

Types of lasers

This classification of laser types is based on the active medium

1 -Solid-state lasers

2- Liquid-state lasers

3 - Gas lasers

Solid-State Lasers

Solid-state lasers are made up of an active medium, a pumping source, a power supply, and accessories

Question: Why are solid-state lasers capable of very high powers?

Answer:

Because the concentration of active ions that produce the laser is very high ($10^{20} - 10^{22}$ ions/cm³), and this is called the doping ratio. While the concentration of active ions in the best cases is only (10^{18} ions/cm³) in liquid and gaseous states.

Question: What is the main function of the crystal that hosts the active ions in solid-state lasers?

Answer:

There are three main functions of the host crystal: it represents a stable medium in which the active ions are distributed, and this determines the power of the output laser beam. It also determines the concentration of active ions (doping ratio). In addition, the type of crystal affects the wavelength of the output laser beam.

What is the difference between?

Solid-state laser	Liquid-state lasers	Gas lasers
Active Medium Solid state	Active Medium Liquid dye	Active Medium Low-pressure gas
Pumping Optical pumping (flash lamp)	Pumping Optical pumping using (another laser)	Pumping Electrical discharge method (anode and cathode)
It emits a narrow range of wavelengths	It emits a wide range of wavelengths	It emits a narrow range of wavelengths
Example Ruby, Nd-glass	Example Dye laser	Example He-Ne, Ar ⁺³ ions, CO ₂ laser

What is the difference between?

Laser Crystal: Neodymium Glass	Laser Crystal: Neodymium-YAG
Lower Resistance	Higher Resistance
Less Hardness	Higher Hardness, less fracture
Lower Thermal Conductivity	10 times higher Thermal Conductivity
Pulse Mode Operation Only	Continuous and Pulse Mode Operation
Four-level system	Four-level system
Active ions are Neodymium ions	Active ions are Neodymium ions
Active ions concentration up to 6%	Active ions concentration about 1.5%
Lower melting point	Higher melting point
Wider emission linewidth	Narrower emission linewidth
Lower gain	Higher gain
Broad absorption band	Narrow absorption band
Higher spontaneous emission rate	Lower spontaneous emission rate
Higher energy storage	Lower energy storage
Higher overall efficiency (5%)	Lower overall efficiency
Wavelength (1.06 μ m)	Wavelength (1.06 μ m)
as an Amplifier	as an Oscillator

Applications	Operating mode	Wavelength (um)	The nature of the active medium	Laser
Industrial, Military, Measurements Medical Communications	Continuous pulsating	0.7-0.824- levels	solid	Alexandrite
Medical, Measurements, Spectral	Continuous pulsating	0.488 , 0.5145	gas	Ar+3
Spectral Analysis	pulsating	6.613-5.59	gas	CO
Industrial, Military, Measurements Medical Communications	Continuous pulsating	10.6	gas	CO2
Medical, Spectral	pulsating	0.116 , 0.16	gas	H2
Medical, Measurements,	Continuous	0.325 , 0.442	gas	He-Cd
Measurements	Continuous	0.6328	gas	He-Ne
Biological	pulsating	0.337	gas	N2
Industrial Medical, Measurements,	pulsating	1.06	solid	Nd:Glass
Communications Industrial Measurements,	Continuous pulsating	1.064	solid	Nd:YAG

Medical Military,				
Communications Medical, Measurements,	Continuous	0.5401	gas	Ne
Industrial, Military, Measurements Medical Communications	Continuous pulsating	0.635-0.605	liquid	RB
Industrial Medical, Measurements,	pulsating	0.6943	solid	Ruby
Industrial Medical, Spectral	pulsating	0.173	gas	Xe2

What is the difference between?

Argon Ion Laser	Ruby Laser
Ionic gas	Solid
Four-level	Three-level
Active medium :Argon ions	Active medium: Sapphire crystal is made of aluminum oxide and inlaid with chromium ions (Cr ³).
Electric pumping	Optical pumping
Wavelength & 514.5 nm 488 nm	Wavelength 694 nm

What is the difference between?

