



LASER APPLICATIONS

Chapter One

Modulations of the Laser Output

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CHAPTER ONE: MODULATIONS OF THE LASER OUTPUT

1-1) Introduction

This chapter sheds light on the methods and techniques used to harness the laser beam for practical applications. For example, lasers are used for metal cutting and welding, which requires increasing the laser beam's power or obtaining a laser beam that operates in a single axial mode for spectral studies or communications applications. There are several innovative methods to improve laser output and make it more flexible in application.

1-2) Measure the Dimensions of Laser Beam

1) Beam Radius:

A laser beam has no sharp edges defining it; rather, its distribution is Gaussian. The following relationship expresses its intensity distribution:

$$I = I_0 e^{\frac{-2x^2}{\omega_z^2}} \dots\dots\dots (1-1)$$

I represents the intensity at the center, x represents the distance from the center, and ω_z represents the radius of the ray at z , which is an approximate diameter for a Gaussian ray and is expressed by the following relation:

$$\omega_z = \left(\frac{\lambda L}{\pi}\right)^{1/2} \dots\dots\dots (1-2)$$

The edges of the ray are represented by points where the intensity is equal to $(1/e^2)$, or approximately (13%) of the intensity at the center. This region appears to the eye as the edges of the ray.

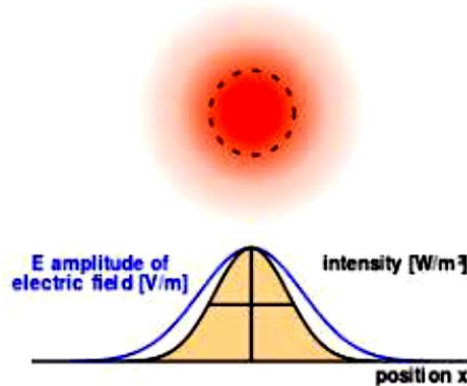


Figure (1-1): Practical measurement of the laser spot radius

To determine the distribution of electromagnetic field intensity at any location (inside and outside the resonator), taking into account the effect of resonant diffraction, the radius of the laser spot at any position along the optical axis z can be found, assuming the resonator is confocal and the center of the resonator is ($z = 0$), using the following formula:

$$\omega_z = \omega_0 \left[1 + \left(\frac{2z}{L} \right)^2 \right]^{1/2} \dots\dots\dots (1-3)$$

Where ω_0 represents the radius of the laser spot at the center of the resonator ($z = 0$).

$$\omega_0 = \left(\frac{\lambda L}{2\pi} \right)^{1/2} \dots\dots\dots (1-4)$$

The laser beam narrows at the position where the laser spot has the smallest area, i.e., when ($z = 0$). Therefore, we conclude that the radius of the spot at both mirrors at position ($z = L/2$) is:

$$\omega_{\frac{L}{2}} = \left(\frac{\lambda L}{\pi} \right)^{1/2} \dots\dots\dots (1-5)$$

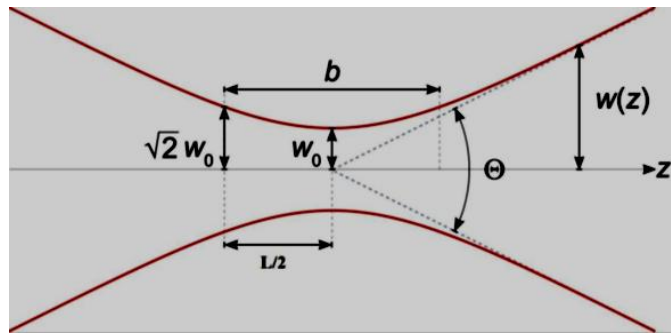


Figure (1-2): The distribution of laser beam intensity within the laser chamber shows the waistline

2) The Wave Front Curvature Radius:

A laser beam is also described by the wavefront radius. The wavefront of a laser beam is spherical because:

- 1- The laser beam is coherent (all its wavelets are in phase).
- 2- The wavefront is the surface where the wavelets are in phase.
- 3- The laser beam experiences a small degree of divergence.

Divergence relative to the main mode of the laser beam is calculated as the divergence angle:

$$\theta_{div} = \frac{\lambda}{\pi \omega_0} \dots\dots\dots (1-6)$$

The beam curvature radius changes as the beam propagates in both directions (right and left). The curvature radius of the wavefront at position z along the z -axis is expressed by the relation:

$$R_z = z \left[1 + \left(\frac{L}{2z} \right)^2 \right] \dots\dots\dots (1-7)$$

The value of the radius of curvature of the wavefront is equal to infinity in the beam waist region and decreases as we move away from this region before increasing again. Similarly, the value of R_z at the position of the two mirrors ($z = L/2$) is equal to L because the surface of the mirror represents a spherical wavefront.

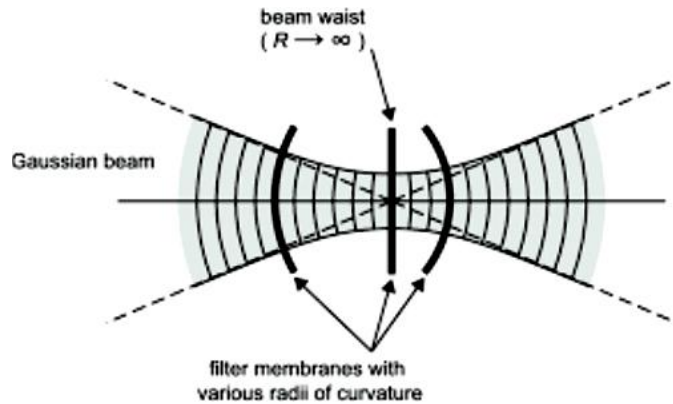


Figure (1-3): The wavefront coincides with the radius of curvature of the mirror

1-3) Laser Frequency Stabilization

There are two common methods used to stabilize the frequency in gas lasers, and in both the operating frequency is fixed at a specific position relative to the shape of the gain curve:

- The first relies on the fact that the gain curve is symmetrical around its central point. If we consider the situation when there are two modes operating at the same time and they have the same radiation density, they must be equidistant from both sides of the peak of the gain curve. Any shift in the mode frequency will lead to an increase in the radiation density of one mode and a decrease in the other. If we can monitor the radiation density of both modes and employ the difference between them to operate a feedback circuit that controls the length of the cavity, we will be able to stabilize the required frequency.

