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Instructor: **Prof. Mansoor Sheik-Bahae**

Semiconductor Saturable Absorber Mirror (SESAM)

Yule Zhang & Yanrui Zhao

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1. General Introduction

Since 1992, semiconductor saturable absorbers have become the important components in the compact mode-locking solid-state lasers [1]. This invention offers the possibilities for passive pulsed solid-state laser systems, extending from Q-switched pulses in the nanosecond and picosecond regime to mode-locked pulses from 10's of picoseconds to sub-10 fs. In this report, we will review the theory and designs of semiconductor saturable absorber mirrors (SESAM) and focus on some specific topics such as structure design of the SESAM and parameters control, Q-switched mode-locking vs. CW mode-locking, and finally talk briefly about its extended application in ring lasers.

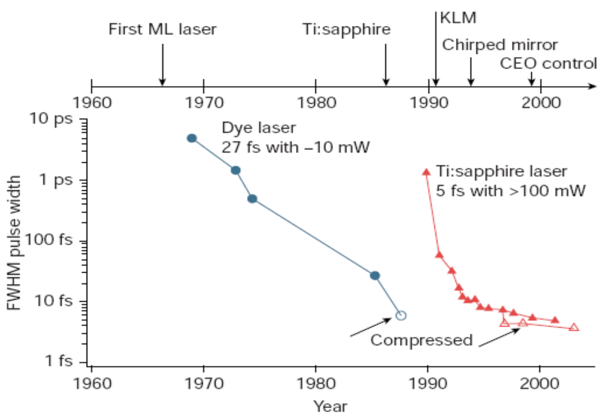

Fig. 1. History of mode-locked pulsed laser technology [2].

Mode-locking is one of the most popular techniques to obtain ultrashort pulsed lasers. Lasers with multi-gigahertz repetition rates are key components of many applications. They are used in high-capacity telecommunication systems, photonic switching devices, and optical interconnections and for clock distribution etc. Figure 1. shows the history of mode-locking technology since 1960 [2].

A saturable absorber is a material that has decreasing light absorption with increasing light intensity. The key parameters for a saturable absorber are its wavelength range (where it absorbs), its dynamic response (how fast it recovers), and its saturation intensity and fluence (at what intensity or pulse energy density it saturates). Semiconductor materials, however, can absorb over a broad range of wavelengths (from the visible to the mid-infrared). We can also control their absorption recovery time and saturation fluence (typically 1 to $100 mJ/cm^2$) by altering the growth parameters and device design. The SESAM is a saturable absorber that operates in reflection, thus the reflectivity increases with higher incoming pulse intensity [3].

During the past decade, the device design, fabrication process and long-term device reliability have been significantly improved. There are SESAM designs that can cover wavelengths from <800 nm to >1600 nm, pulsewidths from femtoseconds to nanoseconds, and power levels from milliwatts to >100 watts.

