

Lecture 5

Multi-Element Propagation

Part 1:

Short Pulse Fiber Laser

Part 2:

Mamyshev Oscillator

Part 3:

Micro Comb Generator



Multi-Element Propagation: Short Pulse Fiber Lasers

The layout of a typical short pulse oscillator (not only fiber laser) is shown in the image containing several elements in a ring cavity forming a ring.

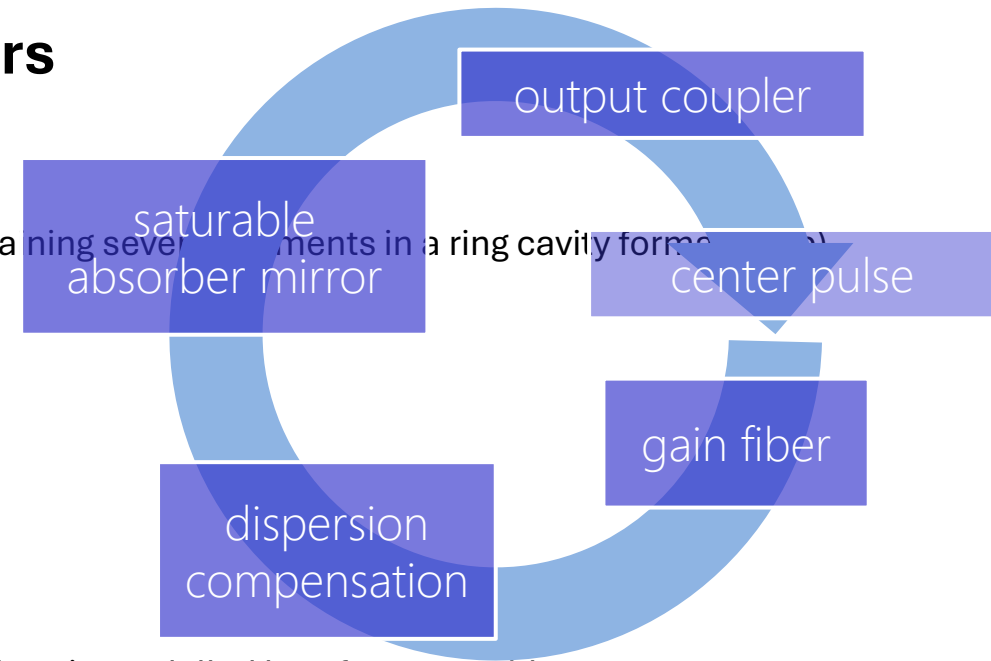
Each Element is modelled by an element typically based on the NLSE:

$$iA_z + \frac{g}{2} A + i\beta_2 A_{tt} = i\gamma |A|^2 A$$

Other elements might be simulated by other means, for example, the saturable absorber mirror is modelled by a fast saturable reflectivity/transmission according to:

$$R = R_{unsat} + R_{sat} \cdot \left(1 - \frac{1}{1 + P / P_{sat}} \right)$$

Each element setup used for this tutorial example is explained in the following >>



Multi-Element Propagation: Short Pulse Fiber Lasers

Set up the **gain fiber** as a *standard propagation* with saturable gain. We also use 10 um mode field diameter and a Gaussian gain spectrum of 40 nm width around 1060 nm.

Propagation parameter

Load Save

standard propagation Setup >

general

define free parameters

measure and parse

write file

waveguide

loss 0.0 1/m

gain 30 dB/m

mode diameter 10.0 μm

gamma 0.002415094 1/(W m)

effects

dispersion

SPM / TPA

Raman

self-steepening

LLE

numerics

steps 100

stepsize 0.01 m

distance 1.0 m

adaptive local error 1e-5 presets

Gain

steady state gain (long pulses to cw)

☒ saturate gain with Esat = 1e-11 J

$$g = g_0 / (1 + \frac{E}{E_{sat}})$$

profile

gain profile

Center 1060 nm Width 40 nm

shape Gauss

add second peak

Center 1060 nm Width 40 nm

shape const

ratio of second to first peak (set to zero for only one peak): 0

user defined gain file

☐ use ASCII file for gain profile given in g(1/m) vs. wavelength (separator TAB)

file ...

temporal gain saturation (pulses shorter than population relaxation time)

☐ use temporal gain saturation instead of steady state gain and profiles, with

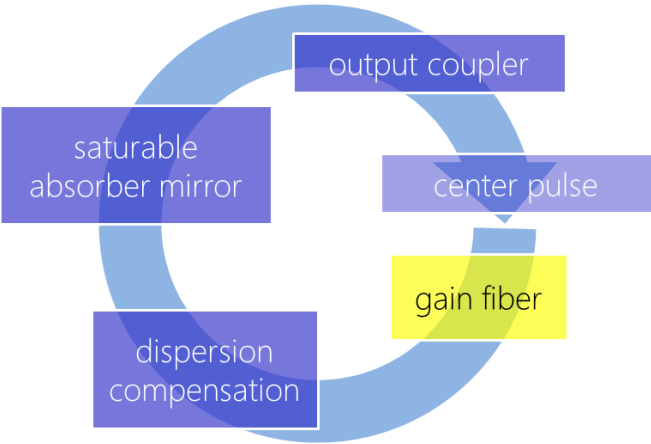
saturation fluence F 30 J/cm²

$$g(T) = g_0 \exp \left(-\frac{1}{E_{sat}} \int_{-\infty}^T |A(t)|^2 dt \right)$$

with $E_{sat} = F \cdot A_{eff}$

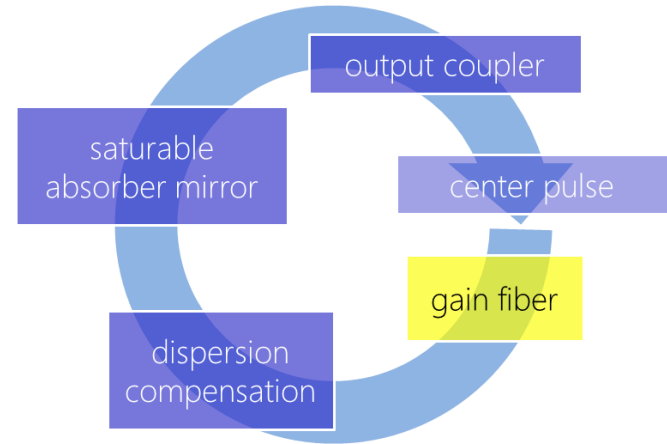
saturation energy with current MFD: J

Back



Multi-Element Propagation: Short Pulse Fiber Lasers

Now set the dispersion of that gain fiber to the dispersion of fused silica (e.g. predefined with its Taylor series at 1060 nm)



Propagation parameter ▾ 🔍 ✕

Load ▾ Save ▾

standard propagation ▾ Setup >

general

define free parameters

☐ measure and parse 100 >

☐ write file

waveguide

loss 0.0 ▾ 1/m

gain 30 ▾ dB/m

mode diameter 10.0 ▾ μm

gamma 0.002415094 ▾ 1/(W m)

effects

☒ dispersion

☒ SPM / TPA

☐ Raman

☐ self-steepening

☐ LLE

dispersion term

$$\frac{\partial A}{\partial z} = \dots + \sum_{n \geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial T^n} A$$

☐ beta 0

☐ beta 1

☐ beta 2

☒ D

dispersion model

☒ Taylor expansion series

☐ Sellmeier coefficients

☐ photonic crystal fiber

☐ gas-filled silica-hollow core fiber

Setup >>

☒ force retarded time frame (beta0=beta1=0)
@ data array center wavelength

☒ Use dispersion

☐ do not use dispersion

☐ auto y min -100 max 100

☐ auto x min 350 max 2400

D (ps/nm/km)

Wavelength (nm)

Dispersion Setup

Taylor Series @ 1060 nm predefined

more ...

more ...

fused silica @1060nm

NKT (core 1.7 μm zD=770,1250) @ 1030nm

NKT (core 1.7 μm zD=750,1600) @ 1030nm

air silica approx@780nm

air silica approx@1060nm (1.7μm=MFD 1.2μm) ZD@665nm

air silica approx@1060nm (3.5μm=MFD 2.9μm) ZD@975nm

air silica approx@1060nm (5.0μm=MFD 4.2μm) ZD@1060nm

NKT LMA 5 (5.0μm=MFD 3.95μm, zD=1035nm) @ 1030nm

NKT LMA 5 (5.0μm=MFD 4.2μm, zD=1070nm) @ 1030nm

air silica approx@800nm (1.7μm=MFD 1.2μm) ZD@665nm

air silica approx@800nm (2μm=MFD 2μm) ZD@770nm

Zhu et. al. @800nm (2μm=MFD 2μm) ZD@743nm

Damian @750nm,1600nm (MFD 1.6μm) ZD@830nm

Cristiani et.al. Opt.Exp.12, 124 (2004)(MFD=3.47μm)ZD@710nm

Dudley et.al. Rev. Mod. Phys., Vol. 78, No. 4, (2006) Fig. 3

Dudley et.al., (2008)

Layertech GT1 1000-1080nm - 250fs @1030nm

Hollow core 1060-02@1030nm

SMF-28 (ZD 1313 nm, S0=0.092ps²/nm/km, D(1550)=17.7 ps²/nm/km)

InF3 fiber (ZD 1640 nm, Yang et. al. Opt. Express 28, 14973-14979 (2020))

zero dispersion @ all

compensate at:

D -27.499385294

S 0.176321

Trust region

from 400

☒ force retarded time frame (beta0=beta1=0)
@ data array center wavelength

copy dispersion
([nm],D[ps/nm/km],b2[ps²/m])

copy beta2 + group delay
[nm],b2 [ps²/m], GD[ps/m]

grating compressor >>

Save

Load

OK

Cancel

Beta1 0 ps/m

Beta2 0.01640341019153872 ps²/m

Beta3 4.427598189728069e-5 ps³/m

Beta4 -6.116862670739135e-8

Beta5 2.00994101399889e-10

Beta6 -6.78474442990305e-13

Beta7 2.11068254026679e-15

Beta8 -1.1571317270575e-17

Beta9 1.21431865715793e-19

Beta10 -9.78136736258149e-22

Beta11 5.06311226016692e-24

Beta12 -1.65466283477635e-26

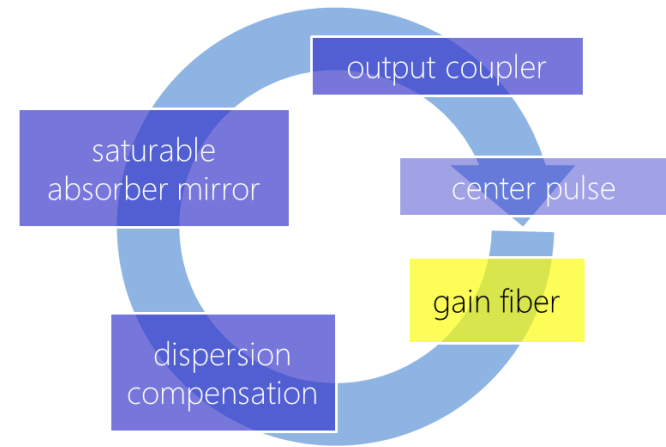
Beta13 3.16818781280129e-30

Beta14 -2.7448256015098e-33

Multi-Element Propagation: Short Pulse Fiber Lasers

Switch on SPM, set the standard values here and make the propagation 1 m long with 100 steps.

Now save the amplifier to the file „**fiber.ppfx**“ for later use as an element.



Propagation parameter ▾ 🔍 ×

Developer Version, compiled Aug 28 2024, 14:27:07

Load ▾ Save ▾

double click to save directly

Recent Files:

Select other file

Remove from list

☒ SPM / TPA

☐ Raman

☐ self-steepening

☐ LLE

steps 100 ▾

stepsize 0.01 m

distance 1.0 ▾ m

adaptive 1e-5 ▾ presets: ▾

Save As

fiberdesk wo code > physics data tutorials > tutorial > tutorial 5 - multi element propagation

Organize ▾ New folder

Name	Date modified	Type	Size
dc.ppfx	1/3/2023 10:16 AM	PPFX File	23 KB
fiber.ppfx	1/3/2023 10:16 AM	PPFX File	24 KB
oc.ppfx	1/3/2023 10:17 AM	PPFX File	23 KB
sam.ppfx	1/3/2023 10:17 AM	PPFX File	23 KB

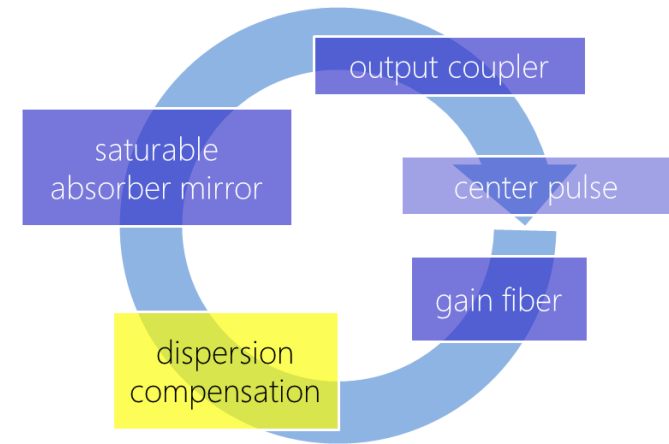
File name: fiber.ppfx

Save as type: parameter file (*.ppfx)

Save Cancel

Multi-Element Propagation: Short Pulse Fiber Lasers

For the dispersion compensation, we only set second order dispersion in the dispersion dialog
Furthermore, set the gain to zero, switch off SPM etc. Only dispersion need to be set.
As it is a linear step, a single step is enough.



gamma0.00241509431/(W m)

effects

dispersion

SPM / TPA

Raman

self-steepening

LLE

numerics

steps1

stepsize1m

distance1m

adaptive local error0

presets:

dispersion term
$$\frac{\partial A}{\partial z} = \dots + \sum_{n \geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial T^n} A$$

dispersion model

Taylor expansion series

Sellmeier coefficients

photonic crystal fiber

gas-filled silica-hollow core fiber

force retarded time frame (beta0=beta1=0) @ data array center wavelength

Use dispersion

do not use dispersion

Setup >>

Dispersion Setup

Taylor Series @ 1060 nm

Beta1	0	ps/m
Beta2	-0.02	ps ² /m
Beta3	0.0	ps ³ /m
Beta4	0.0	
Beta5	0	
Beta6	0	
Beta7	0	
Beta8	0	
Beta9	0	
Beta10	0	
Beta11	0	
Beta12	0	

Save the element as dispersion compensation „dc.ppfx“, as done before, for later use as an element.

