Ultrafast Laser Physics

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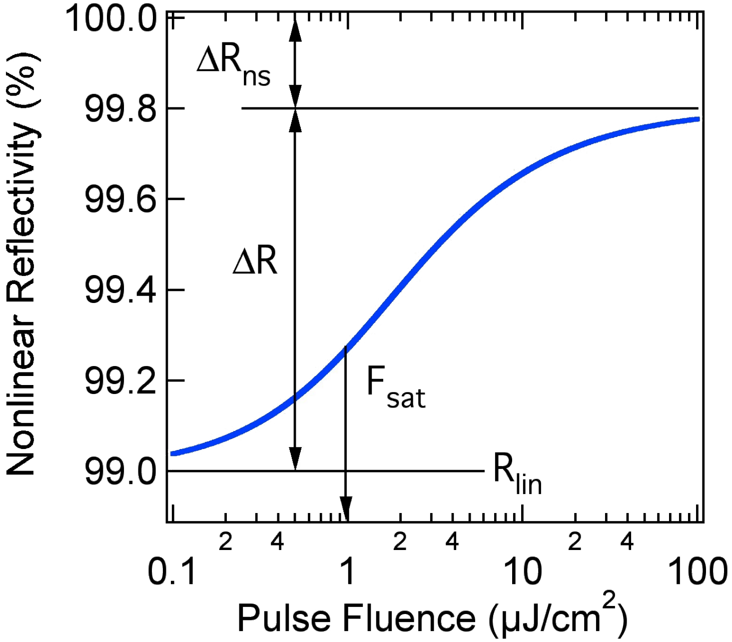
Chapter 8: Passive modelocking: Q-switching instabilities

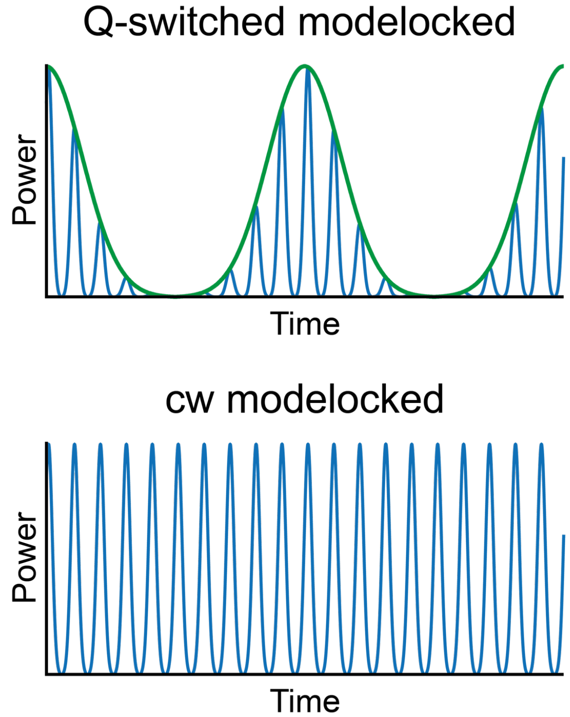
SESAM parameters

nonlinear parameters

$F_{\text{sat}},\ \Delta R,\ \Delta R_{\text{ns}}$



to overcome the stability condition for Q-switched mode locking (QML) threshold



Q-switched modelocking is avoided if...

C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, *JOSA B* **16**, 46 (1999)

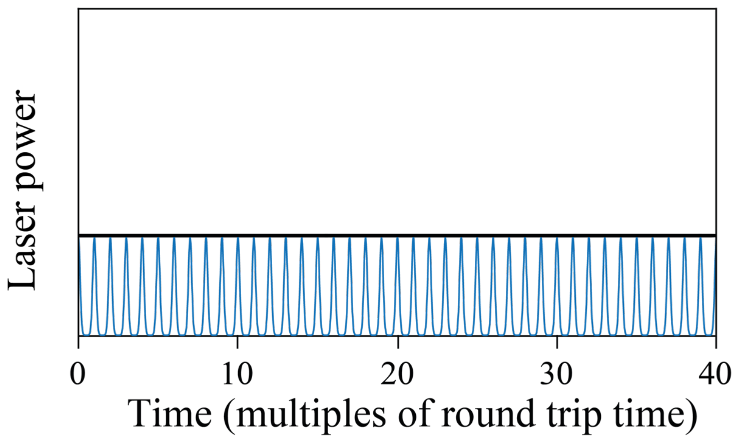
$$E_p^2 > E_{\mathrm{sat,L}} E_{\mathrm{sat,A}} \Delta R$$

$$E_p^2 = \left(\frac{P_{\mathrm{intra}}}{f_{\mathrm{rep}}}\right)^2$$

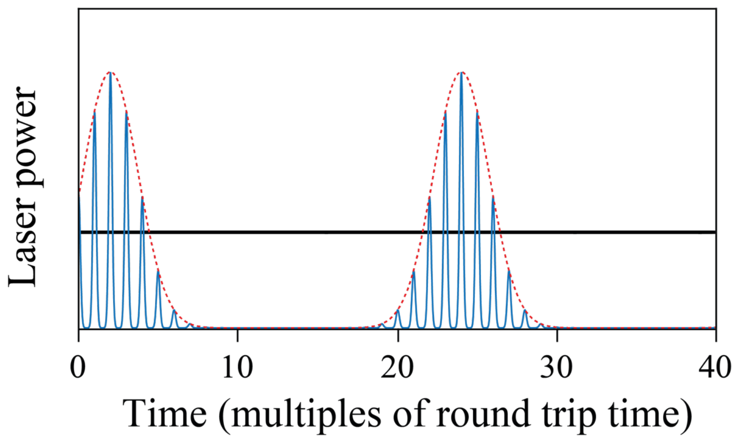
$$E_{\mathrm{sat,L}} \propto \frac{A_{\mathrm{eff,L}}}{\sigma_{\mathrm{em,L}}}$$

$$E_{\mathrm{sat,A}} \Delta R = A_{\mathrm{eff,A}} F_{\mathrm{sat,A}} \Delta R$$

cw modelocking



Q-switched modelocking



Saturation fluence and modulation depth

C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, *JOSA B* **16**, 46 (1999)