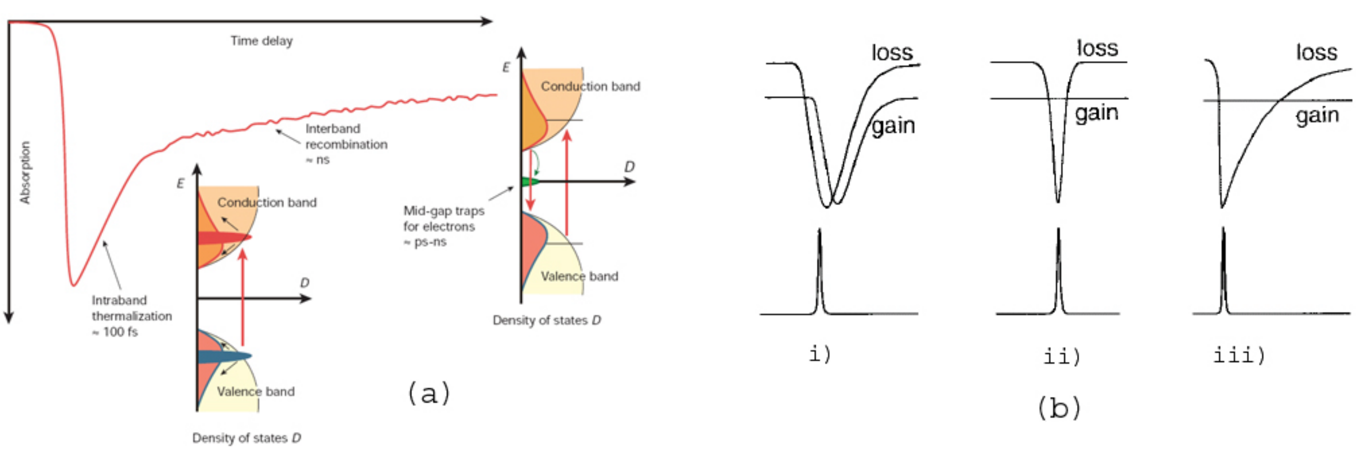

Fig. 2. a) How does semiconductor absorber work? b) fundamental passive mode-locking models: i) passive mode-locking with a slow saturable absorber and dynamic gain saturation. ii) fast absorber mode-locking. iii) soliton mode-locking. [2]

Fig. 2(a) shows how does the saturable absorber work. A semiconductor absorbs light when the photon energy is sufficient to excite carriers from the valence band to the conduction band [2]. Under conditions of strong excitation, the absorption is saturated because possible initial states of the pump transition are depleted while the final states are partially occupied. Within 60~300 fs of excitation, the carriers in each band thermalize, and this leads to a partial recovery of the absorption. On a longer time scale, typically between a few picoseconds and a few nanoseconds—the carrier will be removed by recombination and trapping. The presence of two different time scales can be rather useful for modelocking. The longer time constant results in a reduced saturation intensity for a part of the absorption, which facilitates self-starting mode-locking, whereas the faster time constant is more effective in shaping subpicosecond pulses. Therefore, SESAMs allow us to easily obtain self-starting mode-locking [2].

As the low intensity part of the pulse will be absorbed, while the high intensity part will pass the material with little loss, which result in the compression of the pulse, i.e. the pulse becomes shorter and shorter when it passes through this saturable absorber. And fig.2.b) shows the three fundamental passive mode-locking models. : i) passive mode-locking with a slow saturable absorber and dynamic gain saturation. ii) fast absorber mode-locking. iii) soliton mode-locking. These three basic models show us the different pulses we will get, combining of different gain medium and absorbers [1].

2. Overview of Different SESAMs Designs and Parameters Control

Semiconductor saturable absorbers have the advantage that the relevant absorber parameters can be varied by several orders of magnitude. Thus semiconductor saturable absorbers offer significant improvements in performance compared with other saturable absorber. Now let's go through various designs of SESAM's, which achieve many of the desired properties. Fig. 3 shows four typical designs in historical order.

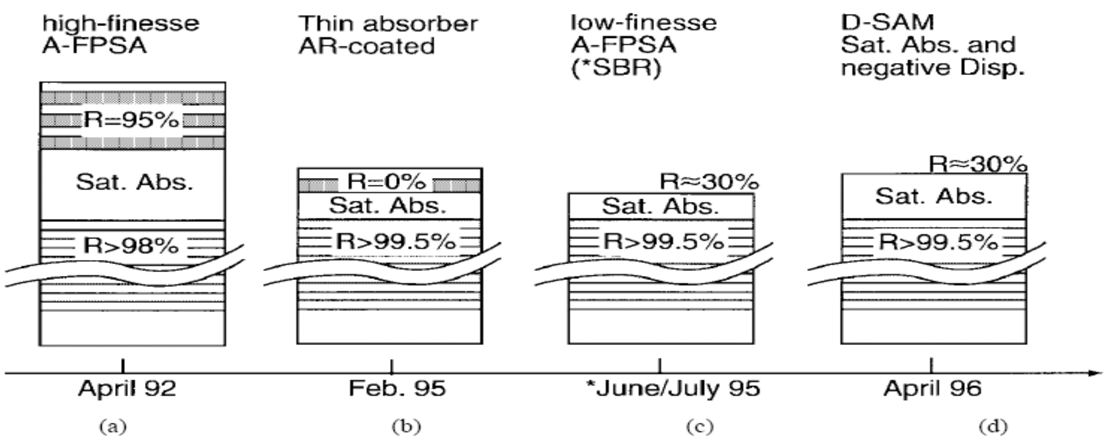

Fig.3. Different SESAM devices. (a) High-finesse A-FPSA. (b) Thin AR-coated SESAM. (c) Low-finesse A-FPSA. (d) D-SAM [1]

