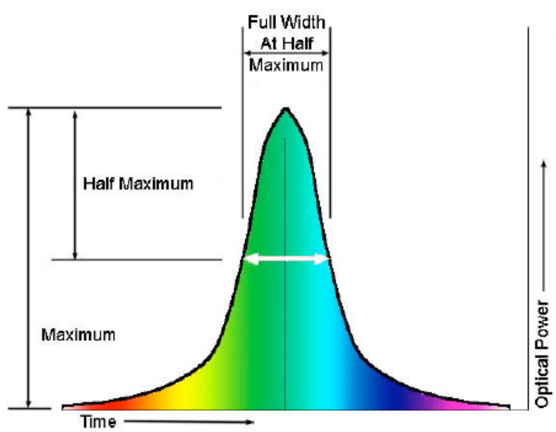
Operation principles of a femto-second Titanium: Sapphire laser system

Διπλωματική Εργασία

Γράσσος Ευάγγελος Στυλιανός Α.Μ. 3053



Υπεύθυνος Καθηγητής: Χαραλαμπίδης Δημήτρης

Υπεύθυνος Ερευνητής: Τζάλλας Παρασκευάς

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1. Abstract:

Ultra-short laser pulses are consider to be those whose duration is less than a few pico-seconds ($10^{13} s$) *long. In this project are presented the operation principles of a femto-second Titanium: Sapphire laser system, describing the complete laser system arrangement as well as the processes that take place and the techniques that are used. The process begins with the generation of the initial laser pulse inside the oscillator using the ''Kerr lens mode-locking technique'' and continuous with the pulse undergoing through the ''chirped pulse amplification (CPA) process''. A method of a laser pulse amplification that consists of three different stages, using three separate devices. These devices are the stretcher the regenerative and multi-pass amplifier and the compressor and are responsible for the formation of the laser pulse until it reaches its final form. The process follow this exact order in the laser system arrangement firstly stretching out the pulse temporally in the stretcher afterwards amplifying the pulse in the regenerative and multi-pass amplifier and lastly compressing the pulse in the compressor until it has reached the desirable duration and power levels.*

2. Introduction:

In 1917 Albert Einstein first was able to conclude that an interaction existed between light and matter and theorized about the process "called stimulated emission" that would amplify light, a process which makes the lasers possible. The laser that is considered to be the first successful attempt was invented by Theodore Maiman in 1960 and it was a ruby laser. Since back then there is a continuous and a non-stop development, improvement and refinement of the techniques and the materials that are used in the attempt to minimize the pulse duration and maximize the power levels of the laser pulse. The Last years the newest lasers have a pulse duration of 10^{-15} seconds (femto-second) and a peak pulse power of 10^{15} watts. Nowadays through scientific and technological advancement we have even overcome these boundaries changing the scale at the levels of a few hundreds of atto-seconds (10^{-18} seconds). Today the use of lasers have numerous applications at various fields of scientific research and technological advancement. The very short pulse duration and very high intensity render lasers necessary in the study of the dynamics on the microscopic systems and in the study of systems at non-linear optics field.

3. Theory:

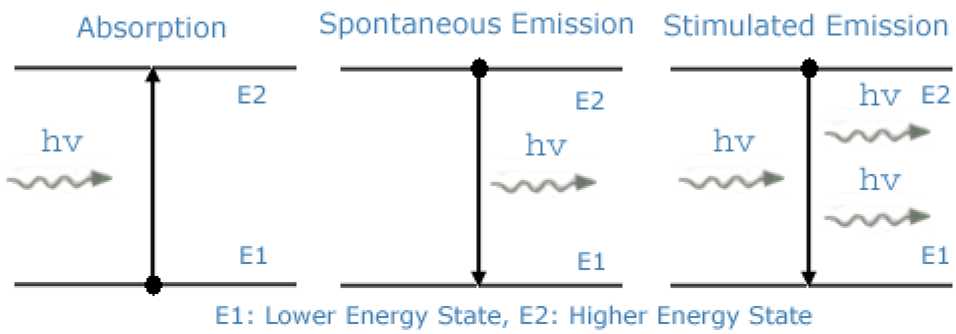
Chapter 3.1

1. Laser Theory: The acronymic means, Light Amplification by Stimulated Emission of Radiation. A laser can be described as an optical source that emits a coherent beam of photons at an exact wavelength or frequencies. The Laser is based and exploits tree fundamental phenomena that occur when an electro-magnetic wave interacts with a material. These phenomena are the processes of Absorption, Spontaneous Emission and Stimulated Emission.

a) Absorption: A photon, with energy $E = hf$, from the radiation field transfers its energy to an electron as potential energy and it then moves from E_1 to E_2, raising the atom's energy and putting it in an excited state.

b) Spontaneous Emission: When an electron in an excited state E_2 drops to a lower state E_1 via decay there is a loss of potential energy in the atom. This is released as a photon and the photon's energy is equal to. $E_2 - E_1 = hf$ The released photon's phase, direction and polarization are all random.

c) Stimulated Emission: When an electromagnetic field is present around an atom, a photon with energy $E = hf$ can stimulate the emission of a twin photon from an excited atom. This twin photon is emitted with identical energy, direction, phase and polarization as the inducing photon, thus amplifying the energy.



2. <u>Laser Idea:</u> Consider two arbitrary energy levels (states) 1 and 2 of a given material and N_1 and N_2 are their respective populations. If a plane wave with a photon flux F is traveling in the z-direction in the material, the elemental change dF of this flux along the elemental length dz of the material is due to both stimulated absorption and stimulated emission process occurring in the gray region of Figure and is given by:

- $dF = \sigma F(N_1 - N_2)dz$

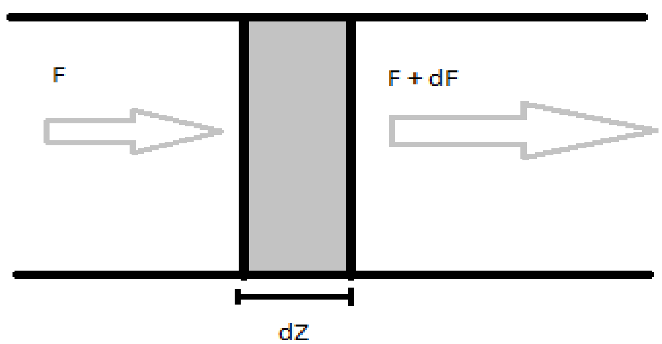


Figure 1: Elemental change dF in the photon flux F for a plane electro-magnetic wave in travelling a distance dz through the material.

The equation above shows that the material behaves as an amplifier if $N_2 > N_1$ while behaves as an absorber if $N_2 < N_1$. At thermal equilibrium populations are described by Boltzmann statistics. If N_1 and N_2 are the thermal equilibrium populations of the two levels then:

➢ $N_2^e / N_1^e = \exp[-(E_2 - E_1)/kT]$

In thermal equilibrium we thus have $N_2^e < N_1^e$. According to equation $dF = \sigma F(N_1 - N_2)$ the material then acts as an absorber at frequency f_0. This is what happens under ordinary conditions. However if a non-equilibrium condition is achieved for which $N_2^e > N_1^e$, then the material acts as an amplifier. In this case we say that there exists a population inversion in the material. This means that the population difference $N_2 - N_1 > 0$ is opposite in sign to what exits under thermodynamic equilibrium. A material in which this population inversion is produced is referred to as an **active medium**. For a laser action to occur, a certain threshold condition must be satisfied. In the laser case, oscillation begins when the gain of the active material compensates the losses in the laser due to output coupling. The threshold condition is reached when the population inversion $N = N_2 - N_1$ reaches a critical value, called the **critical inversion**, given by:

➢ $N_c = N_2 - N_1 = -[\ln R_1 R_2 - 2\ln(1 - L_i)]/2\sigma l$

3. Laser Beam Properties: Laser radiation is characterized by an extremely high degree of monochromaticity, coherence, directionality and brightness. We can add short duration, which refers to the capability of producing very short light pulses.

- Monochromaticity: This property is due to the following two circumstances: (1) Only one electro-magnetic wave of frequency $f = (E_2 - E_1)/h$ can be amplified. (2) Since a two-mirror arrangement forms a resonant cavity, oscillation can occur only at the resonance frequencies of this cavity.

- Coherence: To first order, for any electro-magnetic wave, we can introduce two concepts of coherence, namely spatial and temporal coherence.

- Directionality: This property is a direct consequence of the fact that the active material is placed in a resonant cavity. Indeed it is true, only a wave propagating in a direction orthogonal to the mirrors along the direction of the cavity can be sustained in the cavity.

- Brightness: We define the brightness of a given source of electro-magnetic waves as the power emitted per unit surface area and per unit solid angle: $dP = B\cos\theta dSd\Omega$.

- Very Short Light Pulses: By means of a special technique called **mode-locking,** it is possible to generate and produce very short light pulses whose duration is roughly equal to the inverse of the line-width of the laser transition $2 \longrightarrow 1$.

4. Laser Elements / Components: All the lasers have two basic elements/components in common the laser cavity and the pump power.

I. Laser Cavity / Resonator: It is a cavity that it consists of reflective elements, various mirrors and an output coupler, and contains a homogeneous, isotropic and passive dielectric material, the active or gain medium.

II. Pump Power: The process that is required to excite and raise the atoms to their high energy or excited-state, since (at normal temperatures) most are in a lower energy state and will absorb rather than emit light, is referred to as pumping. The power that is used for that process is called then, pump power.

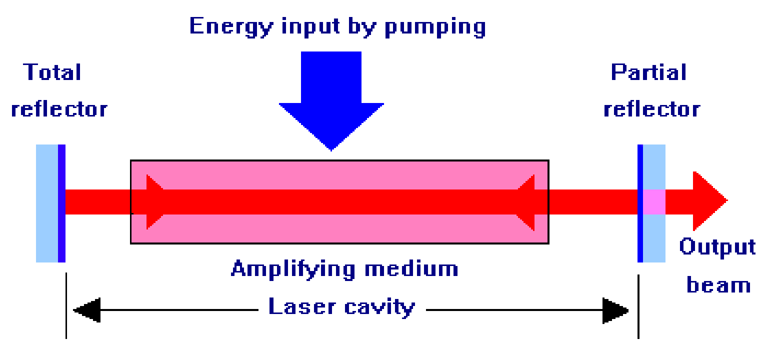


Figure 2: Schematic setup of a laser cavity.

5. Laser Oscillator: An amplifier with a positive feedback is known as an oscillator. The space between the two mirrors is known as the laser cavity or resonator. The beam within the laser cavity undergoes multiple reflections and is amplified each time it passes through the amplification medium. With the modes locked in phase a pulse can be formed and each time the pulse reaches the output coupler, a partial mirror, a small percentage of is allowed to pass through to form the output of the laser. Only a single pulse is formed in each trip as excited atoms in the gain medium returned back to the ground state so for a short while there are insufficient excited atoms to amplify a second pulse. The time between the pulses is equal to the time it takes for the pulse to complete one round-trip inside the laser cavity. The number of pulses output per-second can be calculated as time and frequency have an inverse relationship.

- Time between pulses: $\tau_p = 2L/c$
- Repetition rate / Frequency: $f = 1/\tau_p$

Chapter 3.2

1. Mode: It is a stationary distribution of the electro-magnetic field which satisfies the Maxwell's equations and the boundary conditions. The electro-magnetic field of this distribution can be written as:

- $E(r,t) = E_0 u(r) \exp(i\omega t)$

For every mode of the resonator there will be inevitably some losses. These losses are caused by the diffraction of the electro-magnetic field and result to a loss of a part of energy from the laser cavity. Those losses are referred to as diffractive losses. In reality there are no such stationary distributions in a resonator so the definition of the mode cannot be applied. Despite all that the existence of standing-electro-magnetic-wave distributions that have negligible losses are real and do indeed exists. The electro-magnetic field of such an electro-magnetic distribution can be written as:

- $E(r,t) = E_0 u(r) \exp[(-t/2\tau_c) + i\omega t]$

2. <u>Longitudinal Modes:</u> The existence of longitudinal modes is the most important characteristic of an optical resonator when using lasers as short pulse generators. Longitudinal modes also called axial modes, are known as time-frequency property. For laser oscillations to occur within a laser cavity a wave must be able to self-replicate after two reflections so that the electric fields constructively interfere and add up in phase. When an electromagnetic wave propagating between two parallel mirrors adds constructively with an electromagnetic wave propagating in the reverse direction an electromagnetic field from a standing-wave is established. The mirrors have now formed a resonant cavity and the resulting waves are known as standing-waves. A standing-wave can only exists if the distance between the parallel mirrors is a positive integer multiple of the half-wavelength of the light. All other frequencies of light consequently destructively interfere. The discrete sets of frequencies that are formed directly from these standing-waves are then called the longitudinal modes of the cavity.

