Module 1 Unit 3

PRINCIPLES OF LASERS – NOTES

(As per SVU-R2020 Scheme & Syllabus)

- **Introduction**

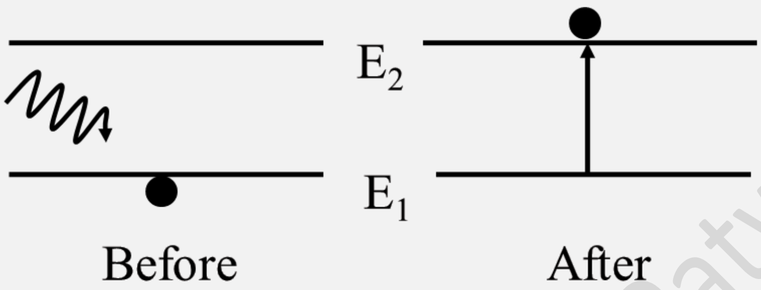
LASER stands for "Light Amplification by Stimulated Emission of Radiation". Laser is a directional, focused, monochromatic, coherent and bright source of light. The difference of laser light from ordinary light is contained in the name itself - the process of *stimulated or triggered emission*. Ordinary light, on the contrary, is a result of *spontaneous or natural emission*. Stimulated emission cannot occur at normal conditions. The first successful laser source was the Ruby laser developed by T. H. Maiman in 1960. Following table gives a comparison between laser and ordinary sources of light.

Laser Sources	Ordinary Sources
1) Laser light consists of almost a single value of wavelength. The spread in wavelength is hardly 10 Å.	Light from ordinary sources consists of wide wavelength range. The spread in wavelength can be thousands of Angstroms.
2) Laser light waves are highly coherent i.e. they are in phase with each other. The coherence length is few metres to few kilometres for some powerful laser sources like the CO_2 laser.	Ordinary light consists of waves with no definite phase relation. The coherence length is few millimetres to centimetres for all ordinary sources including monochromatic sources like sodium vapour lamp.
3) Laser light is highly focused i.e. the beam does not spread much even if it covers very large distances. It has small angular spread, about 10^6 times smaller than ordinary light.	Ordinary sources emit light, which is highly divergent and diffuse. The light has high angular spread.
4) Laser light is directional. It is emitted only in one direction – along the axis of the source in many cases.	Ordinary light is emitted in all directions.
5) The laser beam is highly intense. Large power is concentrated in a small part since the light travels as a narrow beam.	Intensity of ordinary light decreases rapidly with distance as it spreads everywhere.
6) Examples of laser sources: He-Ne laser, Ruby laser, Nd:YAG laser, CO_2 laser, diode laser	Examples of ordinary sources: CFL, halogen lamp, Na-vapour lamp, incandescent bulb, LED

- **Background**

Radiation consists of photons and matter consists of atoms and molecules. Obviously, interaction of radiation with matter means interaction of photons with atoms and molecules. The interaction can be as simple as light absorbed by a material or light emitted from a material. There are three processes, which coexist at all temperatures whenever there is an interaction between radiation and matter. Their proportion may change depending upon the material and its temperature. They are *Absorption, spontaneous and stimulated emission*.

- **Absorption**



Consider an atom residing in the lower energy state E_1 and a radiation of certain energy is incident. The atom may absorb the incident energy (if sufficient) and jump to the next energy state E_2. This process is called as *induced or stimulated absorption* because we have to externally supply energy. The atoms will not automatically jump into the excited states. It means there is no spontaneous absorption as such.

Corresponding to each transition from E_1 to E_2, one photon of energy $h\nu = E_2 - E_1$ disappears and the atom is excited. The number of atoms excited is by absorption process is given by,

$$\left.\frac{dN}{dt}\right]_{ab} = B_{12} N_1 Q$$

Where,

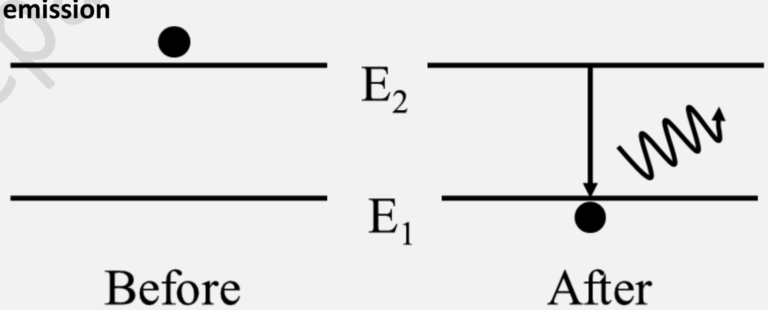
B_{12}: probability of absorption process

N_1: number of atoms in lower energy level E_1

Q: energy density of incident radiation (given in J-s/m^3)

The number of absorption events taking place at any instant is proportional to number of atoms present in the lower energy states. Since atoms tend to stay in the lowest possible energy states, most of the photons are absorbed as radiation penetrates the matter i.e. it is attenuated.

