Laser Lecture 1 Basic Principle of Laser Operation

Light Amplification by Stimulated Emission of Radiation

University of Lucknow | Centenary Year
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Three Components of a Laser

The Amplifying Medium

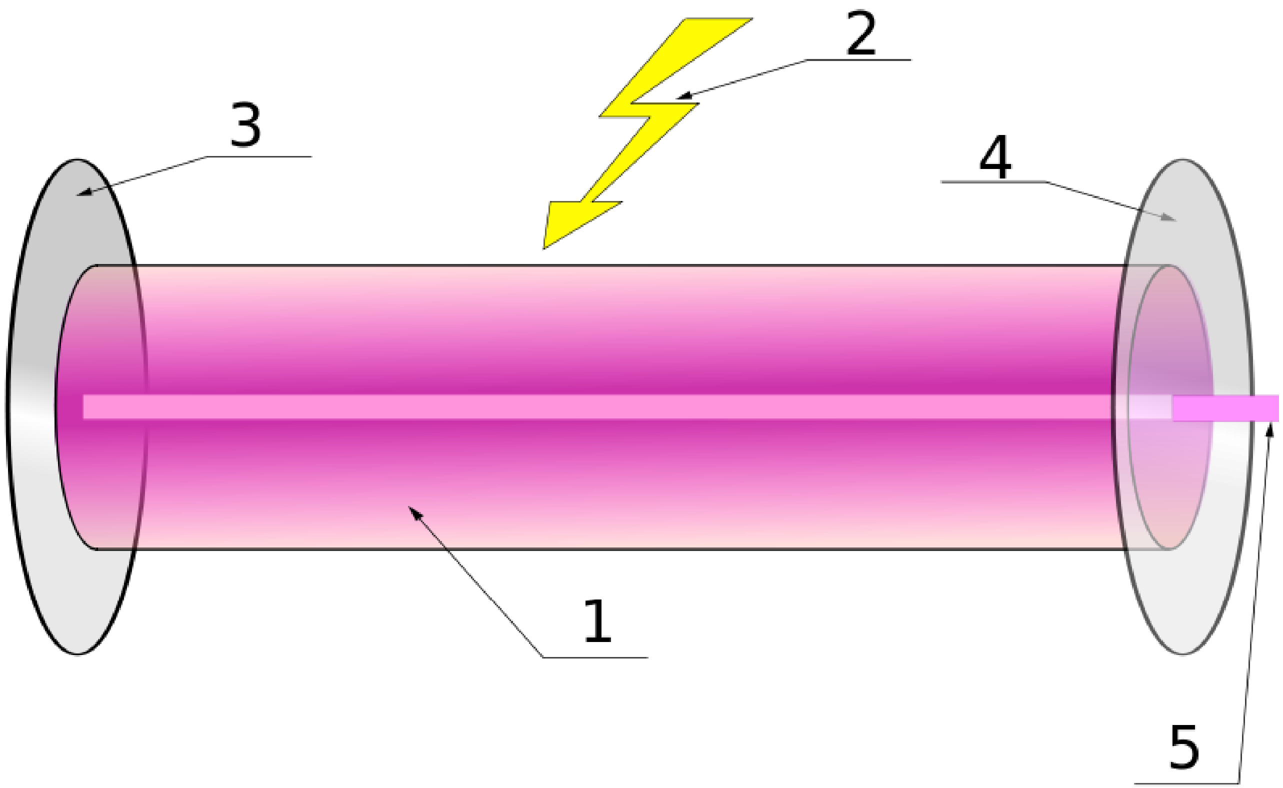
A collection of atoms, molecules and ions which act as amplifiers of light.

Optical Resonator

A pair of mirrors facing each other.
It provides optical feedback to the amplifiers so that it can act as a source of radiation.

The Optical Pump

It is the source of energy which maintains the state of population inversion.



