In situ characterization of semiconductor saturable absorber mirrors in an operating Yb:KGW mode-locked laser

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We report *in situ* characterization of a semiconductor saturable absorber mirror (SESAM) in an operating Yb:KGW mode-locked laser. The technique may be described as a pump–probe experiment in which the intracavity beam acts as a pump beam while the output of the same laser is used as a test beam for the SESAM reflectivity. At zero delay, the probe pulse overlaps in time with the subsequent intracavity pulse. The method is an alternative to standard pump–probe measurements in situations where the intracavity parameters such as energy fluence onto the SESAM, pulse length, and center wavelength cannot be achieved simultaneously with available lasers.

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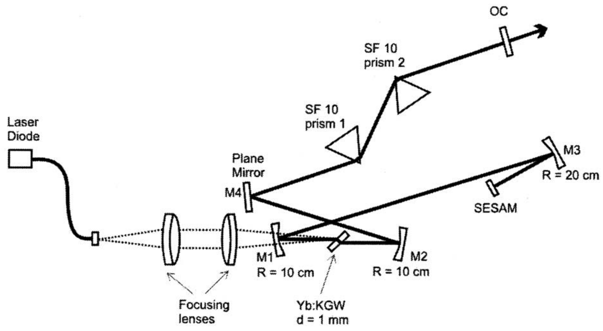
Semiconductor saturable absorber mirrors[1–3] (SESAMs) have been used extensively in recent years for ultrashort pulse generation. Self-starting passive continuous-wave (CW) mode locking was demonstrated for many different solid-state and fiber lasers.[4] A number of saturable absorber characteristics were identified as important parameters affecting the laser dynamics and mode-locking performance.[1] These are the maximum reflectivity change between low and high incident fluence (modulation depth), the recovery time of the reflectivity, the pulse fluence needed to increase the reflectivity to a given fraction of the modulation depth (saturation fluence), and the remaining losses at high fluence (linear losses). As the semiconductor structure design and the growth technology allow a wide range of these parameters, they need to be measured with high accuracy. The modulation depth, saturation fluence, and linear losses may be obtained from nonlinear reflectivity measurements.[5] To determine the dynamic response of the saturable absorber, one should perform pump–probe experiments in which the mirror reflectivity is measured as a function of the delay time between the pump and probe pulses. This kind of measurement becomes challenging for saturable absorber mirrors with a low modulation depth or a high saturation fluence, due to the requirements of high power and detection sensitivity.

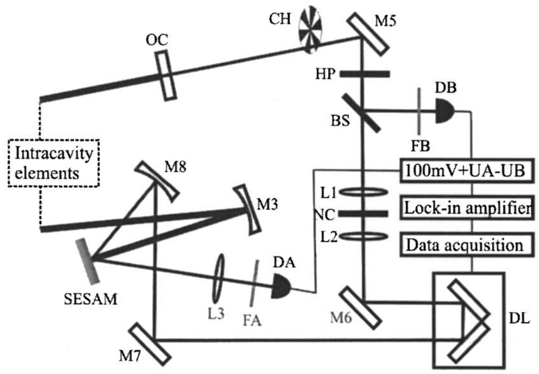
For laser media with small signal gain, as is the case for Yb-doped materials, the laser shows the highest efficiency for low output coupler transmissions, of the order of a few percent. The intracavity pulse energy is 20–100 times higher than the delivered output power. For this reason, it is difficult to arrange a pump–probe experiment that fits the intracavity conditions in terms of fluence, pulse length, and wavelength at the saturable absorber.

We report here, for the first time to our knowledge, *in situ* characterization of a saturable absorber in an operating mode-locked laser. The new technique can be described as a pump–probe experiment in which the intracavity beam acts as a pump beam, while the output beam of the laser is used to monitor the change in SESAM reflectivity. The optical path at zero delay is arranged such that the probe pulse overlaps in time with the subsequent intracavity pulse. Using the significant intracavity power of a CW mode-locked laser oscillator opens the way for time-resolved saturation measurements in cases where amplified pulses would be needed. With this *in situ* technique high average power comes for free.

