TIMING ISSUES IN A TERAWATT LASER SYSTEM

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ABSTRACT

TIMING ISSUES IN A TERAWATT LASER SYSTEM

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In the laser market, there have been various kinds of lasers designed and utilized for different purposes. As time goes on, their powers have been gradually increased from kilowatts (kW) to terawatts (TW). One of the most famous methods in laser science technology is Chirped Pulse Amplification (CPA) which enables table-top terawatt laser systems. This method provides high output power (tens of TW), very short pulse duration (few tens of femtoseconds) and large energy (mJ) for ultrafast lasers. One of the most well-known ultrafast lasers is Titanium:Sapphire laser. This thesis work concentrates on how delay a pulse generator should work so that Verdi and the oscillator pulse coincide. Moreover, by assembling a terawatt laser system, the most important issues are timing between seed pulse and pump pulse and time delays of all components of this system; autocorrelator, pump source, photodiode, Pockels cell, stretcher and dazzler were examined. This timing and the time delays were separately identified for terawatt laser systems. In this study, the aim is to attain the terawatt level output by arranging pump and seed pulses timing and the time delay on the components of the laser system setup.

Keywords: Chirped pulse amplification, time delay, Ti:Sapphire laser

ÖZ

TERAWATT LAZER SİSTEMİNDEKİ ZAMANLAMA SORUNLARI

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Lazer alanında, farklı amaçlar için faydalanılan ve tasarlanan değişik lazer çeşitleri vardır. Zamanla bunların güçleri kilowatt seviyelerinden terawatt seviyelerine aşama aşama artmıştır. Lazer bilimi teknolojisinde en ünlü metodlardan biri masaüstü terawatt lazer sistemlerini sağlayan şekillendirilmiş darbe yükseltme yöntemidir. Bu metod, aşırı hızlı lazerler için yüksek çıkış gücü (terawattın 10'lu katları), çok kısa süreli darbe (femtosaniyenin 10'lu katları) ve yüksek enerji sağlar. Titanyum:Safir lazeri, bir aşırı hızlı lazer çeşitidir. Bu tez çalışması, bir lazer ile osilatörden çıkan sinyali çakıştırmak için sinyal jenaratörünün nasıl çalıştırılması gerektiği konusunda yoğunlaşmıştır. Bunlarla birlikte, Terawatt lazer sistemi kurarak bu sistemdeki en önemli parametre olan zamanlama konuları ve bu sistemin tüm bileşenleri, pompa kaynağı, fotodiyot, Pockels ünitesi, gerdirme ünitesi ve dezlır incelenmiştir. Bu çalışmada amaç pompalama ve besleme darbelerinin zamanlamasını ve lazer sistemindeki parçaların gecikme zamanlarını ayarlayarak sistemden terawatt seviyesinde çıkış gücü elde etmektir.

Anahtar Kelimeler: Şekillendirilmiş darbe yükseltme, geciktirme, titanyum-safir lazeri

To my family..

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ABBREVIATIONS

CLH	Compact Laser Head
CPA	Chirped Pulse Amplification
CW	Continuous Wave
EM	Electromagnetic
GHz	Gigahertz
GW	Gigawatt
KLM	Kerr-Lens-Mode-Locking
mJ	Millijoule
MDC	Mirror Dispersion Control
NEP	Noise Equivalent Power
NM	Nanometer
OC	Output Coupler
OPCPA	Optical Parametric Chirped Pulse Amplification
PW	Petawatt
RE	Ring Electrode
TE	Transverse Electrode
TEM	Transverse Electromagnetic Modes
Ti:Sa	Titanium Sapphire
TW	Terawatt

CHAPTER 1

INTRODUCTION

1.1 Outline

This thesis describes the time jitter issues and subsequent pulse amplification in a Chirped Pulse Amplification (CPA) Terawatt Laser system and the characterization of a Terawatt, femto-second Ti:Sapphire laser oscillator system and its components.

In the first chapter, the specifications and importance of the Terawatt laser is mentioned. The applications, historical background and terawatt laser system are given. The chirped pulse amplification method is also explained.

The Ti:Sapphire Laser is focused on in chapter 2. CPA system components, lasers' working principles and ultrafast lasers are described. The properties of Autocorrelator are mentioned. In addition, Ti:Sapphire spectrum and its graphics are discussed.

Chapter 3 indicates the first Amplifier Stage. Big Sky Laser (CFR 400), Photodetector, Pockel Cell, Dazzler, Stretcher and Compressor used in set-up are explained.

In chapter 4, multipass amplification is clarified. Both the expected events and time delays for the set-up are written and the solutions are presented.

The summary of this study is given in the final chapter.

1.2 Terawatt Lasers

The high power output of a terawatt laser source enables the study of many phenomena which have large energies such as x-ray generation through plasmas. By utilizing ultrashort laser pulses with durations as short as a few tens of femtoseconds (femtosecond is 10^{-15} seconds), laser pulses with power as high as tens of terawatts (Terawatt equals 10^{12} Watt) can be performed in table-top sized lasers. These studies have importance in fundamental sciences such as physics, biology and chemistry. In physics, x-ray generation and plasma physics are the basic application of terawatt lasers and their systems. Potential applications of terawatt lasers considering x-ray generation and plasma physics include ultrahigh-order harmonic generation, photo-ionization pumped x-ray lasers, optical field ionization x-ray lasers, laser wakefield particle acceleration, laser-induced nuclear photophysics, laboratory-based astrophysics, and fast igniter fusion [1].

There have been significant advances in the application of high-power short-pulse lasers to the study of various nonlinear effects under high-intensity optical fields. These studies include multiple-harmonic generation, multiphoton ionization and above-threshold ionization in atomic gases and light absorption in very short scale length plasmas and generation of ultra short x-ray pulses in solid targets. Possible applications to beat wave acceleration, photo ionization-pumped x-ray lasers, plasma x-ray lasers, and pair production in vacuum or in plasmas have been proposed [2].

By focusing on biology and chemistry in defense; these ultra short, femtosecond light pulses have an important role in remote sensing and energy based weapons, additionally, material processing, atmospheric studies, environmental air pollutant monitoring, telecommunications, spectroscopy, radiography, mammography and eye surgery are also some application areas of these types of lasers.

1.3 Background

The laser was invented at the beginning of 1960s. After the invention of the laser, it grew more powerful from the 1970s onward. Some of the pioneering work on different subjects of laser was done at the CEA-Saclay, France, by the group of Mainfray and Manus [2], as well as the discovery of above-threshold ionization by Agostini et al. [3].

Another ground-breaking event during this period, prompted by the development of chirped pulse amplification, was the prediction of high-harmonic generation via recombination of multiphoton-ionized electrons by Shore and Knight [4] and the discovery of the above-threshold ionization by Agostini [5]. This phenomenon was confirmed experimentally soon afterwards by McPherson et al. and Ferrat et al. [6, 7].

Chirped-pulse amplification (CPA), which since its first application to lasers by Gerard Mourou and co-workers in 1985 [8, 9] is now a wide-spread technique in the building of high-power laser systems. An extension of CPA - optical parametric chirped pulse amplification, or OPCPA - has been proposed by Ross *et al.,* (1997) [10, 11] optical parametric chirped-pulse amplification (OPCPA) is one of the most powerful techniques in the generation of a high-energy short duration laser pulses [12, 13]. Its major advantages include high gain, high contrast and high beam quality while maintaining ultrabroad spectral bandwidth. Moreover, the demonstration of the self-mode-locked Ti:Sapphire laser is made by Sibbet and his group in 1990 [14].

The evolution of the CPA systems with respect to pulse duration is demonstrated in figure 1.1 (reference numbers in the figure correspond to that given [1]) for Ti:Sapphire Laser which was first developed in 1991 [1].

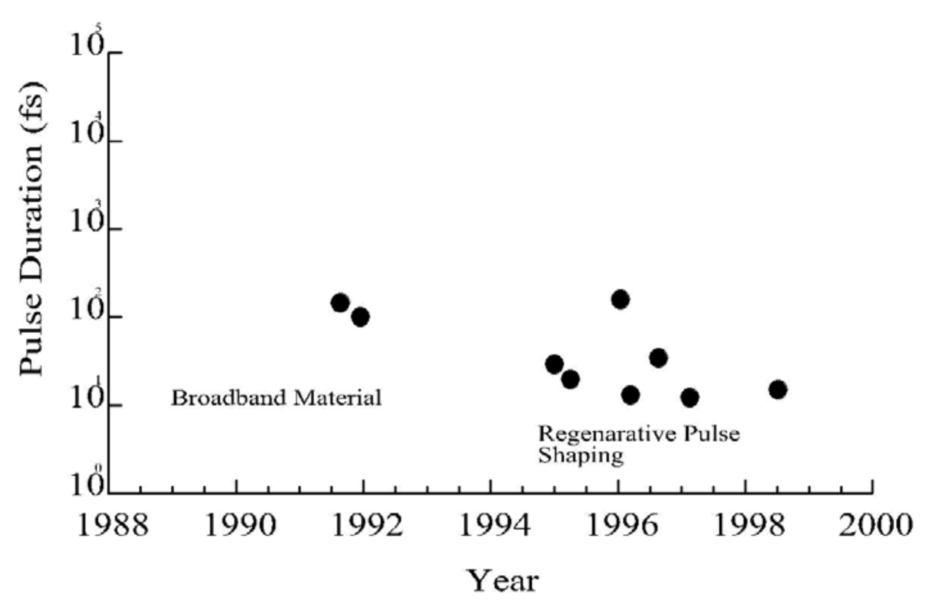

Figure 1.1 Development of Ti-Sapphire Laser

The Ti:Sapphire Terawatt laser was installed in 1992 by the means of CPA method. It has been upgraded several times over the years and is still a state of the art CPA laser. The Jaws at Del Mar Photonics in San Diego multi-terawatt laser system is the first commercially available terawatt pulse laser operating in the near infrared at 1240 nm [13]. The world's most powerful commercial Terawatt (TW) lasers are built by Continuum's Custom Laser Group. Continuum produced the first commercially available Ti:Sapphire Terawatt system in 1992. Since then, Continuum has been producing systems with ever increasing technological advances [12].

The NRL high field physics laboratory was one of the first laboratories to have a table-top terawatt laser system soon after the invention of the chirped pulse amplification (CPA) method.

1.4 Issues and Development of CPA

Amplified laser output has been a problem in the early history of the development of high power lasers. Nonlinear response of a material can be described by introducing a proportional to laser intensity I [W/cm^2] additive to a refractive index at low intensity n_0.

$$n = n_0 + n_2 I \tag{1.1}$$

where, n is index of refraction and n_2 [cm^2/W] is a material dependent nonlinear index coefficient. Remarkably, this simple formula describes vast majority effects in short pulse lasers. Phase of the laser electric field not only depends on intensity according to the Equation 1.1 but also parametrically depends on spatial coordinates and time through the dependence of I on space and time. The spatial dependence leads to intensity dependent focusing lens (Kerr-lens) for beams with larger intensity in the center (most common case) causing beam self-focusing. The temporal dependence causes generation of new frequencies through self-phase-modulation and together with the Kerr-lens provides the most effective modern short-pulse generation mechanism- Kerr-lens-mode-locking (KLM).

Solids are the most efficient laser materials but n_2 in solids is high enough to cause catastrophic (leading to material damage) self-focusing of a laser beam at intensities in the GW/cm^2 range. Efficient extraction of the energy stored in the laser active medium requires that output fluence should be the order of the medium saturation fluence. Typically saturation fluence for solid state laser materials ranges between 1 and 10 J/cm^2, therefore only pulses of nanosecond duration or longer could efficiently be amplified without damaging the laser. Although picosecond lasers were developed, the output fluence for those lasers had to be kept well below saturation fluence to avoid material damage caused by self-focusing. In femtosecond range of the pulsewidth, dye femtosecond lasers were developed but dyes have very low saturation fluence (mJ/cm^2) which resulted in relatively low power. Self-focusing intensity limit kept high power solid state lasers bulky and expensive until introduction of CPA by G. Mourou et al. [15] in late 80s because increasing a beam size seemed to be the only way to increase the output power. D. Strickland and G. Mourou proposed this new technique called “Chirped-pulse amplification (CPA)” with solid state lasers so as to produce high power laser light in 1985 [8].

The technique of CPA has opened new avenues for the production of very high-energy ultrashort duration pulses. This technique also preserves amplifiers and optical components from optical damage. The combination of CPA and ultra broadband solid-state laser materials has made it possible to produce terawatt and even multiterawatt femtosecond pulses with ever increasing average powers. It has been upgraded several times over the years and is still a state of the art CPA laser. It is a solid state laser involving two laser media, titanium doped sapphire (Ti:Sapphire) and neodymium doped glass (Nd:glass). Ti:Sapphire is lasing at the infrared wavelength of 810 nanometers (nm equaling 10^{-9} meters). The lasing wavelength of the Nd:glass is in the infrared at 1064 nm.

Ti:Sapphire is almost an ideal material for CPA lasers. It exhibits excellent mechanical and thermal properties and the largest bandwidth of the laser transition - 230 nm. The saturation fluence of Ti:Sapphire (0.9 J/cm^2) allows efficient energy extraction at sub-nanosecond pulsewidth below damage threshold of dielectric coatings. The only problem with Ti:Sapphire - relatively short lifetime of the upper laser level- 3 ms, makes laser pumping necessary. Frequency doubled Nd:YAG, Nd:YLF, and Nd:glass lasers are used to pump Ti:Sapphire. High energy Nd:YAG lasers with output energy up to 4 J at the wavelength 532 nm and 10 Hz repetition rate are commercially available. Larger energy can be extracted from Nd:glass lasers and is used to pump Ti:Sapphire at lower repetition rate or even on a single shot basis. Ultimate limitation of the output energy is imposed by the available crystal size. Currently, good optical quality crystals of up to ~10 cm diameter are commercially available (Crystal Systems). It means that up to 150 J can be potentially extracted in a single beam (assuming extraction at twice the saturation fluence value). The bandwidth is mainly limited by gain narrowing and can reach 40-50 nm with shaping of the input spectrum. The gain flattening using spectrally selective elements like etalon or birefrengent filter provide spectrum up to 80 nm and pulsewidth below 20 fs.

Lasers with output powers of 50 TW and above at about 30 fs pulse pulsewidth and 10 Hz repetition rate are currently operational at several laboratories (University of Michigan (USA), LOA (France), JAERI (Japan), and MBI (Germany)). A 200 TW single shot laser with longer pulsewidth (100 fs) is built in LLNL. A Petawatt [6] single shot laser is built at JAERI. Recently at the University of Michigan on HERCULES laser we achieved power of 300 TW in 30 fs at 0.1 Hz repetition rate [7].

