LASER GAIN

Amplifiers and oscillators

Direct amplification of light is practical only for a small set of selected materials, because the amplification of most active medium is measured by the fraction of the percentage of each cm of the light-traversed flight within the material. In many laser generators, this limitation or confinement applies to a few materials, and can be overcome by using "mirrors" that direct or reflect light towards the active material and repeat several times and so on. In this order, the length of the active substance becomes longer than the real length by several times. There are some LASER-producing systems, for which mirrors cannot be used, due to pumping conditions or short time to maintain population inversion. Such systems are known as light "amplifiers" rather than "generators" of laser. Laser systems that contain highly reflective mirrors are not amplifiers, but consider to be oscillators. optical feedback Mirrors forming the “optical resonator or optical resonant cavity, which amplifies the electromagnetic radiation emitted by the laser transition. In the beginning, the little emission of the resonant frequency, generated by "spontaneous emission”, it has to be "amplify" until it reaches the steady state, at this stage “the additional energy growth produced by the" stimulated emission “stopped or the growth of "radiation inside the cavity", and thus the stability of the laser output is maintained.

7.2 Loop Gain

When a beam of light has intensity I_0 travels through an active medium located in an optical cavity, it amplified and becomes larger. The gain obtained by the loop gain of the laser is defined as the ratio of the power (intensity per unit time) of the beam at any point in the cavity to the power after the radiation goes back and forth (rotating one loop) and returns to the same point inside the cavity.

The power of the beam at point 1 in Figure 7.3 is P_1. When the light passes through the active medium at point 2, it is amplified to a power of $P_2 = G_a P_1$. After reflection from the HR mirror, the power is $P_3 = R_1 G_a P_1$. This light passes through the active medium again and is amplified to have a power of $P_4 = G_a R_1 G_a P_1$. After reflection from the output coupler at point 5, the power is $P_5 = R_2 G_a R_1 G_a P_1$. This loop accounts for all modifications on the initial beam except for losses. If the round-trip loss is L, the power remaining at point 1 after one complete circuit of the optical cavity is $P_6 = P_5(1 - L)$, or $P_6 = R_2 G_a R_1 G_a P_1 (1 - L)$. Point 6 is identical with point 1 and signifies the completion of one loop.

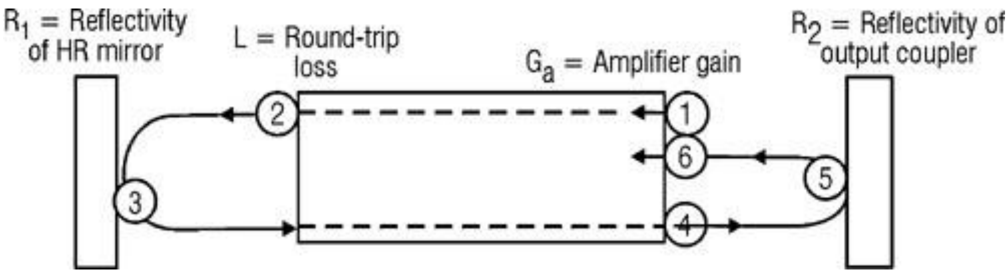

Figure 7.3: Loop gain of a laser

The loop gain of the laser, then, is the ratio of P_6 to P_1, as indicated by Equation 1.

$$G_L = \frac{P_6}{P_1}$$

$$G_L = \frac{R_2 G_a R_1 G_a P_1 (1 - L)}{P_1}$$

$$G_L = G_a^2 R_1 R_2 (1 - L) \quad \dots 7.1$$

Examples 7.1 and 7.2 demonstrate the use of Equation 7.1 in solving a problem.

EXAMPLE 7.1: LOOP GAIN OF A RUBY LASER

Given: A ruby laser has the following characteristics:

$G_a = 3.0$ $R_1 = 0.995$ $R_2 = 0.50$ $L = 0.08$

Find: Loop gain.

