License agreement and manual  $^{\!\!\!1}$ 

# fiberdesk™

last update 17.2.2025

<sup>&</sup>lt;sup>1</sup> some functions might be restricted to higher versions, appearance of graphics user interface depends on actual fiberdesk version and operating system



# Contents

ممطالالس

1.	Gen	eral		.3
	1.1	System re	quirements	. 3
		1.1.1.	Software requirements	3
		1.1.2.	Hardware requirements	3
	1.2	Software l	icense	.3
	1.3	END-USER	LICENSE AGREEMENT (EULA)	. 4
2.	Soft	ware Inte	rface: Overview	7
	2.1	File Menu	I	. 8
	2.2	Main		. 10
		2.2.1.	Create	10
		2.2.2.	Edit	11
		2.2.3.	Propagation	12
	2.3	Manipulat	ion	. 15
		2.3.1.	Data array resolution	15
		2.3.2.	selected data in current view	15
		2.3.3.	Misc	16
	2.4	Postproce	ssing	. 17
		2.4.1.	Panel: Load	17
		2.4.2.	Panel: Noise evaluation	18
	2.5	Multi-Elen	nent Propagation	. 20
		2.5.1.	Panel: Propagation	20
	2.6	View		. 21
		2.6.1.	Panel: Arrangement	21
		2.6.2.	Panel: Font	21
	2.7	Attached V	Windows	. 22
		2.7.1.	Propagation parameter	22
		2.7.2.	Measurements	40
		2.7.3.	Measurement graphs	41

	2.7.4.	Output	.41
2.8	View inter	face	43
	2.8.1.	View	.43
	2.8.2.	Spectrographic content	.45
2.9	Reference	s	. 46

## 1.General

## 1.1 System requirements

## 1.1.1. Software requirements

*fiberdesk* works stable on the following operating systems:

## Microsoft® Windows® 7 / 8 / 8.1 / 10 / 11

In addition, because fiberdesk uses the Thales Sentinel USB Protection System, its drivers for the usage of the USB hardware lock are also required for dongles purchased before 2019. Later ones are driverless, the driver is included in the Windows system.

## 1.1.2. Hardware requirements

Required processor: Intel Pentium or compatible

Required/Recommended RAM: 1 GB or more

## 1.2 Software license

ممطالالس

This program is **NOT** freeware, please see end-user license below. This means that you are not allowed to distribute it anywhere or to modify the executable or any data files within this program. Furthermore, you are not allowed to place this program on a Web Site, but you could place a link to the official website of this program. This program is provided as is. There are no guarantees for you about the safety of your data. Any suggestions and bug reports are welcome. To ask questions, get answers or report bugs visit the official web site.

Official web-site: www.fiberdesk.com



## 1.3 END-USER LICENSE AGREEMENT (EULA)

PLEASE READ THE END-USER LICENSE AGREEMENT CAREFULLY. BY COPYING, INSTALLING OR USING ALL OR ANY PORTION OF THE SOFTWARE YOU ACCEPT ALL THE TERMS AND CONDITIONS OF THIS AGREEMENT. IF YOU DO NOT AGREE TO THE TERMS OF THIS AGREEMENT, DO NOT USE THE SOFTWARE.

This End-User License Agreement (Agreement) is between You (You, Your or the Licensee) and fiberdesk (the Licensor/Producer). This Agreement authorizes You to use the copy of fiberdesk (Software) and accompanying documentation under the terms and conditions set out in this Agreement.

DEFINITION of 'Licensed Software' or 'Product': these shall mean the object code copy of the software programs described attached hereto and which are provided to You pursuant to this Agreement by the Licensor, together with related material in electronic and hard copy form (especially the USB hardware key), and together with all upgrades and updates that may be provided to You from time to time.

## 1. GRANT OF LICENSE

The Licensor grants You the non-exclusive right to use Licensed Software to run and operate the Licensed Software in accordance with the relevant documentation provided to you. Any other use is strictly prohibited. Especially, you may not copy, re-sell, rent, transfer or sub-license the right to use the Licensed Software. You have no right to receive, use, examine any source code or design documentation related to the Product. You may not reverse engineer, decompile, disassemble or otherwise attempt to discover the source code of the Software except to the extent you may be expressly permitted under applicable law to decompile only in order to achieve interoperability with the Software.

## 2. COPYRIGHT

معطااالس

The Licensed Software and all rights, title and interest in, including without limitation, all proprietary rights therein, are owned by the Licensors and are protected by international treaty provisions and applicable national laws. This Agreement does not constitute a sale of the Product or any part of it to You.

## 3. TERMINATION OF LICENSE

This Agreement will become effective from the first day You install the Licensed Software. Some parts, especially the availability of upgrades to you is effective from the day of purchase. You may terminate this Agreement at any time by sending back the Licensed Software and the Hardware key. Licensor may terminate this Agreement at any time upon Your breach of this Agreement, in which event, You agree to by sending back the Licensed Software and the Hardware key and all documentation and related



materials. Except for the License, the remaining terms of this Agreement shall survive termination.

## 4. LIMITED WARRANTY

Licensor warrants to You that the media on which the Licensed Software is located, is free from defects in materials and workmanship under normal use for a period of ninety (90) days from the date of delivery to You. This warranty is granted to You as the original purchaser. It is not transferable. The warranty is void if failure of the Licensed Software has resulted from accident, abuse or misapplication. Licensor will replace media not meeting the above warranty, which is returned to it or the authorized reseller within the ninety (90) day warranty period. If Licensor is unable to deliver a replacement media free from defects in materials and workmanship, You may terminate this Agreement by returning the Licensed Software. The amount paid by You for the Licensed Software will be refunded.