1.4.1 CPA System Components

The CPA technique consists of four basic components: an oscillator; a stretcher; an amplifier; and a pulse compressor..

In CPA, a low-energy and long-duration chirped pulse is amplified to a high energy with a broad-bandwidth solid-state laser extracting its high-stored energy. The amplified pulse is then compressed to a bandwidth-limited short pulse with a pair of gratings. There are several technical issues to be considered applying the CPA technique to generation of a laser pulse of very short duration and very high peak power. The first issue is the limit to the pulsewidth which is determined by the bandwidth of the amplifying medium. The second issue is the maximum power available with the CPA technique, which will be limited by the damage of the gratings used for pulse compression [2].

In ultrafast CPA, a short pulse is generated by a mode-locked laser oscillator and is temporally stretched by an antiparallel grating pair pulse expander. The low-energy and long duration chirped pulse is then amplified to a high energy commensurate with the saturation fluence of the solid-state laser amplifiers. The amplified pulse is then compressed to a transform-limited short pulse of high peak power with a parallel grating pair compressor. Over the past 2 decades, peak powers from terawatt CPA systems have steadily increased from less than a terawatt initially to a record of 1500 TW which is equal to 1.5 PW. At the same time, pulse durations have steadily decreased from greater than a picosecond such as a few tens of femtoseconds. Extremely modest amounts of energy can now be used to achieve multiterawatt peak powers [1].

As the laser pulse is amplified, the power and the intensity of the pulse continuously increases and will reach the breakdown threshold of the laser glass medium. To avoid such consequences, the CPA technique stretches the laser pulse after the oscillator with a diffraction grating to 10000 times and thus reduces the laser intensity and power by the same factor. The stretched pulse can now be safely amplified to the desired high energy per pulse. The stretching process is then reversed by re-compressing and amplified pulse with diffraction gratings in air or vacuum to produce a high power, ultra-short pulse.

The start of our laser system is a femtosource Ti:Sapphire oscillator pumped by a 532 nm Green 6 W Coherent Verdi laser. This laser oscillator produces pulses around 800 nm with pulse duration of about 15 femtoseconds and pulse energies of about 5 nanojoules.

CHAPTER 2

TITANIUM:SAPPHIRE LASER

2.1 How lasers work

Lasers come in wide variety of forms, and the processes that go on inside them differing greatly from one type of laser to another, but all lasers contain an energized substance that can increase the intensity of light passing through it. This substance is called the amplifying medium or sometimes, the gain medium, and it can be a solid, a liquid or a gas. A laser includes at least two mirrors, active medium and pump.

Whatever its physical forms, the amplifying medium must contain atoms, molecules or ions which can store energy that is subsequently released as a coherent light. In a solid state laser the amplifying medium is a crystal containing laser ions of lanthanides (Nd, Er, Yb, and others, or transition elements, Cr, Ti, Ni). In a dye laser, it is a solution of a fluorescent dye in a solvent such as methanol. In a gas laser, it is a mixture of the gases for example helium and neon in helium-neon one. In a laser diode, it is a thin layer of semiconductor material sandwiched between other semiconductor layers.

Increasing the intensity of a light beam that passes through an amplifying medium amounts to putting additional energy into the beam. In laser terminology, the process of energizing the amplifying medium is known as "pumping". A laser consists of a pumped amplifying medium positioned between two mirrors as indicated below figure 2.1. The purpose of the mirrors is to provide what is described as 'positive feedback'. This means simply that some of the light that emerges from the amplifying medium is reflected back into it for further amplification. An amplifier with positive feedback is known as an oscillator.

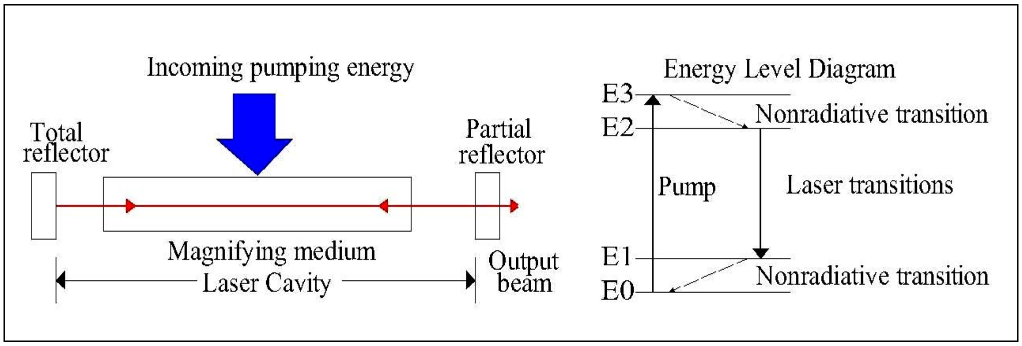

Figure 2.1 Laser Cavity

The space between the two mirrors is known as the laser cavity as shown in the figure 2.1. The beam within the cavity undergoes multiple reflections between the mirrors and is amplified each time it passes through the amplifying medium. One of the mirrors reflects almost all of the light that falls upon it (total reflector in the above diagram). The other mirror reflects between 20% and 98% of the incident light depending upon the type of laser, the light that is not reflected being transmitted through the mirror. This transmitted portion constitutes the output beam of the laser.

Now the question is how an amplifying medium amplifies light. A photon of light is absorbed by a laser atom (ion) in which one of the outer electrons is initially in a low energy state (Fig. 2.2). The energy of the atom is raised to the upper energy level and remains in this excited state for a period of time that is typically less than

10^{-6} second. It then spontaneously returns to the lower state with the emission of a photon of light.

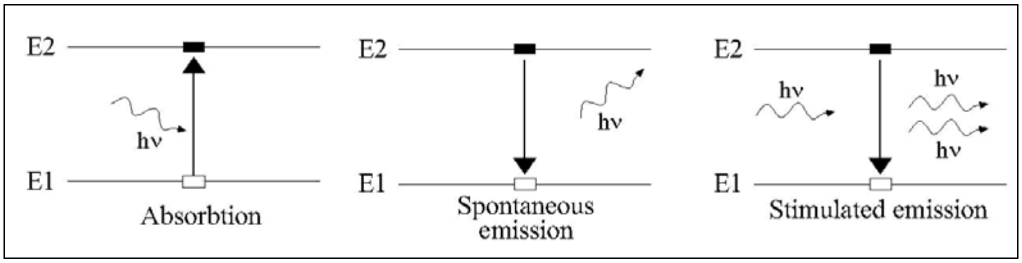

Figure 2.2 Absorption, spontaneous and stimulated emissions

Absorption is referred to as a resonant process because the energy of the absorbed photon must be equal to the difference in energy between the low and upper levels. Similarly, the photon emitted will have energy equal to the difference in energy between the two energy levels. These common processes of absorption and spontaneous emission cannot give rise to the amplification of light.

If a photon of light interacts with the excited atom, it can stimulate a return to the lower state. One photon interacting with an excited atom results in two photons being emitted. When a number of these in-phase wave trains overlap each other, the resultant radiation field propagates in the one direction. Stimulated emission is the process that can give rise to the amplification of light. If stimulated emission is to predominate, we must have more atoms in the higher energy state than in the lower one. This unusual condition is referred to as a population inversion and it is necessary to create a population inversion for laser action to occur.

Surely laser cavity is also very important for a laser in many other aspects; for example, its dimension decides the longitudinal laser modes. Modes are the standing oscillating electromagnetic waves which are defined by the cavity geometry. Generally speaking a light mode means possible standing electromagnetic (EM) waves in a system. The number of modes in this meaning is huge. Laser mode means the possible standing waves in laser cavity. We see that stimulated lights are transmitted back and forth between the mirrors and interfere with each other as a result only light whose round trip distance is integer multiples of the wavelength λ can become a standing wave. That is:

$$m = 2L/(c/\nu) = 2L/\lambda \text{ , or } \nu = m\, c/(2L),\ \Delta\nu = c/(2L) \tag{2.1}$$

where L is the length of cavity, c is the light speed in laser cavity, ν is the frequency of standing wave, λ is the wavelength, m is an integer, $\Delta\nu$ is the frequency difference between two consecutive modes. The number of longitudinal modes may be very large; it can also be as small as only a few (below 10).

When these modes oscillate, they interfere with each other, forming the transverse standing wave pattern on any transverse intersection plane. This mechanism decides the Transverse Electromagnetic Modes (TEM) of the laser beam, which is the wave pattern on the output aperture plane. We use the sign TEM_{mnq} to specify a TEM mode, where m is the number of radial zero fields, n is the number of angular zero fields, q is the number of longitudinal fields, and we usually use TEM_{mn} to specify a TEM mode, without the third index. A table of TEM patterns is shown in figure 2.4. Clearly, the mode pattern affects the distribution of the output beam energy. Clearly, the higher the order of the modes the more difficult it is poor to focus the beam to a fine spot. That is why some times TEM_{00} mode or Gaussian beam is preferred.

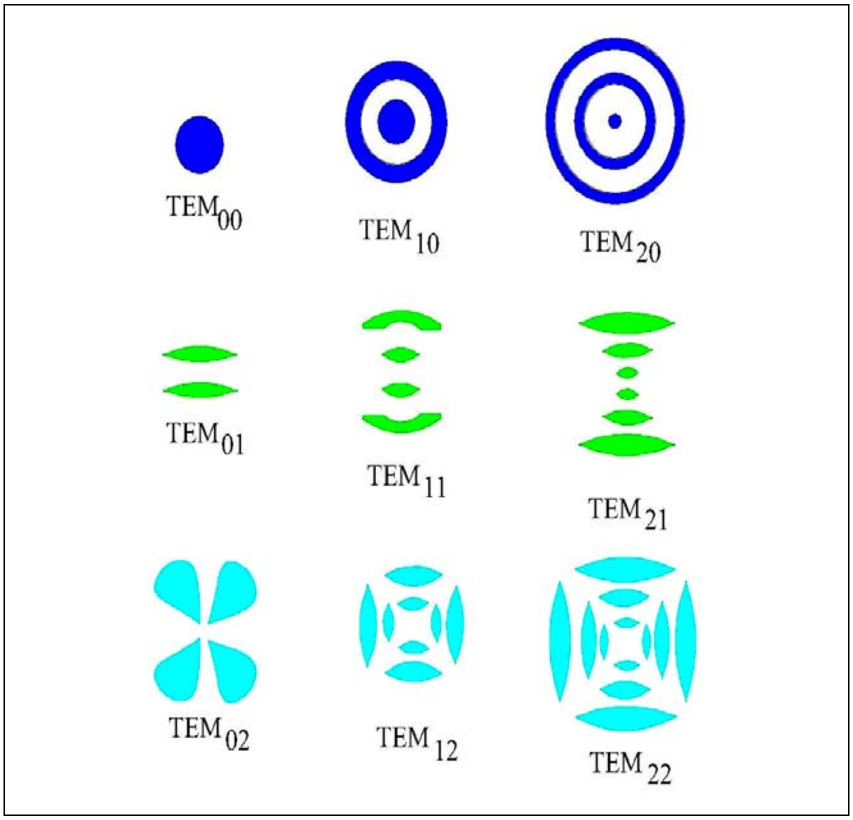

Figure 2.3 Laser Transverse Modes.

Finding substances in which a population inversion can be set up is central to the development of new kinds of laser. The first material used was synthetic ruby. Ruby is crystalline alumina (Al_2O_3) in which a small fraction of the Al_3^+ ions have been replaced by chromium ions, Cr_3^+. It is the chromium ions that give rise to the characteristic pink or red color of ruby and it is in these ions that a population inversion is set up in a ruby laser.

City College of the City University of New York has played a pioneering role in the development of tunable solid-state lasers based on the Cr^{+4} ion. Chromium-doped for sterite ($Cr:Mg_2SiO_4$) lasers tunable in the 1.13 - 1.37 mm range.

2.2 Ti:Sapphire

Titanium-doped sapphire is denoted by Ti:Sapphire or Ti^{3+}:Sapphire. It is a widely used transition-metal-doped gain medium for tunable lasers and femtosecond solid-state lasers. It was introduced in 1986 [16] and thereafter Ti:Sapphire lasers have developed in the fields of ultrashort pulse generation and widely wavelength tunable lasers. Ti:Sapphire is the material of choice for ultrashort-pulse, 50 fs, high average power applications due to its large gain bandwidth and excellent thermal properties. Ti:Sapphire would be the optimal material for the generation of high-intensity pulses, except for its short lifetime 3 ms and location of absorption band 400–600 nm which results in difficulties in producing simple pump sources [17].

Ti:Sapphire lasers are also very convenient for pumping test setups of solid-state lasers (e.g. based on neodymium- or ytterbium-doped gain media), since they can easily be tuned to the required pump wavelength and allow one to work with very high pump brightness because of high output power of typically several watts and their good beam quality. Some basic properties of the Ti:Sapphire gain medium (given in table 2.1 [18]) are as follows.

- Sapphire whose chemical formula is Al_2O_3 has an excellent thermal conductivity given in table 2.1.
- The Ti^{3+} ion has a very large gain bandwidth, allowing the generation of very short pulses and also wide wavelength tunability while it uses a birefringent tuner. The maximum gain and laser efficiency are obtained around 800nm. The possible tuning range is between ~650 nm and 1100 nm.
- There is also a wide range of possible pump wavelengths. Those wavelengths are located in the green spectral region, where powerful laser

diodes are not available. In most cases, several watts of pump power are used. For instance, 20 Watt is enough to pump for a Ti:Sapphire laser. Originally, Ti:Sapphire lasers were in most cases pumped with 514-nm argon ion lasers. Although Argon ion lasers are powerful, they are inefficient, expensive and bulky. Other kinds of green lasers are now available. Additionally, frequency-doubled solid-state lasers based on neodymium-doped gain media are widely used. The pump wavelength is typically 532 nm.

- The upper-state lifetime of Ti:Sapphire is short such as 3.2 μs. The pump intensity needs to be high, since the saturation power of Ti:Sapphire is very high. Therefore, a pump source with high beam quality is required for operations.
- Ti:Sapphire has huge emission bandwidth and high laser cross sections [18].