SESAM

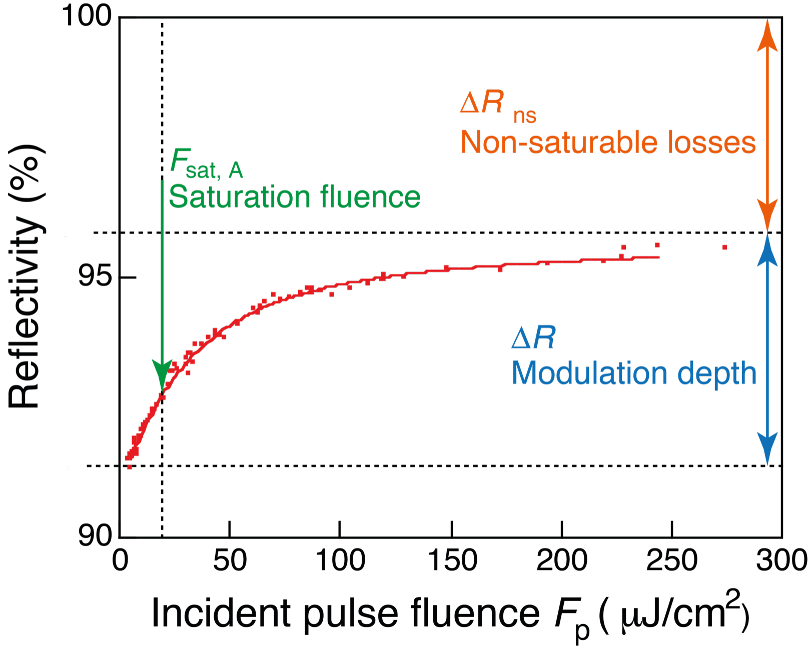
$$E_p^2 > E_{\mathrm{sat,L}} E_{\mathrm{sat,A}} \Delta R$$

$$A_{\mathrm{eff,A}} F_{\mathrm{sat,A}} \Delta R$$

Semiconductor saturable absorber mirror

$$F_{\mathrm{sat,A}} \propto \frac{1}{\sigma_A}$$

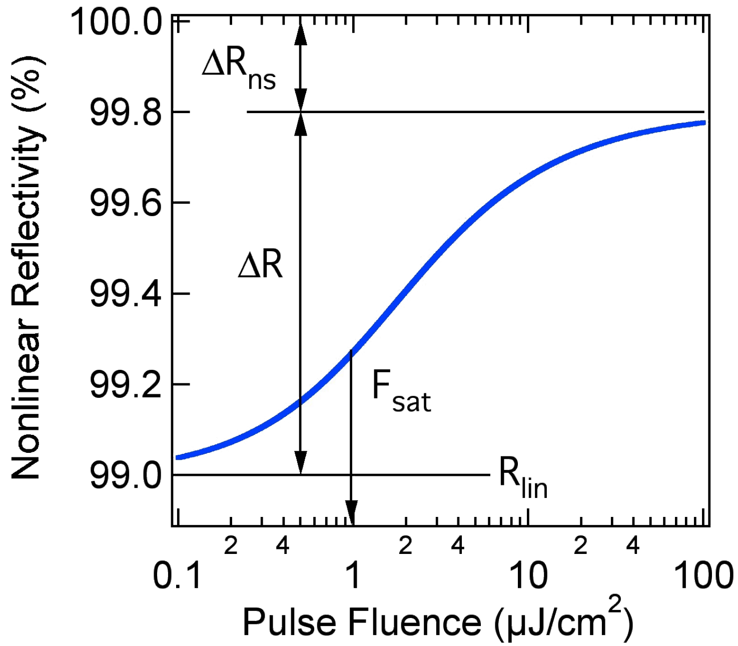
Absorber	$\sigma_A \quad [\mathrm{cm}^2]$
ion-doped solid-state	$10^{-19} - 10^{-22}$
dye	10^{-16}
semiconductor	10^{-14}



SESAM parameters

nonlinear parameters

$F_{\text{sat}}, \ \Delta R, \ \Delta R_{\text{ns}}$



to overcome the stability condition for Q-switched mode locking (QML) threshold

$$F_p^2 > F_{\text{sat}} \cdot \Delta R \cdot F_{\text{sat,L}} \cdot \frac{A_{\text{eff,L}}}{A_{\text{eff,A}}}$$

F_{p} : intracavity fluence

F_{sat} : saturation fluence of the absorber

ΔR : modulation depth

$F_{\text{sat, L}}$: saturation fluence of the gain

A : area in gain medium and on absorber

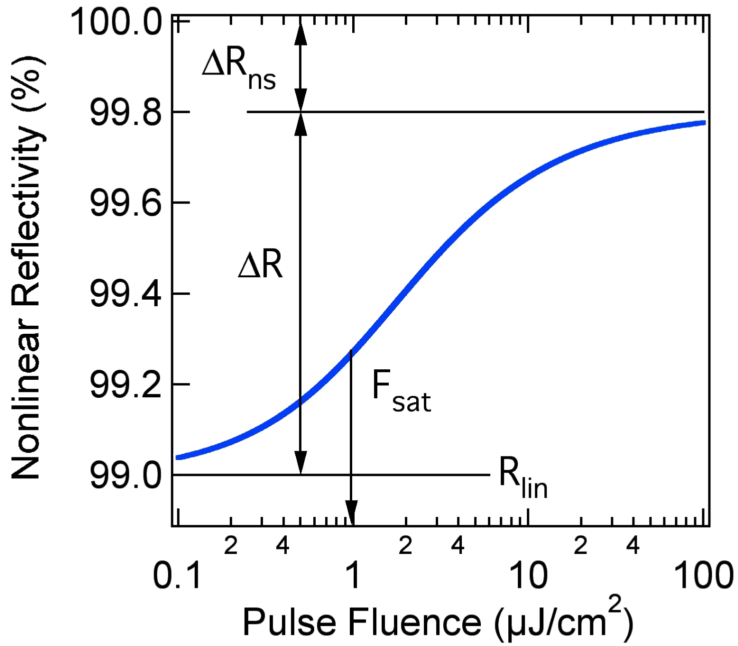
C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, U. Keller, JOSA B **16**, 46-56 (1999)