- **Spontaneous emission**



An atom raised to its excited state does not stay there for long time because the excited state is inherently unstable. Excited atoms rapidly de-excite due to the natural tendency of atoms to seek for the lowest energy state. This type of process in which, atom on its own releases a photon is called as *natural or spontaneous emission.*

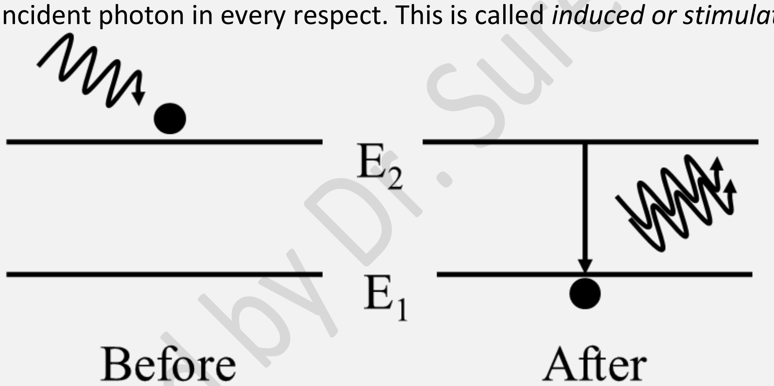
Corresponding to each transition E_2 to E_1, one photon of energy $h\nu = E_2 - E_1$ appears. The number of atoms de-excited by spontaneous emission is,

$$\left.\frac{dN}{dt}\right]_{sp} = A_{21}N_2$$

Where,
A_{21}: probability of spontaneous emission process
N_2: number of atoms in higher energy level E_2
The number of spontaneous emission events taking place at any instant is proportional to number of atoms present in the higher energy state. The process of spontaneous emission is completely probabilistic.

- **Stimulated emission**

This type of process also exists along with the above two processes but at room temperature, spontaneous emission dominates stimulated emission and the latter is generally negligible. The idea behind stimulated emission is that the process of emission need not be always probabilistic but we can make some transitions to occur. A photon of energy $h\nu = E_2 - E_1$ or greater can induce the excited atom to de-excite to release energy in the form of another photon. The released photon is identical to the incident photon in every respect. This is called *induced or stimulated emission*.



Corresponding to every induced transition E_2 to E_1 due to a single photon, two identical photons of energy $h\nu = E_2 - E_1$ appear. The number of atoms de-excited by stimulated emission is,

$$\left.\frac{dN}{dt}\right]_{st} = B_{21}N_2Q$$

Where,
B_{21}: probability of stimulated emission process
N_2: number of atoms in higher energy level E_2
Q: energy density of incident radiation
The number of stimulated emission events taking place at any instant is primarily proportional to number of atoms in the higher energy state.

The spontaneous emission events are completely probabilistic meaning there is no control to which and how many atoms will de-excite at a given time and which energy levels are involved. Therefore spontaneously emitted light is incoherent, divergent, diffused and undirected. It may or may not be monochromatic. Light from ordinary sources (e.g. bulb, tube light, LED, Na – light, candle, burner etc) is a result of spontaneous emission.

The process of stimulated emission has following advantages over spontaneous emission:

1) The process is controllable from outside. We can control the intensity and energy density of inducing radiation.
2) The induced radiation is identical to the incident radiation in every respect: energy, frequency or wavelength, phase, state of polarization, direction of propagation etc.
3) By selecting proper active medium and resonance conditions, multiplication of photons is achieved. This leads to oscillations of radiation within a specially prepared region called as optical resonance cavity.

As a result, we get a highly monochromatic, coherent, directional, focused and intense. Thus, to obtain laser light means to obtain light amplification (rather oscillations) by stimulated emission of radiation at a desired wavelength.