Components of a typical laser:

1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler
5. Laser beam

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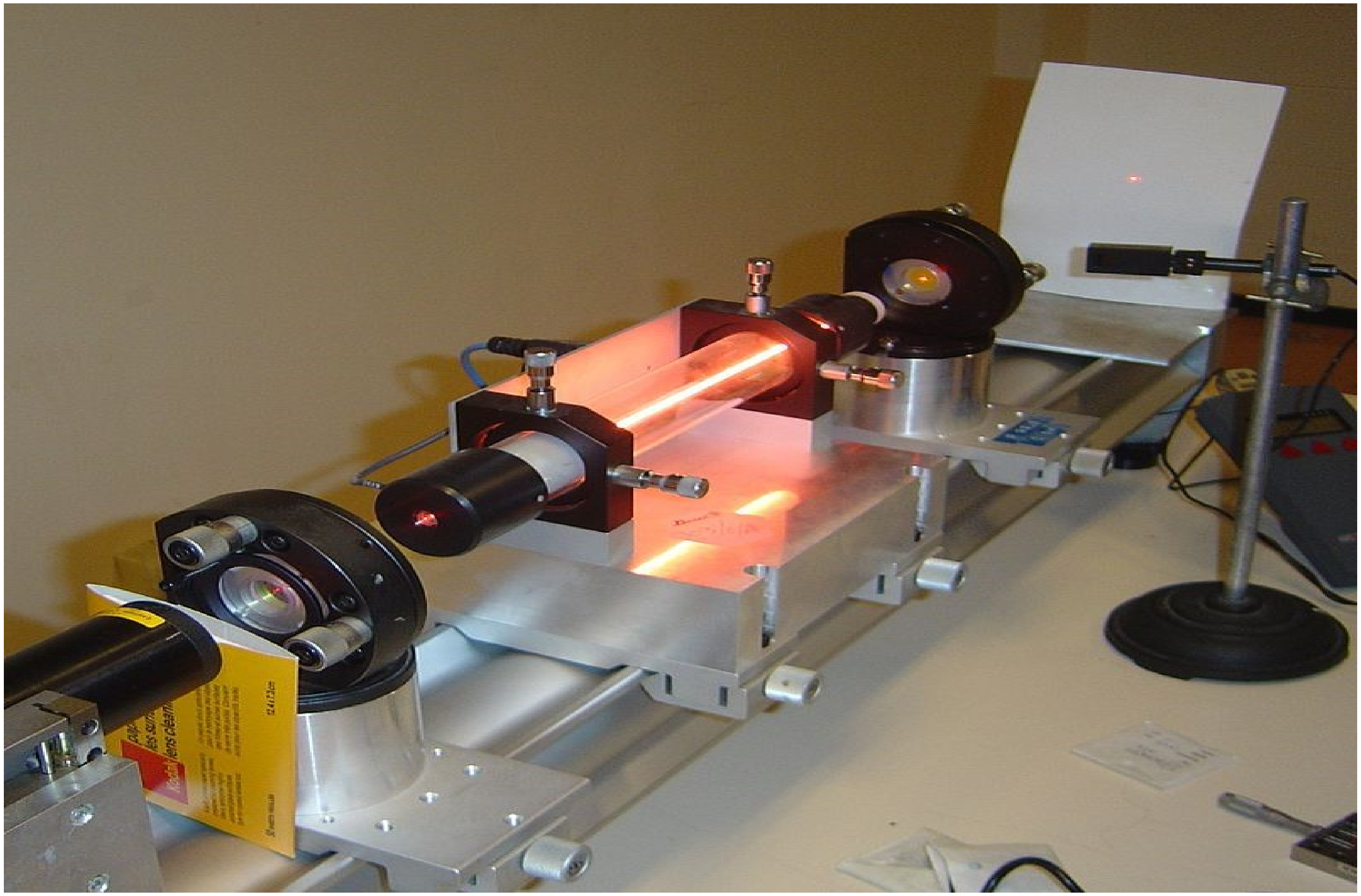

