DEVELOPMENT OF CONTINUOUS WAVE AND MODE LOCKED TITANIUM SAPPHIRE LASER

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To my beloved Ayahanda and Bonda: Wan Razali bin Wan Ismail and Zainab binti Hassan and my sweet brother and sister: Wan Lukman and Fatimah Zahra.

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ABSTRACT

A Ti:sapphire laser was developed based on self mode-locking technique using a “Z” folded cavity. Diode pumped solid state laser Verdi 5 was used as a pumping source with fundamental wavelength of 532 nm (suitable for the absorption band in Ti:sapphire crystal). Laser cavity was aligned by a set of mirrors with a high reflectivity of 99.8% to reflect the beam within the range of 720 nm to 820 nm, and an output coupler with a 5% transmission. A pair of prism was employed to control the dispersion for producing femtosecond pulse. The pulse was initiated via an external perturbation. The stability of the laser was sustained by providing a water cooling system. The laser operated in two modes which are continuous wave mode (CW) and pulse mode with mode-locked (ML) mechanism. The maximum output power of the CW Ti:sapphire laser is 1.12 W corresponding to a pumping power of 5.5 W and the efficiency of 26%. The optimum average power of mode-locked Ti:sapphire laser is 577 mW corresponding to the same pumping power of 5.5 W and a lower efficiency of 18%. The frequency of mode-locked laser pulse obtained is 96.43 MHz. The spectrum of laser radiation is centered at 806.74 nm with a bandwidth of 22.37 nm at full width half maximum (FWHM). The pulse duration of the mode-locked Ti:Sapphire laser is 30.53 femtosecond.

ABSTRAK

Pengayun laser Ti:nilam telah dibangunkan berdasarkan teknik mod terkunci sendiri menggunakan rongga lipatan “Z”. Diode pam laser keadaan pepejal Verdi 5 telah digunakan sebagai sumber pengepaman dengan panjang gelombang asas 532 nm (sesuai untuk jalur penyerapan bagi hablur Ti:nilam). Rongga laser disusun atur melalui satu set cermin yang terdiri daripada cermin pantulan tinggi (99.8%) untuk memantulkan alur dalam julat 720 nm hingga 820 nm, dan pengganding keluaran dengan penghantaran 5%. Sepasang prisma untuk mengawal sebaran digunakan untuk menghasilkan denyut femtosaat. Denyut dicetuskan melalui gangguan luaran. Kestabilan laser dikekalkan dengan membekalkan sistem air penyejukan. Laser dioperasi dalam dua mod iaitu mod selanjar dan mod denyut dengan mekanisma mod terkunci. Kuasa keluaran maksimum laser selanjar Ti:nilam ialah 1.12 W sepadan dengan kuasa pengepaman 5.5 W dan kecekapan 26%. Kuasa purata optimum bagi laser Ti:nilam mod terkunci ialah 577 nm sepadan dengan kuasa pengepaman yang sama iaitu 5.5 W dengan kecekapan yang lebih rendah 18%. Frekuensi laser denyut mod terkunci ialah 96.43 MHz. Spektrum sinaran laser berpusat pada 806.74 nm dengan lebar jalur 22.37 nm pada lebar penuh separuh maksimum. Tempoh denyut bagi laser Ti:nilam mod terkunci ialah 30.53 femtosaat.

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LIST OF SYMBOLS

E - Energy
h - Planck constant
ω - Frequency
ΔE - Standard deviation in the energy
Δt - Pulse's temporal duration
$\Delta\omega$ - Spectral bandwidth
$\phi(\omega_0)$ - Absolute phase
$\phi'(\omega_0)$ - Group velocity
$\phi''(\omega_0)$ - Group velocity dispersion
$\phi'''(\omega_0)$ - Third Order Dispersion
ω_0 - Central frequency
λ - Wavelength
l - Distance between the apexes of the prism
n - Index of refraction of the prisms
λ - Free space wavelength of interest
β - Propagation angle of a ray
$d^2P/d\lambda^2$ - Dispersion in cavity
$d^2n_{cry}/d\lambda^2$ - Product of second order dispersion of crystal
t - Thickness of the crystal
δ - Stability parameter
f - Focal length
d - Arm length

R - Radius of curvature

θ - Optimal fold angle

τ_p - Pulse width

$\Delta\nu$ - Gain bandwidth

c - Light speed

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Through the improvement of lasers, currently it is possible to observe motion in nature with unprecedented temporal resolution. With the ultrafast (10^{-15}) laser usage, exploring physical phenomena is possible. Ultrafast laser are currently following the path already taken by many physic invention. The continuing development of ultrafast laser technology have led to many new and fascinating application in physics, engineering, chemistry, biology and medicine (Sutter *et al.,* 1998).