Note: When an atom absorbs a photon/s, the energy is actually shared by its orbital electrons. The electrons are either transferred to higher energy states or they even be dislodged from the atom. It is normally a practice to say that the atom is excited instead of calling electrons being exited. Following this, it is also a practice of showing an atom itself, transferred from one energy state to the other.

- **Laser-Physics Terms and Concepts:**

When studying lasers, we come across to a number of important terms and concepts. Some of them are listed below to get a brief idea about principles of lasers.

Population

The number of *active* atoms occupying a particular energy state is called population of that energy state. Active atoms mean atoms, which are likely to be excited by incident radiation or atoms, which are already excited by absorbing photon/s and are about to de-excite. Thus, N_1 and N_2 is population of state E_1 and E_2 respectively. According to Boltzmann's statistics, the popolations , N_1 and N_2 are given by

$N_1 = g_1 e^{-E_1/kT}$ and $N_2 = g_2 e^{-E_2/kT}$ where, g_1 and g_2 are called "degeneracy" of levels E_1 and E_2 respectively. An energy level is said to be degenerate if the same energy level corresponds to different states (quantum states) of a system.

$$\therefore \frac{N_1}{N_2} = \frac{g_1}{g_2} e^{(E_2-E_1)/kT}$$

Let both the energy levels E_1 and E_2 be non-degenerate and are singly occupied (only one quantum state corresponding to one energy level) so that $g_1 = g_2$ and

$$\therefore \frac{N_1}{N_2} = e^{(E_2-E_1)/kT} \qquad \text{--- (1)}$$

At equilibrium, since $E_2 > E_1$, $N_1 >> N_2$ that is, the lower state E_1 is said to be *populated* as compared to the excited state E_2 which seems obvious.

Equilibrium conditions and Einstein's coefficients

At equilibrium (dynamic equilibrium, where energy exhange takes place), the number of upward transitions is equal to the number of downward transition so that the ratio N_1/N_2 remains constant. This gives

$$\left.\frac{dN}{dt}\right]_{ab} = \left.\frac{dN}{dt}\right]_{sp} + \left.\frac{dN}{dt}\right]_{st}$$

$$\therefore B_{12}N_1Q = A_{21}N_2 + B_{21}N_2Q$$

According to Einstein's statistical theory, the probabilities of stimulated events i.e. absorption and emission are the same i.e. is $B_{12} = B_{21}$. Therefore we get $\frac{N_1}{N_2} = 1 + \frac{A_{21}}{B_{21}Q}$.

Using (1) above, we can write:

$$Q = \frac{A_{21}}{B_{21}}\left(\frac{1}{e^{(E_2-E_1)/kT} - 1}\right)$$

Let $E_2 - E_1$ corresponds to radiation of energy E = hν, where ν is frequency of radiation according to Planck's formula.

$$\therefore Q = \frac{A_{21}}{B_{21}}\left(\frac{1}{e^{h\nu/kT} - 1}\right)$$

Comparing this equation with the Blackbody radiation formula according to Planck's theory:

$$Q = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{e^{h\nu/kT}-1}\right) \qquad \text{--- (2)}$$

we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \qquad \text{--- (3)}$$

It indicates that the ratio of probabilities of spontaneous to stimulated emission goes as cube of frequency of radfiation emitted. This indicates that achieving laser emission i.e. stimulated emission becomes more and more difficult at higher frequencies or shorter wavelengths.

Above ratio is also called ratio of Eintein's A dn B coefficients.

Further, let us find the ratio of rates of spontaneous and stimulated emission:

$$R = \frac{\left.\frac{dN}{dt}\right]_{sp}}{\left.\frac{dN}{dt}\right]_{st}} = \frac{A_{21}N_2}{B_{21}N_2Q} = \frac{A_{21}}{B_{21}Q}$$

Using (2) and (3) above, we get

$$R = e^{h\nu/kT} - 1 \qquad \text{--- (4)}$$

Equation (4) gives the ratio of rates of spontaneous and stimulated emission processes. It indicates that for a given frequency of radiation, the ratio varies exponentially with temperature.

- At room temperatures and at thermal equilibrium, absorption and spontaneous emission processes nearly balance each other. At equilibrium, $N_1 >> N_2$ and also, $A_{21} > B_{21}$. RHS of both terms are less that unity and the stimulated emission is negligible with other two processes. Therefore, we do not observe laser light in normal conditions and the light due to all ordinary sources is a result of spontaneous emission processes.
- Q must be made large enough so that product on RHS of first term becomes greater than unity. Further, we have to make $N_2 > N_1$. Since this cannot happen naturally, we have to supply energy to the atoms and maintain them in higher energy levels.

