Dynamics of Active Mode Locking in Broad-Band Continuous Wave Lasers

K. P. J. Reddy and Jim A. Tatum

Abstract—Theoretical analysis for the dynamics of mode locking in an AM mode-locked broad-band tunable solid-state laser is presented. The analysis is applied to study the pulse evolution inside the AM mode-locked Ti:Al₂O₃ laser. It is shown that the pulsewidth reaches a steady-state value after about 77 500 round-trips inside the laser cavity which corresponds to 258 μ s. An expression for the threshold condition for the mode-locking process is presented. The analysis yields the design parameters required for building an AM mode-locked laser.

I. INTRODUCTION

ULTRASHORT light pulses of picosecond and sub-picosecond duration are routinely used for scientific, medical, and industrial applications. Commonly, these pulses are produced by the mode-locked dye lasers which are capable of generating pulses broadly tunable in the near-UV to near-IR region. However, the dye lasers have a major drawback due to the photodegradation of the dye solution. Recently, broadly tunable solid-state lasers have been found to provide an attractive alternative to dye lasers in the near infrared region [1].

Mode locking of tunable solid-state lasers has been achieved using active [2], passive [3], self- [4], synchronous [5], additive-pulse mode locking [6], and resonant passive mode-locking [7] techniques. Of all the tunable solid-state lasers Ti:sapphire has been extensively investigated both experimentally and theoretically [8]. Mode-locked pulses of 11 fs duration have been produced recently in an intracavity dispersion compensated self-mode-locked Ti:sapphire laser [9]. However, there are many scientific and engineering applications which need tunable picosecond pulses with high reliability. Active mode locking is the best suited technique for producing these pulses from broad-band solid-state lasers. This method is free from the stability and reproducibility problems faced by the other methods of mode locking. Hence efforts are being made to understand the characteristics of active mode locking of broadly tunable lasers. Recently, Darrow and Jain [8] published detailed analysis of the actively mode-locked broad-band lasers and their theoretical re-

sults compared well with the experimental results of Ti:Al₂O₃ laser. In their paper the analysis is based on the theoretical model developed earlier by Kuizenga and Siegman [10] for active mode locking of a solid-state laser. In this model a steady-state Gaussian pulse is assumed to circulate in the laser resonator and after traversing the intracavity elements and after experiencing the cavity loss, the pulse that returns to the starting point is assumed to stay unchanged. The extension of this model in [8] is achieved for broadly tunable solid-state lasers by including a bandwidth tuning element inside the laser cavity and accounting for the effect of dispersion in the intracavity optical components on the mode-locked laser pulse. However, the analysis concentrates on the steady-state characteristics and has paid no attention to the pulse forming dynamics. Studies of mode-locking dynamics have been reported recently for other techniques of mode locking in Ti:sapphire laser where it has been shown that complete mode locking is achieved after 200 μ s in self-starting additive-pulse mode locking [12], millisecond, and 230 μ s in passive mode locking by HITCI [12] and DDI [13], respectively.

In this paper we report the theoretical study of the dynamics of active mode locking of broad-band CW solid-state lasers. The primary interest in this paper is focused on the temporal evolution of the pulsewidth and the pulsewidth-bandwidth product of the mode-locked pulse inside the laser cavity. The importance of the analysis lies in the fact that first it helps in determining the time interval required to complete the mode-locking process of the time interval required to recover if the mode-locked laser is perturbed. Second, the analysis results in the determination of the modulation index required to achieve mode locking, which is important for designing the modulator. The approach used in the analysis is essentially an extension of the self-consistent theory of Kuizenga and Siegman incorporating the modifications for the broad-band laser systems suggested in [8]. Although we have considered here only the case of AM mode locking with zero detuning, the analysis can be easily extended for the finite detuning and FM mode locking.

