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SESAMs structure design for GHz femtosecond lasers

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ABSTRACT

SESAM mode locked femtosecond laser at higher frequency up to gigahertz repetition rate suffers from the tendency for Q-switching instabilities. Increasing the pump power and decreasing the spot size at both the laser crystal and SESAM could help to stabilize the cw mode-locking of a gigahertz ultrafast laser. However, this is limited by the available laser diode pump power and may result in SESAM damage. Two photon absorption (TPA) effect in SESAM will generate 'roll over' effect of nonlinear reflectivity curve, which will decrease the critical pulse energy and critical pump power for cw mode-locking. By designing SESAM structures, we could optimize the 'roll over' effect and suppress the Q-switching instabilities. From simulation, we find out that enhanced SESAM with a cap layer thickness of 116 nm and first GaAs layer thickness of 517 nm will lead to a minimum critical pump power of 12.1 W for our designed 1 GHz laser cavity.

1. Introduction

High repetition rate ultrafast pulsed lasers are important tools for many applications such as optical data transmission [1], nonlinear bio-imaging [2], frequency metrology [3] and so on. Increased repetition rate to gigahertz range can also be excellent sources for optical frequency comb [4]. SESAM mode locked Yb doped ultrafast laser could be a good option for gigahertz repetition rate laser. It combines the favorable properties of cost efficient diode pumping, an intrinsic low quantum noise level and robustly mode-locking without critical cavity alignments [5,6]. In 2010, Pekarek, Fiebig et al. reported first SESAM modelocked Yb:KGW gigahertz femtosecond laser, they generated 120 mW output power in 317 fs pulses at 1 GHz repetition rate [7]. Later Klenner et al. in the same group increases the output power to 3.4 W in 125 fs pulses at 1.06 GHz [4]. In 2014, they further improve the laser performance by using a new Yb:CALCO crystal to a 3.5 W average output power in 60 fs pulses at 1.8 GHz [8]. In 2015, this group again pushes the output power to 4.1 W in sub-100 fs pulses at 5 GHz repetition rate [9].

Gigahertz ultrafast laser develops fast in the last 10 years. The output power gets higher and higher, while the repetition rate gets larger and larger. However most of the authors only pay attention to the laser cavity design to improve the laser performance. For example: they use novel DBR tapered diode laser other than traditional multimode fiber coupled LD as pump to improve the pumping efficiency [10]; they use new crystals such as Yb:CALGO to shorten the pulse duration [8]; and they use compact three mirrors structure to stabilize the cw mode-locking by Kerr lens effect [9]. However, few people talk about SESAM structure design, which might be another solution to stabilize gigahertz cw mode-locking running and decreasing the required pump power.

In this paper, we will first go through the cw mode-locking criteria and design a 1 GHz ultrafast laser cavity. Rate equations will be introduced into the ultrafast laser cavity design to calculate the pump power required for stable cw mode-locking ultrafast laser. Then we will theoretically analyze how SESAM structure influences the SESAM's reflectivity curve as well as cw mode-locking pulse energy and pump power. We also will compare three different kinds of SESAM structures and come out with an optimized SESAM design to minimize the required pump power for stable cw mode-locking running.

2. Critical pulse energy and pump power for a cw mode-locking laser

Normally a SESAM consists of a cap layer d_0, an absorber layer in a spacer with thickness of d_1 (first GaAs layer) and a Bragg mirror, as shown in Fig. 1. Cap layer may not be necessary for anti-resonant SESAM and resonant SESAM. We should mention here that in our simulation, Si_3N_4 is used for cap layer, while GaAs and AlAs are used for Bragg mirror. But other materials like InP/InGaAsP would also be used.

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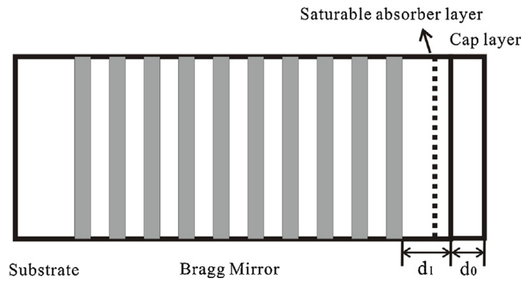

Fig. 1. Structure of a typical SESAM.

Because the incident laser pulse has a very short pulse duration and then a very high peak power, laser induced two photon absorption in SESAM can not be ignored. For a top hat sech2-shaped incident laser pulses, we know from [11] that the SESAM reflectivity with fluence F_p can be calculated as the following equation:

$$R(F_p) = R_{ns}\frac{\ln\left(1+\left((R_{ns}-\Delta R)/R_{ns}\right)\left(e^{F_p/F_{sat}}-1\right)\right)}{F_p/F_{sat}}e^{-F_p/F_2} \quad (1)$$

where R_{ns} is non-saturable losses in the structure, ΔR is the modulation depth, F_{sat} is the saturation fluence of SESAM, F_p is the incident pulse fluence applied on the SESAM, and F_2 is the inverse slope of the induced absorption effect (TPA) [11]:

$$F_2 = \frac{\tau_p}{0.585\int \beta(z)n^2(z)\left(\left|E_n(z)\right|^2\right)^2 dz} \quad (2)$$

where τ_p is the pulse duration of the incident pulse; $\beta(z)$ is the local two photon absorption coefficient: $\beta_{GaAs} = 0.07$ cm/MW for GaAs and the two photon absorption coefficients for AlAs and Si_3N_4 is nearly zero and can be ignored [11,12]; $n(z)$ is the local refractive index; and $E_n(z)$ is the normalized electric field.

The field distribution $E_n(z)$ is dependent on the SESAM's structure and the chosen semiconductor material [13–15]. From Eq. (2), by changing the structures and material of the SESAM, we could tune the value of F_2.