Solution :

$$G_L = G_a^2 R_1 R_2 (1 - L)$$

$$G_L = (3.0)^2 (0.995)(0.5)(1 - 0.08)$$

$$G_L = (9.0)(0.995)(0.5)(1 - 0.08)$$

$$G_L = 4.12$$

EXAMPLE 7.2: LOOP GAIN OF AN ARGON LASER

Given: The following are characteristics of the components of an argon ion laser:

- The reflectivity of HR mirror: 99.8%
- Transmission of output coupler (T): 4.2%
- Scattering and absorption loss of output coupler (S + A): 0.05%
- Round-trip loss (excluding mirror loss): 0.8%
- Amplifier gain: 1.05

Find: Loop gain.

Solution :

Determine reflectivity of output coupler:

$$R_2 = 1 - (T + S + A)$$

$$R_2 = 1 - (0.042 + 0.0005)$$

$$R_2 = 1 - (0.0425)$$

$$R_2 = 0.9575$$

Write remaining quantities as decimal fractions:

$R_1 = 0.998$

$G_a = 1.05$

$L = 0.008$

Calculate the loop gain:

$G_L = G_a^2 R_1 R_2 (1 - L)$

$G_L = (1.05)^2 (0.998)(0.9575)(1 - 0.008)$

$G_L = (1.1025)(0.998)(0.9575)(0.992)$

$G_L = 1.045$

If the loop gain of a laser is greater than one, the laser output power is increasing. If the loop gain is less than one, the output power is decreasing. If the loop gain is exactly one, the output power is steady.

7.3 Gain in CW Lasers

The output power of a continuous-wave laser is more or less constant on longer time scales. When the laser is operating continuously, the output power is constant despite the fact that the number of photons in the cavity increases when passing through the amplifying medium then decreases when reflected off the mirrors. Thus, the number of photons gained is equal to the number of photons lost.

Figure 7.4 relates loop gain and output power of a CW laser as a function of time from the moment the laser is turned on. The excitation mechanism begins to operate at a time t_0. At time t_1, a population inversion is established, and the amplifier gain is one. However, lasing does not begin at time t_1 because the losses in the cavity result in a loop gain of less than one. At time t_2, the loop gain reaches unity, and lasing begins. Both loop gain and output power increase until loop gain reaches a maximum value at t_3. At this point, the laser output power is increasing at its maximum rate, and the maximum condition of population inversion exists.

As lasing continues past t_3, stimulated emission moves atoms from the upper lasing level to the lower lasing level faster than the atoms can be replaced. This process reduces the population inversion; consequently, both amplifier gain and loop gain are decreased. At t_4, the laser stabilizes with a steady output power and a loop gain of one.

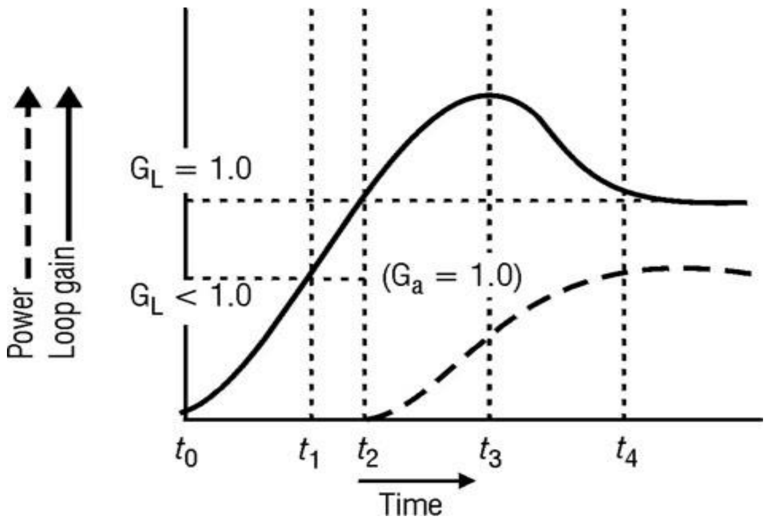

Figure 7.4: Loop gain and output power in a CW laser

The loop gain of a CW laser in steady state operation is always one. The amplifier gain may be found by the substitution of this value for loop gain into Equation 7.1 and by the solving for amplifier gain, as in Equation 7.2.

$$G_L = G_a^2 R_1 R_2 (1 - L)$$

$$1 = G_a^2 R_1 R_2 (1 - L)$$

$$G_a^2 = \frac{1}{R_1 R_2 (1 - L)}$$

$$G_a = \sqrt{\frac{1}{R_1 R_2 (1 - L)}} \quad \ldots 7.2$$

Example 7.3 illustrates the use of Equation 7.2.