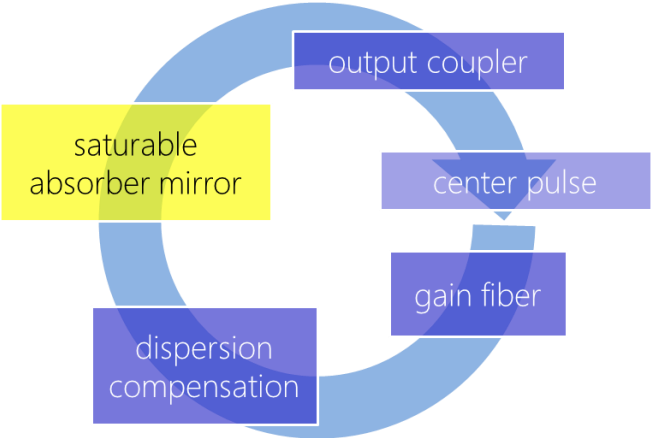
fiberdesk
nonlinear pulse propagation

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Multi-Element Propagation: Short Pulse Fiber Lasers

The saturable absorber is a different model, select „saturable absorber“ on top of the propagation parameter dialog.

Then, set it up with the parameters on the right.



Propagation parameter

saturable absorber

Setup >

Saturable Loss

☒ Fast saturable loss

R070%

dR30%

PA100W

$$R = R_0 + \Delta R - \frac{\Delta R}{1 + \frac{|A(T)|^2}{P_A}}$$

OK

Cancel

☐ saturable absorber mirror with time constants

unsaturated reflectivity60%

saturable reflectivity30%

saturation fluence80μJ/cm²

focal spot diameter10μm

saturation energy0.062831852nJ

temporal response A0.2ps

☐ use R=R0+dR*sin²((Pi/2)*(P/PA)+phi_0)

R070

dR30

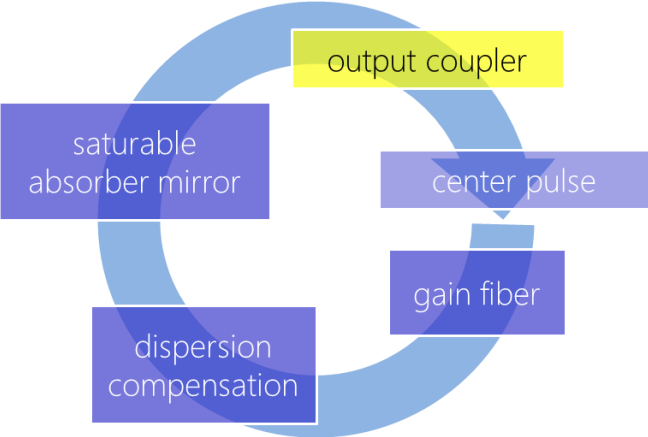
PA1

phi_00

Save the element as „SA.ppfx“, as done before, for later use as an element.

Multi-Element Propagation: Short Pulse Fiber Lasers

The output coupler can be modelled by a simple **field manipulation**, where the field is multiplied by the outcoupling ration.



Manipulation

☐ Create Pulse

☐ Create double pulse by adding a copy of the pulse to its time-reversed version

change repetition rate to Hz

ps

delay ps amount

☒ take phase shift into account (Mach-Zehnder interferometer)

☒ Complex Multiplication Temporal

Loop over

a

b

b

During the loop over all data points, the following variables are accessible for describing the real and imaginary part for multiplication in addition to all other parser values. They are evaluated each step in the loop.

h - helper variable

h - helper variable

k - integrated to index

k - integrated to index

t - time in sec

wl - wavelength in m

f - frequency in Hz

Ar - real part of complex amplitude

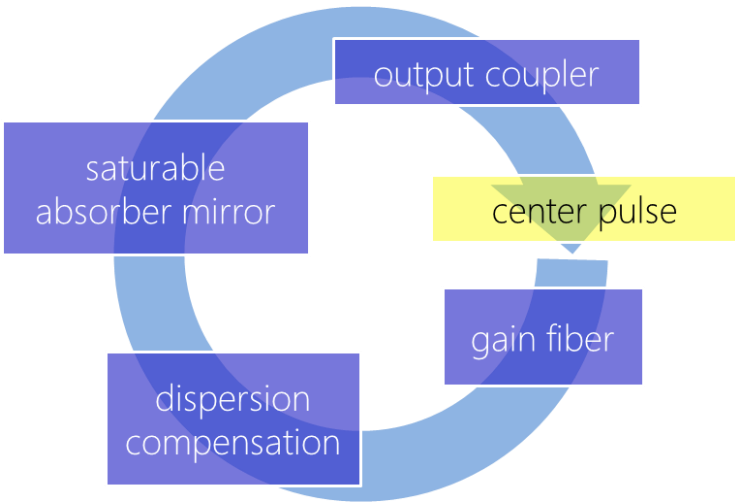
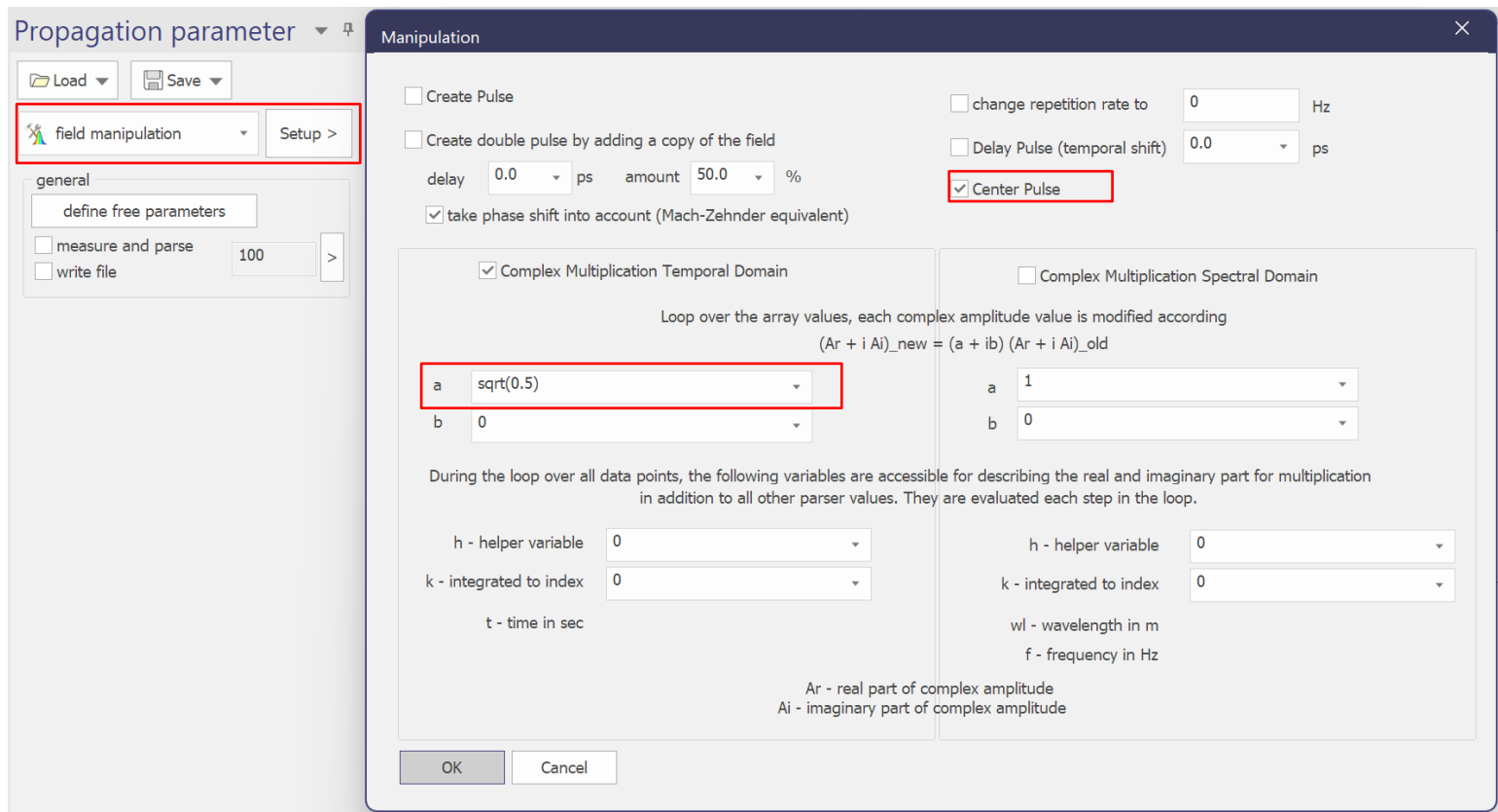
Ai - imaginary part of complex amplitude

OK Cancel

Multi-Element Propagation: Short Pulse Fiber Lasers

Centering the pulse in the time domain helps to converge the pulse, as changes are measured in the time domain. This is done in the field manipulation dialog.

It also means that it can be combined with the field manipulation of the output coupler before in a single element. The full manipulation dialog is shown below.

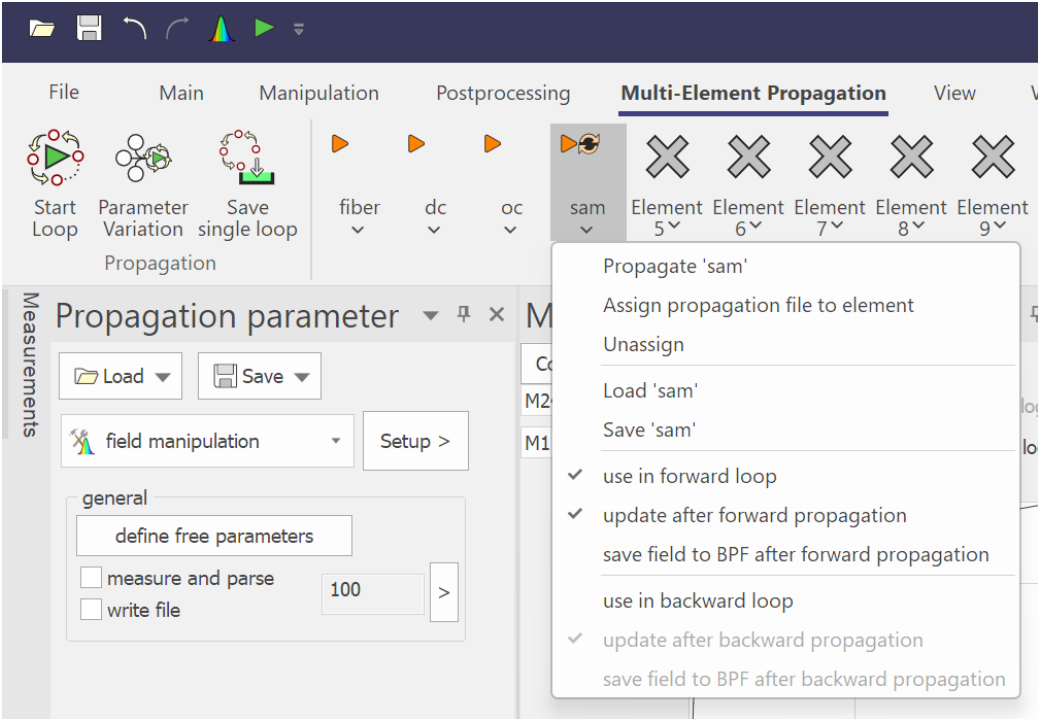
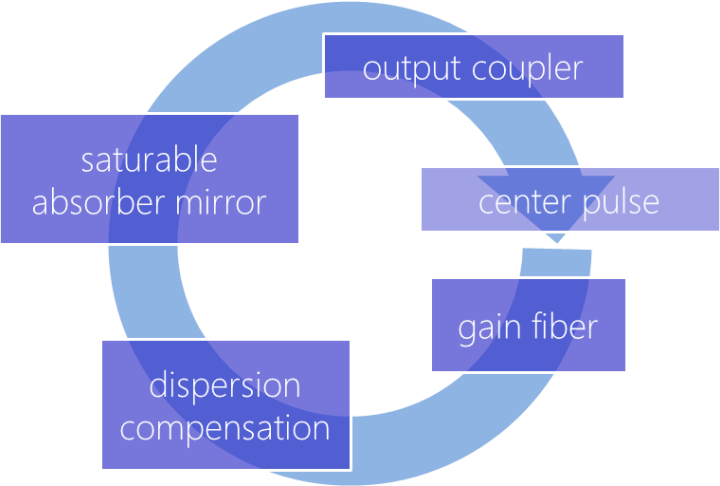


Save the element „OC.ppfx“, as done before, for later use as an element.

Multi-Element Propagation: Short Pulse Fiber Lasers

With all elements defined, let put together the multi-element propagation:

- assign all files to elements in the right order of the cavity
- Select „use in forward loop“ for all elements
- Select the last one to be updated after each loop to see convergence live during simulation
- Icons on top change according to selected status



Multi-Element Propagation: Short Pulse Fiber Lasers

Before the start of the multi-element propagation, we need to define the initial conditions, that is, the field where the propagation should start.

So, create the initial field with the right parameters for the final field and usually, for such short pulse oscillators, the initial condition is nothing else then quantum noise.

Pulse Profile and Data Array

data array setup

Size1k (2^10)

array center wavelength1060nm

half intervall5ps

field profile definition

TypeGauss

FWHM1ps

TempShift0ps

phase0rad

wavelength1060nm

2nd order0fs²

spectral phase0fs³

energy0J

average power0W

repetition rate1e+11Hz

☐scramble spectral phase (random phase)

☐phase diffusion modell with given linewidth

☒add quantum noise (one photon per spectral node)

double pulsing

separation0ps

relative magnitude0

☒create field in data array 1

☐add field to data array 1

OK

Apply

Cancel

reset

```
graph TD; A[saturable absorber mirror] --> B[center pulse]; B --> C[gain fiber]; C --> D[dispersion compensation]; D --> A; E[output coupler] --- A;
```

Field

Power / μW

Time / ps

Spectrum

Power / $\mu\text{W ps}^2$

Wavelength / μm

Initial field in temporal and spectrum domain.