Helium-Neon Laser	Ruby Laser
An atomic gas (a mixture of helium and neon)	Solid
Four-level	Three-level
Active medium: Neon-helium atoms act as a catalyst	Active medium: Sapphire crystal is made of aluminum oxide and inlaid with chromium ions (Cr^{3+}).
Electric pumping	Optical pumping
Wavelength 1.15 μm 3.39 μm	Wavelength 694 nm
High directivity	Low efficiency

Ar⁺ Laser	CO₂ Laser
Pumping Electrical discharge using anode and cathode in two stages: ionization of neutral gas and excitation of gas ions	Electrical discharge using anode and cathode
Transitions occur between electron levels of the Ar ⁺ ion	Transitions Occur between vibrational-levels of CO ₂ molecule
Active Medium Ar ⁺ ions	Active Medium mixture CO ₂ + N ₂ + He
Emitting wavelengths 488 nm, 514-5 nm (Visible, Blue-Green)	Emitting wavelengths 10.6 μm , 9.6 μm (Infrared)
Lower efficiency, requires high current consumption	high efficiency when used with large sizes and high power

"Question: Which type of the following lasers has the smallest divergence angle (θ_{div}) if the minimum beam radius inside the resonator is equal to (1mm)?

The lasers are: KrF, N₂, He-Ne, Nd:YAG, CO₂

Liquid lasers have the following advantages:

1. The possibility of obtaining a broad spectrum of laser wavelengths, which is called tuning.
2. The ease of forming the active medium (dissolving the dye in the solution).
3. The ease of changing the dye concentration by simply diluting or concentrating the solution.
4. Absence of crystal defects.
5. The ease of cooling by circulating the solution

Disadvantages of liquid lasers:

- 1- Instability due to fluid movement
- 2-The solvent can prevent laser generation
- 3-It is very affected by heat
- 4-The dye decomposes when exposed to light

Advantages of semiconductor laser

- 1- Small in size 50*10*300
- 2-Cheap price
- 3-It is pumped directly using electric current
- 4-Its efficiency is high, up to 32%
- 5-The intensity of the emitted laser beam can be controlled by controlling the electrical pumping current

Advantages of Using Lasers:

1. No direct contact between the sample and the laser system, therefore there is no contamination or mechanical stress.
2. The use of lasers does not affect the physical properties of the material because the affected area is very small.
3. Lasers can be used with different materials such as metals, ceramics, glass, and wood without damaging the material.
4. The possibility of working in difficult places such as corners, bends, and others.
5. The work is done with high speed and accuracy, for example, the cutting process of metals can be done at a speed of (10m/min), which is ten times faster than traditional methods.
6. The laser operation process can be programmed automatically for the purpose of accuracy.

7. Very high powers can be obtained.
8. The laser beam is not damaged as a result of use, as is the case with machines used in traditional methods such as cutters, arc welding, and drills.
9. Laser work is done quietly and without pollution as in traditional methods.
10. Laser Cutting, Laser Drilling, Laser Welding

Disadvantages of Using Lasers:

1. The manufacturing and operating costs of the laser system are high.
2. The laser system requires good experience to operate and maintain.
3. High power risks.
4. The laser system requires precise control.

Absorption rate and stimulated emission rate

We assume a two-level system and assume that the atom is present (1 & 2) in the ground state (level 1) in the presence of a magnetic field with an intensity (ρ) and a single frequency (ν) or angular frequency ($\omega = 2\pi\nu$). The presence of the field means a time-dependent disturbance and leads to the possibility of the atom being in the plane (level 2) provided that the energy Perturbation is equal to the energy difference between the two levels (1 & 2). To describe the state we use the Hamiltonian function (H)

$$H = H_0 + H \dots\dots\dots (26)'$$

Where H_0 is the Hamiltonian of the atom in the absence of an electromagnetic field, an undisturbed atom.