EXAMPLE 7.3: AMPLIFIER GAIN OF A CW LASER

Given: A CW Nd:YAG laser contains mirrors R_1 = 0.998, R_2 = 0.980 and a round-trip loss of 0.5%.

Find: Amplifier gain during CW operation.

Solution :

$$G_a = \sqrt{\frac{1}{R_1 R_2 (1 - L)}}$$

$$G_a = \sqrt{\frac{1}{(0.998)(0.980)(1 - 0.005)}}$$

$$G_a = \sqrt{\frac{1}{(0.998)(0.980)(0.995)}}$$

$$G_a = \sqrt{\frac{1}{0.973}}$$

$$G_a = \sqrt{1.028}$$

$$G_a = 1.014$$

If the power of the excitation mechanism is increased, the laser output power may increase; but a new steady state condition will be reached with a loop gain of one. The amplifier gain will be the value that produces a loop gain of one.

The amplifier gain measured in chapter five, "Lasing processes," is called the "small signal gain," which is the gain of the active medium for optical signals that are so small that their amplification does not significantly reduce the population inversion. The actual amplifier gain of CW lasers is less than the small signal gain because the power removed by the laser beam does reduce the population inversion. This reduced value of amplifier gain is referred to as "saturated gain."

7.4 Calculating Loop Gain (G_L) With Losses

We assume that the losses occur uniformly along the length of the cavity (L). In analogy to the Lambert formula for losses, we define loss coefficient (α), and using it we can define absorption factor M:

$$M = e^{-2\alpha L} \quad \dots 7.3$$

M = Loss factor, describe the relative part of the radiation that remain in the cavity after all the losses in a round trip loop inside the cavity. All the losses in a round trip loop inside the cavity are $1 - \mathrm{M}$ (always less than 1).

α = Loss coefficient (in units of 1 over length).

2L = Path Length, which is twice the length of the cavity.

Adding the loss factor (M) to the equation of E_5:

$$\mathrm{E}_5 = \mathrm{R}_1 \times \mathrm{R}_2 \times \mathrm{G}_a^2 \times \mathrm{E}_1 \times \mathrm{M} \quad \dots 7.4$$

From this we can calculate the Loop gain:

$$GL = \frac{E5}{E1} = \mathrm{R}_1 \times \mathrm{R}_2 \times \mathrm{G}_a^2 \times \mathrm{M} \quad \dots 7.5$$

As we assumed a uniform distribution of the loss coefficient (α), we now define gain coefficient (β), and assume active medium gain (G_a) as distributed uniformly along the length of the cavity.

$$G_a = e^{\beta L} \quad \dots 7.6$$

Substituting the last equation in the Loop Gain:

$$G_L = R_1 R_2 e^{2(\beta-\alpha)L} \quad \dots 7.7$$

7.5 Calculating Gain Threshold (G_L)th

The radiate power inside the cavity increases after each cycle of the round-trip through the active material, and the laser beam is produced if the gain more than one for a single cycle (G> 1). If for one cycle the gain is (G <1), the radiate power decreases after each round passage back and forth through the active material and the radiation oscillates in the resonator will Decays, and no laser beam is generated.

. If the gain for one cycle is equal to one (G = 1), this condition is called Threshold Gain to amplify the radiation, and the beginning to obtain the oscillation of the radiation inside the resonator and generate a laser beam. ... 7.8 The (th) sign is usually marked when the code earns the threshold. For continuous laser, the threshold condition is:

$$(G_L)_{th} = 1 = R_1 R_2 {G_a}^2 M = R_1 R_2 e^{2(\beta-\alpha)L}$$

EXAMPLE 7.4:

The active medium gain in a laser is 1.05. Reflection coefficients of the mirrors are 0.999, and 0.95. Length of the laser is 30 cm. Loss coefficient is α=1.34×10^{-4} cm^{-1}.

Find: 1. The loss factor. 2. The Loop gain. 3. The gain coefficient.