Keep ΔR and F_{sat} small to avoid Q-switching instabilities

SESAM parameters

nonlinear parameters

$F_{\text{sat}},\ \Delta R,\ \Delta R_{\text{ns}}$



to overcome the stability condition for Q-switched mode locking (QML) threshold

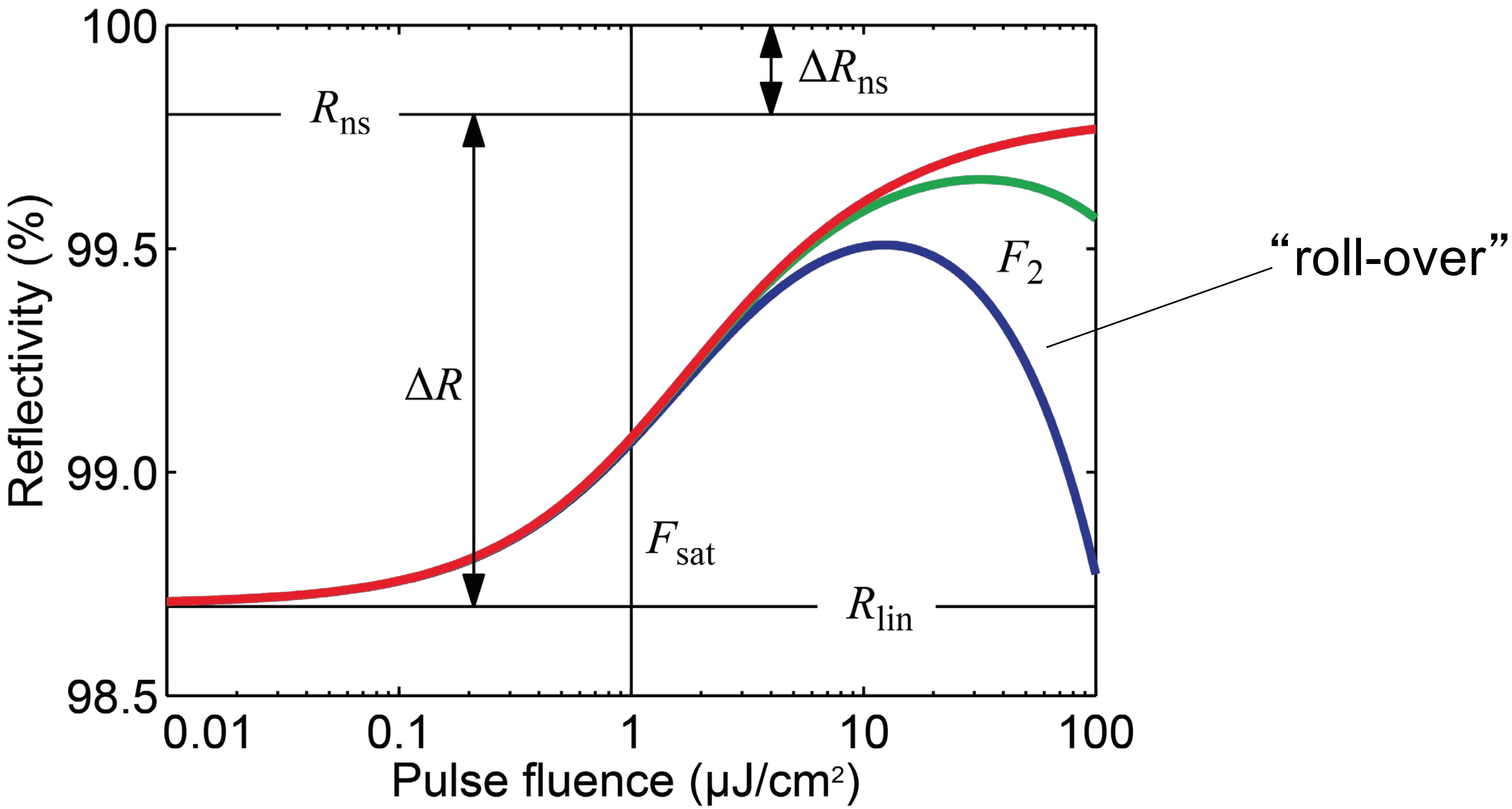
$$F_p^2 > F_{\text{sat}} \cdot \Delta R \cdot F_{\text{sat,L}} \cdot \frac{A_{\text{eff,L}}}{A_{\text{eff,A}}}$$

Issues for high pulse repetition rates:
$E_{p,\ GHz}$ 10^{-3} smaller than $E_{p,\ MHz}$

- F_{sat} ~ few tens of μJ/cm²
- ΔR < 1% is required

Keep ΔR and F_{sat} small to avoid Q-switching instabilities

SESAM response with roll-over (inverse sat. absorption)



T. R. Schibli et al., *Appl. Phys. B* **70**, S41-S49 (2000).
R. Grange et al., *App. Phys. B* **80**, 151-158 (2005).

Inverse saturable absorption improves QML threshold

Simple stability condition, $F_2 \rightarrow \infty$

$$F_p^2 > F_{\mathrm{sat}} \cdot \Delta R \cdot F_{\mathrm{sat,L}} \cdot \frac{A_{\mathrm{eff,L}}}{A_{\mathrm{eff,A}}}$$

F_P = intracavity fluence

$F_{sat,L}$ = gain saturation fluence

F_{sat} = absorber saturation fluence

C. Hönninger, et al., JOSA B **16**, 46-56 (1999)

Modified stability condition

$$F_p^2 > \frac{F_{\mathrm{sat}} \Delta R}{\frac{1}{A_L F_{\mathrm{sat,L}}} + \frac{1}{A_A F_2}}$$

