How to build an Er:fiber femtosecond laser

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17.02.2016
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Ultrafast laser

Time domain: pulse train

Frequency domain: comb
Frequency comb laser

Time domain: pulse train

Frequency domain: comb
Mode locking

Establish a precise phase relation between the modes of the cavity with a well defined phase -> pulses
Mode locking: How to

Solution: Nonlinearity

Kerr lens mode locking
Ti:sapphire laser

Time domain: pulse train

Frequency domain: comb
Fiber lasers

Guided operations: the mode is confined in an optical fiber

PRO

• Virtually alignment free
• Robustness
• Weakly affected by the environment
• Stability

CONS

• Careful design (you cannot optimize it)
• (Low power)
• (dispersion management)
Possible Gain Media

Yb: 1030 nm

Er: 1550 nm

Tm/Ho: ~2000 nm

... In general: rare earth ions in silica matrix
CW vs femtosecond

CW laser diode

Femtosecond laser
- short pulses
- frequency comb

PROBLEM: dispersion
Linear propagation of short pulses

Examples
Er:fiber laser
Er$^{3+}$ ions as gain medium

1550 high transparency window for fused silica

True 3-level system

Lasing at 1550 requires significant population inversion!!
Er$^{3+}$ ions more details

3 level system

Lifetime of the lasing level is fairly long: 10 ms

Green fluorescence
Mode locking operations in a fiber laser

Three approaches:
- Active modulation
- Instantaneous Nonlinearity
- Ultrafast saturable absorber
Femtosecond fiber laser 1: figure of 8

Asymmetry in the path between clockwise and counterclockwise propagation

The isolator is the lossy component
Femtosecond fiber laser 2: Polarization Rotation

Nonlinearity: XPS

Typically it requires outcoupling to free space within the oscillator
Femtosecond fiber laser 2: Polarization Rotation

![Diagram](image)

<table>
<thead>
<tr>
<th>Fiber</th>
<th>GVD$_{1.55 \mu m}$ (ps$^2$/km)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>-19.7</td>
<td>528</td>
</tr>
<tr>
<td>F2</td>
<td>-4.76</td>
<td>2340</td>
</tr>
<tr>
<td>F3</td>
<td>0.9</td>
<td>393</td>
</tr>
<tr>
<td>EDF</td>
<td>19</td>
<td>680</td>
</tr>
</tbody>
</table>
Femtosecond fiber laser 3: Saturable Absorber

SAM works as a mirror only if the optical power in the cavity is sufficiently high.

It has to show a dynamical behavior and recover the “lossy” condition really quickly.
Femtosecond fiber laser 3: Saturable absorber
Germanium Saturable Absorber Mirror

![Diagram of Germanium Saturable Absorber Mirror]

- Mirror: 433 nm Au
- 3 nm Cr
- Substrat: 606 nm Ge
- 500 μm Si [p-(B)]
- AR-Coating: 180 nm Si₃N₄

![Graph of Normalized Intensity vs Wavelength (nm)]

- Y-axis: Normalized Intensity
- X-axis: Wavelength (nm)

- Conduction band
- Intraband relaxation
- Coulomb interaction
- Recombination
InGaAs Saturable Absorber Mirror

Direct gap semiconductor

GaAs at the center of the Brillouin zone
InGaAs Saturable Absorber Mirror
Solitonic Oscillator

Solitonic propagation condition

\[ P_0 t_0^2 = \frac{|\beta_2|}{\gamma} \]

Where

\[ \gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}} \]

The pulse temporal profile is:

\[ P(t) = P_0 \text{sech}^2 \left( \frac{t}{t_0} \right) \]
Transform Limit pulse duration of approximately 300 fs  
Output power 2/3 mW
Femtosecond fiber laser 3: Saturable absorber
Femtosecond fiber laser 3: Saturable absorber
Femtosecond fiber laser: polarization
Discussion

Noise performances (Shot noise)

Environmental robustness

Optimization

Pulse energy
Femtosecond Er:Fiber-Amplifier

**Single pass amplifier**
2.5 m long gain medium (Er:PM-Fiber) with normal dispersion
980 nm pump light injected from both sides (each with 700 mW)
Amplification up to 330 mW, → Pin/Pout ≈ 500
Spectral broadening due to SPM (Self Phase Modulation) and other nonlinear effects in EDF and collimator fiber
Recompression of the pulse in a silicon prism compressor
Nonlinear amplifier: dispersion management

