Pulse generation and dispersion compensation

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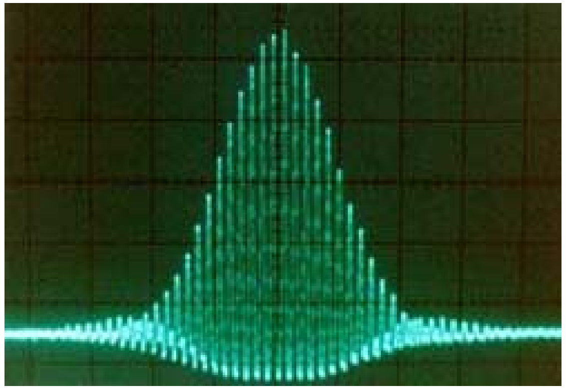
BIPM comb workshop, March 13-14, 2003

Outline

Pulse generation

- fundamentals of mode-locking – the mode comb
- SAM and SPM
- „artificial“ saturable absorbers



Dispersion

- types of dispersion
  - material
  - geometrical
  - µ-structured
- dispersion and the mode comb

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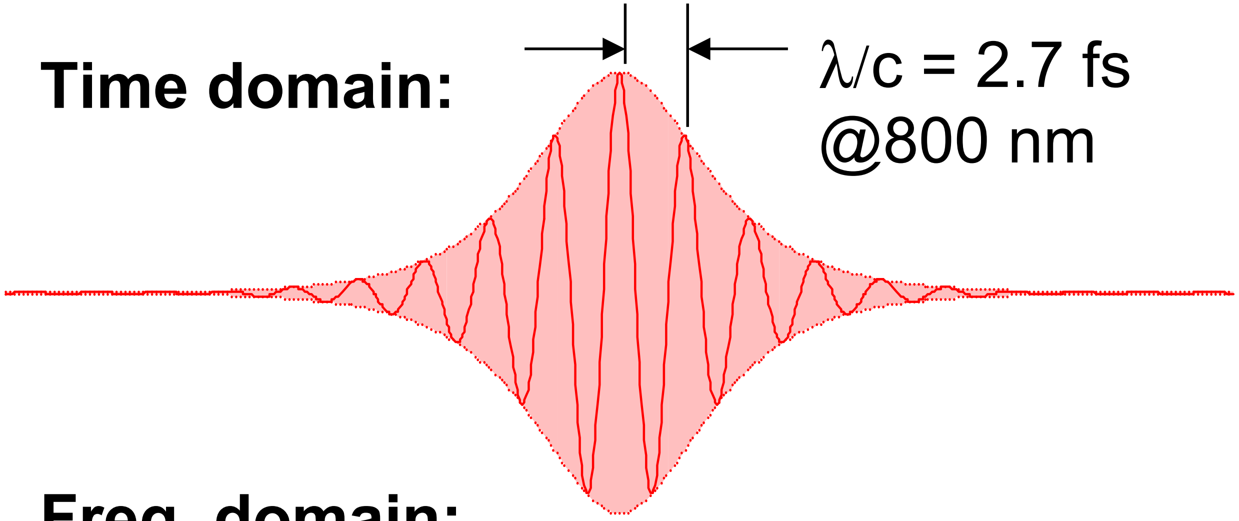
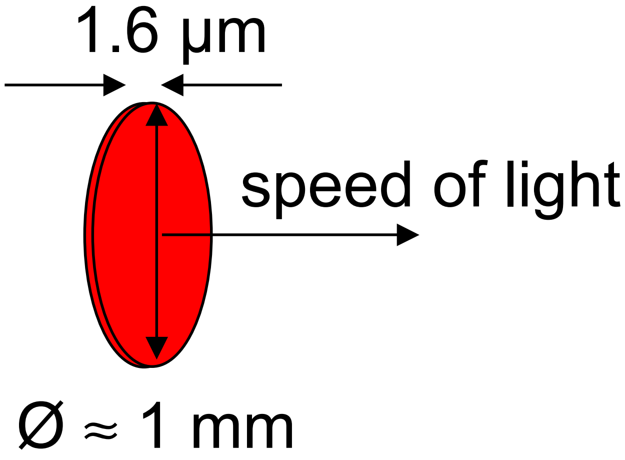
Two-cycle pulses – octave-spanning light membranes

Time domain:



λ/c = 2.7 fs
@800 nm

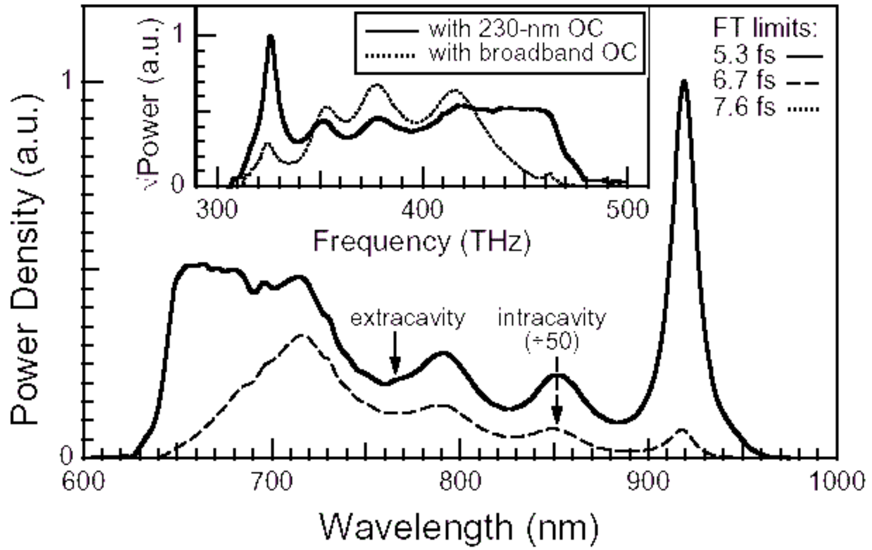


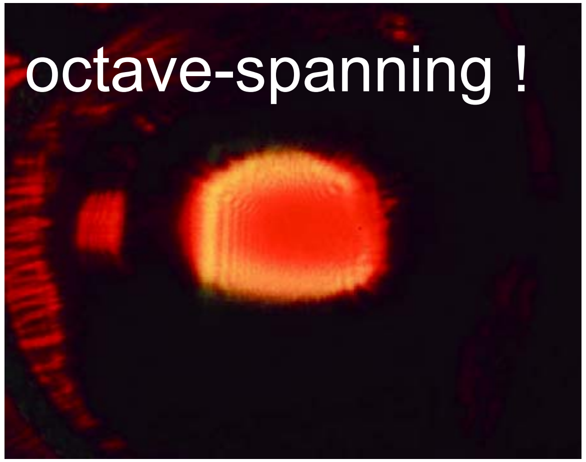
1.6 µm

speed of light

Ø ≈ 1 mm

Freq. domain:





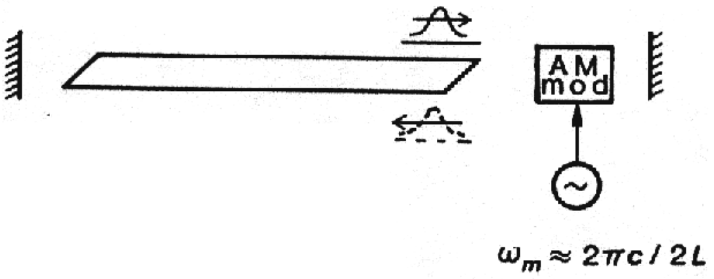
octave-spanning !

Refs.: G.Steinmeyer, *Science* **286**, 1507 (1999); D.H. Sutter, *Opt. Lett.* **24**, 631 (1999)

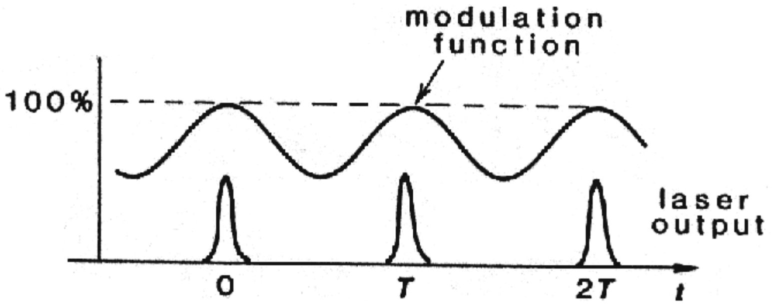
Mode-locking

Intracavity optical switch opens and closes synchronously with the propagating optical pulse

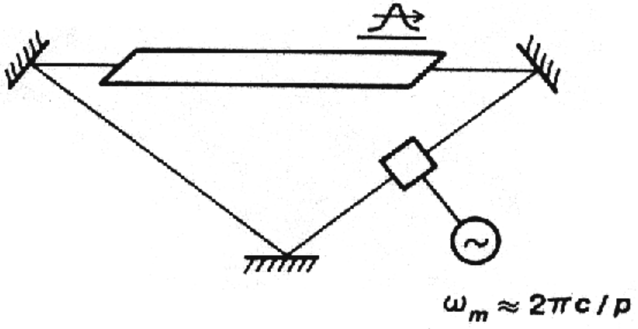
standing-wave cavity:



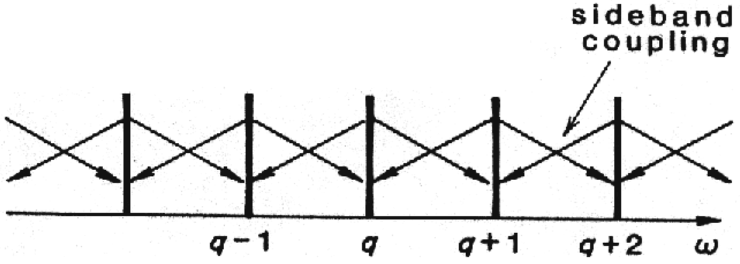
mode-locked time behavior:



ring laser cavity:

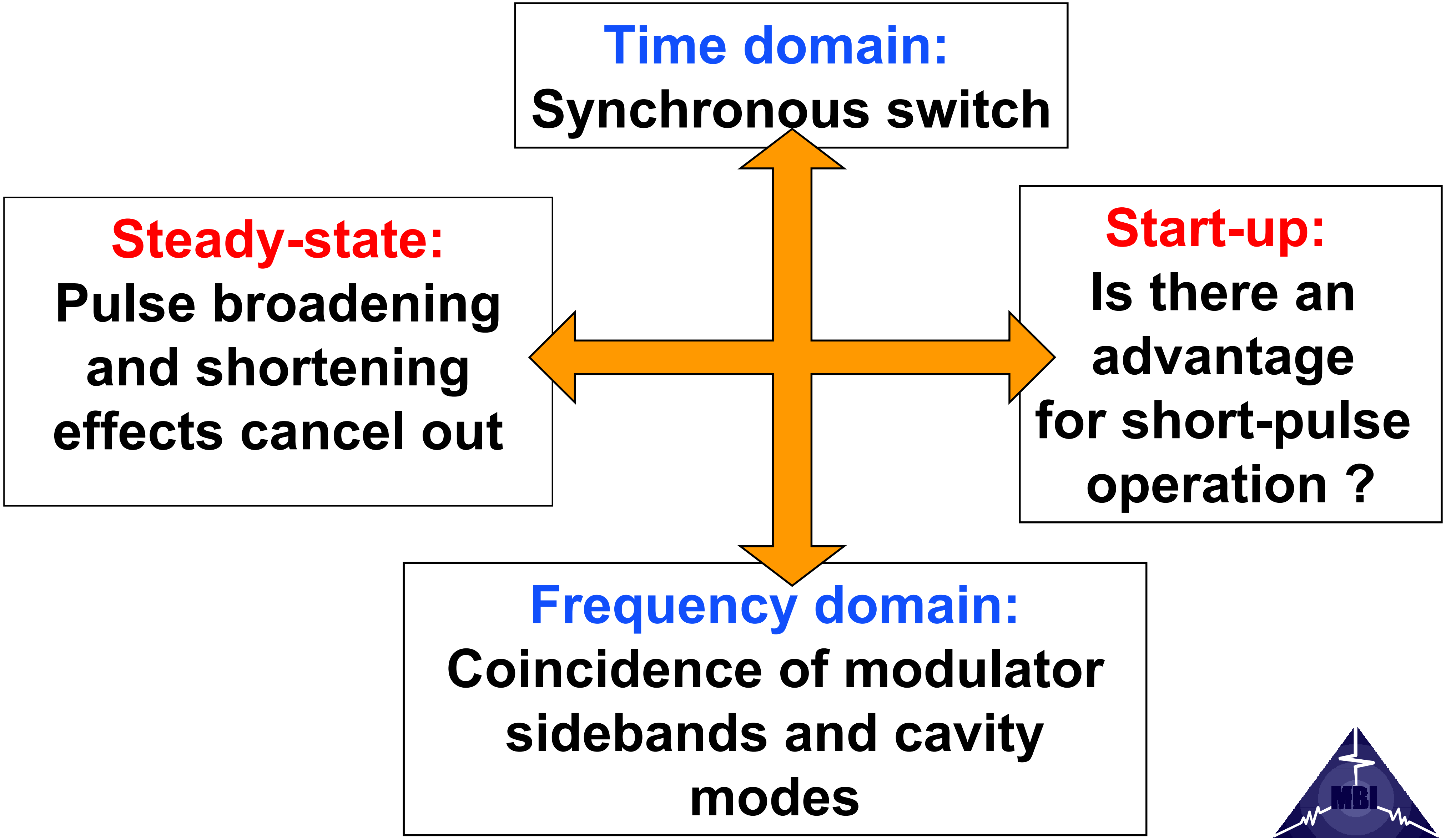


mode-locked frequency behavior:



Ref: A.E. Siegman, *Lasers,* University Science Books, 1986

Understanding Mode-Locking



Time domain:
Synchronous switch

Steady-state:
Pulse broadening and shortening effects cancel out

Start-up:
Is there an advantage for short-pulse operation ?