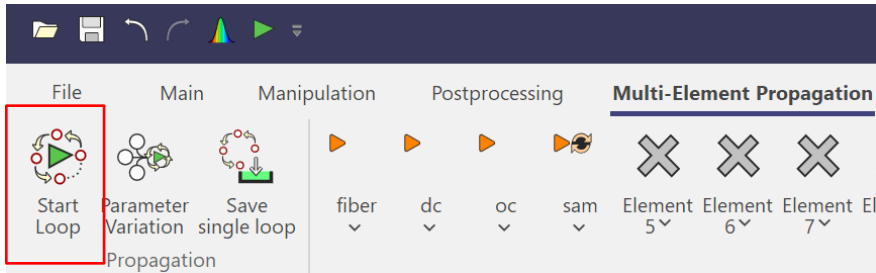
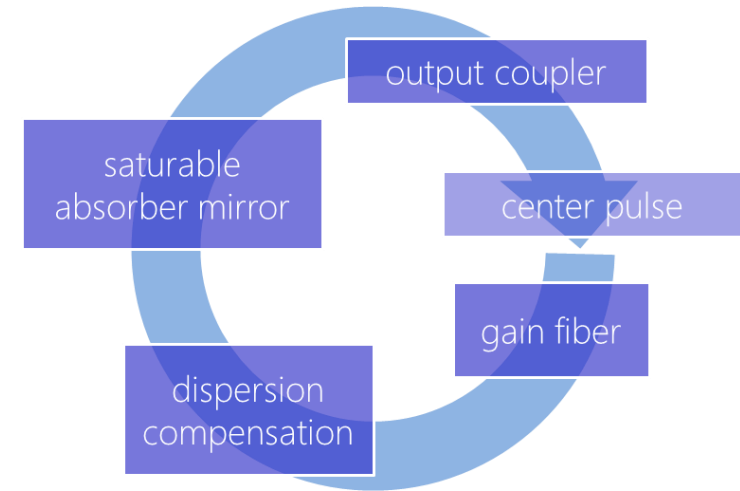
fiberdesk
nonlinear pulse propagation

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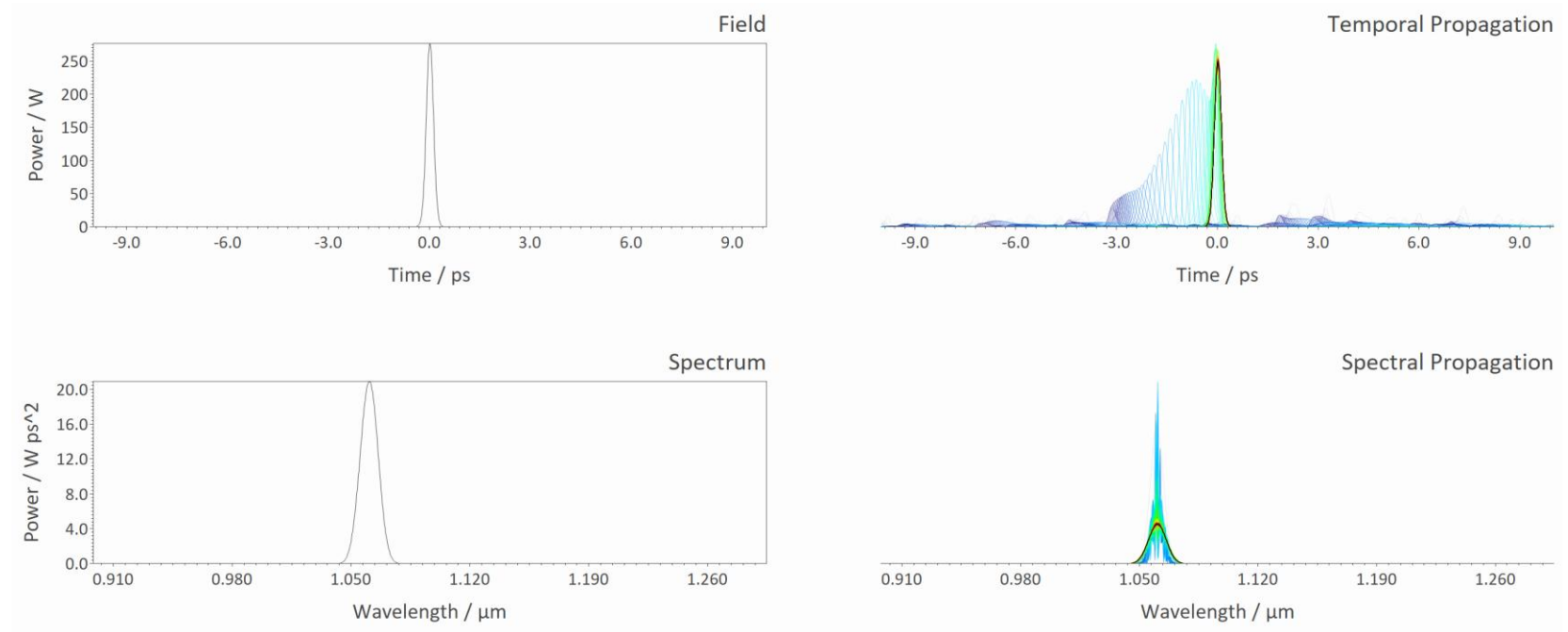
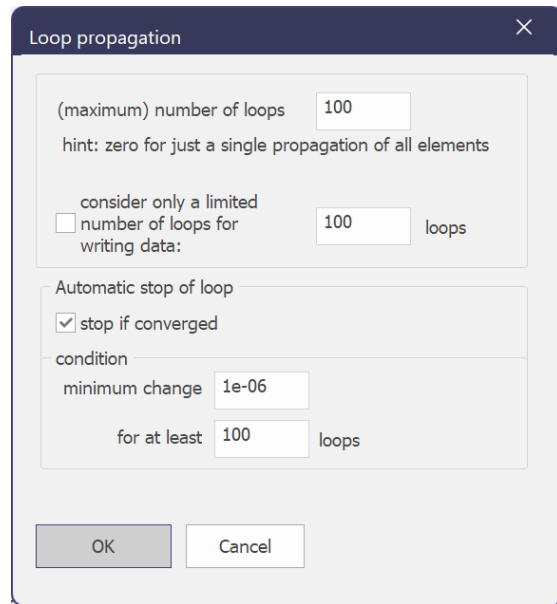
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Multi-Element Propagation: Short Pulse Fiber Lasers

Now press „Start Loop“ with the setup dialog and press „Ok“ to let the simulation run.






You should see, that the field and spectrum is converging to a solution that is stable:

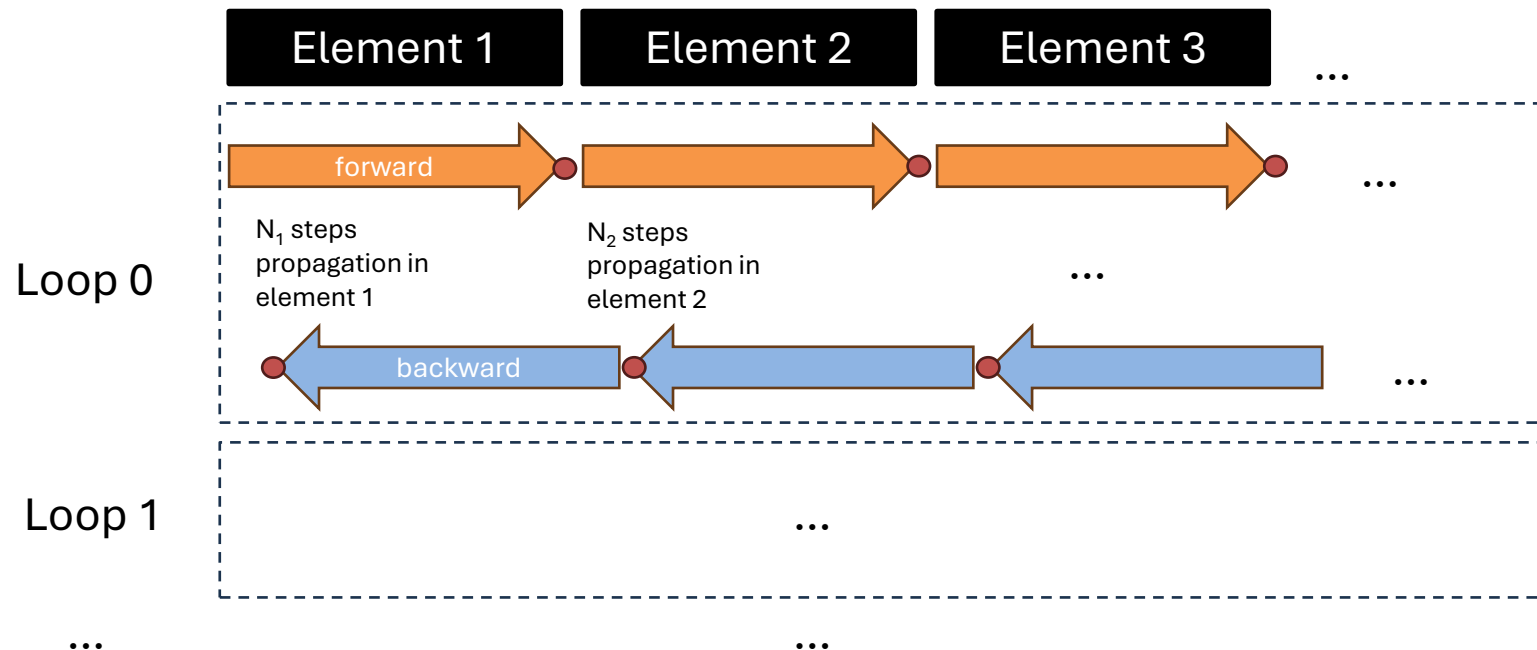
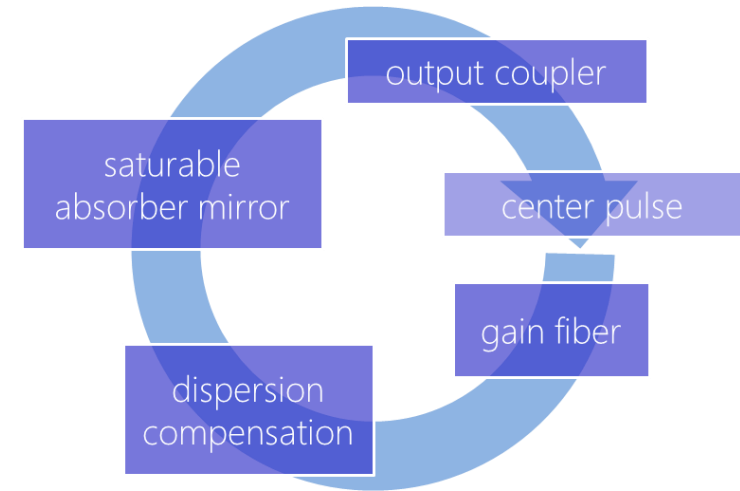


Multi-Element Propagation: Short Pulse Fiber Lasers

How do I get information out of the multi element propagation?

Let us first take a look at the possibilities of data along the propagation:




- Changes along each elements propagation  
- Only the result at the end of each element 
- Both depend on the loop count

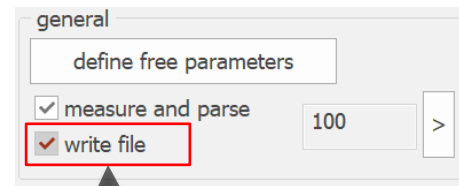


Multi-Element Propagation: Short Pulse Fiber Lasers

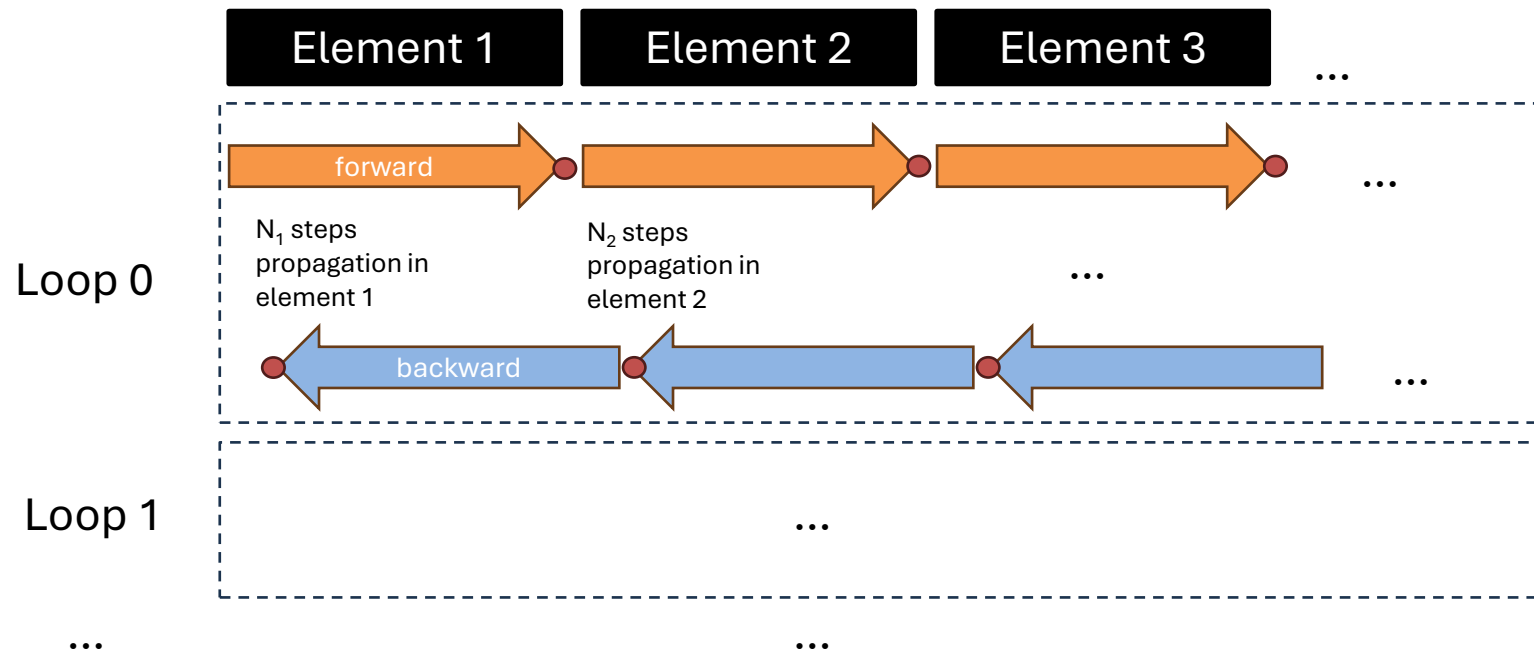
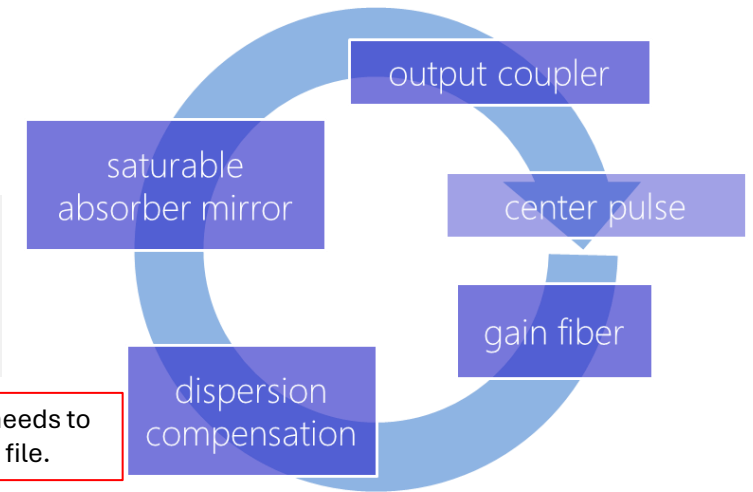
How do I get information out of the multi element propagation?

