

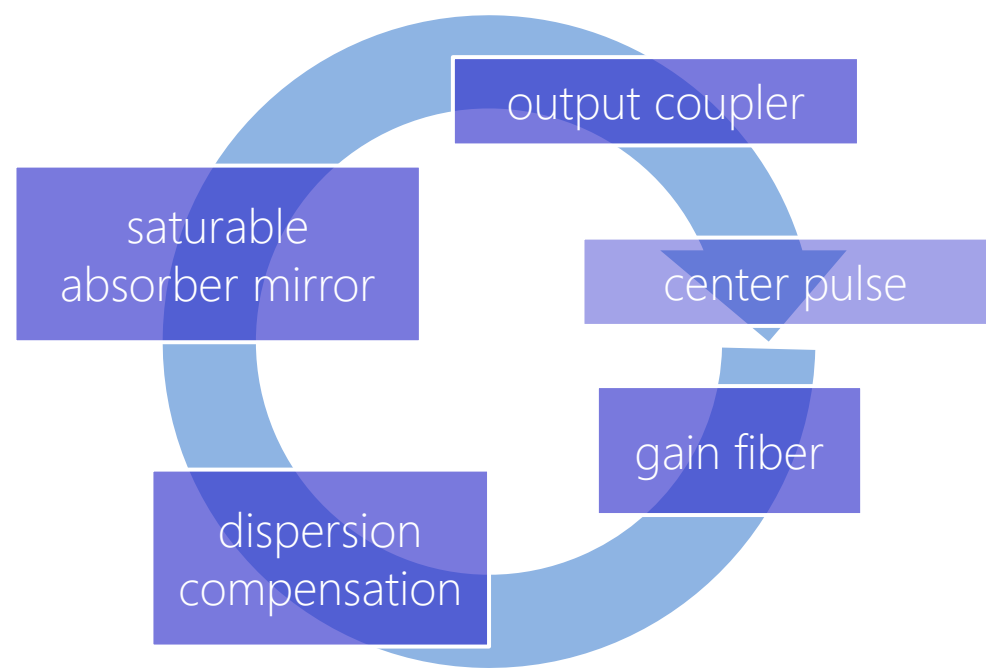
# lecture 5

## Multi-Element Propagation



# lecture 5

## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



- fiber laser cavity:

*ring cavity*

*Fast saturable absorber modelled by reflectivity  $R$*

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

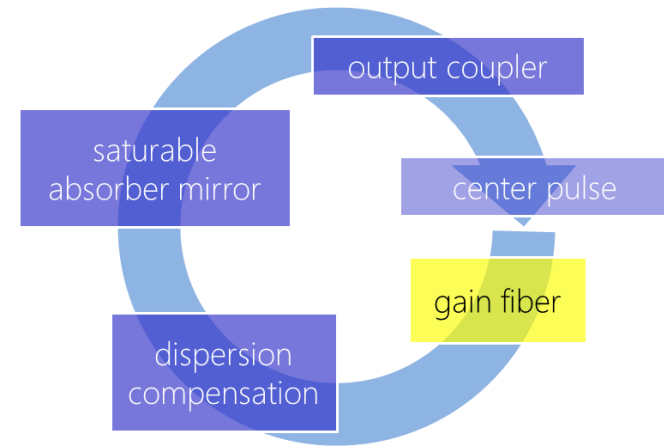
- modelling of each part by the NLSE

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

# lecture 5

## Multi-Element Propagation: Example: Short Pulse Fiber Lasers

Set up the gain fiber as a standard propagation with saturable gain

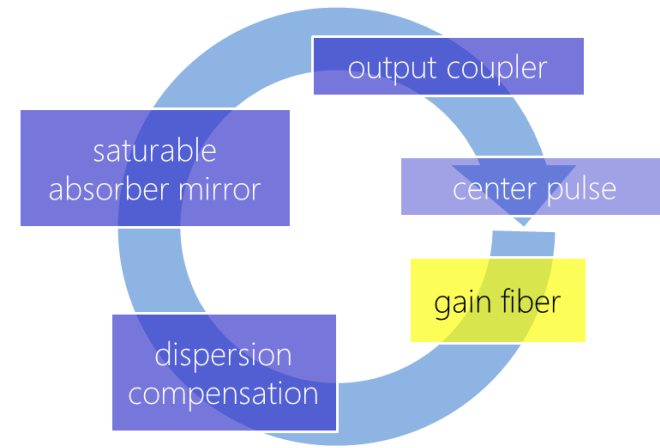


The Gain dialog box shows the configuration for a gain profile. The gain profile is centered at 1060 nm with a width of 40 nm and a Gaussian shape. The gain saturation is checked and set to  $1e-11$  J. The gain equation is  $g = g_0 / (1 + E / E_{sat, gain})$ . The user-defined gain file section is empty.

The Propagation parameter dialog box shows the configuration for a standard propagation. The gain is set to 6.90776 1/m. The MFD is 10.0 μm, gamma is 0.0023880 1/(W m), and Esat is 23.561 μJ. The simulation parameters are checked for dispersion, spm, and temporal gain saturation, and unchecked for Raman and self-steepening. The steps are 100, stepsize is 0.01 m, and distance is 1.0 m.

# lecture 5

## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



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

save as fiber.ppf

- ←
- New
- Load (Field and Multi-Element Settings)
- Save (Field and Multi-Element Settings)
- Save As ...
- Recent
- Load propagation parameter
- Save propagation parameter

Dispersion Setup

Taylor Series @ 1060 nm predefined fibers: more ...

Beta	Value	Unit
Beta1	0	ps/m
Beta2	0.01640341019153872	ps <sup>2</sup> /m
Beta3	4.427598189728069e-5	ps <sup>3</sup> /m
Beta4	-6.11686e-08	
Beta5	2.00994e-10	
Beta6	-6.78474e-13	
Beta7	2.11068e-15	
Beta8	-1.15713e-17	
Beta9	1.21432e-19	
Beta10	-9.78137e-22	
Beta11	5.06311e-24	
Beta12	-1.65466e-26	
Beta13	3.16819e-30	
Beta14	-2.74483e-33	

dispersion term

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

dispersion model

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

Use dispersion

predefined fibers:

- 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
- Layertech GTI 1000-1080nm - 250fs @1030nm
- Hollow core 1060-02@1030nm
- zero dispersion @ all

Trust region from 400

force retarded time frame (beta0=beta1=0)

copy dispersion [[nm],D[ps/nm/km],b2[ps<sup>2</sup>/m]]

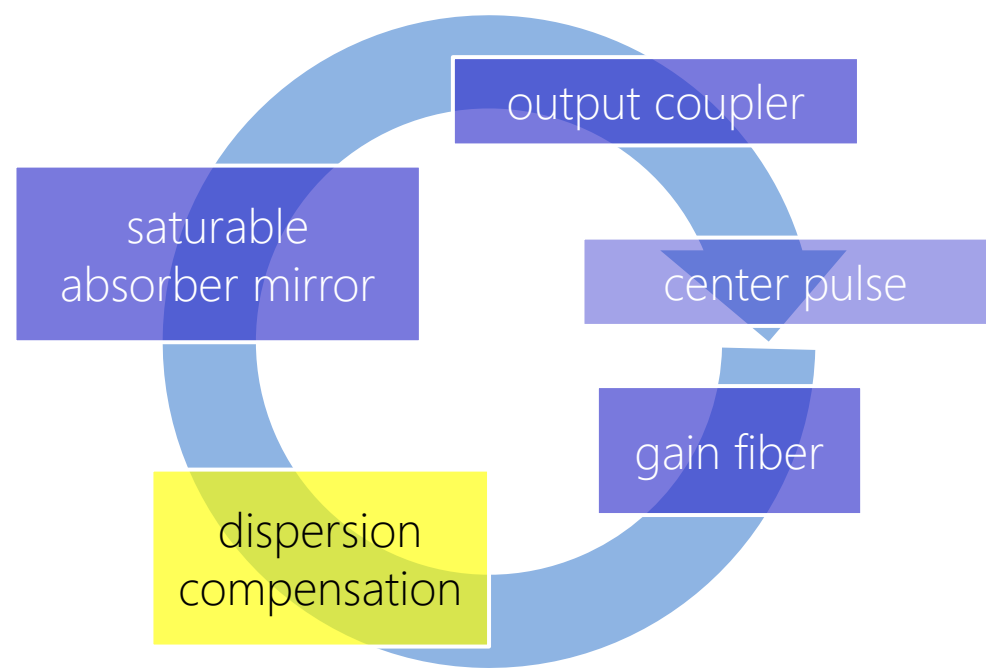
copy beta2 + group delay [nm],b2 [ps<sup>2</sup>/m], GD[ps/m]

max 2400

1.12 1.19

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Multi-Element Propagation:  
Example: Short Pulse Fiber Lasers