We note that not all frequencies under the Gain curve can produce a laser, but only those frequencies that satisfy the condition that the gain must be greater than the loss, and this is achieved in the frequency range $(\nu_2 - \nu_1)$. We also note that the loss does not depend on the frequency, and in this case, the loss on the curve is represented as a function of the frequency by a straight line.

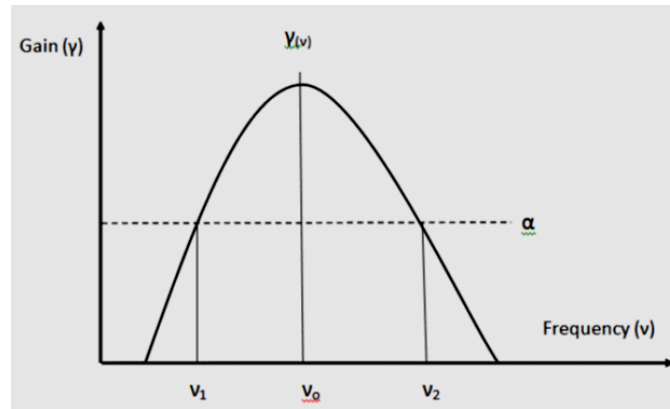


Figure (1-4): Gain and loss curve as a function of frequency

- The second method for stabilizing the frequency depends on a phenomenon known as the Lamb dip. This phenomenon is related to the reasons for the widening of the gain curve in gas lasers. Laser transition is known as a non-uniform amplitude transition. This simply means that the different frequencies that give a single emission line result from the overall transitions of different groups of atoms. The main reason that groups of atoms emit at different frequencies is the difference in the relative speeds of these atoms along the emission axis. This is actually an example of the Doppler effect.

If the laser is initially operating close to ν_0 , the frequency can be fixed at that value by controlling the cavity length, thus reducing the power output to its minimum value. Several methods can be used to change the cavity length, for example:

- 1- Heating the cavity.
- 2- Placing a mirror on a piezoelectric crystal so that its position changes with the applied potential difference.
- 3- Focusing the laser beam. All laser beams have a degree of divergence, even at very small distances. At relatively large distances, the beam diameter changes linearly with distance. By placing a suitable converging lens in the path of the diverging beam, this divergence is reversed, producing a converging beam at a distance approximately equal to f (the focal length of the lens) from the lens.

1-4) Laser Emission Lines Selection

A laser beam is produced by the transition of excited atoms from higher to lower energy levels, provided the necessary conditions are met for the gain to outweigh the loss. In many lasers, multiple laser transitions of different wavelengths occur simultaneously. Although these combined transitions yield high power output, we often need a high-purity (mono-wavelength) laser beam. This can be easily achieved by using a prism (or diffraction grating or filters) placed inside the resonator between one of the mirrors and the active medium. The prism disperses the beams according to their wavelength. For example, if the laser emits two wavelengths, λ_1 and λ_2 , and the goal is to retain the beams of wavelength λ_1 , these beams will strike the mirror perpendicularly after exiting the prism and thus return along the same path inside the resonator. The λ_2 wave, however, suffers greater refraction in the prism, deviates from its path, and experiences significant loss and decay. Due to its greater resolving power, it is preferable to use a single wavelength.

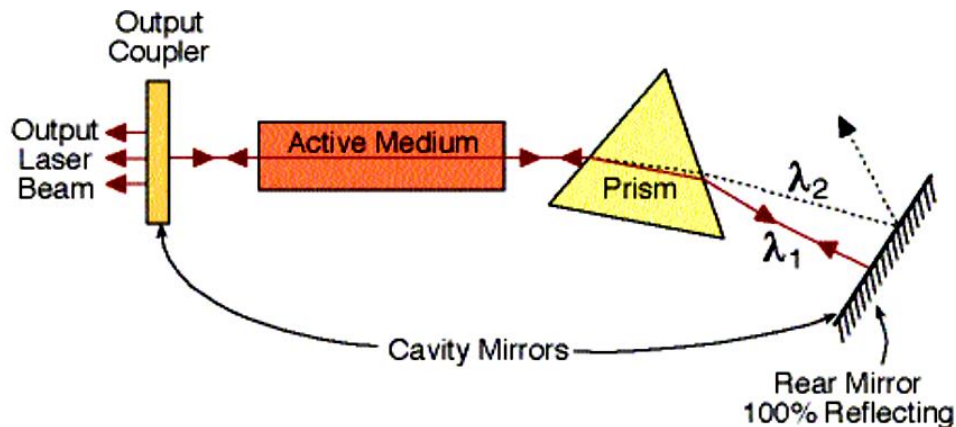


Figure (1-5): Diagram illustrating how one of the two wavelengths is selected for laser emission

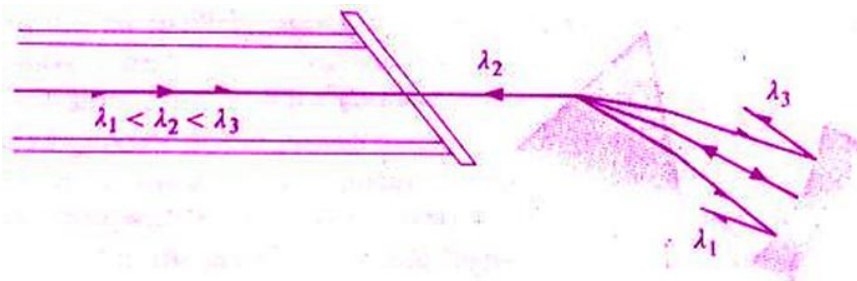


Figure (1-6): The ability to magnify only one wavelength from a range of wavelengths using a prism