A_A = beam size area on the absorber

T. R. Schibli et al., *Appl. Phys. B* **70**, S41-S49 (2000).

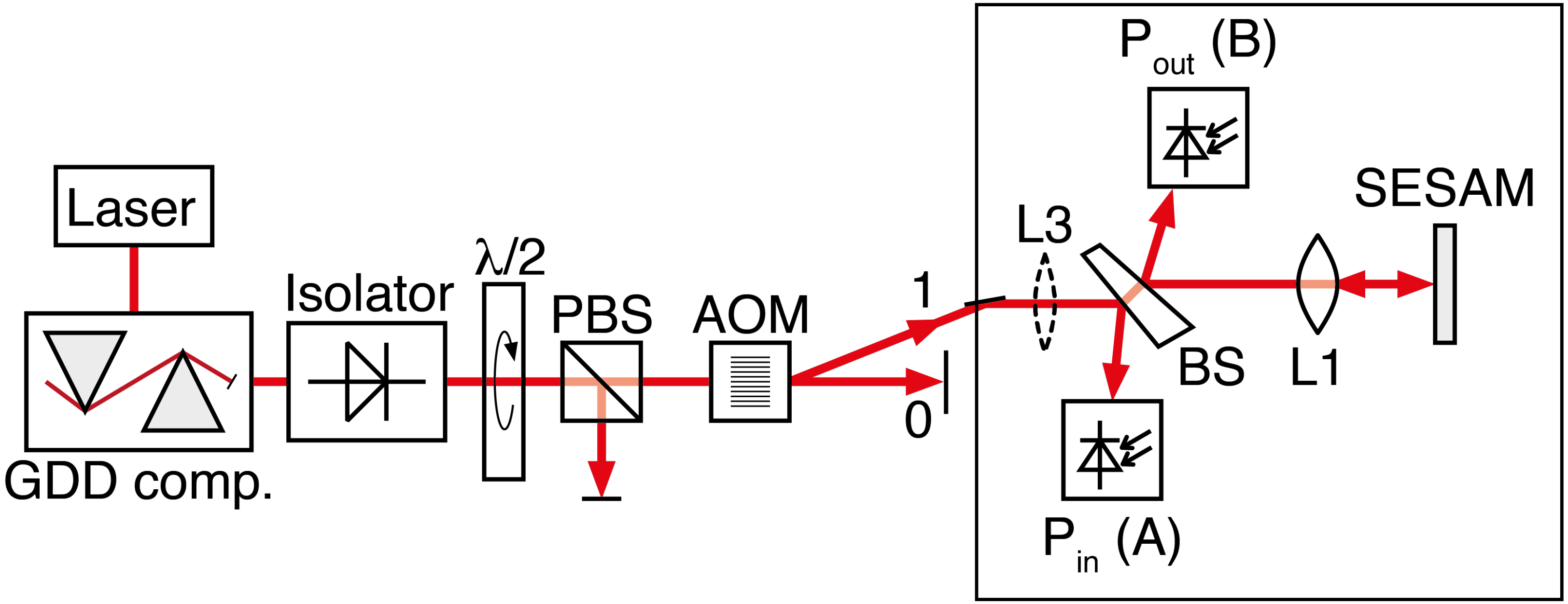
R. Grange et al., *App. Phys. B* **80**, 151-158 (2005).

- Reduced QML threshold
- Less need of minimization of the mode size in the gain medium

- Measurement of SESAM parameters

Original measurement setup

Haiml et al., *Appl. Phys. B* **79**, 331-339 (2004)