Frequency domain:
Coincidence of modulator sidebands and cavity modes

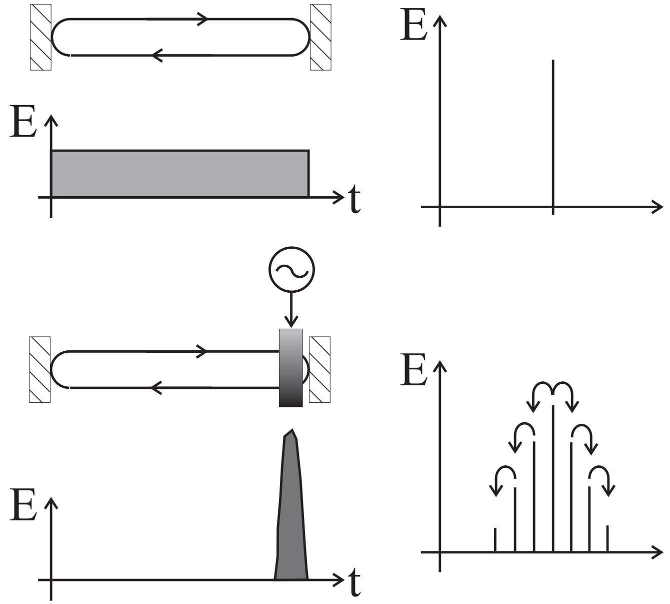
Passive vs. active mode-locking

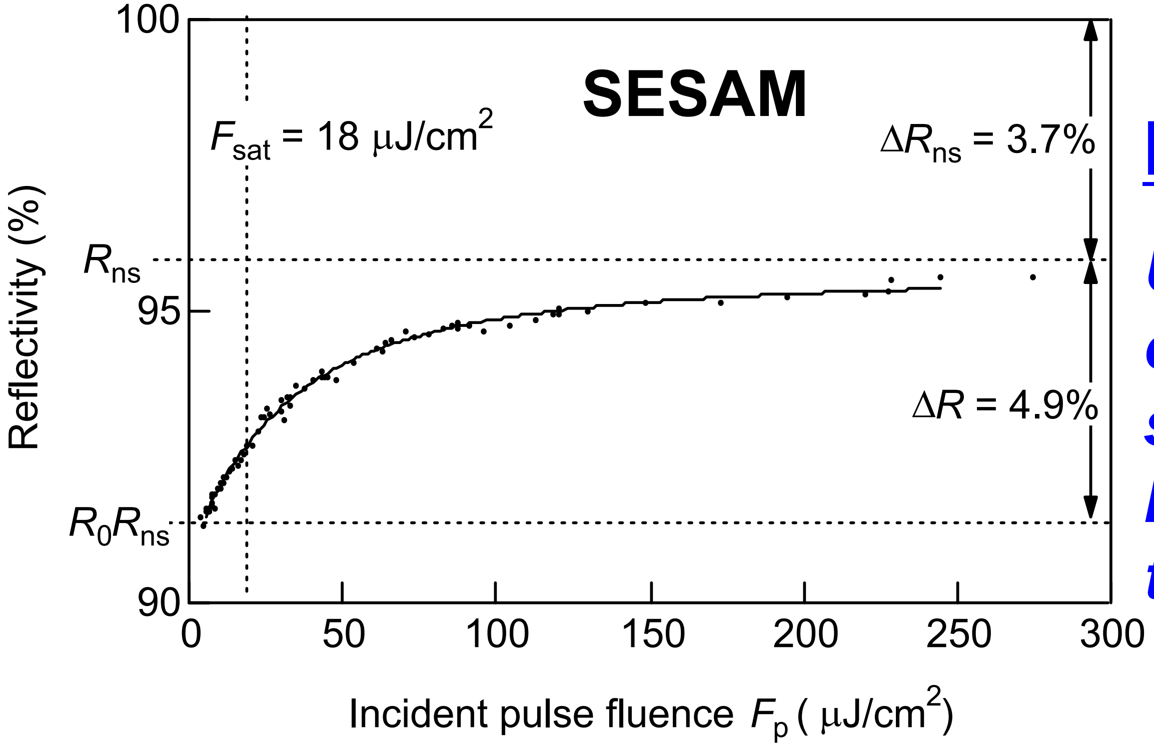
Active mode-locking:

Drive modulator with rf wave; generated sidebands coinciding with optical cavity modes

cw:

mode-locked:





Passive mode-locking:

Use nonlinear transmission characteristics of a saturable absorber. Pulse modulates its own transmision

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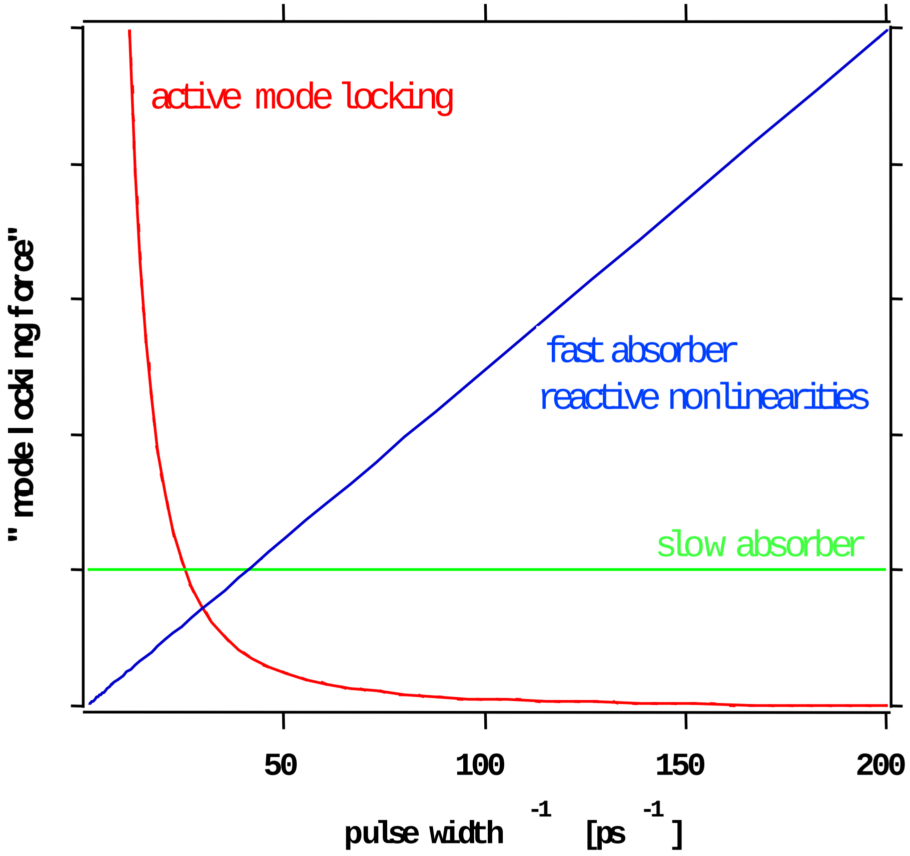
Mode-locking force

- **Mode-locking force = pulse shortening / roundtrip**
- **Balance with gain bandwidth / dispersive broadening**
- **fast absorbers for shortest pulses, slow absorbers for reliable start-up**



shorter Pulses

Ref.: E.P.Ippen, *Appl. Phys.* **B 58**, 159 (1994)

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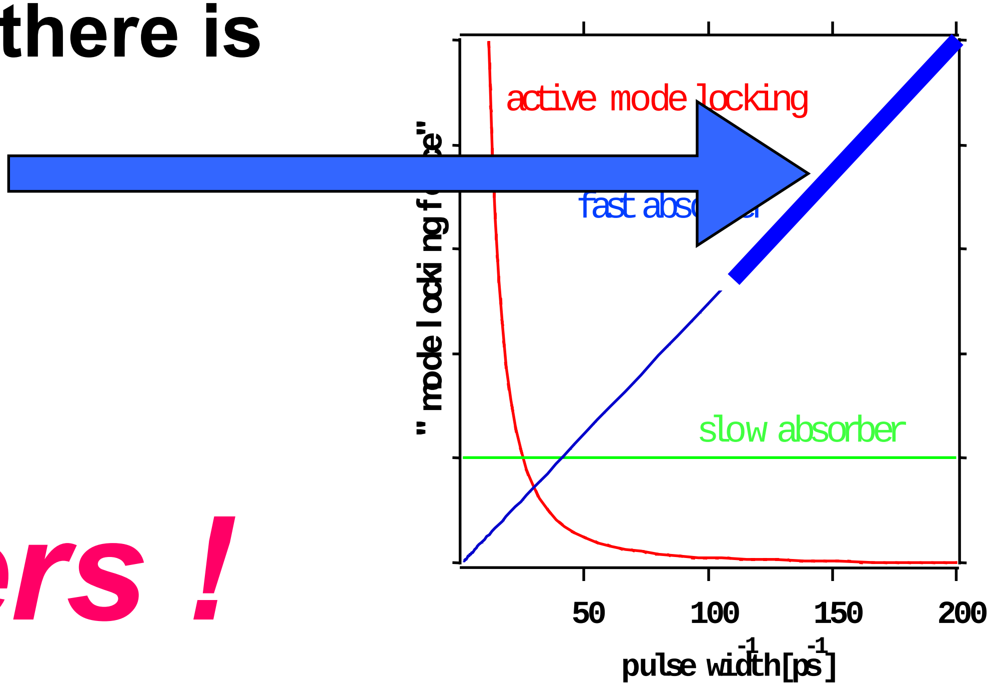
Initiating and sustaining mode-locking

- **For the shortest pulses, there is no way around a fast saturable absorber !**



Speed matters !

- **But: it may prove useful to add a slow effect to get mode-locking started.**

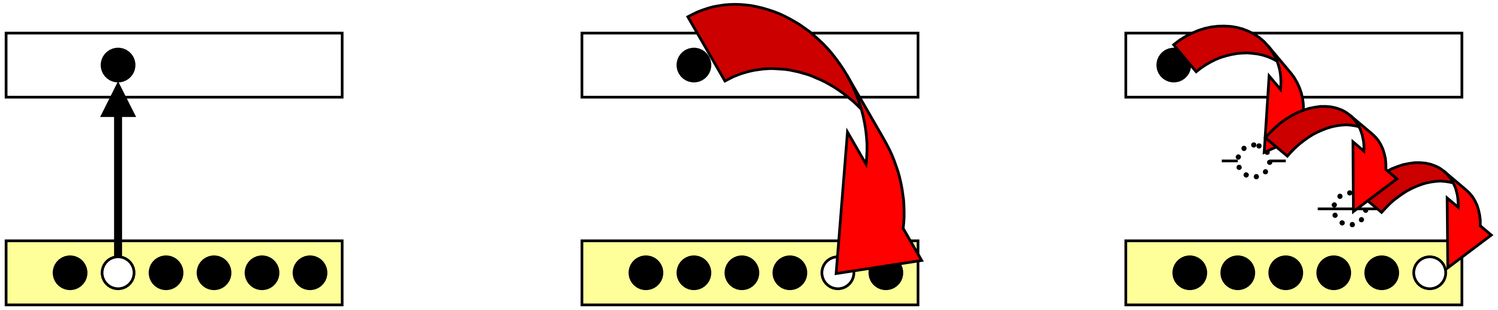
  (combine fast absorber with active mode-locking or SESAM...)

