

Optical characteristics of semiconductor saturable absorber mirrors investigated by the reflection Z-scan technique

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Abstract

Recently, the semiconductor saturable absorber mirror (SESAM) has become a key component of passive mode-locked solid-state lasers. Here we present a simple method based on the reflection Z-scan technique to measure the key optical parameters of SESAM such as saturation fluence and modulation depth. The experimental results demonstrate that our method is able to perform with a high accuracy of 10^{-4} and a dynamic range of over four orders of magnitude.

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1. Introduction

Considerable progress has been made in ultrashort-pulse generation with Ti:sapphire lasers in recent years [1–3]. Pulse width of 5 fs generated directly from a laser oscillator based on Kerr-lens mode-locking (KLM) technique was reported [4]. In this laser, Kerr nonlinearity acts as an equivalent fast saturable absorber, therefore making it difficult for the laser to self-start from CW intensity fluctuation. More recently, semiconductor saturable absorber mirror (SESAM) assisted mode-locking has become a standard technology for self-starting femtosecond solid-state lasers [5–10]. The proper design and characterization of SESAM is also used to control mode-locked solid-state laser dynamics [11] and improve laser performances such as obtaining shortest pulse widths [12], highest average and peak power from a passively mode-locked laser [13], extending the pulse repetition rate to 160 GHz [14] and

obtaining stable Q-switching of compact microchip lasers with short pulse width and high pulse energy [15]. In general, the response time of SESAM is about several picoseconds [16], which is very short compared with the pulse spacing of femtosecond laser in our experiment. The manufacture of SESAM is complicated and there are many factors affecting the structures and properties of SESAM. A simple and convenient method is therefore required to test the characteristics of manufactured SESAM and select good ones. Haiml et al. investigated the optical properties of SESAM with a mature system [17]. Here we present a simple method based on the reflection Z-scan technique with a normal low-power Kerr-lens mode-locked (ML) Ti:sapphire femtosecond laser. The setup is simple and its performances are convenient. Moreover, our experimental results have a high precision (10^{-4}) and a wide dynamic range (10^4) similar to those reported by Haiml et al.

2. Experimental setup

The experimental setup based on the reflection Z-scan technique is shown in Fig. 1, which is similar to a report of

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our previous work [18]. A homemade Kerr-lens mode-locked (ML) Ti:sapphire laser that delivers 50 fs pulses at 800 nm with a 100 MHz repetition rate is used as the light source. A feature of our femtosecond laser is the ability to switch conveniently between the CW and the mode-locking modes. The incident laser beam is focused with a lens L_1 of focal length $f_1 = 60$ mm onto the sample under test. The lens L_1 is mounted on a motorized translation stage (Physik Instrumente, M-405.DG) with a resolution of $0.1 \mu\text{m}$ controlled by a computer and scanned exactly along the beam axis (z -direction) of the incident laser beam. To prevent breadthways moving of beam spot on the sample during Z -scanning the focus lens L_1 , we set the incident laser beam passing through the center of the lens L_1 very carefully. A beam-splitter, BS, introduces the beam reflected by an SESAM through a lens L_2 and a filter F into a photodiode used as the detector. The lens L_2 with an enough large clear aperture is used to collect all reflected light. The neutral density filter F attenuates the light intensity to prevent the saturation of the photodiode. The output of the detector is fed into a digital lock-in amplifier and then the received data are recorded and analyzed with a computer.

The sample under test, an SESAM for mode-locked Ti:sapphire lasers (whose structure is similar to that of the SESAM described in Ref. [18]), is tilted with a small angle to prevent back-reflections into the laser cavity which would disturb mode-locking of the light source. The angle must be small enough not to change the reflectivity of the SESAM when in operation. From Fig. 1 we can see if the tilted sample was moved along the beam axis, the position of reflected spot on the beam splitter would be changed and thus some reflected beam would fall out of the detector. Therefore, in the experiments, we scan the lens L_1 instead of the sample along the beam axis of the incident beam (z -direction) to keep the direction of the reflected beam fixed during the measurements. Furthermore, a suitable spot size on the receiving area of the photodiode was set to ensure the photodiode was working in the linear range during the experiments.

To calibrate the reflectivity of the sample, we replaced the sample with a reflecting mirror with a given reflectivity of 97.99% for mode-locked Ti:sapphire lasers. The mirror

was set with the same angle as the sample misaligned in the experiments. Under a given incident light power, the reading of the signal from the lock-in amplifier is V_m , which is directly proportional to the reflectivity of the reflecting mirror, R_m , and the experimental data with the SESAM sample, V_s , is also recorded. The reflectivity of the sample R_s is thus given by

$$R_s = R_m \frac{V_s}{V_m}, \quad (1)$$

where V_s is read with the sample under test.

