Contrastive study of two SESAMs for passive mode-locking in Nd:YVO_4 laser with low pump power

Yang Liu (刘 阳)[1], Liqun Sun (孙利群)[1], Yonggang Wang (王勇刚)[2,3], Qian Tian (田 芊)[1], Xiaoyu Ma (马骁宇)[2], and Zhigang Zhang (张志刚)[3]

[1]*State Key laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing 100084*

[2]*Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083*

[3]*Ultrafast Laser Laboratory, School of Precision Instrument and Optoelectronics Engineering, University of Tianjin, Tianjin 300072*

Received June 20, 2005

Two semiconductor saturable absorber mirrors (SESAMs), of which one is coated with 50% reflection film on the top and the other is not, were contrastively studied in passively mode-locked solid-state lasers which were pumped by low output power laser diode (LD). Experiments have shown that reducing the modulation depth of SESAM by coating partial reflection film, whose reflectivity is higher than that between SESAM and air interface, is an effective method to get continuous wave (CW) mode-locking instead of Q-switched mode-locking (QML) in low power pumped solid-state lasers. A simple Nd:YVO_4 laser pumped by low power LD, in which no water-cooling system was used, could obtain CW mode-locking by the 50% reflector coated SESAM with average output power of $\sim$ 20 mW.

OCIS codes: 140.4050, 160.6000, 140.3580.

Semiconductor saturable absorber mirrors (SESAMs) have turned out to be the most promising device for passive mode-locking in solid-state lasers since the first demonstration in 1992[1]. Laser pulses from femtosecond to nanosecond have been generated in solid-state lasers by using SESAMs as absorber[2]. During the past decade, investigations are mainly focused on three aspects, short pulse duration, high single pulse energy or average output power, and pulse repetition rate as high as GHz. However, in some applications, such as pulsed laser sensor, compact lasers with pulse duration around several picoseconds and average output power on the order of milliwatt are needed. Therefore, mode-locked laser without cooling system which is pumped by low power is demanded.

However, Q-switching tendency will be dominant in mode-locked solid-state laser with SESAMs pumped by low power due to its low value of intracavity average power[3]. For continuous wave (CW) mode-locking, it should satisfy the following relation

$$\left(\frac{P_{\text{intra}}}{f_{\text{rep}}}\right)^2 > F_{\text{sat,L}} A_{\text{eff,L}} F_{\text{sat,A}} A_{\text{eff,A}} \Delta R, \tag{1}$$

where the parameter P_{intra} is intracavity average power, f_{rep} is pulse repetition rate, $F_{\text{sat,L}}$ is saturation fluence of gain material, $A_{\text{eff,L}}$ is average laser mode area inside the crystal, $F_{\text{sat,A}}$ is saturation fluence of the saturable absorber, $A_{\text{eff,A}}$ is average mode area inside the absorber, and ΔR is modulation depth of the saturable absorber. From Eq. (1), for given pump system and cavity design, in which P_{intra} and f_{rep} are fixed, reducing ΔR can increase the possibility of CW mode-locking. But if ΔR is too low, no modulation will occur in a laser with low pump power.

Figure 1 shows the structures of two SESAMs. A layer of 15-nm-thick InGaAs grown at low temperature acts as the saturable absorber, and the bottom Bragg mirror gives a high reflectivity of 99.5%. The semiconductor/air interface reflectivity of SESAM 1# is about 30% Fresnel-reflection. SESAM 2# coated with three pairs of SiO_2/Al_2O_3 gets a reflectivity as high as 50%. The increase of the reflectivity at the surface of SESAM reduces the light entering into the absorber layer, and hence decreasing the modulation depth ΔR.

A four-mirror folded cavity was used to realize a stable CW mode-locking operation, as depicted in Fig. 2. The pump source was an 808-nm fiber-coupled laser diode (LD), whose maximum output power was only 2.2 W

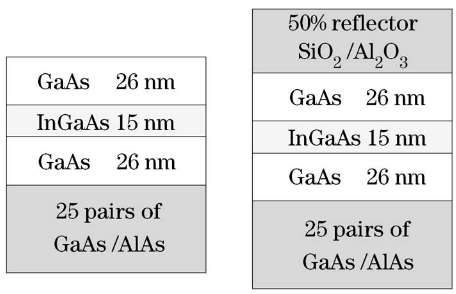

Fig. 1. Structures of two SESAMs. Left: no coating on the top (1#), 30% Fresnel-reflection; right: 50% reflection film on the top (2#).

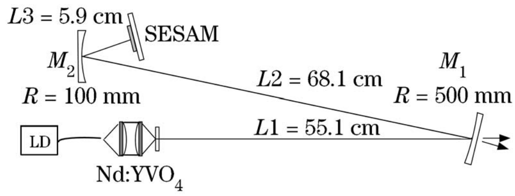

Fig. 2. Schematic of the passively mode-locked Nd:YVO_4 laser.