Virtual vs. real transition nonlinearity

excitation

direct relaxation

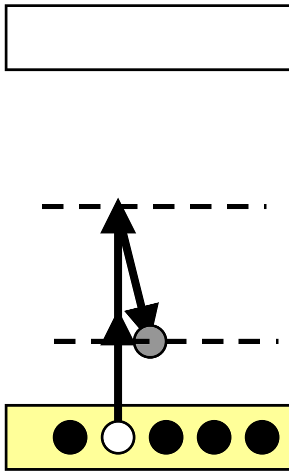
intermediate states



real
transitions
semiconductor
(dye, SESAM)

very slow
≈ 100ps

somewhat faster
≈ 1ps



virtual
states
wide bandgap
material
(opt. Kerr)

ultrafast

$\tau_{relax} \approx (E_{gap}/h)^{-1}$

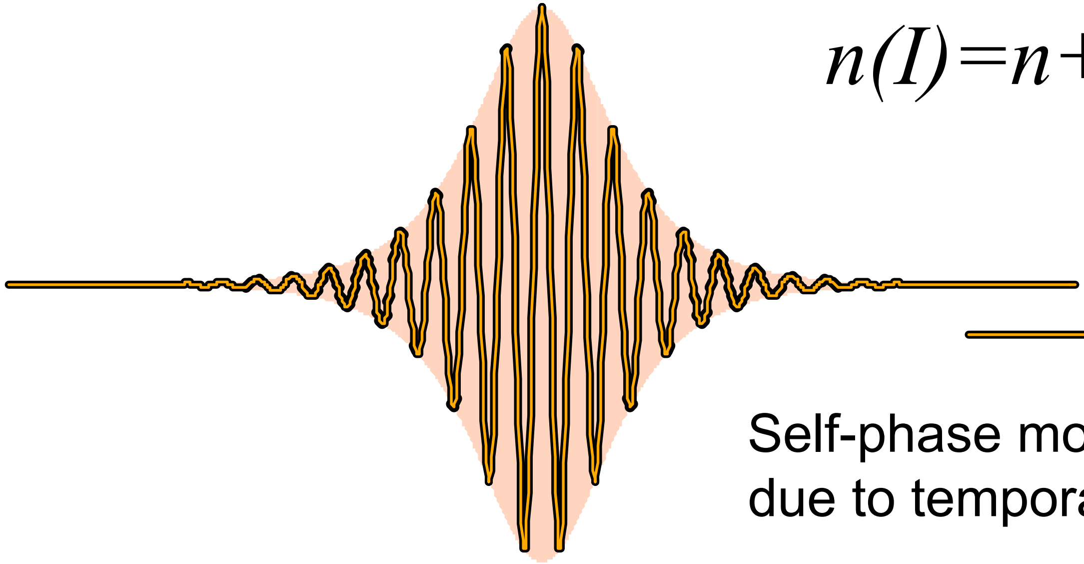
< 1 fs

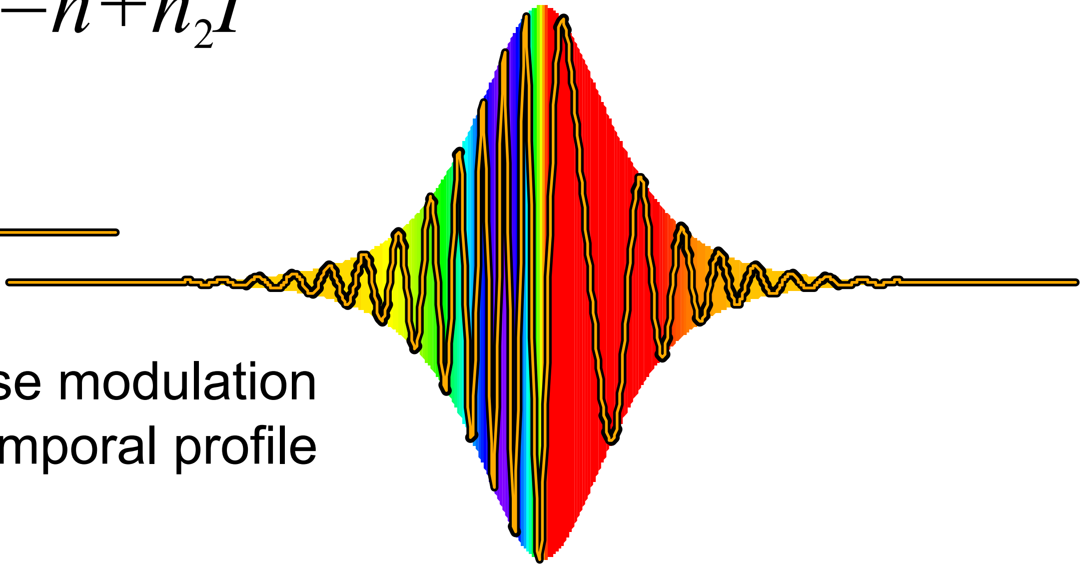
reactive nonlinearity

The all-optical Kerr-effect

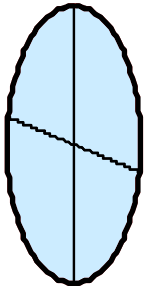
Refractive index changes with intensity

$$n(I)=n+n_2I$$

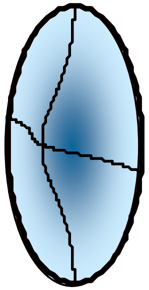




Self-phase modulation
due to temporal profile

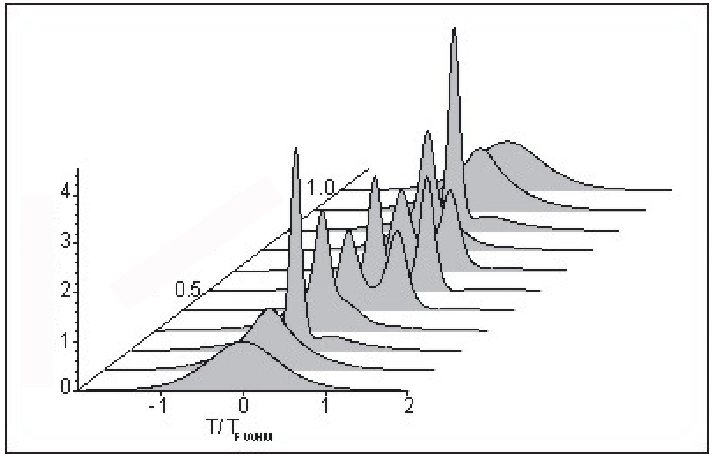


Self-focusing due to
transverse profile



Building an Kerr-based saturable absorber

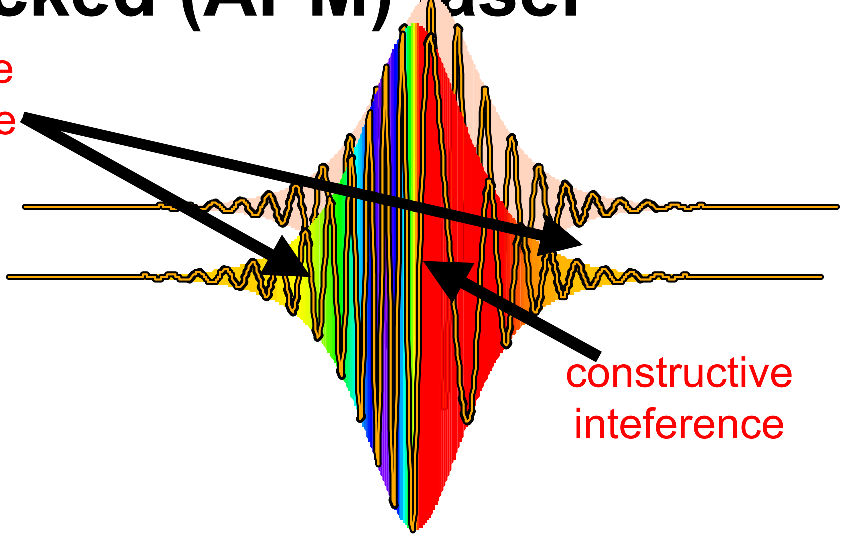
1. The soliton laser



SPM can be used for pulse compression

L.F. Mollenauer and R. Stolen, *Opt. Lett.* **9**, 13 (1984)

2. The additive-pulse mode-locked (APM) laser



destructive inteference

constructive inteference

Heterodyning of SPM‘d and regular pulse yields compression

E.P. Ippen et al., *Opt. Lett.* **15**, 183 (1990)

3. The Kerr-lens mode-locked (KLM) laser

D.E. Spence et al., *Opt. Lett.* **16**, 42 (1991)

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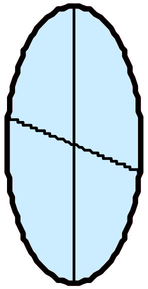
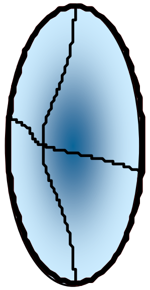
Using a Kerr-lens as a modulator

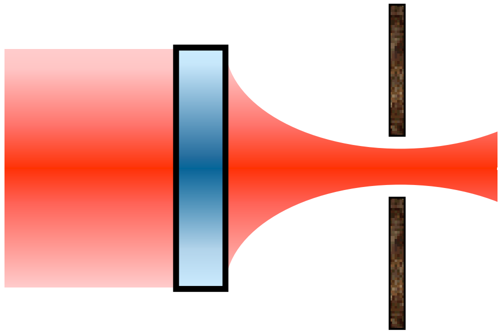
Refractive index depends on intensity

$$n(I)=n+n_2I$$



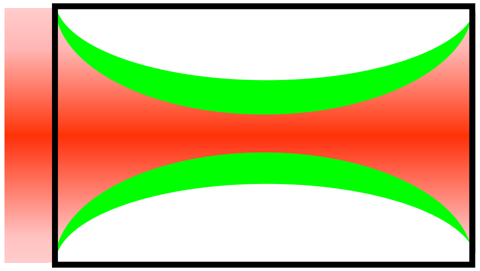
self-focusing
translates
into





Lower loss at aperure
("hard aperture KLM")

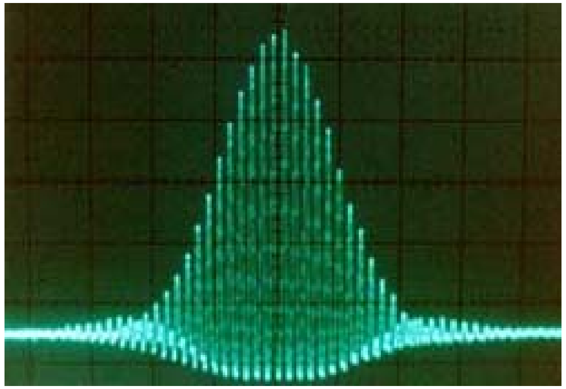
or...



Higher gain due to increased
overlap with pump
("soft aperture KLM")

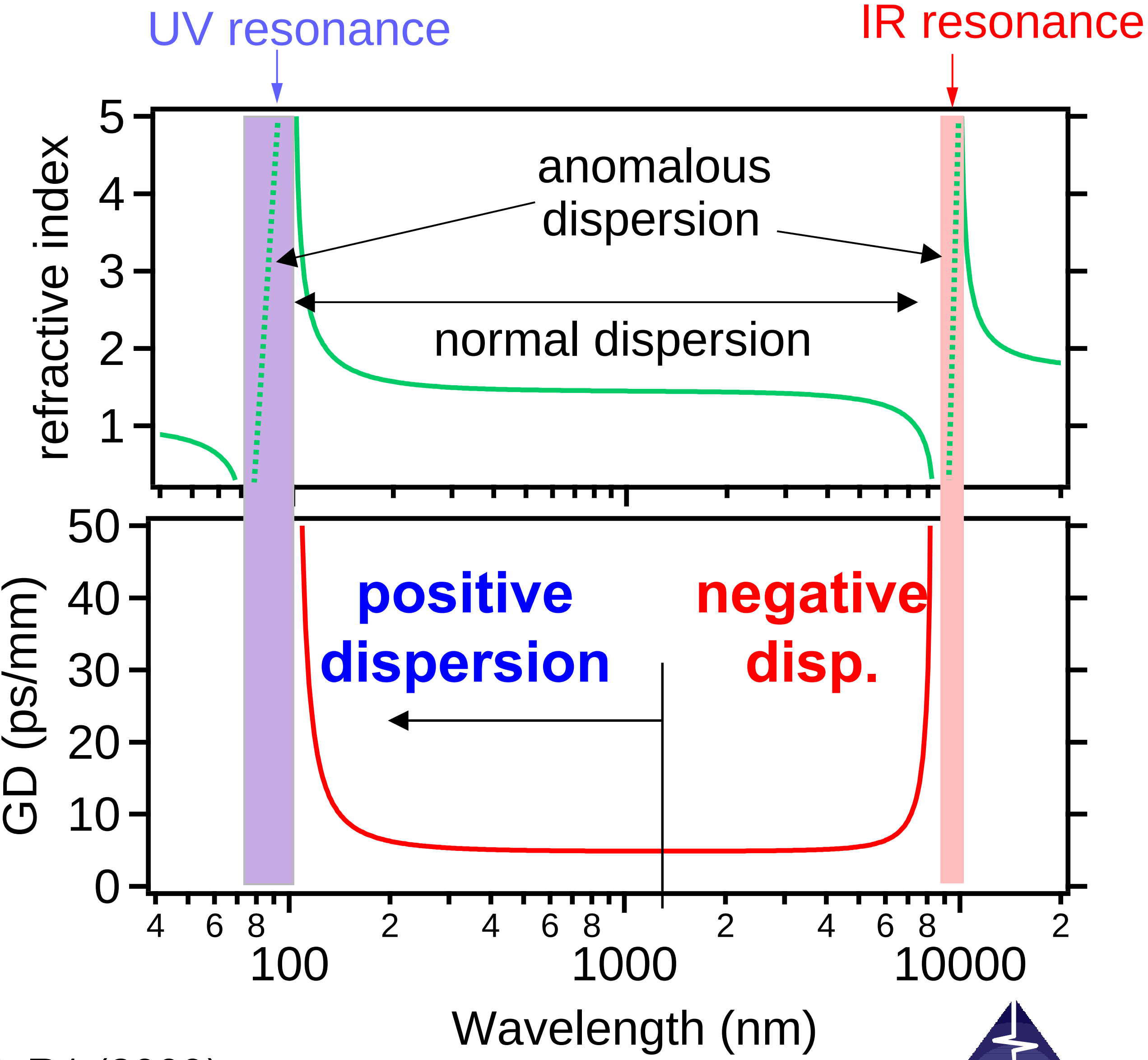
Summary – mode-locking driver mechanism

- advantage for the pulsed operation over cw (initiate and stabilize mode-locking)
- for short pulses, you need a really fast absorber (but real absorbers are not fast)
- use electronic nonlinearity (virtual states, reactive)
- use mediating mechanism to convert to SAM (APM, soliton laser, KLM)
- SAM prevents fallback into cw, SPM generates bandwidth