- The condition for a standing-wave: $L = m\lambda / 2$
- Speed of light: $c = \lambda f$
- Repetition rate / Frequency: $f = mc / 2L$

3. <u>Mode-Locking:</u> Is a technique or a method in optics by which a laser can be made to produce pulses of light of extremely short duration (ultra short pulses on the order of picoseconds or femtoseconds) and of very high intensity, which is then called mode-locked laser. Mode-locking essentially "locks" all the modes in the laser in phase with one another, resulting to a periodic train of ultra shorts pulses output emission. These ultra-short pulses occur as a result of the constructive interference of the laser modes for a short duration of time, and the destructive interference of the modes at all other times. The laser can operate at a number of wavelengths which satisfy the standing-wave condition. Any one of the wavelengths which satisfy this condition is a longitudinal mode. When several modes are lasing simultaneously, they add to each other so that on a random basis, there will be instants at which the light from all the modes will add to create an intense sum and other times when this sum will be less intense, depending on the relative timing or phase of each mode. It can be shown that the larger the number of modes, the higher the instantaneous intensity will be. If the phase between each mode is adjusted non-randomly and held constant, the peak powers become much larger and the random spiking between these pulses diminishes. This is referred to as locking

the modes together, hence the term mode-locking. Once the modes are locked together, it can be shown that the larger the number of modes locked together, the higher the pulse intensity and the narrower the pulse. Interestingly, the frequency of the pulses is precisely equal to the frequency separation of adjacent longitudinal modes:

- Circular Frequency: $\omega = 2\pi f = \pi c / L$

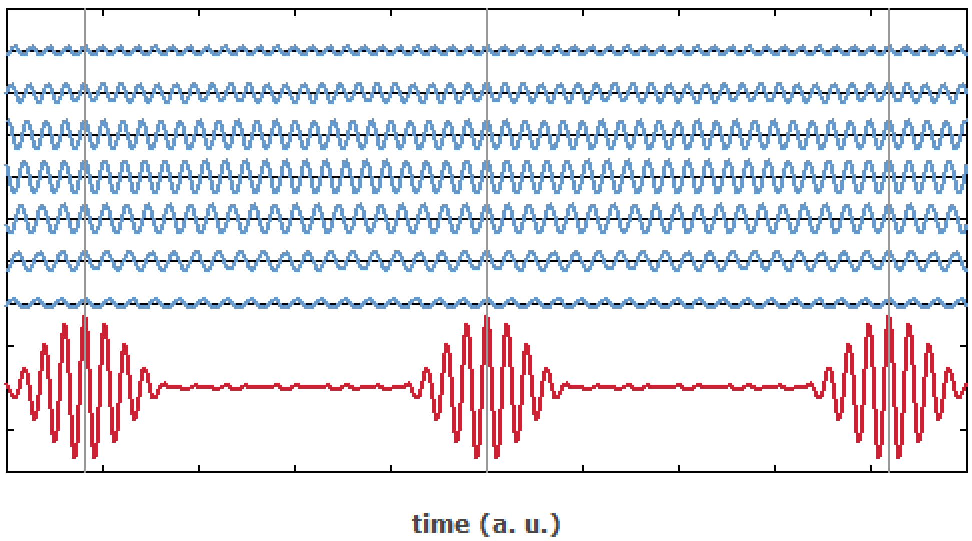


Figure 3: Illustrates a synthesis of a periodic pulse train by superposition of sinusoidal oscillations with equally spaced frequencies, corresponding to different axial resonator modes in a mode-locked laser. The larger the number of frequency components involved, the shorter can be the duration of the generated pulses.

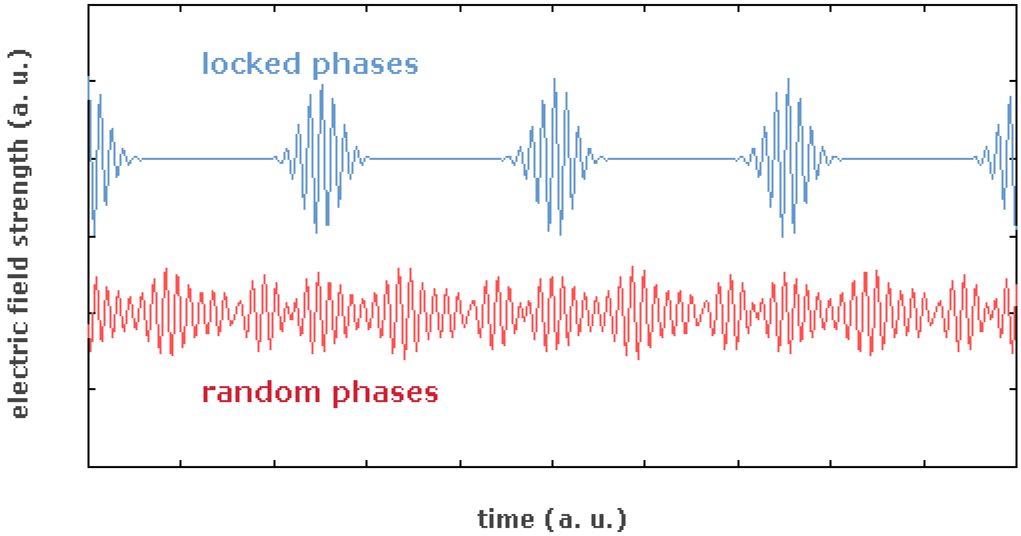


Figure 4: Illustrates that an important aspect is that there must be a fixed phase relationship between these modes. The blue curve shows a pulse train with a fixed phase relationship, so that at regular temporal positions (e.g. at t=0) the electric fields of all frequency components add up to a maximum of the total field strength. The red curve shows the electric field for the same strength of all frequency components, but with random relative phases.

4. Active Mode-Locking: Involves the very fast periodic modulation of the resonator losses or of the round-trip phase change. In order to initiate the pulse, some sort of optical shutter (electro/acousto-optic modulator), referred to as a modulator, is opened, closed and opened again at precisely the correct rate to allow a pulse of light to pass through the shutter as it travels back and forth between the high reflector and output coupler making a complete round-trip. Only light that arrives at the shutter at precisely the correct time to pass through without being blocked will be amplified. Since the shutter is closed at all other times, a second pulse cannot be formed. This results in the constructive interference of the laser modes for a short duration of time, and destructive interference of the modes at all other times, causing the coupling of modes to occur. It is not necessary to fully close the shutter. A sinusoidal modulated transmission with a modulation frequency equal to the inter-mode frequency separation $\Delta f = c/2L$ causes the attenuation of any radiation not arriving at the time of peak transmission. Said that in another way, the modulator frequency must be precisely equal to the repetition rate (pulse frequency). Since the time between pulses depends on the length of the cavity, any change in the length of the cavity must be accompanied by an accurate re-

adjustment of the modulator frequency. Alternatively, the cavity length can be regulated so that repetition rate always matches the modulation frequency.

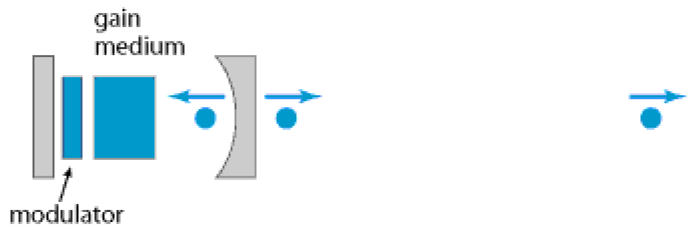


Figure 5: Schematic setup of an actively mode-locked laser.

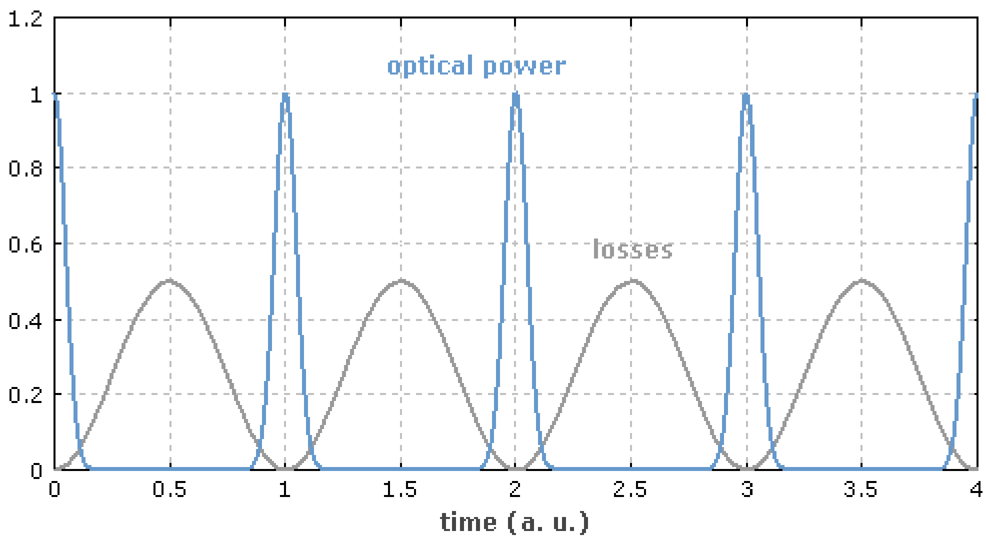


Figure 6: Shows the temporal evolution of optical power and losses in an actively mode-locked laser. The modulator causes increased losses for the pulse wings, effectively shortening the pulses. As the pulse duration relative to the pulse period is typically much smaller than shown, the pulse-shortening effect of the modulator is usually very weak.

5. Passive Mode-Locking: Allows the generation of much shorter (femtosecond) pulses. Passive mode-locking works by placing a **saturable absorber** inside the laser cavity, which does not need an external modulating signal to operate. This method introduces a self-adjusting amplitude modulation into the cavity and allows

far shorter pulses than active mode-locking basically because a saturable absorber, when driven by already short pulses, can modulate the resonator or cavity losses much faster than any electronic modulator. As a pulse begins to form it travels through the cavity encountering the gain medium and the saturable absorber. When the pulse reaches the saturable absorber the leading edge is strongly absorbed. The relaxation time of the absorber in a Titanium: Sapphire laser is longer than the pulse duration, which means that the tail of the pulse will pass through the now saturated absorber without being attenuated. Once the pulse reaches the gain medium the now leading edge which is the central part of the pulse will be strongly amplified by the unsaturated gain, while the tail of the pulse will experience much less amplification as the gain becomes saturated. After oscillating many times, the pulse will have a very strong maximum and be very narrow because the centre of the initial pulse is not affected by the absorber and is amplified by the gain medium, where as the wings feel the opposite and are attenuated. Any other oscillating low intensity light experiences more loss than gain and subsequently dies out during further round-trips. The shorter the pulse becomes, the faster the loss modulation, provided that the absorber has a sufficiently short recovery time. The pulse duration can be even below the recovery time of the absorber. All absorbers for ultra-short pulses are slow absorbers and have a recovery time larger than the pulse duration.

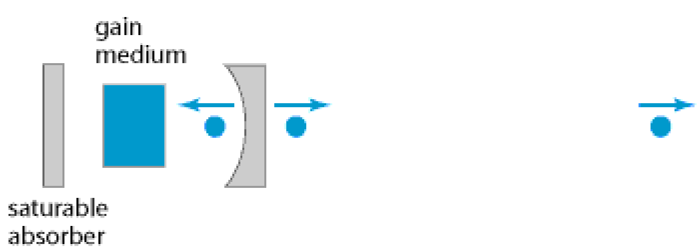


Figure 7: Schematic setup of a laser which is passively mode-locked with a saturable absorber mirror, e.g. a SESAM.

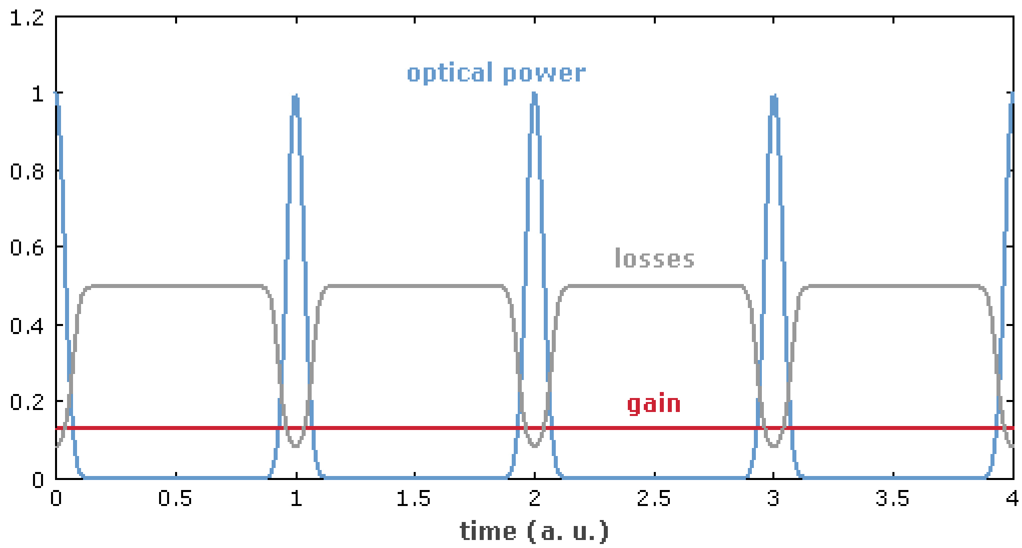


Figure 8: Shows the temporal evolution of optical power and losses in a passively mode-locked laser with a fast saturable absorber. The shorter the pulse becomes, the faster will be the loss modulation. The gain stays approximately constant, as gain saturation is weak.

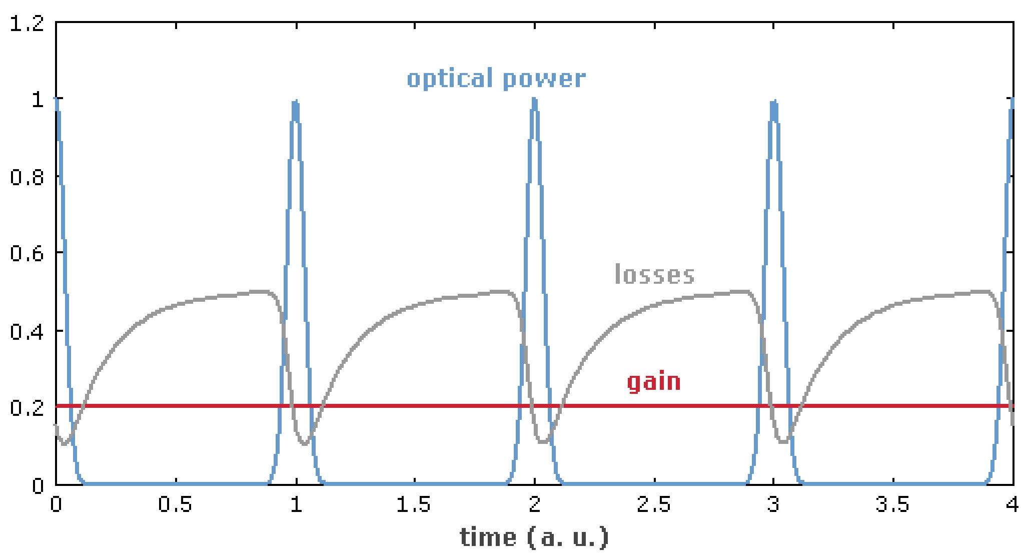


Figure 9: Shows the temporal evolution of optical power and losses in a passively mode-locked laser with a slow saturable absorber. The saturable absorber causes a loss modulation which is fast for the leading wing of the pulse, whereas recovery of the absorber takes some longer time.

