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Simulation of the passively mode-locked laser with a SESAM

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ABSTRACT

By solving the Haus master equation through split step Fourier transform method, several programs which can simulate the soliton mode-locked dynamic processes of the passively mode-locked solid laser with a semiconductor saturable absorber mirror (SESAM) are established, based on a MATLAB environment. The pulse evolution equations are solved numerically. Sample calculations for a diode-pumped Nd^{3+}:YVO_4 (0.5% doped) laser with a SESAM are presented to demonstrate the use of the simulation programs and the related formulas. Several theoretical results such as the pulse width, the peak power and the average output power are obtained with a given cavity structure, which are in good agreement with the reported experimental results.

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1. Introduction

The demonstration of mode locking in a range of solid-state lasers in the mid-1960s opened up the era of a new class of laser systems that is now described as ultrashort-pulse or ultrafast lasers, which have many applications in the medical and the other fields, such as surgery, angioplasty, dermatology, information storage, coherent telecommunications, etc., so it has attracted great attention in the recent years. Short laser pulses with pulse widths on the order of nanoseconds were obtained for the first time by Hargrove et al. in 1964 [1], using active mode-locking (ML). In the same year, it was reported that laser systems introduced diode-pumped source could have strongly increased efficiency [2,3]. One year later, the first passively Q-switched mode-locked laser was demonstrated by Mocker and Collins [4] and pulses shorter than 1 ns were realized by De Maria in 1966 [5]. On the other hand, pulses shorter than 1 ps were generated firstly with a dye laser by Ippen et al. in 1972 [6].

As a unique and exciting passively mode-locking element for solid state laser system, semiconductor saturable absorber mirrors (SESAMs) have been used to generate mode-locked pulses from 10s of picoseconds to sub-10 fs [7]. The SESAM generally comprise one or more semiconductor saturable absorber layers monolithically integrated into a mirror structure, which can be employed as an additional intracavity laser element for initialization and stabilization of the mode-locking process [8,9]. In recent years, SESAMs have become a key component in the development of ultrashort pulse solid-state lasers [10–13], and much more experimental results are reported, for instance, 5.3 W, 6.2 W and 8.1 W averaged output power with the conversion efficiency of 31.2%, 35% and 41% were obtained by adopting the SESAMs in *Z* cavity of Nd:YVO_4 mode-locked lasers [14,15], respectively. However, there are many ambiguously answered or even unanswered questions about the dynamic mechanisms involved, such as the evolution process of mode-locking pulse in the whole laser cavity, the overlapping effects of different parameters, and the profile of output soliton pulse. Besides experimental method, computer simulations have the potential to provide considerable insight into the dominant dynamic processes. One big advantage of such simulations is that the influence of one or just a few processes and properties can be studied separately, which is mostly impossible in experiments. Also, parameter ranges that are still unavailable experimentally can be studied, and therefore predictions of the most suitable parameter values can be made. Therefore, it is of theoretical interest to establish simulation programs to describe the dynamic process of passively mode-locked laser with a SESAM.

In this paper, based on Haus master equation and split step Fourier transform, the simulation programs of passively mode-locked solid lasers are established. Sample calculations for a diode-pumped Nd^{3+}:YVO_4 (0.5% doped) laser with a SESAM are presented to demonstrate the use of the simulation programs and related formulas. Several theoretical results of the stable mode-locking pulse such as the profile of an output soliton, the evolution of pulse energy and time–bandwidth product, with key parameters pulse width, peak power, repetition rate and average output power are worked out with a given cavity structure, which are in good agreement with the reported experimental results.

2. Principle of soliton mode-locking

Taking all effects into account, the linear ones: loss, dispersion, gain and gain dispersion, as well as the nonlinear ones like saturable absorption $q(T,t)$ and self-phase modulation (SPM) with self-phase

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modulation coefficient δ [16], the mode-locking master equation can be given under the assumption of small changes in pulse shape and elements within one round trip in the time domain [17]:

$$T_R\frac{\partial A(T,t)}{\partial T}=j\sum_{n=2}^{\infty}D_n\left(j\frac{\partial}{\partial t}\right)^n A(T,t)+g(T)\left(1+\frac{1}{\Omega_g^2}\frac{\partial^2}{\partial t^2}\right)A(T,t)-lA(T,t)-q(T,t)A(T,t)-j\delta|A(T,t)|^2A(T,t) \quad (1)$$

where $g(T)$ is the gain; Ω_g is the half width; $D=-(\partial^2k/2\partial\omega^2)L_g$ is the group-delay dispersion parameter, representing the difference in delay for the wavelengths caused by the dispersive medium, where k is the wave vector, L_g is the length of dispersive medium, and ω is the angular frequency; $A(T,t)$ is the wave amplitude; t is a time scare which resolves the shape of the pulse and T is on the order of multiples of the round-trip time T_R ($T=n\cdot T_R$) in the resonator.

If a slow saturable absorber (recovery time much longer than the pulses) is involved instead of loss modulators in active mode-locking, the soliton-like pulse is shaped by group-delay dispersion (GDD) and SPM, and this regime has been called soliton passive mode-locking. Then the master equation is rewritten as:

$$T_R\frac{\partial A(T,t)}{\partial T}=\left[g-l+\left(\frac{g}{\Omega_g^2}+\frac{1}{\Omega_f}+jD\right)\frac{\partial^2}{\partial t^2}-j\delta|A(T,t)|^2-q(T,t)\right]A(T,t) \quad (2)$$

where $1/\Omega_f$ is the filtering action, and saturable absorption $q(T,t)$ obeys the following equation:

$$\frac{\partial q(T,t)}{\partial t}=-\frac{q-q_0}{\tau_q}-\frac{|A(T,t)|^2}{E_{sat.abs.}}q \quad (3)$$