3. Results and discussion

3.1. SESAM parameters

As shown in Fig. 3, there are three key parameters describing the characteristics of an SESAM: the saturation fluence F_{sat} , the modulation depth ΔR and the nonsaturable losses ΔR_{ns} . The saturation fluence F_{sat} is the fluence required for absorption saturation to start. The modulation depth ΔR and nonsaturable losses ΔR_{ns} in reflectivity are defined as

$$\Delta R = R_{\text{ns}} - R_{\text{lin}}, \quad (2)$$

$$\Delta R_{\text{ns}} = 1 - R_{\text{ns}}, \quad (3)$$

where R_{lin} is the linear reflectivity for pulses with ‘zero’ pulse energy fluence, and in our experiments, we consider it as the reflectivity measured with as low an incident pulse energy fluence as possible to ensure the sample under test is not saturated at all. R_{ns} is the reflectivity for ‘infinitely’ high pulse energy fluences when all saturable absorption is bleached. The nonlinear reflectivity R versus the incident pulse energy fluence F_p will be discussed in detail later.

3.2. Results and numerical simulations

R_{lin} is a fundamental parameter for calculation of SESAM parameters based on the measured data, so that it is important to measure R_{lin} with as low an incident pulse energy fluence as possible. To this end, we switched the running state of the laser to the CW mode, and then measured V_{lin} and V_m with an incident laser power of 0.8 mW. The experimental data are shown in Fig. 2(a), and thus we get the linear reflectivity R_{lin} of the sample by using Eq. (1): $R_{\text{lin}} = R_m \frac{V_{\text{lin}}}{V_m}$, the mean value of data $\bar{R}_{\text{lin}} = 0.9290$ with the standard deviation $\text{SD} = 3.385 \times 10^{-4}$.

To measure the nonlinear reflectivity R , we switched the laser to mode-locking mode with an incident laser power of 40 mW and scanned the lens L_1 with a velocity of $100 \mu\text{m/s}$ along the z -direction. The nonlinear reflectivity R can be calculated as $R = R_{\text{lin}} V/V_{\text{lin}}$, where V was the reading of the signal from the lock-in amplifier during the scan. A curve of the nonlinear reflectivity R versus the z -position of the sample is shown in Fig. 2(b). The incident light pulse energy fluence F_{sat} is connected with the z -position of the sample around the beam waist of the light. This curve indi-

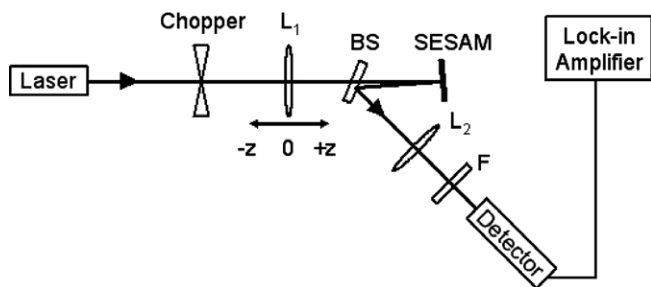


Fig. 1. Experimental scheme for measurement of optical characteristics of broadband semiconductor saturable absorber mirrors based on the reflection Z -scan technique.