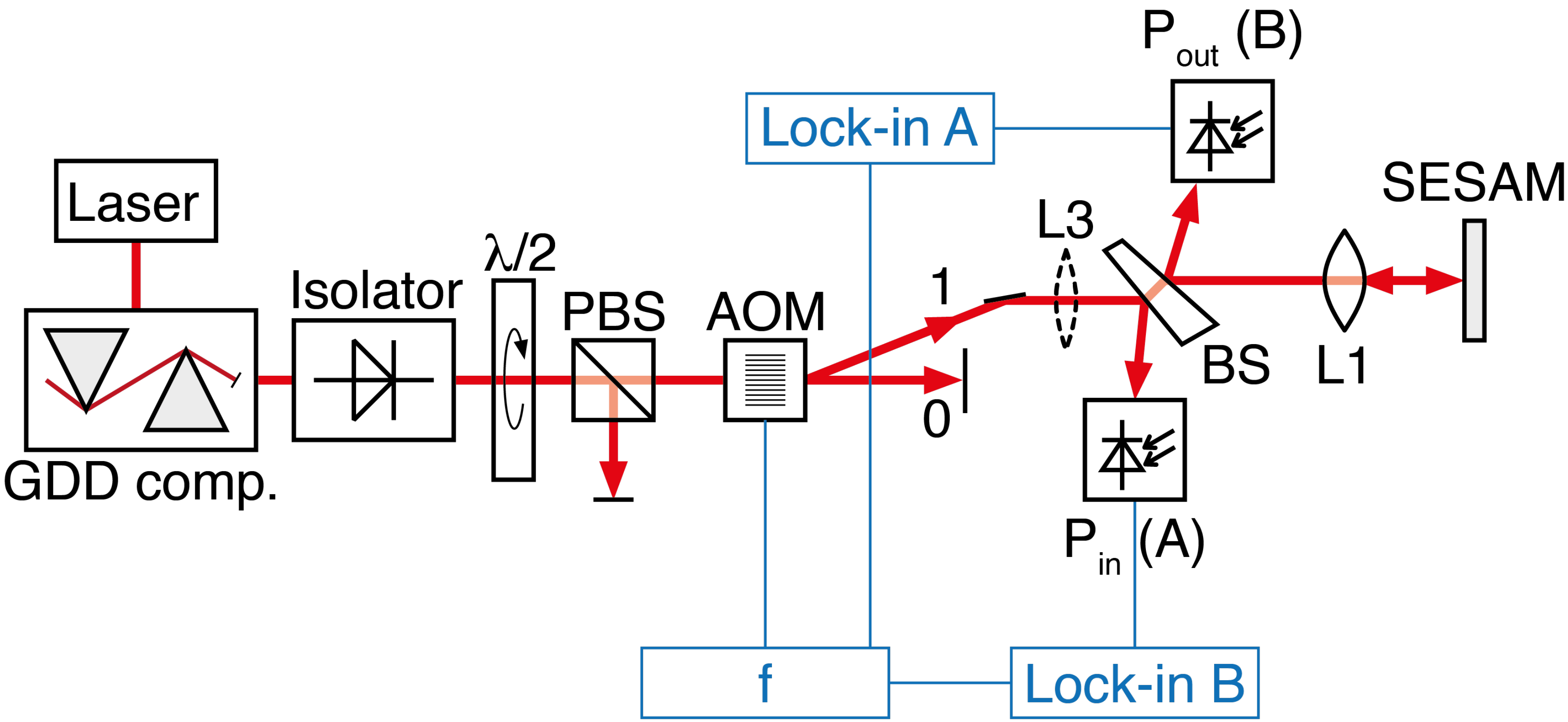
Photodiode A: $\propto P_{\mathrm{in}}$

Photodiode B: $\propto R \cdot P_{\mathrm{in}}$

Reflectivity of the SESAM: $R = \dfrac{B}{A}$

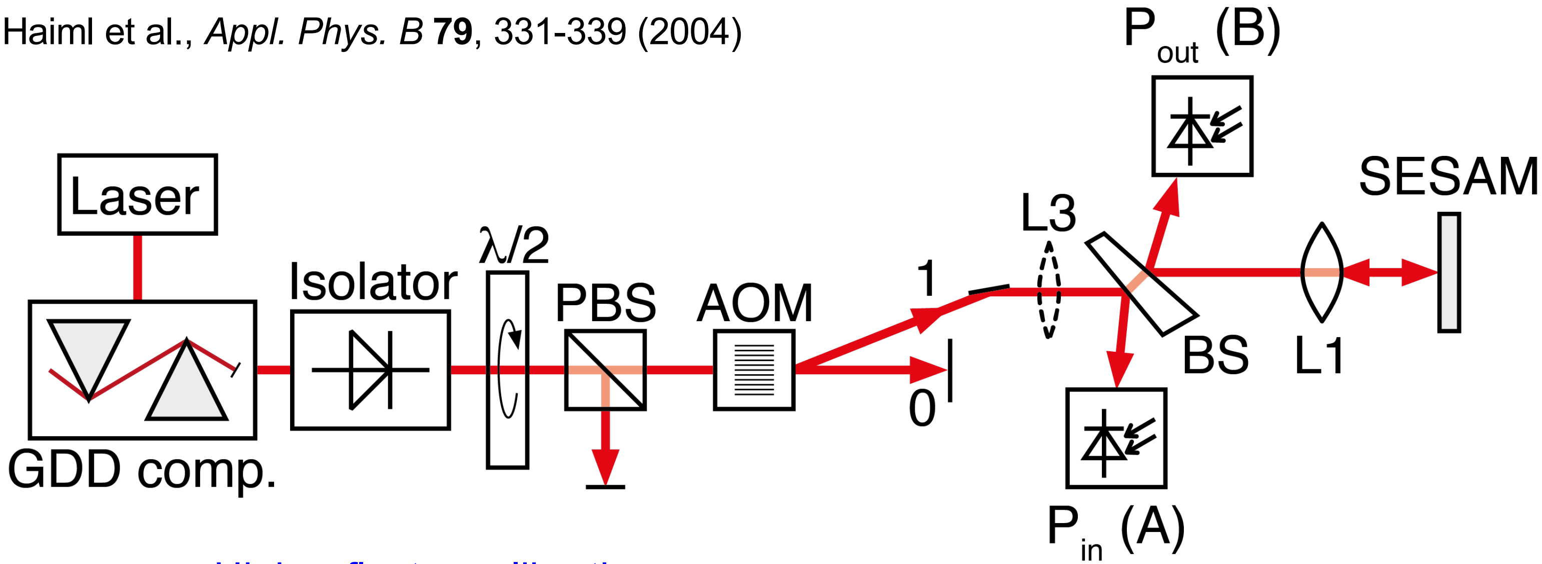
Original measurement setup

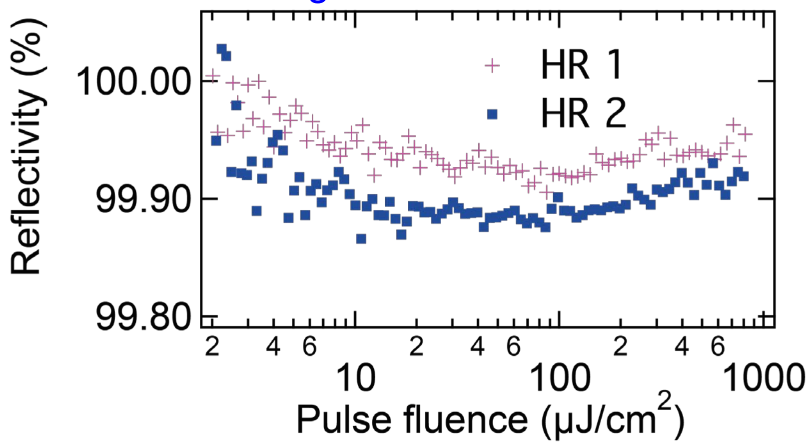
Haiml et al., *Appl. Phys. B* **79**, 331-339 (2004)

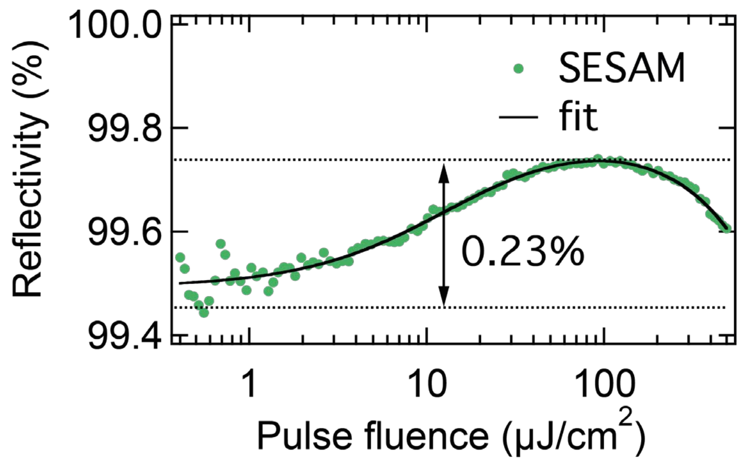


Original measurement setup

Haiml et al., *Appl. Phys. B* **79**, 331-339 (2004)