II. ANALYSIS

The analysis proceeds by assuming a Gaussian pulse to circulate in the laser resonator. Necessary approximations are made to the transmission functions of the intracavity

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elements such as laser gain medium, bandwidth limiting element, and the acoustooptic modulator to keep the pulse Gaussian. The effect of each intracavity element on the parameter γ defining the pulse parameters is separately calculated. Unlike in the steady-state theory, in this analysis the total change in the Gaussian pulse shape parameter is equated to differential increment ($\Delta\gamma$) in the shape parameter. This leads to a differential equation in terms of the parameter γ . The solutions of this differential equation are then used to obtain the temporal variation of the pulsewidth and pulsewidth-bandwidth product of the Gaussian pulse. Finally, the fundamental differential equation governing the mode-locking process is examined to determine the threshold value of the modulation index necessary to achieve mode locking.

The electric field of the circulating Gaussian pulse inside the laser cavity is assumed in the form, $E(t) = (E_0/2) \exp(-\gamma t^2) \exp(j\omega_p t)$ where ω_p is the center frequency and $\gamma = \alpha - j\beta$ is the shape factor in which α and β are related to the pulsewidth and the pulsewidth-bandwidth product through the equations $\tau_p = (2 \ln 2/\alpha)^{1/2}$ and $\tau_p \Delta f_p = (2 \ln 2/\pi)(1 + (\beta/\alpha)^2)^{1/2}$, respectively. The change in γ due to the passage of the pulse through the homogeneously broadened broad-band laser medium with the gain $g(\omega) = G \exp[-(2jg/\Delta\omega)(\omega - \omega_a) - (4g/\Delta\omega^2)(\omega - \omega_a)^2]$ where, $G = e^g$, g is the saturated round-trip amplitude gain, ω_a is the atomic line center, and $\Delta\omega$ is the atomic linewidth, is given by

$$\Delta\gamma_A = -16g\gamma^2/\Delta\omega^2. \quad (1)$$

Here we have assumed that $\omega_a = \omega_p$ (no detuning).

The transmission function through the host of the gain medium, focusing optical cavity components, cavity bandwidth limiting elements, and the medium of the modulator is assumed in the form [8],

$$\begin{aligned} \tau_{\text{cavity}}(\omega) = & \exp[-j(P|\lambda=\lambda_a)\omega_a/c] \\ & \cdot \exp\{(j/c)\lambda_a^2[d/d\lambda(P/\lambda)|_{\lambda=\lambda_a}](\omega - \omega_a)\} \\ & \cdot \exp[(-4/\Delta\omega_i^2 - jD/\pi^2)(\omega - \omega_a)^2] \end{aligned} \quad (2)$$

where P is the round-trip optical path length, c is the speed of light in vacuum, λ_a is the wavelength of light at the gain peak, $\Delta\omega_i$ is the bandwidth of the tuning element, and $D = (\lambda_a^3/8c^2)(d^2P/d\lambda^2|_{\lambda=\lambda_a})$ represents the round-trip cavity group velocity dispersion. The change introduced by the transmission function (2) in γ is given by

$$\Delta\gamma_{\text{cavity}} = -4\gamma^2(4/\Delta\omega_i^2 + jD/\pi^2). \quad (3)$$

Assuming the round-trip transmission of the amplitude modulator in the form $a(t) = \exp(-\theta_m^2 \omega_m^2 t^2)$ where θ_m is the peak round-trip depth of amplitude modulation and ω_m is the modulation frequency, the change in γ due to the passage through the modulator is given by

$$\Delta\gamma_{AM} = \theta_m^2 \omega_m^2. \quad (4)$$

The net change in γ during one round-trip time is given by the summation of (1), (3), and (4). Thus

$$\begin{aligned} \Delta\gamma/\Delta t = & [\theta_m^2 \omega_m^2 - 16(g/\Delta\omega^2 + 1/\Delta\omega_i^2 \\ & + jD/4\pi^2)\gamma^2](c/2L) \end{aligned} \quad (5)$$

where $\Delta t = 2L/c$ is the round-trip traversal time for the pulse inside the laser cavity of length L .