(made in Institute of Semiconductors, CAS). The fiber had a core diameter of 100 μm and a numerical aperture of 0.22. A couple of lens with total focal length of 25 mm was used to re-image the pump beam out of fiber into the gain crystal. The calculated spot size inside the crystal was 67.7 μm. An a-cut $3 \times 3 \times 1$ (mm) Nd:YVO_4 crystal with Nd^{3+} concentration of 1 at.-% was used as gain medium in our experiment. The crystal was wrapped with indium film and bedded into a copper heat sink to transfer heat in a simple way. One of the light-passing faces of the crystal was dichroic coated to replace a mirror, and the other face was coated for antireflection (AR, $R < 0.2\%$) at the lasing wavelength. Besides the surface of gain crystal, the resonator was composed of two concave mirrors M_1, M_2, and a SESAM as flat mirror at the same time. M_1 (radius of curvature of 50 cm) acted as output coupler mirror with a partial transmittance of 0.1% at 1064 nm, giving a total output coupler of 0.2%. M_2 was a reflection mirror with the radius of curvature of 10 cm which focused the beam onto the SESAM. $L1$, $L2$, and $L3$ were chosen to be 55.1, 68.1, and 5.9 cm, respectively (given cavity length of 129.1 cm), so that the laser mode radius was optimized to be $\sim$ 280 μm inside the Nd:YVO_4 crystal and $\sim$ 34 μm on the SESAM[4]. The heat load on the SESAM was handled simply by mounting the SESAM on a small copper heat sink.

Output behaviors of both lasers were observed with the change of the pump power, as shown in Fig. 3. The lasing threshold is about 190 mW. The poor average output power is due to the low transmissivity of the output mirror, which in fact is a total reflection mirror with slight tilt angle. But the output power on the order of milliwatt is enough for our application of pulsed laser sensor.

The slight increase of the output power of SESAM #2 is because that higher top reflectivity of SESAM gives lower nonsaturable insertion loss. More difference of performance between two SESAMs lies on the mode-locking state, as listed in Table 1, CWML is CW mode-locking.

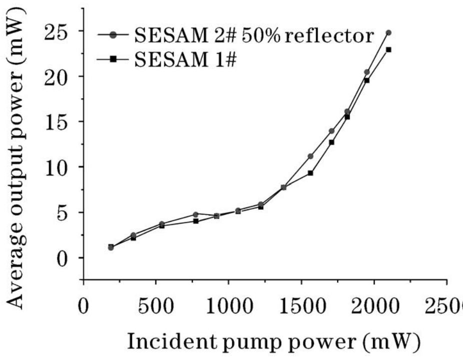

Fig. 3. Variation of average output power versus incident pump power.

For SESAM #1, Q-switched mode-locking (QML) occurs almost as soon as the solid-state laser is turned on. From pump power of 190 mW to 1.3 W, the laser is in stable QML stage, the trace in time domain is shown in Fig. 4. When the pump power increases to 1.3 W, CW mode-locking appears, but it is unstable with a strong tendency towards QML. Since QML happens at 190-mW pump power, we think that the modulation depth of SESAM #1 is high enough to generate saturable absorb, in fact, it is too high to get stable CW mode-locking in such low pump power. As discussed before, we got SESAM #2 by coating a layer of 50% reflection film on the top of SESAM #1. SESAM #2 is designed to have lower modulation depth which helps to generate CW mode-locking. From Table 1, the laser with SESAM #2 is in CW operation until the pump power reaches 540 mW. From 540 mW to 2.2 W (the maximum of the LD) of pump power, the laser is in stable CW mode-locking operation, and there is no QML stage. Waveform of the CW mode-locked pulse train in Nd:YVO_4 laser with SESAM #2 was shown in Fig. 5. The repetition frequency of 116 MHz was decided by the cavity length.

As mentioned before, 50% coating also reduces the nonsaturable loss of the SESAM, thus increases the intracavity average power P_{intra}. From Eq. (1), this also helps to generate CW mode-locking. However, a detailed discussion shows that the decrease of ΔR is the key factor in the CW mode-locking.

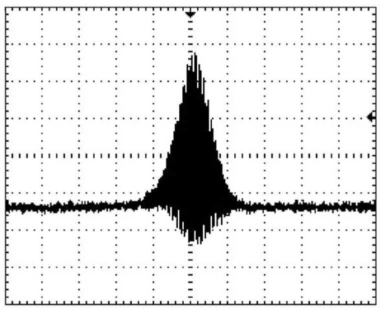

Fig. 4. Waveform of QML in Nd:YVO4 laser with SESAM #1.

