Details on nonlinear propagation

- Supercontinuum generation .. Page 2
 - o create a pulse
 - choose parameters
 - o press start
 - put result to memory
 - repeat with higher accuracy
 - o check measurements
 - o noise and coherence

- Export propagation data .. Page 11
- Dispersion and retarded time frame .. Page 15

Create a pulse with the following data:

Gaussian pulse with 100 fs duration, temporal windows +/-2 ps, 2k datapoints, temporal shift: -1 ps, energy 1 nJ (repetition rate and corresponding average power are not of importance here, the energy in the field determines the intensity and thus, nonlinear interaction), central wavelength of pulse and of data array center: 1060 nm, added quantum noise (one photon per spectral bin)



distance: 0.000 m position: 0.000 m energy: 999.981 pJ average power: 99.998 W roundtrip: 0

fiber is: NKT-ZD-975 with \sim 3 µm MFD, dispersion preselected. Length is 0.2 m and 100 steps. Switch on "write file" to save the propagation to a file for later post-processing.

Dispersion	Setup				*	
Taylo	r Series @ 1060	nm	prede	fined	air silica approx@1060nm (3.5µm: • acwidth=41(
					more fused silica @1060nm	
Beta1	0	ps/m	compensate at		NKT (core 1.7 µm zD=770,1250) @ 1030nm NKT (core 1.7 µm zD=750,1600) @ 1030nm	
Beta2	-0.01185	ps²/m	D	19.865851791	air silica approx@780nm air silica approx@1060nm (1.7µm=MFD 1.2µm) ZD@66	
Beta3	7.995e-5	ps³/m	s	air silica approx@1060nm (3.5µm=) S 0.187213 air silica approx@1060nm (5.0µm=)		
Beta4	-1.00392e-07		Terretori		NKT LMA 5 (5.0µm=MFD 3.95µm, zD=1035nm) @ 1030 NKT LMA 5 (5.0µm=MED 4.2µm, zD=1070nm) @ 1030r	
Beta5	1.21005e-10		from	0	air silica approx@800nm (1.7µm=MFD 1.2µm) ZD@665	
Beta6	4.0347e-14				Zhu et. al. @800nm (2µm=MFD 2µm) ZD@770nm Zhu et. al. @800nm (2µm=MFD 2µm) ZD@743nm	
Beta7	0				Cristiani et.al. Opt.Exp.12, 124 (2004)(MFD=3.47µm)ZD	
Beta8	Beta8 0		Dudley et.al. Rev. Mod. Phys., Vol. 78, I Layertech GTI 1000-1080nm - 250fs @			
Beta9	0				Hollow core 1060-02@1030nm zero dispersion @ all	
Beta10	0		✓ force ret	e (beta0=beta1=0)		
Beta11	0				m	
Beta12	0					
Beta13	0					
Beta14	0					
					copy dispersion	
grating compressor >>		Sa	ave		([nm].D[ps/nm/km].b2[ps²/m])	
OK Cancel		Lo	bad		copy beta2 + group delay [nm].b2 [ps²/m]. GD[ps/m]	
					$r_1, \dots, r_{k-1} \in R_k = \{1, \dots, 3\}, \dots = R_k = \{1, \dots, 1\}$	
100.	.000 GHZ				-120.0	

Propagation parameter × standard propagation • waveguide 0.0 loss 0.0 gain 0

0.0268343815513627 1/(Wm)

MFD

gamma

Esat

3

2.1205 _{µJ}

μm

simulation									
🖌 dispersion	✓ Raman								
🖌 spm / TPA	✓ self-steepening								
parameter									
🗴 temporal ga	ain saturation								
atona	1000								
steps	0.0000								
stepsize	0.0002 m								
distance	0.2 🛒 m								
measure and	parse								
🗹 write file	100								
adaptive local error	1e-07								
	presets: *								

Additionally, switch on all nonlinear effects Raman response function is simple Lorentz



self-steepening without shock term

term self steepening

$$\frac{\partial A}{\partial z} = \dots + i\gamma \left(1 + i\tau_{\text{shock}} \frac{\partial}{\partial T} \right) \left(A(T) \int_{-\infty}^{\infty} R(\tau) |A(T - \tau)|^2 d\tau \right)$$

$$\tau_{\text{shock}} = \tau_0 + \tau_A = \frac{1}{\omega_0} - \left[\frac{1}{n_{\text{eff}}} \frac{dn_{\text{eff}}(\omega)}{d\omega} \right]_{\omega_0} - \left[\frac{1}{A_{\text{eff}}} \frac{dA_{\text{eff}}(\omega)}{d\omega} \right]_{\omega_0}$$
additional shock time tau_A 0.0 fs
$$\checkmark \text{ use self steepening term} \qquad \textbf{x} \text{ exclude self steepening}$$