6. Saturable Absorber: Is an optical component with a certain optical loss, which is reduced at high optical intensities. A saturable absorber is a non-linear passive element that has an intensity-dependent transmission property, so that the absorption coefficient decreases as the intensity of light passing through it increases meaning it will allow the transmission of high intensity light with relatively little absorption and will absorb low intensity light. When a saturable absorber is used to mode-locked a laser, the laser is simultaneously **Q-switched**. A saturable medium can mimic the fast shutters (electro/acousto-optic modulator) used for active mode-locking, providing the pulse has a sufficiently large irradiance to allow it to saturate the absorber each time it passes through. The shorter the pulse becomes, the faster the loss modulation, provided that the absorber has a sufficiently short recovery time. The pulse duration can be even below the recovery time of the absorber. If the absorber recovery time is well below the pulse duration, the absorber is called a fast absorber. In that case, the loss modulation basically follows the variation of the optical power. However, mode locking can also be achieved with a slow absorber, having a recovery time above the pulse duration. All absorbers for ultra-short pulses are slow absorbers and have a recovery time larger than the pulse duration.

7. Q-switching: Also known as, giant pulse formation, is a technique by which a laser can be made to produce a pulsed output beam. The technique allows the production of light pulses, of high energy and extremely high (gigawatt level) peak power, by modulating the intra-cavity losses and thus the Q-Factor or Quality Factor of the laser resonator. For another technique for pulse generation Q-switching leads to much lower pulse repetition rate, much higher pulse energies and much longer pulse duration compared to mode-locking. Q-Factor is the ratio of the resonance frequency f_0 and the Full Width at Half Maximum (FWHM) bandwidth δf of the resonance.

- $Q = f_0 / \delta f$

Q-switched mode locking is an operation regime of a passively mode-locked laser where the intra-cavity pulse energy undergoes large oscillations, related to a dynamic instability (un-damped relaxation oscillations). The pulse energy may even become extremely small for a number of subsequent pulses, before the next bunch of pulses is generated. The principle of Q-switching works as follows: We introduce some type of variable attenuator (or switch) inside the laser cavity. If the attenuator is functioning, light which leaves the gain medium does not return and laser action does not occur. This attenuation inside the cavity corresponds to a decrease in the Q-Factor of the optical resonator. A high Q-Factor corresponds to low resonator losses per roundtrip, and vice versa. The variable attenuator is called Q-switch. Initially the laser medium is pumped while Q-switch is set to prevent feedback of light into the gain medium (producing an optical resonator with low Q). This produces a population inversion, but laser operation cannot occur yet since there is no feedback from the resonator. Since the rate of stimulated emission is dependent on the amount of light entering the medium, the amount of energy stored in the gain medium increases as the medium is pumped and will reach at very high values. Due to losses from spontaneous emission and other processes, after a certain time the stored energy will reach some maximum level, the medium is said to be gain saturated. At this point, the Q-switch device is quickly changed from low to high Q, allowing feedback and the process of optical amplification by stimulated emission to begin. Because of the large amount of energy already stored in the gain medium, the intensity of light in the laser resonator builds up very quickly, this also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser, known as a giant pulse, which may have a very high peak intensity. There are two types of Q-switching, active and passive which achieved by an acousto/electro-optic modulator or a saturable absorber as the variable attenuator, Q-switch, respectively.

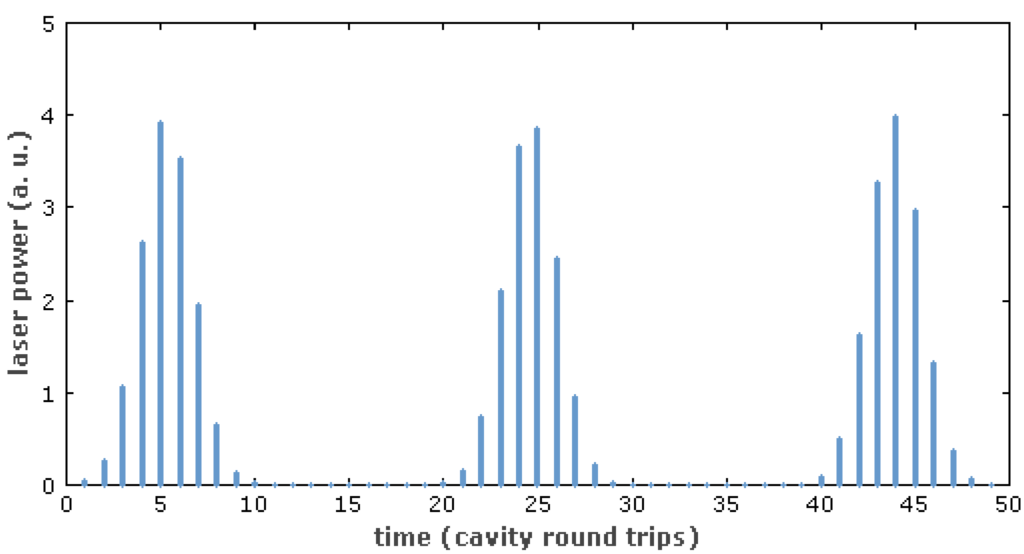


Figure 10: Illustrates the evolution of the optical power in a passively Q-switched laser under conditions of Q-switched mode locking. Bunches of ultra-short pulses are generated.

Chapter 3.3

1. <u>Refractive Index:</u> In optics the refractive index or index of refraction, *n,* of a substance (optical medium) is a dimensionless number that describes how light, or any other radiation, propagates through that medium. It is defined as the speed of light in a vacuum divided by the velocity of light in a material is equal to the index of refraction, n:

- $n = c / v_{ph}$

The index of refraction of a material has implications for the light passing through the material. Therefore the larger the value of the refractive index is the lower the velocity of light in the material becomes. Refraction is the change in direction of a wave due to a change in its transmission medium. Refraction is essentially a surface phenomenon. The phenomenon is mainly in governance to the law of conservation of energy and momentum. Due to change of medium, the phase velocity of the wave is changed but its frequency remains constant. Also refractive index n, according to Snell's law, defines the how much a beam will bend or be reshaped when it strikes a surface.

2. <u>lens:</u> A lens is an optical device which transmits and refracts light, converging or diverging the beam. A simple lens consists of a single optical element. A compound lens is an array of simple lenses (elements) with a common axis. A convex lens is a common refractive element that is thicker in the middle than at the edges, causing the light to slow down more in the middle than in the edges. The light is focused towards the centre as it becomes bent inwards. In this case the lens has a constant index of refraction, n, but still, since there is more glass in the middle than the edges, the edges are slowed down less. A lens can also be formed by making the index of refraction at the center of the material higher than the index at the edges. This also bend light and is referred to as a gradient index lens.

Chapter 3.4

1. Optical Kerr Effect: The Optical Kerr Effect a.k.a. the Quadratic Electro-Optic Effect (QEO Effect), is a non-linear optical interaction of light in a medium with an instantaneous response. The Kerr effect can be described as a modification of the refractive index in response to an applied electric field. The Kerr Effect is an effect occurring when intense light propagates in crystals and glasses but also in other media such as gases. It' s physical origin is a non-linear polarization generated in the medium, which itself modifies the propagation properties of the light. When the intensity of the light is sufficiently high enough the electric field of the light becomes strong enough to distort the structure of the atoms in the material and change its refractive index. The induced index change is directly proportional to the square of the electric field and this leads to an intensity dependent refractive index in the material:

- Intensity dependent refractive index: $n(r) = n_0 + n_2 I(r)/2$

2. Kerr Lens: When a short optical pulse propagates through a non-linear medium, the Kerr Effect leads to a phase delay which is the largest on the beam axis and smaller outside the axis. The beam is more intense in the center compared to the edges, so the index of refraction at the centre will become higher than at the edges, which causes the light to experience Self-Focusing and forces the beam diameter to decrease. This modified refractive index distribution then acts like a focusing lens thus a gradient index lens is formed. Since it's the Optical Kerr Effect which alters the refractive index, the lens that is formed is referred to as a Kerr Lens.

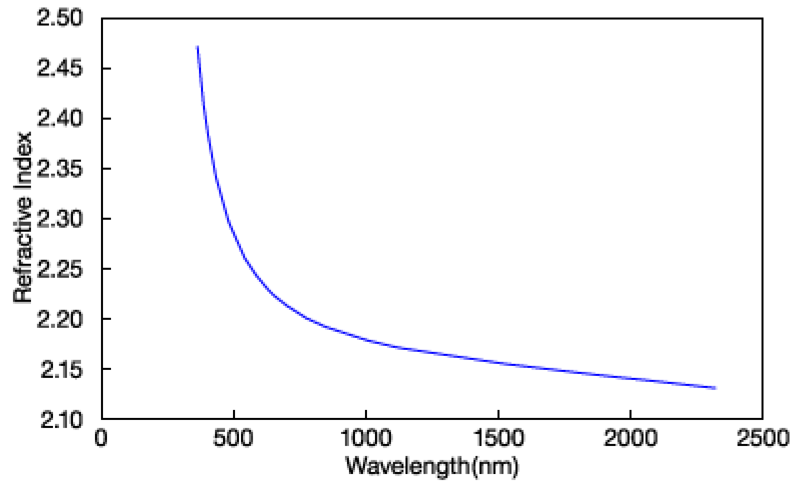
3. Kerr Lens Mode-Locking: Is a method of mode-locking lasers via a non-linear optical process known as the optical Kerr Effect. This method allows the generation of a train of ultra-short ultra-fast pulses of light with a duration as short as a few

femto-seconds. Kerr Lens Mode-Locking is a technique of passive mode-locking a laser, using an artificial saturable absorber system.

4. Non Self-Starting Mode-Locking: Some passively mode-locked lasers exhibit difficulties with starting the mode-locking process: after turning on the pump power, there are no intensity fluctuations to create a significantly strong Kerr lens effect thus the laser will operate in a (possibly noisy) continuous-wave mode. The generation of ultra-short pulses can be started with an external intervention by the means of knocking on an optical component of the laser resonator or vibrating a mirror.

Chapter 3.5

1. Dispersion: In optics, dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency, or alternatively when the group velocity depends on the frequency. Media having such a property are termed dispersive media. Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature, or group-velocity dispersion (GVD) to emphasize the role of the group velocity. Normal dispersion is distinguished for $k^{"} > 0$ and anomalous dispersion for $k^{"} < 0$. Where k is the wave-number. The graph of refractive index (n) versus wavelength (λ) shows a hypothetical dispersion curve and its shape is typical of many common materials which are transparent in the optical spectrum. The shape is typical in the sense that the index decreases monotonically with increasing wavelength while maintaining a gradual upward curvature. This is referred to as normal dispersion, whereas a material with a downward curvature is referred to as having anomalous dispersion. Normal dispersion, where the group velocity decreases with increasing optical frequency, occurs for most transparent media in the visible spectral region. Anomalous dispersion sometimes occurs at longer wave-lengths.



Mathematical description of chromatic dispersion of first second and higher order is defined via the Taylor expansion of the wave-number k (change in spectral phase per unit length) as a function of the angular frequency ω (around some center frequency ω_0):

➢ $k(\omega) = k_0 + \partial k / \partial\omega(\omega - \omega_0) + \partial^2 k / 2\partial\omega^2 (\omega - \omega_0)^2 + \partial^3 k / 6\omega(\omega - \omega_0)^3 + \ldots$

The zero-order term describes a common phase shift.

The first -order term contains the inverse group velocity and describes an overall time delay without an effect on the pulse shape:

➢ $k^{'} = \partial k / \partial\omega = 1 / v_{gr}$

The second-order term contains the second-order dispersion or group delay dispersion (GDD) per unit length:

➢ $k^{''} = \partial^2 k / \partial\omega^2$.

The third-order term contains the third-order dispersion (TOD) per unit length:

➢ $k^{'''} = \partial^3 k / \partial\omega^3$

2. <u>Group Velocity Dispersion:</u> The wavelength of an ultra-short pulse of light cannot be determined precisely since it is formed by the sum of a distribution of wavelengths on either side of the center wavelength. The width of the distribution

is inversely proportional to the length of the pulse. The production of a short pulse of light from the distribution requires the timing or phase between each component wavelength to be exact and accurate, for the pulse to reach the optimum short-length. An ultra-short pulse will become longer after it has passed through glass. This is due to the fact that in all normal materials, the index of refraction and hence the speed of light depends non-linearly on the wavelength. At a given wavelength, the refractive index n(λ) determines the phase velocity or the velocity of a monochromatic wave. The first derivative $dn(\lambda)/d\lambda$ (or slope) of the refractive index curve, determines the group velocity and thus defines the velocity of a wave packet (short light pulse) with a central wavelength λ. The second derivative of the curve, $d^2n(\lambda)/d\lambda^2$, determines the group velocity dispersion, which governs the rate at which the frequency components of a wave packet change their relatives phases. Group velocity dispersion causes temporal reshaping of wave packets this can be a broadening or a shortening shape change depending upon the initial conditions (**chirp**) of the wave packet spectrum.

3. <u>Chirp:</u> The term chirp means that the frequency of the wave packet (or of the optical pulse) is time-dependent. A pulse is positively chirped if its instantaneous frequency increases from the leading edge to the trailing edge. This is the type of chirp which will normally be imparted to a pulse after traversing normal materials with an upward curvature. Its blue spectral components will be retarded with respect to the red , creating a systematic variation of phase with respect to wavelength. Similarly, a pulse is said to be negatively chirped if its red spectral components have been retarded with respect to the blue.

4. <u>Self-Phase Modulation:</u> Is a non-linear optical effect of light-matter interaction. An ultra-short pulse of high intensity light, when traveling in a medium, will induce a varying local refractive index of the medium that is dependent on the light field intensity due to the optical Kerr Effect. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse' s frequency spectrum. In other words due to the Kerr Effect, high optical intensity in a medium causes a non-linear phase delay which has the same temporal shape as the optical intensity. Therefore the leading and trailing edges of the pulse will cause less change in the index than the center where the intensity is highest. Frequency components propagating through the material are thus phase shifted differently depending upon when they occur in the pulse. This phenomena actually generates

new frequencies (or eliminates old ones depending upon the initial conditions). These frequency components are inherently chirped and can broaden the pulse unless the pulse is compensated. Self-Phase Modulation itself is not a dispersive effect, but it causes a pulse to no longer be transform-limited when crossing a transparent material, which means the pulse is then subject to dispersion. Dispersion causes the redder parts of the pulse to have a higher velocity than the bluer parts, forcing the front of the pulse to move quicker than the back, temporally broadening the pulse. In anomalous dispersion the opposite is true and the pulse temporally compressed. The self phase modulation becomes stronger as the pulse becomes more intense, in turn causing more broadening.