Note: To achieve stimulated emission we have to make $N_2 > N_1$. But this is reserve condition of what is observed at equilibrium condition. Since we have to disturb the equilibrium condition, lasers are often called as *non-equilibrium processes***.**

Population inversion

There must be more atoms in the higher energy level E_2 than in the lower energy level E_1 in order to achieve stimulated emission exclusively. This is a non-equilibrium process as noted above in which the higher energy state is pore populated than the lower energy state. When this situation is achieved, the population between the energy levels E_1 and E_2 is said to be *inverted* and the medium or region in which this is achieved is said to be transferred in the state of *population inversion*.

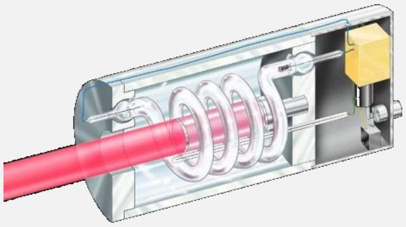
Active system or active medium

The region in which the state of population inversion is achieved is called as the *active medium or active system*. The actual laser light is emitted from this region. The system can be a solid, liquid or gas. Further, the whole system may not take part in population inversion; only a fraction of it is responsible. For example, in semiconductor diode laser, it is the depletion region which goes in the state of population inversion and not the entire diode. In Ruby laser, the lattice sites occupied by Cr^{3+} ions act as active centres and the Al_2O_3 crystal (Ruby) just acts as host and heat sink.

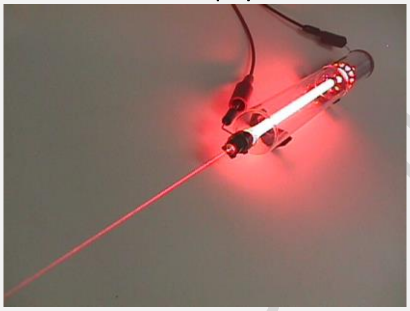
Pumping

For maintaining the state of population inversion, the atoms have to be continuously raised to excited states. It requires energy to be supplied to the system from outside. The process of supplying energy to the system with an objective of keeping it into the state of population inversion is called as pumping. Various methods used for pumping are:

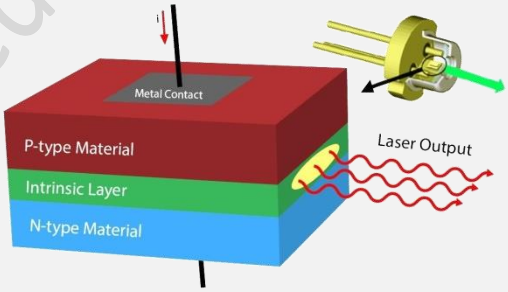
1) **Optical pumping:** A source of light (photons) is used to supply energy. For example, in Ruby laser, the Ruby crystal is surrounded by Xenon flash lamp. The material absorbs the incident radiation and a number of Cr^{3+} ions are excited to higher states. Stimulated emission results if necessary population inversion is achieved properly.



2) **Electrical pumping:** An electric field is set up by a pair of oppositely charged electrodes. For example, in He-Ne laser, the molecules of helium are ionized and accelerated by the electric field. They gain kinetic energy in this process making many molecules to get transferred into the excited states. Stimulated emission results when population inversion is achieved.