1-5) Single-Mode Operation

The light produced by a laser operating in a single axial mode is closest to that of a monochromatic light source, which has a limited spectral width. This width determines the accuracy of the term "monochromatic light source". The smallest possible width achievable from a single axial mode laser is required in many practical applications. A laser with high spectral purity (a single longitudinal mode) is needed, where the spectral linewidth contains several longitudinal oscillation modes. The concept of a single axial mode laser relies on increasing the distance between adjacent axial modes to a distance at least equal to the width of the spectral curve. Thus, the axial mode q_0 is the mode where the gain exceeds the loss, while the other modes q_{0-1} or q_{0+1} fall outside the gain curve. To achieve this, we aim to reduce the resonator length L until the frequency interval between two successive modes ($c/2L$) is greater than the emission linewidth, i.e., modifying the resonator to satisfy the condition ($c/2L > \Delta\nu$). This means that the smaller L , the greater the gain. The length of the amplifier increases as the distance between the two axial modes increases. A disadvantage of this method is that reducing the length of the active medium will limit the laser power. To obtain a laser operating in a single transverse oscillation mode (TEM_{00}), a laser resonator uses an aperture barrier that blocks all other transverse oscillation modes except the lowest-frequency transverse oscillation mode (TEM_{00}).

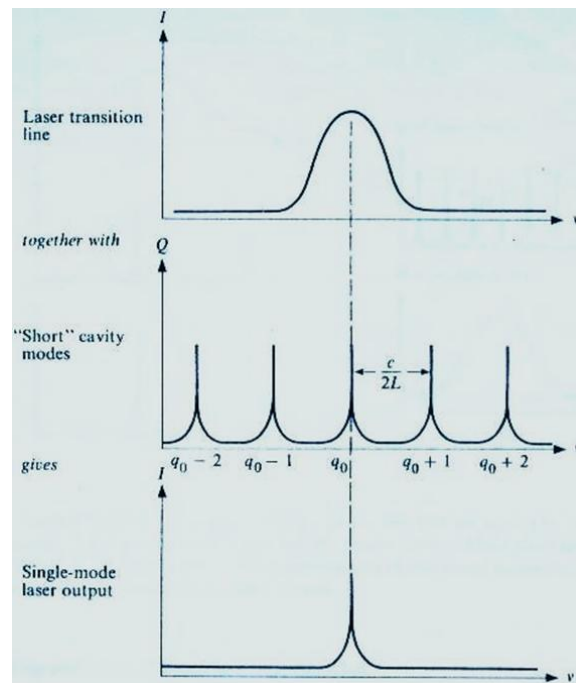


Figure (1-7): Single oscillation operation

1-6) Continuous and Pulsed Operate

The behavior of the operating product is described as a continuous wave according to the rate equations, which describe the balance between the rates of change in the total qualification and the total number of laser photons. They provide a simple and practical description of laser operation and the flow of its product. Constant, stable pumping gives the stability of the laser product, which determines its continuous wave (CW) characteristic. The pumping rate is constant and has a certain value for the transmittance of the laser output mirror. The reason for the existence of the limiting value for the transmittance of the mirror is that increasing the transmittance leads to an increase in the laser output and at the same time leads to an increase in the resonator losses. To study the characteristics of the time-dependent laser product (pulsed laser) based on solving the rate equations, and for pumping that changes with time in the way we want (the laser product is a function of time), by finding the relationship between the reverse qualification and the number of laser photons.

1-7) Q-Switching

This is one of the techniques for obtaining short bursts of oscillation (nanometer-length, megawatt-power pulses), meaning it's a method for generating short, focused beams of radiation from a laser. In lasers with typically pulsed output, a single, very high-power, short-duration pulse can be generated, while a continuous-output laser can produce a series of pulses. In many applications (drilling, welding, high-speed imaging, and optical radar), there is a critical need for a high-power laser with a short pulse duration. The relationship between power (P), pulse energy (E), and pulse duration ($\Delta\tau$) is as follows:

$$Power_{(watt)} = \frac{Energy_{(Joul)}}{Time_{(sec)}} \dots\dots\dots(1-8)$$

For example, in a laser with a pulse energy of approximately (1 Joule) and a duration of (1 ms), after quality control, the pulse duration becomes approximately (1 ns), thus increasing the pulse power from (1 kW) to (1000 mW).

High-power single pulses can be practically obtained by introducing a time- or intensity-dependent loss into the resonator. The Q-switching technique relies on temporarily stopping the laser by controlling the loss level during pumping to maximize the inverse distribution. This increases the gain to a value significantly above the threshold. Then, the loss level is reduced to the baseline, causing stimulated emission over a short period, resulting in a high-power laser pulse. In other words, if, upon reaching a high degree of reverse distribution, the resonator loss suddenly decreases (increases Q), it is said that the quality factor of the resonator has been fixed to a high value, and that the laser oscillation begins suddenly and normally, but with a high quality factor, where the gain remains high due to the presence of a very high reverse distribution.

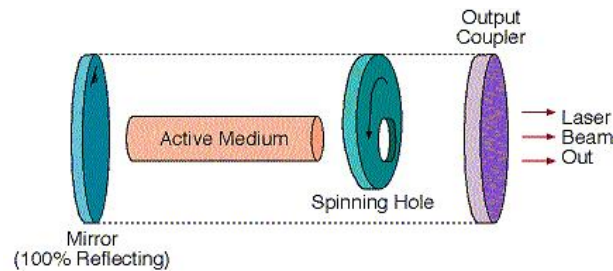


Figure (1-8): The idea of the quality factor

The figure above illustrates the concept of loss control, where a circular disc with an aperture is placed rotating rapidly around the optical axis of the laser. When the beams are blocked from the mirror behind the disc, the count is increased and the yield is magnified because the level of loss is very large. When the aperture in the disc reaches the level of the optical axis, the loss is at its lowest level while the yield is still at its highest level. This will lead to the emission of a laser pulse in a short period of time, which means enormous energy. The Q-switching process can be performed using a closed gate called a Q-switch, placed inside the resonator to isolate it from the laser's active medium. The Q-switch acts as a shutter that can be opened suddenly within the laser cavity. The gate opens after the medium is pumped. For this technique to be effective, the pumping rate must be greater than the spontaneous emission rate; otherwise, the upper energy level will deplete faster than it can be replenished, preventing the achievement of a significant inverted distribution. Furthermore, the Q-switch must operate rapidly compared to the laser's oscillation growth rate; otherwise, the latter will grow slowly, resulting in a long-lasting, low-power pulse. Ideally, the switch should operate for a time of at least (10 ns).