Fig.3(a) shows the first intracavity SESAM device, which was the antiresonant Fabry-Perot saturable absorber (A-FPSA) [1]**.** It has a rather high top reflector. Thus it is called the high-finesse A-FPSA. The Fabry-Perot is typically formed by the lower semiconductor Bragg mirror and a dielectric top mirror, with a saturable absorber and possibly transparent spacer layers in between. The thickness of the total absorber and spacer layers are adjusted such that the Fabry-Perot is operated at antiresonance. Operation at antiresonance results in a device that is broad-band and has minimal group velocity dispersion. The top reflector of the A-FPSA is an adjustable parameter that determines the intensity entering the semiconductor saturable absorber and, therefore, the effective saturation intensity or absorber cross section of the device.

High finesse antiresonant Fabry-Perot saturable absorber (A-FPSA) device was the first intracavity saturable absorber that started and sustained stable CW mode-locking of Nd:YLF and Nd:YAG lasers in 1992 [1]. It has been used to passively Q-switch microchip lasers, generating pulses as short as 56 ps. Femtosecond pulse durations τ_p have been generated with Ti:sapphire (τ_p=19fs), Yb:YAG (τ_p~500fs) etc.

In the design of Fig.3 (b) AR-coated SESAM, the top mirror is replaced with an AR-coating. Using the incident laser mode area as an adjustable parameter, the incident pulse energy density can be adapted to the saturation fluence of the device. The AR-coated SESAM device can be viewed as one design limit of the A-FPSA with a ~0% top reflector. However, an additional AR-coating increases the modulation depth of this device and acts as a passivation layer for the semiconductor surface that can improve long-term reliability of this SESAM device. These AR-coated SESAM's have started and stabilized a soliton mode-locked Ti:sapphire laser achieving pulses as short as 34 fs [1].

Fig. 3 (c) shows the Low-Finesse A-FPSA. High finesse A-FPSA and AR-coated SESAM are the two design limits of the A-FPSA, while low-finesse A-FPSA is the intermediate design. It is achieved with no additional top coating resulting in a top reflector formed by the Fresnel reflection at the semiconductor/air interface, which is typically ~30%. The Bragg reflector does not play a key role in its operation and does not actually saturate. Thus, a metal reflector can replace the Bragg reflector. The limitations of low-finesse A-FPSA devices include the bandwidth of the lower Bragg mirror, and potentially higher insertion loss than in the high-finesse A-FPSA. Pulses as short as 19 fs have been generated with the high-finesse A-FPSA compared to 34 fs with the low-finesse A-FPSA using the same lower Bragg mirror, for example. Replacing the lower Bragg mirror with a broad-band silver mirror resulted in self-starting 10-fs pulse and more recently pulses as short as 6.5 fs with a KLM-assisted Ti:Sapphire [1].

D-SAM design is shown in Fig. 3 (d). The dispersive saturable absorber mirror (D-SAM) incorporated both dispersion and saturable absorption into a device similar to a low-finesse A-FPSA, but operated close to resonance. Saturable absorption and dispersion compensation in a semiconductor Gires-Tournois-like structure, called a dispersion-compensation saturable absorber mirror (D-SAM). The D-SAM, in contrast to the A-FPSA, is operated close to the Fabry-Perot resonance, which tends to limit the available bandwidth of the device. In Cr:LiSAF laser with this device, 160 fs pulses was achieved without further dispersion compensation or special cavity design. That was the first time that both saturable absorption and dispersion compensation have been combined within one integrated device [1].

