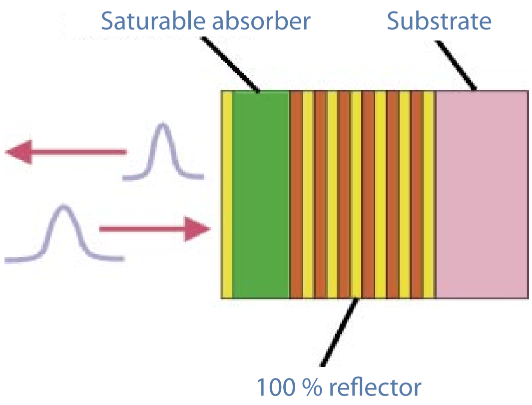
SAM

Saturable Absorber Mirror

1. Aim of SAM

Passive mode-locking techniques for the generation of ultra-short pulse trains are preferred over active techniques due to the ease of incorporation of passive devices into various laser cavities. A passive mode-locking device, the saturable absorber mirror (SAM), can be used to mode-lock a wide range of laser cavities. Pulses result from the phase-locking (via the loss mechanism of the saturable absorber) of the multiple lasing modes supported in continuous-wave laser operation. The absorber becomes saturated at high intensities, thus allowing the majority of the cavity energy to pass through the absorber to the mirror, where it is reflected back into the laser cavity. At low intensities, the absorber is not saturated, and absorbs all incident energy, effectively removing it from the laser cavity resulting of suppression of possible Q-switched mode-locking. Moreover, due to the absorption of the pulse front side the pulse width is slightly decreased during reflection.



2. Parameters

A SAM consists of a Bragg-mirror on a semiconductor wafer like GaAs, covered by an absorber layer and a more or less sophisticated top film system, determining the saturable loss. Although semiconductor saturable absorber mirrors have been employed for mode-locking in a wide variety of laser cavities, the SAM has to be designed for each specific application. The differing loss, gain spectrum, internal cavity power, etc, of each laser necessitates slightly different absorber characteristics. The most important parameters of a SAM are: saturable absorption; non-saturable loss; relaxation time saturation fluence; eflection and absorption bandwidth.

3. Saturable absorption

A SAM is a nonlinear optical device. Therefore the absorption A depends on the light intensity I in the laser cavity by $A = A_0 / (1 + I/I_{sat})$ eq(1) , where: A- absorption; A_0 - small signal absorption (saturable absorption); I- light intensity (measured in W/m^2); I_{sat}- saturation intensity. The absorption A is proportional to the square of the electric field strength of the standing wave at the position of the absorber layer. Therefore the saturable absorption of the SAM can be adjusted by the design. Typical values of the small signal (saturable) absorption A_0 and the saturation intensity Isat are: $A_0 = 1\%$; $I_{sat} = 10$ MW/cm^2.

4. Non-saturable loss

Non-saturable losses are caused by the transmission and the absorption of the Bragg mirror. The absorption of the thin film stack can be very low (< 0.1 %). The transmission loss of the Bragg mirror decreases with increasing number of the high and low index film pairs. The transmission loss of an AlAs/GaAs multilayer stack of 25 film pairs at the design wavelength is < 0.1 %. Beside this the high reflection band width and the group delay dispersion of the mirror has to be taken into account, especially in the case of ultra short pulses. The sum of the non-saturable losses can be described by a value Ans', which is typical < 0.3 % at the design wavelength.

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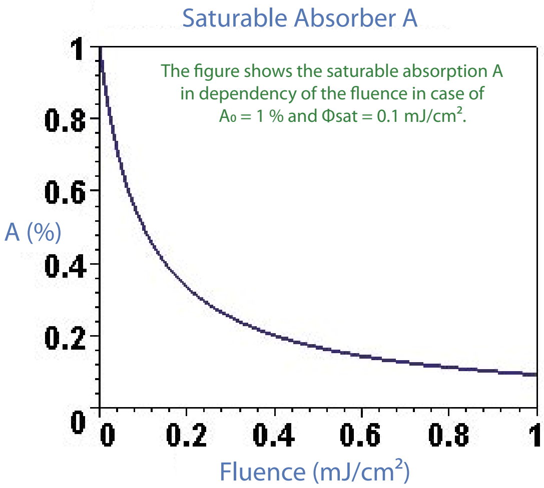
5. Relaxation time

