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GENERATION OF FEMTOSECOND PULSED FROM TI:SAPPHIRE OSCILLATOR

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ABSTRACT

A Ti:Sapphire oscillator was aligned to form a Z" folded cavity. Diode pumped solid state laser with wavelength of 532 nm was employed as a pumping source. The oscillator comprised a set of mirrors including high reflectivity of 99.8% mirror and an output coupler with 5% transmission. A pair of prism was interposed into the cavity to induce mode-locked pulses. External perturbation was introduced to initiate femtopulse generation. The femtosecond pulse spectrum was found to be centered at 806.74 nm with bandwidth of 24.8 nm at full width half maximum (FWHM). The pulse duration of the signal is estimated to be as 27.56 femtosecond.

INTRODUCTION

Ultrafast laser was first generated in 1965 by passive mode-locking of a ruby laser [1]. 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 [2].

The 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 [3]. 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. Several mode-locking methods for Ti:sapphire laser were reported, which including active mode-locking with an acoustic optical modulator, additive pulse mode-locking, passive mode-locking using organic dyes or semiconductor doped glass as saturable absorber and resonant passive mode-locking [4,5]. Perhaps among all of the various schemes, KLM is the most famous and simplest technique used [6]. In this present paper, the generation of femtosecond pulse from Ti:sapphire oscillator is discussed.

THEORY

Construction of the Ti:sapphire oscillator is different than the regular setup as common laser design which is in straight line. Basically, there are two commonly used cavities for Ti:sapphire oscillator as depicted in Figure 1.

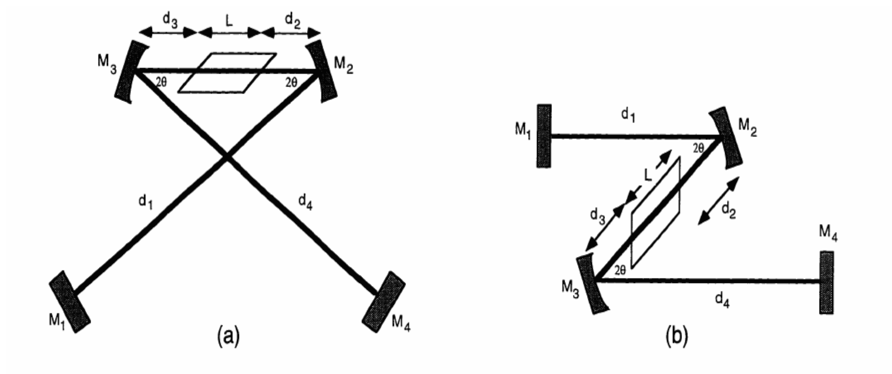

Figure 1: Commonly used cavity for Ti:sapphire oscillator [6].

The Ti:sapphire oscillator design can be in an "*X*" or "*Z*" configuration. The folded cavity is suitable to obtain good mode matching with pump and to provide tight focusing in the mirror [7]. Beside it can control the astigmatism produce from laser cavity by adjusting the angle of the arm. Both types work equally well and usually selected based on considerations of available space in setting up the cavity [8], nevertheless, for Ti:sapphire oscillator "Z" configuration is commonly used [9].

The Ti:sapphire crystal as an active medium, normally cut at Brewster angle. The presence of such angle introduced astigmatism in the cavity which lead a beam waist size difference between sagittal (perpendicular to the plane of incident) and tangential (parallel to the plane of incident) plane [10]. Astigmatism needs to be reduced because it can cause unstable mode-locking [11] and also reduced output power. For real "Z" folded cavity, astigmatism cannot be completely compensated but minimized by titling the folding mirrors to a certain angle extension. The optimal fold angle for the cavity to reduce astigmatism can be calculated using the following equation [12];

$$2Nt = 2f\sin\theta\tan\theta \equiv R\sin\theta\tan\theta \qquad (1)$$

where

$$N = (n^2 - 1)\sqrt{n^2 + 1/n^4} \qquad (2)$$

By solving the Equation (1) and (2) we can get the angle:

$$\theta = \text{arc}\cos\left[-\mathrm{C} + \sqrt{\mathrm{C}^2 + 1}\right] \qquad (3)$$

where

$$\mathrm{C} = \frac{t\left(n_{\mathrm{T}}^2 - 1\right)\sqrt{n_{\mathrm{T}}^2 + 1}}{n_{\mathrm{T}}^4 \mathrm{R}} \qquad (4)$$

where t and n_{T} are the thickness and the refractive index of the Brewster angle medium, R is the radius of curvature of the folding mirrors. With refractive index of n_{T} = 1.76, a thickness of t = 13 mm and curvature radius of R = 100 mm. From the calculation θ is obtained as 19.24°.