Let us first take a look at the possibilities of data along the propagation:

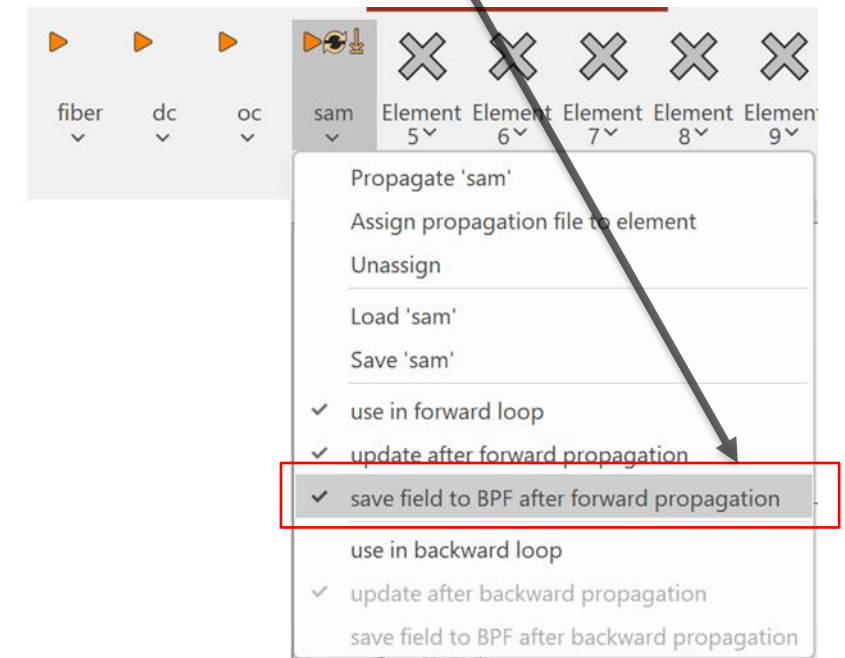
- Changes along each elements propagation  
- Only the result at the end of each element 
- Both depend on the loop count



To save the full propagation results in *each element*, „write file“ needs to be switched on and saved to the particular elements propagation file.



To save *the results after the elements*, select it in the sub-menu of the element:



Multi-Element Propagation: Short Pulse Fiber Lasers

How do I get information out of the multi element propagation?

Example:

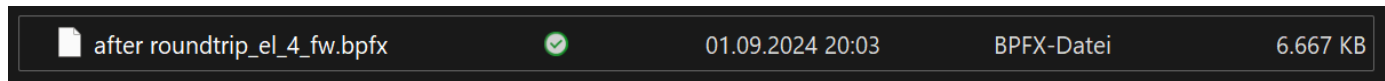
- Only the result at the end of each element ●



On start you will be asked about a filename, if not given in the dialog. Please use a filename, that is a base filename, as the element number and forward/backward signature will be attached to this base filename.

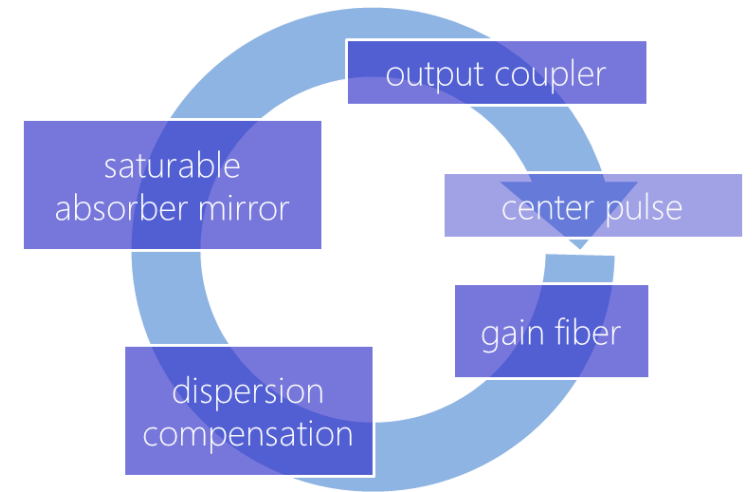
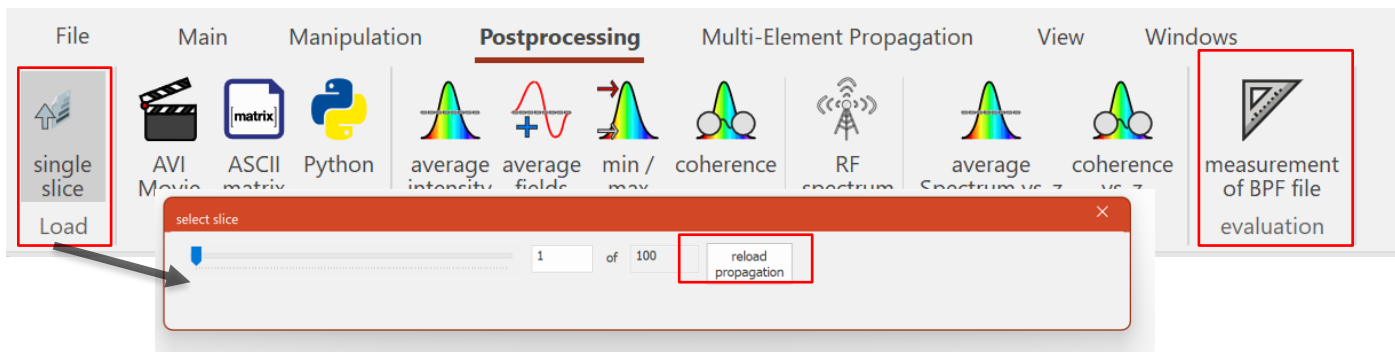
In my case, I used „after_propagation“ as the filename

After the multi-element propagation is finished, the following file is created:

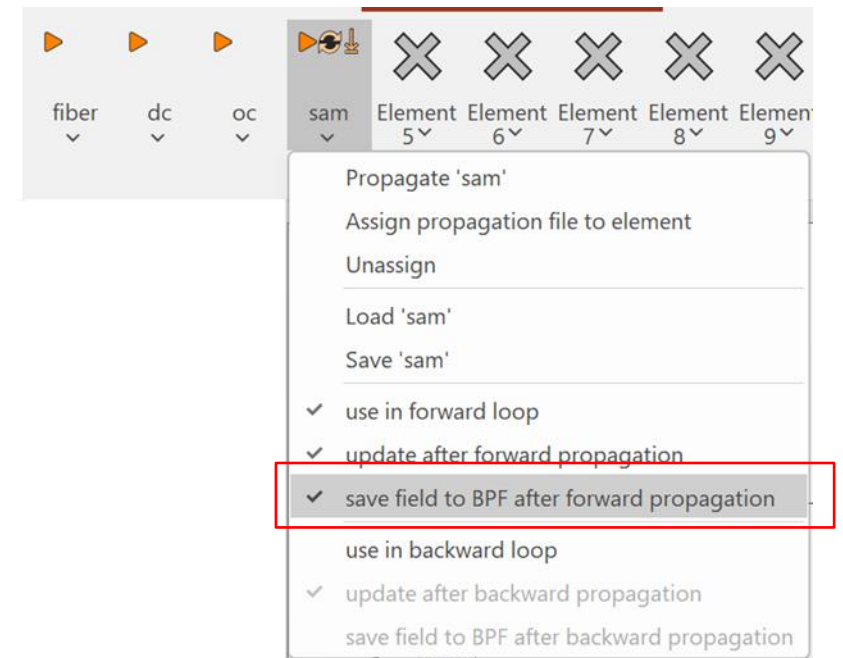


You can reload the field depending on the loop count, and also reload it into fiberdesk's 2D plot.

Also consider measurements with this propagation file.

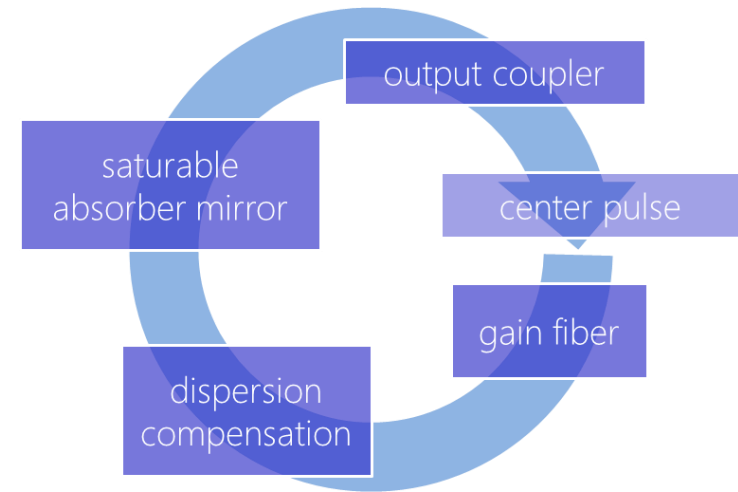


To save the results after the elements, select it in the sub-menu of the element:



Multi-Element Propagation: Short Pulse Fiber Lasers

You can also load, display and manipulate the saved data in PYTHON. Download the python script (jupyter notebook) from the homepage to process BPFx files.



Preview Code Blame 282 lines (282 loc) · 239 KB Raw Copy Download Edit

Example Reading propagation files - bpfx

Import the necessary libs, after installing them in your environment. Please also ensure that lxml is installed by

```
conda install lxml
```

```
In [5]: import matplotlib
import struct
import base64
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
```

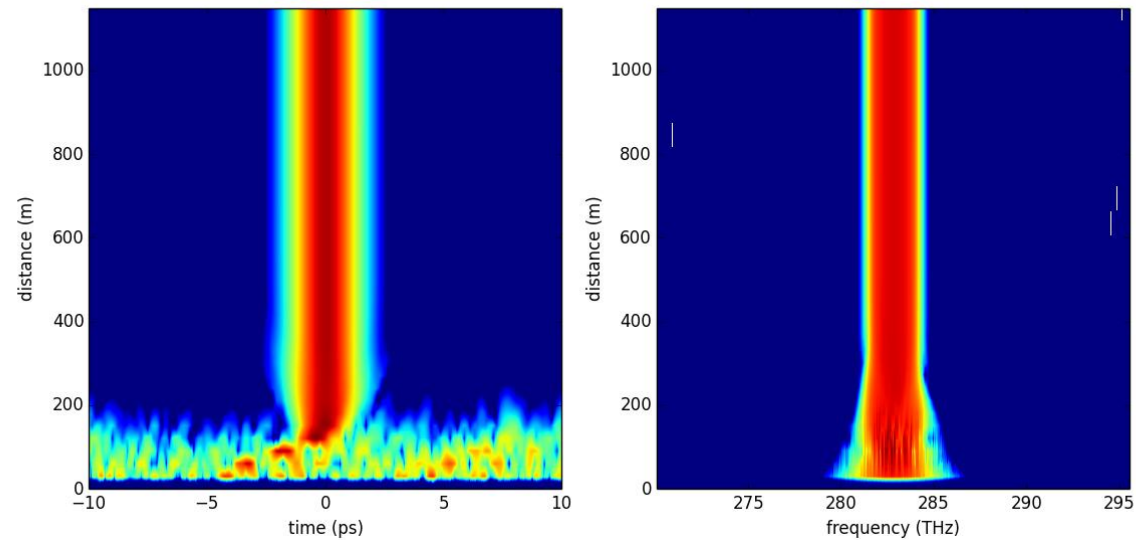
Now define the following class that load the fiberdesk propagation file (bpfx) that is actually an xml file, so pandas read_xml is used.

```
In [6]: class fiberdesk_bpfx:
def __init__(self, name):
    self.filename = name
    self.frames = 0
    self.bSecondFieldSaved = 0
    self.datapoints = 0
    self.time_intervall = 0.0
    self.freq_intervall = 0.0
    self.frequency_0 = 0.0
    self.distance = 0.0

    self.df = pd.read_xml(name)

    last_index = self.df.index.size-1 # minus header
    if "number_of_frames" in self.df.columns:
        self.frames = int(self.df.at[last_index, "number_of_frames"])
    #print(self.frames)
    entries = last_index / self.frames
    if "datapoints" in self.df.columns:
        self.datapoints = int(self.df.at[last_index, "datapoints"])
    #print(self.datapoints)

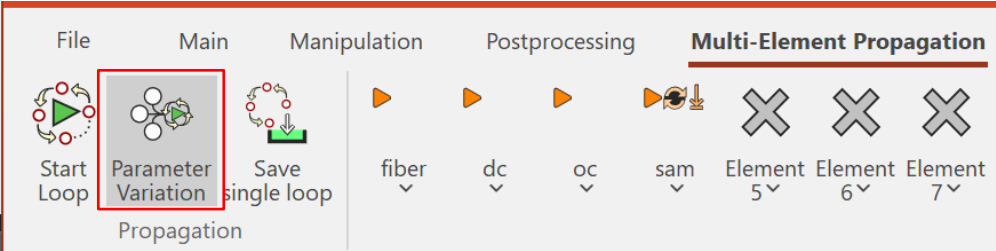
    # read axis from first entry (index 0), assume that it does no change along propagation
    if "freq_intervall" in self.df.columns:
        self.freq_intervall = self.df.at[0, "freq_intervall"]
    if "time_intervall" in self.df.columns:
        self.time_intervall = self.df.at[0, "time_intervall"]
    if "FrequencyNull" in self.df.columns:
        self.frequency_0 = self.df.at[0, "FrequencyNull"]
    if "accumulated_distance" in self.df.columns:
        pos = self.df["accumulated_distance"].dropna().to_numpy()
        self.distance = np.max(pos)-np.min(pos)
    #print(self.distance)
```