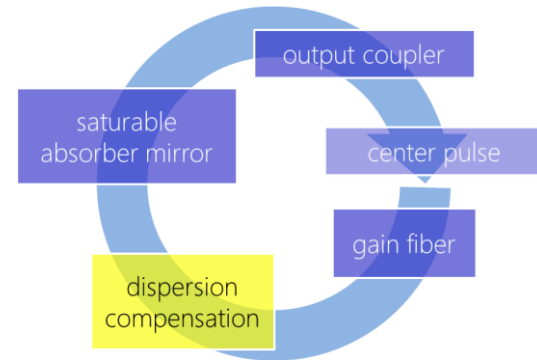
For the dispersion compensation, we only set second order dispersion.

Before, 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, see next slide.

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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



simulation

dispersion  Raman

spm  self-steepening

parameter

temporal gain saturation

steps

stepsize  m

distance  m

live  measure

write file

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

force retarded time frame (beta0=beta1=0)

Use dispersion  do not use dispersion

Setup >>

Dispersion Setup

n-th Order Dispersion

predefined fibers:

Taylor Series Expansion @  nm

Beta1	<input type="text" value="0"/>	ps/m	compensate at:	<input type="text" value="800"/>	nm
Beta2	<input type="text" value="-0.02"/>	ps <sup>2</sup> /m	D	<input type="text" value="33.52886"/>	ps/(nm <sup>2</sup> *km)
Beta3	<input type="text" value="0.0"/>	ps <sup>3</sup> /m	S	<input type="text" value="-0.0632621"/>	ps/(nm <sup>3</sup> *km)
Beta4	<input type="text" value="0"/>				
Beta5	<input type="text" value="0"/>		Beta10	<input type="text" value="0"/>	
Beta6	<input type="text" value="0"/>		Beta11	<input type="text" value="0"/>	
Beta7	<input type="text" value="0"/>		Beta12	<input type="text" value="0"/>	
Beta8	<input type="text" value="0"/>		Beta13	<input type="text" value="0"/>	
Beta9	<input type="text" value="0"/>		Beta14	<input type="text" value="0"/>	

Trust region

from  nm to  nm

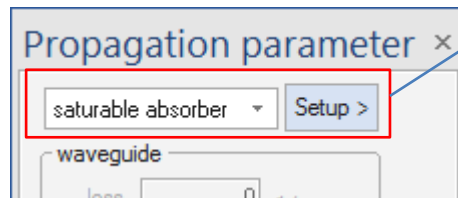
save as dc.ppf

# lecture 5

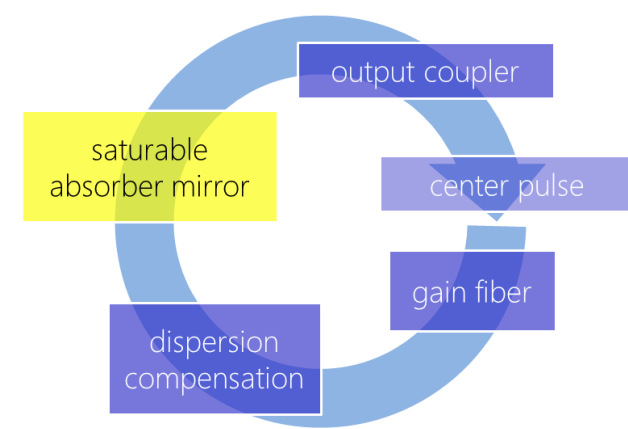
## Multi-Element Propagation: Example: Short Pulse Fiber Lasers

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.



save as SA.ppf



### Saturable Loss

Fast saturable loss

R0  %  
dR  %  
PA  W

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

saturable absorber mirror with time constants

unsaturated reflectivity  %      temporal response A  ps  
saturable reflectivity  %  
saturation fluence   $\mu\text{J}/\text{cm}^2$   
focal spot diameter   $\mu\text{m}$   
saturation energy  nJ

use  $R=R_0+dR*\sin^2((\text{Pi}/2)*(P/\text{PA})+\text{phi}_0)$

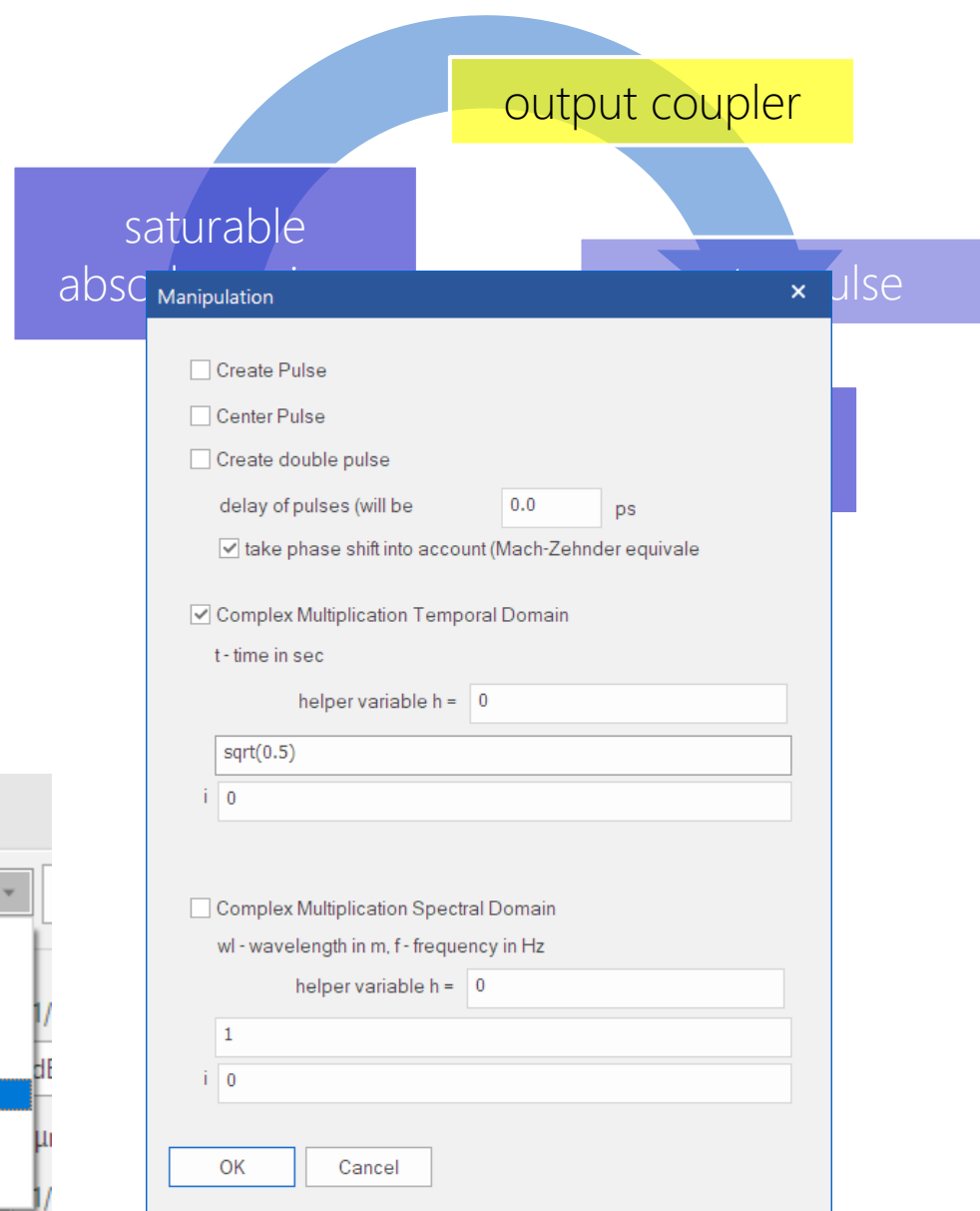
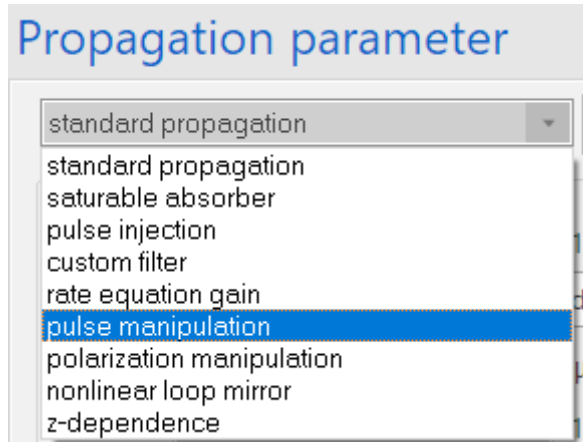
R0       dR       PA       phi\_0