Table 2.1 Special Properties of Ti:Sapphire

Property	**Value**
chemical formula	$Ti^{3+}:Al_2O_3$
crystal structure	Hexagonal
mass density	3.98 g/cm^3
tensile strength	400 MPa
melting point	2040 °C
thermal conductivity	33 W/(mK)
thermal expansion coefficient	$\sim 5\times10^{-6}K^{-1}$
thermal shock resistance parameter	790W/m
Birefringence	negative uniaxial
Refractive index at 633 nm	1.76
temperature dependence of refractive index	$13\times10^{-6}K^{-1}$
Ti density for 0.1% at. Doping	$4.56\times10^{19}cm^{-3}$
fluorescence lifetime	3.2μs
emission cross section at 790 nm	$41\times10^{-20}cm^2$

2.3 Ultrafast lasers

Ultrafast lasers, which generate optical pulses in the picosecond and femtosecond range, have progressed over the past decade from complicated and specialized laboratory systems to compact, reliable instruments. Semiconductor lasers for optical pumping and fast optical saturable absorbers, based on either semiconductor devices or the optical nonlinear Kerr effect, have dramatically improved these lasers and opened up new frontiers for applications with extremely short temporal resolution (much smaller than 10 fs), extremely high peak optical intensities (greater than 10 TW/cm^2) and extremely fast pulse repetition rates (greater than 100 GHz). Six years after the first laser was demonstrated, De Maria and co-workers [19] produced the first ultrashort pulses, estimated to be just picoseconds long, using a passively modelocked Nd:glass laser.

Modelocking is a technique that generates ultrashort pulses from lasers. We distinguish between active and passive modelocking, and the latter can generate much shorter pulses using saturable absorbers. Modelocking is used to generate ultrashort pulses from lasers. A schematic set-up with a gain and a loss element inside a laser resonator is shown in figure 2.5. An output coupler partially transmits a small fraction of the laser pulse out of the laser resonator equally spaced by the resonator round-trip time. Typically an intracavity loss modulator is used to collect the laser light in short pulses around the minimum of the loss modulation with a period given by the cavity round-trip time $T_R = 2L/v_g$, where L is the laser cavity length and v_g the group velocity (that is, the propagation velocity of the peak of the pulse intensity). There are two type of modelocking: passive and active as shown in the figure 2.5. For active modelocking, an external signal is applied to an optical loss modulator typically using the acousto-optic or electro-optic effect. Such an electronically driven loss modulation produces a sinusoidal loss modulation with a period given by the cavity round-trip time T_R. The saturated gain at steady state then only supports net gain around the minimum of the loss modulation and therefore only supports pulses that are significantly shorter than the cavity round trip time.

For passive modelocking, a saturable absorber or Kerr lens are used to obtain a self-amplitude modulation of the light inside the laser cavity. Such an absorber introduces some loss to the intracavity laser radiation, which is relatively large for low intensities but significantly smaller for a short pulse with high intensity. Thus, a short pulse then produces a loss modulation because the high intensity at the peak of the pulse saturates the absorber more strongly than its low intensity wings. The loss modulation with fast initial loss saturation (that is, reduction of the loss) is determined by the pulse duration and typically a somewhat slower recovery that depends on the detailed mechanism of the absorption process is in the saturable absorber. In effect, the circulating pulse saturates the laser gain to a level that is just sufficient to compensate for the losses from pulse itself, although any other circulating low-intensity light experiences more loss than gain and thus dies out during the following cavity round-trips. The obvious remaining question is how passive modelocking starts. Ideally, it starts from normal noise fluctuations in the laser. One noise spike is strong enough to significantly reduce its loss in the saturable absorber and thus will be more strongly amplified during the following cavity round trips, so that the stronger noise spike continues to further reduce its loss and continues its growth until reaching steady state, where a stable pulse train has been formed. Generally, we can obtain much shorter pulses with passive modelocking using a saturable absorber, because the recovery time of the saturable absorber can be very fast, resulting in a fast loss modulation. Modelocked pulses are much shorter than the cavity round-trip time and therefore can produce an ideal fast loss modulation that is inversely proportional to the pulse envelope. In comparison, any electronically driven loss modulation is significantly slower because of its sinusoidal loss modulation. In the time domain, this means that a modelocked laser produces an equidistant pulse train, with a period defined by the round-trip time of a pulse inside the laser cavity T_R and a pulse duration τ_p. In the frequency domain, this results in a phase-locked frequency comb with a constant mode spacing that is equal to the pulse repetition rate $\nu_R = 1/T_R$.

The spectral width of the envelope of this frequency comb is inversely proportional to the pulse duration.

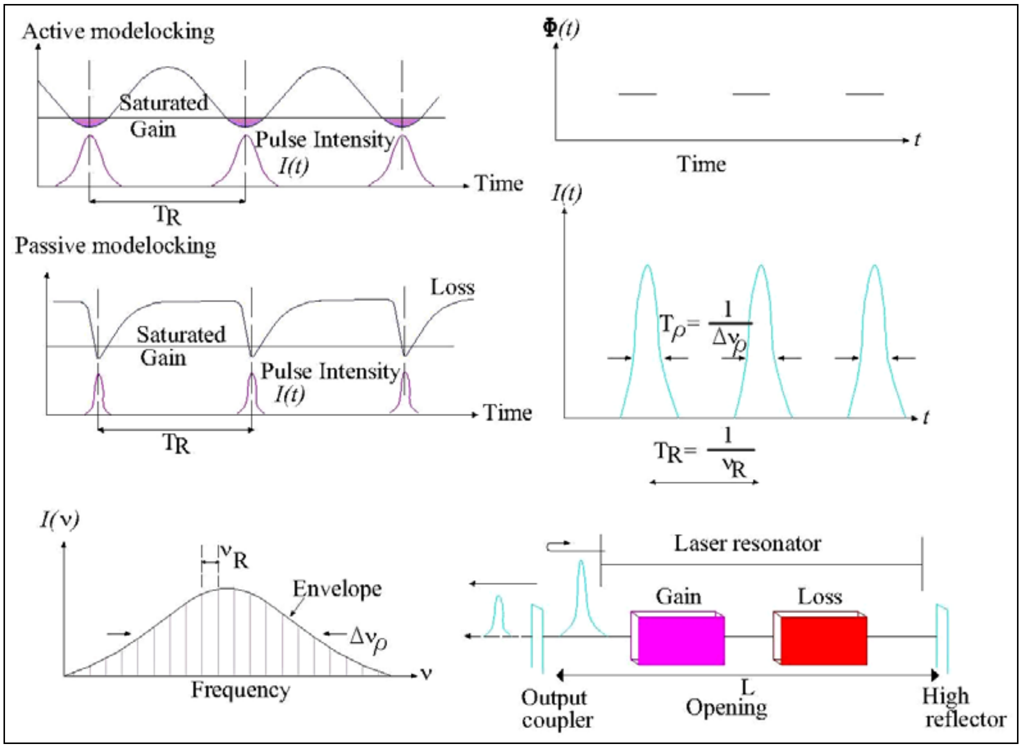

Figure 2.4 Modelocking.

Kerr lens modelocking (KLM) is obtained through a Kerr lens at an intracavity focus in the gain medium or in another material (figure 2.5), where the refractive index increases with intensity $\Delta n = n_2\, I(r,t)$, where n_2 is the nonlinear refractive index and I(r,t) the radial- and time-dependent intensity of a short-pulsed laser beam. In combination with a hard aperture inside the cavity, the cavity design is made such that the Kerr lens reduces the laser mode area for high intensities at the aperture and therefore forms an effective fast saturable absorber. In most cases, however, soft-aperture KLM is used, where the reduced mode area in the gain medium improves for a short time the overlap with the (strongly focused) pump beam and therefore the effective gain. A significant change in mode size is only achieved by operating the laser cavity near one of the stability limits of the cavity. To sum up, the nonlinear optical Kerr effect is caused by a dependence of the index of refraction on intensity. Along the axis of propagation z, this causes a phase retardation of the most intense part of the temporal pulse profile. This effect is also called self-phase modulation. In the plane perpendicular to z, the retardation causes a deformation of the phase fronts. In the central part of the spatial beam profile the phase front experiences an additional curvature. For example, the Kerr effect causes an effect similar to a lens. So, the transverse Kerr effect is also referred to as a Kerr lens [20].

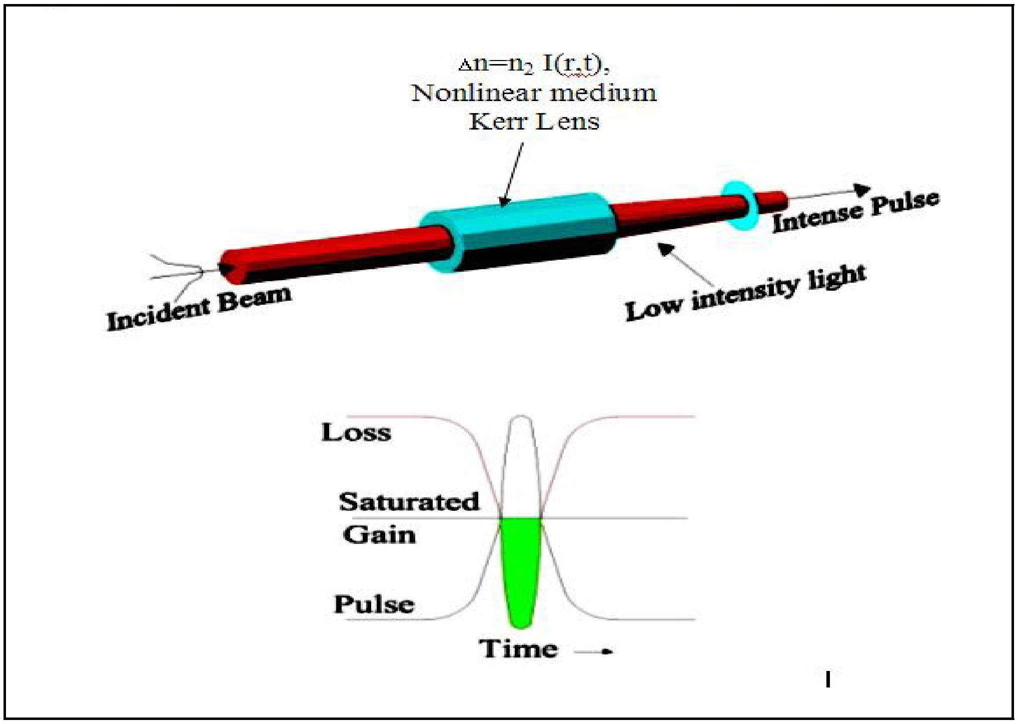

Figure 2.5 Kerr Lens Modelocking.

2.4 Autocorrelator

Correlation methods are generally employed to measure the duration of ultrashort laser pulses produced by modelocking. One possible setup, known as an autocorrelator is shown in the figure 2.6.

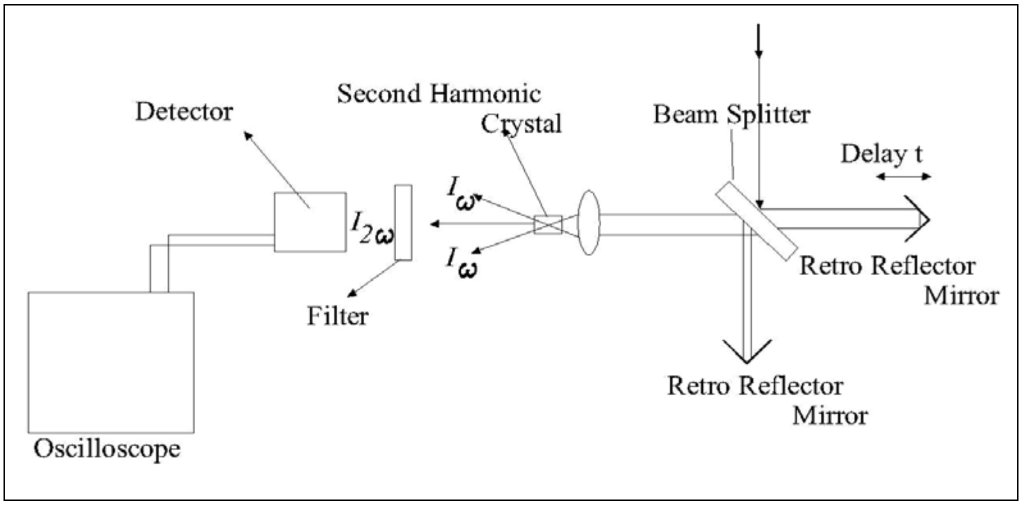

Figure 2.6 The experimental arrangement of an optical autocorrelator for measuring the pulsewidth of mode-locked pulses.

Here, the output of a mode-locked laser is split into two equal-intensity beams, which travel different path lengths in the two arms of a Michelson interferometer. The pulses are then combined in a non-linear crystal that generates the second-harmonic signal. After separating the fundamental light with a filter, a detector monitors the second-harmonic signal. One of the interferometer arms is varied in a periodic manner to change the delay between the two pulse trains. The temporal delay τ between the pulses can be calculated in terms of the displacement Δl of the variable arm from as the following.

$$\tau = \frac{2\Delta l}{c} \tag{2.2}$$

where c is the speed of light. For example, a displacement of 1 mm corresponds to 6.7 ps of delay. Since the second-harmonic conversion efficiency depends on the square of the power at the fundamental wavelength, the generated second-harmonic signal will be a strong function of the delay between the pulses. In particular, if the two beams are collinear and a detector with a slow time response is used, it can be shown that the generated second-harmonic signal will be proportional to the function $A(\tau)$ given by

$$A(\tau) = 1 + 2G^{(2)}(\tau) \tag{2.3}$$

Here, τ is the delay given in and $G^{(2)}(\tau)$ is the normalized second-order autocorrelation function which can be expressed in terms of the pulse intensity I(t) as

$$G^{(2)}(\tau) = \frac{\int_{-\infty}^{+\infty} dtI(t)I(t+\tau)}{\int_{-\infty}^{+\infty} dtI(t)^2} \tag{2.4}$$

For a mode-locked laser pulse, the function $A(\tau)$ has a peak at $\tau=0$ with a width (FWHM) of τ_{AC} as shown in figure 2.7. Furthermore, as it can be seen from the figure, in the case of collinear autocorrelation, a 3:1 contrast ratio between the peak and the background second-harmonic signal intensities is predicted as the delay is varied.