Solution :

1. The loss factor M:

$M = e^{-2\alpha L} = e^{-2\times1.34\times10^{-4}\times30} = 0.992$

2. The Loop gain (G_L):

$G_L = R_1 R_2 {G_A}^2 M = 0.999 \times 0.95 \times 1.052 \times 0.992 = 1.038$

Since $G_L > 1$, this laser operates above threshold.

3. The gain coefficient (β):

$G_a = e^{\beta L}$

$\beta = \frac{lnG_a}{L} = \frac{ln1.05}{30} = 1.63 \times 10^{-3}\ cm^{-1}$

The gain coefficient (β) is greater than the loss coefficient (α), as expected.

EXAMPL7.5: *Calculating Cavity Losses*

Helium Neon laser operates in threshold condition. Reflection coefficients of the mirrors are 0.999, and 0.97. Length of the laser is 50 cm. Active medium gain is 1.02. Calculate:

1. The loss factor M.
2. The loss coefficient (α).

Solution :

Since the laser operates in threshold condition, $G_L = 1$. Using this value in the loop gain:

$(G_L)_{th} = 1 = R_1 R_2 {G_A}^2 M$

1. The loss factor M:

$$M = \frac{1}{R_1 R_2 {G_A}^2} = \frac{1}{0.999 \times 0.97 \times (1.02)^2} = 0.9919$$

As expected, $M < 1$. Since $G_L > 1$, this laser operates above threshold.

2. The loss coefficient (α) is calculated from the loss factor:

$$M = e^{-2\alpha L}$$

$$\alpha = \frac{lnM}{-2L} = \frac{ln0.9919}{-100} = 8.13 \times 10^{-5}\ cm^{-1}$$

Attention:

If the loss factor was less than 0.9919, then $G_L < 1$, and the oscillation condition was not fulfilled.

EXAMPLE 7.6: *Active Medium Gain in CW Argon Ion Laser*

Reflection coefficients of the mirrors are 0.999, and 0.95. All the losses in round trip are 0.6%. Calculate the active medium gain.

Solution :

For finding the active medium gain G_L, the loss factor (M) must be found. All the losses are $1 - M$.

$1 - M = 0.06 \Rightarrow \qquad M = 0.994$

Using this value in the threshold loop gain:

$$(G_L)_{th} = 1 = R_1 R_2 G_a^2 M$$

$$G_a = \frac{1}{\sqrt{R_1 R_2 M}} = \frac{1}{\sqrt{0.999 \times 0.95 \times 0.994}} = 1.03$$

The active medium gain must be at least 1.03 for creating continuous output from this laser.

Gain and Output Power of CW Laser

In the CW laser, when the lasing condition is stabilized, the increase in pumping increases the gain of the small signal, but saturation gain is not affected and remains equal to the $(Ga)_{th}$ threshold gain. The laser output power will increase and the system will settle on higher power, when the net gain is equal to the threshold gain, since both the population inversion and the small signal gain increase. Increasing pumping increases the number of excited atoms and, as a result, fills the gaps within the gain curve more quickly. Figure 7.5 shows the effect of the input power in the continuous wave laser CW on the following factors:

1. Gain of the active medium.
2. the loop gain
3. Laser output power.

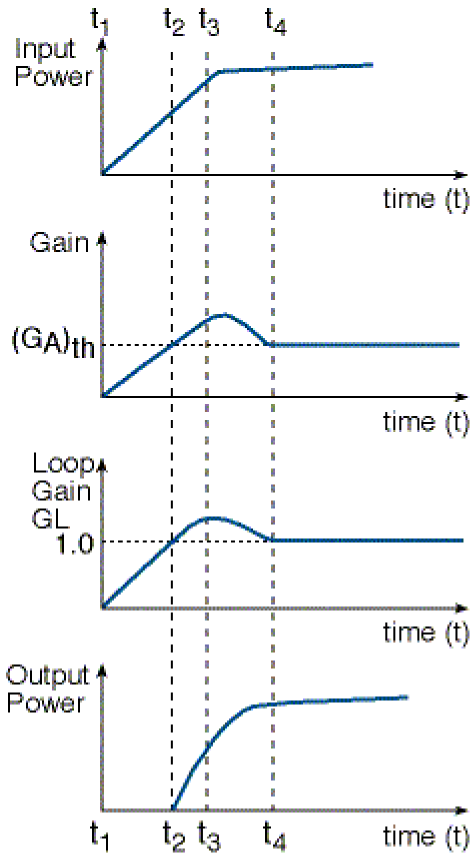

Figure 7.5: Gain and Output Power as a function of time for CW laser.

