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Analyze the stability zones of mode-locked Ti: sapphire femtosecond laser

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***Abstract*— In this work the mode-locked Ti:sapphire laser based on the Kerr lens mode-locking (KLM) mechanism have been analyzed. The aim of this paper is focus on the experimental aspects of realizing the stability zone of mode locked Ti:sapphire femtosecond laser. In fact the stability of the cavity was depended on the stability parameter. The stability zone have been obtained by changing the separation between curve mirrors of the Ti:sapphire oscillator. The stability zone will influence the mode-locked output of the Ti:sapphire laser.**

***Index Terms*—stability zone, mode-locked laser, Ti:sapphire laser, stability parameter, soft aperture.**

I. INTRODUCTION

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, dual-wavelength DIAL systems, fundamental research, spectroscopy, as well as tunable Optical Parametric Oscillators (OPO) pumping and simulating diode pumping in solid-state lasers [1], [2].

The optical Kerr effect is the nonlinear mechanism (i.e., intensity-dependent), which affects the laser light in both the spatial and temporal domains. The effect is a third-order nonlinear process, where the refractive index of the material is intensity-dependent [3], given by:

$$n(I) = n_0 + n_2 I \tag{1}$$

Where I is the light intensity and n_0 , n_2 are the linear, weak-field part and nonlinear part of refractive index, respectively.

Kerr lens mode-locking (KLM) is a process based on the nonlinear effect of self-focusing [4]. This effect will produce an intensity-dependent change in the refractive index of material and creating a lens which is focused the beam within the material. Two techniques can be used to achieve KLM which is hard aperture and soft aperture technique. This methods are common to induce losses on the continues wave (CW) mode compared to the pulsed mode.

In this paper we provide a detailed description of the theoretical and experimental physics of the stability zone of a Kerr lens mode-locked (KLM) Ti:sapphire laser. Also we provide a detailed analysis of the stable Gaussian modes of the optical cavity.

A detailed description regarding the Ti:sapphire crystal properties can be found in [5], [6], including: molecular/electronic structure, absorption/emission spectra, crystal growth techniques, doping level, figure of merit, etc.

II. EXPERIMENTAL DETAILS

The overall experimental setup of mode-locked Ti:sapphire is illustrated in figure 1. The Z-shaped cavity are used for this setup. The feedback end mirrors M_3 and M_4 are the high-reflector (HR) and output-coupler (OC), respectively. A lens of focal length 100 mm, (L), was employed to focus pump laser beam. The curved mirrors, M_1 and M_2 with focal length f_1 and f_2 are used to focus the laser into the crystal. The distance between the curved mirrors controls the spatial mode and stability range of the cavity.

Since the Ti:sapphire crystal and other optical elements in the cavity are dispersive, the pulse is deformed as it passes through them, due to the wavelength dependence of the refractive index thus a pair of prism, p_1 and p_2 needs to control and compensate the dispersion in the cavity [7]. From M_2 to M_3 with a length $80\ cm$ and from M_1 to OC with a length $60\ cm$ are two arms for this cavity.

To prevent reflection losses in the cavity the Ti:sapphire crystal is inserted at Brewster's angle witch introduces astigmatism [8]. The angles θ_1 and θ_2 are defined for astigmatism compensation.

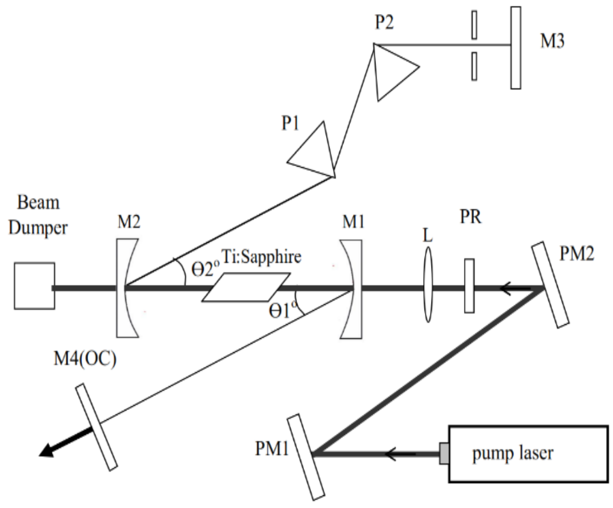

Figure 1. Schematic diagram of the experimental setup. (P1, P2 is prism, M_1-M_4 is mirror, L is lens, PR is polarization rotator, OC is output coupler PM1, PM2 is pumped mirror).

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III. RESULTS AND DISCUTIONS

A. Optical Cavity Analyze

The useful technique to analyze light beam in an optical cavity is using $ABCD$ matrix. The beam at the system input is represented by a vector, V_{in} , containing the distance, x_{in} , above the optical axis and the beam angle, θ_{in} , with respect to the optical axis. The beam at the output of the system can be calculated by, V_{out} , containing x_{out} and θ_{out} [9]:

$$\begin{pmatrix} x_{out} \\ \theta_{out} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_{in} \\ \theta_{in} \end{pmatrix} \qquad (2)$$

The simple schematic for the folded cavity is shown in figure 2 which is equivalent with lens system for the matrix analysis. For this system we can define the distance between the curved mirrors as:

$$d_f = f_1 + f_2 + t\left(1 - \frac{1}{n}\right) + \delta \qquad (3)$$

Where t and n are the thickness and refractive index of Ti:sapphire crystal, δ is stability parameter (measures the shift from a perfect telescope), f_1 and f_2 is focal length of curved mirrors.