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Multi-Element Propagation:  
Example: Short Pulse Fiber Lasers

Outcoupling:

50% means complex multiplication  
with  $\text{sqrt}(0.5)$

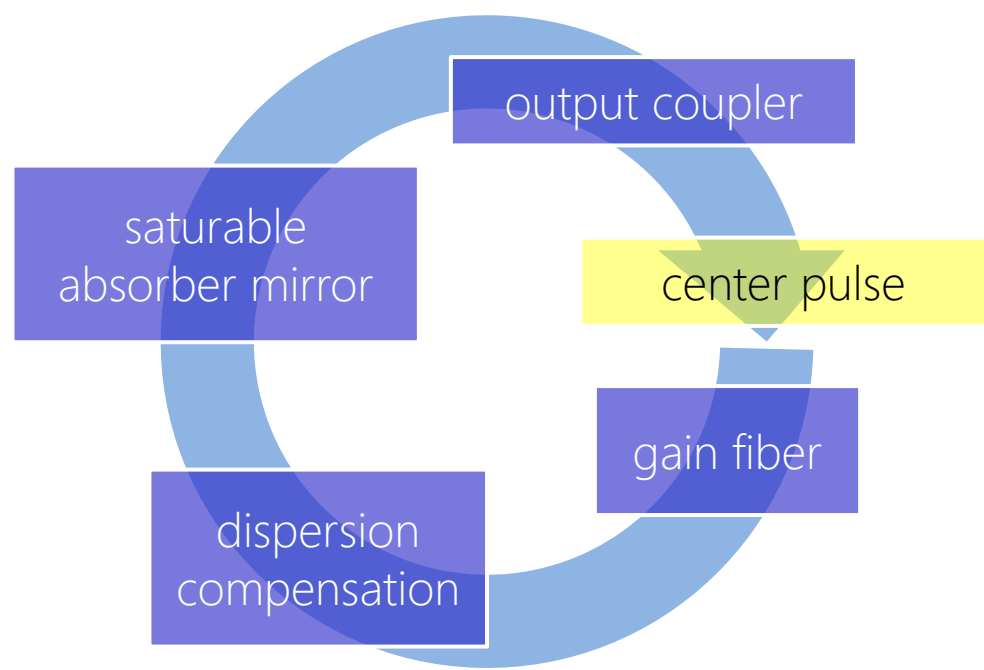


save as OC.ppf

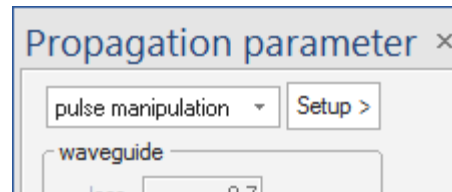
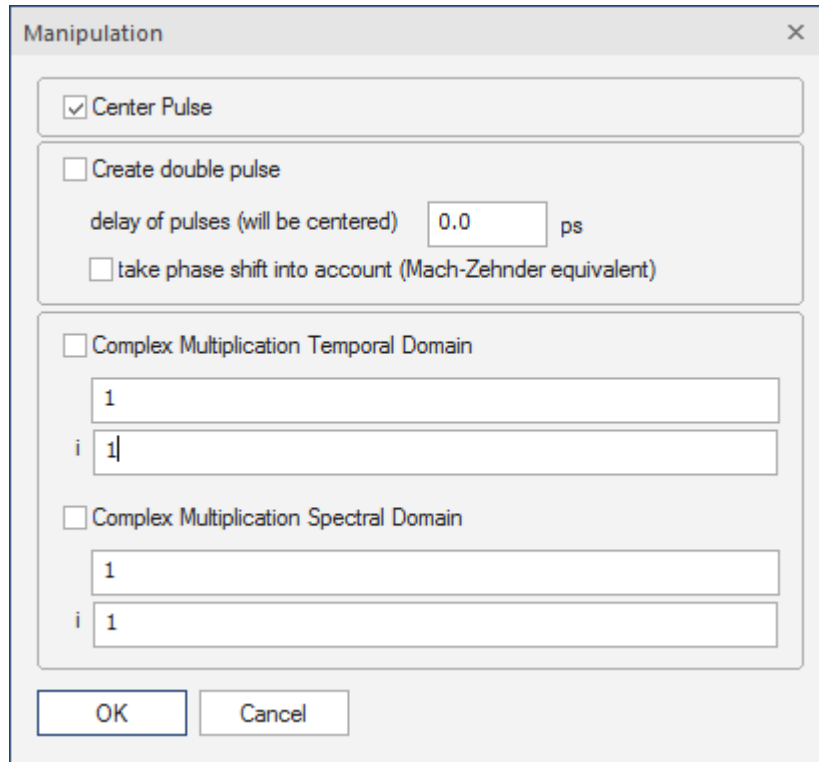


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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



- Center pulse in the time domain, helps to converge the pulse, as changes are measured in the time domain
- Can be combined with OC.ppf in a single element



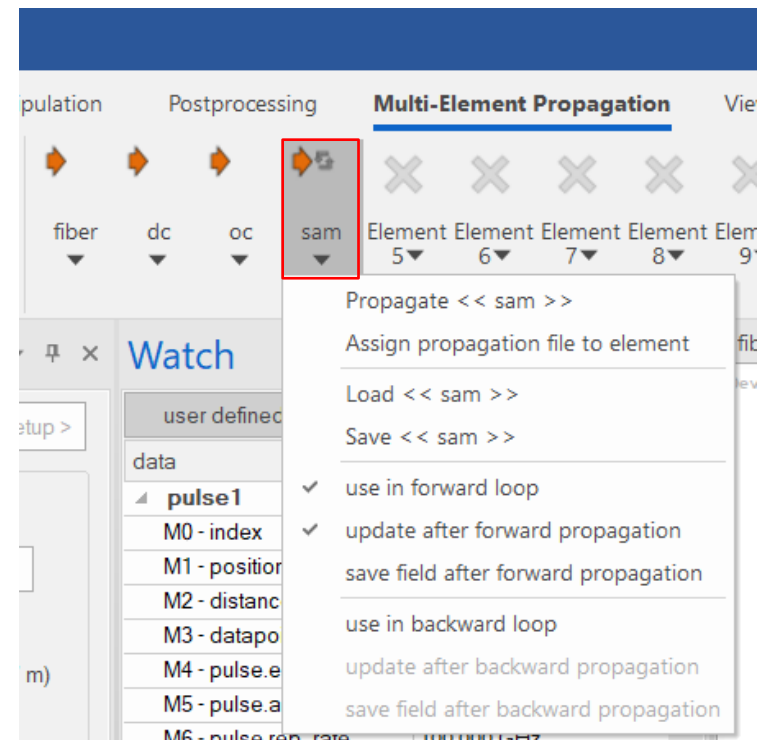
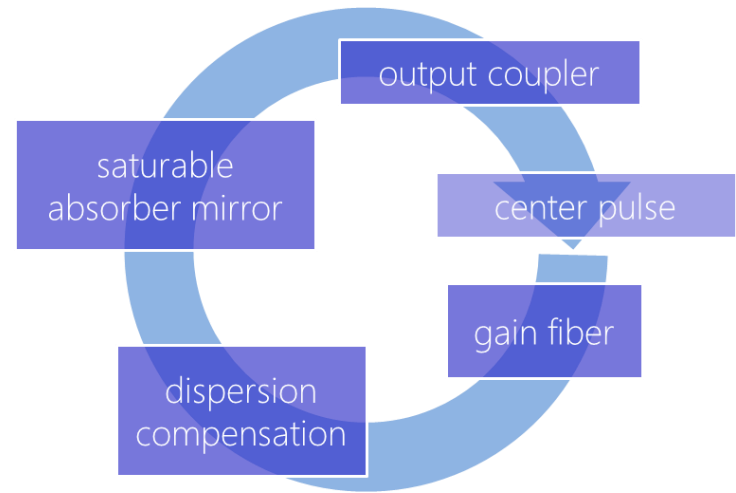
save as center.ppf