We can deduce two essential conditions for Q-switching:

- 1- The pumping rate must be faster than the spontaneous decay rate of the laser's upper energy level; otherwise, achieving a significant inverted distribution will be impossible.
- 2- The Q-switching mechanism must be fast compared to the process of building laser vibrations, otherwise these vibrations gradually increase, thus producing a long pulse with low power. In practice, this means that the switching must be within the range of (ns).

1-7-1) Q-Switching Methods

1) Mechanical Method:

This was the first method used to fine-tune the quality factor of a laser device. It involves using a mirror (or prism) capable of rotating around its axis at a very high speed of approximately (50,000) revolutions per minute. This mirror replaces one of the two fixed resonator mirrors. As the mirror rotates, the loss (Q) is large except for a specific period in each rotation, which is the moment when the two mirrors are aligned and parallel. Before reaching this position, the flash lamp is activated by a trigger mechanism linked to the mirror's rotation. This trigger mechanism pumps the laser medium until the mirrors are perfectly parallel. During this time, the inverse distribution in the medium is achieved without the laser emission process beginning. When the mirrors are perfectly parallel (Q being large), fine-tuning of the quality factor occurs, allowing the fine-tuning pulse to grow. This rotating mirror method is relatively inexpensive, robust, and easy to use, and it can be used with lasers operating at any wavelength. However, it is considered a slow switching device, providing less power than other methods.

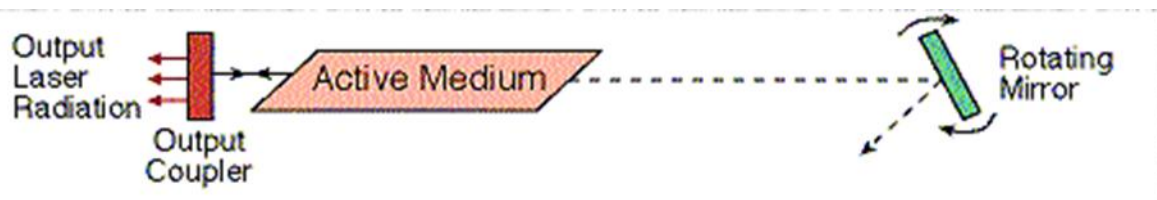


Figure (1-9): The rotator mirror method

When the two mirrors face each other, the laser is produced. To increase the number of pulses per second, a special cylinder with many mirrors rotates. Thus, in each rotation of the cylinder, many pulses are emitted, as each mirror on the cylinder faces the cavity separately.

2) Electro-Optic Transducer:

It is one of the most useful methods, and it uses photoelectric modifiers as switches to control the quality factor, such as a Pockell cell or a Kerr cell. The light is unpolarized, so a polarizer is placed inside the resonator, accompanying the photoelectric cell. The photoelectric cell is connected to a high voltage, so it acts as a quarter-wavelength plate to convert the incident light, which is linearly polarized, into circularly polarized light. When these rays are reflected from the laser mirror, the direction of rotation of the polarization is reversed. After the rays pass through the cell a second time, we will get light with linear polarization, but in a plane perpendicular to its first polarization direction. Thus, the rays do not pass through to be reflected from the other resonator mirror, and thus the operation of the resonator is disrupted. However, when the value of the voltage applied to the cell decreases to zero, there is no rotation of the polarization plane, and thus control of the quality factor occurs. The change in voltage, which must be synchronized with the pumping mechanism, can be achieved in a time of less than (10 ns), and thus we obtain rapid control of the quality factor.

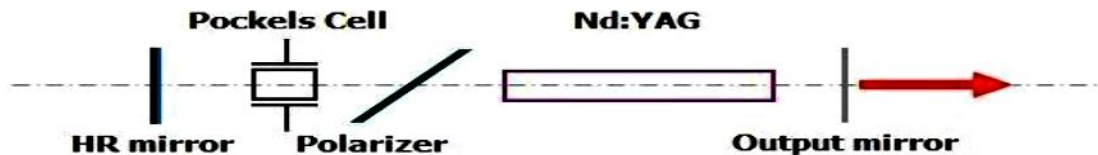


Figure (1-10): Quality factor based on the Pockle effect

3) Acousto-Optic Transducer:

This is a synonymous method that uses acoustic-optical modulators. In this case, an acoustic beam is used that is dropped onto the modulator, which works to deflect part of this beam out of the resonator, causing a large loss (Q) (small). When the acoustic wave is interrupted, the specificity factor is tightened. This method is used in the case of continuously pumping the laser medium to obtain a series of specificity factor-tightening pulses, as is the case with Nd: YAG and CO₂ lasers. The acoustic-optical effect is the change in the refractive index of a material by the mechanical stress associated with the acoustic waves when they pass through that medium. The stress, and therefore the refractive index, will change periodically with a wavelength equal to the wavelength of the acoustic wave. In fact, the acoustic waves create a diffraction grating that can be used to deflect the light beam.