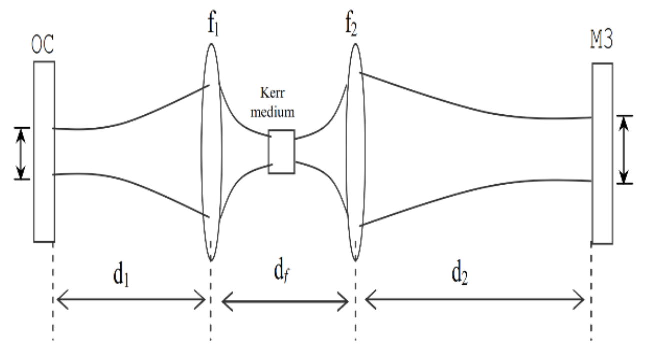

Figure 2. Schematic diagram of the tightly focused four mirror resonator configurations.

We can use the $ABCD$ matrix method to find the range of values for δ where the cavity is spatially stable. The condition for resonator stability is [10]:

$$\left|\frac{A+D}{2}\right| < 1 \qquad (4)$$

Where A and D are the elements of an $ABCD$ matrix that represents a single round trip in the cavity with respect to an arbitrary reference plane. When solving the stability requirements of the cavity illustrated in Figure 2, one finds that the laser is stable for two ranges of δ values:

$$\delta_0 < \delta < \delta_1 \quad , \quad \delta_2 < \delta < \delta_3 \qquad (5)$$

Where

$$\delta_0 = 0 \quad , \quad \delta_1 = \frac{f_2^2}{d_2 - f_2} \quad , \quad \delta_2 = \frac{f_1^2}{d_1 - f_1}$$
$$\delta_3 = \delta_1 + \delta_2 \qquad (6)$$

Then we can find the four stability limits according to the mode size behavior on the cavity end mirrors.

B. Gaussian Modes

The Gaussian mode is represented by the complex beam parameter:

$$q = z + iz_R \qquad (7)$$

Where z_R is the Rayleigh range of the beam given by $z_R = \frac{\pi w_0^2}{\lambda}$ and w_0 is the mode radius at the beam focus $z = 0$. To calculate the CW complex beam parameter at any reference plane in the cavity, one can represent the complete round trip in the cavity as an $ABCD$ matrix with respect to a chosen reference plane. Then we can find:

$$w^2 = \frac{|B|\lambda}{\pi}\sqrt{\frac{1}{1 - \frac{(A+D)^2}{4}}} \qquad (8)$$

Where w is the beam spot size at the reference plan. **A natural location to calculate the complex beam parameter is at the flat end mirrors**, where the mode must arrive with a flat phase front. For mode-locked operation the additional Kerr lens must be considered. The presence of a lens-like effect inside the crystal dramatically changes the stability behavior of the cavity. We use the soft aperture technique to mode-locked operation.

The working point for mode-locking is near a stability limit, where the laser mode is tightly focused in to the crystal. By substituting the Equation 6 with $f_1 = f_2 = 5cm$, $d_1 = 60cm$, $d_2 = 80cm$, $n = 1.76$ and $t = 5mm$ the δ_1 , δ_2 and δ_3 are equal to $0.333\ cm$, $0.454\ cm$ and $0.787\ cm$ respectively. The mode waist radius at the end mirrors as a function of the separation, δ , between the curved mirrors is shown in figure 3.

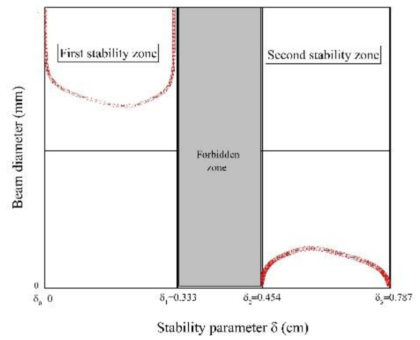

Figure 3. CW mode size on the end mirror, M_4 (OC) , as function of the stability parameter δ .

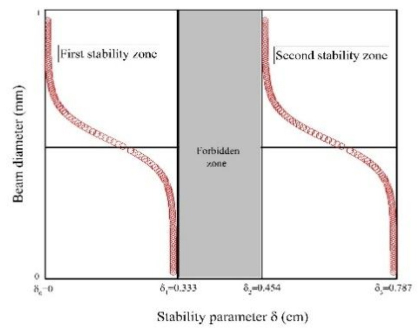

Figure 4. CW mode size on the end mirror, M_3 , as function of the stability parameter δ .