Dispersion in optics

- **UV and IR resonances govern phase properties at mid gap**
- **Resonances „store“ energy, causing a delay close to resonance**
- **Below ~1000nm, only positive slope of GD(ω), i.e. *positive dispersion***



Reviews: G.Steinmeyer, *J. Opt. A* **5**, R1 (2003)
I.A. Walmsley, *Rev. Sci. Instrum.* **72**, 1 (2001)

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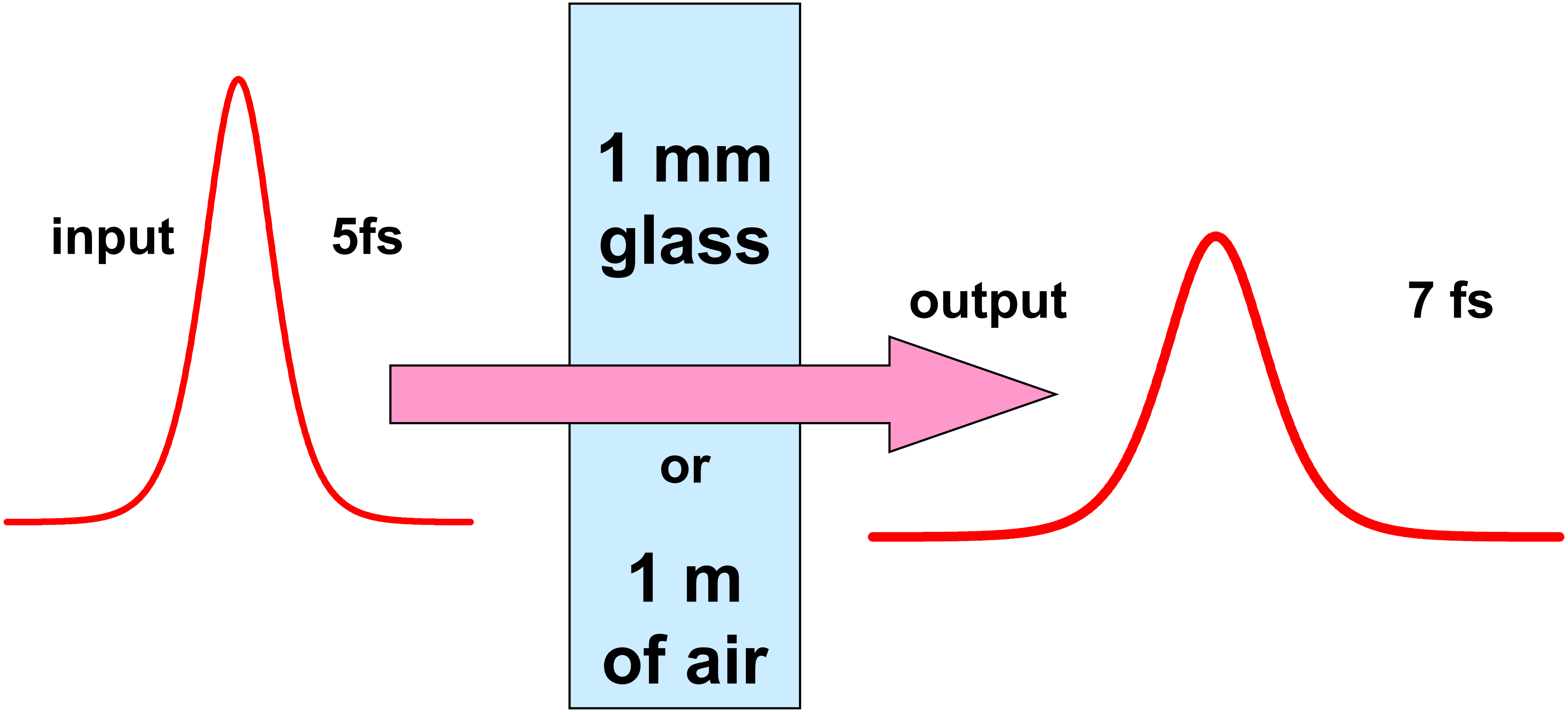
Dispersion makes pulses longer !



input

5fs

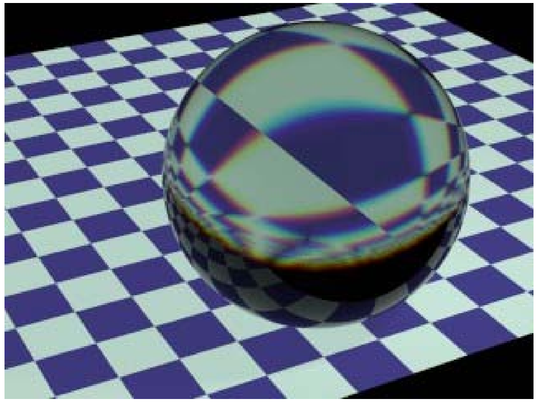
1 mm glass

or

1 m of air

output

7 fs



Ref.: G.P.Agrawal, *Nonlinear Fiber Optics*

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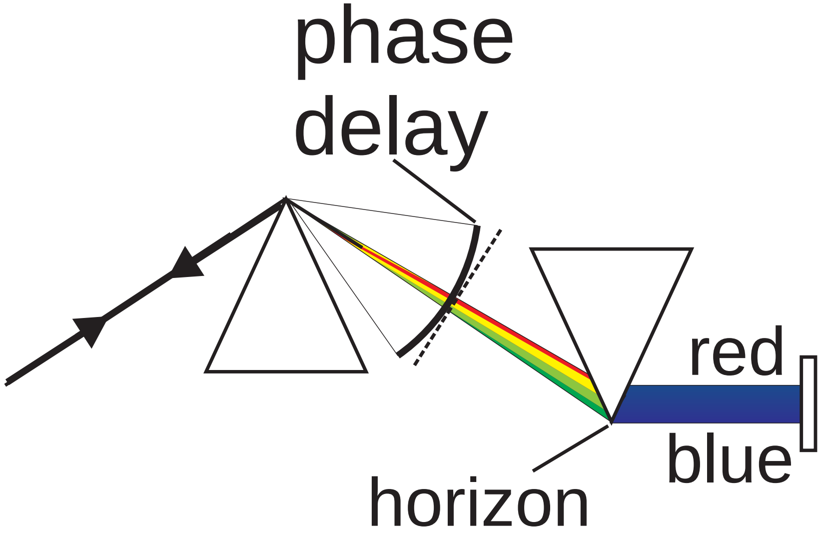
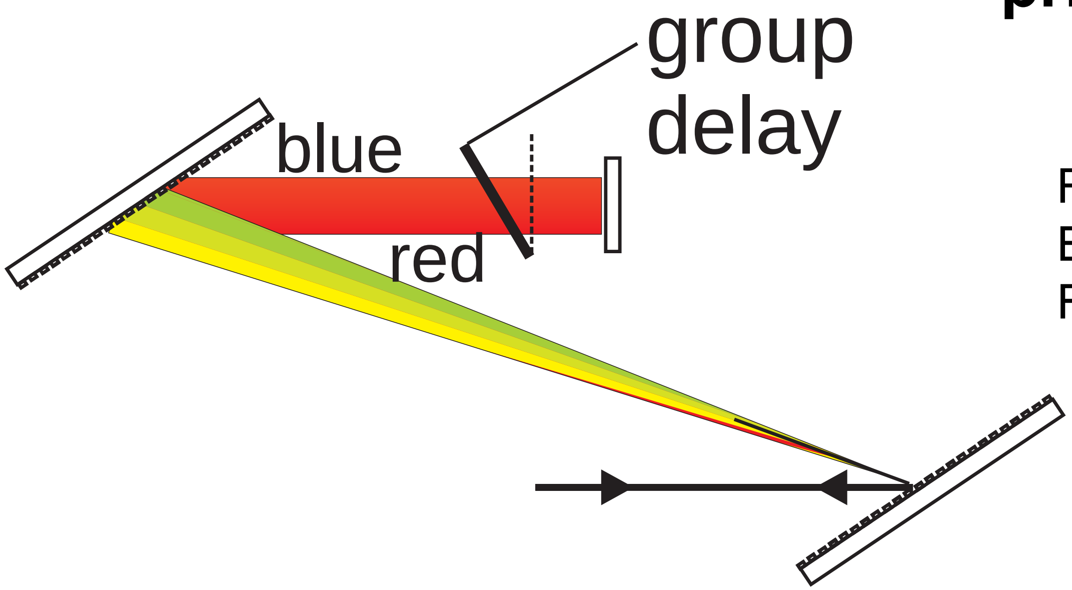
One cannot compensate material dispersion by material dispersion





So we have to create
pseudo materials
to recompress a pulse!

And this can be done by prism and grating sequences

Refs.:
E.B.Treacy, *IEEE JQE* **5**, 454 (1969)
Fork et al., *Opt. Lett.* **9**, 150 (1984)

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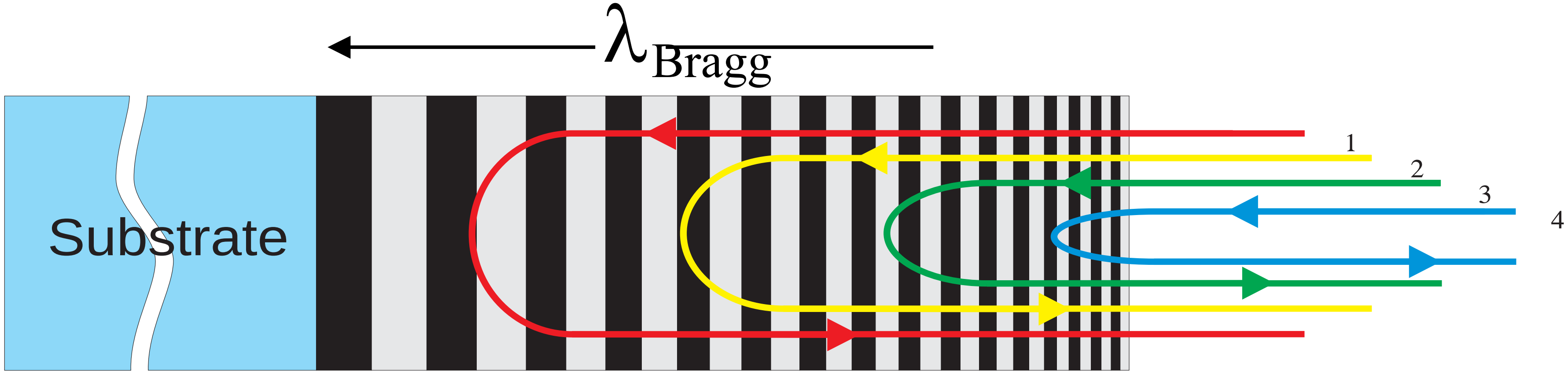
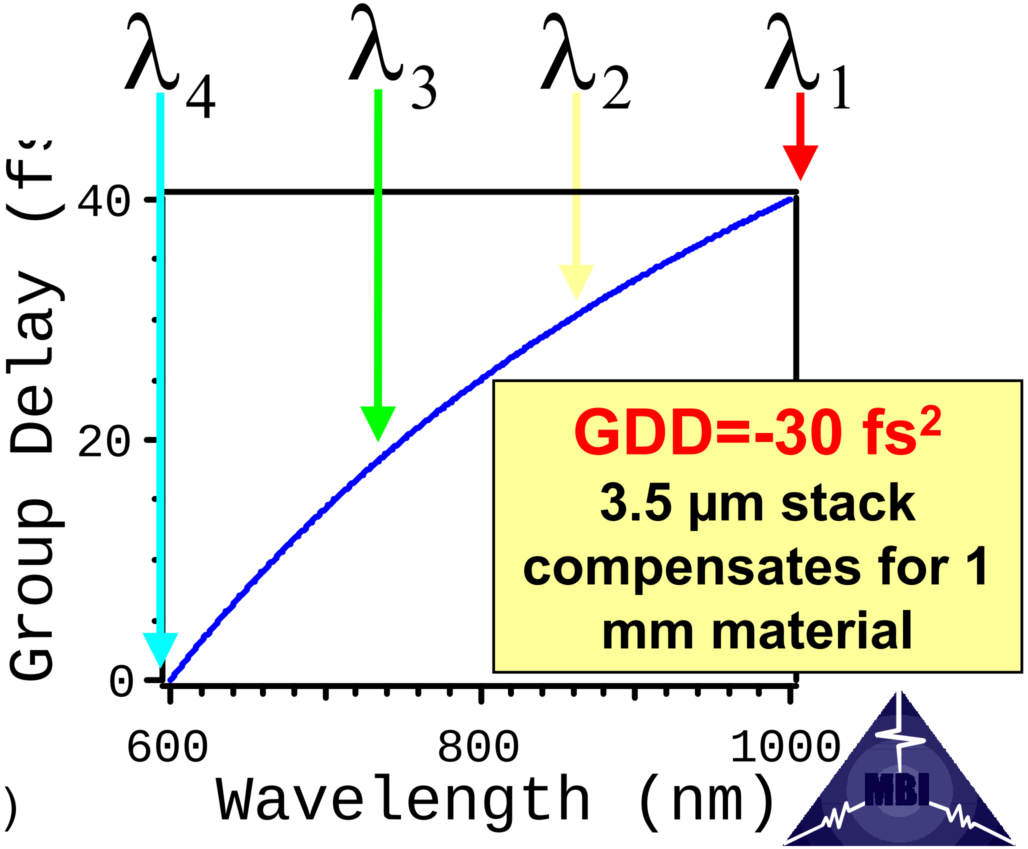
Chirped mirrors – microstructured disp.