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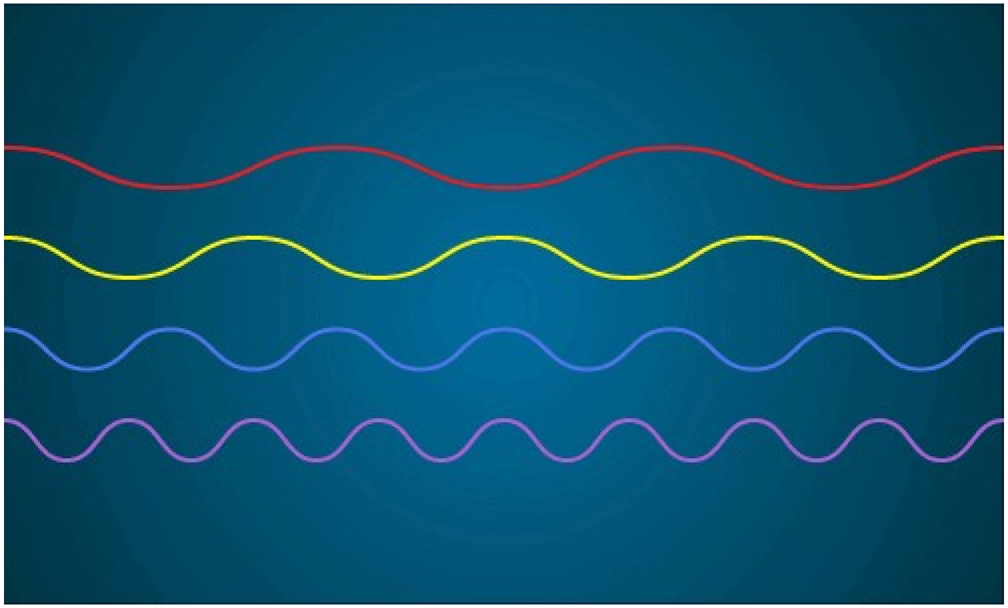
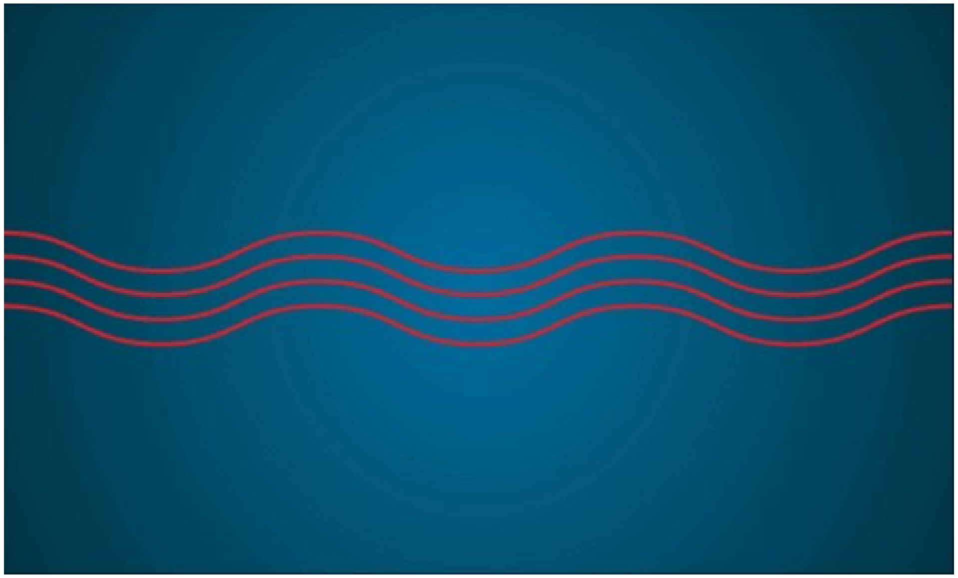
White light: Each color of light has a different wavelength.