Among the ultrafast lasers, Ti:sapphire laser is the most popular laser used. Current areas of activity using Ti:sapphire lasers include nonlinear conversion, high-repetition-rate systems, extended operating range and novel resonators. The widespread applications of Ti:sapphire include LIDAR (Rodriguez *et al.,* 2004), dual-wavelength DIAL systems, fundamental research, spectroscopy, as well as tunable Optical Parametric Oscillators (OPO) pumping and simulating diode pumping in solid-state lasers (McKinnie *et al.*, 1997 and Xu *et al.,* 1998)

The development of ultrafast laser technology has shown the rapidly progress over the past decade. This is due to the great feature of the lasers that give superior performance for many applications. There are four features of the ultrafast laser that makes it so special. The first feature is the ultrashort pulse duration. Through this feature this laser allows very fast temporal resolution. Therefore this kind of laser can ‘freeze’ the motion of fast moving object including molecules and electrons. Professor Ahmed Zewail has won a Nobel Prize in chemistry by observing the molecule reaction in slow motion using ultrafast laser (Smith, 1999). The second feature of ultrafast laser is high pulse repetition rate. With multi gigahertz repetition rates, this laser was used in high capacity telecommunication systems, photonic switching devices, optical interconnection and for clock distribution. The third feature is, ultrafast laser have broad spectrum which supports good spatial resolution for optical coherence tomography (OCT). OCT is a technique for non-invasive cross-sectional imaging in biological systems. Lastly, the ultrafast laser has high peak intensity. This high intensity source makes ‘non-thermal’ ablation (without increase temperature) is possible. The ability of intense ultrashort-pulse lasers to fabricate microstructures in solid targets is very promising and the quality of ablated holes and pattern is much better using femtosecond laser.

1.2 Literature survey

Over the last two decades there have been a series of impressive achievements in the technology of short pulse lasers. From tens of picoseconds in the mid 1970’s, laser pulse durations have now been reduced to only a few femtosecond pulses of 20 -100 fs are common in many laboratories. The reduction of pulse duration has been accompanied by large increases in the peak pulse intensity, from 10^{14} - 10^{15} W/cm^2 in the mid 1980's up to 10^{18} - 10^{22} W/cm^2 in 2004 (Tate, 2004). The improvement of the ultrashort pulse laser is shown in Figure 1.1.

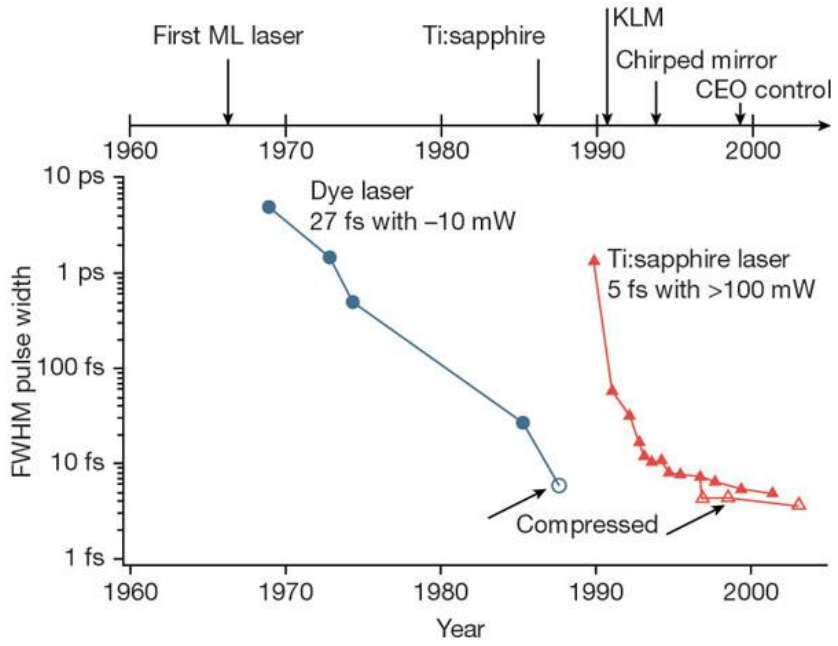

Figure 1.1 The improvement of ultrashort pulse generation (Keller, 2003)

Figure 1.1 illustrated the improvement in pulse generation since the first demonstration of a laser in 1960. Until the end of the 1980s, ultrashort pulse generation was dominated by dye lasers, and pulses as short as 27 fs with an average power of 10 mW was achieved (Valdmanis and Fork, 1986). After external pulse compression a pulses as short as 6 fs was produced. However, this situation changed with the discovery of the Ti:sapphire lasers.