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## Multi-Element Propagation:

### Example: Short Pulse Fiber Lasers

- 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

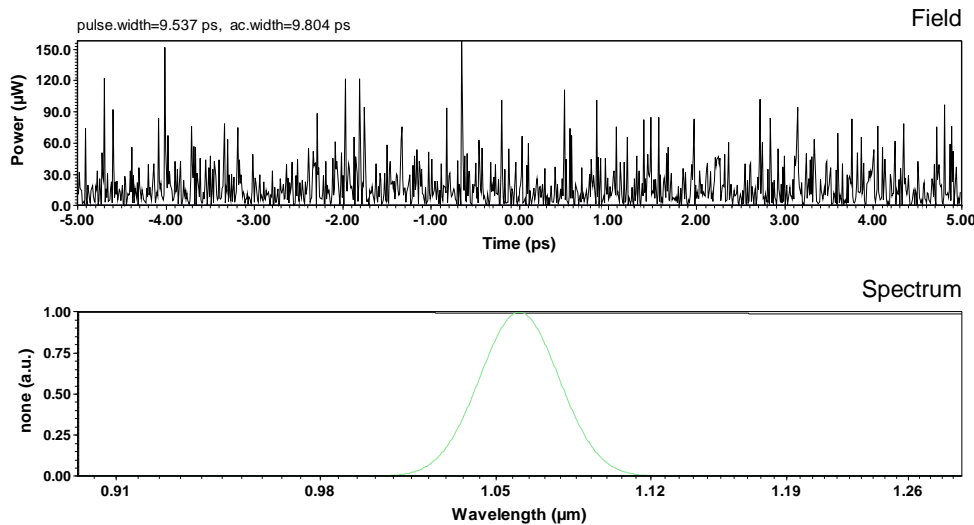


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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers

(1) create initial pulse, e.g. quantum noise

(green spectrum is the gain spectrum from „fiber.ppf“)



distance: 0.000 m position: 0.000 m energy: 191.864 aJ average power: 19.186 µW roundtrip: 0

Pulse Profile and Data Array
✕

data array setup

Size 1k (2<sup>10</sup>)

array center wavelength 1060 nm

half interval 5 ps

field profile definition

Type Gauss

FWHM 1 ps

TempShift 0 ps

phase 0 rad

wavelength 1060 nm

2nd order spectral phase 0 fs<sup>2</sup>

3rd order 0 fs<sup>3</sup>

energy  0 J

average power  0 W

repetition rate 1e+11 Hz  cw

scramble spectral phase (random phase)

phase diffusion modell 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

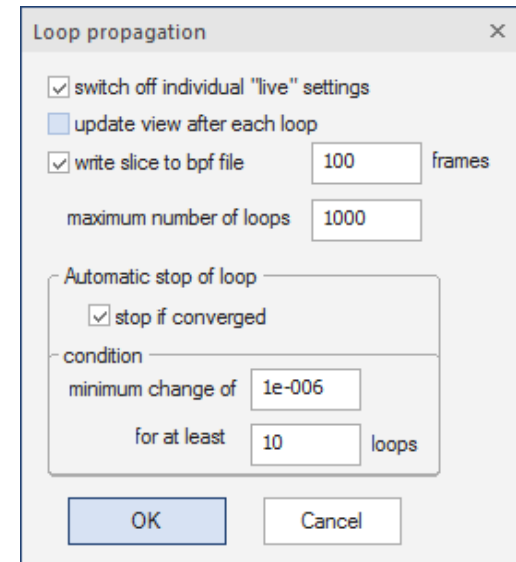
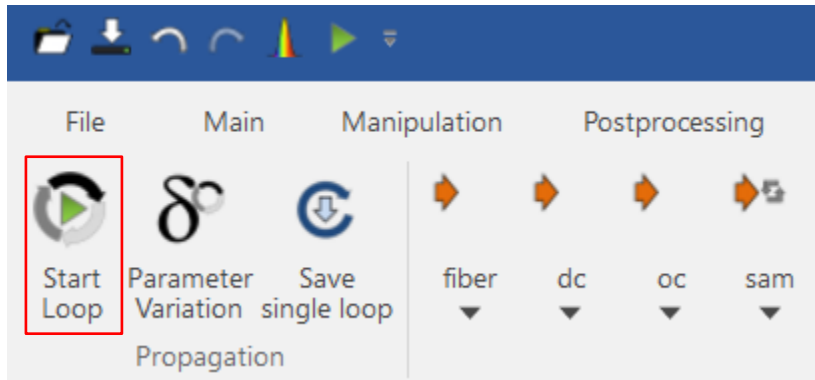
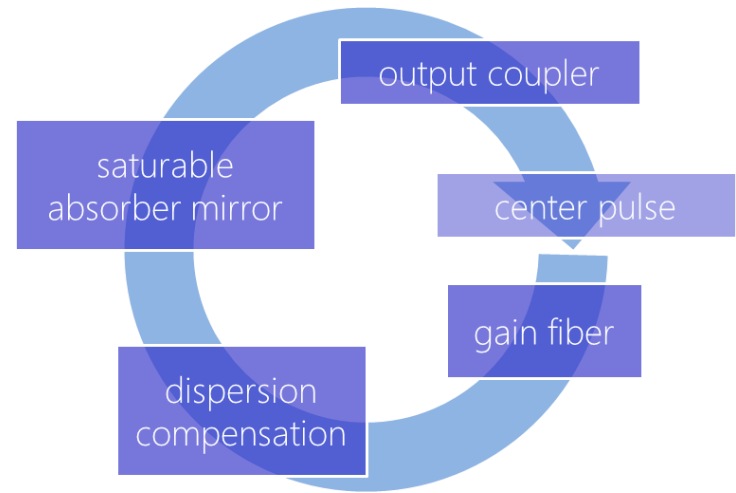
OK
Apply
Cancel
reset

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## Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

- (1) start loop (switch on „write slice ... „ for later postprocessing)