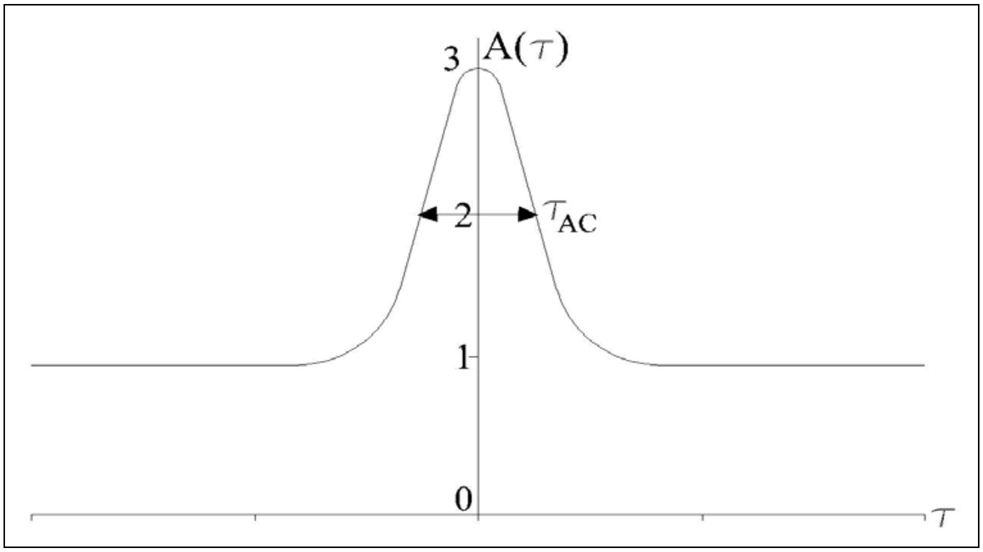

Figure 2.7 Typical collinear autocorrelation of a mode-locked laser pulse.

Verification of the 3:1 ratio in collinear autocorrelation also serves as a good test of successful mode locking, since the same ratio becomes 2:1 for a noise burst with no mode locking. From a measurement of τ_{AC}, the actual pulsewidth τ_p can be determined by assuming a pulse profile that is in agreement with the theoretical model that describes the particular mode-locking mechanism. For example, τ_{AC}/τ_p is 1.55 and 1.44 for sech ^{2} and Gaussian shaped pulses, respectively.

2.5 Femtosource and System Components

Ultra-short pulse generation at the cutting edge of optical time resolution has been radically changed by chirped multi layer mirrors.

The mirror dispersion control set is comprised of specifically designed chirped mirrors for broadband intra-cavity group delay dispersion control in a Ti:Sapphire oscillator, while low dispersion quarter wave mirrors are used for coupling the pump beam into and the mode-locked pulse out of the resonator.

The mirror dispersion control set, combined with a thin highly doped Ti:Sapphire crystal offers the possibility of generating optical pulses with quality, stability and reproducibility.

This potential can be exploited with a number of mode locking mechanisms, for example, saturable absorber mode locking, additive pulse mode locking or self mode locking. 8 fs optical pulses can be generated from a self mode locked Ti:Sapphire oscillator.

The system includes the following components:

1- A central mechanical unit-the compact laser head (CLH). It contains the most delicate parts such as the highly doped Ti:Sapphire crystal, the dichroic dispersive focusing mirrors for the resonator beam, the focusing lend for the pump beam and the short arm with the end mirror. The laser head should never be opened. If it is opened, it will get polluted in dusty atmosphere. There are three micrometer screws on it. They will be used for optimizing lasing operation, getting mode-locking by adjusting the position of the crystal, the stability range end mirror inside the CLH.

2- Optics and opto-mechanical components for femtosecond oscillator.

3- A periscope including steering optics and precision mirror mounts for coupling the pump beam into the oscillator.

4- Extra-cavity dispersion control.

2.5.1 Water Cooling

The water cooling removes the heat from the Ti:Sapphire crystal by stabling the temperature. Water temperature should be set between 18 and 20 Celsius degree. The heat removing unit is composed of connections for water cooling fitting to the chiller of the pump source [21].

2.5.2 Pump Source

The mode has to be TEM_{00} from a 532 nm green pump laser. The pump power should always be less than 10 W for optimum mode locked operation; moreover it should be less than 200 mW during the first alignment. The compact laser head needs a horizontally polarized pump beam (π-polarized). The polarization can be rotated and also the beam height can be adjusted for the polarization rotation utilizing from the periscope as shown in the figure 2.8 [21].

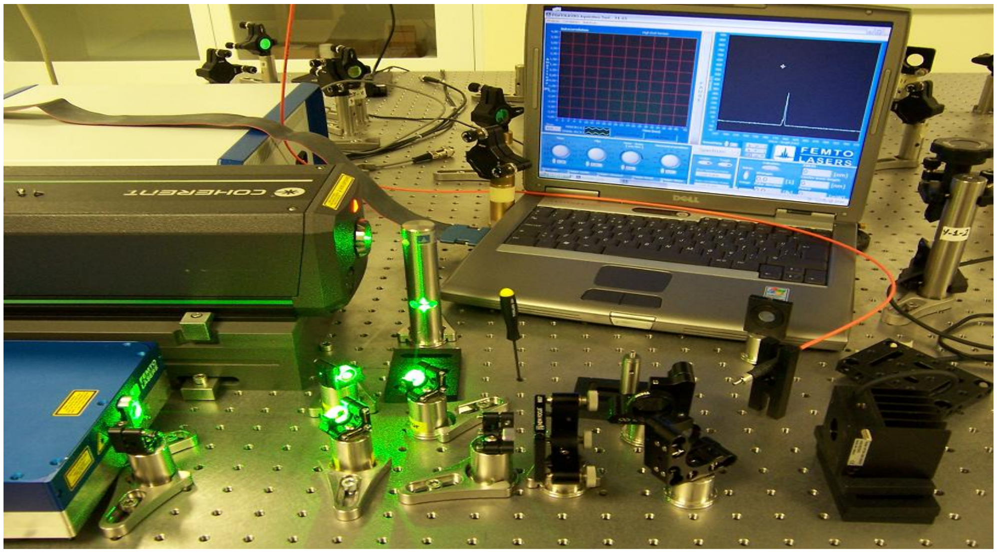

Figure 2.8 Pump source, periscope and oscillator

The pump laser has to be aligned to deliver an output beam parallel to the optical table in a height using periscope. Optimal height for pump laser is 119.8 mm the output beam of the periscope has to be aligned parallel to the optical table in a height of 50.8 mm by rotating the periscope around the vertical axis. Once again, the pump beam has to be aligned parallel to the optical table in a height of 50.8 mm after it passes through two steering mirror and the beam should pass through the center of the aperture the compact laser head [21].

One can make the alignment by adjusting CLH. The pump beam has to hit the reticle in the middle of the crosshair. One can use the output beam from the pump laser to define the resonator axis for an approximate alignment of the cavity, after the output beam is coupled through the aperture into CLH. Ti:Sapphire crystal transmits about 30% of the incident pump laser radiation. A small part of the transmitted pump beam will be reflected towards the short cavity arm and has to hit the reticle in the centre. During all operations, CLH should not be opened. It is necessary, since the laser head can be polluted and cause unstable operation [21]. Therefore, the long cavity arm can be aligned using amplified spontaneous emission from the Ti:Sapphire crystal or the transmitted green light from the pump laser and the short cavity arm is pre-aligned.

The output coupler (OC) can be aligned by reflecting the amplified spontaneous emission beam back into the gain medium. Amplified spontaneous emission signal transmitted through the OC must be detected with Silicon photo detector. If the optics used is clean, the applied procedure will give rise to laser oscillation and the pump power will be of the order of 4-5 W [21].

2.5.3 System Specifications

The system specifications of the femtosource (belonged to Femtolasers Productions GmbH, Vienna, model no: Femtosource Scientific, brand: Femtolasers) as given by the manufacturer can be seen in table 2.2

Table 2.2 System Specifications of the Femtosource

FEMTOSOURCE	sPRO	s20
Pulse duration	< 12 fs	< 20 fs
Spectral width	> 75 nm	> 40 nm
Output power (average)	> 300 mW	> 300 mW
Output energy at 75MHz	> 4 nj	> 4 nJ
Pump beam diameter	2 mm (1/ e^2), TEM_{00}	2 mm (1/ e^2), TEM_{00}
Pump power at 532 nm	5 W	5 W
Cooling water	18-22 ^{0}C, 10 W	18-22 ^{0}C, 10 W

2.6 Ultrashort Pulses from the MDC Oscillator

Optical pulses as generated in mode-locked lasers can be extremely short. There is no commonly accepted definition of “ultrashort”, but usually this label applies to pulses if their pulse duration is at most a few tens of picoseconds, and often in the range of femtoseconds [22].

The quality of intra-cavity dispersion control is very important in order to produce high quality optical pulses in the sub 20 fs range. The chirped mirrors which are used in the mirror-dispersion-control (MDC) Ti:Sapphire oscillator ensures bandwidths as broad as 80 THz [21].

To generate high quality optical pulses between the sub 20 fs and sub 12 fs, the oscillator has to be mode locked. Mode locking has to start when the spectrum becomes brighter and the speckles disappear. The position of the curved mirrors and the position of the gain medium have to be optimized after the mode locking is started. During this optimization, on the oscilloscope a stable pulse train is observed. 1 ns response time photodiode must be used so as to monitor the output of the laser. The spectrum and the pulse duration of the self mode locked MDC Ti:Sapphire oscillator is measured with a spectrometer and an autocorrelator. The test pump power value is 4 W, cw power is 700 mW, modelocked output power is 480 mW and autocorrelation is 9 fs. The test results are shown in figure 2.9 [21].

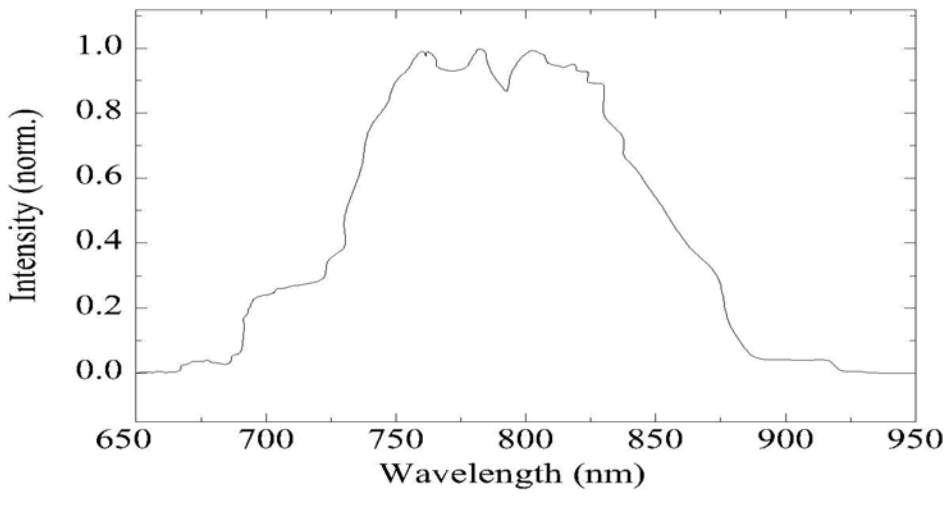

Figure 2.9 Spectrum of the oscillator 126nm@792nm.

The output coupler is wedged because of preventing unwanted reflections from the rear side of the substrate. Furthermore, the rear side of it is AR-coated. The compensating plate is placed very near to the output coupler. It compensates the angular dispersion (spatial chirp). The output coupler, the compensating plate and the autocorrelator cause material dispersion. This is a positive dispersion for the system. Extra two mirrors must be added to the system to compensate the material dispersion.

For the set up of the CLH, the below procedure must be applied.

First of all, the pump laser must be considered. It has to be 200 mW. The output beam has to be set 120 mm beam height horizontally. Lastly, one must set the output beam parallel to the hole line. And then, pump laser can be locked.

Secondly, the periscope must be adjusted. The periscope must be centered horizontally. And also it must be rotated to get 50.8 mm beam height at the steering mirror. Next, one must be sure that CLH is parallel to the hole line and feed the green beam through the entrance aperture. CLH should be rotated in order to see green beam at the rectile at the back side of it. After these operations, the cavity mirrors must be arranged. Finally, the output coupler has to be observed. Before optimizing cw-power, one has to adjust output coupler, end mirror of the short-cavity-arm and crystal position [21].

CHAPTER 3

THE FIRST AMPLIFIER STAGE

3.1 Introduction

The first amplifier stage includes photodiode, Pockels cell, stretcher and dazzler unit which cause time delays in an ultrafast CPA laser system. At the beginning, it starts with Ti:Sapphire oscillator. The output frequency of Ti:Sapphire oscillator is 75 MHz with the ultrashort pulse duration of 15 fs full width at half maximum (FWHM). The speed of optoelectronic devices is normally limited by the components used on the electronic side of the device. Obviously, it is limited by the speed of an electronic pulse generator or the response time of a laser diode [20]. In this system, the pulses come into the photodiode every 13 ns. The rise time of the photodiode is smaller than 200 ps. Thus, the photodiode has also a time delay. The next time delay is measured 4-7 ns because of Pockels cell. This is also an effect of timing issues in a terawatt laser system. Thirdly, the stretcher part must be considered with 75 MHz and if the time delays will be calculated. FWHM is 200 ps. when laser is passing through stretcher. Then, the dazzler unit is the third part causing timing delay. The dazzler`s duty at the amplifier stage is to shape the spectral amplitude and phase of an optical pulse in the Ti:Sapphire CPA laser system. To do so, the crystal unit is placed between the stretcher and the amplifier part [23]. Therefore, especially, photodiode, Pockels cell, stretcher and dazzler units have to be clarified in this chapter.

3.2 Photodiode

A photodiode is a type of photo detector. It converts light into current or voltage, depending on the type of operation. Photodiodes can operate in photovoltaic or photoconductive mode.

A diode is a two terminal component. One of those terminals has electrical properties varying according to the direction of the flow of charge carriers through it. The most common function of a diode is to allow an electric current to the flow in one direction. It is called forward biased. If it is to block the current in opposite direction, then it is called reverse biased.

Nowadays, the most frequent diodes are made from the semiconductor. For instance, they are mostly Silicon or Germanium. A semiconductor has electrical conductivity in between a conductor and an insulator. Moreover, it can be controlled over a wide range depending on the mode of operation.

A photodiode is a p-n junction or p-i-n structure. If a photon of sufficient energy hits the diode, an electron will be excited. It means that a mobile electron and a positively charged hole will be occurred. These carriers' motion produces photocurrent.

A photodiode's material is very significant to define the properties of diode. The ratio of photocurrent to a corresponding level of light is responsivity of a photo detector. Like responsivity, photo detectors have many properties such as rise time, fall time, frequency response, cut off frequency, bandwidth, dark current, reverse breakdown voltage and noise equivalent power.