- Difference in refractive index: $\Delta n = n_2 I = \lambda k E^2$

5. Compensation: There are many dispersive elements within a laser cavity that create phenomena like Group Velocity Dispersion (GVD) and Self-Phase Modulation (SPM). An oscillating pulse that circulates in the cavity will receive a slight chirp from each of these dispersive elements that encounters in every round-trip. The cumulative effect from a lack of compensation for both GVD and SPM effects of even a very small chirp per round trip would create a temporal broadening to the pulse's substructure. There is thus the requirement of an element or a system of elements which has negative GVD, that is, the relationship between wavelength and speed or refractive index is reverse of what it is in normal material. In principle, negative chirps could be introduced by propagating the pulse through a material at a wavelength where the curvature of the refractive index curve was downward but in practice this is not very practical. To accomplish this with some variability in the magnitude of the desired compensation it is usually necessary the construction of some type special optical system. The existence of a finite second derivative of the refractive index with respect wavelength was required in order to create GVD. In fact this does not only apply to simple material dispersion curves but can be generalized to any optical system by realizing that a more general description of GVD requires the existence of a finite second derivative of the optical path-length with respect to wavelength. For a given wavelength and a given optical system, one can express the phase evolution of the light wave traveling through the system by taking into account all the effects that occur along the optical path, including refraction at surfaces. A path-length curve, can be constructed for any complex optical structure having wavelength dependent beam paths. GVD can therefore be regarded as a property of an optical construction.

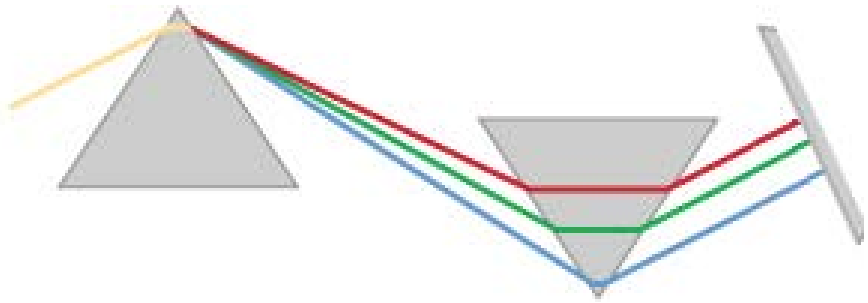


Figure 11: Principal of GVD Compensation.

Chapter 3.6

Chirped - Pulse Amplification (CPA): Is a technique for amplifying an ultra-short laser pulse up to the peta-watts level with the laser pulse being stretched out temporally and spectrally prior to amplification. Before passing through the amplifying medium, the pulses are chirped and temporally stretched to a much longer duration by means of a strongly wavelength dispersive element system such as gratings or prisms. This reduces the peak power to a level where detrimental effects in the gain medium are avoided. In CPA an ultra-short laser pulse is stretched out in time prior to introducing it to the gain medium using a pair of gratings that are arranged so that the low-frequency component of the laser pulse travels a shorter path than the high-frequency component does. After going through the grating pair, the laser pulse becomes positively chirped, that is, the high-frequency component lags behind the low-frequency component and has longer pulse duration than the original by a factor of 10^3 to 10^4. Then the stretched pulse, whose intensity is sufficiently low compared with the intensity limit of giga-watts per square centimeter, is safely introduced to the gain medium and amplified by a factor of 10^6 or more. Finally, the amplified laser pulse is recompressed back to the original pulse width through the reversal process of stretching. A dispersive compressor is used, an element with opposite dispersion (typically a grating pair) which removes the chirp and temporally compresses the pulse to a duration similar to the input pulse duration.

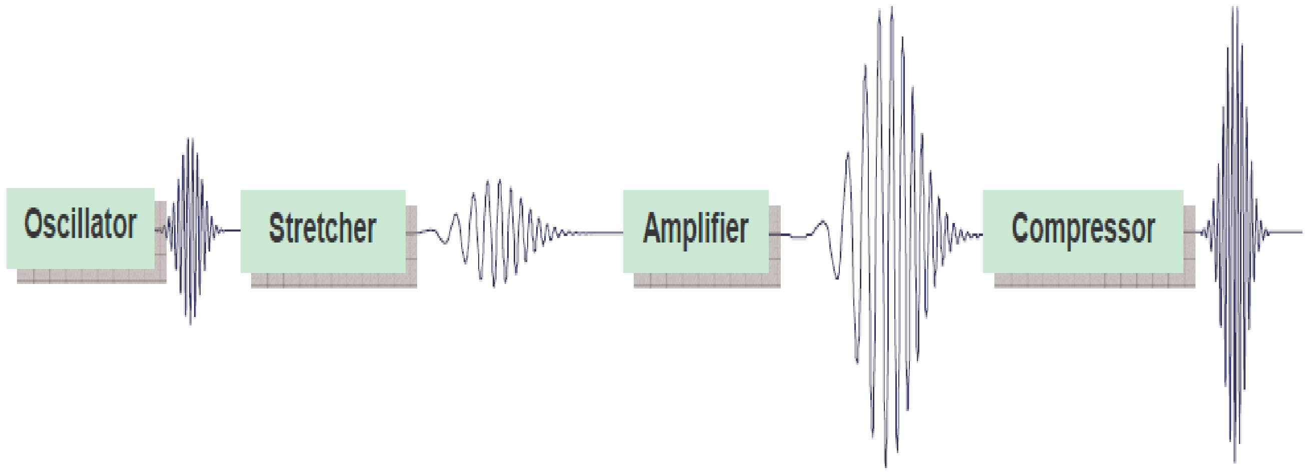


Figure 12: Principal of chirped pulse amplification

Chapter 3.7

<u>Second Harmonic Generation or Frequency Doubling</u>: Is a non-linear optical process in which photons interacting with a non-linear material are effectively "combined" to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons.

We first introduce some physical concepts using the simplifying assumption that the induced non-linear polarization P^{NL} is related to the electric field E of the electro-magnetic wave by a scalar equation;

- $P^{NL} = 2\varepsilon_0 dE^2$

where d is a coefficient whose dimension is the inverse of an electric field. The physical origin of the equation stems from the non-linear deformation of the outer, loosely bound, electrons of an atom or atomic system, when subjected to high electric fields.

We consider a monochromatic plane wave of frequency ω propagating along some direction, denoted as the z-direction, within a non-linear crystal. The origin of the z-axis is taken at the entrance face of the crystal. For a plane wave of uniform intensity, we can write the following expression for the electric field $E_\omega(z,t)$ of the wave:

- $E_\omega(z,t) = \{E(z,\omega)\exp[i(\omega t - k_\omega z)] + c.c.\}/2$

where $c.c.$ stands for the complex conjugate of the other term appearing in the brackets and:

- $k_\omega = \omega / c_\omega = n_\omega \omega / c_0$

where c_ω is the phase velocity in the crystal of a wave of frequency ω, n_ω is the refractive index at this frequency, and c is the speed of light in vacuum. The substitution of equation E_ω into equation P^{NL} shows that P^{NL} contains a term oscillating at frequency 2ω. Namely:

- $P_{2\omega}^{NL} = \varepsilon_0 d\{E^2(z,\omega)\exp[i(2\omega t - 2k_\omega z)] + c.c.\}/2$

The equation describes a polarization wave oscillating at frequency 2ω with a propagation constant $2k_\omega$. This wave is expected to radiate at frequency 2ω to generate an electro-magnetic wave at the second harmonic (SH) frequency 2ω. The radiated SH field can be written in the form:

- $E_{2\omega}(z,t) = \{E(z,2\omega)\exp[i(2\omega t - k_{2\omega} z)] + c.c.\}$

where

- $k_{2\omega} = 2\omega / c_{2\omega} = 2n_{2\omega}\omega / c_0$

is the propagation constant of a wave frequency 2ω. The physical origin of SHG can thus be traced back to the fact that, as a result of the non-linear relation P^{NL}, the electro-magnetic wave at the fundamental frequency ω beats with itself to produce a polarization at 2ω. Comparison between equations $P_{2\omega}^{NL}$ and $E_{2\omega}$ reveals a very important condition that must be satisfied if this process is to occur efficiently, the phase velocity of the polarization wave ($u_P = 2\omega/2k_\omega$) must equal that of the generated electro-magnetic wave ($u_E = 2\omega/2k_\omega$). This condition can be thus written as:

- $k_{2\omega} = 2k_\omega$

Note that, according to equations k_ω and $k_{2\omega}$ equation $k_{2\omega} = 2k_\omega$ implies that:

- $n_{2\omega} = n_\omega$

We now return to the problem of induced non-linear polarization. In general in an anisotropic medium, the scalar relation P^{NL} does not hold, so a tensor a relation must be introduced. First, we write the electric field $E^\omega(r,t)$ of the electro-magnetic wave at frequency ω and a given point r and the non-linear polarization vector at frequency 2ω, $P_{NL}^{2\omega}(r,t)$ in the form:

- $E^\omega(r,t) = \left[E^\omega(r,\omega)\exp(i\omega t) + c.c.\right]/2$
- $P_{NL}^{2\omega}(r,t) = \left[P^{2\omega}(r,2\omega)\exp(2i\omega t) + c.c.\right]/2$

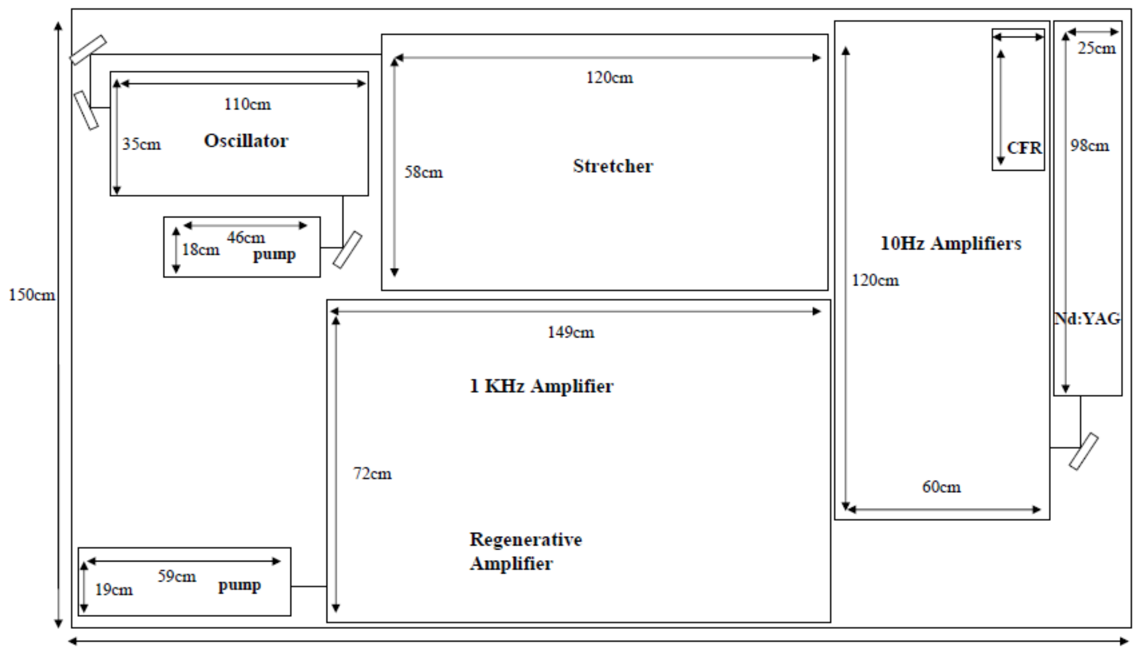
A tensor relation can then be established between $P^{2\omega}(r,2\omega)$ and $E^\omega(r,\omega)$. In fact, the second harmonic polarization component along the i-direction of the crystal can be written as:

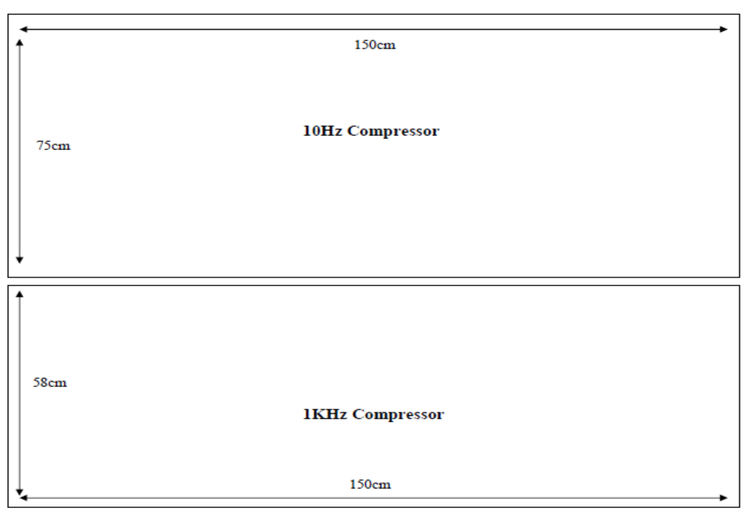
- $P_i^{2\omega} = \sum_{j,k=1,2,3} \varepsilon_0 d_{ijk}^{2\omega} E_j^\omega E_k^\omega$

4. Experiment:

Chapter 4.1

Laser System Complete Arrangement:





The experimental part of the project describes the complete arrangement of Titanium: Sapphire amplified laser system and analyzes the process from the generation to the final formation of the pulse. Titanium: Sapphire laser system consists of a laser oscillator Mira Seed which is pumped by a Verdi laser, a stretcher, a regenerative amplifier and a multi-pass amplifier with repetition rate at 1kHz which are pumped by a Photonics Industries laser, two multi-pass amplifiers with repetition rate at $10\,\mathrm{Hz}$ lastly two compressors for the laser beams at 1kHz and at $10\,\mathrm{Hz}$ with energy output beam at $3\,\mathrm{mJoule}$ and $150\,\mathrm{mJoule}$ per pulse respectively and central wavelength of the pulse at $800\,\mathrm{nm}$. The spectral bandwidth of the final pulse is approximately $24\,\mathrm{nm}$.