3. Q-switched Mode-Locking vs. CW Mode-Locking

In many applications, such as telecommunication and laser gyroscope, we want the pulse sequence to be CW mode-locking instead of Q-switched mode-locking. From [3], they came to the conclusion that the Q-switched mode-locking will be avoided if the following equation can be satisfied [3].

$$E_p^2 > E_{sat,L} E_{sat,A} \Delta R \qquad (1)$$

Where E_p is the intracavity energy, defined by $P_{\mathrm{int}ra} / f_{rep}$, $P_{\mathrm{int}ra}$ is intracavity average power and f_{rep} pulse repetition rate. $E_{sat,L}$ is the saturation energy of the laser medium and it is proportional to $A_{eff,L} / \sigma_{em,L}$ where $A_{eff,L}$ is the average mode area inside the laser medium, and $\sigma_{em,L}$ is the emission cross-section of gain material. $E_{sat,A}$ is the saturation energy of the absorber, which can be represented by $E_{sat,A} = A_{eff,L} F_{sat,A} \Delta R$. $A_{eff,A}$ average mode area inside the saturable absorber, $F_{sat,A}$ saturation fluence of absorber and ΔR is the modulation depth of the saturable absorber.

$$E_P^2 > E_{sat,L} E_{sat,A} \Delta R$$

$$E_P^2 = \left(\frac{P_{intra}}{f_{rep}}\right)^2, \quad E_{sat,L} \propto \frac{A_{eff,L}}{\sigma_{em,L}}, \quad E_{sat,A} \Delta R = A_{eff,A} F_{sat,A} \Delta R$$

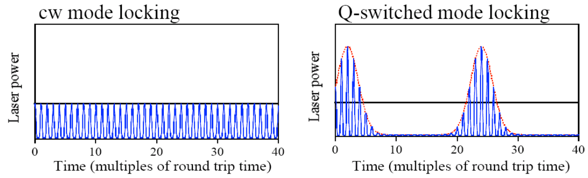

Fig. 4. Q-switch vs. CW Mode-locking [3]

This equation is for the picosecond regime mode-locked solid-state lasers. This stable condition is derived from the coupled rate equations assuming that the saturable absorber is fully saturated.

Q-switching instabilities occur when the pulse energy is temporarily increased because of noise fluctuations in the laser, which then gets even further increased because of the stronger saturation of the saturable absorber. This has to be balanced by a stronger saturation of the gain [3]. Stability means that the relaxation oscillation damped. The physical explanation of Eq. (1) can be, if the pulse energy rises slightly owing to relaxation oscillations, this pulse energy fluctuation first grows exponentially because of the stronger bleaching of the absorber. However, the increased pulse energy starts to saturate the gain. The laser is stable against QML if the gain saturation is sufficient strong to stop the exponential rise.

Typically the SESAM is operated with an incident pulse fluence of about three to five times that of the saturation fluence. This saturation level of the absorber provides nearly the maximum modulation depth without damaging the device. Higher saturation also reduces the tendency for Q-switching instabilities because of thermal effects and two-photon absorption. From [5], it has been confirmed the presence of two-photon absorption in commonly used SESAMs structures by time-resolved differential reflectivity measurements. With pump-probe measurement confirmation that TPA is the dominant cause of the reflectivity drop observed in the saturation energy measurement. And they also theoretically predict that TPA will expand the CWML stability regime against QML. Fig. 5 illustrates the calculated stability regions in a logarithmic plot of the saturation power of the absorber versus the pulse energy, both normalize to the gain saturation $[(I_A A_A / I_L A_L)\, versus\, (W / W_L)]$, where A_A is the area of the spot focused on the absorber, I_L is the saturation intensity of the gain, A_L is the area of the beam in the gain medium and W is the pulse energy [5]. The solid line in Fig.5 indicates the instability boundary when TPA is not included; the inclusion of TPA reduces the instability boundary to the dashed line. In conclusion, TPA has increased the region for stable CWML and it can also enable a laser to reach a CWML state that was not previously attainable.

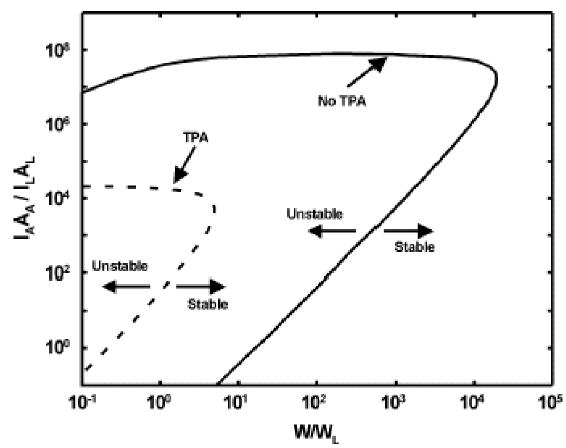

Fig. 5. Calculated stability contours for a fast saturable absorber mode-locked laser. [5]

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4. Semiconductor Absorber in Ring Lasers

SESAM can also be used in the ring laser configurations. In Fig. 6 a), one cavity mirror is replaced by the SESAM to realize the mode-locking operation of the ring laser [6]. As the cavity length is long, two lenses (L) are used to obtain tight focus on the SESAM, so that high saturation of the absorber can be obtained. This configuration will result in bi-directional operation of a pulsed ring laser, which is the basic model for the laser gyroscope.