Considering those specifications, Silicon photo detector was chosen for terawatt laser system. ET-2000 is the model of the detector here. In this system, photodiode is located between Ti:Sapphire oscillator and Pockels Cell. It is placed after Ti:Sapphire oscillator, since photodiode is needed here in order to measure the number of pulses coming from the oscillator per second. Definitely, the purpose of this photodiode is to measure the frequency of the laser coming from the oscillator before going to Pockels Cell. The frequency of laser light must be 75 MHz after the oscillator. Photodiode has to confirm this value and protect this frequency level for Pockels Cell. Because, the first function of photodiode is associated with frequency response. The second one is concerned with time domain. As all photodiodes, there is a rise time of ET-2000, too. The rise time is approximately 200 ps as shown in the table 3.1. So, the time delays of the laser set up begin with photodiode. Ti:Sapphire oscillator sends a laser pulse every 13 ns. And each pulse has the length of 15 fs. Although this photodiode is not fast enough to measure 15 fs, it is the best one nowadays. More detailed specifications of this detector are given in the following table 3.1 [25].

Table 3.1 System Specifications of the Femtosource.

Model of the photodiode	ET-2000
Detector type	PIN
Rise time	< 200 ps
Fall time	< 350 ps
Responsivity at 830 nm	0.4 mA/W
Bias Voltage	3 V
Cut off frequency	> 1.5 GHz
Active Area	0.006 mm^2
Dark current	< 1 nA
Junction Capacitance	< 4 pF
Reverse Breakdown Voltage	40 V
Acceptance Angle (1.2 angle)	20 ∞
Noise Equivalent Power (pW/$\sqrt{Hz}$)	< 0.1

Some of the quantities at above table are crucial for the experiments. For example, rise time is the time required for the detector output level to change from 10% to 90%of the peak output level. Secondly, the time required for the photo detector output level to change from 90% to 10% of the peak output level is fall time. Next, cut off frequency means the frequency at which the detector output power decreases by 3 dB from the output at 100 kHz. An effective capacitor is formed at the P-N junction of a photodiode. The junction capacitance is one of the major factors in determining the speed of a photodiode, too. Lastly, noise equivalent power (NEP) is the amount of the incident photon energy equivalent to the intrinsic noise level of the device, providing a signal to noise ratio of 1 [25].

ET-2000 photo detector is also suitable for a variety of pulse width measurement and pulse profiling applications. It uses PIN photodiodes and a reverse bias. This photodiode utilizes the photoelectric effect to convert light energy into an electrical current. The reverse bias consists of either 3 V lithium cell(s) or a wall plug in power supply, depending on the amount of bias voltage needed and the intended application of the photo detector. All photo detectors contain their own output connectors. Connecting the photo detector to an oscilloscope is all that is required for operation. This photo detector can be fitted with fiber optic connectors [25].

ET-2000 monitors the output of Q-switched lasers, mode locked lasers and cw lasers. It is associated with time domain and frequency response measurements, also. Its other applications are measuring the pulsewidth or viewing the pulse profile of Q-switched lasers, the alignment of cw and pulsed lasers and triggering applications.

3.3 Pockels Cell

When an applied voltage induces birefringence, the division of a ray of light into two rays when it passes through certain types of material and an electro-optic crystal is considered such as KD*P and BBO (β-barium borate), Pockels cells change the polarization state of light passing through it. When they are used with a polarizer, these cells can function as optical switches, or laser Q-switches. Commonly, Q-switches are employed in laser cavities for the purpose of shortening the output pulse, resulting in a light beam with enhanced peak intensity [7]. The next reason of using a Pockels cell is preventing the feedback of a laser cavity by using a polarizing prism. This prevents optical amplification by directing light of a certain polarization out of the cavity. Because of this, the gain medium is pumped to a highly excited state. When the medium has become saturated by energy, the Pockels cell is switched, and the intracavity light is allowed to exit. This creates a very fast, high intensity pulse. Q-switching, chirped pulse amplification and cavity dumping use this technique [26].

High-speed electronic drivers correctly matched to the Pockels cell produce the best results for short pulse applications [7].

The Pockels effect results from the linear term of the following equation if E is an applied DC field;

$$1 / n^2 = 1 / n^2_0 + rE + RE^2 \tag{3.1}$$

where n is the refractive index, n_0 is the refractive index in the absence of an applied field, r and R are the linear and quadratic electro-optic coefficients respectively and E is the electric field [10].

The Pockels effect can be considered as a special case of two wave mixing, where one of the waves in the incident optical wave and the other in a field of zero frequency. The optical electric field, E, can be small, because the DC field is itself large enough to produce nonlinear behavior. In general, the DC field redistributes electrons in such a way that birefringence is induced in an otherwise isotropic material, or new optic axes appear in naturally birefringent crystal. Since the Pockels effect is a second order effect relative to the polarization, it is not found in isotropic materials having inversion symmetry. All crystalline materials exhibiting a Pockels effect are also piezoelectric, that is, they show induced birefringence because of mechanical strain [10].

In one configuration of the Pockels Cell, the natural optical axis of the crystal is aligned parallel to the applied field. Fast and slow axes are induced in a plane normal to the applied field. For instance, there is a crystal placed on the x-axis and its height towards y-axis and depth of it is on the z-axis. Moreover, a voltage is applied to the crystal. If the Pockels cell crystal is rotated with an identified angle according to the x and y-axes, a vertically polarized light wave E_0 incident on the crystal along the field direction has equal amplitude components. These components experience different refractive indices and different speeds through the crystal. Thus, the crystal behaves as a phase retarder and the component waves emerge with a phase difference [10].

The polarizer analyzer pair transforms phase modulation into amplitude modulation. Therefore, the transmittance of the system can be modulated by variations in the applied voltage. Variations of a signal voltage superimposed on the voltage are transformed into variations in light intensity in such a device known as a Pockels electro-optic modulator [10].

The Pockels cell can be used also with the fields oriented orthogonally to the beam direction, an arrangement that simplifies placement of the electrodes. The electrodes are usually end rings. They allow the light beam to pass through and provide a uniform field in the crystal [10].

Quantum Technology manufactures three types of Pockels cells, using high quality strain-free crystals of electro-optic materials [27]:

1) Series QS Transverse Electrode (TE) BBO crystal Pockels cell (200 nm to 1064 nm) for high speed, high average power switching.

2) Series QC Ring Electrode (RE) KD*P crystal Pockels cell (300 nm to 1064 nm) for low loss intra-cavity switching.

3) Series LN (TE type) Lithium Niobate crystal Pockels cell for (800 nm to 2500 nm) Q-Switching and modulation.

Series QC Pockels cell indicated in figure 3.1 whose model number is HVP-5XX-DR-BM of Ouantum Technology is used in the set-up described here. QC Pockels cells utilize crystals with two levels of deuteration, 95 % KD*P and 99 % KD*P. The first type is suitable for switching a Ruby laser. The second type is useful for a Nd:YAG laser. The second type is suitable for operation because of Nd:YAG laser. These industry standard Q-Switches are available in dry or wet versions. The crystal is coated with Polymer coating for dry operation or index-matched for low loss in housing with AR coated windows. The diameter of QC-10 is 35 mms and the length is 45 mms. Two crystal devices, such as QC-10-2 are available in most Models for lower half-wave voltage operation [27].

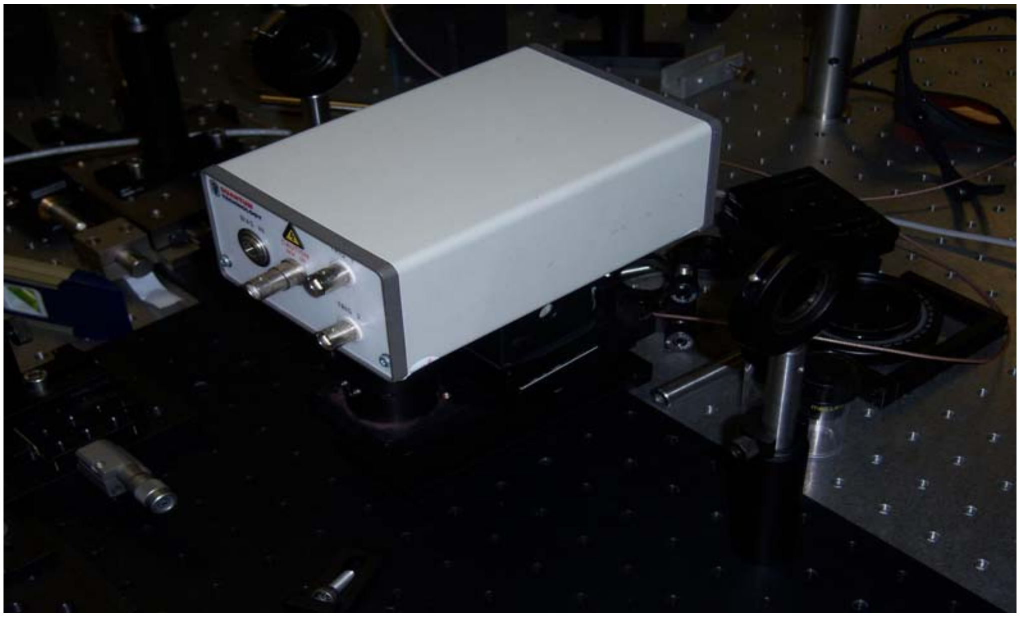

Figure 3.1 Pockels Cell

Pockels Cell specifications are as below in table 3.2 [27].

Table 3.2 Specification of Pockels Cell

Model No	QC – 10
Material	KD*P
Aperture	10 mm
Contrast	1000:1
VI/4 @ 1064 nm	3.4 kV
Model No.	HVP-590 (Digital)
Risetime	4-7 ns
Falltime	4-7 ns
Pulse width	9 ns
Rep rate	2 kHz
Max output	9,000 Volts

3.4 Stretcher

In CPA system, the oscillator output is stretched in the grating stretcher such that the red frequency components travel ahead of the blue. The peak intensity is reduced in the process. That means that the stretcher broadens the laser pulse, since laser pulse can not damage optics of the system. To avoid this damage, the pulse outgoing from the oscillator has to be stretched in the stretcher stage as shown in the following figure 3.2.

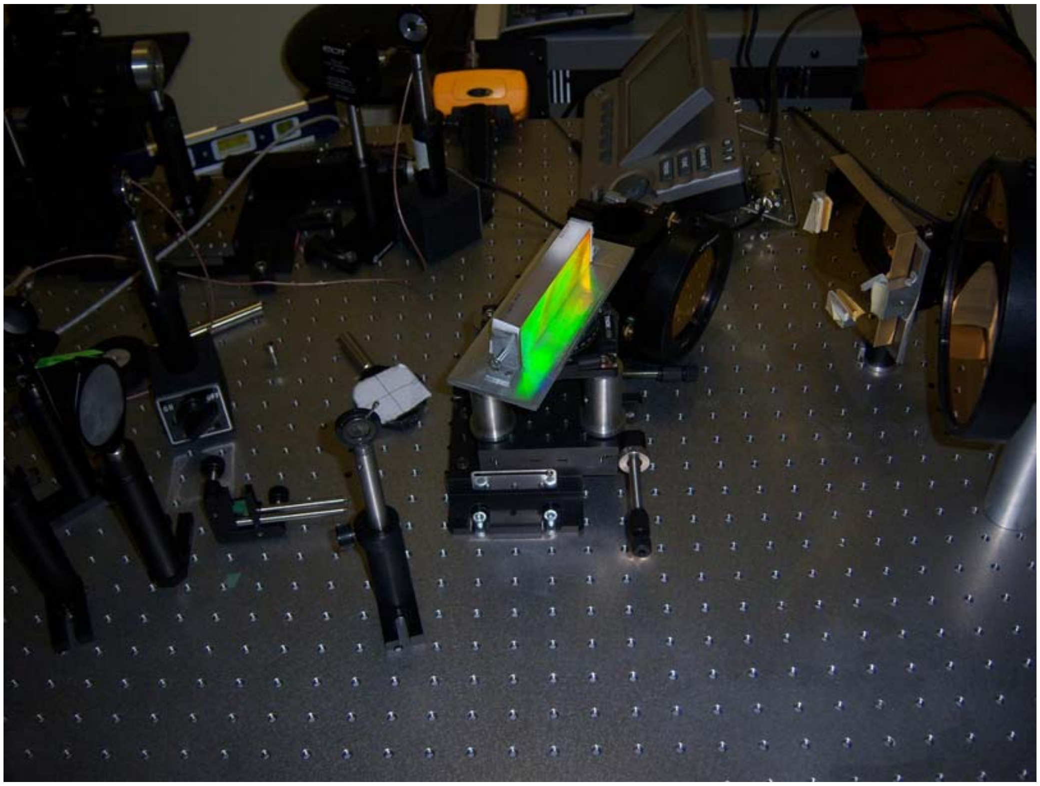

Figure 3.2 Stretcher

Amplification of ultrashort pulses, at high energy with high-repetition rate requires careful consideration of several important factors. In particular, dispersion must be carefully controlled. First, the control of the dispersion is essential to get ultrashort pulses in a CPA system, especially while stretching the pulse. Indeed, one of the most significant achievements in chirped pulse amplification design has been the control of the phase dispersion. To compensate the dispersion from many materials, such as Ti:Sapphires, Pockels cells, polarizers, and so on, several techniques have been developed so far. The dispersion has been figured out in the design of aberration-free stretching systems. Lemoff and coworkers canceled out the higher order dispersions from the materials by the aberration of the stretcher consisting of two cylindrical mirrors and two gratings [28]. Moreover, the aberration free stretcher developed by G. Ch´eriaux et al. and simultaneously by Du et al. is one of the new generations of stretcher design. The name of this type of stretcher is Öffner triplet design [29].

The stretched pulse is then amplified in a multipass amplifier before recompression in a grating pair compressor. Indeed, a straightforward design for amplification of femtosecond pulses is based on the multipass scheme.

The ability to stretch ultra short pulses with no optical aberration, to amplify pulses and to compress amplified chirped pulses result in energies at the joule scale in tens of femtoseconds with corresponding peak powers as high as 100 TW. The only way to obtain such high peak powers, amplification of longer picosecond pulses to energies ranging from hundreds of joules up to kilojoules. But such high energies induce a strong heating of the crystal. This produces a spatially dependent gradient of the refractive index of the crystal and causes an unwanted focusing of the amplified beam. For increasing temperature so as to reduce it, the water cooling is used [30]. If thermal considerations can be adequately addressed, the combination of high average power pumping, ultrashort pulse duration, and chirped pulse amplification makes systems capable of terawatt peak power conceivable [29]. The main difficulty that has to be overcome is the thermal load of the Ti:Sapphire crystals. Various technical solutions have been considered until now. Water-cooling is the simplest and has the advantage to be daily running for years. A first successful demonstration performed in 1993 was followed in 2000 [31].

