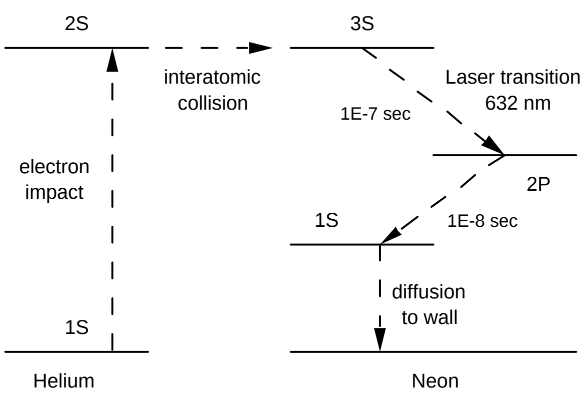


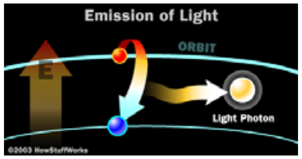
Band structure near a semiconductor p-n junction.
Left: No forward-bias voltage. Right: Forward-bias voltage present



Three level energy diagram of the He-Ne laser transition

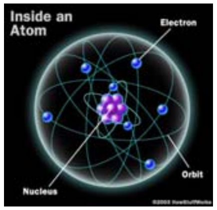






The laser process in a HeNe laser starts with collision of electrons from the electrical discharge with the helium atoms in the gas. This excites helium from the ground state to the long-lived, metastable excited states. Collision of the excited helium atoms with the ground-state neon atoms results in transfer of energy to the neon atoms. This is due to a coincidence of energy levels between the helium and neon atoms.

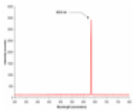
This process is given by the reaction equation:
He* + Ne → He + Ne* + ΔE



Fundamentals of Laser Operation

If the atom is in the excited state, it may decay into the ground state by the process of spontaneous emission:

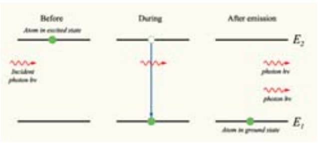
$$E_2 - E_1 = h\nu \qquad N(t) = N(0)e^{-\frac{t}{\tau_{21}}}$$



the rate of which stimulated emission, where ρ(ν) is the radiation density of photons :

$$\frac{\partial N}{\partial t} = -B_{21}\rho(\nu)N \qquad g(\nu) = \frac{1}{\pi}\frac{(\Gamma/2)}{(\nu-\nu_0)^2 + (\Gamma/2)^2} \qquad g(\nu=\nu_0) = \frac{2}{\pi\Gamma}$$

Stimulated emission cross section $\sigma_{21}(\nu) = A_{21}\frac{\lambda^2}{8\pi n^2}g(\nu)$



Optical amplification $\Delta N_{21} = \left(N_2 - \frac{g_2}{g_1}N_1\right)$

where g_1 and g_2 are the degeneracies of energy levels 1 and 2, respectively

General gain equation

$$\frac{dI}{dz} = \frac{\gamma_0(\nu)}{1+\bar{g}(\nu)\frac{I(z)}{I_S}} \cdot I(z) \qquad \gamma_0(\nu) = \sigma_{21}(\nu)\cdot\Delta N_{21}$$

Saturation intensity:

$$I_S = \frac{h\nu}{\sigma(\nu)\cdot\tau_S}$$

$$\ln\left(\frac{I(z)}{I_{in}}\right) + \bar{g}(\nu)\frac{I_{in}}{I_S}\left(\frac{I(z)}{I_{in}} - 1\right) = \gamma_0(\nu)\cdot z$$

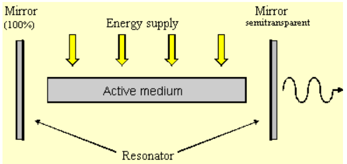
Gain: $G = G(z) = \frac{I(z)}{I_{in}}$ $\qquad \ln(G) + \bar{g}(\nu)\frac{I_{in}}{I_S}(G-1) = \gamma_0(\nu)\cdot z$