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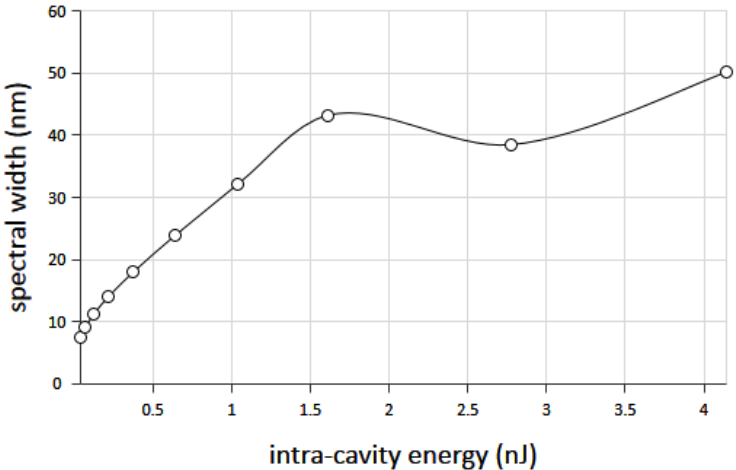
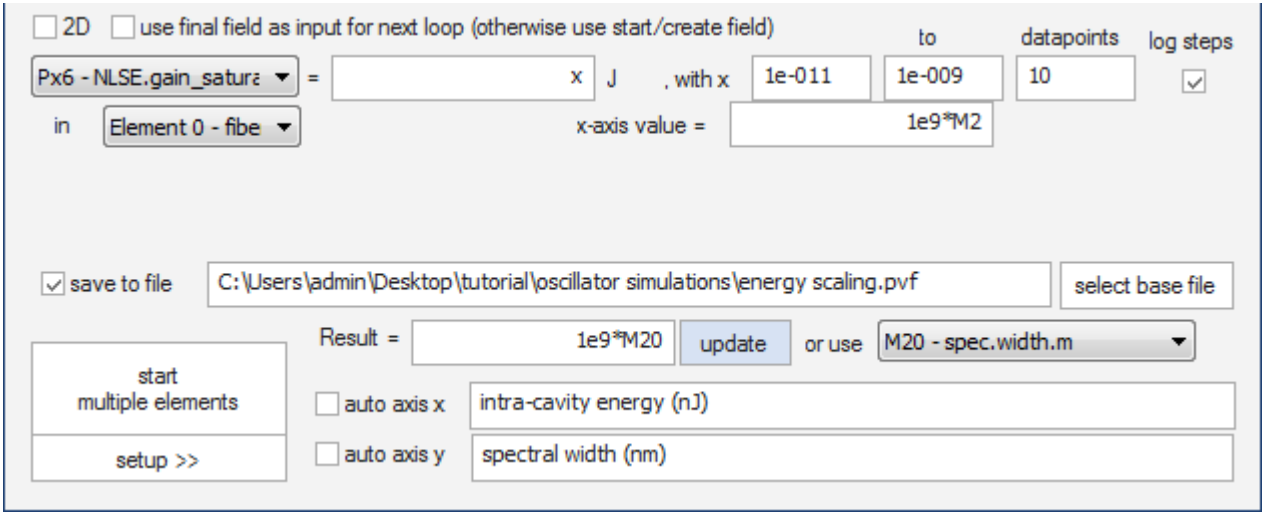
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers



Multi-element > Parameter variation

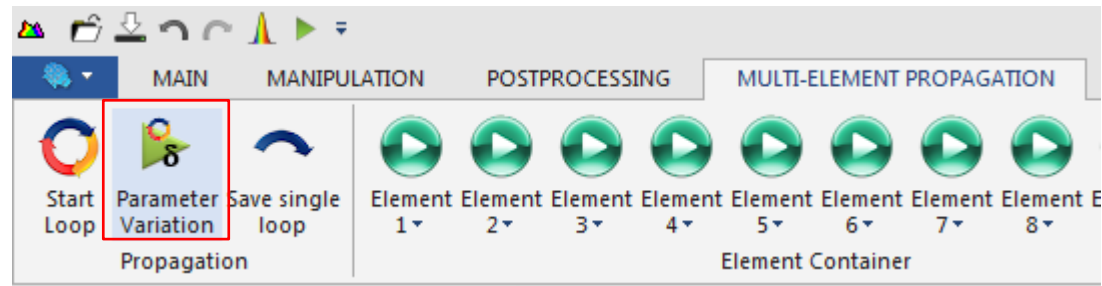
we change the gain saturation to increase the energy (remark: intracavity energy!)



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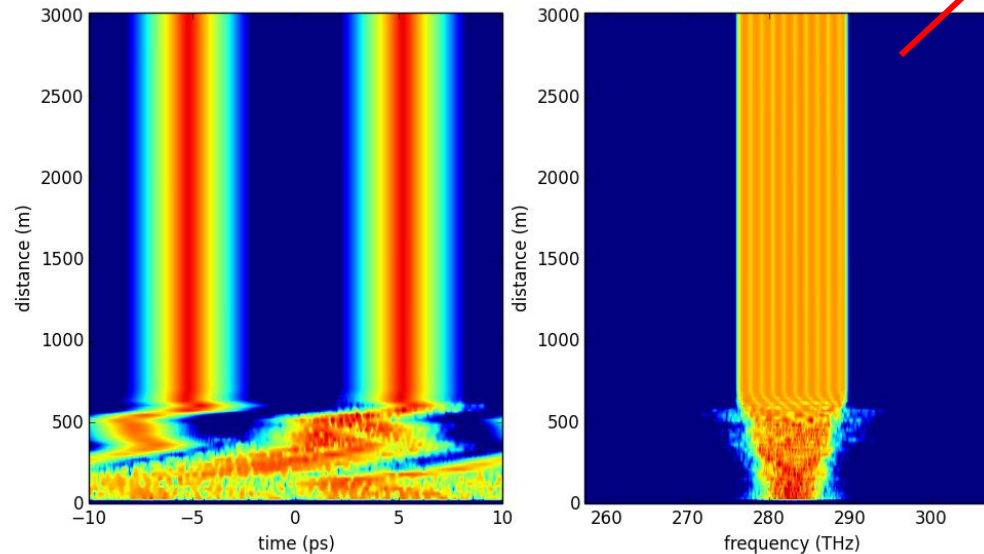
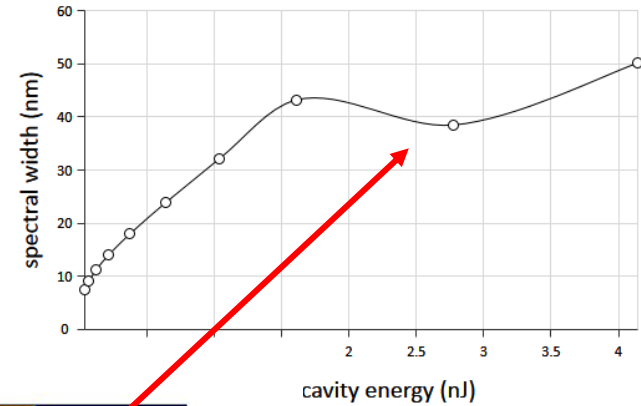
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers



Multi-element > Parameter variation

we change the gain saturation to increase the energy (remark: intracav



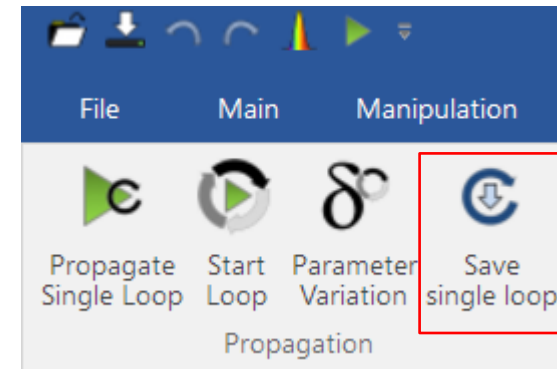
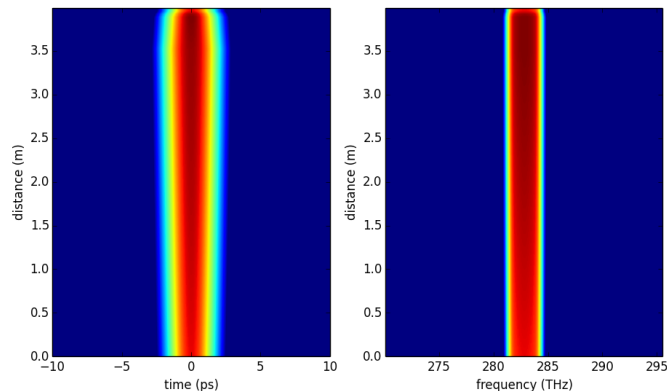
lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

Intracavity evolution

- (1) select stable solution from saved file
- (2) specify slices to be saved
- (3) post-process



Dialog

forward	backward	filename	distance		slices
<input checked="" type="checkbox"/>	<input type="checkbox"/>	ons\fiber-simple.ppf	0	m	100
<input checked="" type="checkbox"/>	<input type="checkbox"/>	simulations\DC.ppf	0	m	10
<input checked="" type="checkbox"/>	<input type="checkbox"/>	simulations\SAM.ppf	0	m	1
<input checked="" type="checkbox"/>	<input type="checkbox"/>	simulations\OC.ppf	0	m	1
<input checked="" type="checkbox"/>	<input type="checkbox"/>	simulations\center.ppf	0	m	1
<input checked="" type="checkbox"/>	<input type="checkbox"/>		0	m	0
<input checked="" type="checkbox"/>	<input type="checkbox"/>		0	m	0
<input checked="" type="checkbox"/>	<input type="checkbox"/>		0	m	0
<input checked="" type="checkbox"/>	<input type="checkbox"/>		0	m	0
<input checked="" type="checkbox"/>	<input type="checkbox"/>		0	m	0

sum of slices: 113

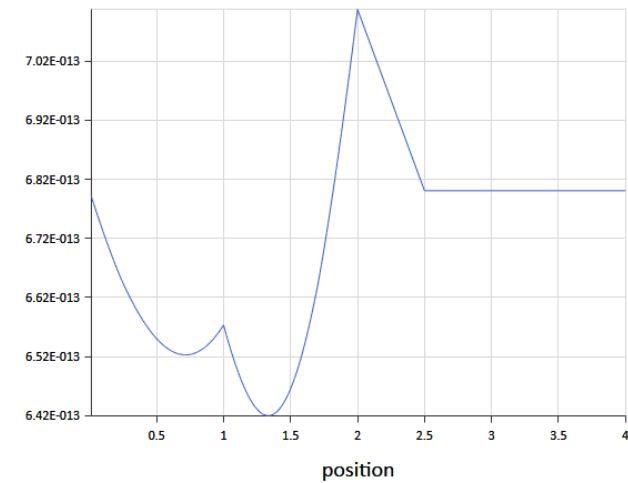
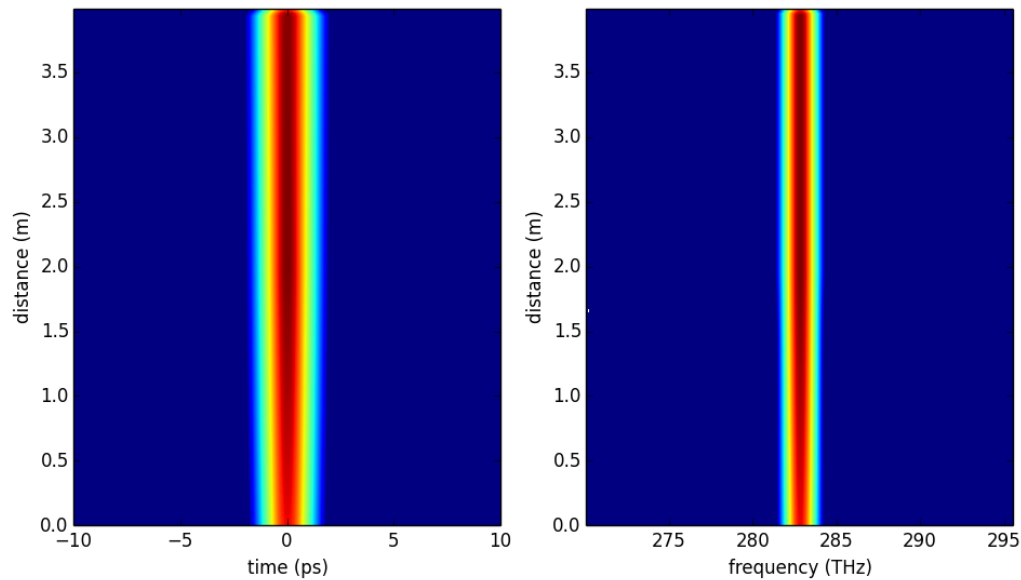
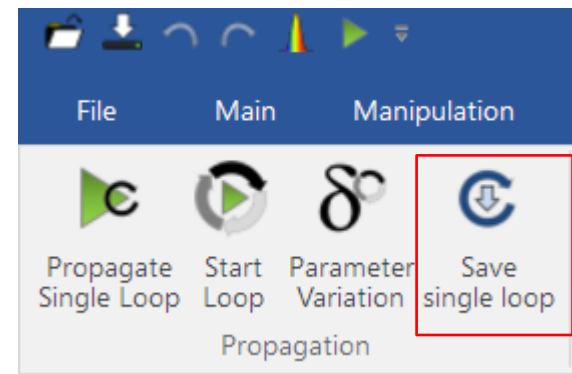
Cancel Save to BPF file >>

lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

soliton solution: $\beta_{2@DC} = -0.06 \text{ ps}^2$

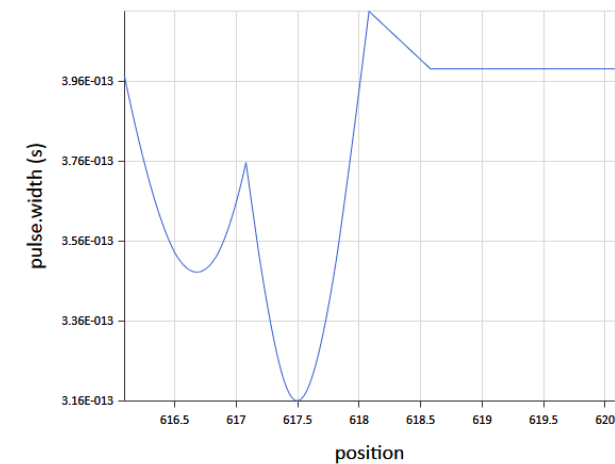
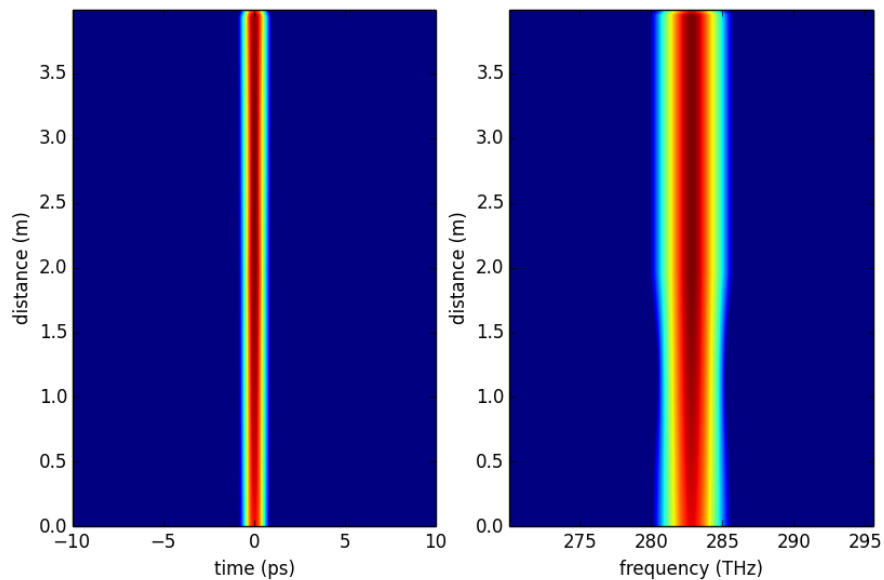
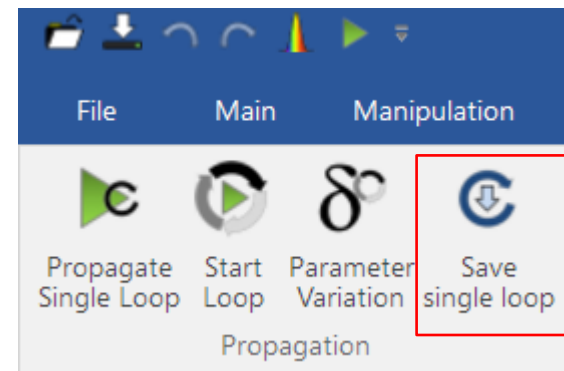


lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

soliton solution: $\beta_{2@DC} = -0.04 \text{ ps}^2$

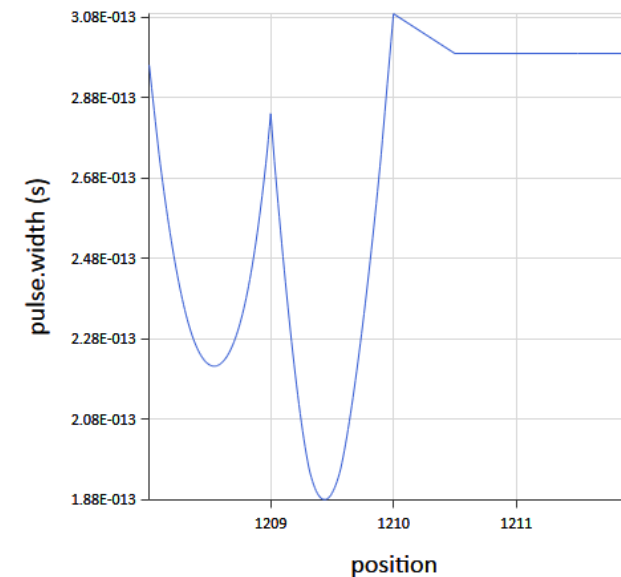
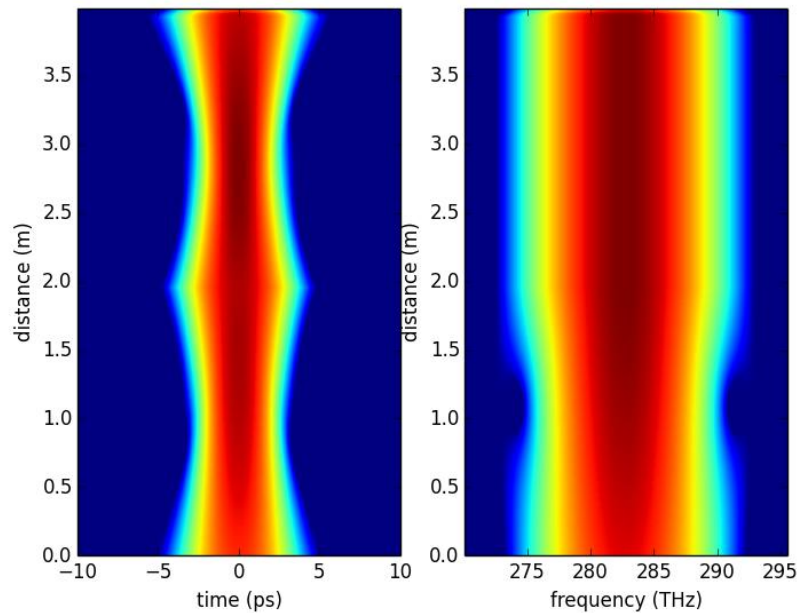
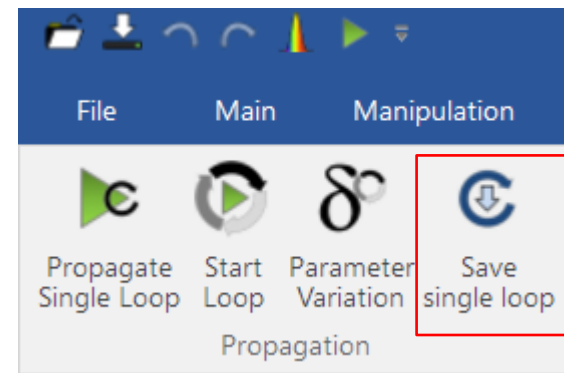


lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

toward stretched pulse: $\beta_{2@DC} = -0.03 \text{ ps}^2$

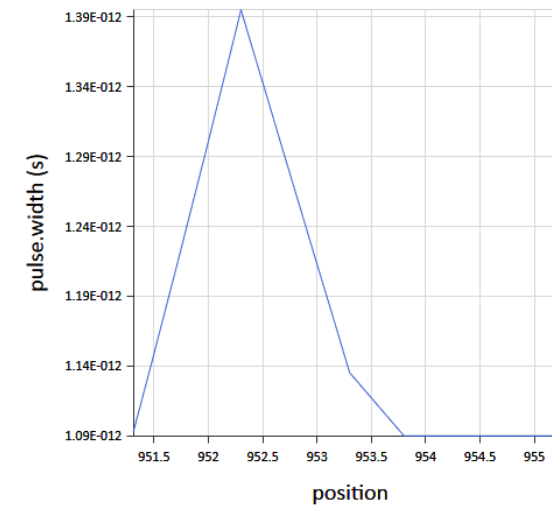
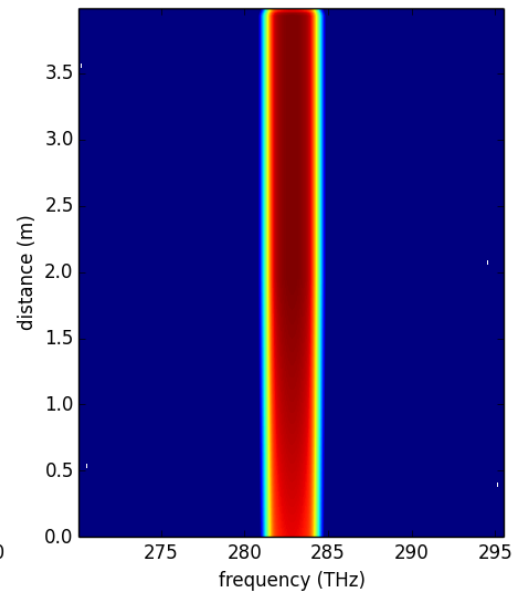
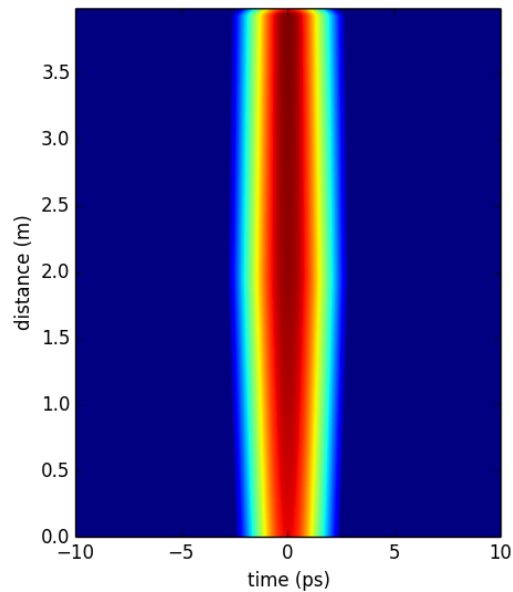
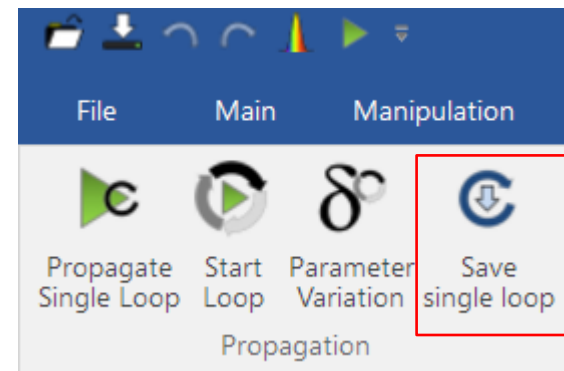


lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

similariton: $\beta_{2@DC} = -0.02 \text{ ps}^2$

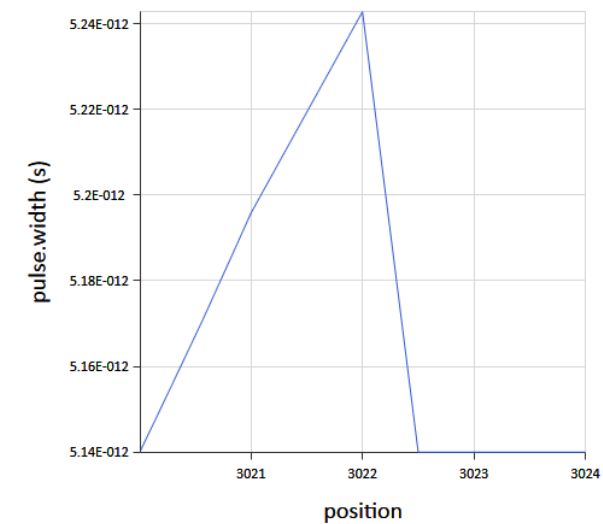
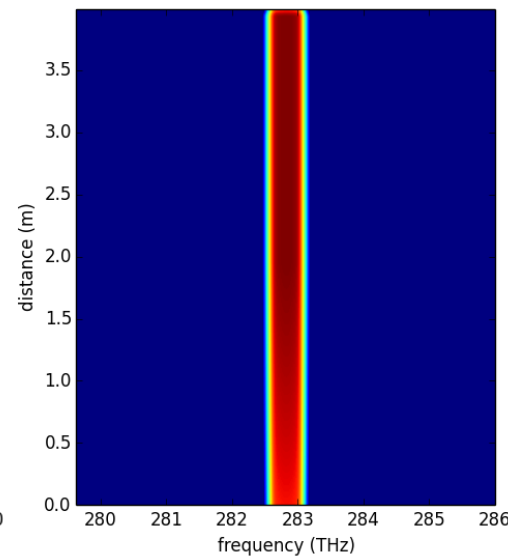
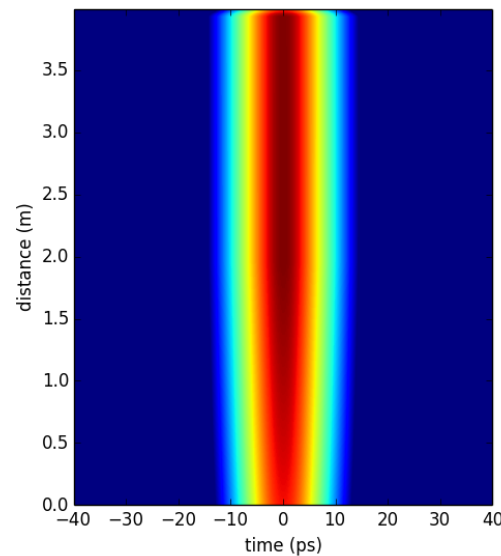
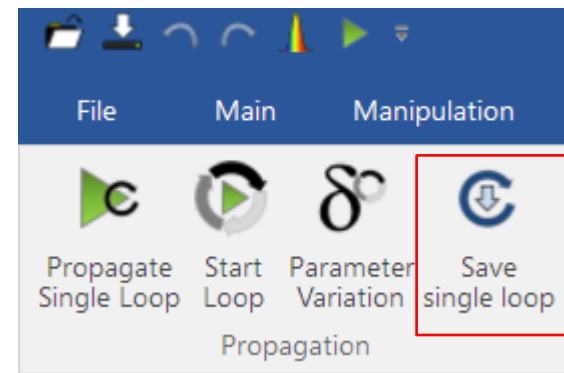


lecture 5

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

chirped pulse oscillator: $\beta_{2@DC} = +0.02 \text{ ps}^2$



Lecture 5

Multi-Element Propagation

Part 1:

Short Pulse Fiber Laser

Part 2:

Mamyshev Oscillator

Part 3:

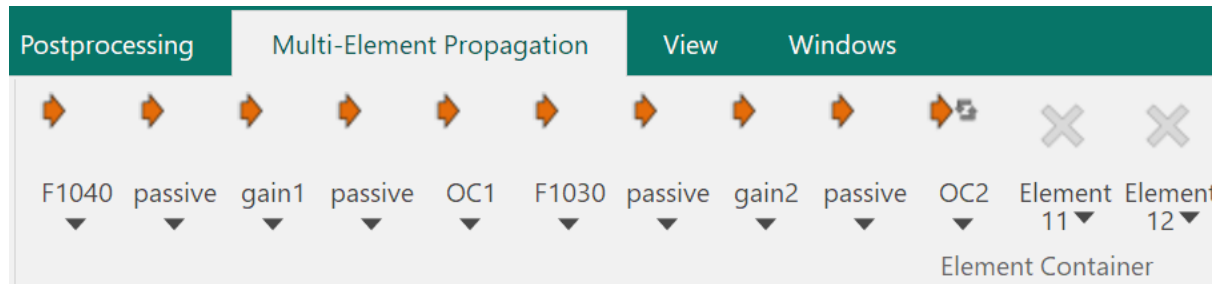
Micro Comb Generator



Multi-Element Propagation: Mamyshev Oscillator

See Z. Liu, Z. Ziegler, L. G. Wright, and F. W. Wise. "Megawatt peak power from a Mamyshev oscillator." *Optica* **4**, 649 (2017).