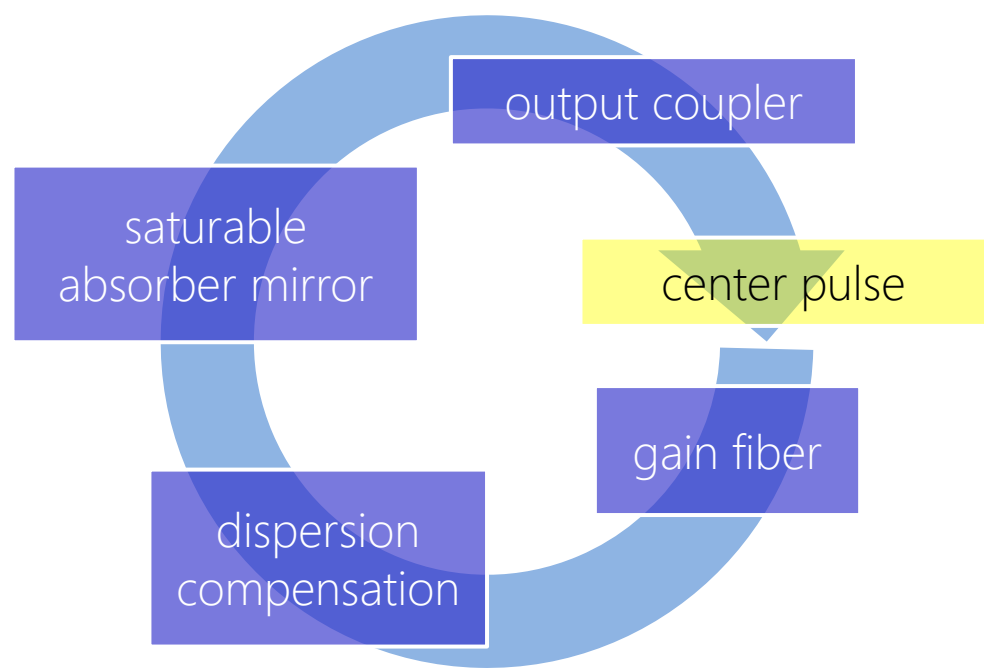


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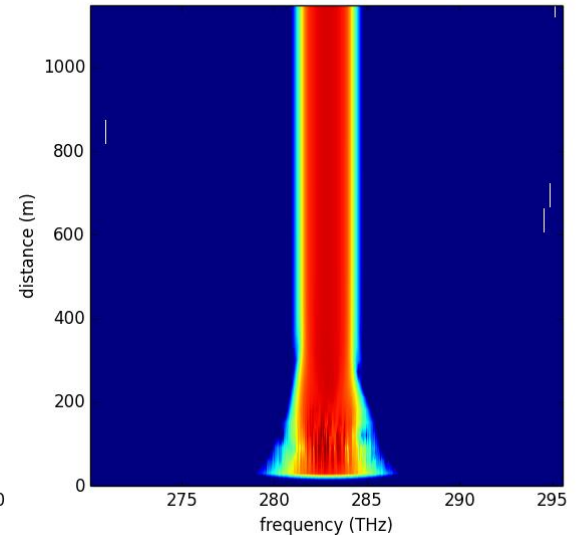
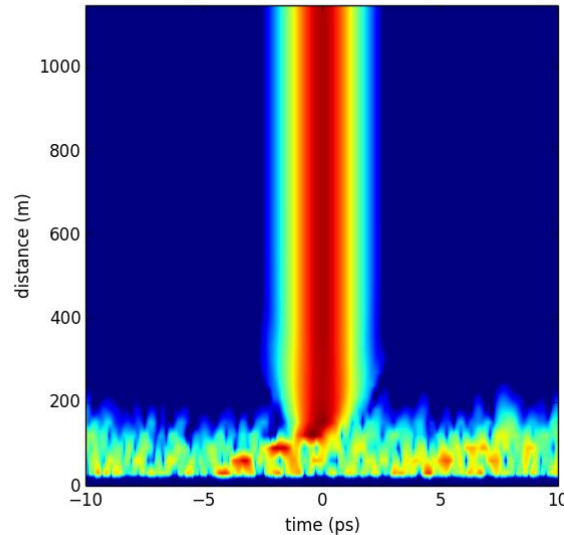
## Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

Download the python script from the homepage to process BPF files.



```
Spyder (Python 2.7)
File Edit Search Source Run Debug Interpreters Tools View ?
220 dist = 3020
221
222 data_spec/= data_spec.max()
223 spec=np.reshape(np.log10(data_spec),(frames,data_spec.shape
224 data_time/= data_time.max()
225 time=np.reshape(np.log10(data_time),(frames,data_time.shape
226
227 fig1 = plt.figure()
228 ax = fig1.add_subplot(121)
229 bx = fig1.add_subplot(122)
230
231 # range is the logarithmic dB range
232 # e.g 40 = -40 dB
233 range = 40.0
234 r=-range/10.0
235 levels=np.linspace(r,0.0,N)
236
237 # draw the field
238 x = np.linspace(t_min,t_max,data_time.shape[0]/frames)
239 y = np.linspace(0.0,dist,frames)
240 X, Y = np.meshgrid(x, y)
241 pi=ax.contourf(X,Y,time,levels,extend = 'both')
242 ax.set_xlabel('time (ps)')
243 ax.set_ylabel('distance (m)')
244
245 # draw the spectrum
246 x = np.linspace(s_min,s_max,data_spec.shape[0]/frames)
247 y = np.linspace(0.0,dist,frames)
248 X, Y = np.meshgrid(x, y)
249 pi2=bx.contourf(X,Y,spec,levels,extend='both')
250
251 bx.set_xlabel('frequency (THz)')
252 bx.set_ylabel('distance (m)')
253
254 plt.show()
```

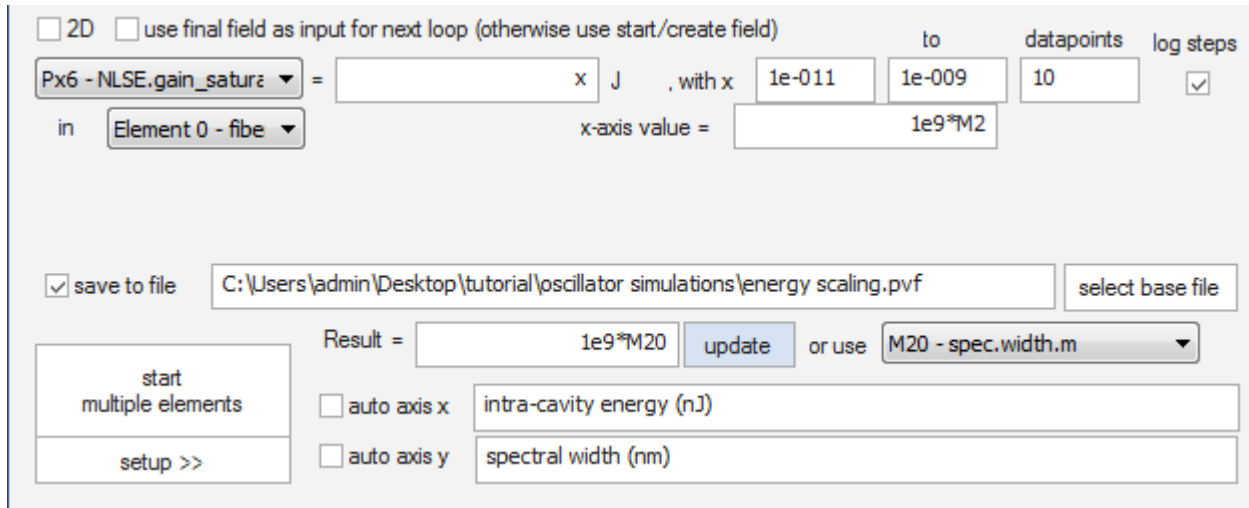
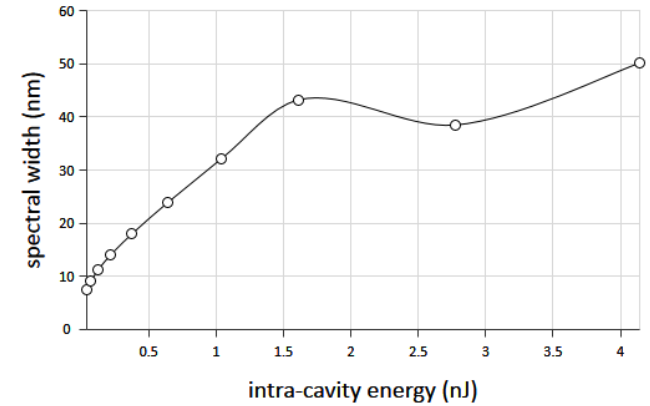
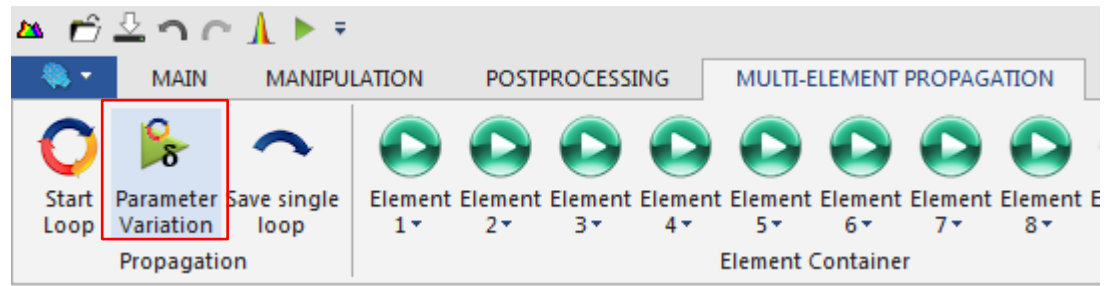


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## Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

Multi-element > Parameter variation  
 we change the gain saturation to increase the energy (remark: intracavity energy!)