Propagation parameter

 \times

standard p	ropag	ation		*	Setu	p >		
waveguide								
loss	0.0 1/m							
gain				0	1/m			
MFD				3	μm			
gamma	0.026	834381	55136	27	1/(W n	n)		
Esat			2.12	05	μЈ			
simulation								
🖌 disp	ersion	✓	Rama	n		ך ך		
🖌 spm	/ TPA	√	self-ste	еер	ening			
paramet	er							
× temp	ooral g	ain satu	uration	1				
step	s				1000			
stepsiz	e				0.0002	m		
distanc	e			t).2 📳	m		
measu	ire and	Inarse						
✓ write fi	le	100						
ada	ptive	1e-07						
1000	Circr	presets	3:	*				

fiberdesk nonlinear pulse propagation

$\frac{\partial A}{\partial r} = \frac{\alpha}{2} A + \sum_{i} \beta_{i} \frac{t^{(i)}}{n!} \frac{\partial}{\partial T^{(i)}} A + i\gamma \cdot (1 - f_{i}) \left(1 + \frac{i}{\omega_{i}} \frac{\partial}{\partial T}\right) \frac{n(z, r)}{n!} \int_{-\infty}^{\infty} \frac{n(z, r-r)}{n!} \frac{dr}{dr}$

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propagate 0.2 m, 100 steps, firstly with 0.01 adaptive local error, save result via "memory" > "set", then **Undo** to return to initial field, change the adaptive local error to 0.0001, re-run and compare on log scale (numerical errors reduced).

lecture 2

 $\frac{\partial A}{\partial z} = \frac{\alpha}{2} A + \sum \beta_{z} \frac{i^{\alpha\beta}}{\sigma t} \frac{\partial}{\partial r^{\alpha}} A + i\gamma \cdot (t - f_{z}) \left(1 + \frac{i}{\omega_{z}} \frac{\partial}{\partial T}\right) \left(A(z, T) \int_{T} R(\mathbf{r}) \left(A(z, T - \mathbf{r})\right)^{2} d\mathbf{r}$

fiberdesk



The adaptive algorithm is bounded by the local error set.

If you rerun the propagation with the option "measure and parse" switched on, it can be analysed in the measurement graph



Example: supercontinuum generation with local error <1e-5

Measurements also allow for more detailed analysis:



Example: supercontinuum generation energy drop due to intrapulse Raman shift of the soliton, once it is "created"

File	Main	Manipulat	tion	Postproce	essing	Multi-Element	t Propagation	View	Wind	lows					
Δ	E Change p	ulse energy	3	@ °	opy spectrun	n (wavelength)	copy dispersion			8		🔹 noise variation		Set	Clear 🗹 display
	add quant	tum noise	U	L co	opy current v	view	scramble spectra	al phase			/赤\	👢 set z=0	<u>•</u>	Recall	M+
Field			Undo	Redo co	opy spectrog	jram (ASCII)			Start	parameter variation	RE Results		Compress	Swap	M-
Create					Edit					Propa	agation			Memory	

noise and coherence: same starting pulse as before via "Create Pulse Dialog", check "quantum noise added", then use "propagation" > "parameter variation" dialog with iterating pulse creation

Pulse Profile and	Data Array		×						
Half Intervall	2	🗘 ps +/-	ps						
FWHN	0.1	• ps +/-	ps						
TempShi	-1	🗘 ps +/-	ps						
phase	0	🗘 rad+/-	rad						
Size 2k (2	2^11) • T	ype Gauss	-						
wavelength	1060	✿ nm+/-	nm						
2nd order spectral	-10000	▲ fs² +/-	fs²						
3rd order	0	♠ fs³ +/-	fs²						
energy	1e-09	Ĵ J +/-	J						
average	100	\$ W +/-	W						
repetition rate	1e+11	🗘 Hz 🗌 cw							
scramble s	spectral phase (r	random phase)							
phase diffu	icion modell with	given linewidth							
🗹 add quantu	um noise (one pł	hoton per spectral	node)						
double pulsin	g								
separatior 0 ps relative 0 nagnitude									
✓ create field in	✓ create field in data arrav 1 □ create field in data arrav 2								
add field to d	ata array 1	add field to data	array 2						
ОК	Apply C:	ancel	reset						