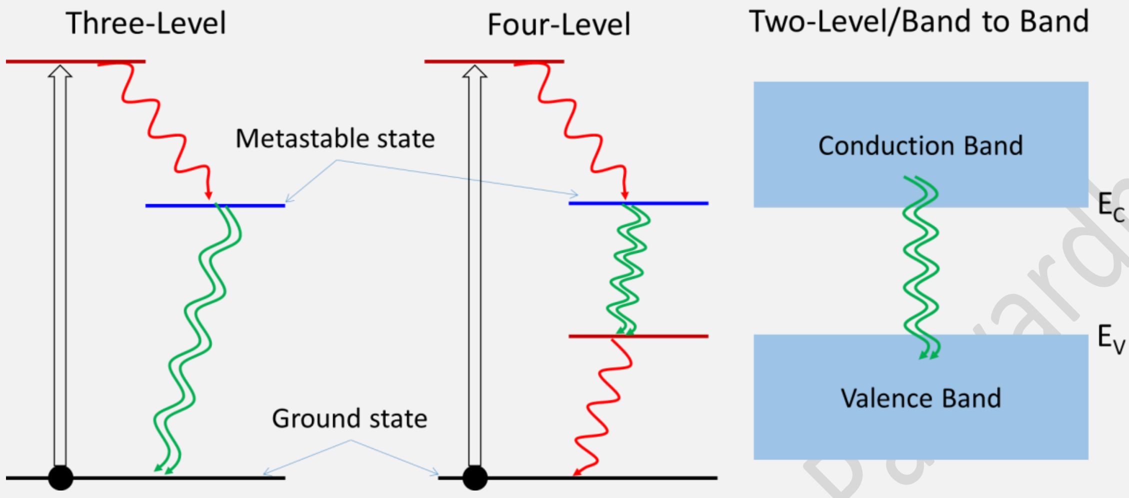


3) **Direct conversion:** Electrical current itself achieves pumping. This is achieved in diode lasers. The energy levels used are conduction band and valence band. The forward bias enhances diffusion currents of holes and electrons to flow into either sides getting many electrons in the conduction band and holes in the valence band. The population inversion is established between these energy bands.



Pumping schemes

Generally, three or more energy levels are involved in the event of laser output (except for diode lasers). The systems in which three energy levels are involved are said to have *three-level pumping* scheme e.g. Ruby laser and those using four energy levels are said to have *four-level pumping* scheme e.g. He-Ne laser and Nd:YAG laser. The energy levels, which are actually involved in laser transitions, are called as *upper and lower lasing levels* and the transition between these states is called as *laser transition* (indicated by green waves).



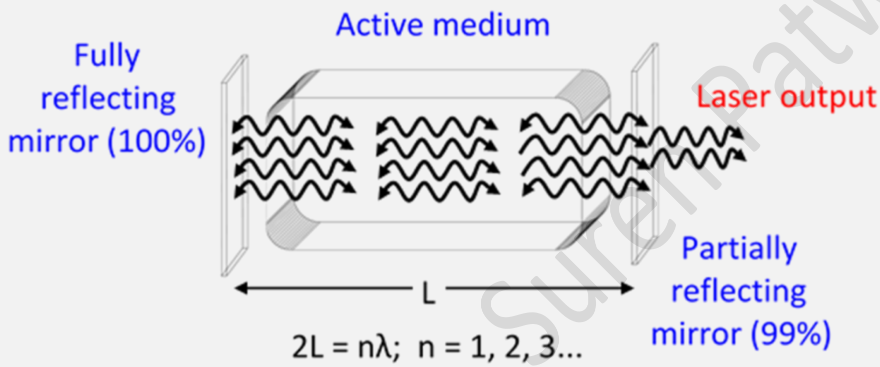
1) **Three level pumping:** In three-level pumping, the lower level is normally, the ground state energy level (black coloured). The atoms are first raised from the ground state to an excited state E_3 (red coloured). These atoms normally de-excite to an intermediate energy state E_2 (blue coloured) by some non-radiative process like emission of heat energy. E_2 being a metastable state, the atoms, they have lasing transition from there to the ground state E_1. The atoms have to be constantly raised from the ground state to an excited state. It is very difficult to alter the population of the ground state since it is the most stable energy level. High pumping power is required to achieve population inversion.
2) **Four level pumping:** In four-level pumping, lower as well as upper energy levels are some intermediate excited energy states. Atoms are first pumped to an excited state E_4 (red coloured). From there, they quickly return to level E_3 (blue coloured) by some non-radiative process like emission of heat. E_3 being a metastable state, the atoms have a lasing transition to state E_2 (red coloured). From E_2 again they de-excite to ground state by transferring energy during non-radiatve process like collisions etc. It is easier to achieve population inversion between two excited states rather than pumping atoms continuously from the ground state. Population inversion is achieved faster. Further, Lesser pumping power is required to keep lasing transitions going once the atoms are raised to higher energy levels from the ground state. Therefore four-level pumping schemes are efficient that three-level schemes.
3) **Two level pumping:** This word is quite misleading because the levels are not singular energy states but they are rather *energy bands*. Such type of pumping is achieved in diode laser. The electrons are transferred from the valence band to the conduction band and they come back to valence band by giving laser radiation. Some of the input energy is of course, lost but the diode lasers can give maximum output efficiency even better that 70% at times.