- ⇒ **thin sputtered layers of TiO_2 and SiO_2**
- ⇒ **engineerable dispersion**
- ⇒ **compensation of arbitrary material dispersion**



GDD=-30 fs^2
3.5 µm stack compensates for 1 mm material

R. Szipöcs et al., *Opt. Lett.* **19**, 201 (1994)

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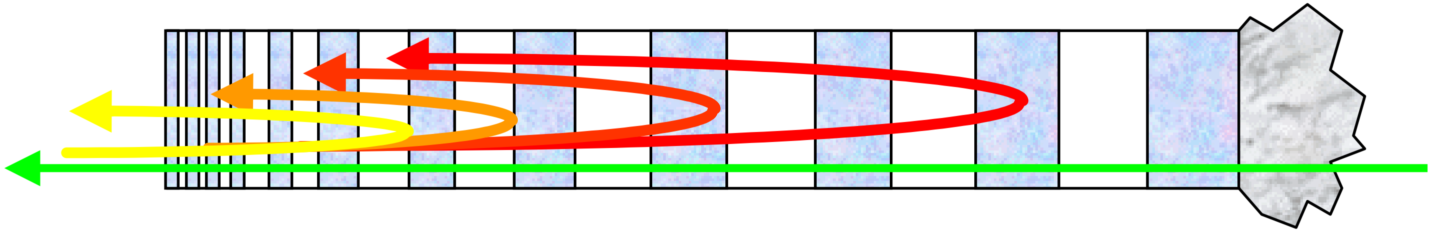
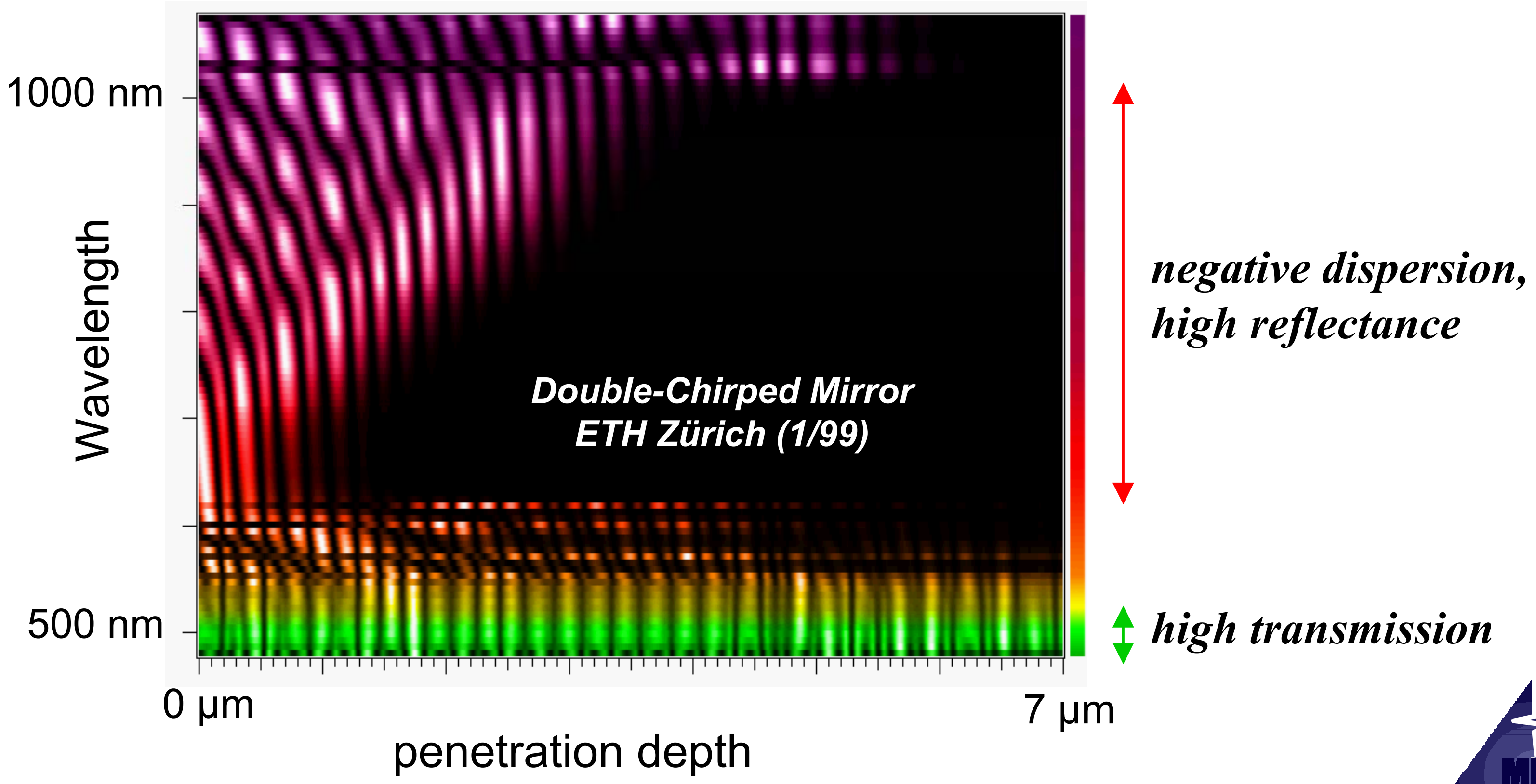
Chirped Mirrors





Ref.: G.Steinmeyer, *Science* **286**, 1507 (1999)

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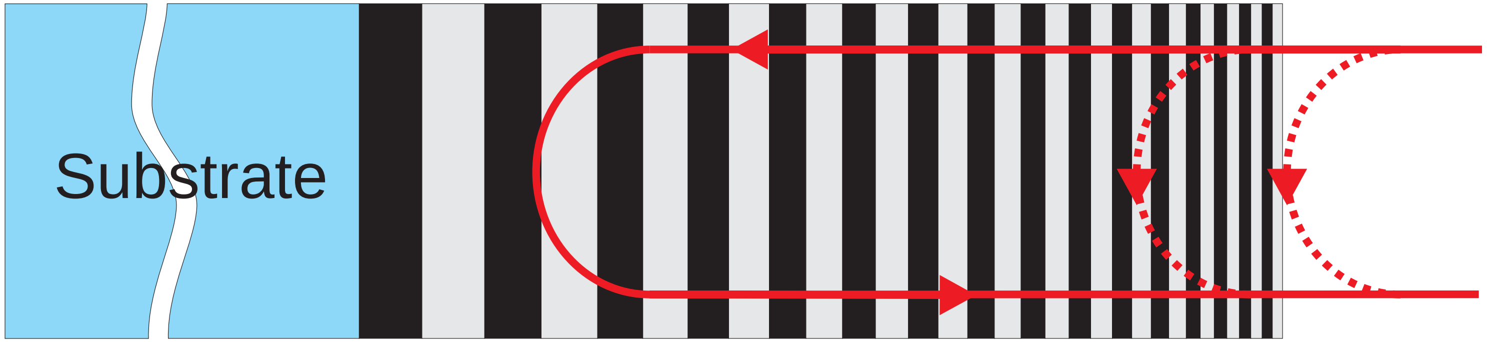
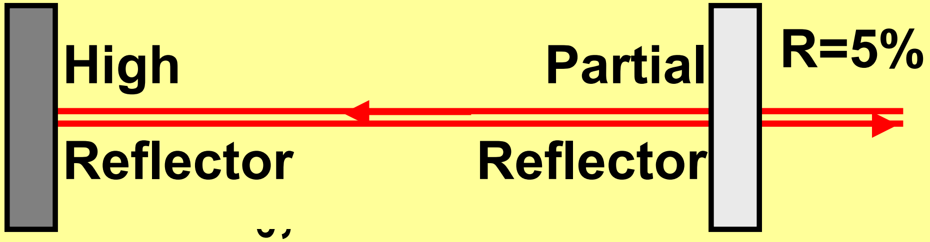
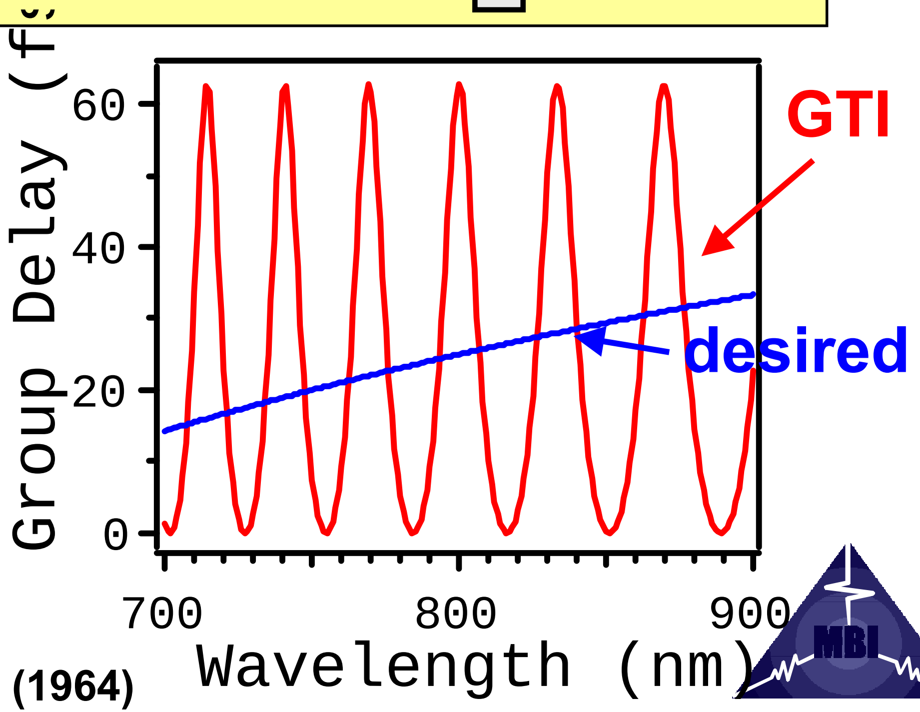
Why this isn‘t easy: dispersion oscillations



Gires-Tournois Interferometer



- **front interface + high reflector form an *GTI***
- ***dispersion oscillations***
- **magnitude comparable to net device dispersion**