The atomic mechanism is energizing to activate at time t_1. and Leading to increase in the gain of the active medium and an accompanying with increase in loop gain. Upon arrival to a time t_2, the gain of the active medium is equal to the threshold gain, and the loop gain value is equal to one.

When the Lasing process begins to operate, the output power of the laser increases. At time t_3 the input power has reached its constant condition (constant input power).

The active medium gain is a little above threshold, and the loop gain is a little above "1". The gain for the active medium is then slightly higher than the threshold limit, and the loop gain is slightly higher than the one. The laser output power continues to rise until the time reaches t_4, and then reaches the constant state value. The gain of the active medium is then equal to the threshold gain, and the loop gain is equal to one.

Gain in Pulsed Lasers

In a pulsed laser, supplying power to exited the active medium atoms it has to be instantaneously and significantly exceeds the ability of supplying energy to laser of the continuous wave mode. from the Pulse laser can obtain at high values for both amplification and loop gain, as well as achieving a large population inversion. Figure 7.6 graphically illustrates the output power of the laser and the loop gain for a laser work in a pulse mode as a function of time. Starting from time t1, rapidly increasing in the active medium gain and the loop gain, as a result of the strong pumping, they are reach the value one, and the gain of the active medium reaches the threshold value and then the lasing process begins.
The loop gain continues to raise because the output energy has not reached the saturation value. At time t_2, the output rises accordingly.

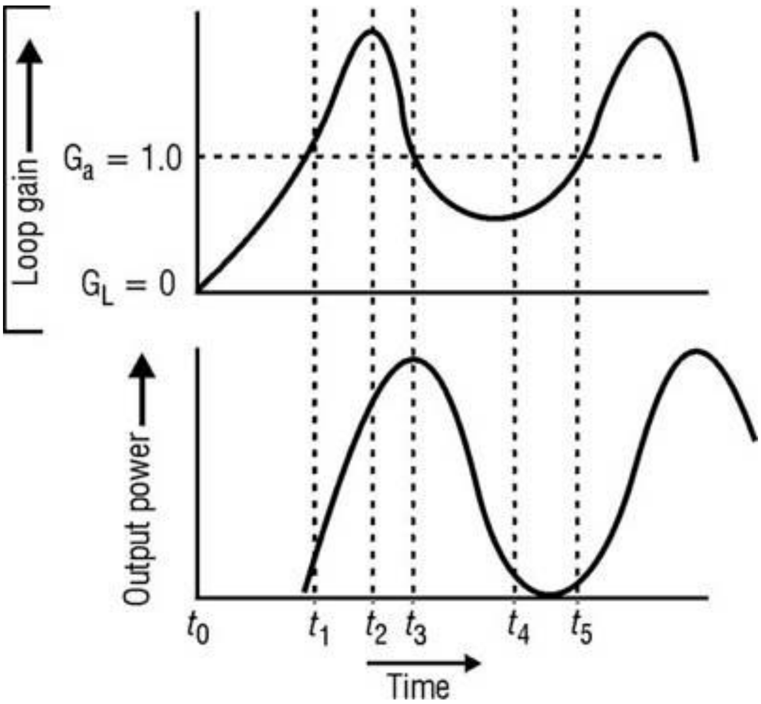

Figure 7.6: Loop gain and output power of a pulsed laser

Up to t_3The high value of a loop gain causes a high pulse of lasers. Thus, the gain of the active medium is below the threshold value. The loop gain is then less than 1, and the population inversion is completely exhausted by the time of t_4, the laser process stops, loop gain rises again at time t_5, and the whole process begins again as long as pumping continues. This operation, is repeated several times during one pulse of the excitement mechanism, resulting in thousands of spikes in the output laser pulse Note Figure 7.7.