3.4.1 Stretcher and compressor design

There are several ways to construct compressors and stretchers. However, a typical Ti:Sapphire-based chirped-pulse amplifier requires that the pulses are stretched to 200 picoseconds, which means that the different wavelength components must experience about 10 cm difference in path length. The most practical way to achieve this is with grating-based stretchers and compressors. Stretchers and compressors are characterized by their dispersion. With negative dispersion, light with higher frequencies (shorter wavelengths) takes less time to travel through the device than light with lower frequencies (longer wavelengths). With positive dispersion, it is the other way around. In a CPA, the dispersions of the stretcher and compressor should cancel out. Because of practical considerations, the stretcher is usually designed with positive dispersion and the compressor with negative dispersion.

In principle, the dispersion of an optical device is a function $\tau(\omega)$, where τ is the time delay experienced by a frequency component ω. (Sometimes the phase $\varphi(\omega) = 2\pi\tau(\omega)c / \lambda(\omega)$ is used, where c is the speed of light and λ is the wavelength.). Each component in the whole chain from the seed laser to the output of the compressor contributes to the dispersion. It turns out to be hard to tune the dispersions of the stretcher and compressor such that the resulting pulses are shorter than about 100 femtoseconds. For this, additional dispersive elements may be needed.

3.4.2 With Gratings

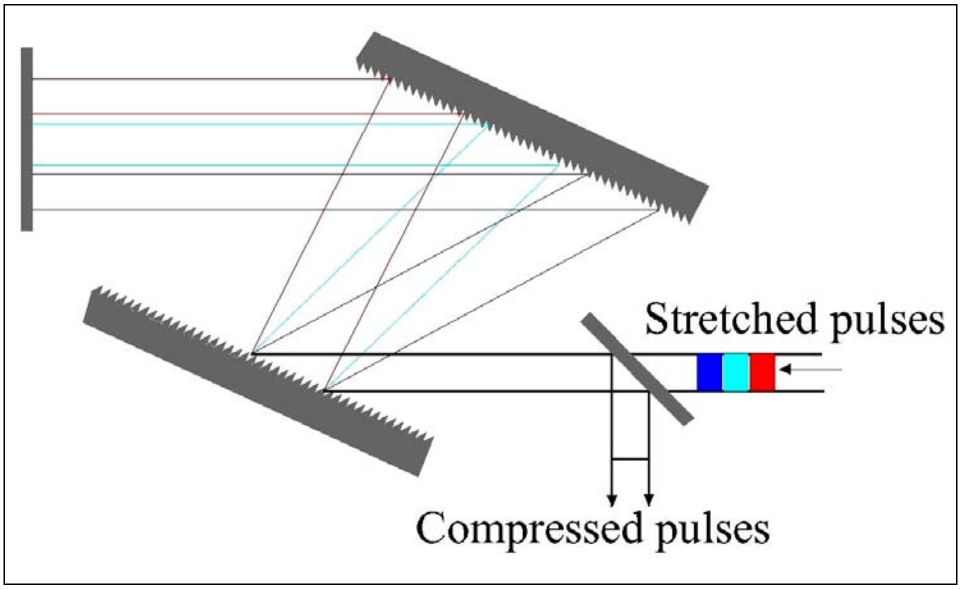

Figure 3.3 Schematic layout of a grating-based compressor with negative dispersion

Figure 3.3 shows the simplest grating configuration, where long-wavelength components travel a larger distance than the short-wavelength components (negative dispersion). It also indicates that the short wavelengths (in blue) come out first. Often, only a single grating is used, with extra mirrors such that the beam hits the grating four times rather than two times as shown in the picture. This setup is normally used as a compressor, since it does not involve components that could lead to unwanted side-effects when dealing with high-intensity pulses. The dispersion can be tuned easily by changing the distance between the two gratings.

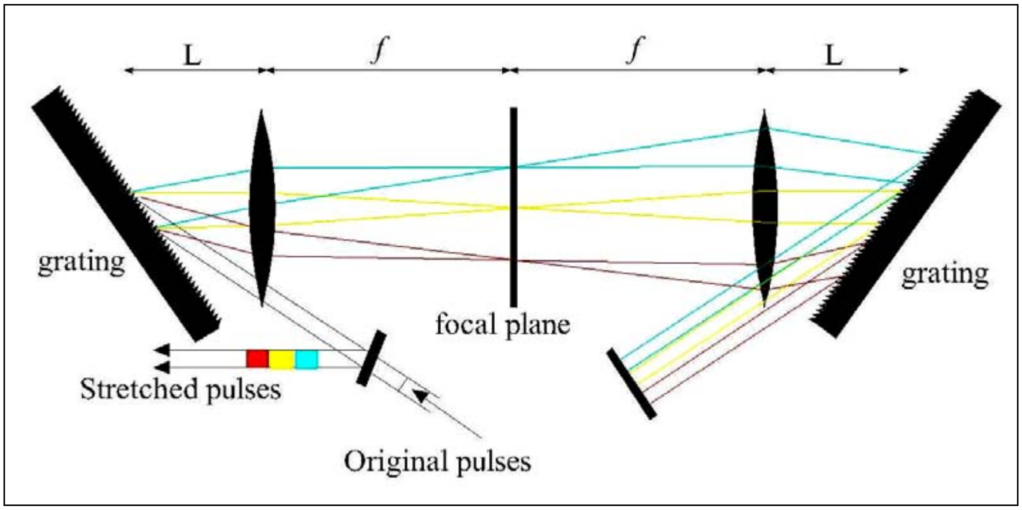

Figure 3.4 Schematic layout of a grating-based stretcher.

Figure 3.4 indicates that the long wavelength (in red) come first. In this case, L is smaller than f which leads to a positive dispersion. It also shows a more complicated grating configuration that involves focusing elements, here depicted as lenses. The lenses are placed at a distance 2f from each other (they act as a 1:1 telescope), and at a distance L from the gratings. If L < f, the setup acts as a positive-dispersion stretcher and if L > f, it is a negative-dispersion stretcher. And the case L = f is used in the pulse shaper. Usually, the focusing element is a spherical or cylindrical mirror rather than a lens. As with the configuration in figure 3.4, it is possible to use an additional mirror and use a single grating rather than two separate ones. This setup requires that the beam diameter is very small compared to the length of the telescope; otherwise undesirable aberrations will be introduced. For this reason, it is normally used as a stretcher before the amplification stage, since the low-intensity seed pulses can be collimated to a beam with a small diameter.

With prisms it will be as the figure 3.5. Then, it is called prism compressor.

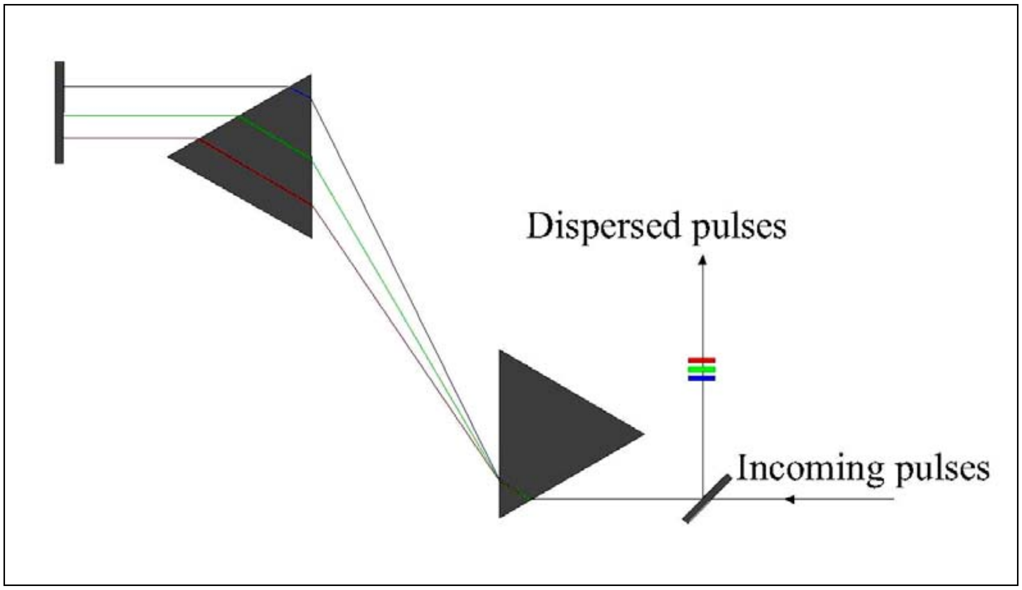

Figure 3.5 Prism Compressor.

This configuration has a positive dispersion. Although the different wavelengths appear to travel along very different paths, the effective path length differences are rather small, as indicated by the colors of the dispersed pulse.

It is possible to use prisms rather than gratings as dispersive elements, as in figure 3.5. Despite such a simple change the set-up behaves quite differently, as to first order the no group delay dispersion is introduced. Such a stretcher/compressor can have both a positive or negative dispersion, depending on the geometry and the material properties of the prisms. With lenses, the sign of the dispersion can be reversed. For a given distance between the dispersive elements, prisms generate much less dispersion than gratings. Prisms and gratings are sometimes combined to correct higher order dispersion, in which case the distance between the prisms is on the order of 10 meters rather than 50 cm as with a grating compressor. Gratings lose power into the other orders while prisms lose power due to Rayleigh scattering [32].

Considering the stretcher, amplifier and compressor part, the following figure 3.6 indicates the general view of setup.

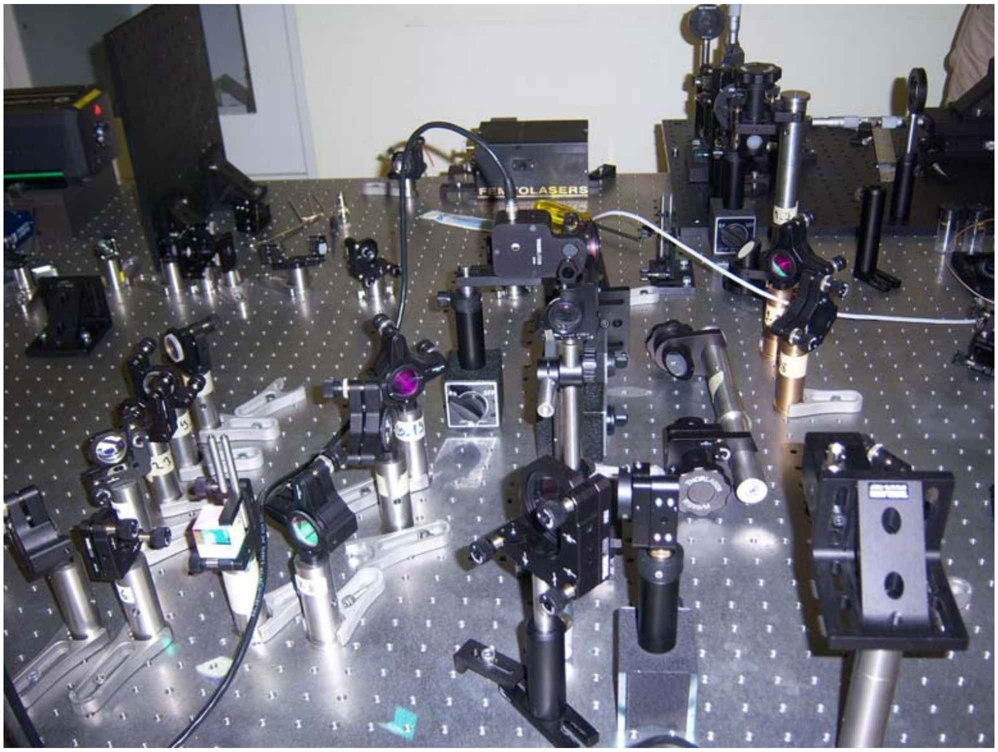

Figure 3.6 General View.

3.5 Dazzler System

The dazzler system is an acousto-optic programmable dispersive filter. This system is invented by Pierre Tournois. It is based upon a collinear acousto-optic interaction. The dazzler system is used in an ultrafast laser system because of performing both spectral phase and amplitude programmation of laser pulses, maintaining solutions to control the femtosecond pulses and not requiring complicated optical set ups and any calibration process in order to obtain accurate results. Additionally, the phase control in Dazzler is obtained through true group delays without any discontinuities versus wavelengths [33]. The last purpose of using Dazzler system is that it is placed before the amplifier due to its damage threshold.

In the dazzler unit, for instance; it is used at 750 nm as an example for a dazzler centered at 800 nm. Additionally, the power amplifier stage shifts the spectrum to the red because of the gain saturation; the red component of the chirped pulses traveling in the leading position advantages from a larger population inversion, leading to a stronger amplification. Another way for compensating this situation can be choosing the input laser spectrum so as to make spectral narrowing and gain saturation compensate for each other during the amplification stage [20].

Also, the dazzler can be considered as a pulse shaper at the output of an optical parametric amplification. It causes Dazzler dispersion. In order to compensate it, a pulse compressor must be used after dazzler crystal unit [20].

Two major problems become so as to produce high energy femtosecond pulses. These problems have to be overcome. Firstly; amplification in multipass configuration, which allows a high energy gain, induces a narrowing of the initial laser spectrum with respect to the stimulated emission cross section of the amplifying medium [20].

Next; the thermal effects induced by the strong average pump power in the amplifier crystal is the second problem. The heating of the laser medium produces a spatially dependent increase of its refractive index, determined by the transverse energy distribution of the pump beam and the intrinsic thermo-mechanical properties of the medium, thereby leading to unwanted thermal lensing of the amplified beam. This effect can be more or less compensated for by the use of a negative lens, this is essentially a point design where a particular focal length is chosen in order to compensate for a given temperature, and leads to a strong thermal dependence of the amplifier that prevents pumping modifications. Furthermore, transverse inhomogeneities of the pumping energy induce local heating of the crystal and distort the wavefront of the amplified pulse [20].

By the means of dazzler system, the spectral narrowing and distortions because of the amplification processes can be settled and adjusted. For this unit, acousto-optic programmable dispersive filter is used to get output pulses with desired order. These are the effects of improvements on the temporal, the spatial and the wavefront profiles of the amplified beams [20].

The amplification stage induces the spectral modifications consisting of gain narrowing and gain shifting as mentioned before. There is also spectral phase change. Dazzler, also called programmable acousto-optic dispersive filter, is used after Pockells Cell to control the spectral amplitude and phase of the pulse by interacting the laser light [20].

This system is made up of three basic parts. Two parts are an acousto-optic crystal and an RF generator. Moreover, a laptop computer is needed as the third part of this system.

3.5.1 Acousto-optic Crystal

An acousto-optic crystal is an active component. It involves acousto-optic interactions. This allows shaping the spectral phase and amplitudes of an optical pulse. The optical and acoustic beams have to be aligned. The threshold of this crystal is 100 MW/cm^2 [20].