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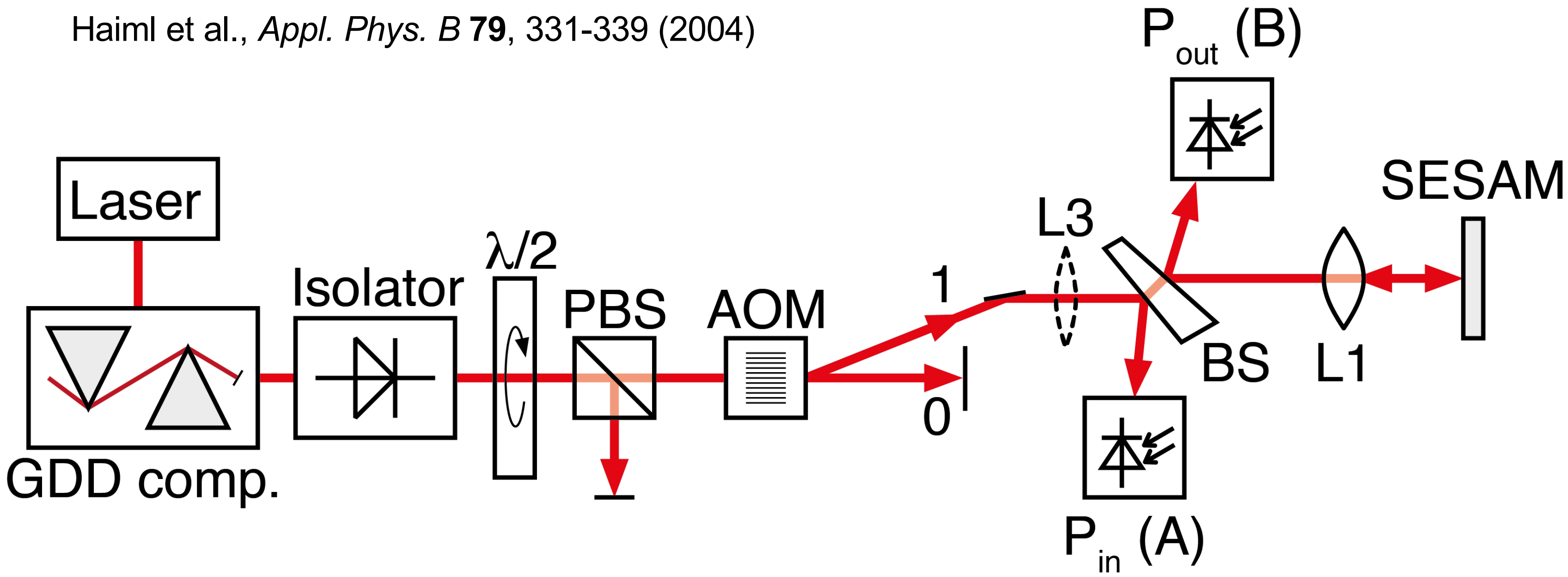
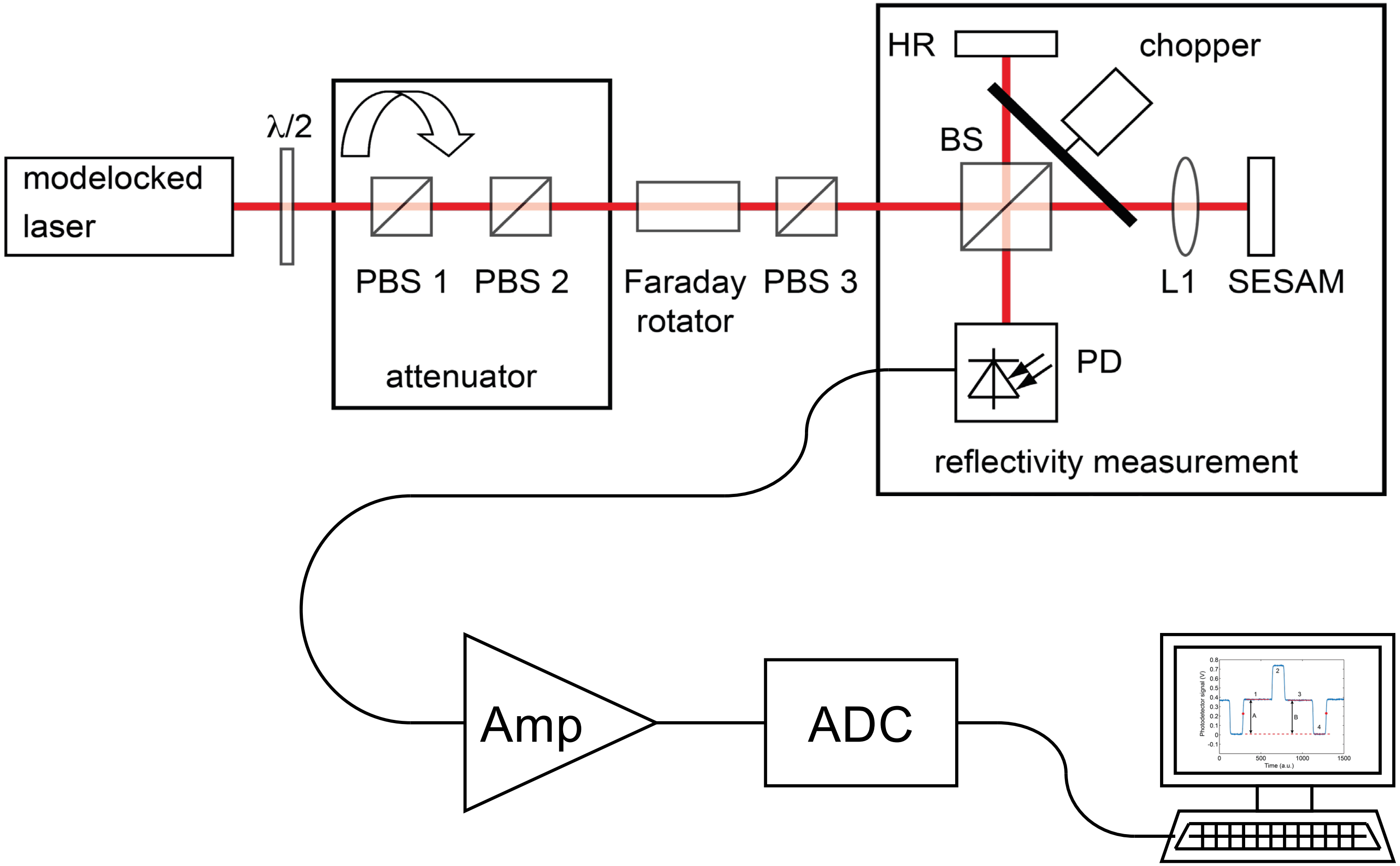