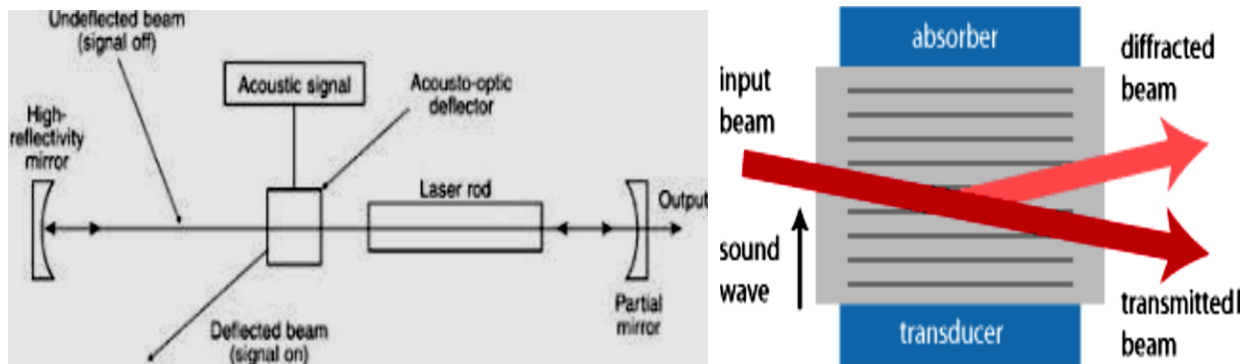


Figure (1-11): Quality factor based on Audio-optical converter

4) Saturable Absorber (Passive):

This method utilizes a saturable absorber (a dye that can absorb light) inside the laser resonator. Saturable absorbers are materials (often dye solutions) whose absorption decreases with increasing incident radiation. At the beginning of the pumping process, the dye solution is a good absorber, thus preventing laser action and providing good reverse beam distribution. As the pumping in the medium increases, the dye solution reaches saturation and becomes saturable, meaning it can no longer absorb light (the dye or solution is said to have bleached). This change leads to an increase in radiation and consequently an increase in the dye's transmittance. Thus, in a very short time, the dye can transition from a state of high absorption to a state of near-transparency, generating a powerful pulse that triggers the specification process. After a very short period, the dye regains its activity. This method is very suitable for specification processes because it does not require a synchronization mechanism with the pumping process. The only requirement is to use a dye in a suitable solvent placed in a transparent (glass) cell (although care must be taken when selecting the concentration) and the appropriate dye materials. Krypton cyanide for ruby lasers and hexafluoride sulfur for carbon dioxide (CO_2) lasers).

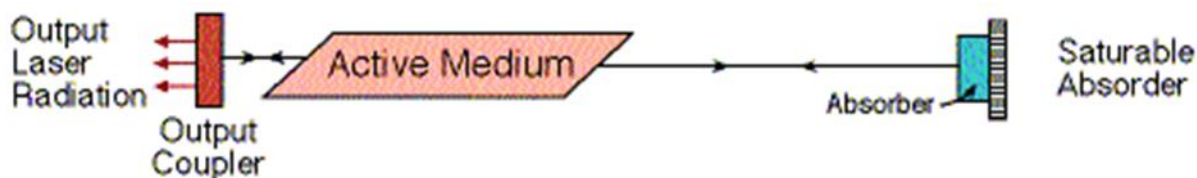


Figure (1-12): Quality factor using absorbent dye

1-8) Mode Locking

Mode locking, or pattern locking, is another technique used to obtain high-power, extremely short-duration laser beams (pulse duration a few picoseconds and power a few gigawatts). High-power laser pulses can be obtained using Q-switching technique, but this method fails when used with laser materials where the lifetime of the upper energy levels is short. In these materials, spontaneous emission occurs at high speeds, preventing the aggregation of atoms in the upper energy levels due to the reverse distribution, thus preventing energy storage at this stage. The optimal solution lies in controlling the waveforms within the chamber to obtain extremely short, high-frequency pulses. In Q-switched pulsed lasers, a single, massive light pulse is produced during each pumping cycle, while in pattern locking, a train of extremely short pulses is produced, separated by equal time intervals. The laser resonator contains a large number of oscillation modes, and therefore, the laser output as a function of time depends on the relative frequency of these modes, as well as their phase and amplitude. In a non-locked laser, all these parameters are subject to change over time, and therefore the laser output is prone to random fluctuations. If we assume that all oscillation modes have the same amplitude E_0 , then the light intensity emitted for a number q of oscillation modes is equal to:

$$I = qE_0^2 \dots\dots\dots(1-9)$$

Figure (1-13) shows the configuration of three oscillation modes with equal frequency intervals ($\delta\nu = \frac{c}{2L}$) but different phases. The resultant indicates the laser output intensity with possible random fluctuations. When a technique is used that forces the oscillation modes to maintain a relatively constant phase between them (phase locking), the laser output will exhibit a type of regular repetition, i.e., it will have a regular pulse shape with a regular interval between pulses and high power. A laser output with this arrangement is called a "locked-mode laser", and this type of output is important in many applications. In a locked-mode laser, the energy between its two mirrors is compressed into a pulse shorter than the resonator itself. This pulse travels back and forth between the mirrors. Each time this pulse reaches the front mirror, a portion of it is emitted as a locked-mode pulse using a mode load. This load opens once per pulse cycle in the resonator, allowing a small amount of energy to escape, and remains closed for the rest of the time. Only the locked-mode pulse is allowed to oscillate.