3.5.2 RF Generator

The driver of the crystal unit is the RF generator. It includes the fast electronics generating the RF signal needed by acousto-optic crystal. The RF generator is an interface between the crystal and laptop computer. It produces the analog high power RF signal. However, RF generator manages with the triggering process, too. It deals with the other functions which can not be treated by computer. It can also drive the crystal in a standalone mode. Since, it keeps in memory the last signal, mode set up and triggers [23].

RF generator and total unit create an arbitrary waveform signal. If the unit is calibrated in the continuous mode and is generated for each trigger signal in single mode once, the signal repeats periodically.

RF generator has front and rear panel which can be changed with the models of the generator. The front panel controls the generation process. The rear panel monitors with an oscilloscope for the detailed description [23].

3.5.2 Computer

This computer is used for the following functions;

- Communication initialization
- Zeroing of RF signal
- Spectrum generation from amplitude function and phase function
- Setting of central frequency for amplitude and phase functions
- Dial programming of amplitude function as super Gaussian of the given width with Gaussian hole

- Dial programming of phase function as a polynomial
- Reading amplitude and phase functions from files
- Setting of waveform amplitude
- Setting of waveform duration
- Storing and retrieving of the waveforms for multiple pulses
- Launching waveform to RF unit
- Choose two waveforms or alternate at each trigger between two stored waveform.

All operations are adjusted from the main window except trigger delay and mode setting. Implementation of the dazzler is between stretcher and amplifier before amplifier in an ultra fast laser system [23].

A dazzler system is used to form spectral amplitude and phase of an optical pulse in an ultra fast CPA laser system. It inserts the crystal unit among the stretcher and amplifier. Since, dazzler's dispersion can be compensated by compressor unit. It is put before amplifier because of its damage threshold (100 MW/cm^2). The queue is as below [20].

Oscillator – Pockels Cell – Stretcher – Dazzler Crystal Unit – Amplifier – Compressor

To shape the spectral amplitude, avoid gain narrowing and get a flat spectral shape, dazzler is necessary. It is also used for making smooth phase over the spectrum [23].

CHAPTER 4

MULTIPASS AMPLIFICATION AND TIME DELAYS

Amplification is allowed the pulses coming from oscillator to be the millijoule or joule level at a reduced repetition rate. To amplify pulses over more than nine orders of magnitude, the only alternative method for producing such high peak powers is the high energy amplifying materials used to reach kilojoule levels [20]. To prevent damage in the amplifier chains, the oscillator pulse is stretched into the picosecond range before amplification. This reduces its peak power by the stretching ratio and also prevents nonlinear optical effects. After amplification the pulse can be recompressed into the femtosecond range using a grating sequence with exactly opposite dispersion of the stretcher and the amplifier material dispersion. This restores short pulse duration and allows for the generation of extremely high peak powers [34].

In order to produce extremely high peak powers, it is necessary to overcome high amplification level phenomena. An optical parametric amplifier (OPA) is a laser light source that emits light of variable wavelengths by an optical parametric amplification process [35]. The OPA is used to amplify a large bandwidth and chirped signal pulse prior to recompression. It is pumped by a beam from a laser such as Nd:glass, Ti:Sapphire, Nd:YAG, etc. [36]. Optical parametric chirped pulse amplifiers are identified as attractive sources of ultrashort high power laser pulses. Most of the work done in this field has been due to the development of extremely high power multi-TW systems [35]. As an example of OPA, if the incident pump pulse is the 800 nm output of a Ti:Sapphire laser, the output is in the near-infrared region and the sum of the wave number of which is equal to 12500 cm^{-1}. A parametric amplifier consists of a single diode. The OPA is used to achieve high gain at very high frequencies. The optical parametric amplifier has a wider bandwidth than a Ti-sapphire-amplifier, but the Ti:Sapphire laser has a wider bandwidth than optical parametric oscillator. Noncolinear OPAs were developed to have a constant gain. For instance, β-barium borate (BBO) as the material, pump with 400 nm and signal around 800 nm, leads to a bandwidth 3 times as large of that of a Ti-sapphire-amplifier. After propagation through 1 mm BBO, a short pump does not overlap with the signal anymore. So, for high gain amplification in long crystals chirped pulse amplification has to be used. Long crystal introduces such a big chirp that a compressor is needed anyway. The higher gain per mm for BBO compared to Ti:Sa and the lower amplified spontaneous emission allows for higher overall gain [37].

Amplification has two types, pre-amplification and multipass amplification. Multipass can be used for the compensation of group velocity dispersion; constant intensity with increasing signal power done by means of lenses and refocusing the beams in the crystal, broadband amplification by detuning the crystals, complete pump depletion by offsetting the pump and signal in time and space at every pass and high gain. Since the direction of the beams is fixed, multiple passes cannot be overlapped into a single small crystal like in a Ti:Sa amplifier. Unless one uses noncolinear geometry, amplified beams must be adjusted onto the parametric fluorescence cone produced by the pump pulse [37]. When a multipass noncollinear optical parametric chirped pulse amplifier seeded by pulses from a femtosecond Ti:Sapphire oscillator and pumped by an Nd:YVO_4 q-switched, frequency doubled laser is used, pulse energy exceeding 1.7 mJ is achieved with four passes through a single crystal for this kind of a system. The upper limit of the gain available in the nanosecond pulse pumped OPCPA systems is imposed by the material damage by pump pulses is approximately 1 GW/cm^2. Unlike a common laser amplifier, the parametric amplifier cannot store energy and thus the amplified and the pump pulses should be of comparable duration. This can be achieved by using a stretcher with extremely large diffraction gratings. This method is not very easy. For a typical system, the stretched seed pulse duration is below 1 ns while the pump pulse is 6–10 ns long. It has been proposed that high gain and high conversion efficiency can be achieved with several nonlinear crystals separated by adjustable time delays so the shorter seed pulse overlaps with different temporal parts of the longer pump pulse in different crystals. However, one can easily achieve higher gain by using several passes through the amplifier [35].

Preamplifier stage has different types. This stage increases the pulse energy. A high-gain preamplifier stage is placed just after the pulse stretcher in the most high-power ultrafast laser systems. It is designed to increase the energy of the nJ pulses from the laser oscillator to the 1–10 mJ level. The majority of the gain of the amplifier system occurs in preamplifier stage. The preamplifier can be followed by several power amplifiers designed to increase the output pulse power to the multiterawatt level. 8-pass is the pre-amplifier stage and 4-pass is the amplifier stage for this set up [38]. Pre-amplification allows a high energy gain and induces a narrowing of the initial laser spectrum with respect to the stimulated emission cross section of the amplifying medium (centred around 780 nm for Ti:Sapphire) [20]. Moreover, the successive power amplifier stages shift the spectrum to the red because of the gain saturation. Due to amplification in high peak power, laser systems deal with the thermal effects induced by the strong average pump power in the last amplifier crystal. The heating of the laser medium produces an increase of its refractive index, determined by the transverse energy distribution of the pump beam and the intrinsic thermo-mechanical properties of the medium, thereby leading to unwanted thermal lensing of the amplified beam. This effect can be compensated by the use of a negative lens; a particular focal length is chosen in order to compensate for a given temperature [37].

The design of the amplifier systems is difficult, expensive and important. Titanium doped sapphire has seen the most widespread use in all potential amplifier media in the last decades. Solid-state amplifier media described here is also titanium-doped sapphire. This material has advantages of relatively long upper level lifetimes and high saturation fluences (≈1 Jcm^{-2}). Moreover, it has several very desirable characteristics which make it ideal as a high-power amplifier material, including a very high damage threshold (approximately 8–10 Jcm^{-2}), and a high thermal conductivity (≈46 WmK^{-1} at 300 K). Therefore, pulses with energy >1 J can be extracted from a small diameter rod (2 cm), and the gain is sufficiently high that only two amplifier stages are required to reach this energy level. Furthermore, it has a broad gain bandwidth (≈200 nm), so it can support an extremely short pulse. Finally, it has a broad absorption bandwidth with a maximum at 500 nm making it ideal for frequency-doubled YAG pump lasers [38]. Frequency-doubled Nd:YAG laser is used as pump source for amplifiers. As well as increasing the pulse energy, the amplification process can shape and shift the spectrum of the pulse. This is due to the finite gain bandwidth of Ti:Sapphire. The successive passes through the amplifier edges of the pulse depletes the excited-state population so that the red edge of the pulse can experience a higher gain than the blue edge of the pulse. That is the spectral shifting. It should be noted that gain narrowing, spectral shifting and gain saturation occur in all amplifier media, and are least severe for Ti:Sapphire [38].

There are two basic pre-amplifier designs, regenerative and multipass. Regenerative amplifier as shown in the figure 4.1 consists of a cavity and Pockels Cell whose duty is pulse picking. Its design is just like an oscillator [39]. The low-energy chirped pulse is injected into the cavity using a time-gated polarization device, a Pockels cell and a polarizer. A low-gain configuration is typically used in the regenerative cavity to prevent amplified spontaneous emission (ASE) build-up. ASE can build up quite rapidly in a regenerative configuration with high gain. The beam overlaps between the pump and signal pulse is usually quite good in a regenerative configuration. Regenerative amplifiers are typically used for long pulse (50–100 fs) in high-power laser systems. Since, the Pockels cells and polarizers can add high-order dispersion to an amplifier system. However, regenerative amplifiers have also been used to generate pulses of 30 fs and shorter duration [38].

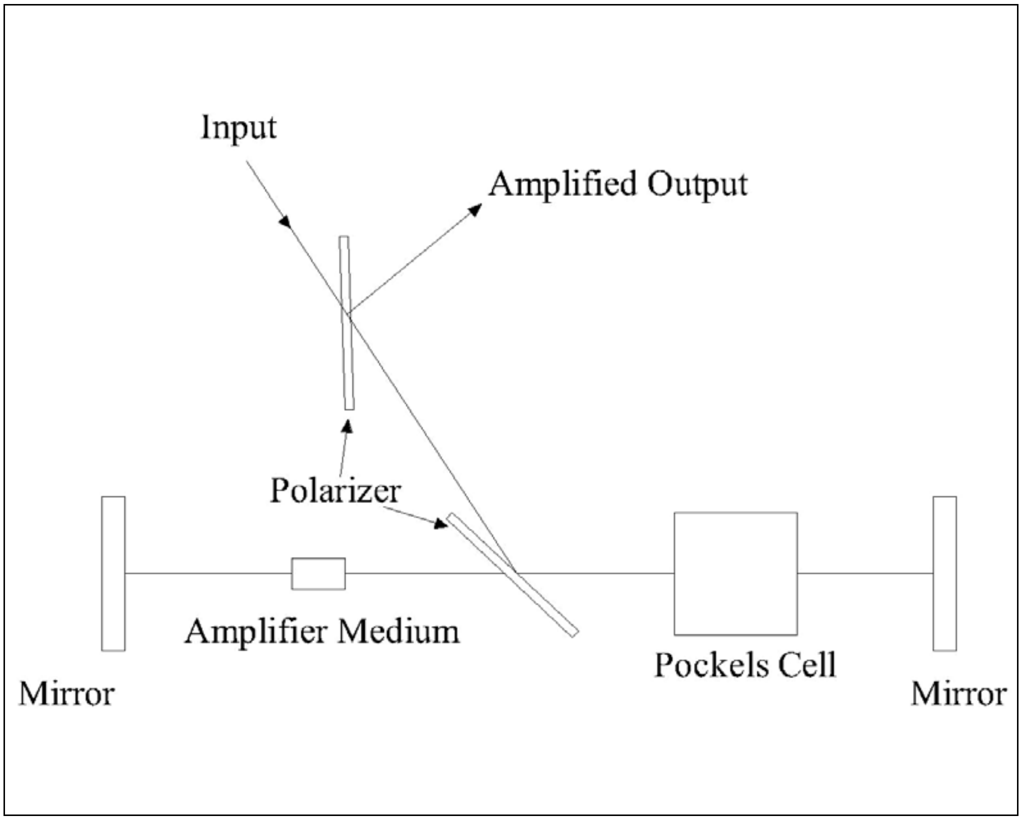

Figure 4.1 Regenerative Amplifier Design

A multipass preamplifier configuration differs from the regenerative amplifier as seen in the figure 4.2. The beam passes through the gain medium multiple times without the use of a cavity in the multipass preamplifier stage. ASE can be suppressed to a greater degree than with a regenerative amplifier. Therefore, multipass amplifiers typically have higher gain per pass according to the regenerative amplifiers. Consequently, shorter pulses are easier to send for recompression. Moreover, regenerative preamplifiers are more efficient than multipass preamplifiers. Because, the pump and signal overlap must change on successive passes through the gain medium in order to extract the beam [38].

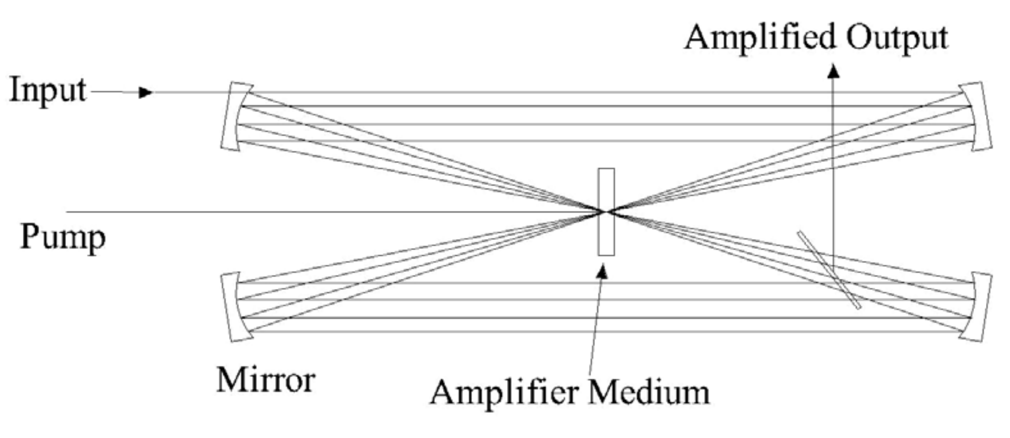

Figure 4.2 Multipass Amplifier Design

A set of flat mirrors was used to steer the seed beam in such a way that it made four passes through the pumped region of the crystal. To keep the pump-seed angle the same for all four passes, the amplified beams are aligned on a cone around the pump beam direction. The seed pulses were obtained from a train of pulses 800 nm, generated by a Ti:Sapphire oscillator operating at 75 MHz. The pulses were stretched in a grating stretcher to about 200 ps and single pulses were selected at 10 Hz repetition rate by a Pockels cell. After the Pockels cell, the beam propagated approximately 10 m in the air. The amplifier was pumped by a q-switched, frequency doubled Nd:YAG laser operating in a single longitudinal mode with 532 nm wavelength. A combination of a half waveplate and a polarizing beam splitter was used for precise control of the pump pulse energy. We estimate that the maximum pump pulse energy used corresponded to approximately 50% of the damage threshold for the crystal. An unsaturated gain fit of the data assuming G ~ exp ($\sqrt{E_p}$) where G is gain and Ep is the pump pulse energy, At high pump powers the output pulse energy saturates and pulse energy fluctuations decrease. The fluctuations to the timing jitter and beam pointing fluctuations are attributed over a long 10 m distance between the femtosecond oscillator and the amplifier. The amplification of the first three passes was about 102 per pass for the highest pump energy used 42 mJ. The fourth pass had amplification between 4 and 5 due to saturation [35].