The model of the Mamyshev oscillator is using the following elements:



It uses two separated filters at 1030 nm and 1040 nm as well as passive and active fibers in between. The gain fibers are different after the filter. An output coupler is used at the end.

Multi-Element Propagation: Mamyshev Oscillator

The filters are defined as follows:

Pulse manipulation propagation

Saved as: 1040.ppf

The 'Manipulation' dialog box for the 1040.ppf filter shows the following settings:

- ☐ Create Pulse
- ☐ change repetition rate to 0 Hz
- ☐ Create double pulse
- delay of pulses (will be 0.0 ps
- ☐ take phase shift into account (Mach-Zehnder equival...
- ☐ Delay Pulse (temporal shift) 0.0 ps
- ☐ Center Pulse
- ☒ Complex Multiplication Temporal Domain
- t - time in sec
- helper variable h 0
- sqrt(0.75)
- i 0
- ☒ Complex Multiplication Spectral Domain
- wl - wavelength in m, f - frequency in Hz
- helper variable h 0
- sqrt(0.7*exp(-(wl-1040e-9)^2/(4e-9)^2)
- i 0
- OK Cancel

Contains a general loss of 25 % and a filter transmission of 70%. The width ($1/e^2$) is 4 nm centered at 1040 nm.

Pulse manipulation propagation

Saved as: 1030.ppf

The 'Manipulation' dialog box for the 1030.ppf filter shows the following settings:

- ☐ Create Pulse
- ☐ change repetition rate to 0 Hz
- ☐ Create double pulse
- delay of pulses (will be 0.0 ps
- ☒ take phase shift into account (Mach-Zehnder equival...
- ☐ Delay Pulse (temporal shift) 0.0 ps
- ☐ Center Pulse
- ☒ Complex Multiplication Temporal Domain
- t - time in sec
- helper variable h 0
- sqrt(0.75)
- i 0
- ☒ Complex Multiplication Spectral Domain
- wl - wavelength in m, f - frequency in Hz
- helper variable h 0
- sqrt(0.7*exp(-(wl-1030e-9)^2/(4e-9)^2)
- i 0
- OK Cancel

Similar, but centered at 1030 nm.

Multi-Element Propagation: Mamyshev Oscillator

The passive fiber is defined as a standard propagation. The dispersion is only second order at 1035 nm.

standard propagation

Saved as: **passive.ppf**

The screenshot displays the fiberdesk software interface. The 'Propagation parameter' window is on the left, and the 'Dispersion Setup' window is on the right.

Propagation parameter window:

- standard propagation** (selected)
- waveguide**
 - loss: 0.0 1/m
 - gain: 0 1/m
 - MFD: 10 μm
 - gamma: 0.00248543689320388 1/(W m)
 - Esat: 23.561 μJ
- simulation**
 - ☒ dispersion
 - ☒ Raman
 - ☒ spm / TPA
 - ☒ self-steepening
 - ☐ parameter
 - ☒ temporal gain saturation
- steps**: 100
- stepsize**: 0.008
- distance**: 0.8
- ☐ measure and parse
- ☐ write file: 100
- adaptive local error**: 6e-07
- presets**: [dropdown]
- ☐ random temporal clipping

Dispersion Setup window:

- dispersion term**
$$\frac{\partial A}{\partial z} = \dots + \sum_{n \geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial T^n} A$$
 - ☐ beta 0
 - ☐ beta 1
 - ☐ beta 2
 - ☒ D
- dispersion model**
 - ☒ Taylor expansion series
 - ☐ Sellmeier coefficients
 - ☐ photonic crystal fiber
 - ☐ gas-filled silica-hollow core fiber
- ☐ force retarded time frame (beta0=beta1=0)
- ☒ Use dispersion
- ☒ do not use dispersion
- ☐ auto y
- min**: -1 **max**: 1

Dispersion Setup window:

- Taylor Series** @ 1035 nm predefined [more ...]
- Beta1**: 0 ps/m **compensate at**: 800 nm
- Beta2**: 0.02 ps²/m **D**: -35.168177876 ps/(nm*km)
- Beta3**: 0.0 ps³/m **S**: 0.0679578 ps/(nm²*km)
- Beta4**: 0
- Beta5**: 0
- Beta6**: 0
- Trust region**
 - from**: 0 nm **to**: 20000 nm

Multi-Element Propagation: Mamyshev Oscillator

The output coupler is again defined as a pulse manipulation:

Pulse manipulation propagation

Saved as: OC1.ppf

Manipulation

☐ Create Pulse

☐ change repetition rate to 0 Hz

☐ Create double pulse

delay of pulses (will be 0.0 ps

☒ take phase shift into account (Mach-Zehnder equival...

☐ Delay Pulse (temporal shift) 0.0 ps

☒ Center Pulse

☒ Complex Multiplication Temporal Domain

t - time in sec

helper variable h 0

sqrt(0.5)

i 0

☐ Complex Multiplication Spectral Domain

wl - wavelength in m, f - frequency in Hz

helper variable h 0

0

i 0

OK Cancel

50% Transmission.

Pulse manipulation propagation

Saved as: OC2.ppf

Manipulation

☐ Create Pulse

☐ change repetition rate to 0 Hz

☐ Create double pulse

delay of pulses (will be 0.0 ps

☒ take phase shift into account (Mach-Zehnder equival...

☐ Delay Pulse (temporal shift) 0.0 ps

☒ Center Pulse

☒ Complex Multiplication Temporal Domain

t - time in sec

helper variable h 0

sqrt(0.12)

i 0

☐ Complex Multiplication Spectral Domain

wl - wavelength in m, f - frequency in Hz

helper variable h 0

0

i 0

OK Cancel

12% Transmission. (88% out-coupling)

Multi-Element Propagation: Mamyshev Oscillator

The first gain fiber is defined as a standard propagation:

Standard propagation

Saved as: gain1.ppf

Propagation parameter

standard propagation Setup >

waveguide

loss 0 nm

gain 10 dB/m

MFD 10 μm

gamma 0.00248543689320388 1/(W m)

Esat 23.561 μJ

simulation

☒ dispersion ☒ Raman

☒ spm / TPA ☒ self-steepening

parameter

☒ temporal gain saturation

steps 100

stepsize 0.025 m

distance 2.5 m

☐ measure and parse

☐ write file 100

adaptive local error 6e-07

presets: ▾

☐ random temporal clipping

Gain

gain profile

Center 1035 nm

Width 40 nm

shape Gauss

add second peak

Center 1060 nm

Width 40 nm

shape const

ratio of second to first peak (set to zero for only one peak): 0

☒ gain saturation, with Esat... 9.15e-9 J $g = g_0 / (1 + \frac{E}{E_{sat}})$

user defined gain file

☐ use ASCII file for gain profile given in g(1/m) vs. wavelength (separator TAB)

file ...

OK Cancel copy shape to clipboard

Measurement

Copy ASCII Copy BMP Save BMP Zoom Out

M1 - position ▾ ☐ log x

M0 - index ▾ ☐ log y

Multi-Element Propagation: Mamyshev Oscillator

The second gain fiber is defined as a standard propagation:

Standard propagation

Saved as: gain2.ppf

The image shows two overlapping windows from a software application. The 'Propagation parameter' window on the left has several sections. The 'standard propagation' dropdown is at the top. Below it, the 'waveguide' section contains fields for 'loss' (0 dB/m), 'gain' (10 dB/m), 'MFD' (10 μm), 'gamma' (0.00248543689320388 1/(W m)), and 'Esat' (23.561 μJ). The 'simulation' section has checkboxes for 'dispersion', 'Raman', 'spm / TPA', and 'self-steepening', all of which are checked. Below this is a 'parameter' section with a checkbox for 'temporal gain saturation' which is checked. At the bottom, there are fields for 'steps' (100), 'stepsize' (0.025 m), and 'distance' (2.5 m). The 'Gain' window on the right has a 'gain profile' section with fields for 'Center' (1035 nm), 'Width' (40 nm), and 'shape' (Gauss). There is also an 'add second peak' section with 'Center' (1060 nm), 'Width' (40 nm), and 'shape' (const). Below these is a 'ratio of second to first peak' field set to 0. A checkbox for 'gain saturation, with Esat...' is checked, and next to it is a field with the value '36.6e-9'. To the right of this field is the equation $g = g_0 / (1 + \frac{E}{E_{sat}})$. Below this is a 'user defined gain file' section with a checkbox for 'use ASCII file for gain profile given in g(1/m) vs. wavelength (separator TAB)' which is unchecked. At the bottom of the 'Gain' window are 'OK', 'Cancel', and 'copy shape to clipboard' buttons. Below the 'Gain' window, there is a table with two columns: 'M18 - spec.center.offset' and 'M19 - spec.photons_N'. The values are '-71.987 fm' and '32.581 x 10^9' respectively. At the bottom of the image, there is a 'Measurement' section with buttons for 'Copy ASCII', 'Copy BMP', 'Save BMP', and 'Zoom Out'. Below these buttons is a dropdown menu for 'M1 - position' and a checkbox for 'log x'.

Propagation parameter

standard propagation

Setup >

waveguide

loss 0 nm

gain 10 dB/m

MFD 10 μm

gamma 0.00248543689320388 1/(W m)

Esat 23.561 μJ

simulation

✓ dispersion ✓ Raman

✓ spm / TPA ✓ self-steepening

parameter

× temporal gain saturation

steps 100

stepsize 0.025 m

distance 2.5 m

measure and parse

write file 100

adaptive local error 6e-07

presets:

Gain

gain profile

Center 1035 nm

Width 40 nm

shape Gauss

add second peak

Center 1060 nm

Width 40 nm

shape const

ratio of second to first peak (set to zero for only one peak): 0

✓ gain saturation, with Esat... 36.6e-9 J $g = g_0 / (1 + \frac{E}{E_{sat}})$

user defined gain file

use ASCII file for gain profile given in g(1/m) vs. wavelength (separator TAB)

file ...