Assuming the changes in γ during one round-trip time interval are small, the ratio $\Delta\gamma/\Delta t$ may be replaced by the continuous time derivative $d\gamma/dt$. Therefore, the above equation is rewritten as

$$\begin{aligned} d\gamma/dt = & (\theta_m^2 \omega_m^2)(c/2L) - 16\gamma^2(g/\Delta\omega^2 \\ & + 1/\Delta\omega_i^2 + jD/4\pi^2)(c/2L). \end{aligned} \quad (6)$$

Solving this equation by the method of separation of variables, we get the transient solution in the form [14], [15],

$$\gamma = \gamma_0 \tanh[(\sigma + j\Omega)(t + t_0)(c/2L)] \quad (7)$$

where t_0 is a constant of integration and

$$\gamma_0 = -[\theta_m^2 \omega_m^2 / 16(g/\Delta\omega^2 + 1/\Delta\omega_i^2 + jD/4\pi^2)]^{1/2} \quad (8a)$$

$$\sigma = \text{Re} [\theta_m^2 \omega_m^2 16(g/\Delta\omega^2 + 1/\Delta\omega_i^2 + jD/4\pi^2)]^{1/2} \quad (8b)$$

and

$$\Omega = \text{Im} [\theta_m^2 \omega_m^2 16(g/\Delta\omega^2 + 1/\Delta\omega_i^2 + jD/4\pi^2)]^{1/2}. \quad (8c)$$

At steady state, (6) gives

$$\gamma = 4\theta_m \omega_m (g/\Delta\omega^2 + 1/\Delta\omega_i^2 + jD/4\pi^2)^{-1/2} \quad (9)$$

from which, assuming $(g/\Delta\omega^2) \ll (1/\Delta\omega_i^2)$ and/or $(D/4\pi^2)$, we can show that the steady-state pulsewidth and pulsewidth-bandwidth products are given by

$$\begin{aligned} \tau_{ps} = & (2^{3/2} \ln 2 / \theta_m f_m \pi^2)^{1/2} \cdot [(1/\Delta f_i^2)^2 + D^2]^{1/4} \\ & \cdot \{[(1/\Delta f_i^2)^2 + D^2]^{1/2} + (1/\Delta f_i^2)\}^{-1/4} \end{aligned} \quad (10)$$

and

$$\begin{aligned} \tau_{ps} \Delta f_{ps} = & (2^{3/2} \ln 2 / \pi) \{1 + (1/\Delta f_i^2)[(1/\Delta f_i^2)^2 \\ & + D^2]^{-1/2}\}^{-1/2}. \end{aligned} \quad (11)$$

These steady-state equations for pulsewidth and pulsewidth-bandwidth product are identical to the corresponding equations derived using steady-state analysis in [8].

Separating real and imaginary parts from (7) we can show that

$$\begin{aligned} \alpha = & (\theta_m \omega_m / 2^{5/2} Z^{1/2}) [X^{1/2} \sinh(2\sigma M) \\ & + Y^{1/2} \sinh(2\Omega M)] \\ & \cdot [\cosh(2\sigma M) + \cosh(2\Omega M)]^{-1} \end{aligned} \quad (12a)$$

$$\beta = (\theta_m \omega_m / 2^{5/2} Z^{1/2}) [Y^{1/2} \sinh(2\sigma M) - X^{1/2} \sinh(2\Omega M)] \cdot [\cosh(2\sigma M) + \cosh(2\Omega M)]^{-1} \quad (12b)$$

where

$$Z = (g/\Delta\omega^2 + 1/\Delta\omega_i^2)^2 + (D/4\pi^2)^2$$

$$X = Z^{1/2} + (g/\Delta\omega^2 + 1/\Delta\omega_i^2)$$

$$M = (c/2L)(t + t_0).$$

Here, M is the number of round-trips the mode-locked pulse makes inside the laser cavity. Using (12a) and (12b) the time dependence of pulsewidth and pulsewidth-bandwidth product are obtained as

$$\tau_p = \tau_{ps} [\sinh(2\sigma M) + (Y/X)^{1/2} \sinh(2\Omega M)]^{-1/2} \cdot [\cosh(2\sigma M) + \cosh(2\Omega M)]^{1/2} \quad (13)$$

$$\tau_p \Delta f_p = (\tau_{ps} \Delta f_{ps}) [\sinh(2\sigma M) + (Y/X)^{1/2} \sinh(2\Omega M)]^{-1} \cdot [\sinh^2(2\sigma M) + \sinh^2(2\Omega M)]^{1/2}. \quad (14)$$

Equations (13) and (14) describe the dynamics of pulse evolution inside the mode-locked broad-band tunable solid-state lasers starting from the initial continuous wave (CW) operation. It is important to note that although we have considered only the case of AM mode locking with zero detuning the frequency chirp β which contributes to the total bandwidth is not zero. The finite value of β is due to the group velocity dispersion effects of the material media inside the laser cavity.