where τ_q is the absorber recovery time, $E_{sat.abs}$ is the saturation energy, and q_0 is the initial loss. Eq. (2) has a simple steady state $sech^2$ solution [18], and the soliton order $N_{soliton}=\sqrt{(|\delta||A_{peak}^2|\tau_{FWHM}^2)/(1.762^2\cdot|D|)}$ exactly matches the soliton theory. For a $sech^2$ pulse shape with $N_{soliton}=1$. The approximation of pulse width is given by:

$$\tau_{FWHM}=\sqrt{\frac{|D|}{|\delta|}}|A_{peak}^2|^{-1}\approx\sqrt{\frac{1.76\times2\times0.88|D|}{B}}\approx1.76\cdot\frac{2|D|}{|\delta|E_p} \quad (4)$$

where B is a measured value for the phase change within one total round trip, calculated by $\sum_i\delta(i)\cdot|A_{peak}^2(i)|$ (i representing the position for each major change of A_{peak}). E_p is the energy of the pulse. $|A_{peak}^2|$ represents the peak power of the pulse. And using a laser cavity with large output coupler rate T_{OC} decreases the need for large internal negative GDD by a factor of $T_{OC}/1\text{n}(1-T_{OC})$

$$\tau_{FWHM}\approx-1.76\cdot\frac{2|D|\cdot\ln(1-T_{OC})}{|\delta|E_P\cdot T_{OC}} \quad (5)$$

3. Simulation setup

3.1 Evolution equations

By means of the split-step Fourier method, the propagation of ultrashort pulse described by Eq. (2) was numerically simulated. To obtain the solution, various cavity elements and optical effects are all taken as operators, such as a loss operator $\hat{O}_l$, a gain operator $\hat{O}_g$, an operator $\hat{O}_{SPM}$ describing the SPM, a similar operator $\hat{O}_{GDD}$ for the GDD, an operator $\hat{O}_{OC}$ incorporating the T_{OC}, and an operator $\hat{O}_{sat.abs.}$ for the saturable loss due to a SESAM.

$$A(t+T_R)=\hat{O}_{OC}\cdot\hat{O}_{sat.abs.}\cdot\hat{O}_l\cdot\hat{O}_{SPM}\cdot\hat{O}_{GDD}(\hat{O}_{SPM}\cdot\hat{O}_{GDD}\cdot\hat{O}_g\cdot\hat{O}_l)\cdot A(t) \quad (6)$$

reproducing the changes of the electric field $A(t)$ after one round trip.

3.1.1 Gain

During the mode-locking operation, the gain is acting as major filtering element in the frequency domain [19,20], which can be described by:

$$g(\omega,T)=\frac{g(\omega_0,T)}{1+((\omega-\omega_0)/\Omega_g)^2} \quad (7)$$

In case of gain broadening due to saturation $\Omega_g=(\Delta\omega_L/2)\sqrt{g_0/(g(\omega_0,T))}$, where $\Delta\omega_L$ is the inherent bandwidth of the gain material. The filtering action of the gain in the frequency domain can be described by:

$$\hat{O}_g(\omega)=\exp\left(\frac{1}{2}\cdot g(\omega,T)\cdot2\right) \quad (8)$$

where the factor 1/2 in the exponential represents the fact that $\exp(g(\omega,T))$ is a power gain, and the factor 2 for twice passing the gain medium in one roundtrip.

For times on the order of the period of revolution, the gain might change with time due to the relaxation and saturation effects. When discretizing the derivative ($\partial g(T,t)/\partial t)=((g_0-g)/\tau_g-(2|A(T,t)|^2)/E_{sat,g})g$) numerically, we get:

$$g(T,t+\Delta t)=-\frac{g(T,t)-g_0}{\tau_g}\Delta t+\left(1-\frac{2|A(t)|^2}{E_{sat,g}}\Delta t\right)g(t) \quad (9)$$

For the time in between laser pulses, the relaxation of the gain was accounted for by the use of:

$$g(t+\Delta T)=g_0-(g_0-g(t))\exp\left(\frac{-\Delta T}{\tau_g}\right) \quad (10)$$

Here $\Delta T=T_R/2$, which can be numerically calculated for all times t.

3.1.2 Losses of SESAM

Mostly the bandwidth of the gain medium acts as a filter in the frequency domain, whereas all other elements have a bandwidth much larger compared with the spectral width of the mode-locked pulses, consequently, any filtering action of the saturable absorber is neglected in the simulation.

The loss analysis and the development of the corresponding operator $\hat{O}_{sat.abs.}$ is done in accordance with the reasoning for the development of the temporal behavior of the gain operation $\hat{O}_g$. When discretized numerically, the derivative Eq. (3) is rewritten as:

$$q(T,t+\Delta t)=-\frac{q(T,t)-q_0}{\tau_q}\Delta t+(1-\frac{|A(T,t)|^2}{E_{sat.abs.}}\Delta t)q(T,t) \quad (11)$$

For the time between pulses, Eq. (3) is given by:

$$q(t+\Delta T)=q_0-(q_0-q(t))\exp(-\Delta T/\tau_q) \quad (12)$$

With this formula, the respective operator acts on the electric field $A(t)$ as follow:

$$\hat{O}_{sat.abs.}=\sqrt{1-q(t)} \quad (13)$$

Fig. 1 shows the corresponding saturation characteristic curve, which is obtained by calling Eq. (11) recursively in the program.

3.1.3 Losses of mirror

For transmission losses of the laser mirrors, because of large bandwidth mentioned above, the loss can be considered to be constant in the frequency and time domain. In such a case, the operator $\hat{O}_l$ is given by $\hat{O}_l=\sqrt{1-l}$, where $0\le l\le1$ represents the power loss inside the resonator.

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