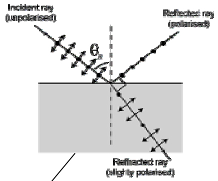
Large signal: $G \to 1$

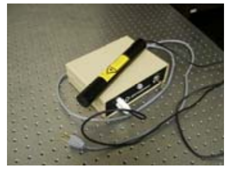
$$I(z) = I_{in} + \frac{\gamma_0(\nu)\cdot z}{\bar{g}(\nu)}I_S$$

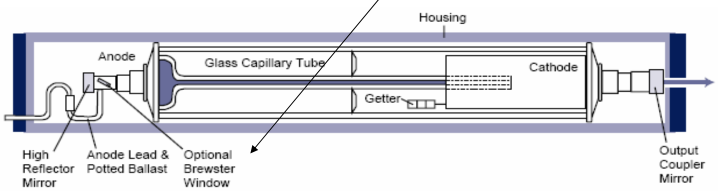
The intensity of the stimulated emission [W/m²]

Saleh, Bahaa E. A. and Teich, Malvin Carl (1991). *Fundamentals of Photonics*. New York: John Wiley & Sons. ISBN 0-471-83965-5.









General description of a HeNe laser

The typical HeNe laser is basically an optical cavity that consists of a glass capillary tube with a mirror at each end. The tube contains a helium and neon gas mixture that, when excited, utilizes the mirrors at each end of the tube to transform the spontaneous emission into a stimulated laser light emission. One mirror (called the high reflector mirror) reflects virtually 100% of the light, while the other (called the output coupler mirror) reflects approximately 99%. Therefore, about 1% of the light will exit the laser at the desired wavelength.

Some HeNe lasers do not incorporate internal mirrors but, rather, include a special glass window, called a Brewster window. This window is mounted at a precise angle (Brewster angle) to allow light to pass through and become linearly polarized. The output coupler mirror is positioned outside of the HeNe tube. The light is almost completely transmitted, virtually cutting out reflection and resulting in a minimal loss of output power. This intense, clearly visible light is ideal for applications requiring the observation of extremely tiny particles, such as dust.

Examples of transverse Gaussian laser modes

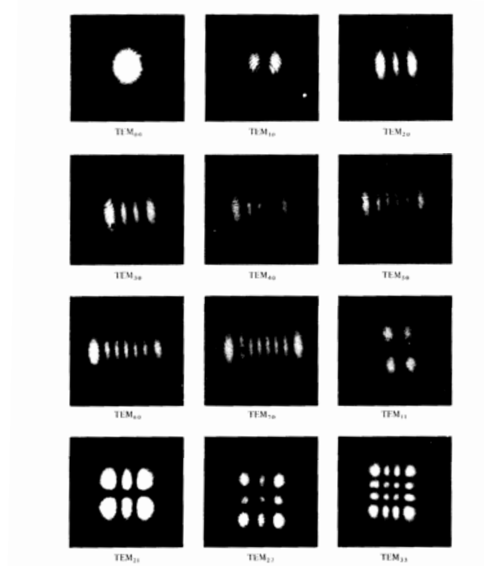
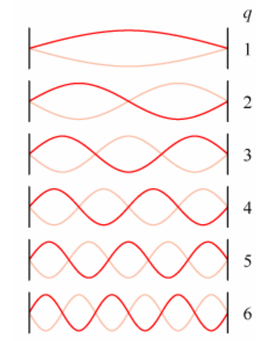


Figure 2-8 Intensity photographs of some low-order Gaussian beam modes. (After Reference [14].)

Examples of longitudinal laser modes



$$L = q\frac{\lambda}{2} \qquad \Delta\nu = \frac{c}{2L}$$

$$\Delta\nu = \sum_i \frac{c}{2n_iL_i} = \frac{c}{2}\left[\frac{1}{n_1L_1} + \frac{1}{n_2L_2} + \frac{1}{n_3L_3} + \cdots\right]$$