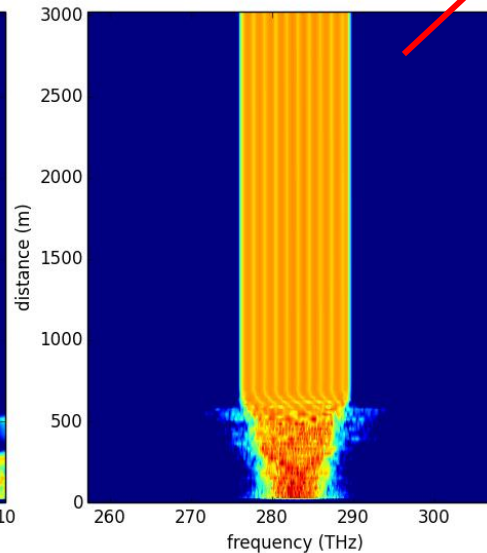
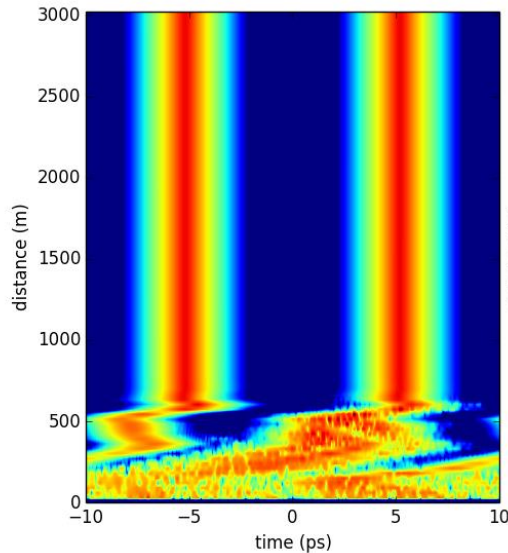
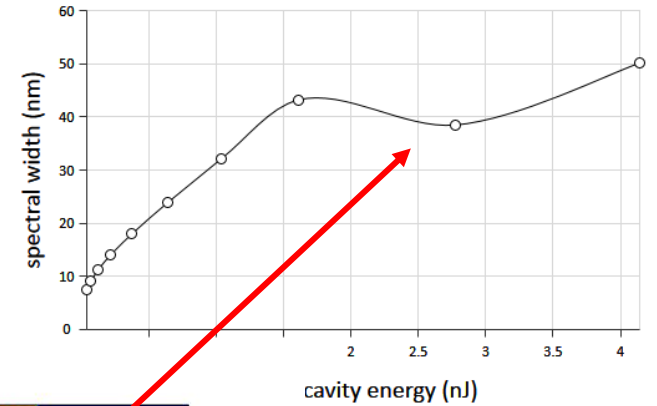
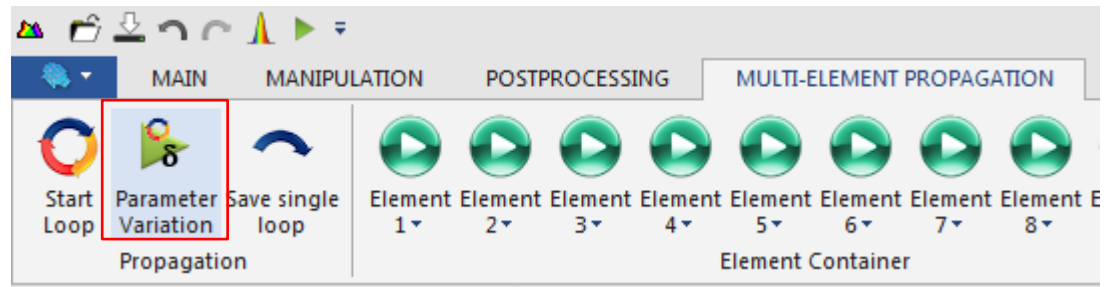


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## Multi-Element Propagation:

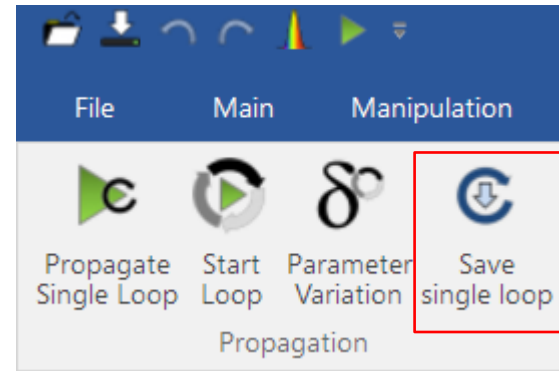
Example: Short Pulse Fiber Lasers

Multi-element > Parameter variation  
 we change the gain saturation to  
 increase the energy (remark: intracavity  
 energy!)



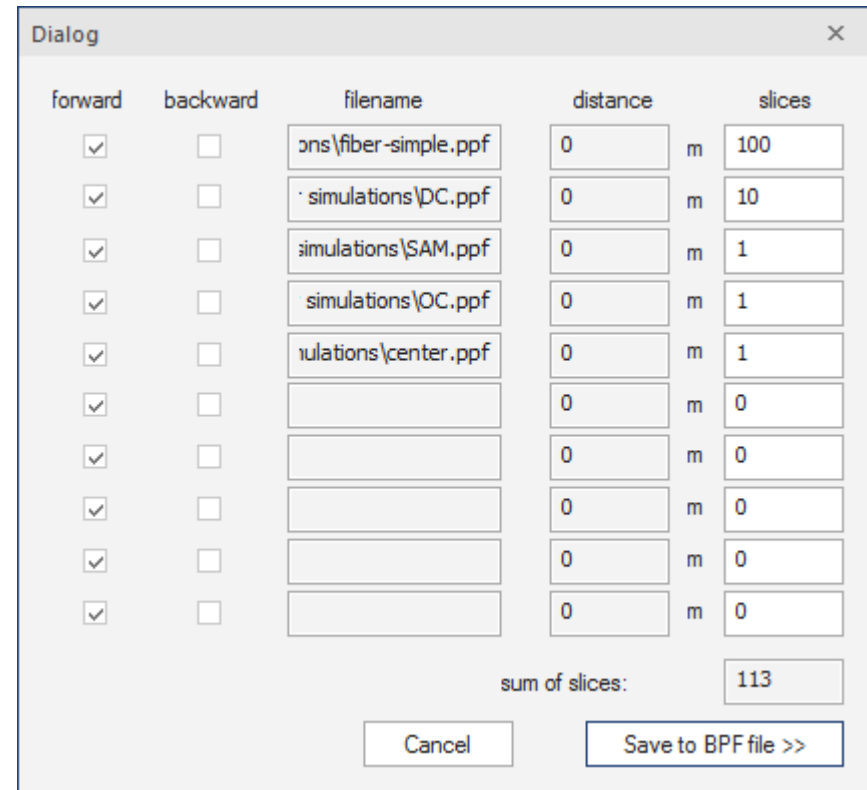
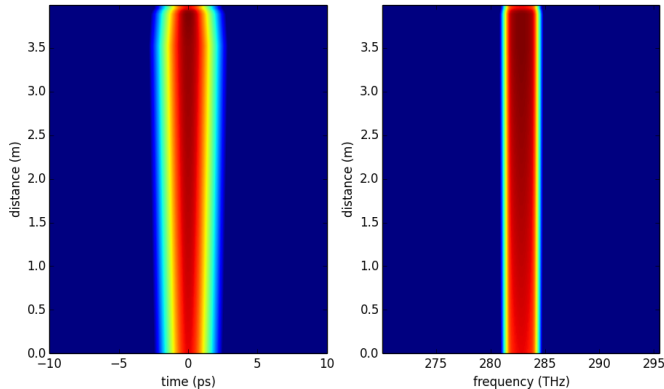
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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