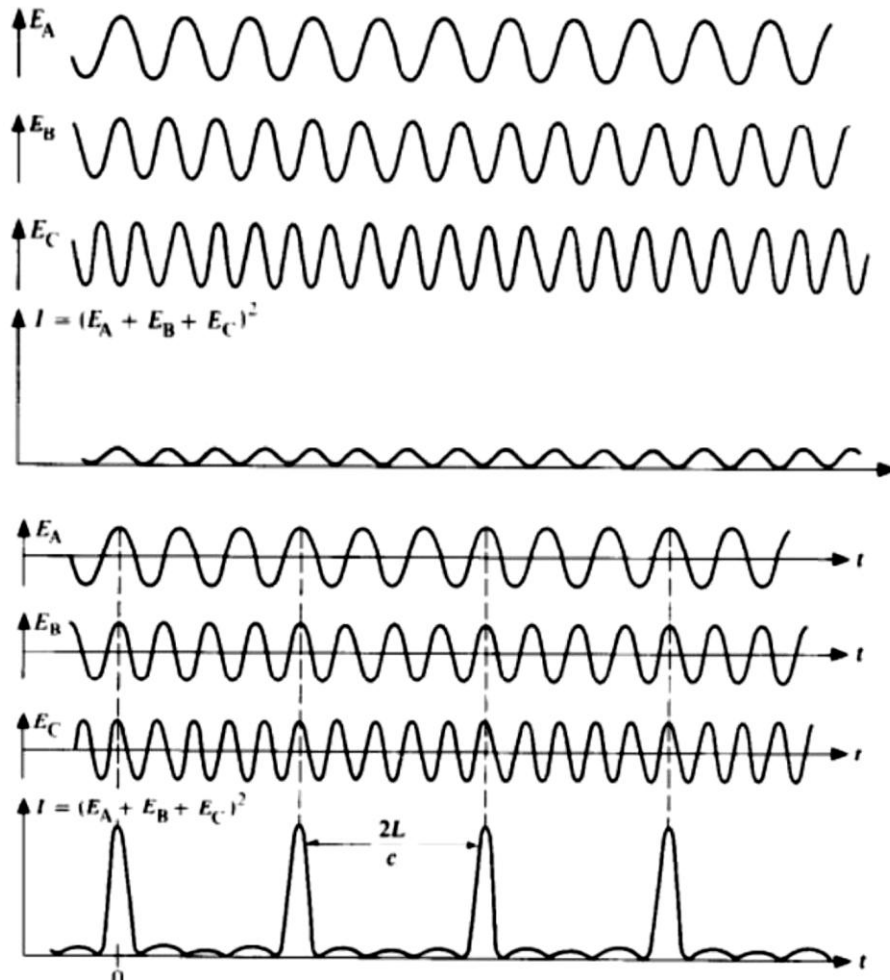


Figure (1-13): Oscillation formulas

The output of a locked-mode laser consists of a series of very short pulses. The time interval between two successive pulses is the distance traveled by the pulse inside the resonator ($2L$) divided by its speed c , i.e., its repetition time:

$$\Delta T = \frac{2L}{c} \dots\dots\dots(1-10)$$

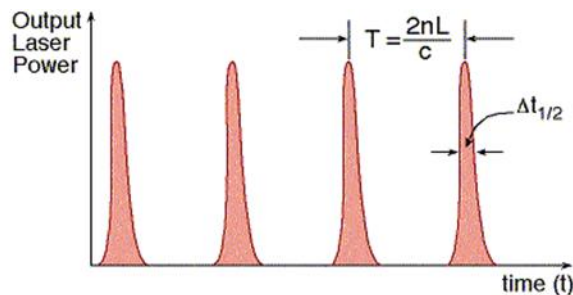


Figure (1-14): Frequency interval

The duration of a locked-mode pulse (pulse width) is defined as the time required to reach the peak, i.e., the time between the minimum and maximum intensity. It is expressed as:

$$\Delta\tau_p = \frac{1}{q} \frac{2L}{c} \dots\dots\dots(1-11)$$

It is equal to the reciprocal of the spectral linewidth of the laser output:

$$\Delta\tau_p = \frac{1}{\Delta\nu} \dots\dots\dots(1-12)$$

The ratio between the time interval of one pulse and the width of a single pulse is equal to the number of oscillation modes:

$$\frac{\Delta T}{\Delta\tau_p} = \frac{\frac{2L}{c}}{\frac{2L}{qc}} = q \dots\dots\dots(1-13)$$

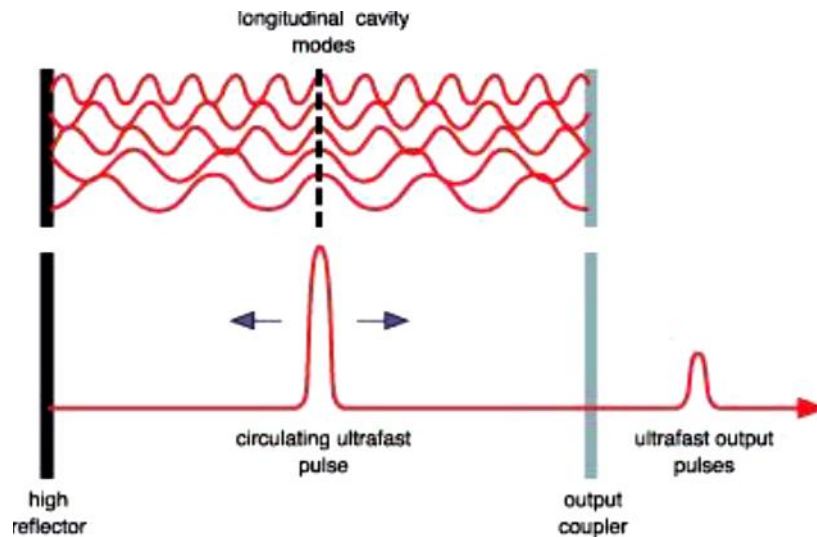


Figure (1-15): High-power, short-duration laser pulse

To achieve high power and short pulse durations, two essential conditions must be met:

- 1- A large number of oscillation modes must be available within the resonator (depending on the spectral linewidth and the resonator length).
- 2- The oscillation modes must maintain a constant, defined phase relationship with each other. This is achieved through mode locking.