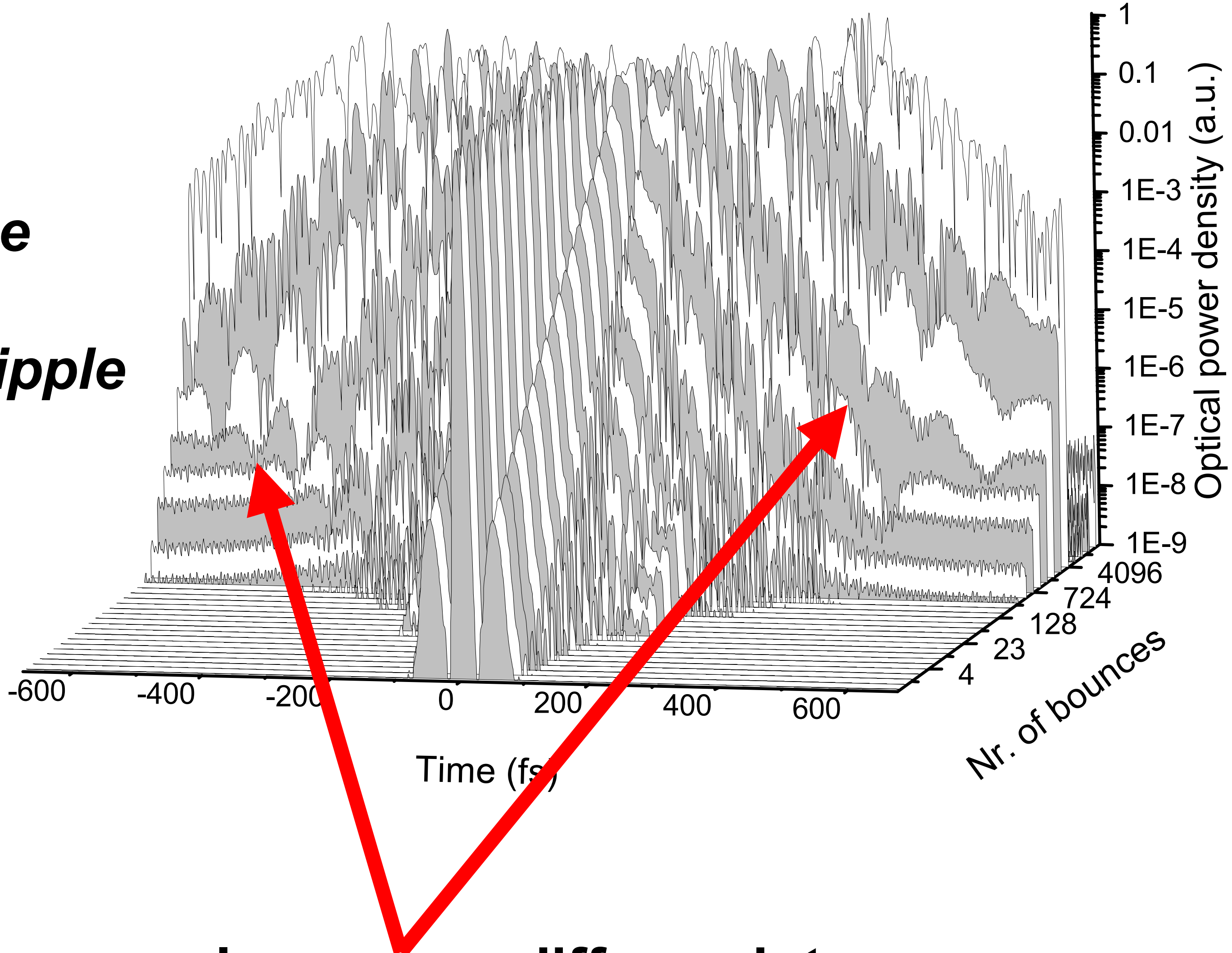


Ref.: Gires et Tournois, C.R. Acad. Sc. Paris, **258**, 6112 **(1964)**

GD ripple spoils pulse contrast

Simulation ⇒

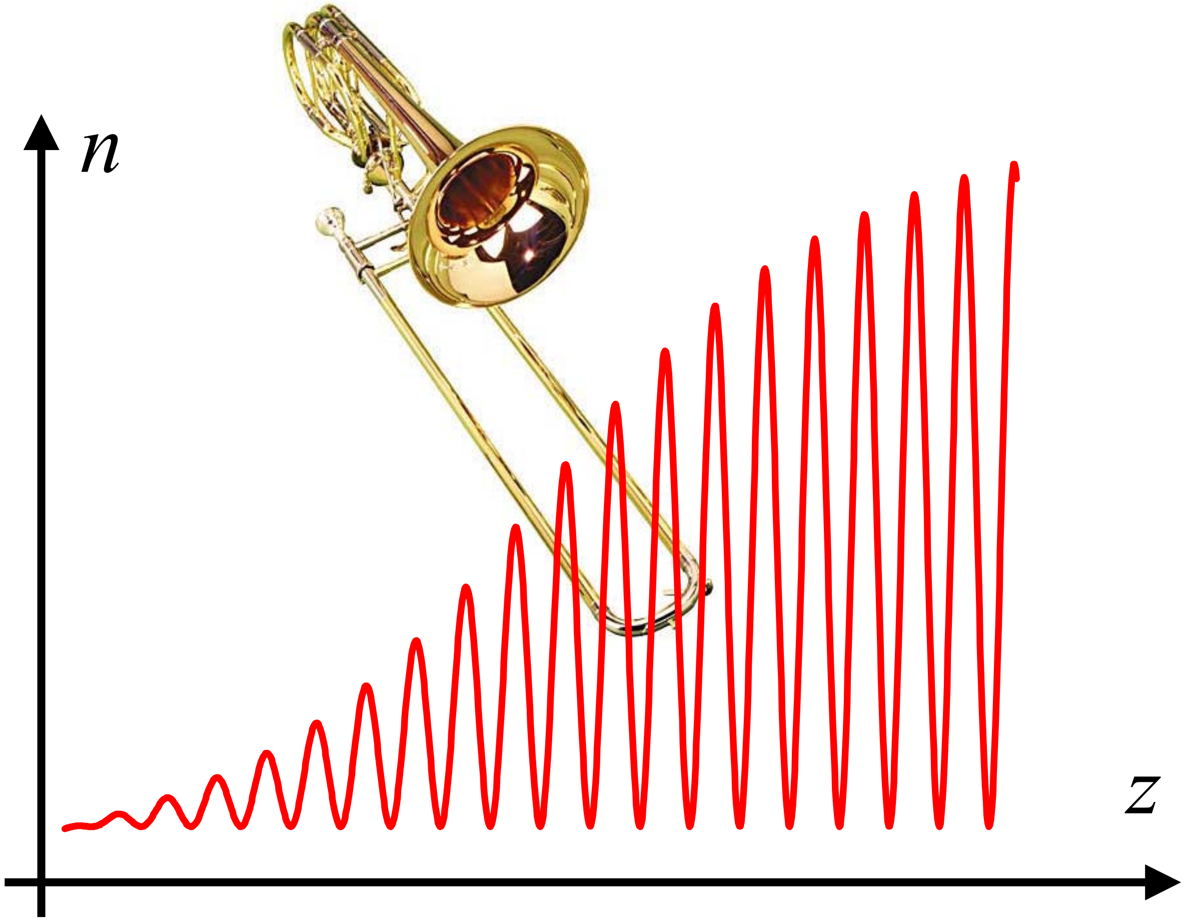
decay of 5-fs pulse after multiple bounces off low-ripple chirped mirrors



pulse energy diffuses into temporal continuum

G. Steinmeyer, submitted to *IEEE J. QE.*

Fight ripple of Bragg gratings: Apodization



apodize Bragg grating to remove impedance discontinuities !

Ref.: J.Albert et al., *Electron. Lett.* **31** (1995)

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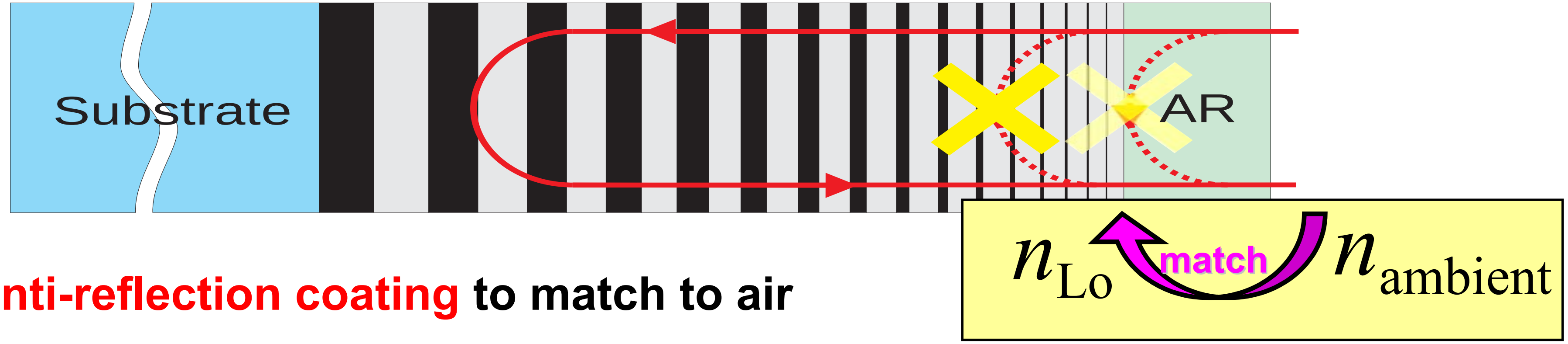
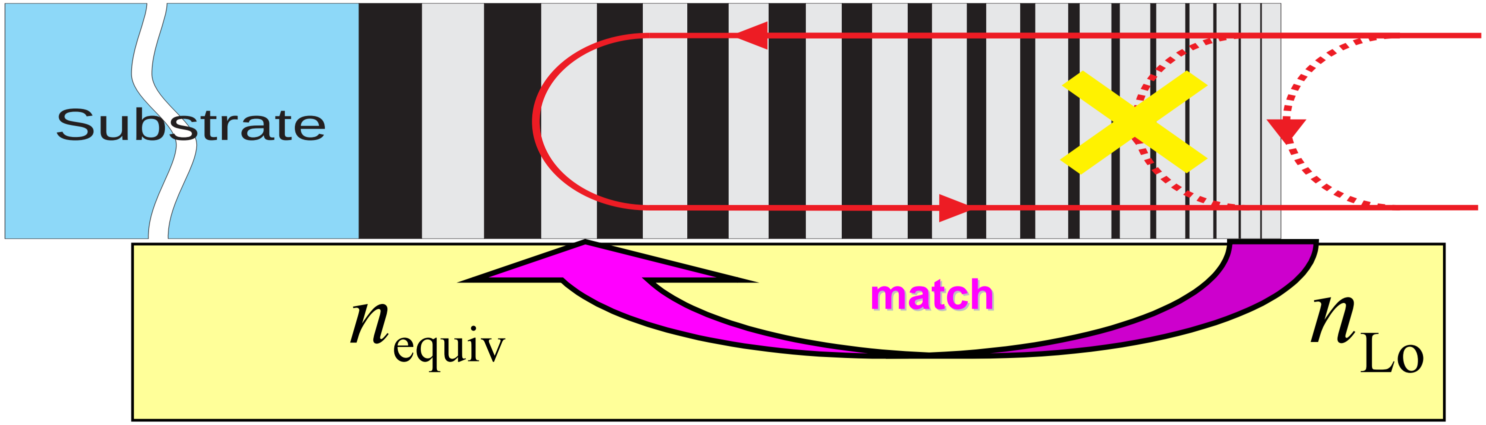
Double-Chirped Mirrors



① **anti-reflection coating to match to air**



② **chirp the duty-cycle of high and low index material**
- adiabatic match from low index material to effective index

F.X. Kärtner et al., *Opt. Lett.* **22**, 831 (1997)
N. Matuschek et al., *IEEE J. Sel. Top. Quantum Electron.* **4**, 197 (1998)

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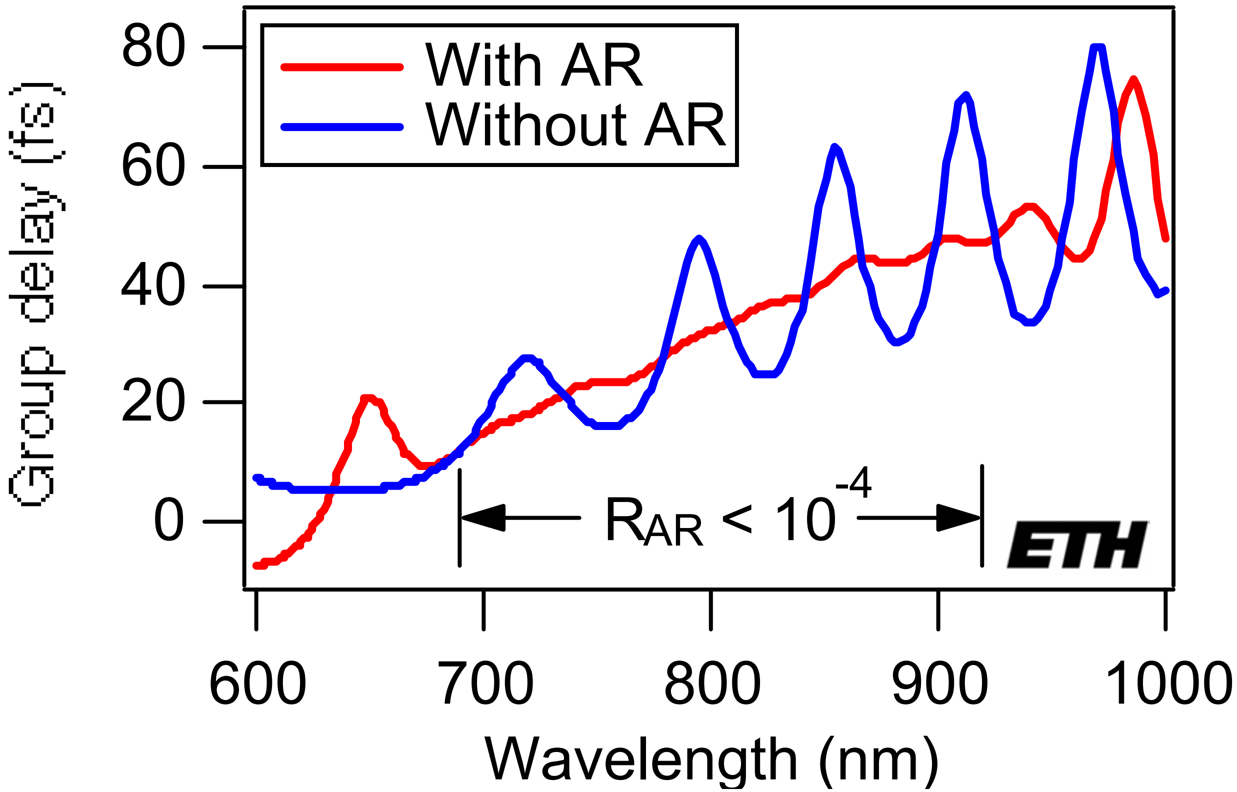
Double-Chirped Mirrors



For use inside a Ti:sapphire laser, residual group delay oscillations on the order of 1 fs are desirable.