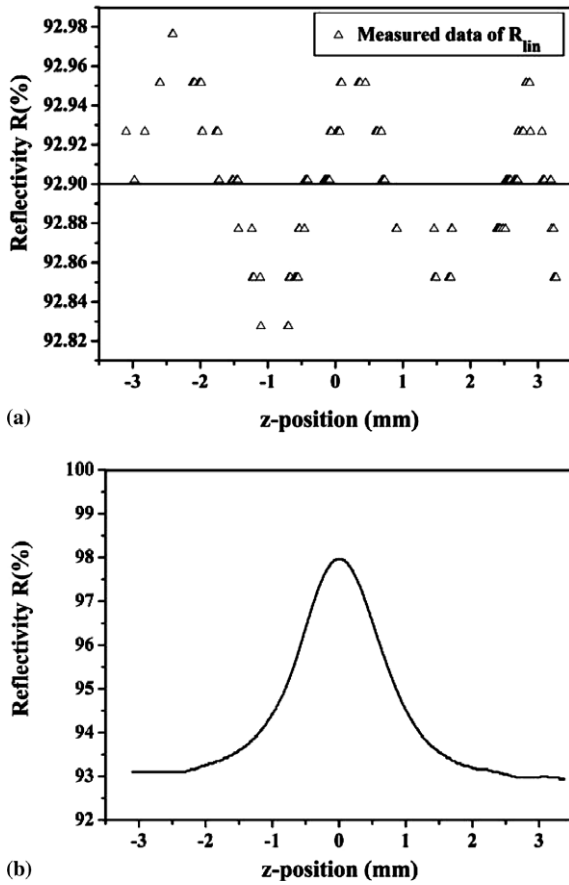


Fig. 2. Measured reflectivity versus the z -position of the sample around the focal point: (a) the linear reflectivity R_{lin} with an incident laser power of 0.8 mW in CW mode and (b) the nonlinear reflectivity.

cates that the reflectivity keeps fixed at the beginning and then increases as the spot size focused on the sample decreases. At zero position, the beam spot is minimal, i.e. the sample is at the beam waist of the focused beam. So the reflectivity rises up to the highest corresponding to the maximum incident pulse energy fluence. To get the beam waist ω_0 on the sample, the beam radius ω_L in front of lens L_1 which is at zero position was measured by using the method of translating pinhole [19]. The experimental data and the Gauss fit showed the laser beam was almost a Gauss beam and we got the result of $\omega_L = 2.54$ mm for $1/e^2$ intensity. Thus, the beam waist can be calculated as $\omega_0 = \frac{\lambda f_1}{\pi \omega_L} = 6 \mu\text{m}$, where λ is the wavelength of incident light in the vacuum and f_1 is the focal length of L_1 . Consequently, we can get the relationship between the incident pulse energy fluence F_p and the position z :

$$F_p = \frac{E_p}{\pi \omega^2(z)} = \frac{E_p}{\pi \omega_0^2 \left(1 + \left(\frac{z\lambda}{\pi \omega_0^2}\right)^2\right)}, \quad (4)$$

where E_p is the incident pulse energy, $\pi \omega^2(z)$ is the beam spot size at the position z of the sample. The nonlinear reflectivity R versus the incident pulse energy fluence F_p is shown in Fig. 3. Filled points are measured data and

the solid curve is fitted with the following equation in Ref. [17]:

$$R(F_p) = R_{ns} \frac{\ln \left(1 + \frac{R_{lin}}{R_{ns}} (e^s - 1)\right)}{s}, \quad (5)$$

where $s = F_p/F_{sat}$. The incident pulse energy fluence was increased from about $0.5 \mu\text{J}/\text{cm}^2$ to $450 \mu\text{J}/\text{cm}^2$. When the incident pulse energy fluence F_p is equal to the saturation fluence F_{sat} , $R(F_{sat})$ can be calculated by Eq. (5) with given R_{lin} and R_{ns} , and thus we can obtain the saturation fluence F_{sat} from experimental data with $R(F_{sat})$. In Fig. 3, we fit the experimental data by setting $R_{ns} = 0.9810$ and $F_{sat} = 11 \mu\text{J}/\text{cm}^2$. For illustration, the same curve is plotted on a linear scale (a) and a logarithmic scale (b). The nonlinear reflectivity R increases and approaches R_{ns} gradually with increasing incident pulse energy fluence, and the measured SESAM parameters with theoretical calculation are $\Delta R = 5.20\%$, $F_{sat} = 11 \mu\text{J}/\text{cm}^2$, $R_{ns} = 98.10\%$ and $\Delta R_{ns} = 1.90\%$. In the experiments, we found that our setup could