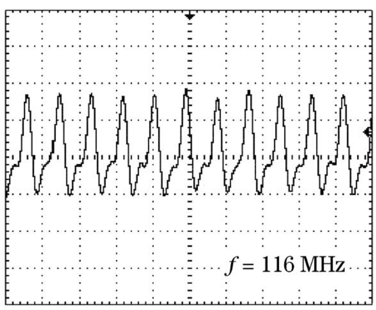

Fig. 5. Pulse train of CW mode-locking in Nd:YVO_4 laser with SESAM #2.

Table 1. Mode-Locking State of Both SESAMs under Different Pump Powers

Pump Power (mW)	190	345	541		1221	1378	1815	2000
SESAM #1	QML	QML	QML	···	QML	CWML	CWML	CWML
SESAM #2	CW	CW	CWML	···	CWML	CWML	CWML	CWML

Equation (1) can be changed into

$$\left(\frac{P_{\text{intra}}}{f_{\text{rep}}}\right) > E_{\text{pc}}, \quad (2)$$

$$E_{\text{pc}} = (F_{\text{sat,L}}A_{\text{eff,L}}F_{\text{sat,A}}A_{\text{eff,A}}\Delta R)^{1/2}, \quad (3)$$

where E_{pc} is the minimum intracavity pulse energy required for obtaining stable CW mode-locking. Calculated from the data of Fig. 3, the output power increased 8% after the coating. $P_{\text{intra}} = \frac{1}{2}P_{\text{out}}\frac{1+R}{1-R}$, where R is the reflectivity of the output coupler mirror[5], so P_{intra} increased 8% too. We can not measure ΔR directly for each SESAM since the stable pulsed laser source needed by the measurement is not available, but by assuming that the CW mode-locking threshold for each SESAM is their E_{pc}, E_{pc} can be estimated from the corresponding output power, and ΔR is the only parameter which was changed during the experiments. E_{pc} for SESAM #1 was calculated to be 6.68×10^{-8} J, while E_{pc} for SESAM #2 was calculated to be 3.32×10^{-8} J, which means a reduction of about 50% for ΔR after coating.

Pulse width is an important parameter for application. Both the fast saturable absorber model and the soliton mode-locking model predict longer pulses with a lower modulation depth. In Ref. [6], 34-fs pulse was obtained using an AR-coated saturable absorber; while 40—90-fs pulse was achieved with an antiresonant Fabry-Perot saturable absorber (A-FPSA), which consists of a 96% top reflector. However, because of lacking of instruments, pulse width in our experiments cannot be measured until now, so detailed study on the dependence of pulse width on the top reflectivity will be carried out later.

From the experiments above, SESAM #2 is qualified for CW mode-locked solid-state lasers with low pump power. But in Nd:YVO_4 laser with SESAM #2, when the pump power is near the mode-locking threshold, that is to say, in the beginning of the CW mode-locking stage (from 541 to 774 mW of pump power in our experiments), double-repetition-rates mode-locking occurred, as depicted in Fig. 6. Since the onset of two pulses in the cavity leads to double-repetition-rates output in passively mode-locked lasers, but it has been believed to occur when the saturable absorber is over saturation[2,7]. The reason for this double-repetition-rate output near mode-locking threshold in our experiment is to be studied.

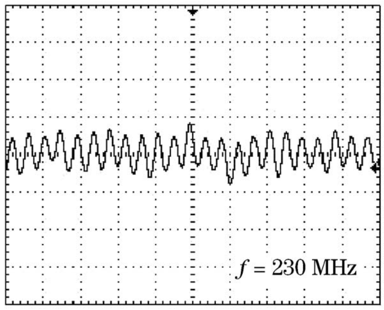

Fig. 6. Double-repetition-rate mode-locking in Nd:YVO_4 laser with SESAM #2 near threshold.

In conclusion, we have contrastively studied two SESAMs in a Nd:YVO_4 laser pumped by low output power LD. Coating the SESAM with reflection film with proper reflectivity turns out to be an effective method to get CW mode-locking in solid-state lasers, and the nonsaturable loss is decreased as well with the coating. With the 50% reflection film coated SESAM, a simple, low cost CW mode-locked solid-state laser without water-cooling is demonstrated. The average output power of the pulsed laser is $\sim$ 20 mW, which is high enough when using in ultrashort pulsed laser sensors.

Y. Liu's e-mail address is yang-liu03@mails.tsinghua.edu.cn.

References

1. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
2. U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2,** 435 (1996).
3. C. Honninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16,** 46 (1999).
4. Y. Liu, L. Sun, Y. Wang, H. Qiu, Q. Tian, and X. Ma, Opt. Eng. (to be published).
5. J. Du, J. He, J. Liu, Q. Jiang, S. Liu, and H. Wang, Chin. Opt. Lett. **2,** 275 (2004).
6. I. D. Jung, L. R. Brovelli, M. Kamp, and U. Keller, Opt. Lett. **20,** 1559 (1995).
7. J. Aus der Au, D. Kopf, F. Morier-Genoud, M. Moser, and U. Keller, Opt. Lett. **22,** 307 (1997).