⇒ residual reflection of AR $< 10^{-4}$

Summary - Dispersion

- There are 3 types of dispersion:
  - material dispersion
  - geometric dispersion (prisms and gratings)
  - µ-structured disp. (mirrors, fiber Bragg gratings, AWGs)

- Material dispersion always positive in the vis/NIR

- Imperfections in the dispersion compensation give rise to pedestal / temporal continuum

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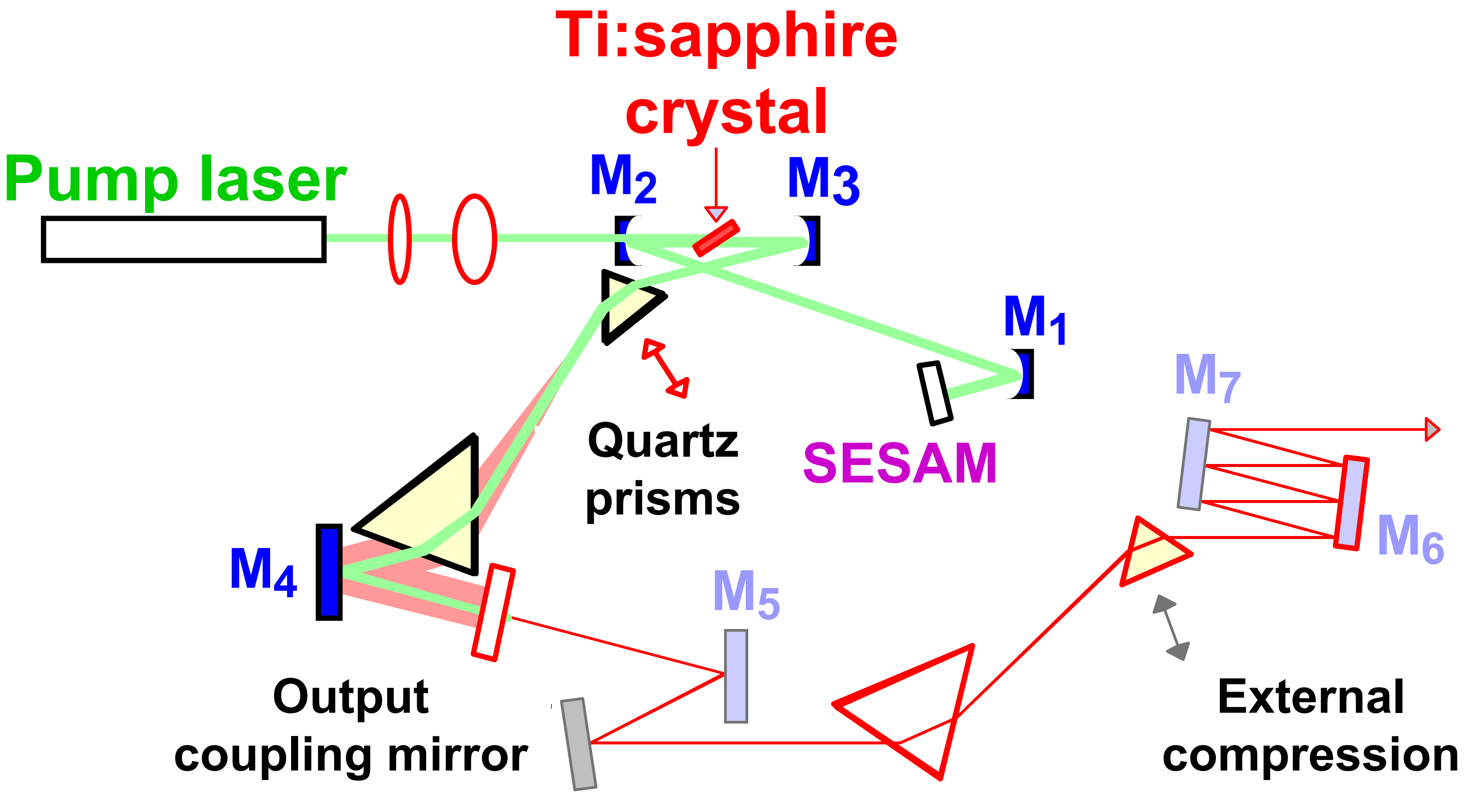
An ultrashort-pulse Ti:sapphire laser

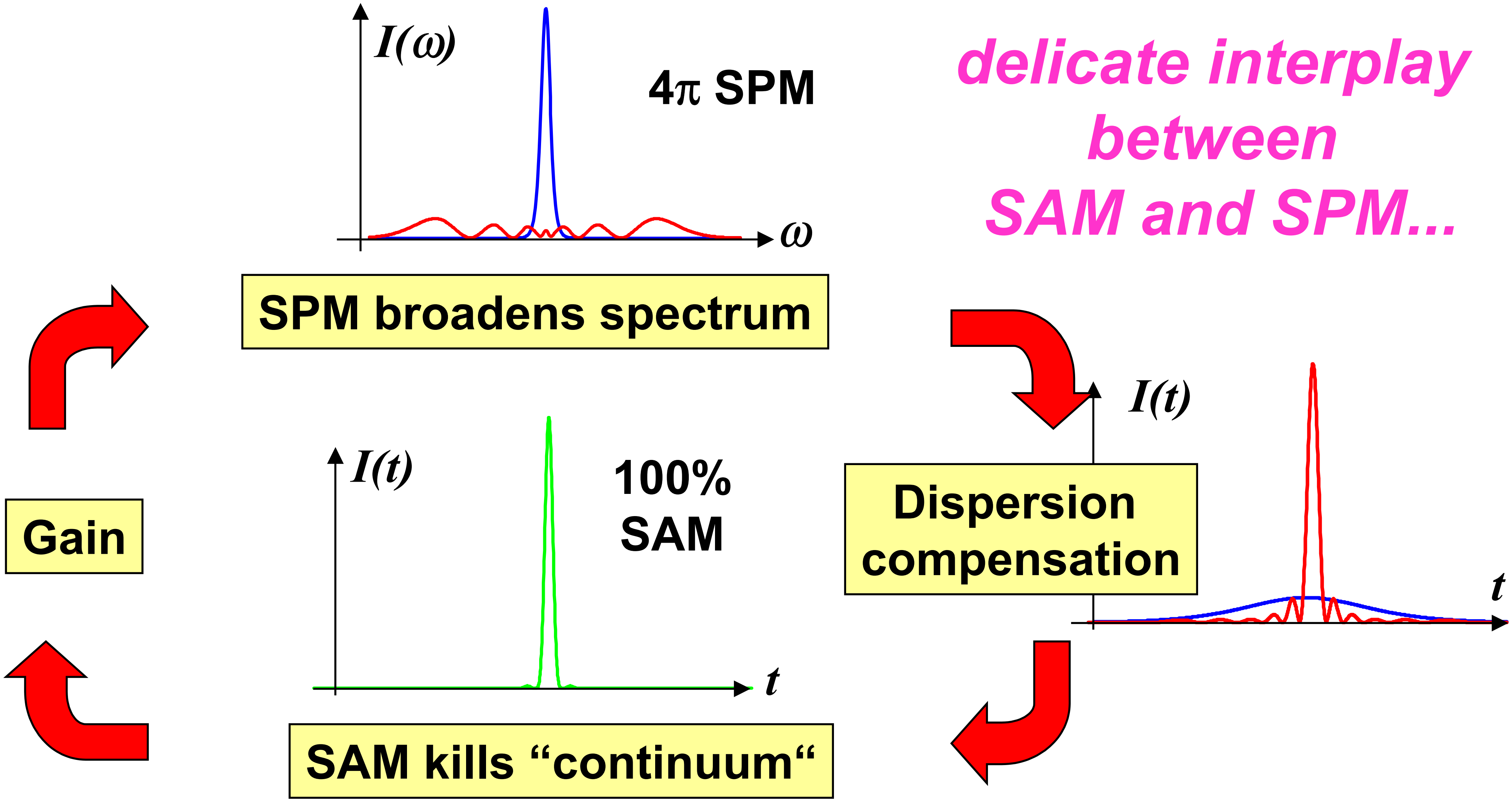


- Dispersion compensation with prisms and chirped mirrors
- Slow absorber to enhance self-starting
- KLM to provide the short pulse

Ref.: D.H. Sutter et al., *Opt. Lett.* **24**, 631 (1999)

How a KLM laser really works...

delicate interplay between SAM and SPM...



SPM broadens spectrum

Dispersion compensation

SAM kills “continuum“

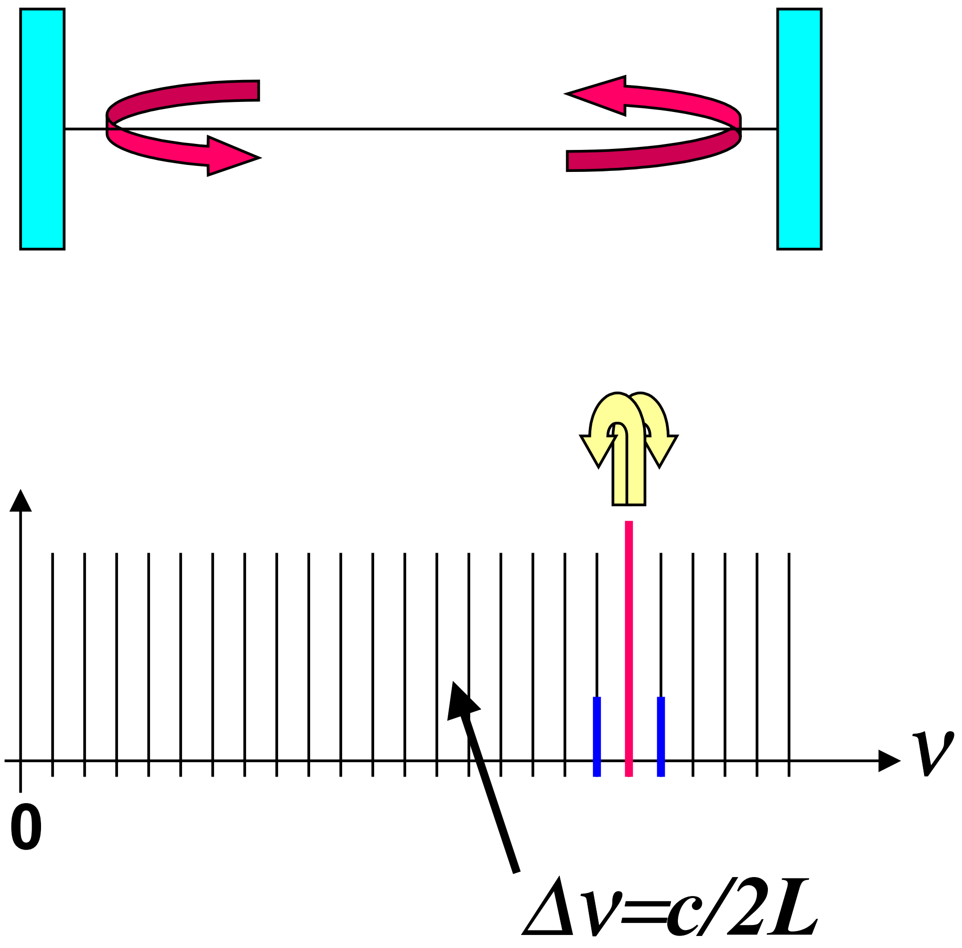
Gain

Haus et al., „Structures for additive pulse modelocking,“ ***JOSA* B 8, 2068 (1991)**

Brabec et al. , „Mode-locking in solitary lasers,“ ***Opt. Lett.* 16 1961 (1991)**

The mode comb

Siegman‘s picture of the laser



Cavity eigenfrequencies:

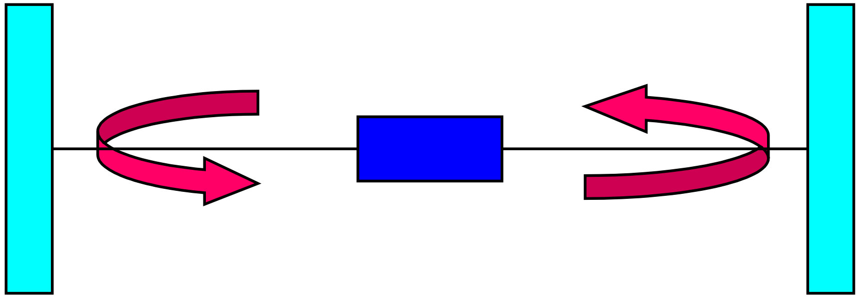
$$\nu_m = m\frac{c}{2L}$$

Modulator creates sidebands at neigboring modes

Ref: A.E. Siegman, *Lasers,* University Science Books, 1986

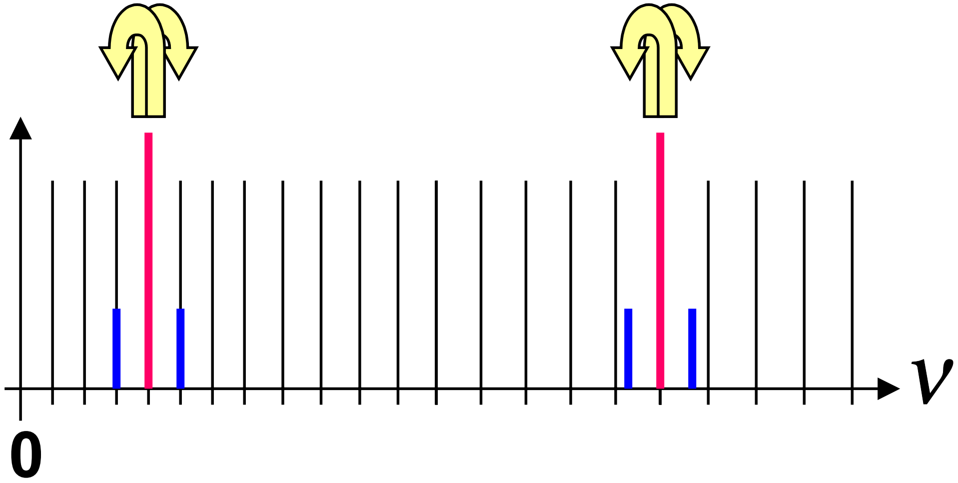
The real world

The cavity contains dispersive material



L is now a function of λ !