Optimization of the nonlinearity during amplification by a pre-stretching fiber

Also the pump diode coupling is a degree of freedom

1 co-propagating, 1 counterpropagating to optimize the inversion profile in the EDF
Bandwidth $\Delta \lambda = 70$ nm
Pulse duration $T_{\text{FWHM}} = 130$ fs
Degree of Polarisation $> 98$
330 mW before compressor and
305 mW after compressor
Pulse energy: 8 nJ
Almost perfect synchronisation possible (43 as)
attosecond timing jitter:
F. Adler, et al.,

tailored spectra:
A. Sell, G. Krauss et al.,
Variable Pulse Compression

Compression in silicon prism sequence
→ variable prechirp
Pumping of highly nonlinear fiber
→ tunability of dispersive wave and soliton
Collimation with off-axis parabolic mirror
→ no chromatic aberration
Nonlinear Pulse Propagation

Quantitative modeling without free parameters:

Gain/absorption

Dispersion up to 6\textsuperscript{th} order (measured via white-light interferometry)

Instantaneous Kerr nonlinearity

Retarded Raman effect

Amplitude and phase spectra of pump (measured via FROG)

→ Central design tool with predictive power

\[ \partial_z A(z, t) = \left[ -\frac{\alpha}{2} - i \frac{\beta_2}{2} \partial_{\tau}^2 + i \frac{\beta_3}{6} \partial_{\tau}^3 \pm \ldots \right] A(z, \tau) + \gamma \left( i - \frac{\partial_{\tau}}{\omega_0} \right) \left[ A(z, \tau) \int_{-\infty}^{\infty} |A(z, \tau)|^2 R(\tau - \tau_1) d\tau_1 \right] \]
Two-stage process

1st step: soliton compression in standard telecom fiber ($l \approx 10 \text{ cm}, \varnothing_{\text{Core}} = 10.5 \mu\text{m}$)

Spectrum broadens and pulse is compressed to 14 fs
2\textsuperscript{nd} step: four-photon interactions in HNF ($\varnothing_{\text{Core}} = 4 \, \mu\text{m}$)

Spectrum splits into two components:
Soliton
Dispersive wave
Tuning via Prechirp

Control of nonlinear frequency shift: prechirp of pump (determines minimum pulse duration before HNF)

\[ P_{\text{out}} > 30 \text{ mW} \text{ (dispersive wave) and } > 50 \text{ mW (soliton)} \]

Spectral range covered: 800 nm to 2400 nm

time evolution in precompression fiber

spectral evolution in HNF
Ultrabroad Spectra I

Optimized dispersion profiles for ultrabroadband and unstructured spectra

Quantitative agreement between simulation and experiment

Maximum spectral width in dispersive wave: $\Delta \lambda = 580$ nm

$P_{\text{out}} = 23$ mW

Compression in glass prism compressor
7.8 fs Dispersive Wave

Retrieved pulse duration: $t_p = 7.8$ fs
→ two optical cycles
Bandwidth limit: 7.0 fs
Good agreement between measured and retrieved spectrum
Perfect match between measured and calculated autocorrelation

Few-Cycle Soliton from HNF 2

- Retrieved pulse duration: $t_p = 31$ fs
- 5 optical cycles
- Fourier limit: 23 fs
- Average output power: 55 mW
Single-Cycle Setup
Single-Cycle Pulse Synthesis

**Large delay times $\Delta t$:**
second-order auto- and cross-correlations

**Decreasing $\Delta t$:**
Cross- correlation shifts towards center
Amplitude of central fringe increases strongly

**Maximum amplitude for $\Delta t = 0$**
Single-Cycle Pulse Characterization

Separate FROG analysis of spectral amplitude and phase of soliton and dispersive wave

Amplitude ratio: linear spectrum

Two missing parameters left for total characterization:

Linear slope (time delay $\Delta t$)

Relative phase $\Delta \varphi$ between dispersive wave and soliton
Single-Cycle Pulses: Results

Determination of phase spectrum from FROG traces and least-square fit of $\Delta \varphi$ and $\Delta t$ to second-order autocorrelation

Temporal amplitude and phase via Fourier transform

Retrieved pulse duration: $t_p = 4.3$ fs

Pulse energy: $E_p = 1$ nJ

$\rightarrow$ Single cycle of light in the telecom wavelength regime
Carrier-Envelope Phase Control

- frequency spectrum consists of equidistant lines with CEO-frequency offset
- slippage of carrier envelope phase due to group and phase velocity mismatch
- control of CEO-frequency essential for:
  - nonlinear physics
  - metrology

\[ f_n = f_{\text{CEO}} + nf_{\text{rep}} \]
Passive CEP Stabilization: Input Spectra