### Intracavity evolution

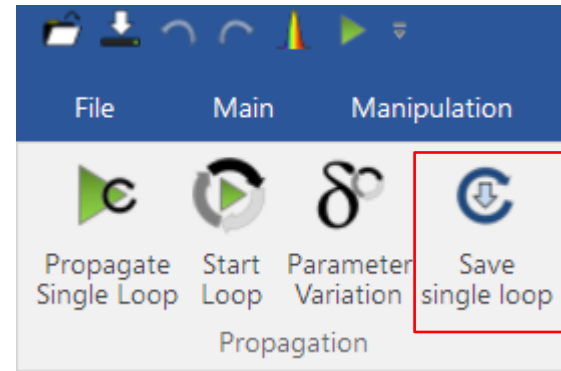
- (1) select stable solution from saved file
- (2) specify slices to be saved
- (3) post-process



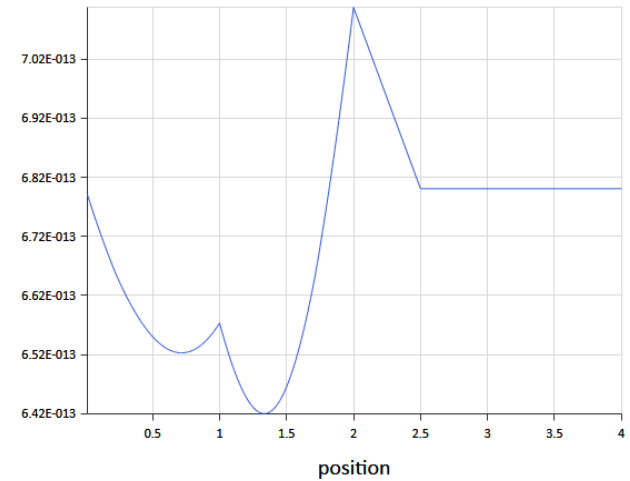
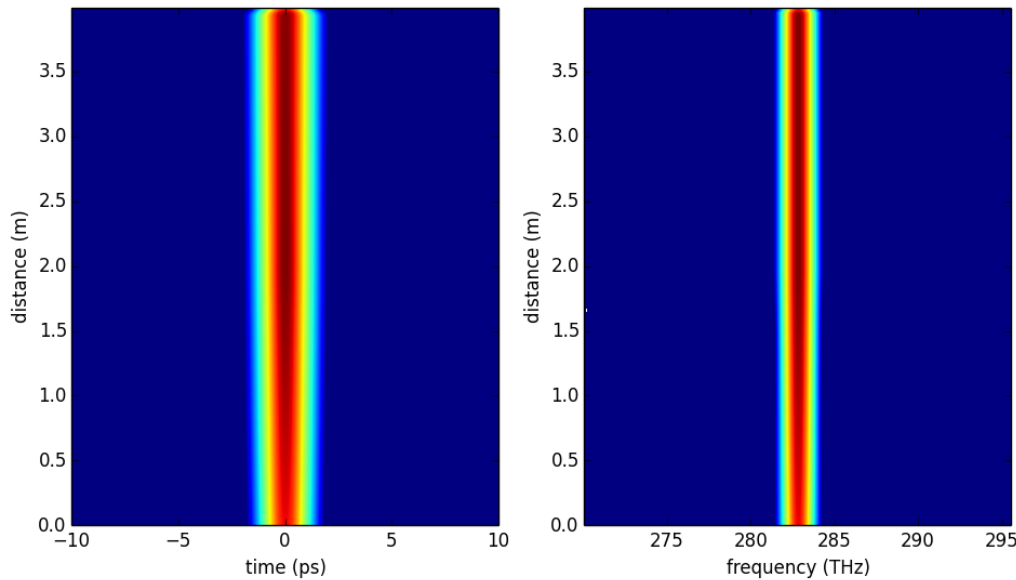


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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



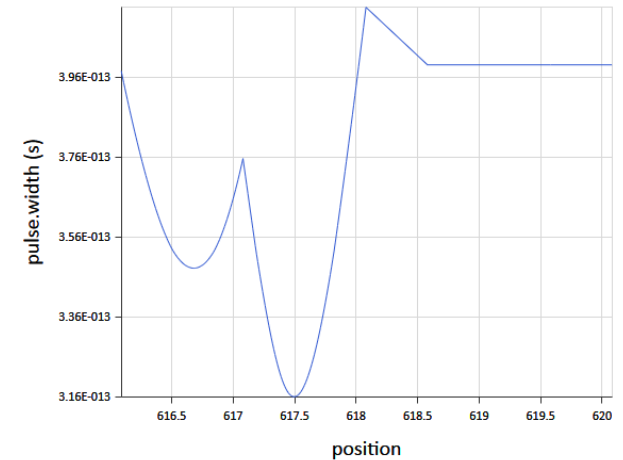
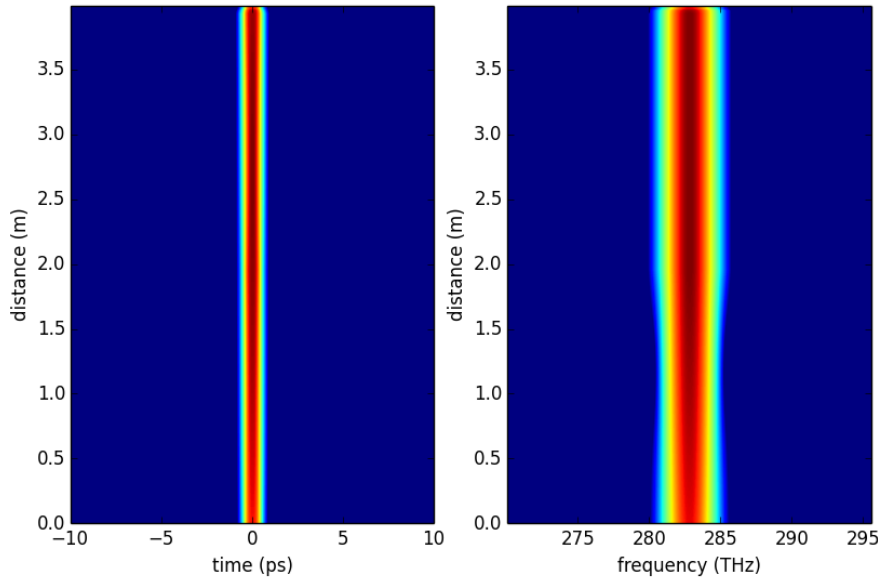
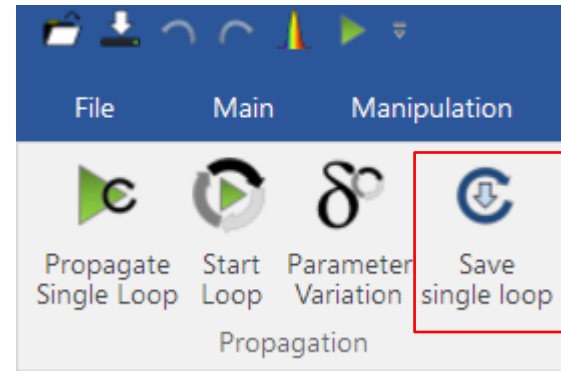
soliton solution:  $\beta_2@DC = -0.06 \text{ ps}^2$