Prisms another important optical component to induce mode lock pulses as well as by compensating the dispersion in the cavity. Without dispersion compensation a longer wavelength of the pulse propagate faster than shorter wavelength leading to pulse stretching. The uncompensated dispersion will make the femtosecond pulse impossible. Dispersion introduce by the geometry of the setup is illustrated in Figure 2. The shorter wavelength goes through less prism material therefore have shorter optical path whereas, longer wavelength goes through more prism material thus have longer optical path. Through this setup the dispersion can be compensated.

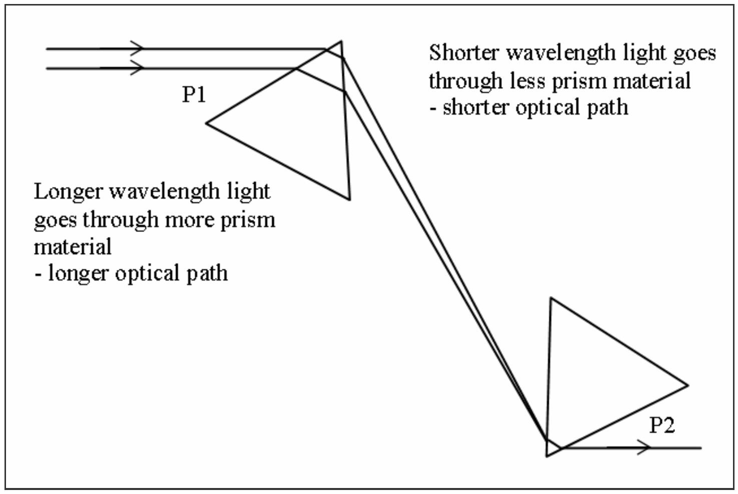

Figure 2: Prism pair operation

In other word the prism pair is function to correct the *group velocity dispersion* (GVD). The dispersion of the cavity $d^2P/d\lambda^2$ is given as [13];

$$\frac{d^2P}{d\lambda^2} = 4l\left\{\left[\frac{d^2n}{d\lambda^2} + \left(2n - \frac{1}{n^3}\right)\left(\frac{dn}{d\lambda}\right)\sin\beta - 2\left(\frac{dn}{d\lambda}\right)^2\cos\beta\right]\right\} \tag{5}$$

where l is the distance between the apexes of the prism, n is the refractive index of the prisms, λ is the free space wavelength of interest and β is the propagation angle of a ray with respect to a reference line drawn between the apexes of the two prisms.

Distance l, required for correction GVD passing through the length of material, in this case Ti:sapphire crystal. The dispersion in cavity $d^2P/d\lambda^2$ is compensate by the negative of second order dispersion of the Ti:sapphire crystal $d^2n_{cry}/d\lambda^2$ and the thickness of the crystal, t. Then Equation (6) is produced.

$$-\frac{d^2n_{cry}}{d\lambda^2}t = \frac{d^2P}{d\lambda^2} \tag{6}$$

By solving the Equation (5) and (6) with n = 1.71125, $dn/d\lambda$ = -0.04958 μm^{-1}, $d^2n/d\lambda^2$ = 0.1755 μm^{-2} (for prism made of SF10 glass at wavelength of 800 nm), t = 13 mm and $d^2n_{cry}/d\lambda^2$ = 0.1745 μm^{-2}. The prism pair separation l is calculated to be 19 cm.

Starting the femtosecond operation was carried out by disturbing the prism using finger to give external perturbation. This disturbance would change the depth of insertion of the prism [19]. As a result, an initial perturbation to generate an intracavity power fluctuation that builds up to a stable circulating femtosecond pulse was produced [20].