The laser light waves travel together with their peaks all lined up, or **in phase**.

https://spaceplace.nasa.gov/laser/en/

Absorption

In the absorption process the optical energy is converted to the internal energy of electrons, atoms, or molecules. When a photon is absorbed, the energy may cause an electron in an atom to jump from a lower energy level to a higher energy level. The electrons absorbing the energy may be part of conductive, insulating, or semiconducting materials. The photons absorbed may be optical photons, with individual energies in the range 1.9 to 3.1 eV having wavelengths in the visible range. In isolated neutral neon atoms in the ground state, electrons occupy the 2p energy level but not the 3s energy level.

These energy levels are separated by an energy gap of Eg=1.96 eV which corresponds to energy of photons of wavelength 632.8 nm, the red color. If a photon of this energy impinges upon neon gas, the photon may be absorbed, and an electron of a neon atom would be excited to the higher energy level. Photons of smaller energy would not be absorbed.

Spontaneous Emission

In the spontaneous emission process an excited electron or molecule decays to an available lower energy level and in the process releases a photon. This process is spontaneous and therefore occurs naturally. The process does not involve any interaction with other photons.

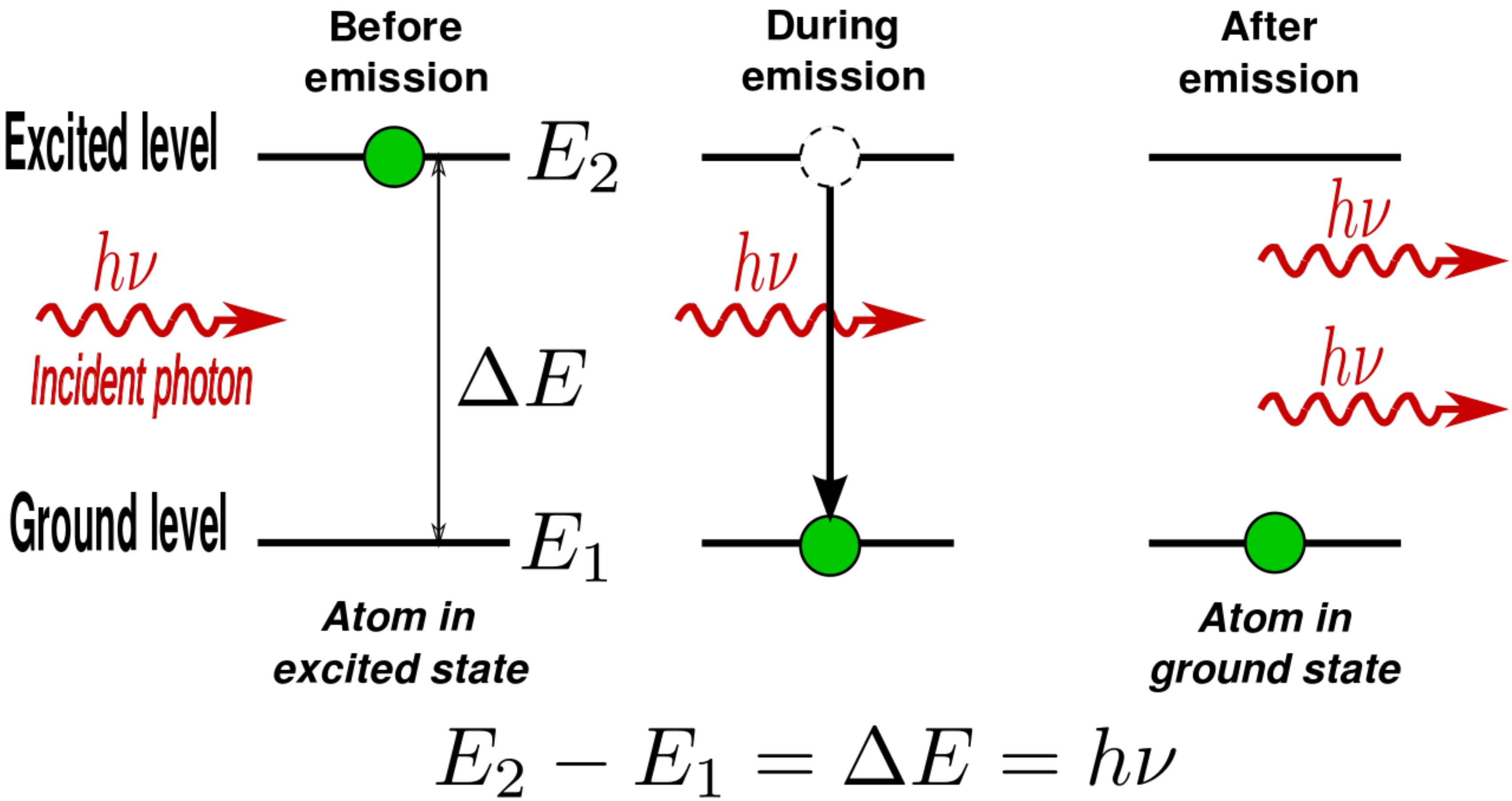
The average time of decay by spontaneous emission is called the spontaneous (emission) lifetime. This spontaneous lifetime may range from some nanoseconds to a few seconds. Like absorption, this process may occur in isolated atoms, ionic compounds, molecules, and other types of materials. The process can occur in solids, liquids, and gases. The released energy may be in the form of heat, mechanical vibrations, or photons. If the energy is released as photons, the process is called spontaneous emission, and the energy of each photon released is equal to the energy difference between the energy levels involved. All the released photons in the spontaneous emission will not have similar direction, phase, and state of polarization.