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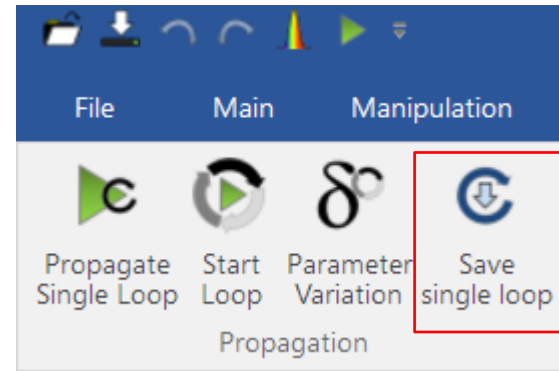
## Multi-Element Propagation: Example: Short Pulse Fiber Lasers

soliton solution:  $\beta_2@DC = -0.04$   
 $\text{ps}^2$

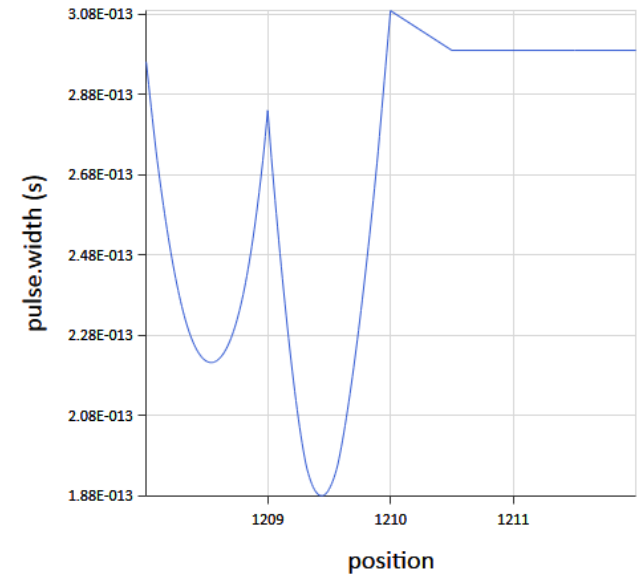
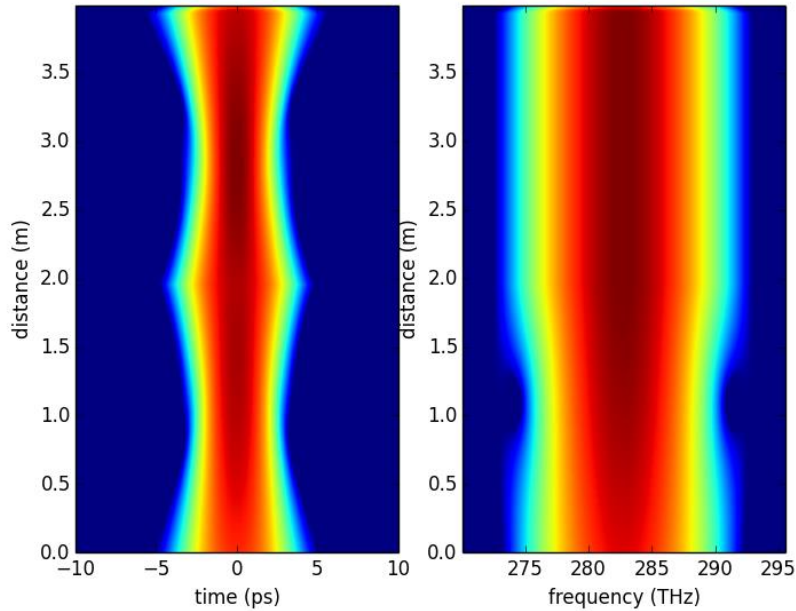


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## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



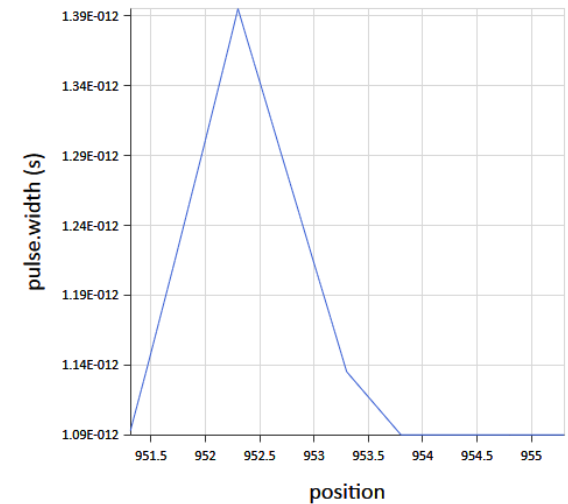
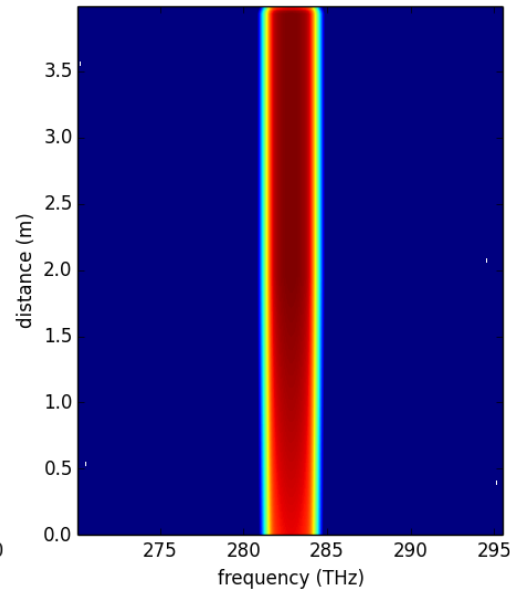
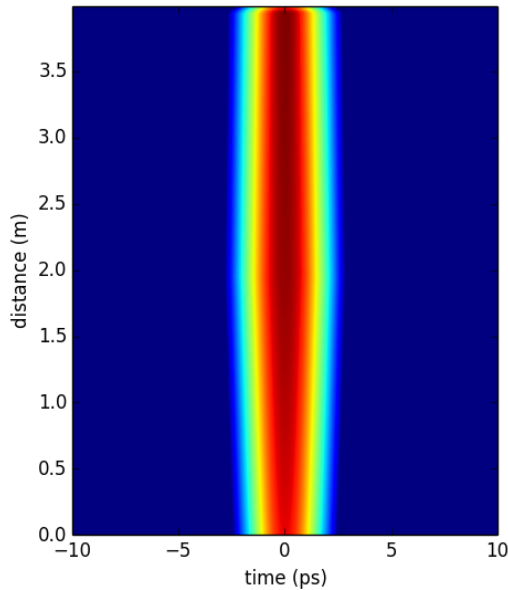
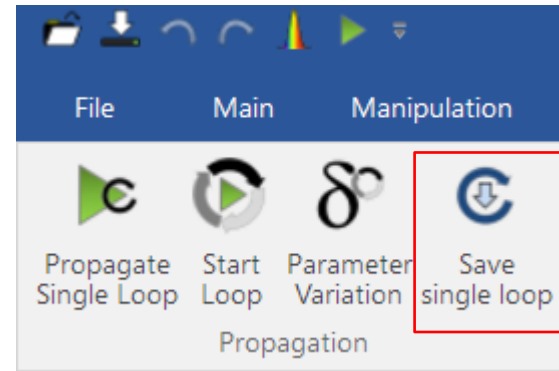
toward stretched pulse:  $\beta_{2@DC} = -0.03 \text{ ps}^2$



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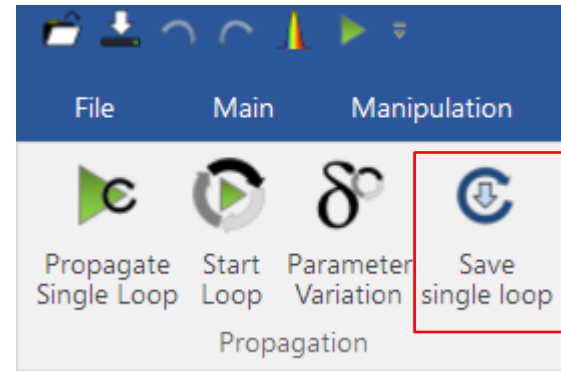
## Multi-Element Propagation: Example: Short Pulse Fiber Lasers

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



# lecture 5

## Multi-Element Propagation: Example: Short Pulse Fiber Lasers



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