The pulse duration of femtosecond pulse could be estimated through the pulse spectrum. The center wavelength λ and the bandwidth Δλ of the spectrum at full wave half maximum (FWHM) are important parameters. These parameters have relationship with pulse frequency Δ*f* which given as [14]

$$\Delta f = \left(\frac{c}{\lambda^2}\right)\Delta\lambda \qquad (7)$$

where c is speed of light. The femtosecond pulse is in the formation of $Sech^2$ pulse shape [15, 16]. The pulse duration of Ti:sapphire laser can be estimated as[17];

$$\Delta t \approx \frac{0.3148}{\Delta f} \qquad (8)$$

EXPERIMENTAL

A titanium sapphire oscillator was aligned to generate a femtosecond pulse. In this alignment Ti:sapphire crystal was utilized as an active medium. The Ti:sapphire has a wide absorption band (extend about 200 nm) center at near 490 nm. Verdi 5 Diode Pumped Solid State DPSS laser was employed as a pumping source. The maximum power of the DPSS laser is 8 W and produced wavelength of 532 nm beam.

The oscillator comprises a set of mirror with reflectivity of 99.8 % and coating with broadband in range of 720 nm to 820 nm. The mirrors include the flat and spherical mirrors. Output coupler with transmission of 5 % was used to transmit the laser beam. The “Z” folded cavity type was selected in this experiment.

The schematic layout of Ti:sapphire oscillator is illustrated in Figure 3. It is consists of output coupler (M1), end mirror (M4), two curve mirrors (M2, M3) with radius of curvature (ROC) of 100 mm to focus into a Ti:sapphire crystal and a pair of intracavity prisms for dispersion compensation**.**

Several major alignments need to be performed. The alignment including a pumping source, focusing beam, linear cavity and cooling system. The first step to align Ti:sapphire oscillator is to adjust the DPSS laser as a pumping source. In this alignment two high reflective mirrors at 532 nm known as pumped mirrors (PM1 and PM2) were used to locate the pumping beam. Only small power of DPSS laser was operated during this alignment that is about 2 W. The mirror PM1 was placed at an angle upon DPSS laser beam. The beam was reflected to the second mirror of PM2. The output of the DPSS laser is in vertical plane of polarization. The polarization beam was rotated to the horizontal plane in order to prepare a Brewster angle condition of the Ti:sapphire crystal. A polarization rotator (PR) was employed and placing into the beam path after PM2. The best condition for the beam to become horizontal is identified when only a small portion of the reflected beam from PR was detected near the DPSS laser window.