If (Ψ) is known at any time ($t > 0$) the time evolution of the state of the atom can be studied by knowing

the change in the wave function Ψ and the time-dependent Schrodinger equation is:

$$H\Psi = i\hbar \partial\Psi/\partial t \dots\dots\dots (27)$$

$$\hbar = h/2\pi \quad i = \sqrt{-1}$$

To solve this equation in terms of Ψ , the non-perturbed eigenfunction is introduced for each of the two levels "1 & 2.."

$$\psi_1 = \mu_1 e^{\frac{-iEt}{\hbar}}, \quad \psi_2 = \mu_2 e^{\frac{-iEt}{\hbar}} \dots \dots \dots (28)$$

$$H_0 \mu_j = E_j \mu_j \quad j = 1, 2, 3, \dots \dots \dots (29)$$

μ It is the dipole moment of the atom when the atom is under the influence of the incident electromagnetic wave, and the wave function of the atom is

$$\Psi = a_1(t)\psi_1 + a_2(t)\psi_2 \dots (30)$$

Where $a_1(t)$ and $a_2(t)$ are complex numbers dependent on time, and $|a_1|^2$ and $|a_2|^2$ represent the probability of finding the atom at time (t) in levels 1 and 2 respectively:

$$|a_1|^2 + |a_2|^2 = 1 \dots (31)$$

To calculate the transition probability W_{12} , we need to calculate the quantity $|a_1|^2$ and $|a_2|^2$:

$$W_{12} = 1/t \quad |a_1|^2 = 1/t \quad |a_2|^2 \dots (32)$$

If the cause of the atomic transition is due to the interaction between the electric field of the incident electromagnetic wave and the electric dipole moment of the atom, which is represented by the equation:

$$H = eE_{(r,t)} \cdot r \dots (33)$$

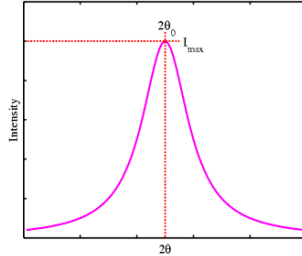
Solving this requires knowing the wavelength of the incident electromagnetic wave compared to the atomic dimensions. When the wavelength of the incident wave is much larger than the atomic dimensions, as in the visible range (e.g., yellow light with a wavelength of 500 nm) and the atomic dimensions are around (0.1 nm), we can arrive at the following expression:

$$W_{12} = (\pi/3n^2\epsilon_0) |\mu_{12}|^2 \rho g (\Delta\omega) \dots (34)$$

Where n is the refractive index of the atomic system, ϵ_0 is the permittivity of free space, and μ_{12} represents the electric dipole matrix element and equals

$$\vec{\mu}_{21} = e \int \mu_2 \vec{r} \mu_1 dV \dots \dots \dots (35)$$

"And μ_{21} represents the magnitude of the vector μ_{21} , which is a value that determines the position of the atom relative to the direction of the electric field of the incident electromagnetic wave. The quantity $g(\Delta\omega)$ represents a function called the 'spectral line shape function,' and its shape depends on the phenomenon that causes the broadening of the spectral line, and it is often expressed by a Lorentzian function as shown in Figure (7).



Equation (34) can be written in terms of the intensity of incident electromagnetic radiation, that is, in terms of:

$$I = \frac{\rho c_0}{n}$$

$$W_{12} = \frac{\pi}{3n^2 \epsilon_0 c_0 \hbar^2} |\mu_{21}|^2 I g(\Delta\omega) \dots \dots \dots (36)$$

$$W_{21} = W_{12} = W \quad (37)$$

$$W = \frac{\pi}{3n^2 \epsilon_0 \hbar^2} |\mu|^2 \rho g(\Delta\omega) \dots \dots \dots (38)$$

$$W = \frac{\pi}{3n \epsilon_0 c_0 \hbar^2} |\mu|^2 I g(\Delta\omega) \dots \dots \dots (39)$$

Allowed transfers and prohibited transfers

From equation (34)

$$W_{12} = \frac{\pi}{3n^2 \epsilon_0 \hbar^2} |\mu_{21}|^2 \rho g(\Delta\omega) \dots \dots \dots (34)$$

The value of W_{12} becomes zero when the function $\mu_{12} = 0$, which occurs when both functions μ_1 and μ_2 are either symmetric or have opposite symmetry.