We know already that the key problem to run a GHz ultrafast laser is to suppress the tendency for Q switching instabilities [9]. In order to obtain stable cw mode-locking laser, the laser pulse energy needs to be larger than the critical pulse energy E_{crit} as Eq. (3). For a given SESAM and laser gain material, laser cavity could be designed to decrease the beam size on both laser crystal and SESAM, in order to decrease the critical pulse energy for cw mode-locking.

$$E_{crit}^2 = \frac{F_{sat,A}A_A\Delta R}{\left(1/F_{sat,L}A_L\right)+\left(1/F_2A_A\right)} \quad (3)$$

We could also calculate the critical output power by E_{crit} and pulse repetition rate f: $P_{crit} = E_{crit} \times f \times T$, where T is the transmission of output coupler. We could calculate the critical pump power needed to obtain cw mode-locking running laser by rate equations for three-level laser as the following equations [16,17]:

$$\begin{aligned}\frac{d\Delta N(x,y,z)}{dt} &= 0\\ &= (f_a+f_b)Rr_p(x,y,z) - \frac{\Delta N(x,y,z)-\Delta N^0}{\tau_f}\\ &\quad - \frac{(f_a+f_b)c\sigma_{eff}\Delta N(x,y,z)}{n}\Phi\phi_0(x,y,z)\end{aligned} \quad (4)$$

$$\begin{aligned}\frac{d\Phi}{dt} &= 0\\ &= \frac{c\sigma}{n}\iiint_{crystal}\Delta N(x,y,z)\Phi\phi_0(x,y,z)dV - \frac{\Phi}{\tau_c}\end{aligned} \quad (5)$$

where ΔN^0 is the unpumped population inversion density; τ_f is the lifetime of the upper laser level; c is the speed of light in vacuum; σ_{eff} is the effective gain emission cross section for the ultrafast laser spectrum of several nanometers:

$$\sigma_{eff} = \frac{\int_{\lambda_1}^{\lambda_2}\sigma(\lambda)d\lambda}{\lambda_2-\lambda_1} \quad (6)$$

n is the refractive index of the laser medium; $\tau_c = 2l_c^*/c\delta$ is the cavity lifetime; $l_c^* = l_c + (n-1)l$ is the optical path length of the cavity, $\delta \equiv L_i + T$ is the round trip loss, L_i is the intrinsic cavity loss. R is the total pump rate, $R = \eta_p\eta_a P_p/h\nu_p$, η_p is the pump quantum efficiency which is usually 1, and η_a is the fraction of incident pump power absorbed in the laser crystal, $h\nu_p$ is the pump photon energy. Φ is the total photon number in the laser cavity $\Phi \equiv 2l_c^* P_{crit}/cTh\nu_L$, $h\nu_L$ is the laser photon energy. $r_p(x,y,z)$ and $\phi_0(x,y,z)$ are the normalized pump distribution and photon distribution respectively. From Eqs. (4) and (5), if the critical output power is known, we could calculate the required critical pump power P_{pcrit}. Usually P_{pcrit} is around several watts for a gigahertz ultrafast laser, which we will discuss in detail later.

3. Cavity design for a 1 GHz Yb:KYW femtosecond laser

For a gigahertz mode locked femtosecond laser, the laser cavity length needs to match the pulse repetition rate. That is to say 1 GHz corresponds to a cavity length of 150 mm, higher frequency corresponds to even shorter cavity length. Here a 'Σ type' laser cavity of 150 mm equivalent cavity length for 1 GHz femtosecond laser, as shown in Fig. 2(a), will be simulated and discussed. M_1 is the output coupler. M_2, M_3 and M_4 are curved mirrors of 30 mm radius. M_5 is the SESAM. For simplicity, we do not consider the tilted angle of both curved mirrors and laser gain material. The distance of l_2, l_3 and l_5 will be fine tuned to make the laser beam size in the laser crystal and SESAM insensitive to distance change. The stimulated laser beam radius inside the laser cavity is shown in Fig. 2(b). The

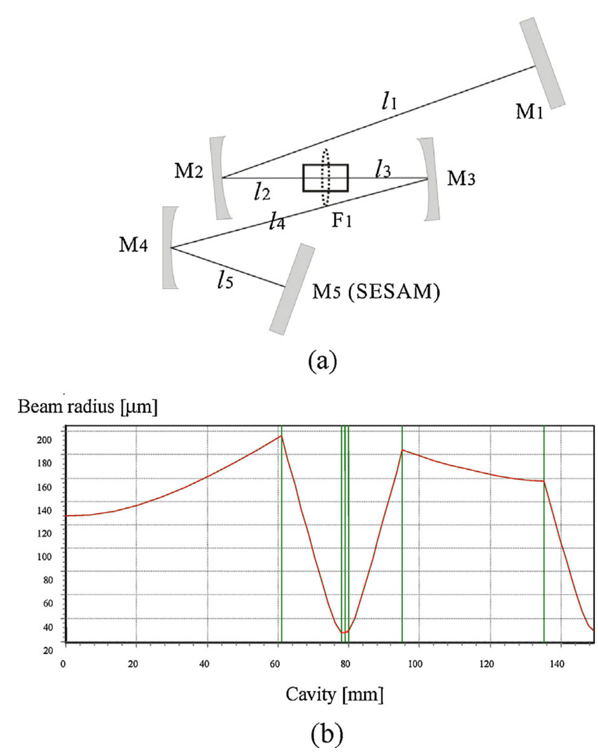

Fig. 2. 1 GHz femtosecond laser cavity: (a) femtosecond laser setup; (b) stimulated laser beam radius inside the laser cavity.