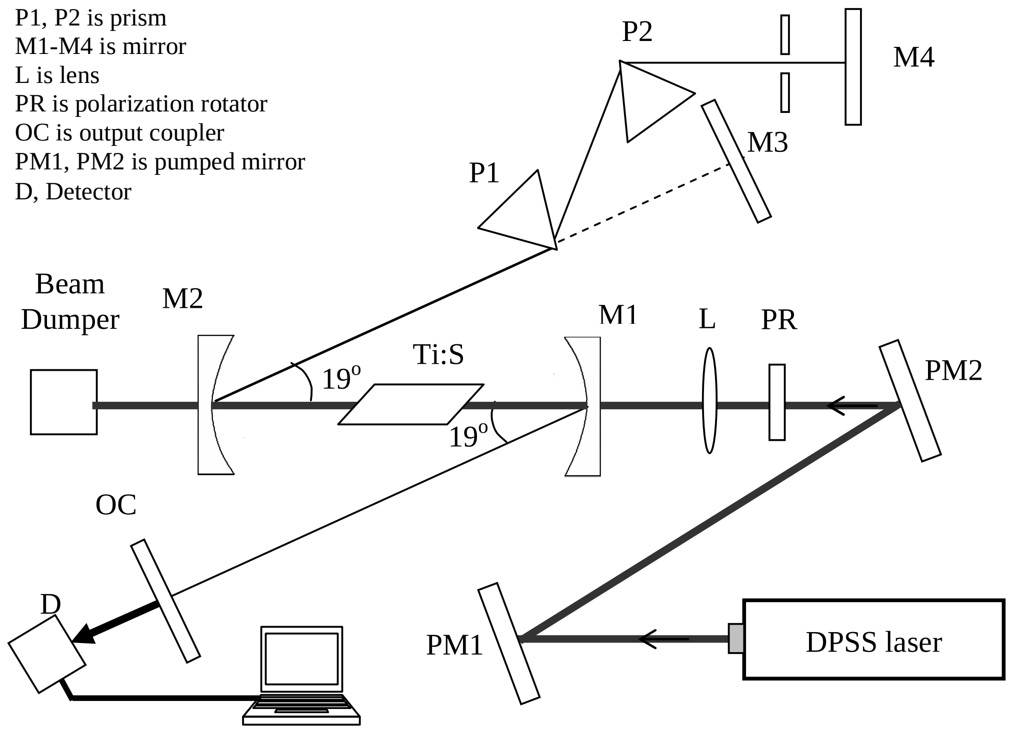

Figure 3: The optical alignment of Ti:sapphire oscillator

A lens of focal length 100 mm was employed to focus DPSS laser beam. The focused beam of DPSS laser was used to excite active medium in this case Ti:sapphire crystal. The stimulated emission from the crystal is then amplified in a linear cavity. The linear cavity was developed by using two concave mirrors M1 and M2. The distance between mirror M1 and M2 surface was chosen approximately at 110 mm. This distance will be optimized during the laser operation. The beam dumper was put beyond the mirror M2 to block the beam.

After optimizing the best position of the focusing lens L, an output coupler OC was inserted into the system. In this case, luminescence of the Ti:sapphire crystal was utilized. The luminescence was illuminated at the center of the output coupler (OC). The presence of the beam can be detected using infrared card. Finally, the configuration of "Z" folded cavity was completed by inserting the last mirror of M3. In order to avoid astigmatism phenomenon, the mirror M3 and OC have to be aligned at an angle of 19^{o} with respect to the optical axis of the pair spherical mirror.

A pair of prism was added in the cavity in order to induce self mode locked pulses. Initially prism (P1) was inserted at near the deviation angle. A second prism P2 was then aligned into the cavity. The distance between the prisms is set around 19 cm as calculated using Equation (5) and (6). The separation of the prisms will introduce negative dispersion in the cavity which is to compensate the dispersion in cavity. After that mirror M4 was aligned. The arm length between the M2 to M4 was set to be in the ratio of 4:3 of the M1-OC length. With the alignment of mirror M4 the basic alignment of mode locked operation was completed. The mirror M3 was used only during alignment procedure but not included during femtosecond operation. A slit is introduced in order to remove the CW beam element in the femtosecond pulse.

Mirror M2 was adjusted and the output power was measured using Newport powermeter. The adjustment was made until the appearance of pulses which can be displayed on the Tektronix oscilloscope. The mode-locked spectrum was detected using Ocean Optics spectrometer. The spectrum was analyzed precisely by using Matrox Inspector Version 2.1 software. The software was particularly used to measure the bandwidth of the spectrum produced by Ti:sapphire oscillator. Meanwhile, ToptiCalc V25 software was used to calculate the pulse duration of the mode locked Ti:sapphire laser signal.

RESULTS

Mode-locked Ti:sapphire oscillator output was obtained at the threshold pumping power of 2.5 W. The insertion of the prism pair in the cavity caused losses in the pumping power. The power is also dissipated by the reflection on the optical components. These factors lower the gain power and at the same time higher the loss. Therefore high pumping power is needed in order to make the laser gain higher than losses in the cavity. The optimum power produced from this system is 577 mW corresponding to pumping power of 5.5 W.

The mode-locked output of the Ti:sapphire oscillator is occurred in region of stability. The stability region is tested within a distance apart of the curve mirrors. This is demonstrated by adjusting the separation between the curve mirrors. One of the mirrors in the cavity that is M2 was provided with micro scale for precise adjustment. The power produced during the adjustment of the mirror M2 was measured. The measurement results are plotted in the graph of Figure 4. The mode-locking pulse is expected to be appeared at the closer boundary of stability zone. In this experiment the near boundary was identified to be in the range of 108.35 mm to 108.75 mm. Hence the femtosecond pulse is should appear within the range of 400 micron in the condition of free vibration and dust.