Meta stable state

Excited atoms have natural tendency to rapidly de-excite to their ground states. This process usually occurs within 10^{-8} seconds. However, there are certain energy states in which excited atoms can reside for as long as 10^{-3} seconds. This interval is long compared to normal de-excitation times of atoms. Therefore these states are called *metastable states*.

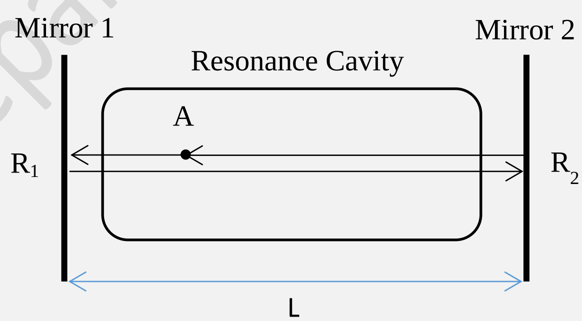
For stimulated emission to occur, the atoms are required to occupy the upper energy level until the triggering radiation is incident. The metastable state allows accumulation of atoms in a higher energy level and we can practically realise the state of population inversion. Meta stable states are extremely important because they assist in maintaining the condition for population inversion (viz. $N_2 > N_1$). Otherwise population of the excited states would rapidly decrease and there would be no laser transitions. In fact, the invention of lasers could not have taken place if elements offering metastable states were not discovered. For example the 2s and 3s states of Ne^+ ions having energies 18.7 eV and 20.66 eV, in He-Ne laser, 4p energy state of Ar^+ ions in Argon gas laser or 1.4 eV energy level of Cr^{3+} ions in Ruby laser are actually metastable states.

Resonant cavity/Optical resonator



Light emitted in the active medium of a laser source initially consists of mostly spontaneously emitted photons. These photons do trigger stimulated emission but since the inducing photons were randomly directed, the stimulated photons are also scattered in all directions. Moreover, they may be incoherent and have random phase. Thus, there is a requirement of tuning all or most of the stimulated radiation. This is achieved by means of a resonant cavity.

Threshold condition for lasing:



Consider a resonance cavity as above with length L. R_1 and R_2 are the reflectivity of two mirrors. Let γ be the overall gain coefficient and α be the overall loss coefficient of the active medium (resonance cavity). The pumping radiation (stimulus) triggered at any arbitrary point A within the active medium will lead to a stimulated emission. For convenience, let the emitted radiaition is directed towards mirror 1. It gets reflected and traverses through the active medium, gets reflected from mirror 2 and comes back at point A, where it started thus completing a round trip. let the initial intensity of the pumping radiation be I_0. Intensity of radiation after traversing distance x from the active medium is given by

$$I(x) = I_0 e^{(\gamma-\alpha)x}$$

On reflection at mirror 1, intensity of radiation becomes $I(x) = R_1 I_0 e^{(\gamma-\alpha)x}$ and after reflection at mirror 2 the intensity gets further modified to $I(x) = R_1 R_2 I_0\, e^{(\gamma-\alpha)x}$. Thus, after one round trip, the intensity will become

$$I = I(x = 2L) = R_1 R_2 I_0 e^{(\gamma-\alpha)2L}$$

$$\therefore \frac{I}{I_0} = R_1 R_2 e^{(\gamma-\alpha)2L}.$$

$\frac{I}{I_0} < 1 \Rightarrow$ net attenuation

$\frac{I}{I_0} > 1 \Rightarrow$ net amplification

$\frac{I}{I_0} = 1 \Rightarrow$ sustained oscillations

The last two conditions together correspond to light amplification, which is an essential step for laser emission. In particular, the last condition tells about the condition on overall gain factor for onset of stimulated emission dominance over spontaneous emission.

By taking $\frac{I}{I_0} = 1$, we get $R_1 R_2 e^{(\gamma-\alpha)2L} = 1$ or $e^{(\gamma-\alpha)2L} = \frac{1}{R_1 R_2}$

Taking log (ln),

$(\gamma-\alpha)2L = \ln\left(\frac{1}{R_1 R_2}\right)$. Rearranging, we get

$$\gamma = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) \qquad \text{--- (5)}$$

equation (5) above is called as “threshold condition fo lasing action”.