By choosing "save to file" and selecting a base file, the parameter variation is saved and all results are store in a BPF file name "..., all x.bpf". This can be used for evaluation, see next slide



the saved files are now used for average spectrum and coherence calcualation via Postprocessing > coherence Postprocessing > average intensity Postprocessing > min / max $|g_{12}(\lambda)| = \frac{\left|\frac{\langle E_1^*(\lambda)E_2(\lambda)\rangle}{\sqrt{\langle |E_1(\lambda)|^2\rangle\langle |E_2(\lambda)|^2\rangle}}\right|$

past both results to clipboard and display in e.g. in Origin .







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You can also average a series of simulations or calculate the coherence along z.

It requires to save the fields along z during parameter variation. To do so, enable "write file" in the propagation parameter setup and run the parameter variation with "save to file" switched-on again. The results can be obtained by the Postprocessing items shown on top, which request you to select the base file for evaluation. Only 1D parameter variation can be used.

> 0,30 0,25 0,00 0,15 0,10 0,05 0,00 2 4 6 8 10 Frequency (a.u.)





Scale

- 7:300E-11 - 5:544E-11 - 3:121E-11 - 3:211E-11 - 3:231E-11 - 1:378E-11 - 1:378E-11 - 7:418E-12 - 7:418E-12 - 3:132E-12 - 3:152E-13 - 3:152E-13 - 3:152E-13 - 3:152E-13 - 3:152E-14 - 3:15

lecture 2 – export propagation data

To make a propagation graph outside of fiberdesk, you **need to have your propagation saved to a file** (switch on "write file" in the propagation parameter windows and do the propagation afterwards).

Then either use the python script to display what is saved in this propagation file (*.bpf) or use the internal function to copy such data as ASCII to the clipboard and paste it, e.g. in Origin.

To copy your data to the clipboard use the functions "Conversion to > ASCII matrix"

First, you will be asked for the BPF file, then choose the "comma/dot" convention.

In the following dialog, you can choose your setting. If you have selection a specific region already of the field, those values will be inserted by default.

Matrix Properties	×
spectrum nm from 661.80801887744 nm to 2669.019360242 nm	Matrix dimx 256 dimy 101
○ spectrum THz from 112.32307358490 THz to 452.99006577240 THz	□ normalize intensity for each slice
) pulse	✓ copy intensity ☐ copy phase
from [-1.501466275659] ps to [1.4985337243401] ps use comma instead of tab as separator	OK Cancel

Once it is copied, the important information are shown. You'll need those to set up your graph in Origin correctly.





In Origin, create a matrix with the same dimensions as your data.



Then select the matrix content and paste then clipboard data into it.