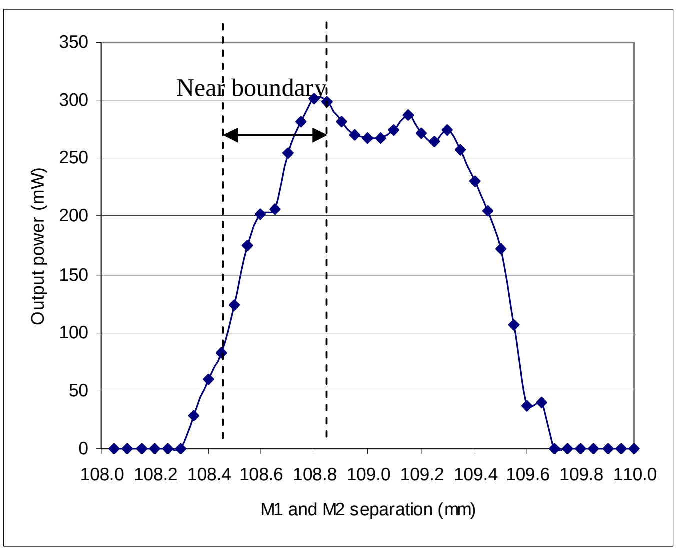

Figure 4: Output power by adjustment of the M1 and M2 spacing

The typical spectrum of femtosecond pulse is shown in Figure 5. Matrox Inspector Vesion 2.1 was employed to measure the bandwidth. The signal shows that the center wavelength of the spectrum is obtained at 806.74 nm. The bandwidth for this particular signal is 24.80 nm measured at Full Wave Half Maximum (FWHM). The information obtained from this particular signal is used to compute the pulse duration of femtosecond signal. Equation (7) and (9) were used to estimate the pulse duration. The pulse duration is calculated by using ToptiCalc V25 software. The calculation result showed the pulse duration of the femtosecond pulse is 27.56 fs by assuming the signal having $Sech^2$ shape.

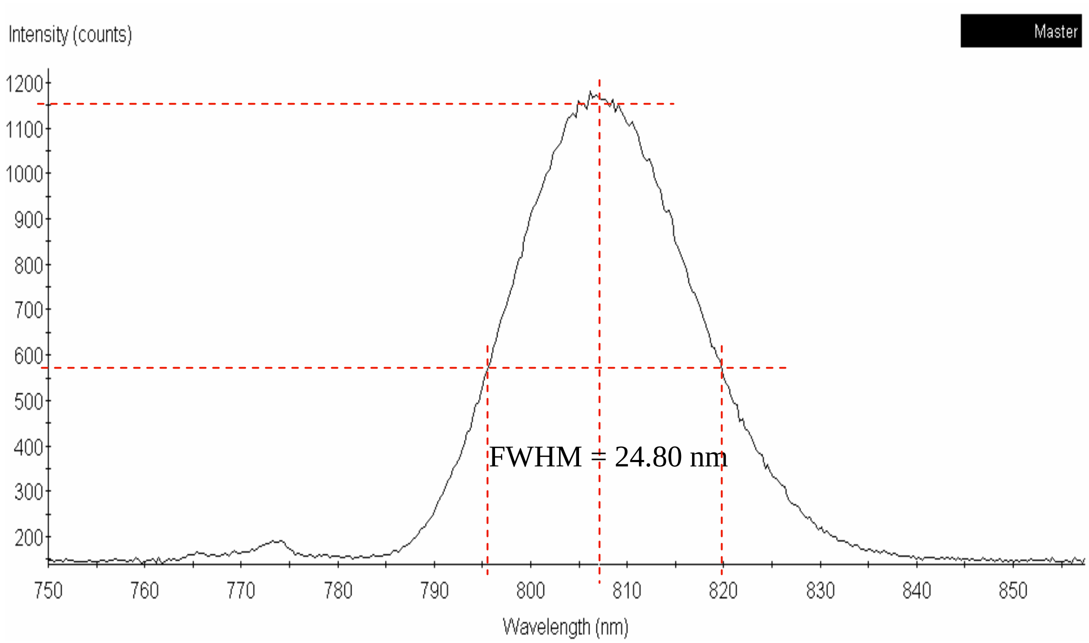

Figure 5: The femtosecond pulse spectrum

CONCLUSION

The femtosecond pulse was successfully generated from Ti:sapphire oscillator. The spectrum of the femtosecond pulse center at wavelength of 806.74 nm with bandwidth of 24.80 nm. The pulse duration was estimated to be as 27.56 fs.

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