Since the discovery of laser action in Ti:sapphire in 1982, Ti:sapphire become one of the most widely used solid-state laser material (Kuhn, 1998). It combines the excellent thermal, physical and optical properties of sapphire with the broadest tunable range of any known material (Eggleston *et al.*, 1988). It can be lased over the entire band from 660 to 1100 nm. The Ti:sapphire crystal also become as the breakthrough of ultrafast solid state lasers because it is first solid state laser medium was able to support ultrashort pulses without cryogenic cooling.

Ultrafast laser was first generated in 1965 by passive mode-locking of a ruby laser (Shapiro, 1977). Then one year later Nd:glass laser was successfully produce pulse duration of some picoseconds by using the same technique. In 1981, the first light pulse with duration less than 0.1 picoseconds or 100 femtosecond was generated by improvements of the passively mode-locked dye laser (Rudolf and Wilhelmi, 1989).

This progress of femtosecond pulses generation by solid state laser have followed from the self mode-locking in a Ti:sapphire laser by Sibbett group in 1991 (Keller, 2003) The self mode-locking behavior has known as *Kerr Lens Mode-locking* (KLM). It is the basis for femtosecond pulse generation in a wide variety of solid state laser system. Nevertheless, several mode-locking methods for Ti:sapphire laser were reported, which including active mode-locking with an acoustic optical modulator, additive pulse mode-locking (APM), passive mode-locking using organic dyes or semiconductor doped glass as saturable absorber and resonant passive mode-locking (RPM) (Keller *et al.,* 1991 and Sarukura and Ishida, 1992). Perhaps among all of the various schemes, KLM is most famous and simplest technique used (Huang, 1995). The KLM of Ti:sapphire lasers was discovered in 1991 and capable to produce the shortest pulse which is less than 6 fs duration. However shorter sub-5 fs pulse has been demonstrated with external cavity pulse compression (Fermann *et al.,* 2001 and Xu *et al.*, 1998). The KLM process will be discussed in detail in Chapter 2

1.3 Problem Statement

A Ti:sapphire crystal is the most important solid state medium to generate femtosecond pulse laser. This is because its posses a broad gain bandwidth. However, it is not an easy task to generate femtosecond laser. Only knowledgeable and experience scientist will be able to take the challenge. The difficulties arise due to the precision optical components and procedure alignment. Therefore this work has been carried out in order to study the design of femtosecond laser.

1.4 Research Objective

The objective of this research is to study the construction of femtosecond laser by using Ti:sapphire crystal based on KLM technique. The study includes the identification of optical components, gain medium and pumping source. The crucial part of the work is the alignment of the laser cavity. Finally, the laser output obtained will be characterized.

1.5 Research Scope

In this research Ti:sapphire crystal was employed as gain medium. The crystal was pumped by green laser. In this case Diode Pumped Solid State (DPSS) laser Verdi 5 was employed. The fluorescence of the crystal immediately produced after excited by

DPSS laser was studied. The configuration of the cavity was chosen to be in “Z” folded type. The lasing was tested in two modes. Firstly in continuous wave operation and secondly in mode-locked operation. A prism pair was conducted to compensate the dispersion. High speed photodetector was utilized to detect the mode-locked signal. The spectrum analyzer was used to measure the wavelength of the output beam and estimate the pulse duration.

1.6 Thesis outline

The thesis is divided into seven chapters. The first chapter will discuss about the ultrafast laser advantages and reviewing some improvement regarding ultrafast laser.

Chapter II reviews the theory related to the research. This will explain the detail of the mode-locking technique and theory behind the development of the Ti:sapphire laser such as dispersion compensation and cavity design.

Chapter III describes the methodology of the project. This would include entire materials used to setup the laser cavity such as active medium, pumping source and optical components. The measurement equipments and software for analysis utilize are also will be included.

Chapter IV explains about the pumping source used to excite the Ti:sapphire crystal. In this part all the specifications and procedure to handle the DPSS laser are provided. Lastly the operation of the laser system and the characterization of the laser output will be discussed.

Chapter V discusses the procedures to align the Ti:sapphire laser. This includes the alignment of the lens, mirrors, output coupler and prism pair for Continuous Wave and mode-locked cavity. In addition, this part also discuss about the optimization of femtosecond operation. Since the alignment of the cavity is very critical, therefore this chapter is the most important part in this work.

The characterization of the Ti:sapphire laser is explained in Chapter VI that have been constructed. This includes the spectrum of the beam, the output power, the beam profile and the estimation of the pulse duration.

Finally the conclusion of the project is made in Chapter VII. The summarization contains the synopsis of the project, the problem involved during the performance of the project. Last but not least, further works to be carried out in the future are suggested.

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