The two stability region are separated by forbidden zone. For symmetric design whereby d_1 equal to d_2, forbidden zone will be removed, in other word there is just a single stability region. When d_1 is shorter than d_2, the position of the outer stability region will shift away from the forbidden zone, but maintain the beam diameter. This shifting also occurs when d_2 is shorter than d_1.

In this design unequal arm was used which is known as asymmetric design. Therefore the stability region is split in two as shown in figure 3 and 4.

C. Kerr Medium Effect

The additional Kerr lens in the pulsed laser mode must be taken into account in order to calculate the Gaussian mode for Mode-locked operation. The nonlinear Kerr lensing process depends on a normalized parameter, P/P_c , where P is the pulse peak power and P_c is the critical power for self-focusing, given by [11]:

$$P_c = \frac{\lambda^2}{4n_2\pi} \tag{9}$$

The result of the numerical calculation of the stability condition, $\left|\frac{A+D}{2}\right| < 1$, for the general cavity configuration (with $\frac{P}{P_c} = 0.21$) illustrated in figure 4.

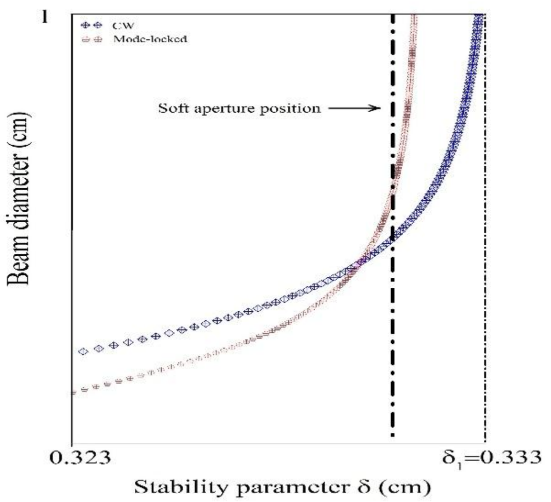

Figure 5. CW and Mode-locked mode size on the end mirror, M_4 near the CW stability limit, δ_1 , with normalized parameter 0.21.

We see that **the mode-locked stability limit is pulled down to lower values of δ by the Kerr lens**.

Note that the solution for the mode-locked mode size illustrated in Figure 4 highly depends on the Kerr medium (crystal) position. Changing the position of the crystal along the beam affects the mode intensity in the crystal and, hence, the nonlinear response, leading to a different solution.

D. Mode-Locked Pulse Occurrence

The Kerr lens mode-locking can be optimized by the adjustment of the arm length ratio. Since the stability of the symmetric cavity is easy to effect by the environment, therefore asymmetric cavity is typically used for KLM laser. For soft aperture Kerr Lens Mode-locking an asymmetric cavity configuration is predicted to be most favorable for strong self-amplitude modulation and δ adjusted to δ_2 in second stability zone.

The stability zone will influence the mode-locked output of the Ti:sapphire laser [12]. **In fact the stability of the cavity was depended on the distance of the curve mirror**. In order to prove this, one of the mirrors in the cavity that is M_2 is provided in micro scale of adjustment to adjust the separation between the curve mirrors. The power produced by adjusting of the mirror M_2 or the spacing between two curve mirrors was measured.

The graph obtained in Figure 5 shows the curve of the second stability zone. The graph can be used to identify the occurrence of the mode-locked pulse. The near boundary is measured to be in the range of $108.35\ mm$ to $108.75\ mm$.

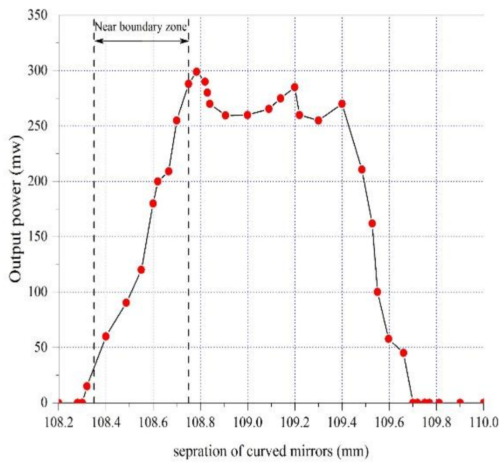

Figure 6. Output power by adjustment of the M_1 and M_2 spacing.

IV. CONCLUSION

In this study the stability zones of the mode-locked of Ti:sapphire femtosecond laser have been analyzed. The Z folded cavity type was set up in this project. The total length of laser cavity is 150.5 cm. The separation between adjacent mirror M1-M2, M2-M3 and M1-OC was 10.5 cm, 80 cm and 60 cm, respectively.

Both types of laser mode have been successful analyzed. We find that the laser is stable for two ranges of δ values bounded between four stability limits, The stability zone has been obtained by changing the separation between M_1 and M_2. For continuous wave beam diameter on the end mirrors, At δ_1, the beam is collimated in the short arm and focused on M_3 in the long arm. This behavior is reversed at δ_2 . In a Kerr medium the Mode-locked stability limit is pulled down by the Kerr lens to lower values of δ.

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