Cavity eigenfrequencies
no more equidistant !

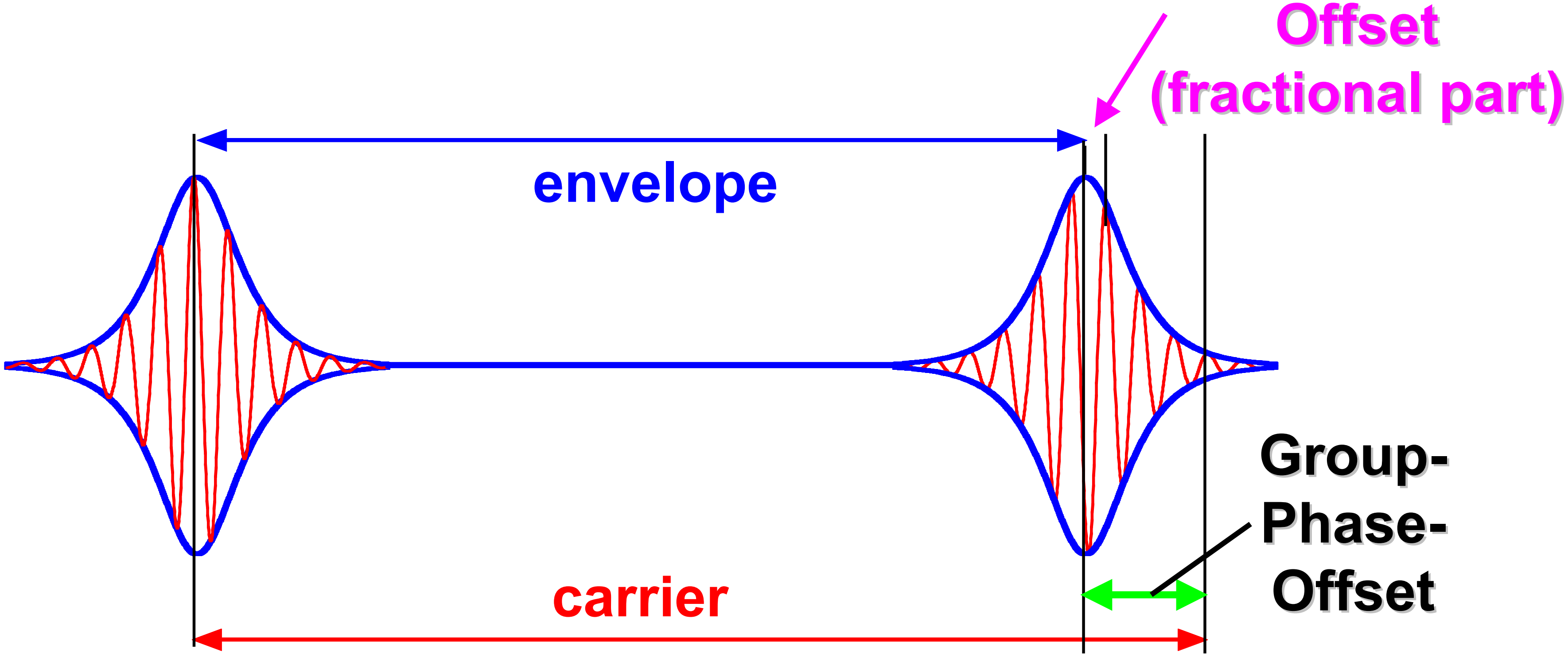


If the modulations fits
on one end of the spectrum
it does not at the other ...

How can we solve this dilemma ?

Carrier Envelope Offset (CEO)

Successive pulses from a mode-locked laser in the *time domain*:



$$\varphi_{\mathrm{GPO}} = \frac{2\pi}{\lambda} L(n_{\mathrm{g}} - n)$$

Ref.: H.R. Telle et al., *Appl. Phys. B* **69**, 327 (1999)

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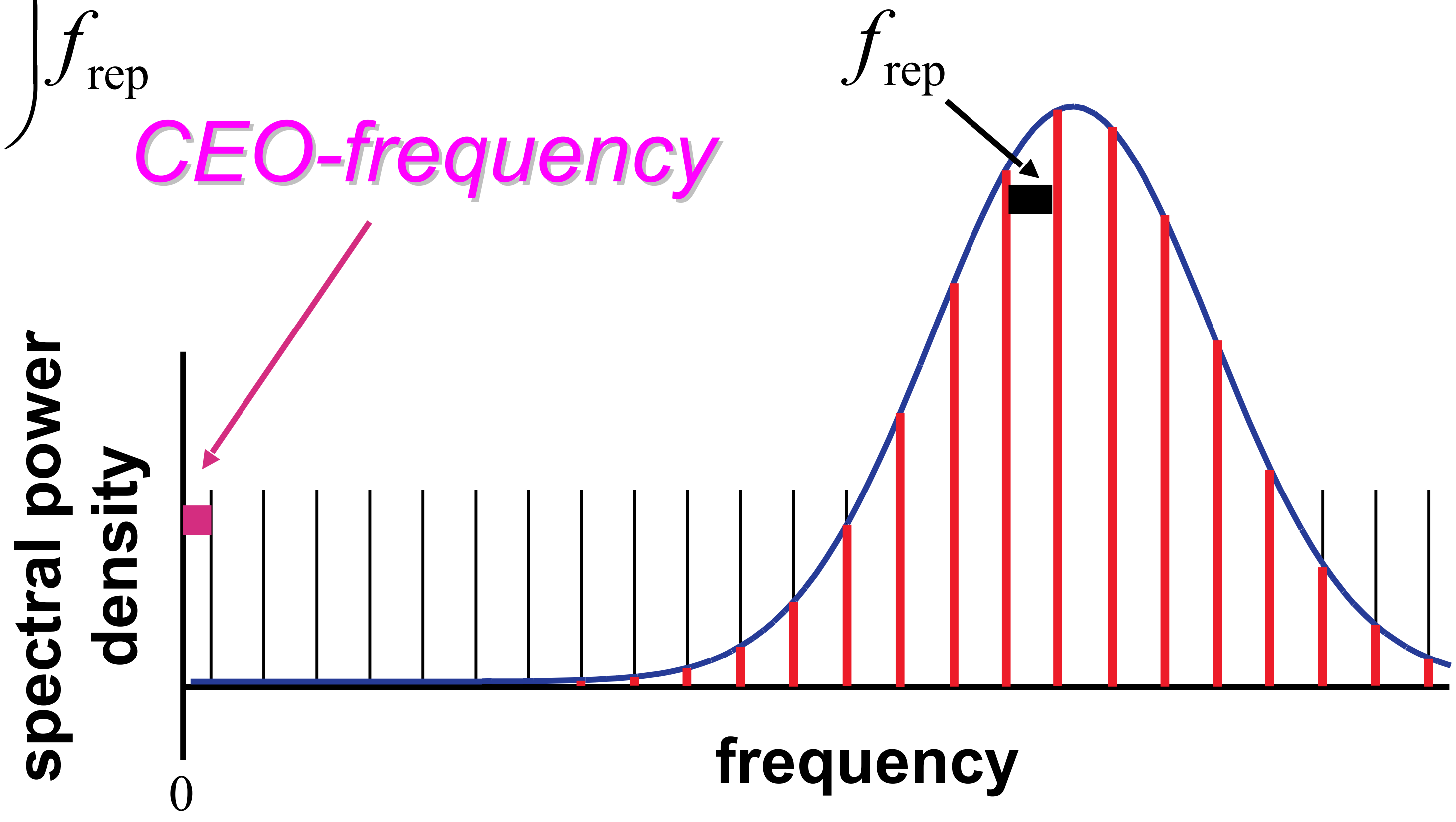
Carrier-Envelope Offset (CEO)

$$\nu_m = \left(\frac{\varphi_{\mathrm{GPO}}}{2\pi} + m \right) f_{\mathrm{rep}}$$



mode-locked laser = optical frequency ruler

- **mode comb uniformity better than 10^{-15}**
- **otherwise rep-rate would be function of wavelength**
- **2 degrees of freedom: "translation" and "breathing"**

Ref: T.Udem et al., *Opt. Lett.* **24**, 881 (1999)

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Comb parameters vs. Intracavity disp.

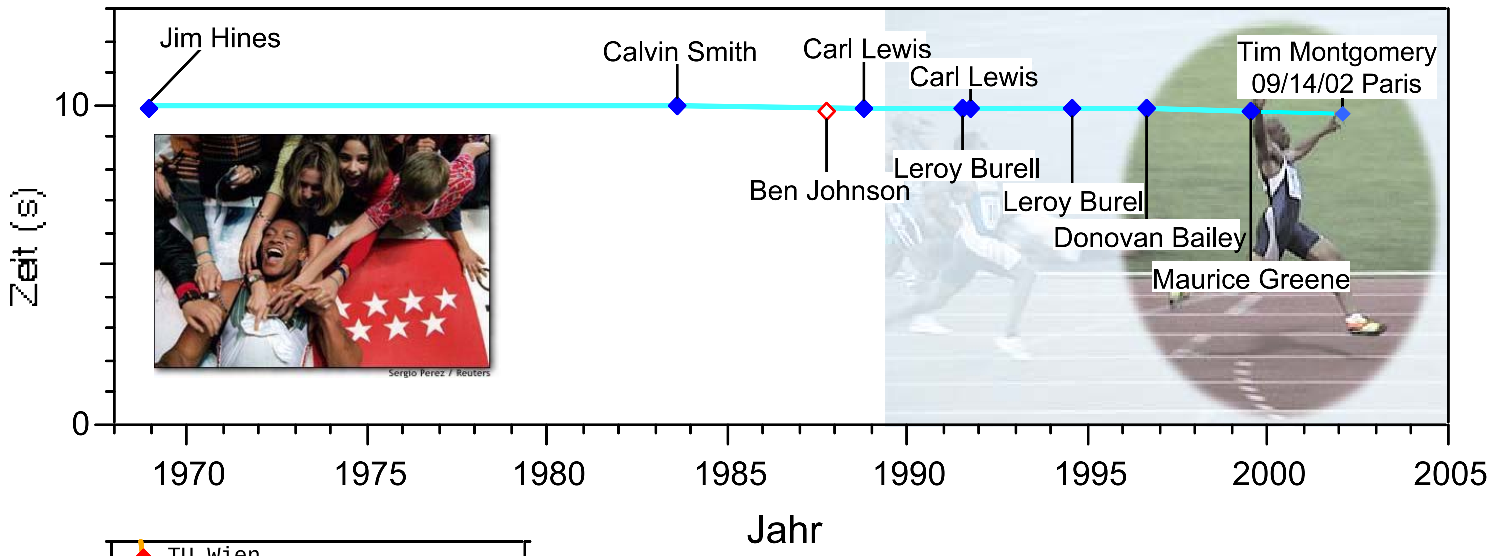
1. **Frequency spacing of the comb determined by the group delay of the cavity**

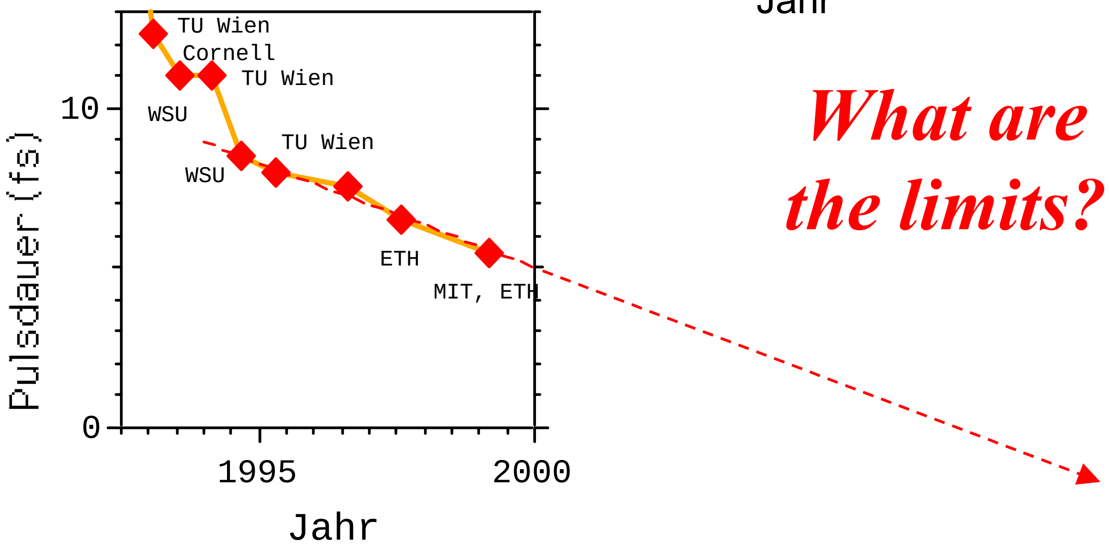
2. **Zero-offset (CEO) of the comb determined by group-phase offset**

3. **All higher-order effects lead to pedestal formation in pulse shaping**
   (to be counteracted by SAM)

Comb frequencies ≠ Cavity eigenfrequencies !!!

World records...





What are the limits?

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