Idea: generation of phase-stable pulses at 1550 nm via DFG, from ultrabroadband HNF spectrum

goal: seed source with carrier-envelope offset frequency set to zero and subsequent amplification

⇒ passive phase locking of fs-Er:fiber technology at full repetition rate of 40 MHz
CEP and nonlinear processes

- **Second Harmonic**: \( \omega_0, \varphi \rightarrow 2\omega_0, 2\varphi + \pi/2 \)

- **Self Phase Modulation**: \( \omega_0, \varphi \rightarrow \omega_0, \varphi + \pi/2 \)

- **OPA**: Pump and Signal \( \omega_s, \varphi_s \rightarrow \) Amplification does not affect CEP

- **Difference Frequency**: \( \omega_1, \varphi_1, \omega_2, \varphi_2 \rightarrow \omega_1 - \omega_2, \varphi_1 - \varphi_2 - \pi/2 \)

- **White Light Generation in a Sapphire Plate**: \( \) supercontinuum by a hollow fiber

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Difference Frequency Generation

\[ \omega_{\text{DF}} = \omega_1 - \omega_2 \]

\[ \varphi_{\text{DF}} = \varphi_1 - \varphi_2 - \pi/2 \]

- Difference-frequency generation (DFG) allows:
  - manipulation of the CEP
  - generation of MIR light

if fields are phase-locked:

\[ \varphi_1 = \varphi_2 + \Delta \varphi \]

\[ \varphi_{\text{DF}} = \Delta \varphi - \pi/2 \pmb{\text{ (const.)}} \]

- DFG between two pulses carrying the same CEP leads to **automatic** phase-stabilization of the DF pulse
General Setup

- Separation of dispersive wave and soliton for compression
- Difference frequency generation in PPLN
- Generation of ultrabroad spectrum in HNF
- Modulation of spectrum via chirp of the seed pulse

- sep
- diffe

\[ \lambda \approx 1550 \text{ nm} \]
Phase-locked Pulses at 1550 nm

- DFG tunable from 1400 nm – 1600 nm
- broadband DFG output
- complete background suppression with two 1550 nm Bragg-mirrors
Reamplification of Phaselocked Seed

6 synchronized output ports after preamp

high power fiber amplifiers for extreme nonlinear optics

frequency comb applications
average power $P = 2.1 \text{ mW}$ @ each port after preamplifier
average power $P = 330 \text{ mW}$ after main amplifier
pulse duration $t_p = 115 \text{ fs}$ after prism compressor
inherently phase-locked 8 nJ pulses at full 40 MHz repetition rate
Characterization of Absolute Phase Stability

\[ \langle (\sin(\omega t + \varphi) + \sin(\omega(t - \tau) + 2\varphi + \pi / 2))^2 \rangle \]

spectrum modulated by: \( 1 + \sin(\omega \tau - \varphi) \)

CEP stable \( \rightarrow \) stationary interference fringes
Long-term Stability of Passive Phase Lock

- integration time of 4 ms implies average over 160,000 pulses
- good fringe visibility indicates extremely good short-term stability

- acquisition of 1000 spectra over 8 s
- RMS of phase amounts to 0.219 rad
- excellent long-term stability for time-domain applications
Seeding Yb and Tm amplifiers

Seed high power fiber laser starting with a compact Er:fiber system.

**Yb**
- 1064 nm
- Power scalable up to a multiW regime
- Mature technology
- Dispersive wave

**Tm**
- 1950 nm
- Broad gain bandwidth
- Particularly promising for future application
- Soliton

**Problem:** supercontinuum coherence at the output of standard PCFs
Supercontinuum coherence

Interference between the SCs generated by two distinct branches of the system
First proof of Tm:amplifier

Amplification at 1950 nm with 2.46 W output average power

10 MHz Tm:amplifier
9 W pump power
High repetition rate for maximum sensitivity

Er:fiber femtosecond laser seeding a high power Yb:fiber amplifier

60 W total output power at 10 MHz repetition rate

Multibranche design for advanced ultrafast applications
Noise Performance and Long-Term Stability

peak-to-peak fluctuation: $< \pm 0.3\%$ during 72 h of operation at full power
White Light Generation

- 2.5 W from Yb:fiber amplifier (less than 5% of the available power at 10 MHz!)
- Focused into 3 mm YAG

⇒ 2 octave spanning spectrum