7.8 Pulse Shape Out of a Pulsed Laser

Sometimes, the pulse of the laser output is not alone but a series of sharp pulses appear as if it were contained in a specific space. This series of pulses, for example, appear in the pulse of a ruby laser as shown in Fig. 7.7, where one pulse of the Ruby is compared to a pulse from the flash lamp used for pumping.

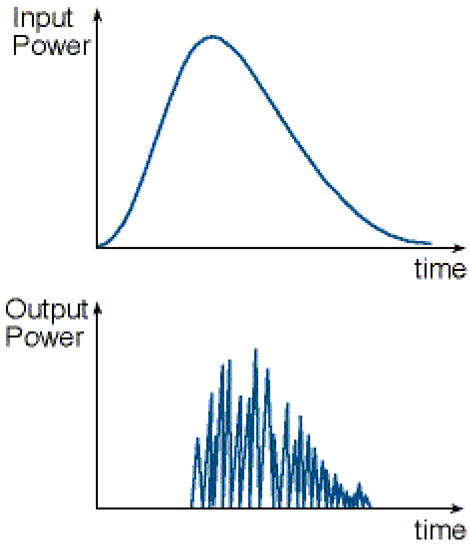

Figure 7.7: single pulse out of a Ruby laser, compared to the pumping pulse from the flash lamp

The duration of laser output pulse lasting about 1 millisecond, and each pulse contains a chain or train consisting of hundreds or thousands of small, dense pulses encased in the laser pulse. Each of these small pulses is called a spike, have a time limit for a few times for the light trip inside the cavity by back and forth, and thus they are short up to a few tens of nanoseconds.

Small pulses or spikes occur within the laser pulse when the lifetime of the exited upper laser state is much longer than the time of light damping within the cavity. These spikes are randomly spaced in time or power, and it is impossible to determine the length or the power of each spike in advance. and it’s Different from each other in length and maximum power. In measurements usually, only the full laser pulse is measured without considering the presence of each spike. The rate of energy of each pulse is computed by calculating the full pulse time and measuring its energy.

In Figure 7.8, it can be observed that the laser pulse begins shortly after the start of the pumping pulse. This time difference is the time it takes for the active medium to reach the lasing threshold value. we also observe the physical illustration of the generation of a chain or train of short pulses (spikes) inside the laser output pulse.

Physical Explanation for the Spikes

The physical explanation for the creation of spikes within the pulse train is described in figure 7.8.

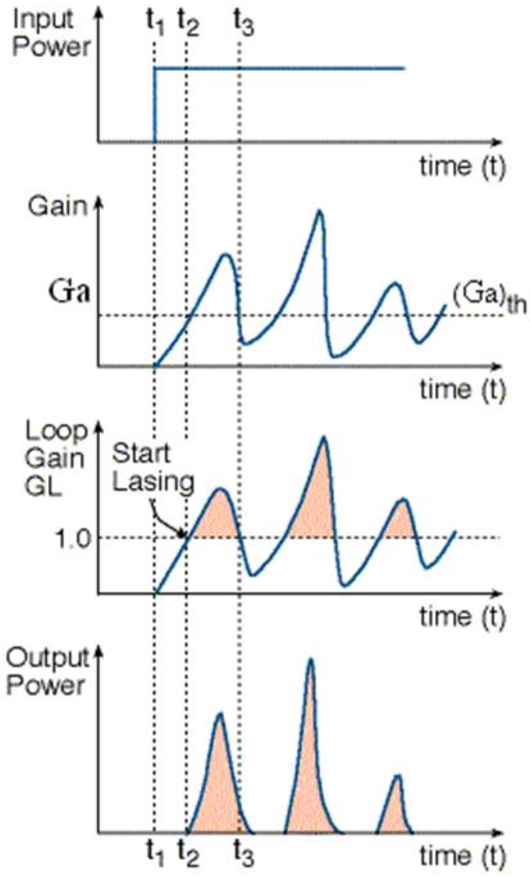

Figure 7.٨: Gain and output power from a pulsed solid state laser.

High pumping cause loop gain (G_L) to rise sharply. Because of the high gain, the spike is being built quickly and causes depletion of the population inversion. Thus, absorption starts, and cause the loop gain to decrease below the threshold value of "1", so lasing process stops. Since pumping continues, the active medium continues to receive excitation energy, and the process repeats itself.