Saturable Absorber Mirrors For Passive Mode-locking

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Abstract: *Saturable absorber mirrors (SAMs) are grown by low-temperature solid-source molecular beam epitaxy. The nonlinear absorber layer consists of one InGaAs quantum well. The devices have response times shorter than 10 ps and small non-saturable losses (less than 0.3%). SAMs with modulation depths between 0.6% and 2.0% were used to mode lock a Yb:KYW laser at around 1040 nm. The minimum achievable pulse duration and the output power decrease by increasing the modulation depth. Pulses as short as 100 fs were obtained with a 2% modulation depth saturable absorber.*

1. Introduction

Semiconductor saturable absorber mirrors are important components used for passive mode locking and Q switching of both solid-state and fiber lasers [1]. They are inexpensive and compact, can be designed to operate in a wide spectral range and have fast response times. A survey about the state of the art of ultrafast passive mode locked laser sources [2,3] and the optical characterization of saturable absorber mirrors [4] is given by U. Keller at al.

The mode of operation of a laser is determined by the properties of the saturable absorber [1].

In this letter we investigated experimentally the influence of the modulation depth of the SAMs on the parameters of a diode pumped Yb:KYW laser.

2. Saturable absorber mirrors

Saturable absorber mirrors were grown by solid-source molecular beam epitaxy. The SAMs consist of a Bragg mirror with 27 AlAs/GaAs quarter-wave layers and a GaAs spacer layer with an embedded absorbing InGaAs quantum well. The devices are covered by a dielectric protection layer. The design is shown in table 1.

Table 1. SAM design

Layer		Function
Si or Ta oxide		dielectric cover
71.2 nm GaAs		barrier
7 nm InGa As		low temperature grown quantum well
71.2 nm GaAs		barrier
74.7 nm GaAs 88.4 nm AlAs	27 x	Bragg mirror
GaAs		substrate

Three different samples with modulation depths of 0.6%, 1.2% and 2.0% have been prepared. To get a fast recovery time, the absorbing quantum well layer is grown at low temperature < 400 °C [5]. The reflection of their Bragg mirrors is > 99.7%. The spectral width of the mirror is about 100 nm. The unsaturated spectral reflection is shown in figure 1.

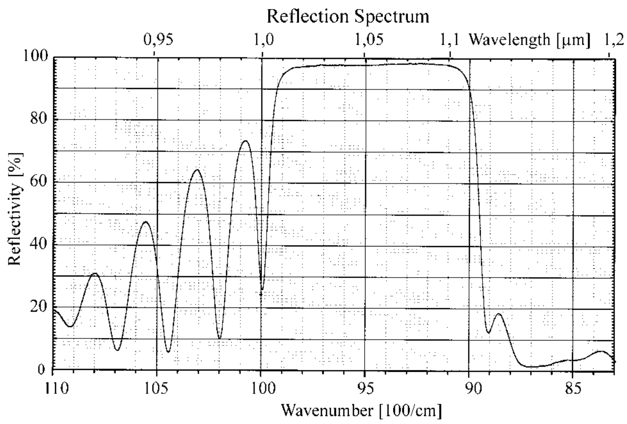

Fig.1. Spectral reflection of unsaturated SAM with 1.2% modulation depth.

3. Laser set-up

We performed mode locking experiments with a diode-pumped Yb:KYW laser. A report of such a laser can be found in [6].

The laser set-up (Fig. 2) is a delta-shape cavity with one arm folded by the plane mirror M4, in order to achieve a more compact design. The 1-mm thick Yb:KYW crystal was placed in the cavity at Brewster angle. The crystal was doped with 5 at% of Yb^{3+} ions and cut for pumping along b axis.

The pumping system consists of a fiber coupled high-brightness laser diode, which provides an output power up to 5 W at 981 nm. The pump beam is focused with two antireflective coated achromatic lenses, resulting in a measured pump spot diameter of 100 µm, which fits well to the designed laser mode in the crystal. The absorption length of the crystal at this pump wavelength is ~ 0.25 mm for polarization parallel to a-axis and ~ 1.7 mm for polarization parallel to c-axis. The pump radiation is not polarized, thus the absorption length is ~ 0.98 mm.

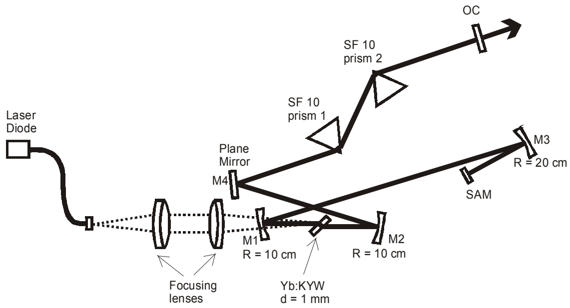

Fig. 2. Experimental set-up for the mode-locked Yb:KYW laser. M1 – M3, curved mirrors; R, radius of curvature; M4, high-reflective plane mirror; OC, output coupler with different transmissions; SAM, saturable absorber mirror.

The folding mirrors M1 and M2 have a radius of curvature of 100 mm and a reflectivity > 99.9% in the range 1020 – 1070 nm.

The 200 mm curved mirror M3 focuses the laser beam onto the SAM in order to achieve a beam radius of ~ 83 µm.

A pair of SF10 prisms separated by 34 cm were inserted in the arm with the output coupler. They compensate for the group velocity dispersion (GVD) introduced by the amplifying medium. In order to minimize the losses at the prism surfaces, the resonator was designed for a low divergence of the output beam.

4. Experimental results

To mode lock the laser described previously, we used SAMs with modulation depths of of 0.6 %, 1.2 % and 2.0 %. In all of this cases, the mode locking regime was selfstarting and stable. The laser shows a typical soliton mode locking behavior, which allows the generation of pulses much shorter than the recovery time of the saturable absorber.

It was reported previously [1,7], that for soliton mode-locking the pulse shortening is limited by the onset of multiple pulsing. Decreasing the negative GVD, i.e. increasing the prism insertion, the pulse becomes shorter until it breaks in two longer pulses. According to [8], the minimum achievable pulsewidth depends on the modulation depth ΔR as follows:

$$\tau_{\min} \propto \frac{1}{\sqrt{\Delta R}} \qquad (1)$$

For a given value of the modulation depth, τ_{min} is dependent on the total cavity loss (including the output coupler transmission T_{OC}) and on the intracavity pulse energy. In order to get the minimum pulsewidth, we tested output couplers with different transmissions. The pulse energy was modified by varying the pump power.

The table 2 shows the shortest pulse durations we achieved, the highest delivered output powers, as well as the corresponding pump powers and output coupler transmissions.

Table 2. Laser parameters achieved for different modulation depths ΔR. τ_{FWHM} – pulsewidth, P_{out} – laser output power, T_{OC} – output coupler transmission, P_{pump} – pump power. The minimum pulsewidth and the maximum output power are indicated with bold letters.

ΔR (%)	τ_{FWHM} (fs)	P_{out} (mW)	T_{OC} (%)	P_{pump} (W)
0.6	**160**	53	1	3.0
	198	**292**	4	4.5
1.2	**140**	63	1	3.2
	156	**228**	4	4.5
2.0	**100**	52	1	4.4
	134	**136**	4	4.5

5. Conclusions

The optimal saturable absorption of the SAM depends on the goal parameters of the mode locked laser. Both, the pulse duration and the output power increases if the saturable absorption decreases.

6. Acknowledgement

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