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Optimization of the mode-locked Nd:YVO_4 laser with a semiconductor saturable absorber mirror

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ABSTRACT

By taking into account the effects of group-delay dispersion (GDD) and self-phase modulation (SPM), an analytic model describing the generation of a pulse in a passively mode-locked laser is developed in order to establish simulation while optimizing a mode-locked Nd:YVO_4 laser with a semiconductor saturable absorber mirror (SESAM), based on the saturable absorber mode-locking theory developed by Haus. Then, the pulse evolution equations are solved numerically through split step Fourier transform method to obtain the dependence of the pulse characteristics on cavity length, group-delay dispersion (GDD), output coupling rate, and pump power, and to determine the key parameters of an optimized mode-locked Nd:YVO_4 laser.

1. Introduction

Picosecond pulse is required in a great number of applications in scientific research and engineering practices such as information storage, coherent communication, and laser medicine. To obtain such pulses, the mode-locking theory was presented in 1964 [1]. Techniques for mode locking are distinguished by two different schemes: active and passive mode-locking. While active mode-locking requires an external clock source that is matched to the cavity round-trip time, passive mode-locking is realized by some intensity dependent loss device introduced into the laser cavity [2]. The first passive mode-locking Nd:glass laser was achieved by De Maria in 1966 [3]. However, long after that, mode-locked solid-state laser was inapplicable because of the phenomenon of Q-switched mode-locking, and the average output power of dye laser was greatly limited. In the mid-1990s, the appearance of a semiconductor saturable absorber mirror (SESAM) [4] immediately made mode-locked solid-state laser available [5–7], by suppressing the instabilities of Q-switched mode-locking. A SESAM consists of a saturable absorber and an epitaxially grown bottom mirror and the semiconductor–air interface integrated into a Fabry–Perot structure. For antiresonant Fabry–Perot saturable absorber, which was first utilized to start and sustain a stable CW mode locking by Keller [4], the thickness of the Fabry–Perot structure was controlled to prevent resonance [8]. With self-start, great stability, and simplicity of its structure, SESAM has been proved to be efficient in passively mode-locked solid-state lasers [9].

Because high peak power and high-energy ultrashort laser pulse proves its great potentiality in many scientific and industrial fields, obtaining higher peak power and shorter pulse length and improving stability have become research hotspots. A large number of experiments have been performed on passively mode-locked solid-state lasers [10–15], and some theoretical analysis on this process has been discussed [16,17]. Our work is focused on how to develop an analytic model based on the saturable absorber mode-locking theory developed by Haus [18], considering the effects of group-delay dispersion and self-phase modulation. The stimulation can enable us to conclude the dependence of the pulse characteristics on the parameters of the gain medium, resonant cavity, and SESAM. The solution can be beneficial to our design of an optimized mode-locked Nd:YVO_4 laser. Similarly, by utilizing this kind of method, we can also optimize lasers by using other kind of crystals as the gain medium.

In this paper, a numerical model of passively mode-locked solid-state laser is introduced, and the implementation of numerical simulation in a Matlab environment is discussed. Then, the pulse evolution equations are solved numerically through split step Fourier transform method. Finally, by changing the values of cavity length, group-delay dispersion (GDD), output coupling (OC) rate, and pump power, the dependence of pulse characteristics on these parameters is determined. Thus, the optimization of a mode-locked Nd:YVO_4 laser is achieved.

2. Soliton mode locking

A single-ended output laser with a five-mirror mode-locking cavity is shown in Fig. 1. The pump source is a fiber-coupled laser-diode, which works at the maximum absorption wavelength

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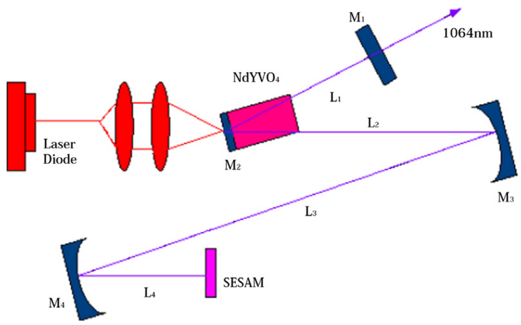

Fig. 1. Schematic of the passively mode-locked Nd:YVO_4 laser with a SESAM.

(808 nm) of the Nd:YVO_4 crystal. The Nd:YVO_4 crystal is a-axis cutting and 0.5% Nd^{3+} doped. Water circulating cooling systems is used for controlling the temperature of the crystal at 25 °C. The crystal's front surface M_2 is high antireflection coated at 808 nm and high reflection coated at 1064 nm, as well as its rear surface is high antireflection coated at 1064 nm. The output mirror M_1 is a plane mirror with a fixed output coupling rate, and M_3, M_4 are both concave mirrors. The distances are indicated by L_1 (between M_1 and M_2), L_2 (M_3 apart from M_2), L_3 (M_4 away from M_3), and L_4 (between M_4 and the SESAM), respectively. All these above constitute the cavity length.