The saturable absorber layer consists of a semiconductor material with a direct band gap slightly lower than the photon energy. During the absorption electron-hole pairs are created in the film. The relaxation time t of the carriers has to be a little bit longer than the pulse duration. In this case the back side of the pulse is still free of absorption, but during the hole period between two consecutive pulses the absorber is non saturated and prevents Q-switched mode-locking of the laser. Because the relaxation time due to the spontaneous photon emission in a direct semiconductor is about 1 ns, some precautions has to be done to shorten it drastically. Two technologies are used to introduce lattice defects in the absorber layer for fast non-radiative relaxation of the carriers: low-temperature molecular beam epitaxy (LT-MBE); ion implantation. The parameters to adjust the relaxation time in both technologies are the growth temperature in case of LT-MBE and the ion dose in case of implantation. Typical values of the relaxation time t of SAMs are between 0.3 and 2 ps.

6. Saturation fluence



The saturation process can be better quantified by the pulse fluence Φ than by the intensity I because of the limited relaxation time t. To minimise the losses, the absorber should be saturable with the expected pulse fluence Φ, e.g. the pulse energy in the laser should be several times more than the saturation energy, but not too high because then the laser tends to exhibit multiple pulsing. An other limitation is the damage threshold of the SAM. A typical saturation fluence Φ_{sat} is about 70 μJ/cm^2 In the laser cavity the incident pulse fluence F can be adjusted by varying the illuminated area a on the SAM. If the intracavity pulse power is low, e.g. because of low pump power, then tighter focussing helps to achieve the necessary saturation fluence Fsat of typically some ten μJ/cm^2. In analogy to eq. (1) the (saturable) absorption A of the SAM can be calculated by: $A= A0/(1+\Phi/(1+\Phi/\Phi_{sat})$ eq.(2), where : A - absorption, A_0 - small signal absorption, Φ - pulse fluence (J/m^2), Φ_{sat} - saturation fluence. The pulse fluence Φ can be derived from the mean output power P of the laser as follows: $\Phi = P/(1-R)\cdot f\cdot a$ eq.(3), where: Φ - pulse fluence (measured in J/cm^2); P - mean output power of the laser; R - reflectance of the output mirror; f - repetition rate of the laser; a- illuminated area on the SAM.

7. Reflection and absorption bandwidth

7.1 Time-bandwidth product (TBWP).

From Heisenberg's uncertainty principle for the conjugated variables pulse width Δt and photon energy E = h•ν the TBWP of a laser pulse is limited to about $\Delta t\cdot\Delta n \geq 1/(2\pi)$, where h = 6.626 •10^{-34} Js is Planck's constant; ν the pulse mean frequency and Δν the pulse bandwidth. An accurate calculation shows, that the minimum TBWP for a Gaussian pulse is Δt• Δν = 0.44 (pulse duration in seconds x pulse bandwidth in Hertz ≥ 0.44). The minimum TBWP for a Sech^{2}pulse is Δt•Δn = 0.32. Most people do not work with frequency ν but prefer wavelength l. Using the relation c=λ•ν the frequency interval Δν is related to the wavelength interval Δλ by $\Delta\nu = - c\cdot \Delta\lambda/\lambda^2\cdot$ c = 2.988•10^8 m/s is the speed of light in the vacuum.

7.2 Reflection bandwidth.

The reflection bandwidth of the SAM has to be larger than the pulse bandwidth. In case of a SAM with an underlying Bragg-mirror the reflection bandwidth is determined by the ratio of the refractive indices nH/nL of the layers in the thin film stack. The relative spectral width w = Δλ/λ of the high reflectance zone of a conventional semiconductor AlAs/GaAs thin film stack is about 0.1. Therefore the width of the high reflection zone of an AlAs/GaAs Bragg-mirror with a center wavelength of 1000 nm is about 100 nm. From the tables above this results in a minimum pulse duration of about 20 fs. For shorter pulses other mirror types, for instance dielectric or metallic mirrors has to be used.

7.3 Absorption bandwidth.

An ideal SAM has a constant saturable absorption for all wavelength of the pulse spectrum. In case of a 5 fs pulse the width of this wavelength interval is some hundreds of nanometers.

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