- Detectors must be able to measure voltages over at least four orders of magnitude with an accuracy of better than 0.1%
- Lock-in detection with two separate lock-in amplifiers (AOM needed for modulation of the incident beam)
- Required performance is close to the linearity limit of the lock-in amplifiers
- Complicated and expensive

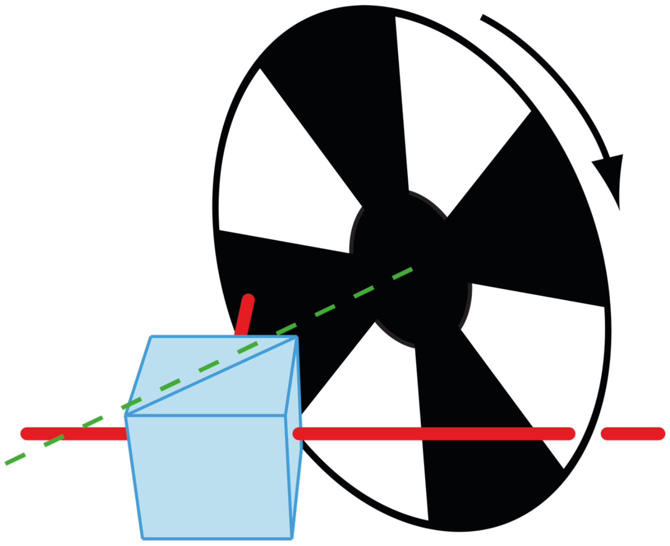
New measurement system

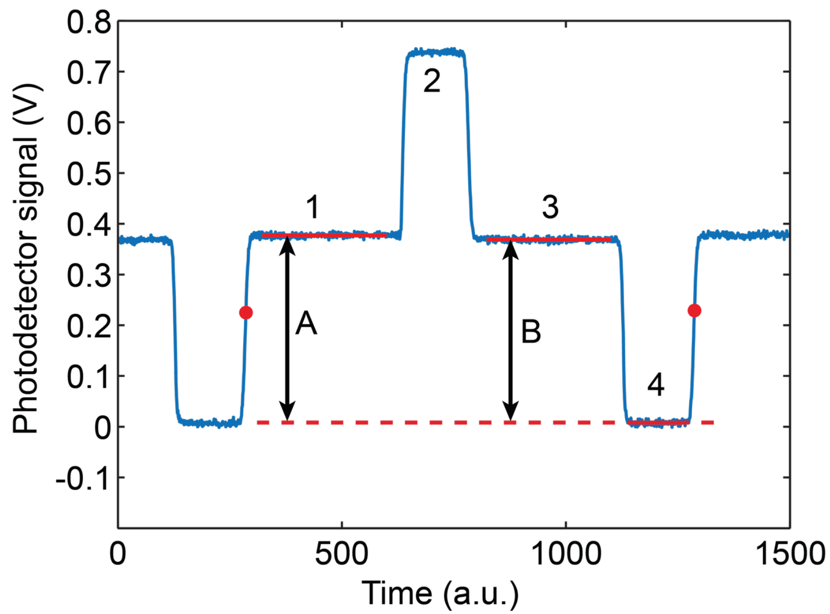
Maas et al., *Optics Express* **16**, 7571 (2008)



New measurement system: detector signal

Maas et al., *Optics Express* **16**, 7571 (2008)



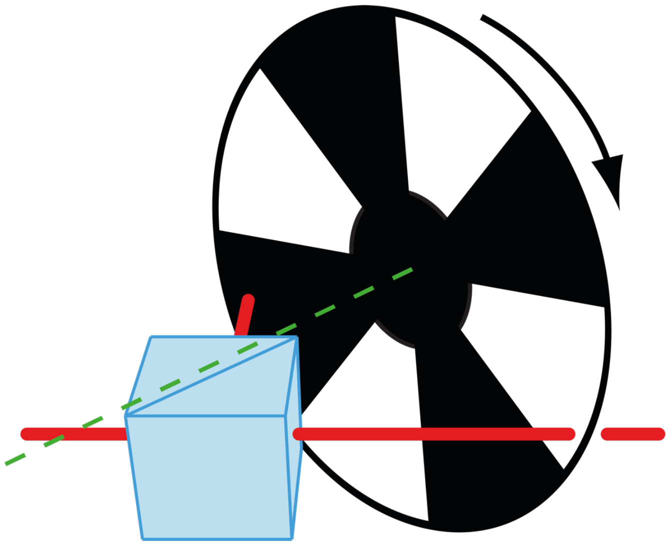


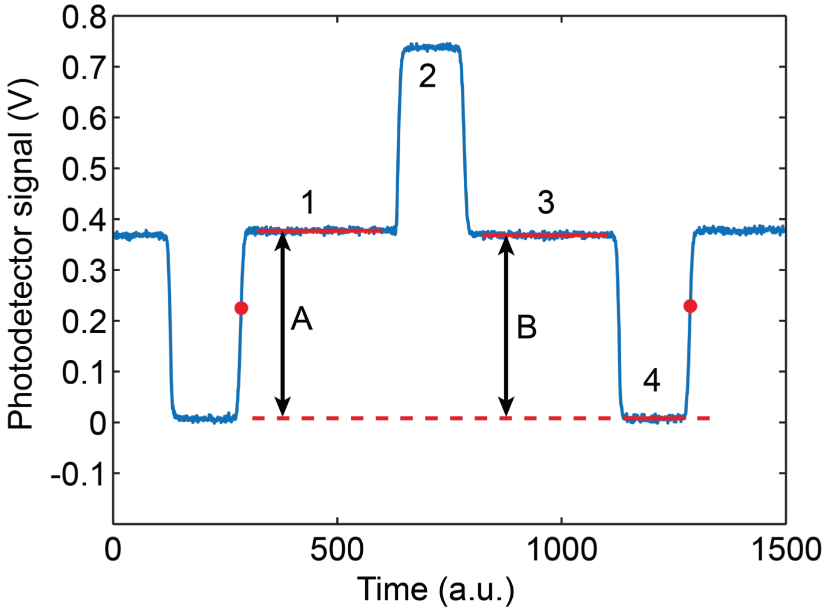
4 "states":