	1	2	3	4	5	6	7		D	
1	9.01344E-7	8.9075E-7	8.80402E-	8.70291E-	8.6041E-7	8.50751E-	8.41306E-	8.	^	
2	9.77678E-7	8.66423E-	8.80413E-	8.81655E-	1.03798E-	4.91632E-	9.24006E-	8.		
3	9.87083E-7	7.95931E-	8.74622E-	6.84171E-	1.25577E-	5.3317E-7	8.76564E-	9.		
4	9.67589E-7	7.61145E-	8.38711E-	3.11023E-	1.19037E-	7.4715E-7	9.70175E-	8.		
5	8.7444E-7	6.75446E-	7.17333E-	2.01647E-	8.6705E-7	5.59435E-	8.70873E-	8.		
6	8.06205E-7	5.56602E-	4.40244E-	5.44829E-	7.99195E-	4.04879E-	6.84173E-	8.		
7	6.96768E-7	5.52905E-	2.68017E-	6.91661E-	7.95001E-	3.61078E-	6.53819E-	8.		
8	5.72037E-7	7.32043E-	2.40336E-	5.24753E-	8.15957E-	3.78075E-	7.13178E-	8.		
9	4.48402E-7	8.54878E-	1.46745E-	2.536E-7	9.88515E-	2.70504E-	8.50684E-	7.		
10	3.45313E-7	8.24044E-	7.14568E-	3.51705E-	9.39453E-	3.44422E-	8.28942E-	7.		
11	2.75031E-7	9.222E-7	9.81212E-	6.62856E-	9.44349E-	4.47923E-	7.14883E-	7.		
12	2.2008E-7	2.5624E-6	1.05434E-	5.46206E-	2.6164E-6	6.0051E-6	8.13744E-	1.		
13	8.25228E-5	1.50242E-	2.65394E-	4.1941E-4	7.10878E-	0.00114	0.00188			
14	0.00375	0.00497	0.00811	0.0125	0.01859	0.02811	0.04406			
15	0.02076	0.02362	0.03127	0.03504	0.0331	0.02795	0.03322			
16	0.0081	0.01434	0.03776	0.12565	0.41535	1.00118	1.66619			
17	0.01526	0.02156	0.09391	0.49641	1.34598	2.35472	2.75423			
18	0.01064	0.02551	0.37942	2.1386	3.88054	3.22455	1.41111			
19	0.02233	0.02152	0.51019	3.28538	4.97333	2.57382	0.33483			
20	0.03519	0.00847	0.52861	4.21199	5.20233	1.56379	0.82745			
21	0.0118	2.40501E-	0.50245	4.3515	5.75595	1.0319	1.16387			
22	0.00469	0.00227	0.46574	4.18735	6.48336	0.86277	1.20599			
23	9.39514E-4	0.01728	0.52685	3.90241	6.89583	0.82631	1.54343		¥	
▲ ₽Ĩ(ASheet1 /	0.03740	0 6 4700	0.00466	e 00.440	< 70045	1 48100	>	.:1	

Let Origin draw a contour plot with the data and setup the appearance to your needs.



Here is an example of a logarithmic intensity plot for the temporal and spectral propagation.



In a future release (2022) fiberdesk 7 will have this feature internally.



Lecture 2 - dispersion and retarded time frame

Background: fiberdesk uses a complex data array for handling the field envelope A(T) numerically in a retarded time frame and uses the NLSE for propagation. Defining the pulse with a central wavelength λ_P can be done with a <u>data array center wavelength</u> λ_{DA} that differs from that <u>central wavelength</u>. Usually, you would require this options, but there are cases, where the wavelength extension during propagation makes it necessary to do so. In this case, nothing really changes during propagation.

Here is an example of the supercontinuum generation with an array centered at the pulse central wavelength and the other one, where it is not. Both produce the same result, if **"force retarded time frame"** is off in the dispersion settings. Especially the pulse stays in the co-moving (retarded) frame. This happens, because the Taylor Series used for dispersion is actually calculated around the center wavelength of the pulse center $\lambda_{TS} = \lambda_{P} - so$ no surprise.



Lecture 2 - dispersion and retarded time frame

If you repeat the simulation with the option "force retared time frame" switched ON in the dispersion dialog, fiberdesk subtracts the offset (beta0) and linear term (beta1, group delay) of the dispersion curve **at the array center**. This makes sense, if your pulse is also at the array center and both are not the same as the Taylor Series wavelength. However, for our example, where the array center is shifted to 1300 nm but both, Taylor Series and pulse center, are still at 1060 nm, the resulting group delay to 1300 nm is added and the temporal evolution is delayed by this amount, tilting the propagation. Nevertheless, the result of the envelope is of course the same (the initial pulse was temporally shifted to account for the delay, so that the propagation looks centered).



Alternative: If "force retared time frame" stays switched off, and you take the group delay directly into the value of beta 1, by pressing "compensate at" and a value of 1300 nm.





Lecture 2 - dispersion and retarded time frame

For other dispersion definitions, like Sellmeier, PCF and gas-filled hollow core fibers, the dispersion is not defined with any wavelength reference like the Taylor-Series but uses the full propagation constant β (or equivalent the refractive index *n*). Thus, you should **switch on** "force retarded time frame" to eliminate any group delay that results from this definition. Again, this removing of the group delay is done at the array center wavelength, so be sure, if you defined your pulse at this array center or not. Here is an example, if it is not retarded - despite the fact that, of course, the result is still correct (not shown here)!



(setting achieves a similar dispersion as the Taylor series before)

