Pulse generation and dispersion compensation

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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
Two-cycle pulses – octave-spanning light membranes

Time domain:

\[ \frac{\lambda}{c} = 2.7 \text{ fs} \]

@800 nm

Freq. domain:

\[ \phi \approx 1 \text{ mm} \]

1.6 µm

speed of light

Mode-locking

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

Understanding Mode-Locking

Time domain:
Synchronous switch

Steady-state:
Pulse broadening and shortening effects cancel out

Frequency domain:
Coincidence of modulator sidebands and cavity modes

Start-up:
Is there an advantage for short-pulse operation?
Passive vs. active mode-locking

Active mode-locking:

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

Passive mode-locking:

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

SESAM

- $F_{\text{sat}} = 18 \, \mu\text{J/cm}^2$
- $\Delta R_{\text{ns}} = 3.7\%$
- $\Delta R = 4.9\%$

Reflectivity (%) vs. Incident pulse fluence $F_p \, (\mu\text{J/cm}^2)$
• Mode-locking force = pulse shortening / roundtrip

• Balance with gain bandwidth / dispersive broadening

• fast absorbers for shortest pulses, slow absorbers for reliable start-up

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

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**
  - Real transitions: semiconductor (dye, SESAM)
  - Virtual states: wide bandgap material (opt. Kerr)

- **Direct Relaxation**
  - Very slow: \( \approx 100\text{ps} \)

- **Intermediate States**
  - Somewhat faster: \( \approx 1\text{ps} \)

- **Reactive Nonlinearity**
  - Ultrafast: \( \tau_{\text{relax}} \approx (E_{\text{gap}}/h)^{-1} \)
  - \(< 1\text{ fs}\)
The all-optical Kerr-effect

Refractive index changes with intensity

\[ n(I) = n + n_2 I \]

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
   

2. **The additive-pulse mode-locked (APM) laser**
   
   Heterodyning of SPM‘d and regular pulse yields compression
   

3. **The Kerr-lens mode-locked (KLM) laser**
   
Using a Kerr-lens as a modulator

Refractive index depends on intensity

\[ n(I) = n + n_2 I \]

Self-focusing translates into

Lower loss at aperture ("hard aperture KLM")

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(\(\omega\)), i.e. **positive dispersion**

Dispersion makes pulses longer!

Ref.: G.P. Agrawal, *Nonlinear Fiber Optics*
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.:
Chirped mirrors – microstructured disp.

⇒ thin sputtered layers of TiO₂ and SiO₂
⇒ engineerable dispersion
⇒ compensation of arbitrary material dispersion

GDD = -30 fs²
3.5 µm stack compensates for 1 mm material

Chirped Mirrors

Double-Chirped Mirror
ETH Zürich (1/99)

Wavelength

penetration depth

1000 nm
500 nm

negative dispersion, high reflectance

high transmission

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

Simulation \[\Rightarrow\]

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!

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

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
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

How a KLM laser really works...

delicate interplay between SAM and SPM...

SPM broadens spectrum

100% SAM

Dispersion compensation

SAM kills “continuum”

$I(\omega)$

$\omega$

$4\pi$ SPM

$I(t)$

$t$

$I(t)$

$\frac{\pi}{4}$

100%

Gain

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

The mode comb

Siegman‘s picture of the laser

Cavity eigenfrequencies:

\[ v_m = m \frac{c}{2L} \]

Modulator creates sidebands at neighboring modes

The real world

The cavity contains dispersive material

$L$ is now a function of $\lambda$!
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?
Successive pulses from a mode-locked laser in the \textit{time domain}:

\[ \varphi_{\text{GPO}} = \frac{2\pi}{\lambda} L(n_g - n) \]

Carrier-Envelope Offset (CEO)

\[ \nu_m = \left( \frac{\phi_{GPO}}{2\pi} + m \right) f_{\text{rep}} \]

CEO-frequency

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"

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?