III. RESULTS AND DISCUSSION

The equations derived in the preceding section are applied to study the dynamics of AM mode-locking process in Ti:sapphire laser. The parameters considered are the saturated gain $g = 0.18$, the gain bandwidth $\Delta f = 197.2$ THz, the tuning element bandwidth $\Delta f_i = 56.9, 13.8$, and 3.45 THz corresponding to one, two and three plate birefringent filters, respectively, the modulation depth $\theta_m = 0.55$, the modulation frequency $f_m = 160$ MHz, and the laser cavity length $L = 0.5$ m. The group velocity dispersion term is taken in the form $D = [62.0 + (18.3 \text{ THz}/\Delta f_i)] \times 10^{-28} \text{ s}^2$ [8].

The steady-state values of the pulsewidth and the pulsewidth-bandwidth products are computed from (10) and (11), respectively, while the time evolution of these variables are computed from (13) and (14) and the results are given in graphical form in Figs. 1 and 2. The mode-locking process reaches steady state when the transient values of pulsewidth and pulsewidth-bandwidth product approach the corresponding values predicted by the steady-state equations (10) and (11), respectively. Thus it is seen from Fig. 1, that starting from a very large initial value the pulsewidth approaches the steady state value after the mode-locked pulse makes very large number of round-

Fig. 1. Variation of the mode-locked pulsewidth as a function of number of round-trips inside the laser cavity for three different tuning elements.

Fig. 2. Variation of the pulsewidth-bandwidth product as a function of number of round-trips inside the laser cavity for three different tuning elements.

trips inside the laser cavity. Therefore, the variation of pulse parameters in a single round-trip traversal through the intracavity elements is very low. Hence the transformation of the finite difference equation (5) into a differential form (6) is justified. Of the three tuning elements the three-plate filter produces the broadest steady-state pulses. Evolution of pulsewidth-bandwidth product shown in Fig. 2 indicates a largest value for the two plate filter. For the remaining two tuning elements this product remains constant and almost equal to an ideal value of 0.440 [10] for the AM case. Larger value of the pulsewidth bandwidth product is due to a finite value of β which grows from zero with the increase of the number of round-trips inside the cavity, as shown Fig. 3. The presence of frequency chirp indicated by $\beta \neq 0$ is due to the inclusion of dispersion effects in the analysis. Thus if $D = 0$ then $\beta = 0$ from (12b). It is important to note that due to the presence of frequency chirp the pulses from the AM mode-locked Ti:sapphire laser with a two-plate tuning element could be further shortened by using pulse compression techniques such as a grating pair.

Comparing the pulsewidth evolution shown in Fig. 1 with the corresponding plot given in [13], it is seen that the oscillatory behavior noticed in the pulsewidth evolution in a passively mode-locked Ti:sapphire/DDI laser is not noticed in the present case. The oscillatory behavior in the passively mode-locked laser is due to the compe-

Fig. 3. Pulsewidth parameter α and frequency chirp parameter β for the mode-locked laser with three different tuning elements.

Fig. 4. Steady-state mode-locked pulsewidth variation as a function of the modulation depth of the AM modulator.

tition between the pulse shortening and broadening forces in the cavity which occurs because of the statistical nature of the pulse evolution in this system. Since the mode-locking process in active mode locking is free from fluctuations, the oscillatory behavior in pulse evolution is not noticed.

The dependence of mode-locked pulsewidth on the modulation depth is investigated and the steady-state values for various values of θ_m are plotted in Fig. 4. The curves shown here again indicate the broader pulses generated by three-plate tuning element at larger values of θ_m . However, for lower values of θ_m all the three tuning elements produce identical values for the steady-state pulsewidth. Also it is noted that the dependence of pulsewidth on the modulation depth is very sensitive for lower values of θ_m .