1. Reference mirror signal
2. Both signals (ignore this)
3. SESAM signal
4. Both arms blocked ➡ background signal

New measurement system: detector signal

Maas et al., *Optics Express* **16**, 7571 (2008)





Nonlinear reflectivity: $R = \dfrac{B}{A}$

Incident fluence:

Calculated from voltage A and pre-amplifier gain

5% accuracy is good enough ➡ 5% inaccuracy of F_{sat}

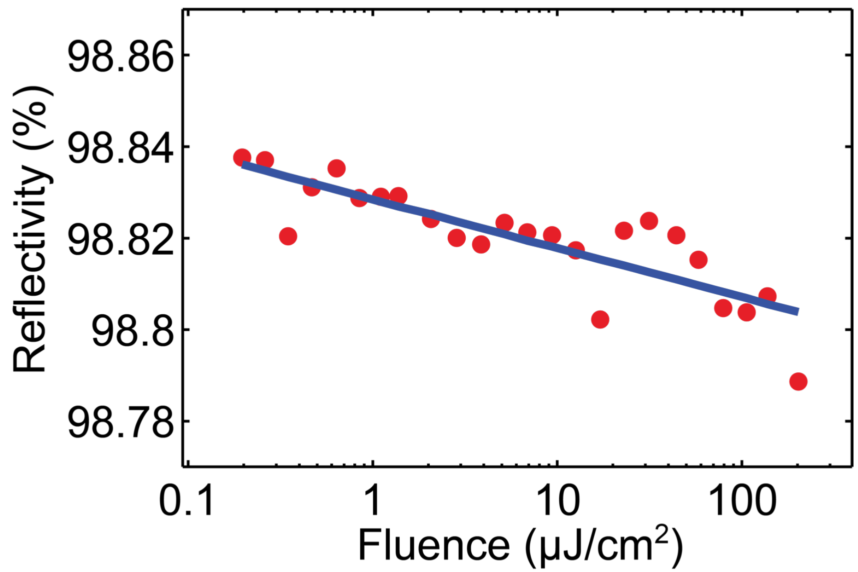
New measurement system: calibration

Maas et al., *Optics Express* **16**, 7571 (2008)

Calibration is done with a HR instead of the SESAM:

Reflectivity should be 100% and flat, but

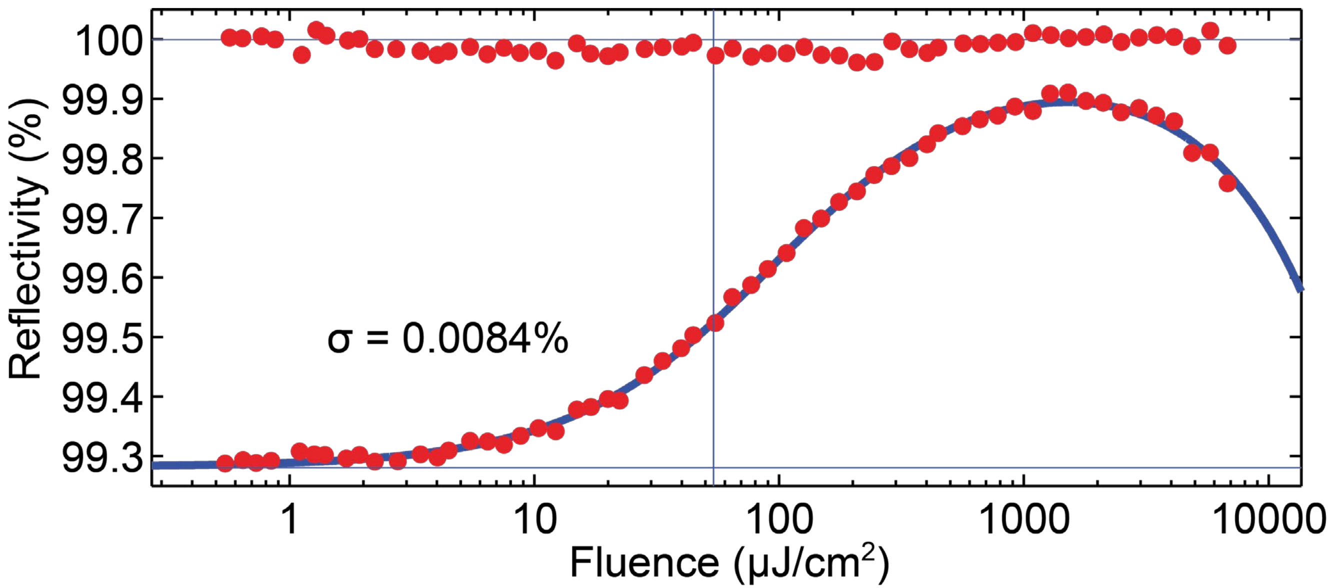
- extra lens in SESAM arm
- systematic errors



➡ Introduction of a calibration function C(F)

The corrected nonlinear reflectivity is then: $R = C(F) \cdot \dfrac{B}{A}$

Measurement example



Laser Source: modelocked $Yb{:}Lu_2O_3$ thin disk laser
570 fs pulses, 65 MHz ➡ induced absorption

Calibration function C(F): second order polynomial of log(F)

HR with correction: flatness of 0.055%

SESAM parameters: F_{sat} = 54 µJ/cm^2, ΔR = 0.72%, F_2 = 3.3 J/cm^2