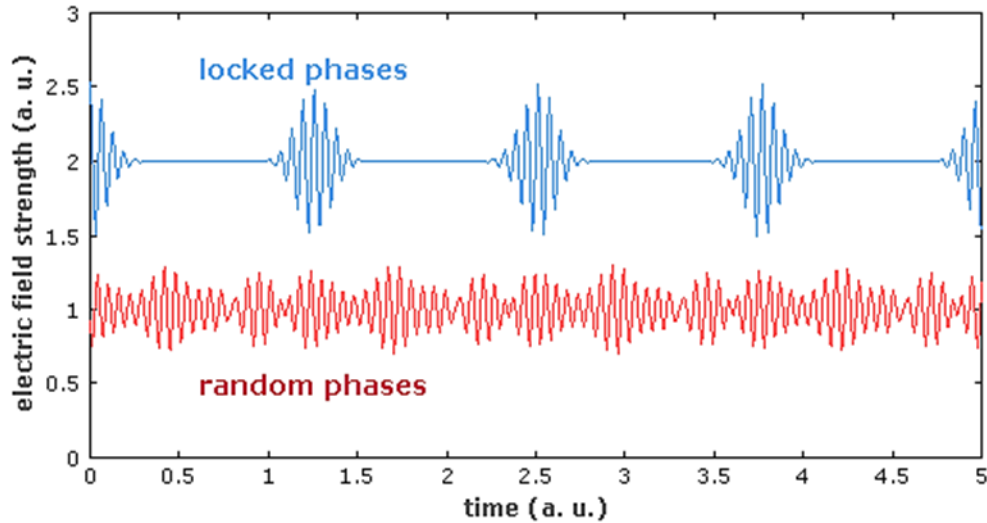


Figure (1-16): Effect of mode locking on laser transition

From the above, we can see that mode (form) locking can be achieved by ensuring that the longitudinal modes maintain a constant phase relationship. This can be accomplished by adjusting the gain and loss of the laser cavity at a frequency equal to the difference between the various modes.

The methods for formula locking are:

- 1- Active formula locking: the photoelectric method and the acoustic-optical method.
- 2- Passive formula locking: using a saturable dye.

1-9) Generate Harmonics

This is one of the most important phenomena in nonlinear optics. Nonlinear optics is a phenomenon where the wavelength of light is changed from one wavelength to another (resulting in a color different from the incident color). The second harmonic (SHG) generation process involves changing the wavelength by doubling the frequency. In 1960, certain materials were discovered that double the frequency of laser light passing through them.

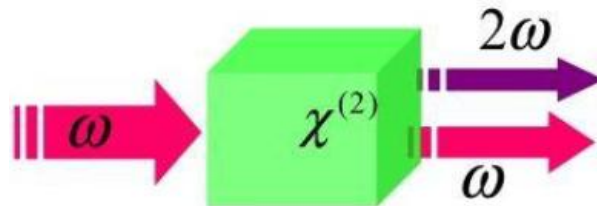


Figure (1-17): Frequency doubling

A green beam with a wavelength of ($\lambda = 0.532 \mu\text{m}$) can be obtained from an invisible beam with a wavelength of ($\lambda = 1.06 \mu\text{m}$) emitted by a Nd: YAG laser. Only a small portion of the original beam is converted to green, while the rest of the beam exits the system unchanged. The same principle can be applied to the laser emitted by a ruby laser ($\lambda = 694.3 \text{ nm}$).

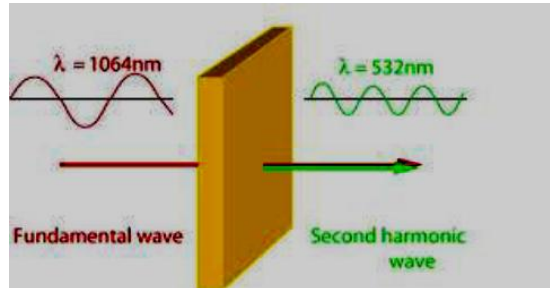


Figure (1-18): The second harmonic of Nd: YAG laser

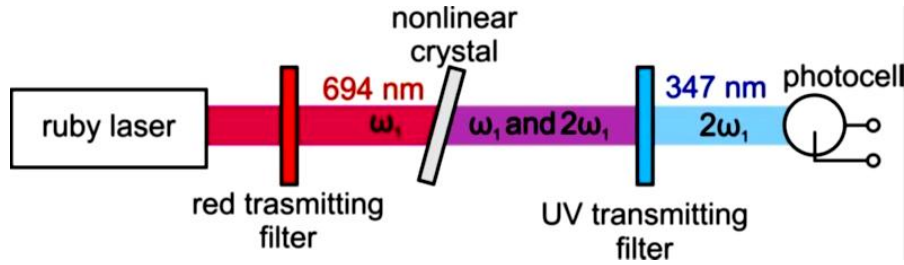


Figure (1-19): The second harmonic of Ruby laser

1-9-1) Physical Interpretation of Nonlinear Optics

In a nonlinear crystal, electrons are bound within a potential well, which acts like a spring, connecting the electrons to the crystal's corners. If an electron is pulled outward from its equilibrium position, the spring will force it back to its original position with a force proportional to the distance it was pulled (the spring force increases with the distance the electron is pulled from its equilibrium position).

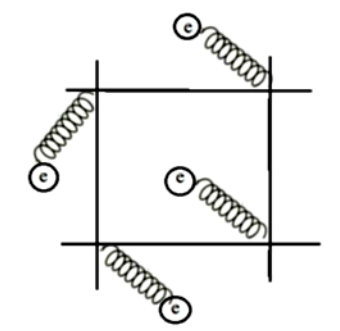


Figure (1-20): Electron Connection to Crystal Corners

The electromagnetic field of light passing through the crystal affects the electrons, pulling them away from their equilibrium position. In linear optical materials, these electrons oscillate around their equilibrium position at a frequency equal to the frequency at which they oscillate, thus emitting light at the same frequency as the incident light.