To estimate the exact time for pulse evolution it is necessary to evaluate the constant of integration t_0 in (7). With the knowledge of the initial conditions of the laser system t_0 could be estimated. However, it is difficult to estimate the initial values in a practical system. An alternative way is to estimate t_0 by estimating the initial value γ_m of the parameter γ . This is achieved as follows. With the knowledge of average number of modes N oscillating inside the laser cavity, and the mode separation frequency f_c , the initial value of the pulsewidth could be estimated using the relationship $\tau_m = 1/Nf_c$. Since the average number of modes does not change, the number of modes can be experimentally measured using a scanning Fabry-Perot etalon. As $\beta = 0$ at the beginning of the mode locking, as shown in Fig. 3, the initial value of γ could be estimated as $\gamma_m = \alpha_m = 2 \ln 2 / \tau_m^2$. For a typical mode-locked Ti:sapphire laser $N = 25$ and $f_c = 300$ MHz, which yield $\tau_m = 133.33$ ps. Assuming that at $t = 0$, $\tau_p = \tau_m$ (13) yields $(t_0 c / 2L) = 2500$. The exact number of round-trips required to reach steady state is computed by subtracting this value from the number of round-trips at steady state shown in Fig. 1. Thus we see that the mode-locked pulse makes about 77500 round-trips inside an AM mode-locked Ti:sapphire laser to reach steady state. This corresponds to the pulse evolution time of 258.33 μ s. This time is

slightly higher than the recently measured value of 230 μ s in the Ti:sapphire/DDI passively mode-locked laser [13].

An estimation of the threshold condition for the mode locking could be obtained by examining the differential equation (6). It shows that the action of the AM modulator is to increase γ (reduce τ_p) and that of the laser medium and the tuning element is to decrease γ (increase τ_p). A steady state is attained when these two effects are balanced. For the estimated value of γ_m , a measure of mode-locking threshold could be obtained from the equation

$$\theta_m^2 > (\gamma_m^2 / \pi^4 f_m^2) (g / \Delta f^2 + 1 / \Delta f_i^2 + jD / 4\pi^2).$$

Since the effect of the modulator is real, the imaginary part could be neglected and the threshold value of θ_m could be estimated from

$$\theta_m^2 \sim (2 \ln 2)^2 (\pi^4 \tau_m^2 f_m^2)^{-1} (g / \Delta f^2 + 1 / \Delta f_i^2).$$

For the AM mode-locked Ti:sapphire laser considered here, this equation yields $\theta_m = 3.85 \times 10^{-3}$. This value signifies the minimum value of the modulation depth required to achieve mode locking. To ensure mode locking and allow for small detuning effects, we can use a value $\theta_m = 0.04$. With this value for the modulation depth the analysis predicts a steady-state pulsewidth of 46.89 ps.

The error introduced in the above calculations due to the error in the estimation of initial values is negligible. For example even assuming an infinite pulsewidth ($t_0 = 0$) would introduce an error less than 3% because of the large number of round-trips the pulse needs to make inside the laser cavity before reaching the steady state. Thus the error introduced by the indeterminacy of the initial pulsewidth does not seriously affect the accuracy of the estimation of the pulse evolution time interval. Likewise the error introduced in measuring the number of oscillating modes which results in the initial pulsewidth estimate will also introduce an error less than 3% in the estimation of the threshold value of the modulation depth. Since the mode-locking threshold is not a well-defined quantity, this error is within the acceptable limit.

IV. CONCLUSION

The dynamics of pulse formation in AM mode-locked broadly tunable CW solid-state lasers has been investigated. The analysis is presented for zero detuning, but it could be easily extended for finite detuning and FM mode-locking process. It is shown that the pulse makes about 7.75×10^4 round-trips inside the AM mode-locked Ti:sapphire laser before reaching the steady state. Thus the system reaches steady state after about 258 μ s which is comparable to that of the passively mode-locked Ti:sapphire laser. An estimate of the threshold condition for the mode locking is also presented. For AM mode-locked Ti:sapphire laser the threshold value of modulation depth to achieve mode locking is found to be equal to 0.04. The error in the calculation of the above quantities is found to be less than acceptable limits.

The analysis thus helps in determining the parameters such as pulsewidth, the minimum modulation index required for mode locking and the time required for reaching the steady state, which characterize the laser. These parameters aid the design of the laser system.

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