Chapter 4.2

Verdi Diode-Pumped Laser:

For the laser action to take place inside the resonator or the laser cavity of the Mira Seed oscillator a *pump power* is required to raise the atoms to their high energy or excited-state. There are many ways of *pumping*, and different methods are appropriate for different atoms. In case of Titanium: Sapphire laser an optical pump at the correct wavelength, in the green-blue region of the spectrum, is required. Several watts of *pump power* are needed because the upper-state lifetime of Titanium: Sapphire is very short at $3.2\,\mu\mathrm{s}$ and the saturation power, the incident optical power required to achieve significant saturation of an *absorber*, is very high. A compact solid-state diode-pumped, frequency-double Nd: Vanadate $Nd:YVO_4$ laser is used that provides a continuous-wave single-frequency green color at $532\,\mathrm{nm}$ output beam at power levels greater than $5\,\mathrm{Watts}$. The laser is frequency-doubled because its lasing wavelengths are $914\,\mathrm{nm}$, $1064\,\mathrm{nm}$ and $1342\,\mathrm{nm}$ so it is clear that doubling the frequency or second harmonic generation (SHG) will halve the wavelength, bringing the middle lasing wavelength ($1064\,\mathrm{nm}$) into the green part of the spectrum ($532\,\mathrm{nm}$).

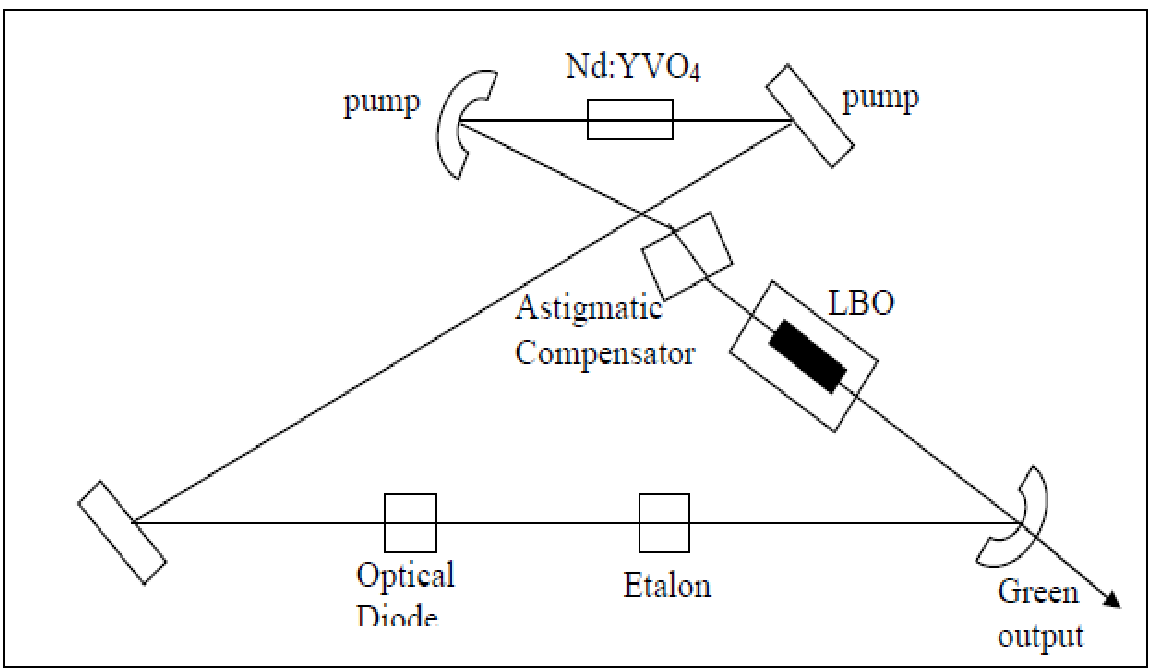
1. **Characteristics - Specifications:**

Is a compact solid-state diode-pumped, frequency-double Nd: Vanadate (Nd:YVO4) laser that provides a continuous-wave single-frequency green color at $532nm$ output beam at power levels greater than $5Watts$.

2. **Elements - Components:**

- Gain Medium, Nd: YVO4 Vanadate
- Frequency Doubling Crystal or Second Harmonic Generator (SHG), LBO crystal: Lithium Triborate LiB3O5
- Single Frequency Optic, Etalon
- Optical Diode
- Astigmatic Compensator
- Two Pump Mirrors
- Two End Mirrors

3. **Design:**



Chapter 4.3

Mira Seed Oscillator Titanium Sapphire Laser (Ti:Al2O3):

1. *Longitudinal modes:* Inside the cavity, only certain wavelengths will be amplified depending on the details of the amplifying medium and the mirrors. The bandwidth of wavelength may be further restricted by filters or other devices. In the case of Titanium: Sapphire laser particularly all of these are employed, the laser will amplify itself from $650\,\text{nm}$ to $1100\,\text{nm}$. The mirrors restrict the bandwidth of the wavelength to approximately 150nm centered about 3 wavelengths. The Birefringent filter selects a relatively narrower portion within this $150\,\text{nm}$ range. The bandwidth is further restricted due to the resonance condition. The requirement is that each lasing wavelength must satisfy the condition that precisely an integral number of half-wavelengths must "fit" between the mirrors. Since the integer is not specified there can be many wavelengths which satisfy this criterion. Each of the wavelengths is referred to as a longitudinal mode.

- The condition for a standing-wave: $L = m\lambda / 2$
- Frequency separation Δf between adjacent modes ($\Delta m = 1$): $\Delta f = c / 2L$

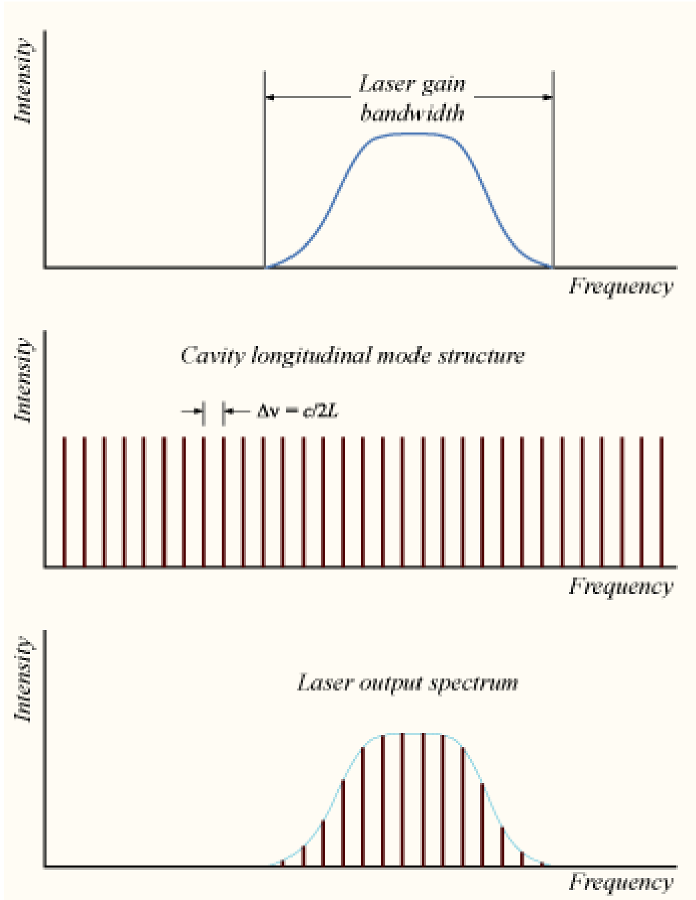


Figure 13: shows a schematic of the longitudinal mode structure in a laser. (a) The laser's gain medium will only amplify light over a certain range of frequencies. This refers to a laser's gain bandwidth. (b) The longitudinal modes are equally spaced by the above Equation. (c) Only the modes whose corresponding frequencies fall into the laser's gain bandwidth will be amplified.

2. *Mira Seed's Artificial Saturable Absorber System*: It is the device that is used for mode-locking on the Mira Seed oscillator and it consists of two parts:

1. A material which decreases the laser beam size in the presence of high intensity pulses such as an artificial saturable absorber based on Kerr lensing in the gain medium.

2. The slit which introduces losses and attenuate the broad low-intensity beams.

In Titanium: Sapphire laser the light itself can alter the index of refraction. This effect is known as the Optical Kerr Effect. The Kerr Lens is formed only when the intensity of the light is extremely high. The instantaneous intensity of mode-locked light pulses are sufficient to form this lens, but the weak intensity of the laser which is operating CW is not. Hence the lens is only formed upon the arrival of a mode-locked pulse. It is this lens which narrows the laser beam and, consequently, a mechanism has now been created which narrows the beam only for mode-locked pulses. The addition of a slit or aperture, to allow only the narrow high-intensity beams to pass un-attenuated and to heavily attenuate the broad low-intensity beams, now forms the complete artificial saturable absorber system. The diameter, position and shape of the slit must be calculated and defined precisely

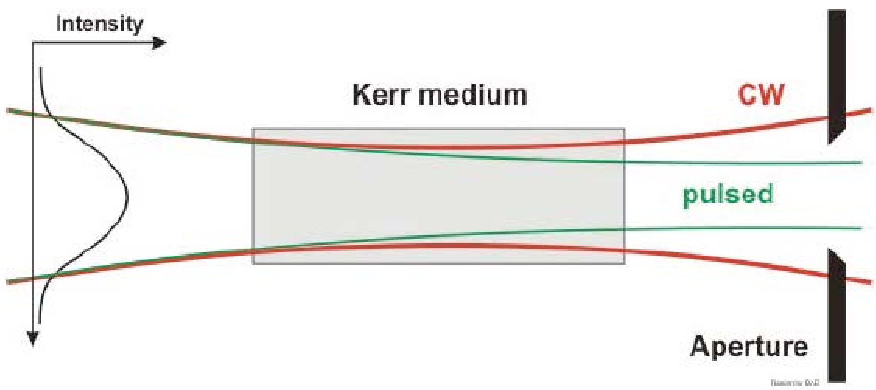


Figure 14: Kerr Lens Mode - Locking

The continuous-wave, green color at 532nm, pump beam, with 5watts power from the Verdi enters the oscillator from the left and is focused through the lens (L) to the mirror (M) and from there is directed towards the gain medium Titanium: Sapphire crystal for the amplification process or the lasing to take place. To initiate the mode-locking and specifically the Kerr Lens or Self mode-locking process an external intervention is needed by the means of knocking or vibrating an optical component of the starting mechanism or starter which will induce very high power fluctuations.

3. *The Starting Mechanism:* Hence, some mechanism must be introduced to create a sufficiently high peak power to start the saturable absorber system and initiate the Kerr Lens Mode-Locking and thus the generation of ultra short pulses. That is

accomplished with some external intervention by changing the cavity length at the proper speed that way very high power fluctuations can be induced. Once the instantaneous power in one of these fluctuations becomes sufficiently high, a Kerr Lens is formed, the beam is narrowed and can pass un-attenuated through the slit. This pulse will become amplified and become the dominant pulse which will form the mode-locked output. In normal operation, Titanium: Sapphire laser has one or two longitudinal modes operating simultaneously. This is due to the fact that all atoms within the gain medium are considered to be equivalent and are capable of emitting light over a range of frequencies and will emit at the same frequency as the stimulating light. Hence, the earliest light to reach high intensity through the amplification process in the gain medium will establish the frequency for all subsequent light. No atoms will remain in their upper state to amplify light at another frequency. For Titanium: Sapphire laser high intensities are gained when the laser operates over as many longitudinal modes as possible. Also of all the longitudinal modes that can lase, there a few that are more likely than others. This is due to the fact that any wavelength selecting element, will cause more losses on either side of the selected wavelength. As the wave selector, in our case the BRF, is changed, some modes are discouraged and others are encouraged. With this in mind it is important to note that the modes can be wavelength shifted by changing the cavity length. If the length is changed rapidly enough there will be new modes oscillating and a transient condition, under which the laser output contains more modes than normally possible, is born. When the number of modes lasing is large enough the peak intensities become high enough to start the Kerr lens mode-locking process. Once the mode-locking has begun it will continue without the need to rapidly change the cavity length or any other external intervention.

4. *Kerr Lens or Self Mode-Locked Laser:* The output of the laser is directly affected by the relative phases, frequencies and amplitudes of the modes. This is apparent from the expression for the total electric field as a function of time:

- $$E(t) = \sum_{n=0}^{N-1} (E_0)_n \exp i(\omega_n t + \delta_n)$$

where $(E_0)_n$, ω_n and δ_n are respectively the amplitude, the angular frequency and the phase of the nth mode. In lasers that are mode-locked, we can presume that $\delta_n = \delta$ therefore:

- $$E(t) = E_0 \exp i\delta \sum_{n=0}^{N-1} \exp i\omega_n t$$

The angular frequency ω_n can be expressed as $\omega_n = \omega - \Delta\omega$, where ω is the angular frequency of the highest frequency mode and $\Delta\omega$ is the angular frequency separation between modes. Therefore:

- $E(t) = E_0 \exp i\delta \sum_{n=0}^{N-1} \exp i(\omega_n - n\Delta\omega)$
- $E(t) = E_0 \exp i(\omega t + \delta) \sum_{n=0}^{N-1} \exp(-\pi inct / L)$

where N is equal to the number of modes.

or

- $E(t) = E_0 \exp i(\omega t + \delta)[1 + \exp(-i\phi) + \exp(-2i\phi) + \exp-(N-1)i\phi]$
- $\phi = \pi ct / L$

As the term in brackets is a geometric progression:

- $E(t) = E_0 \exp i(\omega t + \delta)[\sin(N\phi/2)/\sin(\phi/2)]$
- Irradiance: $I = E(t)E^*(t)$

or

- $I(t) = E_0^2 \left[\sin^2(N\phi/2)/\sin^2(\phi/2)\right]$

This equation gives a lot of information about the mode0locked laser beam. It firstly shows that the shape of the mode-locked laser pulse is dependent on the number of modes, N. In the time interval $t = 2L/c$ (the period of the pulse train), the irradiance I is periodic ($\Delta\phi = 2\pi$). We see from the equation that the irradiance has a maximum value of $N^2 E_0^2$ for values of $\phi = 0$ or $2p\pi$. The irradiance has minimum values of zero when $\phi = 2\pi N$ or $t = [(1/N)(2L/c)]p$, where p is an integer not equal to zero, or a multiple of N. Thus Δt, the time duration of the maxima, (when $\Delta p = 1$) is given by $(1/N)(2L/c)$. This shows that the output of a mode-locked laser consists of a sequence of short pulses, separated in time by $2L/c$, each of peak power equal to N times the average power. The ratio of the pulse spacing to the pulse width is approximately equal to the number of modes:

- $N = (2L/c)/[(2L/c)(1/N)]$

Thus to obtain ultra-short pulses, it is essential to have a large number modes.