1-9-2) Nonlinear Optical Materials

These are materials whose electrons are attached to short springs. If light passes through them, and its intensity is high enough that its electric field can pull the electrons away to the end of the spring, then the relationship between the stored energy and the distance to which the spring is pulled is nonlinear. The electrons return slightly backward and quickly, not to their original positions, and oscillate at frequencies different from the frequency of the incident light. These electrons then emit light at this different frequency. We observe that the displacement **x** is linearly proportional to the force **F**:

$$\mathbf{F} = -\mathbf{k}\mathbf{x} \dots\dots\dots(1-14)$$

where **k** is the constant of proportionality. If this force increases beyond the spring's elastic limit, the relationship becomes nonlinear, as follows:

$$\mathbf{F} = \mathbf{k}_1\mathbf{x} + \mathbf{k}_2\mathbf{x}^2 + \mathbf{k}_3\mathbf{x}^3 + \dots \dots\dots(1-15)$$

When a nonlinear crystal is placed in an electric field, it will become polarized. This polarization depends on the strength of the applied electric field, according to the following linear relationship:

$$\mathbf{p} = \boldsymbol{\alpha}\mathbf{E} \dots\dots\dots(1-16)$$

where **α** represents the polarization coefficient and **E** represents the electric field strength in (V/cm²). When a high-intensity electromagnetic field is applied, the situation changes to nonlinearity:

$$\mathbf{p} = \boldsymbol{\alpha}_1\mathbf{E} + \boldsymbol{\alpha}_2\mathbf{E}^2 + \boldsymbol{\alpha}_3\mathbf{E}^3 + \dots \dots\dots(1-17)$$

$$\mathbf{E} = \mathbf{E}_0\cos(\omega t) \dots\dots\dots(1-18)$$

$$\mathbf{p} = \boldsymbol{\alpha}_1\mathbf{E}_0\cos(\omega t) + \frac{1}{2}\boldsymbol{\alpha}_2\mathbf{E}_0^2 + \frac{1}{2}\boldsymbol{\alpha}_2\mathbf{E}_0^2\cos(2\omega t) + \dots \dots\dots(1-19)$$

Note that the third term is twice the frequency (2ω), meaning that the oscillating dipole moment absorbs light of frequency ω and then emits light of the same frequency plus light of twice the frequency, called the second harmonic of the original beam (SHG). The wavelength of the new light is calculated using the law of conservation of energy (energy of incoming photons = energy of outgoing photons). The nonlinear process can be visualized as the fusion of two photons with wavelengths in the infrared range to produce a green photon. The combined energy of the two photons equals the energy of the photon with the shorter wavelength.

$$\frac{hc}{\lambda_1} + \frac{hc}{\lambda_2} = \frac{hc}{\lambda_3} \dots\dots\dots(1-20)$$

$$\lambda_3 = \frac{\lambda_1\lambda_2}{\lambda_1+\lambda_2} \dots\dots\dots(1-21)$$

The generation of the second harmonic (SHG), also known as frequency doubling, is one of the most common and important examples in nonlinear optics and is highly efficient. The conversion efficiency is defined as the ratio of the power of the outgoing second harmonic to the power of the input, and it depends on several factors such as the crystal length and the cross-sectional area of the beam. The basic requirements for a nonlinear process are as follows:

- 1- A high-intensity light source (laser).
- 2- Compliance with the law of conservation of energy.
- 3- Phase matching.

Phase matching occurs when there is a constant phase relationship between the generated and propagating waves. The most common technique for achieving phase matching involves using birefringent materials. Birefringence is a property of a material in which linearly polarized light has different refractive indices, as in a calcite crystal. The two generated beams have different polarizations; the first is called the ordinary beam, and the second is called the extraordinary beam.

Two methods are used to achieve phase matching in a nonlinear crystal:

- 1- Angular modulation:** The crystal's position relative to the incident laser beam is changed, as the nonlinear refractive index depends on the beam's angle of propagation.
- 2- Thermal modulation:** The nonlinear crystal is heated or cooled until the optimal refractive indices are achieved.

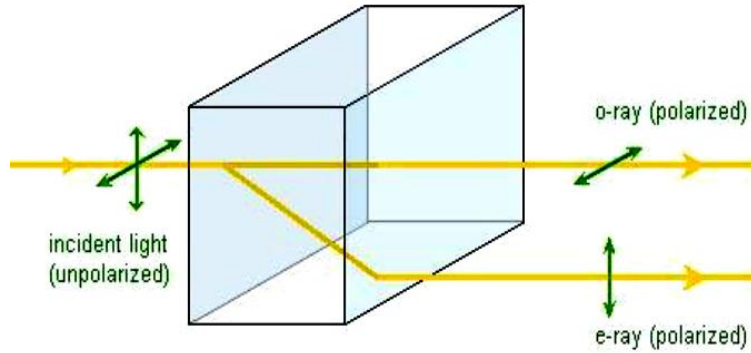


Figure (1-21): Birefringence

1-9-3) Optical Parametric Oscillation (OPO)

In nonlinear processes, the energy of two photons is combined into a single photon with a higher energy (shorter wavelength). This process can also be reversed. The energy of a photon can be split between two new photons, a phenomenon called optical coefficient oscillation (OPO). From the law of conservation of energy, we obtain:

$$\frac{hc}{\lambda_1} = \frac{hc}{\lambda_2} + \frac{hc}{\lambda_3} \dots\dots\dots(1-22)$$

$$\lambda_2 = \frac{\lambda_1 \lambda_3}{\lambda_3 - \lambda_1} \dots\dots\dots(1-23)$$

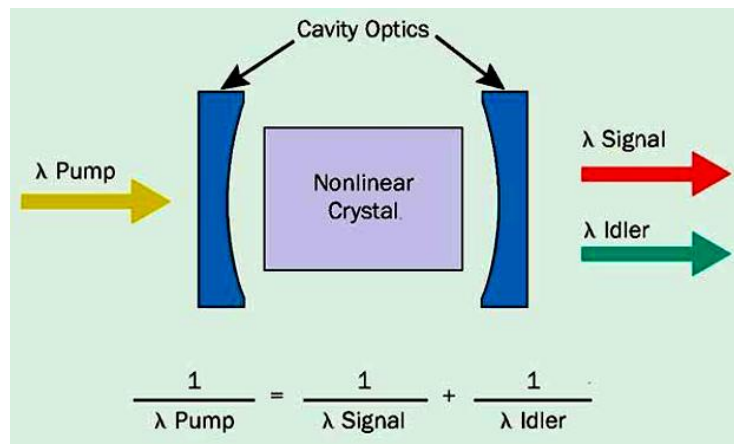


Figure (1-22): Optical Coefficients Oscillation

The OPO must contain an optical resonator, as in a laser. One wavelength is emitted, called the signal, and the other wavelength is reflected from the mirror, called the idler.