The layout of the laser resonator is shown in Fig. 1(a), and the following experimental arrangement for SESAM characterization is displayed in Fig. 1(b). The laser setup consists of a delta-shaped cavity with one arm folded by plane mirror M4, to achieve a more compact design. A 1 mm thick Yb:KGW crystal doped with 5 at.% of Yb^{3+} ions was used as an amplifying medium. The crystal was cut for pumping along the b axis and arranged in the cavity at the Brewster angle. We used a high-brightness fiber-coupled laser diode to pump the laser. It provides an output power of up to 5 W at a center wavelength of 981 nm and with a FWHM spectral bandwidth of 8 nm. The fiber has a core diameter of 50 μm and an effective numerical aperture of 0.15, which leads to a beam quality of $M^2=12$. The pump beam is focused with two antireflective-coated achromatic lenses, resulting in a pump spot diameter of 100 μm, which fits the designed laser mode in the crystal well. Folding mirrors M1 and M2 have a radius of curvature of 100 mm and a reflectivity of better than 99.9% in the range 1020–1070 nm. The 200 mm curved mirror, M3, focuses the laser beam onto the SESAM to a measured beam radius of 82 μm. A pair of SF10 prisms were used to compensate for the group-velocity dispersion (GVD) introduced by the amplifying medium.



(a)



(b)

Fig. 1. (a) Yb:KGW laser cavity and (b) experimental setup for *in situ* characterization of the saturable absorber. M1–M3, curved mirrors; R, radius of curvature; M4, high-reflective plane mirror; OC, output coupler with 3% transmission; SESAM, saturable absorber mirror; M5–M7, plane mirrors; M8, curved mirror; CH, chopper; BS, beam splitter; L1–L3, lenses; NC, nonlinear crystal for SH generation; HP, half-wavelength plate used to adjust the SH intensity; DL, delay line; DA, DB, photodiodes; FA, FB neutral-density filters.

The laser generates a very stable pulse train (<1% peak-to-peak variation), without Q-switching modulations. This was verified by observing the temporal development of the pulse amplitude as well as the frequency spectrum, which shows only the cavity frequency, without any sidebands. A pulse amplitude constant in time is extremely important for high-accuracy measurements.

The output laser beam is used further to monitor the intracavity beam-induced change in SESAM reflectivity, as shown in Fig. 1(b). Pump and probe pulses are delayed with respect to each other by use of optical delay line DL. The probe beam is focused onto the active area of the saturable absorber by curved mirror M8, which has a 50 mm radius of curvature. The angle between the pump and probe beams is 30°.

Because the sample to be investigated is a component of the laser, there are some experimental particularities concerning the spatial overlap and the detection system. The laser output coupler has a transmission of 3%. This results in a contrast between the probe and pump beams that is smaller than 3:100, which cannot be increased due to the geometrical limitations of the resonator. In this condition, the spatial overlap of the two beams is difficult to arrange. In our experiments, the intracavity peak power was high enough to generate a weak—but visible—second-harmonic (SH) signal in the semiconductor structure. We used a 200 μm thick nonlinear crystal, NC, to generate a SH beam that propagates on the same path as the probe beam. The intensities of these SH signals are similar, and their spatial overlap can be achieved much more easily.

In most pump–probe experiments, where small probe signal variations are measured, a chopper is positioned in the pump beam path so that the pump-induced changes in the reflected probe beam can be measured differentially with a lock-in amplifier. This is not possible in our experimental configuration, because the modulation of the intracavity beam would provoke the breakdown of the mode-locking regime. We modulated the probe beam with chopper CH, and we used two photodiodes, DA and DB, and an analog device that amplifies the difference between the two signals. The reflected probe beam is directed to detector DA, and a reference beam taken from beam splitter BS is sent on to detector DB. With a proper choice of transmission of the filter, the signal sent to the lock-in amplifier may be adjusted to a level similar to that of the measured signal. Using the experimental setup described above, we measured the dynamic response of the saturable absorber at different values of pump fluence. The delay-dependent differential reflectivity $\Delta R(t)/R_{\mathrm{lin}}=[R(t)-R_{\mathrm{lin}}]/R_{\mathrm{lin}}$ is given by the signal $[(S_{\mathrm{DA}}-S_{\mathrm{DB}})(t)-(S_{\mathrm{DA}}-S_{\mathrm{DB}})(-\infty)]/S_{\mathrm{DA}}(-\infty)$, where S_{DA} and S_{DB} are the signals of photodiodes DA and DB, respectively. $R(t)$ denotes the SESAM reflectivity at a time delay t between the pump and probe pulses, and R_{lin} is the reflectivity at low fluence. The experiments were performed with 296 fs pulses at a center wavelength of 1031 nm. The intracavity pulse energy was modified by changing the pump power. To keep the pulse length and the center wavelength fixed we adjusted the intracavity GVD by modifying the prism insertion. Figure 2 shows the pump–probe differential reflectivity trace at a pump fluence of $\sim 126\ \mu\mathrm{J/cm}^2$. The nonlinear response exhibits bitemporal behavior, as reported many times for semiconductor saturable absorbers.[2,6,7] The fast com-