There are many ways in which an electron can be excited to a higher energy level by various processes. Table below shows classification of spontaneous emission processes based on the source of energy that excites the electrons.

Sl. No.	The Energy Source	The Physical Process
1	Electromagnetic waves	Photoluminescence
2	Chemical reactions	Chemiluminescence
3	Applied voltages	Electroluminescence
4	Sound waves	Sonoluminescence
5	Biological processes	Bioluminescence

Stimulated Emission

In the stimulated emission process an excited electron, atom or molecule interacts with a photon, we may call it a stimuli, and decays to an available lower energy level, releasing a photon. As with the others, this process can occur in atoms, ions, molecules, etc. It can occur in solids, liquids, and gases. If an incident photon, with energy equal to the difference between allowed energy levels, interacts with an electron in an excited state, stimulated emission can occur. The energy of the excited electron will be released as a photon. The photon thus released will have the same frequency, direction, phase, and state of polarization as the incident photon.



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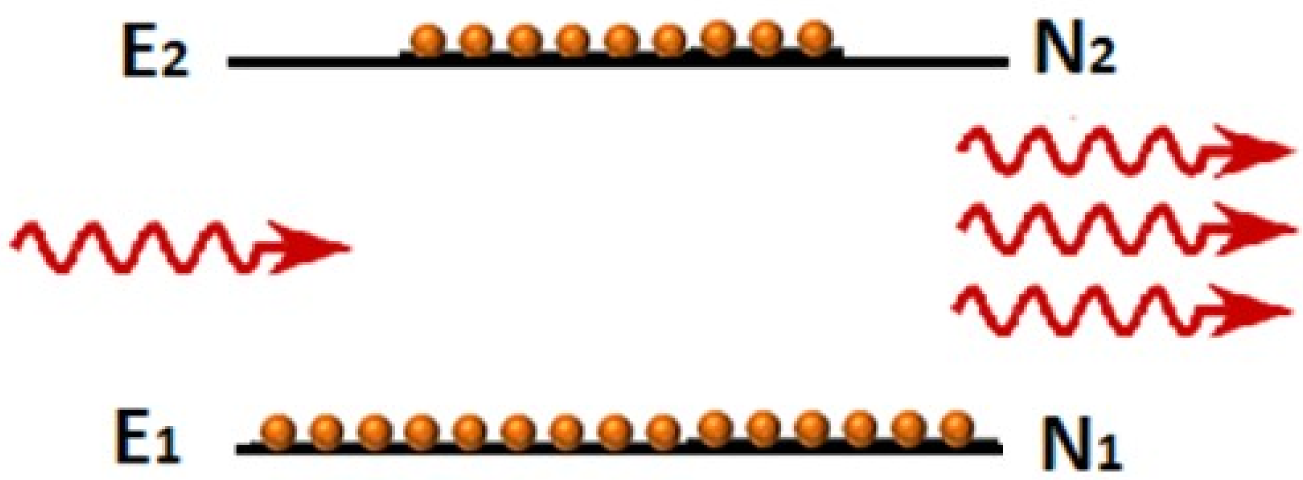
The Einstein Coefficients