The SESAM generally comprises one or more semiconductor saturable absorber layers (quantum wells) integrated into a mirror structure, which can be employed as an additional intracavity laser element for initialization and stabilization of the mode-locking process. For passively mode locked solid-state lasers that operate around 1 μm (Nd^{3+} and Yb^{3+}-doped materials), $In_xGa_{1-x}As$ quantum-well SESAMs with GaAs/AlAs-based Bragg reflectors are selected.

Inside a medium with nonvanishing nonlinear refractive index and group-delay dispersion, just as the laser resonator in Fig. 1, a soliton pulse can be propagating steadily under certain conditions. However, the SESAM is only responsible for starting and stabilizing the pulse shaping process but not for the pulse shaping itself.

The formation process of the ultrashort pulse may be described approximately as Fig. 2. In each round-trip cycle, the pulse will experience gain, loss, self-phase modulation, group-delay dispersion, saturable absorption due to the SESAM, additional phase change, and filtering produced by the gain, the output coupler and the reflector. Therefore, taking all the above effects into account, the performance of a mode-locked laser, including pulse energy, peak power, and pulse width, can be optimized through the proper choice of parameters of the gain medium, the saturable absorber, and the resonator.

Because of the interplay of group-delay dispersion and self-phase modulation, a balance between both is required in order to stabilize the soliton mode-locking process, when the group-delay dispersion, self-phase modulation, energy of the pulse, and the pulse length perfectly match the soliton area theorem, which is given by [19,20]:

$$\tau_{FWHM} = 1.76\frac{2\beta_2}{\gamma_{SPM}E_P} \tag{1}$$

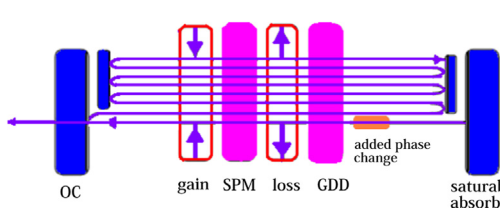

Fig. 2. Schematic of the pulse formation process in the laser cavity.

where τ_{FWHM} is the full width of the pulse at half maximum in the time domain or pulse length; E_P is the pulse energy; β_2 and γ_{SPM} refer to the total amount of group-delay dispersion and the self-phase modulation coefficient in one complete round trip, respectively. Considering the amounts of output coupling rate, the equation should be modified with an extra factor of $-\ln(1-OC)$, which is

$$\tau_{FWHM} = -1.76\frac{2\beta_2}{\gamma_{SPM}E_P}\ \ln(1-OC) \tag{2}$$

3. Numerical model

Taking all the above mentioned effects into account, 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 [18], which is shown in Fig. 2:

$$T_R\frac{\partial}{\partial T}A(T,t) = (-i\beta_2\frac{\partial^2}{\partial t^2} + i\gamma_{SPM}|A|^2)A + \left[g - l + \left(\frac{g}{\Omega_g^2} + \frac{1}{\Omega_f}\right)\frac{\partial^2}{\partial t^2} - l(T,t)\right]A \tag{3}$$

where $A(T, t)$ is wave amplitude, T_R is the period of revolution, g is the saturation gain coefficient in one round trip, l is the power loss coefficient in one round trip, $l(T, t)$ is the saturable absorption, Ω_g is the gain bandwidth, and Ω_f is the bandwidth of filter in the cavity.

By means of the split-step Fourier method, the propagation of ultrashort pulse described by Eq. (3) can be numerically simulated. To obtain the solution, various cavity elements and optical effects are all taken as operators (shown as Fig. 2), such as a loss operator O_l, a gain operator O_g, an operator O_{SPM} describing the self-phase modulation, O_{GDD} for the group-delay dispersion, O_{OC} incorporating the T_{OC}, and an operator $O_{sat,abs}$ for the saturable loss due to a SESAM. Then, the variation of the electric field $A(t)$ after one round trip can be described as [21]:

$$A(t+T_R) = O_{oc}O_{sat,abs}O_gO_lO_{SPM}O_{GDD}(O_gO_lO_{SPM}O_{GDD})A(t) \tag{4}$$

Utilizing Eq. (4), the shape of the pulse and important characteristics including pulse length, energy, and peak power are acquired after each round trip.

3.1. Gain

The gain is acting as a filter in the frequency domain because of its saturation effects, therefore we have

$$g(\omega,T) = g(\omega_0,T)\left[1+\left(\frac{\omega-\omega_0}{\Delta\omega_g}\right)^2\right]^{-1} \tag{5}$$

where $\Delta\omega_g = \Delta\omega_L\sqrt{g_0/g(\omega_0,T)}/2$ is the gain bandwidth in the case of gain saturation, $\Delta\omega_L$ is the gain bandwidth at a small signal gain g_0. Then the operator of the gain medium acting in the frequency domain can be written as

$$O_g(\omega) = \exp\left(\frac{1}{2}g(\omega,T)N^*\right) \tag{6}$$

where N^* is the number of passes through the gain medium. The temporal evolution of the gain over round trips can be drawn from

$$g(t+\Delta t) = -\frac{g(t)-g_0}{\tau_g}\Delta t + \left(1-\frac{A^2(t)N^*}{E_{sat,g}}\Delta t\right)g(t) \tag{7}$$

where τ_g and $E_{sat,g}$ are relaxation time and saturation energy of saturable absorber, respectively.