As the optical pulsed beam passes through the gain medium for amplification and travels through various other mirrors and optical components in the laser cavity experiences phenomena like Self-Phase Modulation (SPM) that derived from the Kerr Lens Mode-Locking and Group Velocity Dispersion (GVD) that is induced from refraction effects of the beam that are caused form the various optical components that encounters in the cavity. These phenomena affect the pulse causing its refraction and turn it into a chirped-pulse, in order for the pulse to get rid the positive chirp, it is diverted through the cavity where it is introduced to the optical elements system that it consists of two prisms (BP) which will compensate for the dispersion.

5. *Compensation:* The optical system used in Titanium: Sapphire oscillator consists of a pair of prisms separated by a distance oriented in a specific way with respect to each other. The choice of a material, orientation and distance between the prisms is such that they introduce a net negative GVD, cancelling out the positive GVD from the rest of the system. The Group Velocity Dispersion Compensation scheme operates as follows: 1) A pulse eventually forms and travels back and forth through the cavity. It is chirped by the self phase modulation (SPM) in the Titanium: Sapphire medium and by group velocity dispersion (GVD) from the other various intra-cavity components such as beam splitters BFR and mirrors. 2) The chirped pulse enters the first prism. Since prisms bend or refract different wavelengths into different angles, the beam spreads as it is then diverted towards to the second prism. 3) The blue components are refracted and bent more severely than the red ones thus creating the possibility of wavelength dependent path lengths for the various rays. This system behaves just oppositely to most materials. The GVD of this system is said to be negative, since the blue part of the pulse travels through the system faster than the red part. 4) The magnitude of the GVD compensation can be controlled by the amount of glass in the prism (path adjustment). The overall system GVD of zero is achieved by orientating the prisms so the light travels through either more or less of the glass.

Finally the pulse passes through the output coupler which allows a part of the pulse to pass through to form the laser output and reflects the rest back for another round-trip of the system.

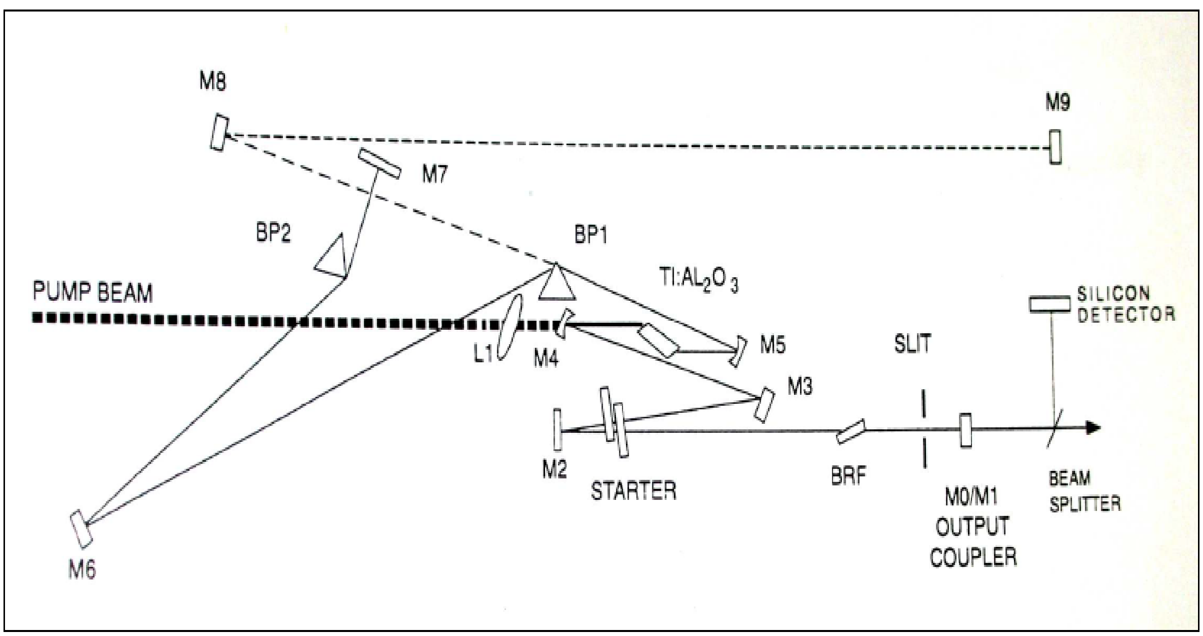
6. **Characteristics - Specifications:**

Is a tunable mode-locked $femto-$second solid-state laser which emits red and infrared light in the range 650 to 1100 nanometers with output energy-beam power at $650\ mili-$watts, central wavelength at $815nm$, repetition rate at $76Mhz$ with bandwidth greater than $50nm$ and pulse width lesser than $20\,fs$.

7. **Elements - Components:**

- Gain Medium, Titanium: Sapphire Crystal (Ti:Al2O3)
- Brewster Prisms
- Beam Splitter
- Focusing Lens
- Output Coupler
- Flat Cavity Mirrors
- Curved Mirrors
- Flat End Mirror
- Pump Fold Mirror

8. **Design:**



Chapter 4.4

Stretcher:

The pulsed output beam that comes out from the oscillator has to be further amplified to reach the limit intensity level of $giga-$watts per square centimeter. To avoid causing any damage to the gain medium during the amplification process the pulse's peak power level must be decreased prior to amplification. In order for that to be done the pulse needs to be stretched out temporally and spectrally. The wavelength dispersive optical system that is used for stretching out and broadening the pulse temporally and spectrally is called stretcher.

1. *Optical System Arrangement:* Its design is based on an all-reflective triplet combination. The triplet combination is composed of two gratings and a telescope system, which consists of two spherical concentric mirrors. The first mirror is concave and the second mirror is convex. This combination presents interesting properties for use in a pulse stretcher. It is characterized by a complete symmetry, so only the symmetrical aberration can appear (spherical aberration and astigmatism). This combination has no-axes coma and exhibits no chromatic aberration, because all the optical elements are mirrors.

2. *The Idea:* The principal is to create different optical paths for each wavelength of the spectrum. The optical stretching system is designed so that the Blue path is longer than the Red one. Therefore, Blue wavelengths take more time to travel through the system than Red ones. Due to Fourier transform properties, a $femto-$second pulse exhibits a broad spectrum (typically $30nm$ for a $30fs$ pulse). Since the bluer part of the spectrum is delayed compared to the redder part when traveling through the stretcher, the output pulse is stretched and looks like a temporal rainbow (red in the leading edge and blue in the trailing edge). The stretching factor depends on the spectral width of the input pulse and on the intrinsic characteristics of the stretcher (grooves density of the gratings, distance between the gratings, number of roundtrips in the stretcher, incidence angle, etc...). For a given stretcher configuration, the wider the input spectrum is, the longer the stretched pulse is.

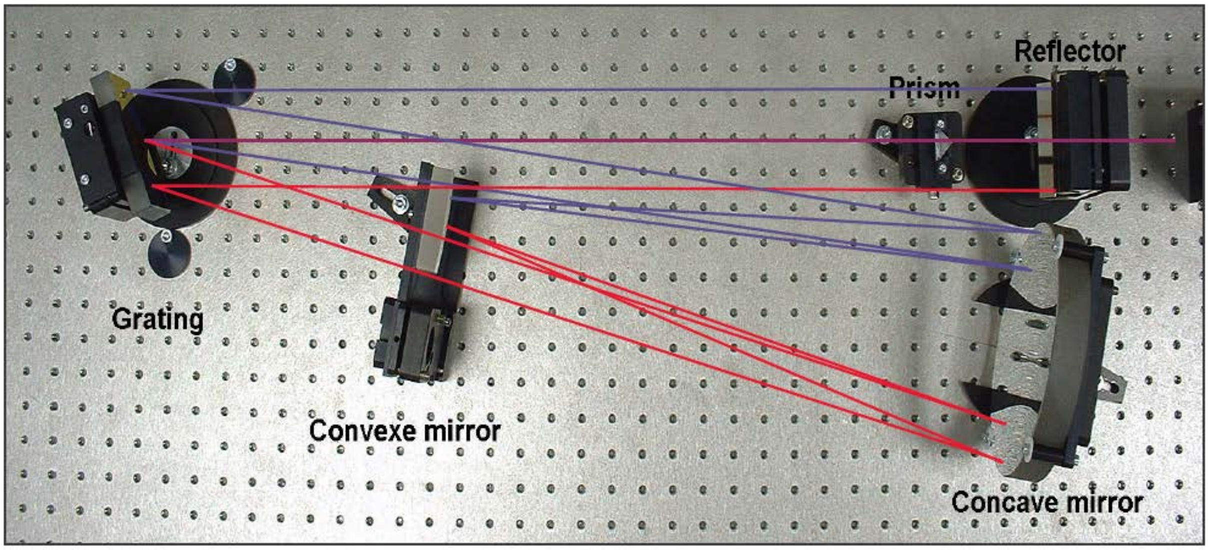


Figure 15: Typical aberration free stretcher design

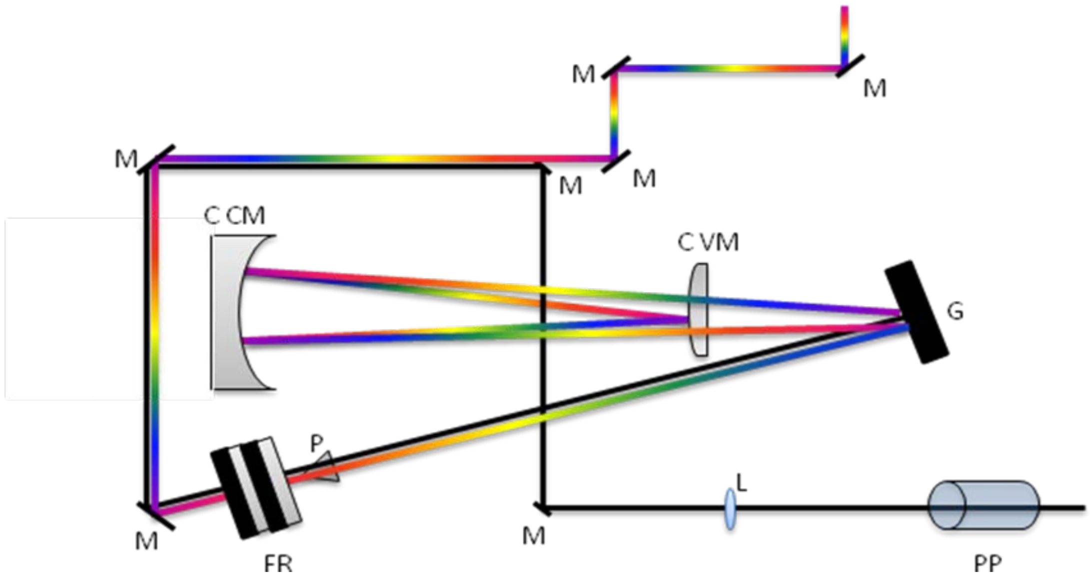
3. **Characteristics - Specifications:**

It is an optical system/arrangement that stretches out and broadens the pulse temporally and spectrally by a factor of 10^3 to 10^4 in order to reduce its peak power. The specifications of the system are strongly dependent on the oscillator performances. Also the pulse duration at the output of the stretcher is linearly dependent on the spectral bandwidth of the beam.

4. **Elements - Components:**

- Focusing Lenses
- Beam Splitters
- Gratings
- Flat mirrors
- Concave mirror
- Convex mirror
- Flat reflectors
- Prism
- Wedge Polarizers
- Pockels cell
- Half-Wave Plate

5. **Design:**



Chapter 4.5

Regenerative Amplifier + Multi-Pass Amplifier 1KHz:

Once stretched, the pulse can be amplified in several amplifier stages, using regenerative amplifier and multi-pass amplifiers. The housing of the regenerative amplifier and the 1KHz amplifier includes the Faraday isolator, the regenerative amplifier, the pulse cleaner and the multi-pass amplifier.

1. *Faraday Isolator:* The Faraday isolator consists of a Faraday rotator coupled with two broadband polarizer's and a half-wave plate. It prevents from feedback into the oscillator and thereby allows the alignment of the regenerative amplifier without pulse cleaner.

2. *Regenerative Amplification:* In this method the passes all follow the same path as the pulse is trapped in the resonator until it has extracted all the energy stored in the medium. The gain per pass becomes irrelevant in this case. The pulse is trapped using a Pockels cell and a broadband polarizer. Firstly the gain medium is pumped so that it accumulates energy, then a pulse is injected into the cavity through a Pockels cell. A voltage is applied to the Pockels cell and its polarization switches to trap the pulse in the resonator. The pulse then oscillates in the cavity and after many round-trips is amplified to a high energy. Finally, another voltage is applied to the Pockels cell to switch its polarization back and allow the pulse to leave the cavity.