To increase the flexibility of the setup, another cavity configuration is designed, as shown in Fig.6 b), instead of using the SESAM, the multi-quantum well (MQW) was redesigned and put in the cavity. Here the semiconductor absorber is not used as a mirror, but a lens. The MQW is put at the focal point of the telescope (formed by L1 and L2) in Fig. 6 b), to achieve a high saturation level. This setup is also used for the laser gyroscope, and the stable CWML is very much desired for measuring the beat note of the counter-propagation beams. By tightly focusing on the MQW, two photon absorption is the dominant effect that causes the lensing effect which result in the self-defocusing as the beam intensity increases.

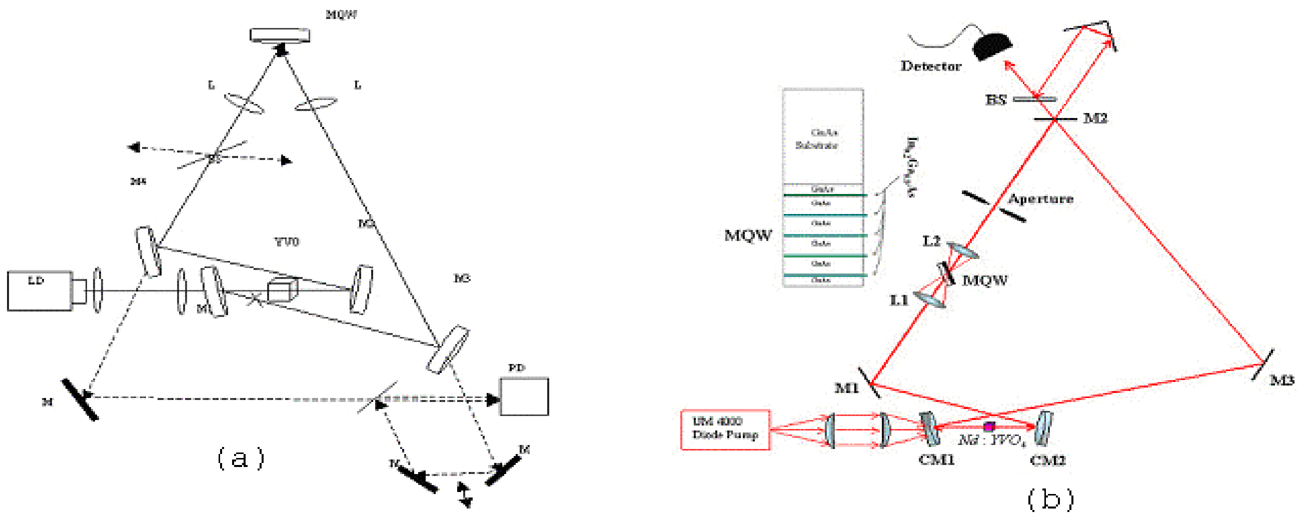

Fig. 6 a) SESAM in a ring laser as an end mirror; b) MQW used as saturable absorber inside the ring laser cavity.

We can refer to the theory in part 3 and consider it using Eq. (1). The main cause of the Q-switched mode-locking here is the gain depletion. Then by putting an aperture to control the intracavity energy so that the gain will not be depleted. Combining the effect of self-defocusing and aperture, a balance region for the loss and gain can be reached which will result in stable CW mode-locking [7].

5. Conclusion and Future work

SESAMs have already become important components used to mode-lock a wide range of both solid-state lasers and fiber lasers. The application of SESAMs will be extended in more fields of solid-state lasers. They are aiming at higher power scaling of more than 100W of average power, more compact structure, and cheaper laser with even higher repetition rate [2].

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