A function $\mu(r)$ is considered symmetric when:

$$\mu(r) = \mu(-r)$$

And a function has opposite symmetry when:

$$\mu(-r) = -\mu(r)$$

In both cases, the sign of the product $\mu_1 * \mu_2$ does not change when replacing r with $-r$.

As shown in equation (35), the result of the integral in these two positions is equal but with opposite signs, canceling each other out. However, when one function is symmetric and the other has opposite symmetry, the product $\mu_1 * \mu_2$ changes sign when changing r to $-r$. Therefore, the result of the integral in equation (34) differs from zero.

Transitions for electric dipoles occur only between atomic states or energy levels with opposite symmetry (i.e., odd-even and even-odd symmetry transitions).

If $W = 0$, then the transition is forbidden.

Transitions for magnetic dipoles occur between atomic states with similar symmetry (i.e., odd-odd or even-even symmetry transitions).

Question: Is the electric dipole moment larger than the magnetic dipole moment? Explain.

Answer:

We assume that the probability of transition due to the interaction of the electric dipole is (W) and the magnetic dipole is (W_m). If the intensity of the incident electromagnetic radiation in the visible range is equal for both cases, then:

$$\frac{we}{wm} = \left(\frac{eaE_o}{\beta B_o} \right)^2 = \left(\frac{eac}{\beta} \right) = 10^5$$

Where a is the atomic radius, E is the electric field strength, B is the magnetic field strength, $cB^\circ = E^\circ$ and $\beta = 9.27 \times 10^{-24}$ Amp.m² is the Bohr magneton.

Transition Section, Absorption Coefficient, Gain Coefficient:

The transition cross-section (σ) of a plane electromagnetic wave with constant intensity (I) is directly proportional to the photon flux (F), that is:

$$W = \sigma F \Rightarrow W/F$$

$$F = 1/\hbar\omega$$

Thus, using equation 36, the transition cross-section is given by the following expression:

$$\sigma = \pi|\mu|^2g(\Delta\omega) / 3n\epsilon_0\hbar \dots (40)$$

That is, the cross-sectional area depends on:

1. The type of material.
2. The frequency of the incident wave.

The cross-sectional area of stimulated emission = cross-sectional area of absorption.

The interaction between electromagnetic radiation and matter can be described by the absorption coefficient, which is related to the cross-sectional area by the relation:

$$\alpha = \sigma(N_1 - N_2) \dots (41)$$

If $N_1 > N_2$, then α (the absorption coefficient) can be expressed by equation 40 as follows:

$$\alpha = (\pi|\mu|^2\omega(N_1 - N_2)g(\Delta\omega)) / (3n\epsilon_0\hbar) \dots (42)$$

Any experimental absorption coefficient (α) depends on the energy levels of the atoms of the material.

The absorption coefficient (α) can be measured directly in terms of intensity using Lambert's law for the transmitted intensity:

$$I_t = I_0 e^{-\alpha t} \dots (43)$$

How much can the transition cross section (σ) be determined using Equation 41? After knowing N_2 and N_1 are the sets of energy levels 2 and 1 respectively.

If a system is in thermal equilibrium, the set of energy levels of an atom is described by the Maxwell-Boltzmann distribution:

$$N_2/N_1 = e^{-(E_2-E_1)/kT} \dots (19)$$

If $N_1 < N_2$, as in part (a) of Equation 41, it becomes negative. In this case, the incident wave is amplified rather than weakened as a result of absorption by the medium. The gain factor G can be expressed as follows:

$$\gamma = \alpha = \sigma(N_2 - N_1) \dots\dots\dots(44)$$