OK Cancel copy shape to clipboard

M18 - spec.center.offset	-71.987 fm
M19 - spec.photons_N	32.581 x 10 ⁹

Measurement

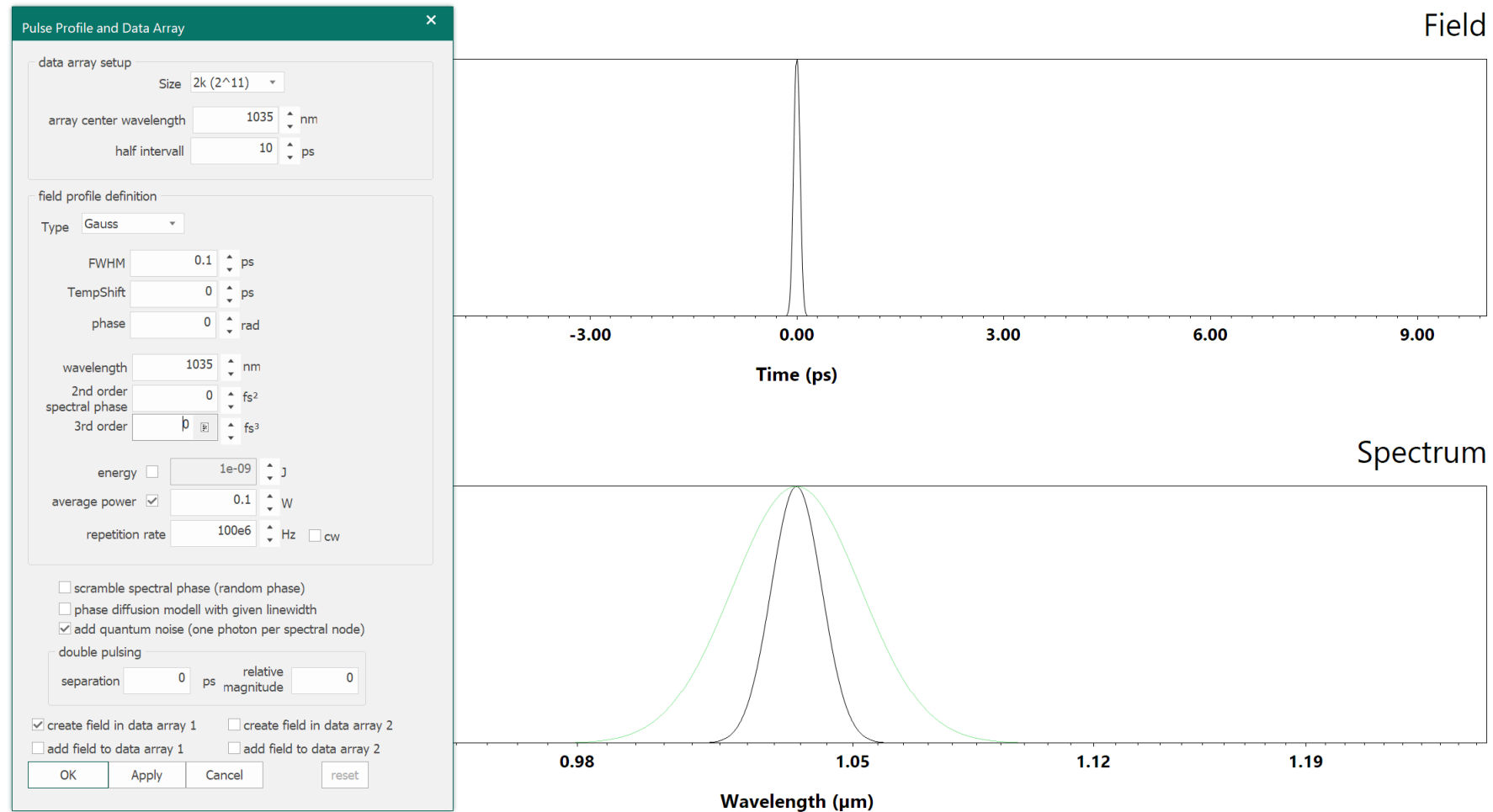
Copy ASCII Copy BMP Save BMP Zoom Out

M1 - position log x

Multi-Element Propagation: Mamyshev Oscillator

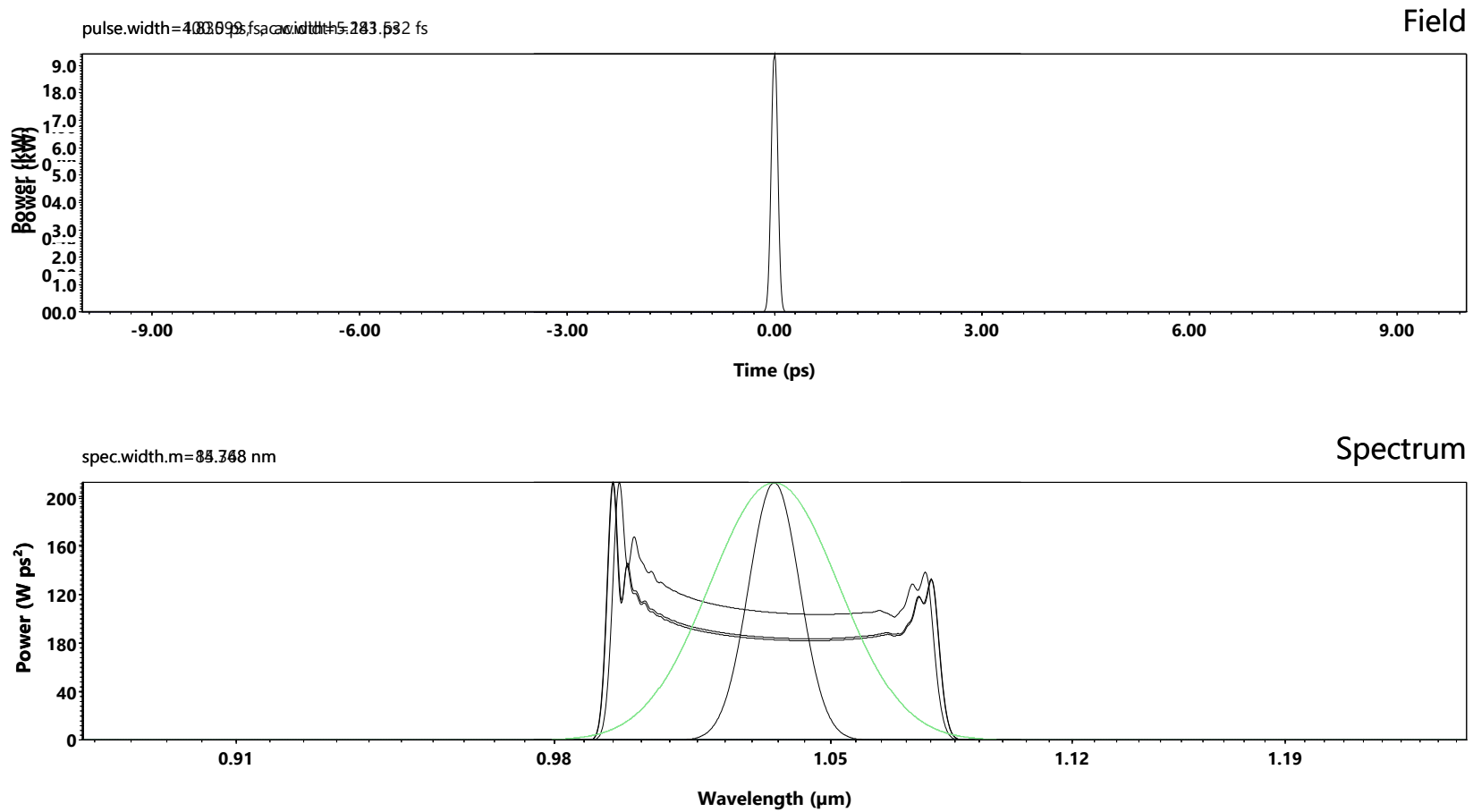
As most Mamyshev oscillators are not self starting, we seed with a short pulse:

Create Pulse:



Multi-Element Propagation: Mamyshev Oscillator

After some roundtrips, we see the pulse converging. However, after many roundtrips, the pulse might destabilize.



Lecture 5

Multi-Element Propagation

Part 1:

Short Pulse Fiber Laser

Part 2:

Mamyshev Oscillator

Part 3:

Micro Comb Generator



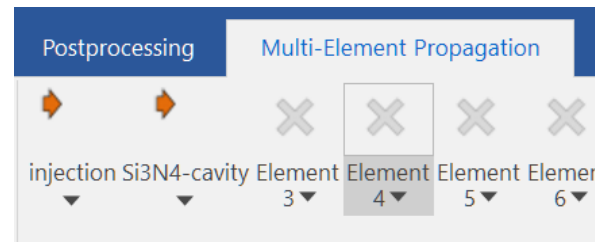
Multi-Element Propagation: Micro Comb Generator

Alessia Pasquazi, Marco Peccianti, Luca Razzari, David J. Moss, Stéphane Coen, Miro Erkintalo, Yanne K. Chembo, Tobias Hansson, Stefan Wabnitz, Pascal Del’Haye, Xiaoxiao Xue, Andrew M. Weiner, Roberto Morandotti, Micro-combs: A novel generation of optical sources, Physics Reports, Volume 729, 2018, Pages 1-81.

Fiberdesk’s multi element propagation can be used to simulate roundtrips in the micro-resonator. Please see section 5.1 of the reference for details. In principle, the first element simulates the in/outcoupling (boundary conditions) and the second element is the nonlinear propagation within the resonator.

$$E^{(m+1)}(0, \tau) = \sqrt{\theta} E_{\text{in}} + \sqrt{1 - \theta} E^{(m)}(L, \tau) e^{i\phi_0},$$
$$\frac{\partial E(z, \tau)}{\partial z} = -\frac{\alpha_i}{2} E + i \sum_{k \geq 2} \frac{\beta_k}{k!} \left(i \frac{\partial}{\partial \tau} \right)^k E + i\gamma |E|^2 E$$

So, only two elements need to be defined:



Please also note that the average propagation equation (LLE) can be used for simulating Micro Comb Generation but are intended for another tutorial.

Multi-Element Propagation: Micro Comb Generator

The injection element is done using the “pulse injection” propagation.
As you can see, in the setup a low transmission (High Q Cavity) and long pulse duration (to simulate a cw injection) is given.

Save as injection.ppf

Propagation param...

pulse injection

Setup >

waveguide

loss

0.0

1/m

gain

0

1/m

MFD

3

μm

gamma

0.026834381551362

1/(W m)

Esat

2.1205

μJ

simulation

☒ dispersion

☒ Raman

☒ spm / TPA

☒ self-steepening

parameter

☒ temporal gain saturation

steps

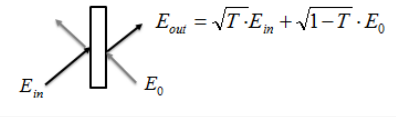
10

stepsize

0.000599584916

m

pulse injection (by adding to current array)



E_0 - existing field in data array

transmission T

0.1

%

E_in - defined below

phase phi_0

0

rad

E_out - interfering fields

Type

Gauss

FWHH

1e6

ps

+/-

0

ps

TempShif

0.0

ps

+/-

0

ps

wavelength

1550

nm

+/-

0

nm

Chirp

0.0

fs²

+/-

0

fs²

energy

0.001e-9

J

+/-

0

J

OK

Cancel

zero deviations

fiberdesk
nonlinear pulse propagation

page 36

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Multi-Element Propagation: Micro Comb Generator

The ring itself is defined as a standard propagation with the dispersion of the material (including the waveguide dispersion), the nonlinearity and length.

The dispersion is a simple second order approx. only.

Save as Si3N4-cavity.ppf

dispersion term

$$\frac{\partial A}{\partial z} = \dots + \sum_{n \geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial T^n} A$$

Dispersion Setup

Taylor Series @ 1550 nm

Beta	Value	Unit
Beta1	0	ps/m
Beta2	-0.02	ps²/m
Beta3	0.0	ps³/m
Beta4	0	
Beta5	0	
Beta6	0	
Beta7	0	
Beta8	0	
Beta9	0	

dispersion model

- ☒ Taylor expansion series
- ☐ Sellmeier coefficients
- ☐ photonic crystal fiber
- ☐ gas-filled silica-hollow core fiber

Setup >>

☒ force retarded time frame (beta0=beta1=0)

☒ Use dispersion ☐ do not use dispersion

self phase modulation / two photon absorption term

$$\frac{\partial A}{\partial z} = \dots + i\gamma(1 - f_R)A(T)$$
$$\gamma = \frac{\omega_0 n_2}{c A_{\text{eff}}} \text{ and } A_{\text{eff}} = \frac{\pi}{4} MFD^2$$

n2 2.3e-19 m²/V

f R 0.15

TPA 0 m/W

TPA is experimental so far ...

☐ saturate SPM

saturation power density 1.0 GW/cm²

☒ use SPM and TPA ☐ exclude SPM

Propagation param...

standard propagation Setup >

waveguide

loss 0.0 1/m

gain 0 1/m

MFD 5 μm

gamma 0.069433962264150 1/(W m)

Esat 5.8904 μJ

simulation

☒ dispersion ☐ Raman

☒ spm / TPA ☐ self-steepening

parameter

☐ temporal gain saturation

steps 10

stepsize 5.99584916e-05 m

distance 0.000599584916 m

☐ measure and parse

☐ write file 100

adaptive local error 1e-07

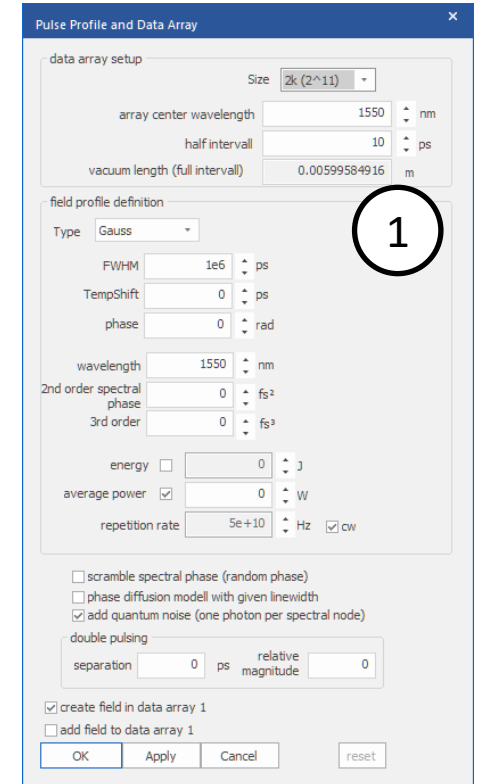
presets:

Multi-Element Propagation: Micro Comb Generator

Starting the multi-element propagation. (Please make sure to have done the first steps of this tutorial to learn multi-element propagation.)

Quick reminder:

- (1) Setup a field with a temporal window fixed to the length of the cavity (here $\sim 60\mu\text{m}$). This allows to draw a roundtrip map later on. We also only use quantum noise as the input come from the injected field.
- (2) Assign the two propagations files to elements and use both in forward loop direction. Also, to see the chance after the propagation, switch on “update after forward propagation” of the second element. You might also save the field after forward propagation, in order to postprocess it later on, e.g. plot the graph on the next slide.
- (3) Setup and start the loop.



Pulse Profile and Data Array

data array setup

Size: $2k (2^{11})$

array center wavelength: 1550 nm

half interval: 10 ps

vacuum length (full interval): 0.00599584916 m

field profile definition

Type: Gauss

FWHM: $1e6$ ps

TempShift: 0 ps

phase: 0 rad

wavelength: 1550 nm

2nd order spectral phase: 0 fs^2

3rd order spectral phase: 0 fs^3

energy: ☐ 0 J

average power: ☒ 0 W

repetition rate: $5e+10$ Hz ☒ cw

☐ scramble spectral phase (random phase)

☐ phase diffusion model with given linewidth

☒ add quantum noise (one photon per spectral node)

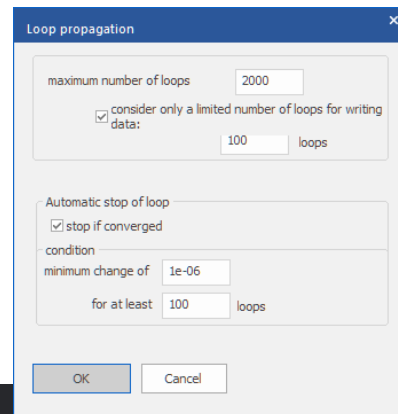
double pulsing

separation: 0 ps relative magnitude: 0

☒ create field in data array 1

☐ add field to data array 1

OK Apply Cancel reset



Loop propagation

maximum number of loops: 2000

☒ consider only a limited number of loops for writing data: 100 loops

Automatic stop of loop

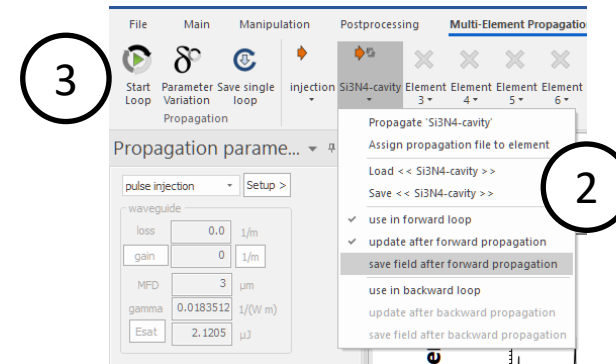
☒ stop if converged

condition

minimum change of: $1e-06$

for at least: 100 loops

OK Cancel



Multi-Element Propagation

File Main Manipulation Postprocessing Multi-Element Propagation

Start Loop Parameter Save single loop injection

Propagation parameters

pulse injection: Setup >

waveguide

loss: 0.0 1/m

gain: 0 1/m

MFD: 3 μm

gamma: 0.0183512 1/(W m)

Esat: 2.1205 μJ

Propagate "Si3N4-cavity"

Assign propagation file to element

Load << Si3N4-cavity >>

Save << Si3N4-cavity >>

☒ use in forward loop

☒ update after forward propagation

☒ save field after forward propagation

☐ use in backward loop

☐ update after backward propagation

☐ save field after backward propagation

Multi-Element Propagation: Micro Comb Generator

Using the python script, you can draw the save file and get this roundtrip map. It shows the built-up of structures from the cw input. The parameters now need to be refined to enable the desired output.