CHAPTER 5

CONCLUSION

The laser system described in this thesis starts from a Ti:Sapphire mode-locked oscillator pumped by an $Nd:YVO_4$ (Yttrium Vanadate) laser, one of the most efficient laser host crystal for solid state lasers. Its lasing wavelength is 532 nm. The Ti:Sapphire oscillator produces laser pulses with the frequency of 75 MHz, mode-locked energy of nearly 400mW and pulse duration of approximately 15 fs. The duration of the oscillator pulses are measured by using an autocorrelator shown in the figure 5.1. The spectrum is measured by spectrometer as in the figure below.

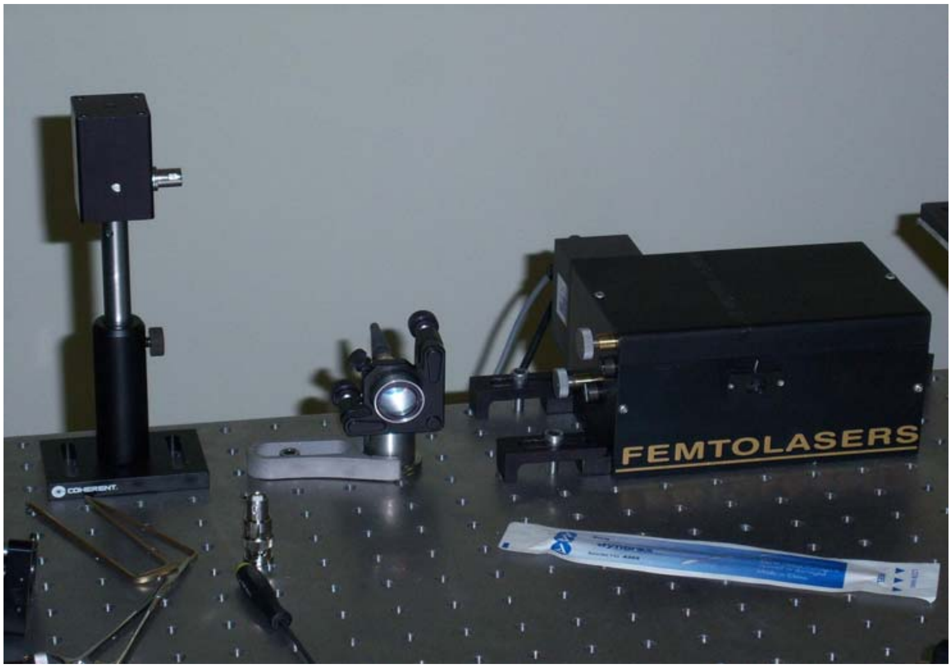

Figure 5.1 Photodiode – Spectrometer – Autocorrelator

Its lasing wavelength is 810 nm. According to these values, the average power can be calculated as in the Equation 5.1.

$$400\text{x}10^{-3}\ \text{W} / 75\text{x}10^{6}\ \text{Hz} \approx 5.3\text{x}10^{-9}\ \text{joule} = 5.3\ \text{nJ} \qquad (5.1)$$

And utilizing average power value, the peak power can be calculated as the following Equation 5.2.

$$5.3\text{x}10^{-9}\ \text{joule} / 15\text{x}10^{-15}\ \text{seconds} = 0.35\text{x}10^{6}\ \text{W} = 0.35\ \text{MW} \qquad (5.2)$$

The oscillator sends the pulse to the photodiode in order to control the frequency of Ti:Sapphire oscillator as given figure 5.2. It also has to adjust the laser pulse and Pockels Cell with each other. The photodiode delays the pulses 200 ps. It is the first delay of the set up. To choose the most useful pulse, Pockels Cell is necessary. To do so, Pockels Cell does pulse picking. The pulse frequency is 10 Hz after it. It means that there is 0.1 second between every pulse. The retardation time of Pockels Cell is between 4 ns and 7 ns. It can be considered as 5 ns.

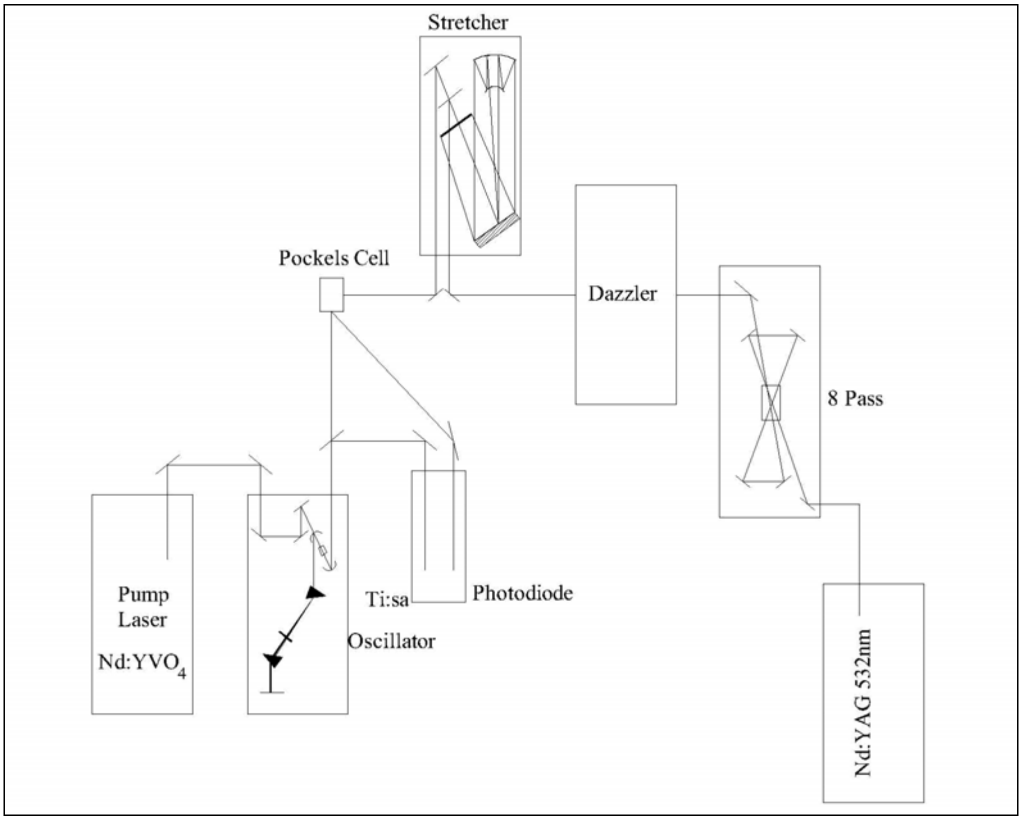

Figure 5.2 The order of Oscillator, Stretcher and Amplifier

The next part of a TW laser system is stretcher. Since, optical system is not desired to be damaged. The chirped pulse amplification technique is successful at resolving this problem by stretching the pulse before amplification. In the system described here, very large stretching ratios are achieved by passing the oscillator pulse through the stretcher [40]. Each pulse is stretched up to 200 ps in an aberration-free stretcher based on an Öffner triplet design [30]. It means that the pulse becomes longer. Therefore, this longer pulse can not damage whole system components. After stretcher, dazzler is located before amplifier in order to shape the spectral amplitude and to avoid gain narrowing and get a smooth spectral shape [23]. As mentioned before, the RF generator unit of dazzler keeps in memory the last trigger. It is very important and helpful to calculate triggers. The delay time of the dazzler is bigger than 4 ps [41]. The pre-amplification stage is after the dazzler part. It is 8-pass amplification in this system indicated in the figure 5.3.

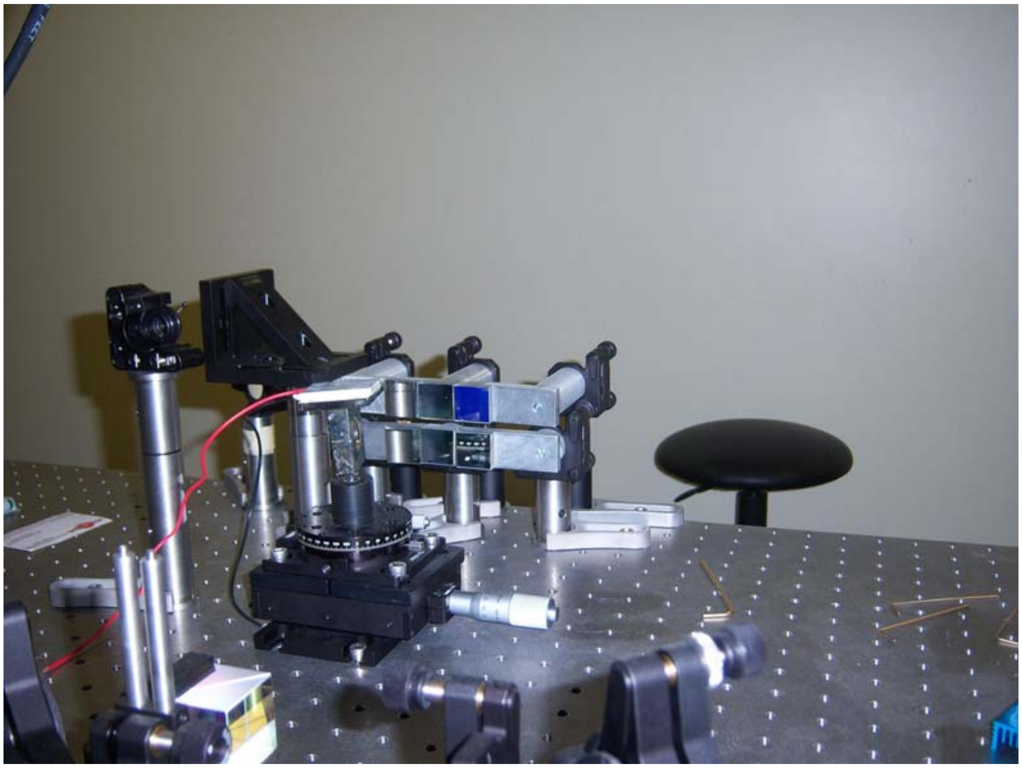

Figure 5.3 The Configuration of 8-pass Amplification

It is pumped by Nd:YAG laser with the wavelength of 532 nm, energy of nearly 155 mJ, pulse duration of 10 ns for pre-amplifier stage. The pulses with 200 ps and approximately 1.5 nJ are come into this stage to reach the millijoule energy level. Ti:Sapphire lasers that are pumped by frequency-doubled Nd:YAG lasers can achieve energy extraction efficiencies that approach ~57% of the pump pulse energy. Most Ti:Sapphire CPA systems, however, achieve only 10–30% efficiency. Multipass preamplifier efficiencies can reach ∼10% [30]. It makes the energy just about 3 mJ after 8-pass amplification which is $2x10^6$ times of the coming energy from stretcher and dazzler. If one more Pockels Cell is used after 8-pass amplification, it acts as a back reflection isolator [20]. To overlap the pump pulse and the oscillator pulse for high power, delay times of all system components till this point have to be measured by Pockels Cell. The total delay until Pockels Cell is $52.04x10^{-10}$ seconds = 5,204 ns. In Pockels Cell there is a pulse generator whose name is Divider Delay II shown in the figure 5.4. It provides two output pulse channels and a synchronization signal. In its delay mode, a signal pulse is output with controlled delay from an input trigger. Each output channel has independent delay control. Both have 25 ns digital delay and 100 ps analog delay over a 25 ns range. 40 MHz internal clock and 110 ns external trigger input pulse has two delays according to delay bypass. All two positions have fixed pulse width. The first one has 16.75 ns delay time by bypassed. The second one has 38.50 ns delay time by delay counter [42].

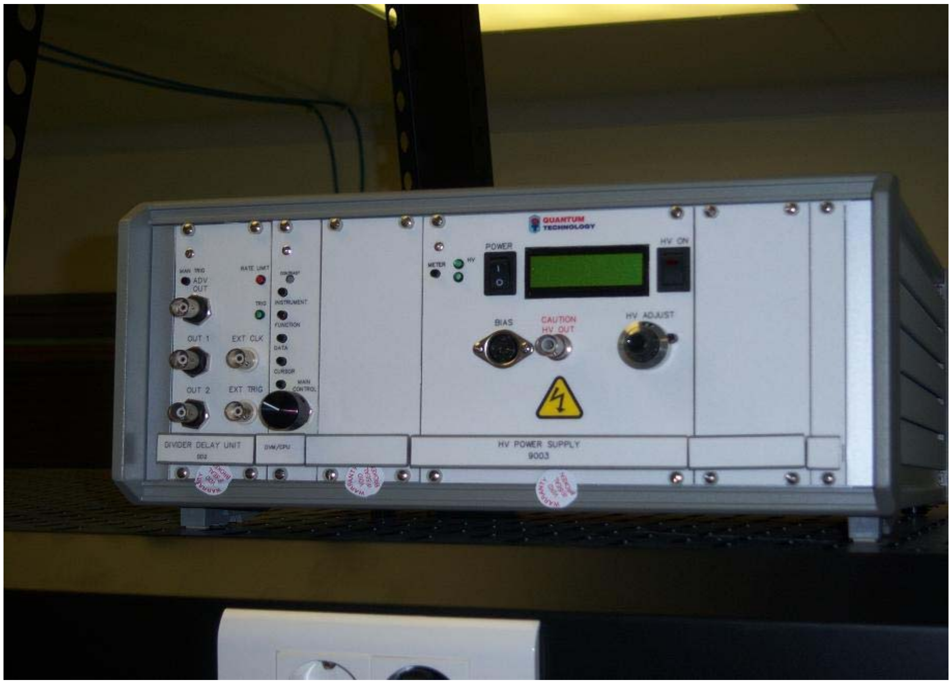

Figure 5.4 The Divider Delay

To sum up, timing issues of a laser system are very important to obtain terawatt level power. Timing delays have to be calculated in order to overlap the pump pulse and oscillator pulse at the exact time in a laser set up.

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