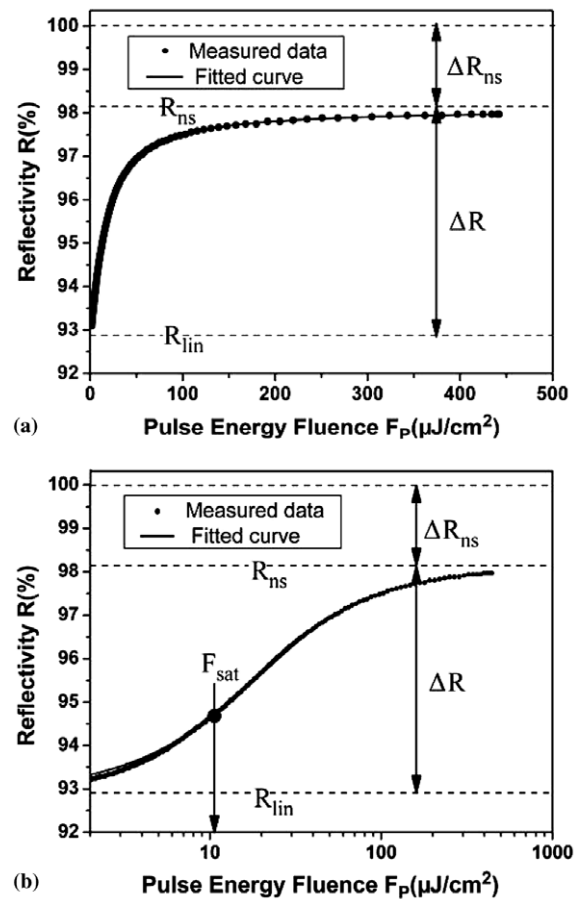


Fig. 3. Measured data (filled points) and fitted (solid) curve according to Eq. (5) for the nonlinear reflectivity $R(F_p)$ at 800 nm for an SESAM as a function of the incident pulse energy fluence F_p : (a) linear scale and (b) logarithmic scale. R_{lin} : linear reflectivity; R_{ns} : reflectivity with saturated absorption; ΔR : modulation depth; ΔR_{ns} : nonsaturable losses in reflectivity; F_{sat} : saturation (pulse energy) fluence. The measured parameters of SESAM under test are $\Delta R = 5.20\%$, $F_{sat} = 11 \mu\text{J}/\text{cm}^2$, $R_{ns} = 98.10\%$ and $\Delta R_{ns} = 1.90\%$.

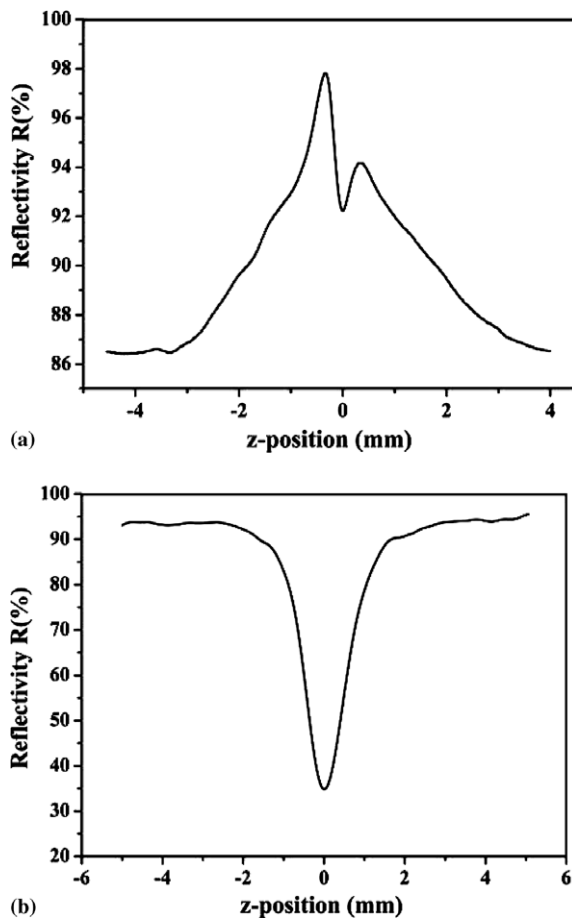


Fig. 4. Some other optical characteristics of another two SESAM samples: (a) a roll-off in the reflectivity curve due to a second-order process like two-photon absorption and (b) an abnormal nonlinear absorption induced by defects caused in the process of manufacturing.

also be used to detect other properties of the SESAM, such as two-photon absorption with a threshold and an abnormal nonlinear absorption, and check up uniformity of quality on the whole working surface. Fig. 4(a) and (b) shows the experimental results for two SESAM samples. First, we performed the measurements of saturable absorption of one sample with different incident laser powers. When the incident laser power was low, we got the saturable absorption similar to that shown in Fig. 2(b). Once the incident laser power was increased up to 150 mW, an asymmetric roll-off at higher fluences appeared in the nonlinear reflectivity curve as shown in Fig. 4(a), where the threshold of two-photon absorption of the sample might be reached.

However, the other sample always behaved as an abnormal nonlinear absorber under any incident laser power. This abnormal phenomenon may be due to defects caused in the process of manufacturing.

In conclusion, we have presented a method based on the reflection Z -scan technique to measure the optical characteristics of SESAM with a normal low-power femtosecond laser. The experimental results demonstrate that our method is simple and easy to perform, but with a high accuracy of 10^{-4} and a dynamic range of over four orders of magnitude. Our method may be used to investigate other kinds of nonlinear reflection devices.

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