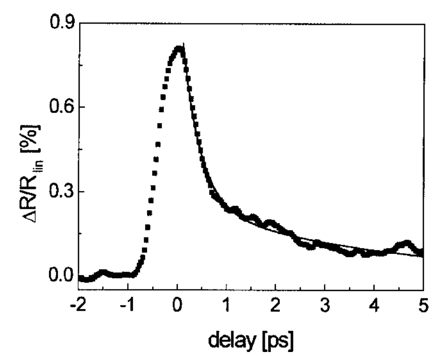


Fig. 2. Differential reflectivity measurement at a pump fluence of $\sim 126\ \mu\mathrm{J/cm}^2$. $\Delta R/R_{\mathrm{lin}}$ is plotted as a function of the delay between pump and probe pulses. The solid curve shows a double exponential fit, with a fast time constant of 370 fs and a slow time constant of 3.9 ps.

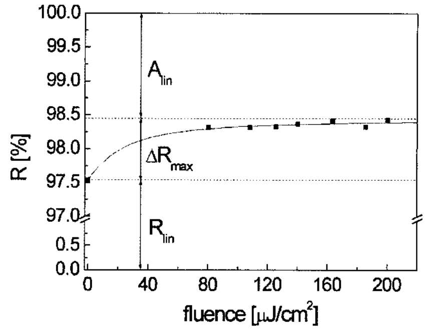


Fig. 3. Nonlinear reflectivity R plotted as a function of the energy fluence on the saturable absorber. The solid curve shows the theoretical curve assuming a modulation depth of 0.91% and a saturation fluence of 14 $\mu J/cm^2$.

ponent is usually attributed to spectral hole burning,[6] while the slow one is attributed to carrier recombination and trapping.[4] The solid curve depicts a double exponential fit with a fast time constant of ~370 fs and a slow time constant of ~3.9 ps. Figure 3 shows the SESAM reflectivity as a function of the incident energy fluence. The differential reflectivity at zero delay was extracted from the pump–probe measurements. R_{lin} was measured using the laser in CW operation and referenced to a high-reflective dielectric mirror. At 1031 nm, $R_{lin}=97.54\pm0.1\%$. The data describe only part of the saturation curve because a stable mode-locking regime does not occur at small fluences on the saturable absorber. However, it can be noticed that the reflectivity remains almost constant with increasing pump fluence. This leads to an accurate determination of the effective modulation depth, $\Delta R_{max}=0.91\pm0.05\%$, and of the linear losses, $A_{lin}=1-\Delta R_{max}-R_{lin}=1.55\pm0.15\%$. The saturation fluence is estimated to be 14 $\mu J/cm^2$.

In conclusion, we have demonstrated *in situ* characterization of a semiconductor saturable absorber mirror used for passive mode locking. The experiments were performed with a Yb:KGW laser, which allows the generation of a stable pulse train without Q-switching modulations. *In situ* characterization of semiconductor saturable absorbers yields the absorber parameters, in particular, the modulation depth and the dynamic response, under the exact laser operation conditions, which is not necessarily achieved by other methods. The technique may also be an alternative to the classical pump–probe measurements in situations where the intracavity parameters such as incident energy fluence, pulse length, and center wavelength are difficult to reproduce simultaneously with available lasers.

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References

1. U. Keller, in *Nonlinear Optics in Semiconductors*, A. Kost and E. Garmire, eds. (Academic, 1998), pp. 211–286.
2. L. R. Brovelli, U. Keller, and T. H. Chiu, J. Opt. Soc. Am. B **12**, 311 (1995).
3. O. Okhotnikov, A. Grudinin, and M. Pessa, New J. Phys. **6**, 177 (2004).
4. U. Keller, Nature **424**, 831 (2003).
5. M. Haiml, R. Grange, and U. Keller, Appl. Phys. B **79**, 331 (2004).
6. P. Langlois, M. Joschko, E. R. Thoen, E. M. Koontz, F. X. Kärtner, E. P. Ippen, and L. A. Kolodziejski, Appl. Phys. Lett. **75**, 3841 (1999).
7. M. J. Lederer, V. Kolev, B. Luther-Davies, H. H. Tan, and C. Jagadish, J. Phys. D **34**, 2455 (2001).