Consider two levels of an atomic system E_1 and E_2



N_1= Number of atoms per unit volume present in energy level E_1
N_2= Number of atoms per unit volume present in energy level E_2

Consider a radiation having energy difference $E_2 - E_1$ falling on the atomic system.

The radiation will interact with the system in three different ways

i. An atom in the lower energy state E_1 can absorb the incident radiation and be excited to E_2

The rate of absorption from level 1 to 2 is proportional to

- Number of atoms present in level E_1
- Energy density of radiation at frequency $\omega = \frac{E_2 - E_1}{\hbar}$

i.e. number of atoms undergoing absorptions from level 1 to 2 per unit time per unit volume

$$\Gamma_{12} = B_{12} u(\omega) N_1$$

B_{12} is the constant of proportionality

$u(\omega)\, d\omega$ = radiation energy per unit volume in the frequency interval ω and $\omega + d\omega$

$u(\omega)$= energy density per unit frequency interval

ii. De-excitation of atoms from level 2 to 1

This can happen in two ways:

a. Stimulated Emission: the radiation incident on the system stimulates to emit radiation

Number of transitions to the lower energy level

$$\Gamma_{21} = B_{21} u(\omega) N_2$$

B_{21} is the constant of proportionality and depends on energy levels E_2 and E_1

b. Spontaneous Emission: Number of atoms making spontaneous transitions per unit time per unit volume

$$U_{21} = A_{21} N_2$$

At thermal equilibrium

Number of upward transitions = Number of downward transitions

$$B_{12}\,u(\omega)N_1 = B_{21}\,u(\omega)N_2 + A_{21}\,N_2$$

$$u(\omega)[B_{12}N_1 - B_{21}N_2] = A_{21}N_2$$

$$u(\omega) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}\,N_2} = \frac{A_{21}}{\frac{N_1}{N_2}B_{12} - B_{21}}$$

According to Boltzmann Law, at thermal equilibrium (for $N_2 < N_1$)

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/k_B T}$$

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/k_B T} = e^{\hbar\omega)/k_B T}$$

$$u(\omega) = \frac{A_{21}}{B_{12} e^{\hbar\omega)/k_B T} - B_{21}}$$

According to Planck's law, the radiation energy per unit frequency interval is

$$u(\omega) = \frac{\hbar\,\omega^3\, n_o^3}{\pi^2\, c^3}\ \frac{1}{e^{\hbar\omega)/k_B T} - 1}$$

Here n_o is the refractive index of the medium

Compare equations

$$B_{12} = B_{21} = B$$

The stimulated emission rate per atom is the same as absorption rate per atom

Ratio of spontaneous emission to stimulated emission coefficients is given by equation

$$\frac{A_{21}}{B_{21}} = \frac{\hbar\omega^3 n_o^3}{\pi^2 c^3}$$

At thermal equilibrium, the ration of the number of spontaneous to stimulated emissions is given by

$$R = \frac{A_{21} N_2}{B_{12} N_2 u(\omega)} = e^{\hbar\omega)/k_B T} - 1$$

Thus at thermal equilibrium, at temperature T, for frequencies $\omega >> k_B T/\hbar$, the number of spontaneous emissions far exceeds the number of stimulated emission

YouTube Channel Link: https://www.youtube.com/channel/UC3rdRYA605bdDdsJdEf0oJw/featured

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