3. *Regenerative Amplifier:* Is a laser cavity, which is seeded by a short pulse coming from the stretcher. The cavity geometry is optimized to produce large Gaussian beams from relatively short cavities. The injection and extraction of a short pulse in the amplifier is obtained by polarization switching in a Pockels cell. The pulses coming from the stretcher are vertically polarized. The injection polarizer reflects them and the polarization is flipped by 90^o after a round-trip in the Pockels cell. They are then transmitted through the polarizer and travel a round-trip in the cavity. After passing a second time in the Pockels cell the polarization is flipped back to vertical and the pulse exits the cavity by being reflected from the polarizer. In order to catch a pulse in the cavity, a quarter-wave voltage is applied on the Pockels cell when the pulse is between the polarizer and the rear mirror. This makes the Pockels cell equivalent to half-wave plate and a round-trip through the cells does not affect the polarization of the pulse. Successive passes through the Titanium: Sapphire crystal then amplify the pulse. When the pulse reaches its maximum energy it is dumped off the cavity by applying a second quarter-wave voltage step to the cell. When the beam coming from the stretcher is blocked, the regenerative amplifier acts as a $nano-$second cavity-dumped laser producing $8\ nano-$second square pulses. Using this regime is a convenient way of aligning the regenerative amplifier cavity.

4. *Pulse Cleaner:* It consists of five broadband polarizer's and a Pockels cell. This device allows the stretched pulse into the regenerative amplifier and sends the output beam to the amplifier by switching the polarization. This device is acting as a temporal gate and cleans the pre-pulses due to imperfections in the regenerative amplifier. The polarizer's located before the cell eliminate the pre-pulses that are horizontally polarized and increase the polarization quality of the main pulse (vertical). The Pockels cell is equivalent to a half-wave plate from the main pulse

when the high voltage is applied, and the vertically polarized pre and post pulses are then sent out by polarizer's located after the cell.

5. *Multi-Pass Amplification:* In this method, the different passes in a multi-pass amplifier are separated geometrically. However the greater the number of passes the more complex the design must be. The design is also limited by the difficulty of focusing each pass through the gain medium. Typically four to eight passes are made, with cascading multi-pass amplifiers used for a greater number of passes. The technique is desirable as it is relative inexpensive, but it needs time-consuming adjustments.

6. *Multi-Pass Amplifier:* Is a five-pass setup, that further amplifies the pulse. The pump beam and the infrared beam are brought to the same size in the amplifier crystal. The gain medium must also be used close to damage threshold to have a high gain per pass ratio.

So at the exit of the housing of the regenerative amplifier and the 1KHz amplifier there are two laser beams that are extracted. One laser beam with repetition rate at 1KHz and energy at $6\ mJoule$ per pulse, that goes straight to the 1KHz compressor in order to be compressed and another laser beam with repetition rate at $10\,\text{Hz}$ and energy at $0.7\ mJoule$ per pulse, that is being driven through the two multi-pass amplifiers in order to be further amplified before the compression process.

7. **Characteristics - Specifications:**

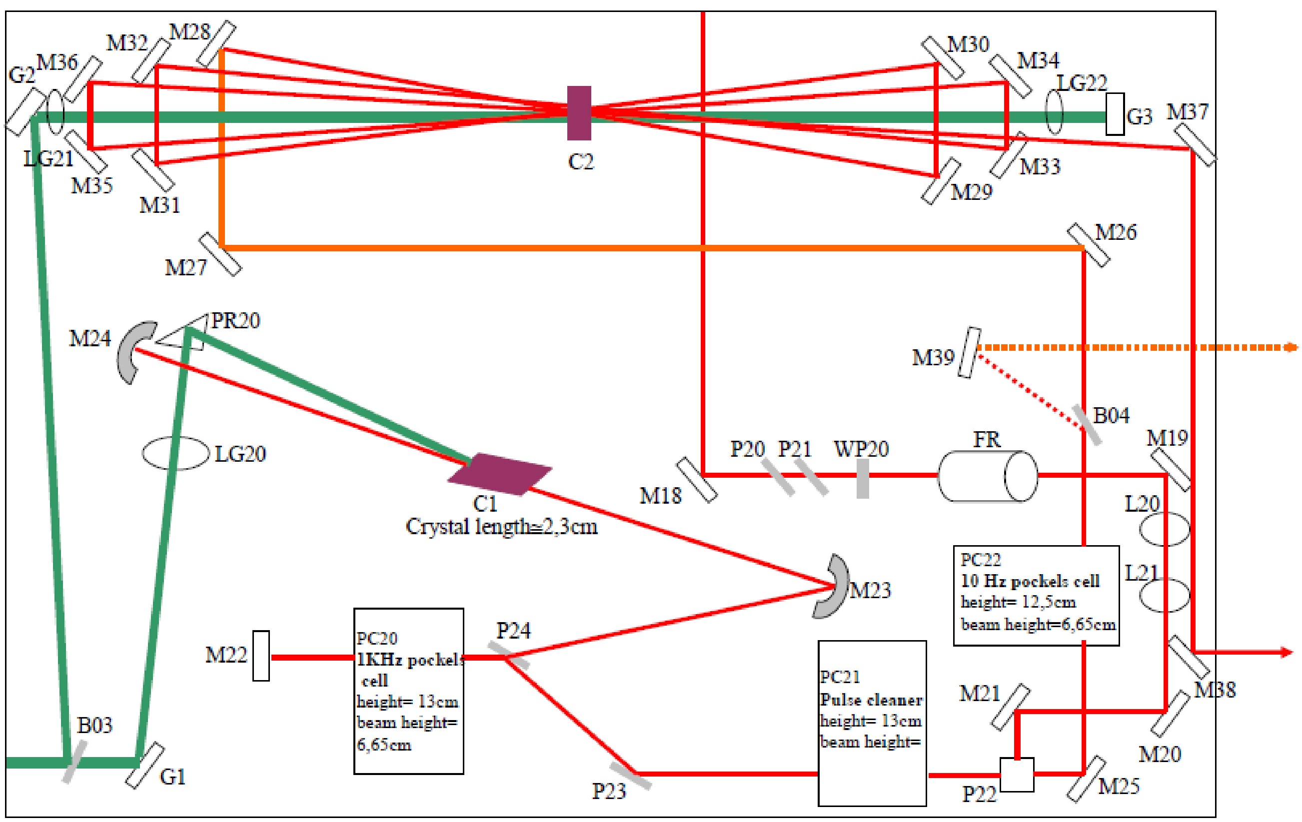
8. **Elements - Components:**

- Flat Mirrors 45^o, $800nm$
- Concave Mirrors 0^o, $800nm$
- Plane Mirror 0^o, $800nm$
- Flat Mirrors 45^o, $800nm$
- Polarizer's Rs
- Polarizer's Tp
- Faraday Isolator
- Wave-Plate

- Convex Lens 800*nm*
- Concave Lens 800*nm*
- Flat Mirrors 45°, 532*nm*
- Flat Mirror 0°, 532*nm*
- Convex Lenses 532*nm*
- Gain Mediums Titanium: Sapphire Crystal
- Prism
- Beam Splitters
- Pockels Cell 1KHz
- Pockels Cell 10 Hz
- Pulse Cleaner

9. Design:

Five pass 1KHz amplifier



Regenerative amplifier

Chapter 4.6

Two Multi-Pass Amplifiers 10 *Hz:*

After comes out from the regenerative amplifier, the laser beam with repetition rate at $10Hz$ and optical power less than $1mJoule$ per pulse, goes through the two multi-pass amplifies so that it can be further amplified.

1. *Two Multi-Pass Amplifiers* $10Hz$: The optical system that amplifies the stretched pulse is composed of two cascading multi-pass amplifiers with repetition rate at $10Hz$. Each amplifier is a four-pass set-up that consists of several optical reflective and focusing elements such as mirrors and lenses, the gain or amplifying medium and the pump power. The first set-up arrangement amplifies the pulse from about $0.7mJoule$ to $22mJoule$ the Titanium: Sapphire crystal is pumped by a CFR 200 Nd:YAG laser with optical power of $120mJoule$ at $532nm$ on both sides. The second set-up arrangement amplifies the pulse from about $20mJoule$ to $300mJoule$ the Titanium: Sapphire crystal is pumped by a Pro-pulse Nd:YAG laser with optical power of $900mJoule$ at $532nm$ on both sides.

Once amplified, the stretched pulse with repetition rate at $10Hz$ and optical power of $300mJoule$ is now ready to experience the last part of "chirped pulse amplification" (CPA), that is to go through the compressor and undergoes the compression process in order to be compressed back to its original duration.

2. **Characteristics - Specifications:**

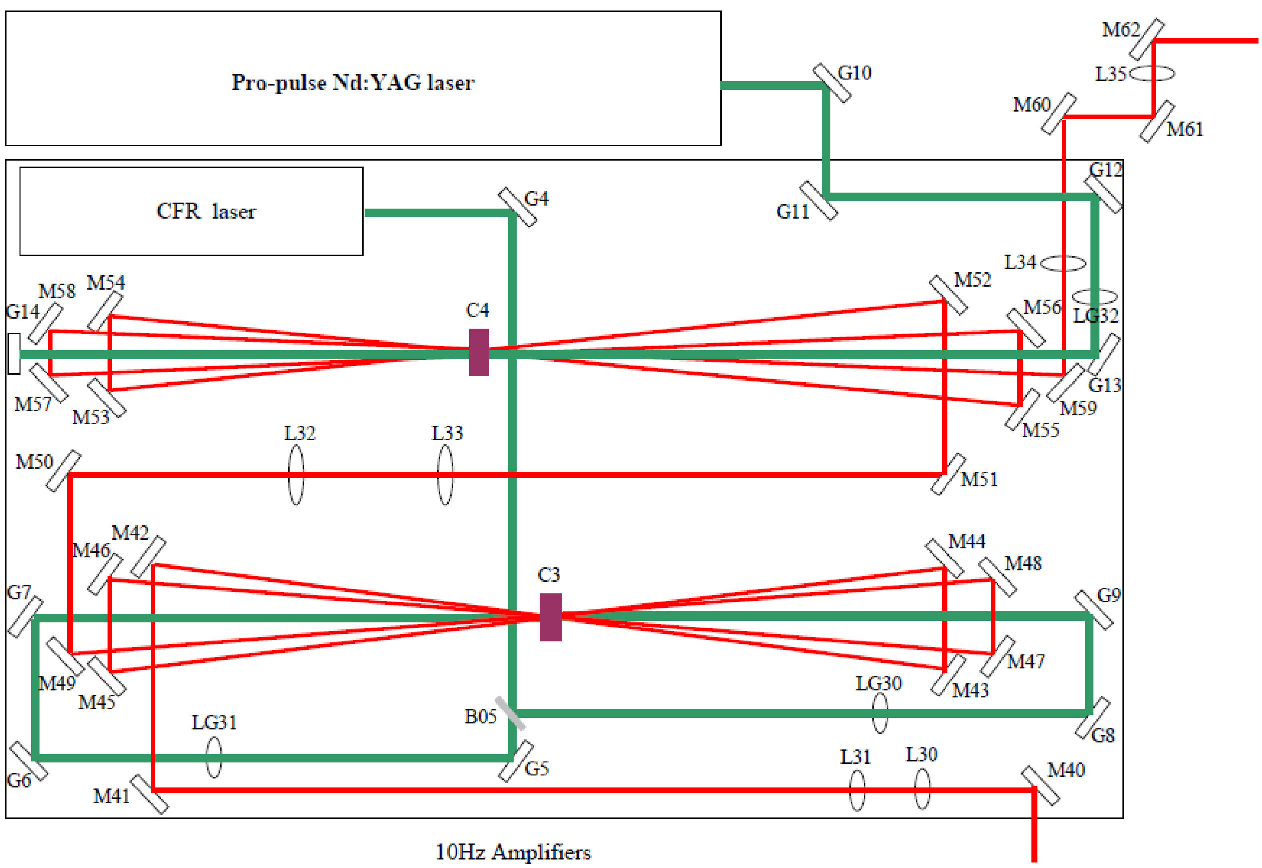
First Multi-Pass Amplifier: Is a four-pass set-up with input and output polarization linear vertical S, input energy $0.7mJoule$, wavelength at about $800nm$, repetition rate at $10Hz$ and output energy $22mJoule$ per pulse.

Second Multi-Pass Amplifier: Is a four-pass set-up with input and output polarization linear vertical S, input energy $20mJoule$, wavelength at about $800nm$, repetition rate at $10Hz$ and output energy $300mJoule$ per pulse.

3. **Elements - Components:**

- Flat Mirrors 45^o, $800nm$, $D = 2.54cm$
- Flat Mirrors 45^o, $800nm$, $D = 10cm$
- Flat Mirrors 45^o, $532nm$, $D = 2.54cm$
- Flat Mirror 0^o, $532nm$, $D = 2.54cm$
- Gain Medium Titanium: Sapphire Crystal
- Cylindrical Lenses
- Convex Lenses, $532nm$
- Beam Splitter

4. **Design:**



10Hz Amplifiers

4.7.2. The Idea: The compressor is theoretically able to compensate for the group delay dispersion (delay versus wavelength) of the pulse introduced by both the stretcher and the amplifier but the gratings are required to be perfectly aligned.

Chapter 4.7

Compressors $1KHz$ ***and*** $10Hz$***:***

Once the amplification process is completed, the pulse must be recompressed back to its original pulse width. This is achieved through the reversal process of stretching using a compressor, an optical device with opposite dispersion which removes the chirp and temporally compresses the pulse to a duration similar to the initial pulse duration.

1. *Optical System Arrangement:* Its design is based on a wavelength dispersion system similar to the stretcher. The optical system composed of two gratings and a telescope system, which consists of a high reflective mirror several flat mirrors a convex lens and a concave lens. In this particular set-up the two gratings with an optimized number of lines transmit the very broad spectrum bandwidth with excellent efficiency also the geometry of the stretcher is designed to obtain the flattest phase dispersion in the overall system.

2. *The Idea:* The compressor is theoretically able to compensate for the group delay dispersion (delay versus wavelength) of the pulse introduced by both the stretcher and the amplifier but the gratings are required to be perfectly aligned.

This group delay can be expended in a Taylor serie:

- $$\tau(\omega) = \tau_0 + \mathrm{A}(\omega - \omega_0) + \mathrm{B}\left(\omega - \omega_0\right)^2$$

The group delay is obtained by differentiation of the phase law:

- $$\phi(\omega) = \phi_0 + \phi_1(\omega - \omega_0) + \phi_2\left(\omega - \omega_0\right)^2 / 2 + \phi_3\left(\omega - \omega_0\right)^3 / 6 + \ldots$$

Hence that $A = \phi_2$ corresponds to the second order dispersion and $B = \phi_3 / 2$ corresponds to the third order dispersion.

In order to compensate for the group delay of the stretcher and the amplifier both the second and the third order dispersion terms must be adjusted. These terms depend on the grating groove density, compressor length and the angle of incidence on the grating. Since two conditions have to be fulfilling at once, two free parameters are needed. The angle of incidence on the grating and the compressor length are the two adjustable parameters of this system.

So, at the end of the complete Titanium: Sapphire system arrangement there are two compressors, one for the laser beam with repetition rate at $1KHz$ and energy $6mJoule$ per pulse that comes straight from the housing of the regenerative amplifier and the $1KHz$ amplifier and another one for the laser beam with repetition rate at $10Hz$ and energy $0.7mJoule$ per pulse that comes through the two multi-pass $10Hz$ amplifiers. Once the compression process is completed the laser beam at $1KHz$ has energy output $3mJoule$ per pulse and central pulse wavelength $800nm$ and the laser beam at $10Hz$ has energy output $150mJoule$ per pulse and central pulse wavelength $800nm$.

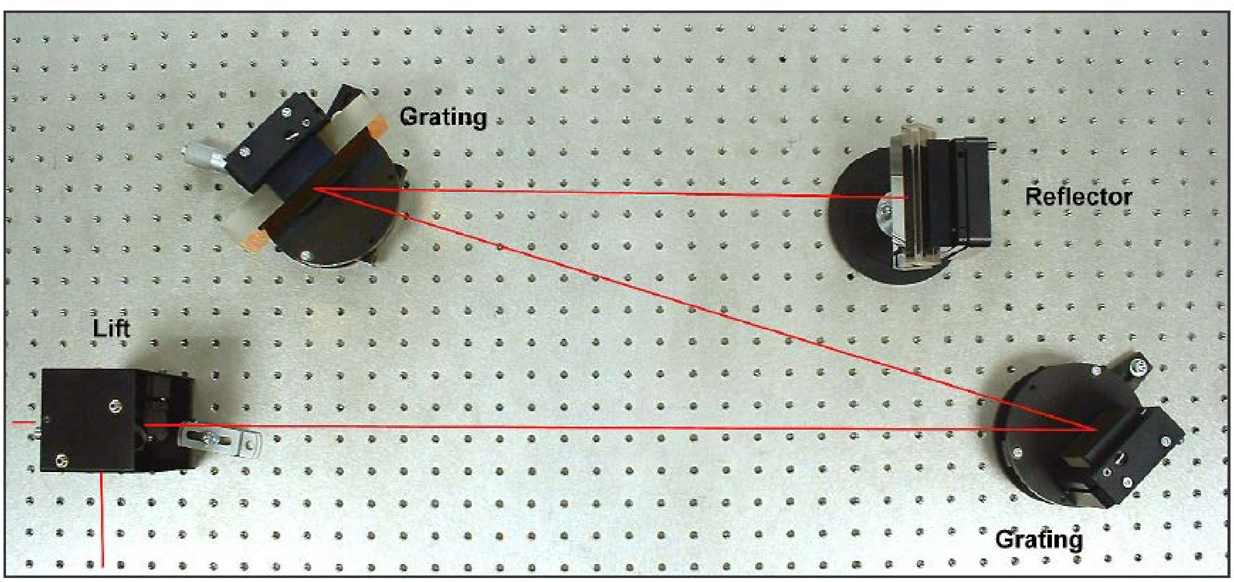


Figure 16: Typical compressor design

3. **Compressor** $1KHz$:

3.1. **Characteristics - Specifications:**

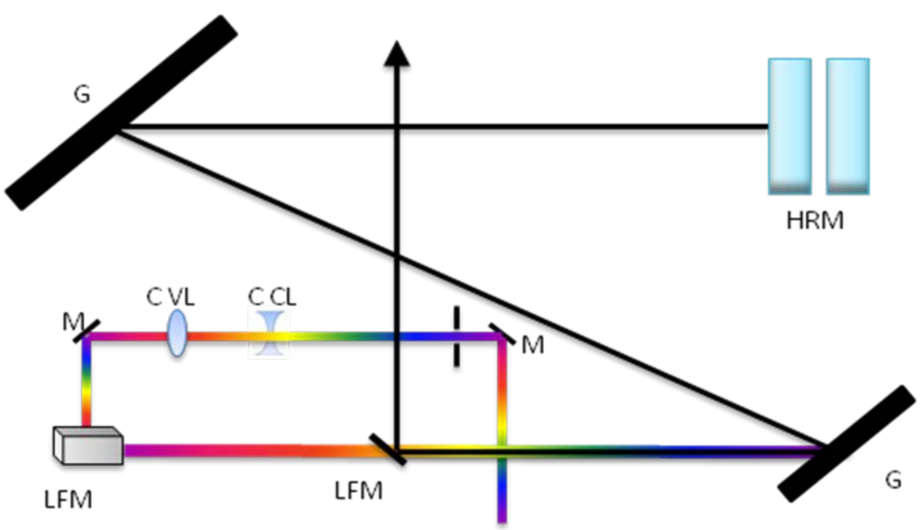
It is a optical system/arrangement that recompresses temporally the pulse back to its almost original duration in order to maximize its peak power. The specifications of the system are strongly dependent on the oscillator and the amplifiers performances.

Compressor $1KHz$: Input energy $6mJoule$ per pulse, output energy $3mJoule$ per pulse repetition rate $1KHz$, central wavelength about $800nm$, pulse duration $20\,fs$, spectral bandwidth about $24nm$.

3.2. **Elements - Components:**

- Flat Mirror
- Concave Lens
- Large Convex Lens
- Large Flat Mirrors
- Gratings
- High Reflective Mirror

3.3. **Design:**



4. **Compressor** $10Hz$ **:**

4.1. **Characteristics - Specifications:**

It is a optical system/arrangement that recompresses temporally the pulse back to its almost original duration in order to maximize its peak power. The specifications of the system are strongly dependent on the oscillator and the amplifiers performances.

Compressor $10Hz$: Input energy $300mJoule$ per pulse, input polarization linear vertical S, central wavelength about $800nm$, output energy $150mJoule$ per pulse, output polarization linear horizontal P, repetition rate $10Hz$, pulse duration $20\,fs$, spectral bandwidth about $24nm$.

Chapter 5

Ultra-Short Laser Pulses:

Ultra-short pulses are generated using mode-locked lasers and are defined as having a pulse duration of a few femto-seconds. In addition to ultra-short pulse duration, ultra-short pulses have a broad spectrum, a high peak intensity and can form pulse trains at a high repetition rate.

The electric field of a laser pulse can be written as:

- $E(t) = E_0(t)\exp i(\omega_0 t + \phi(t))$

where:

- $E_0(t) = E_0 \exp(-t/\tau)^2$

the amplitude of the electric field for a Gaussian laser pulse,

- $\phi(t) = A + Bt + Ct^2 + Dt^3 + ...$

the phase of the field in time domain, ω_0 the central frequency of the pulse and τ the pulse duration at Full Width at Half Maximum (FWHM).

The general time and frequency Fourier transformation of a pulse is:

- $E(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} E(t) \exp(-i\omega t) dt = IFT(E(t)) = E(\omega) \exp(i\omega t + \phi(\omega))$

the phase of the field in the frequency domain (or the spectral phase) is given by:

- $\phi(\omega) = \sum_{m=0}^{\infty} \frac{(\omega - \omega_0)^m}{m!} \left(\frac{\partial^m}{\partial \omega^m} \phi(\omega) \right)_{\omega=\omega_0} = \sum_{m=0}^{\infty} \frac{(\omega - \omega_0)^m}{m!} D_m$

The duration and spectral width of a pulse can then be calculated with standard statistical definitions:

- $\langle \Delta t \rangle = \frac{\int_{-\infty}^{+\infty} t |E(t)|^2 dt}{\int_{-\infty}^{+\infty} |E(t)|^2 dt}$

- $\langle \Delta \omega^2 \rangle = \frac{\int_{-\infty}^{+\infty} \omega^2 |E(\omega)|^2 d\omega}{\int_{-\infty}^{+\infty} |E(\omega)|^2 d\omega}$

These quantities can then be related by the following inequality:

- $\Delta t \Delta \omega \geq \frac{1}{2}$

The last equation is the product of pulse duration and spectral bandwidth and is known as the time-bandwidth product. In principal this means that in order to generate a short pulse of light with a specific duration Δt a broad spectral bandwidth $\Delta\omega$ is required. When equality to $\frac{1}{2}$ is reached in the last equation the pulse is called a Fourier Transform-Limited pulse. The variation in phase of such a pulse is beautifully uniform and so has linear time dependence; the instantaneous frequency is time dependent.

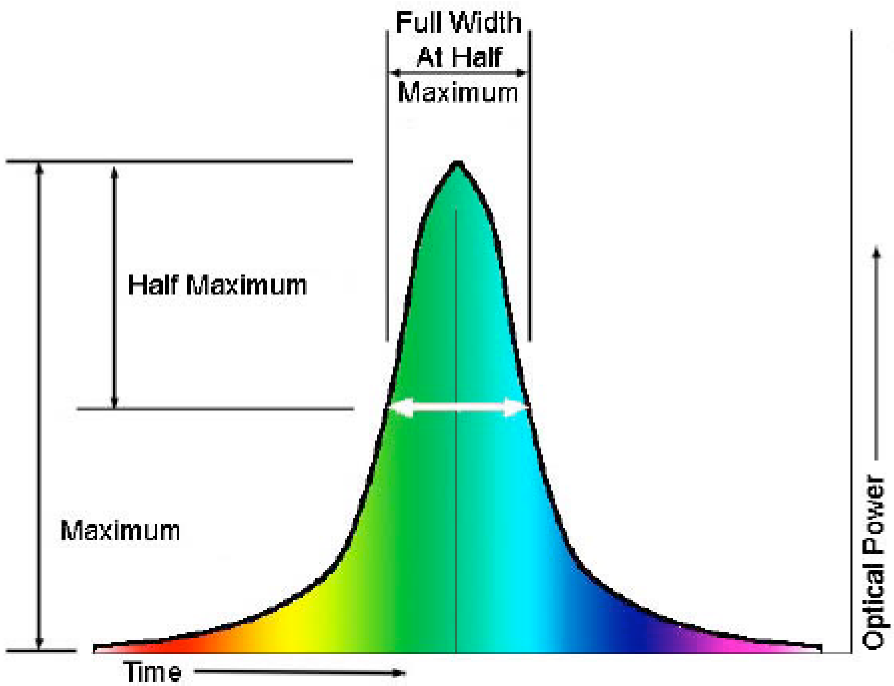


Figure 17: The measurement of 'Full Width at Half Maximum' of a pulse to find its duration

This can define pulse duration, though the more commonly used definition is based on the full width at half maximum (FWHM) principal of optical power against time, as in figure above because experimentally it is easier to measure. The inequality above then becomes:

- $\Delta f \Delta t \geq \mathrm{K}$

where Δf is the frequency at full width at half maximum and Δt is the duration at half maximum. The value K from the Table below depends upon the symmetrical shape of the pulse.

Shape	K
Gaussian function	0.441
Exponential function	0.140
Hyperbolic secant	0.315
Rectangle	0.892
Cardinal sine	0.336
Lorentzian function	0.142

Figure 18: Various values for K depending on the pulse shape

Chapter 6

Conclusions:

Mira Seed Titanium: Sapphire laser is pumped by a Verdi laser that provides a continuous wave single frequency green color at $532nm$ and output beam at power levels greater than $5watts$. Initially the Mira Seed Titanium: Sapphire laser operates in a continuous wave mode and the generation of ultra-short pulses or the mode-locked output can be started only with an external intervention by the means of knocking or vibrating an optical component of the starting mechanism in the laser cavity. Once the mode-locking technique is applied a periodic train of ultra-shorts pulse is emitted from the oscillator or the laser cavity with repetition rate at $76MHz$ pulse duration of $20fs$ pulse energy $3njoule$ per pulse and central wavelength at $815nm$. Now, the output pulsed beam that comes out from the oscillator needs to be further amplified for the pulses to carry more energy. To safely amplify the pulses avoiding any damage in the gain medium caused by non-linear effects such as self-focusing, a technique that is called chirped pulse amplification (CPA) is used. CPA is a technique that consists of three different stages using a separate device in each stage. The first device to partake in this process is called stretcher and it stretches out the pulse temporally and spectrally prior to amplification by a factor of 10^3 to 10^4 reducing its peak power to a level where detrimental effects in the gain medium and in other optical components are avoided. Once the pulse has passed the stretcher its duration is of around $200\,ps$. The second device to follow is called regenerative amplifier and $1KHz$ amplifier and is/are used to safely amplify the pulse within the damage threshold of the amplifying medium. The pulse is trapped inside the cavity and is amplified on each pass through the gain medium. At the exit of the housing of the regenerative amplifier and the 1KHz amplifier there are two laser beams that are extracted. One laser beam with repetition rate at 1KHz and energy at $6\ mJoule$ per pulse, and another laser beam with repetition rate at 10 Hz and energy at $0.7\ mJoule$ per pulse. For the $1KHz$ laser beam, the last part of the CPA process is the compression stage where a device called compressor is used to compress the pulse back to almost its original duration, compensating for the dispersion introduced from both the stretcher and the amplifiers. The laser beam that comes out from the $1KHz$ compressor has repetition rate $1KHz$, energy $6mjoules$ per pulse, pulse duration $20\,fs$, central wavelength $800nm$ and spectral bandwidth $24nm$. For the $10Hz$ laser beam, before is directed towards the $10Hz$ compressor to experience the compression process, is driven through the two multi-pass $10Hz$ amplifiers to undergo further amplification. After amplification the $10Hz$ laser beam has energy $300mJoule$ per pulse. Finally the beam passes through the $10Hz$ compressor completing the CPA process. After compression the laser beam has repetition rate $10Hz$, energy $150mjoule$ per pulse, pulse duration $20\,fs$, central wavelength $800nm$ and spectral bandwidth $24nm$.

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Chapter 4.4

Stretcher