## 5. Limitation of liability

In no event shall Licensor be liable to you for any damages arising out of the subject matter of this agreement or the product under any contract, negligence, or strict liability, for any indirect, special, incidental, or consequential damages, including but no limited to lost profits, costs of procurement of substitute goods or services or property, personal injury, interruption of business howsoever caused arising out of the use or inability to use the licenced software, even if Licencor has been advised of the possibility of such damages. In the event that any exclusion contained herein shall be held to be invalid for any reason and Licensor becomes liable for loss or damage that may lawfully be limited, such liability shall be limited to the amount paid by you to Licensor for the licensed software.

## 6. Updates / UPGRADES

معطااالس

In order to ensure that the software functions properly, the Licencor / fiberdesk publishes **updates** (by sending it to you by email or putting it on the official webpage). If the Software is an update, you must possess a valid license to its version to use this update. Updates improve the workings of the software, i.e. remove bugs. The user is responsible for proper configuration of the software updating process to provide for the highest possible level of functional reliability. Updates may be licensed to you by fiberdesk with additional or different terms, please see comments e.g. in the corresponding blog on the webpage.

Updates are distinguished from **Upgrades**: Upgrades to a new version, which includes new features that were not available in Your version, require a new license that must be purchased (please contact fiberdesk for a quote to Upgrades). However, upgrades are free if released within one year after purchase of Your license but this time period of one year is then not extended.



If a new version is available, updates to previous versions are not guaranteed after one year after purchase of Your license. In that case you need to purchase a new license for an upgrade and update.

Updates and Upgrades may have a different behaviour, for instance in terms of dialogs or file format. The change must not be tracked within fiberdesk, so that there is no liability of fiberdesk to read files saved with a previous version. The customer might keep the older version in order to be able to read files.

## 7. FURTHER LIMITATIONS / SCIENTIFIC BUGS

The Licensor is not responsible for any mistakes in the documentation or scientific errors arising from the results the software produces. However, any of such mistakes can be reported to the licensor and can be updated, if possible and necessary.

8. Support

Technical support is given for any software bug or technical question concerning the functionality of the software. Scientific support, which means that scientific question or problems are solved by the fiberdesk support, are not included in the license. The Licensor may ask such questions, however, the decision for answering is done by fiberdesk. Likewise, no consulting about scientific topics is included in the license.

9. Referencing Fiberdesk

If a scientific citation of fiberdesk is possible use a phrase similar to the following:

[X] simulations done using fiberdesk, <u>www.fiberdesk.com</u>

More specifically, if the predefined dispersion values are used for any kind of publication, please contact the author (webmaster@fiberdesk.com) for information on copyright and citation.

## 10. General Terms

معطااالس

If any part of this agreement is found to be invalid, illegal or unenforceable, it will not affect the validity of the balance of this agreement, which will remain valid and enforceable according to its terms. This Agreement sets out the entire understanding between You and the Licensor and may only be amended in writing in a document signed by both parties.

## 2. Software Interface: Overview

The general graphical layout of **fiberdesk** is shown inFig. 2.1.

エエンドルト・		project - Rondosk			- 0 ×
File Main Manipulation Postpr					0
🔥 🖉 Changa pulsa energy 🥱 🦵	Copy spectrum (wavelength) copy dispersion	A Tota variation and Sat Casa and Anterna			
Field add quantum noise Undo Ted	o copy current view T0 Start parameter	The Picture Compress Root M+			
Create	tdt	Population New Mercey			
Propagation parameter * 0 3	< Measurements * 4		View Properties		+ 3 ×
Losd v Sinv v	user defined resourcements >>		2.Logiview w	A Save View w	
standard presention * Seture a	Position	Impose Helds/WHM weth=1.34 ps. Autocontexton with=50.591 fs Held Specification with.m=50.0414 em     Specification with m=50.0414 em     Specification with m=50.04144 em     Specification with m=50.04144 e	ME 61 Sourt		0
general	(90) index = 100	80	A Ver		~
free parameters	(H1) summit position = 0.200 m		View	View 1	
measure and parse	(H2) accumulated distance - 0.200 m	70 28.0	show the	Field	
percent in	Data Array	60	a x-Axis	These	
loss 0.0 I/m	(H3) datapoints = 2543	\$ 200	start (ps)	-2.000977	
gain 0 L/m	There and Field		stop (ps)	1,999023	
mode dameter 3 µm	Temporal Held		nomalized values on y-axis	(C)	
ganna 0.0208343811 1/(Wm)	(H4) energy = 527,500 pJ (H5) ann mawr = 231,975 W	30	loganthmic auto acale	-	
dieds	(H0) repetition rate = 250 000 GHz		from minimum (%)	0.000000	
dispersion	(HT) contar offset shift = -412.542.5s	20 76	to maximum (%)	102.000000	
SPR/TPA	(HE) FWHM width = 1.134 ps		show real		
self-steepening	(H10) skewness = 0.341		show knog show obase		
O gain saturation	(H11) Austonia = -0.285	-1.40 -0.17 0.07 0.13 1.40 000 200 330 400 500	A Moc		
O UE	(H12) marchage = 7.45 rad (H12) marchager = 535 325 W	Time / ps Prequency / Titz	tied size zoom (%) tile space	100	
autority.	(H14) peak power = 788.591 W		horizontal split top	50	
steps 100	(H15) peak power = 721.059 W		vertical split left	50	
stepsize 0.002 m	(H16) peak power = 8.828 kW (H16) peak power = 8.828 kW		vertical split light	50	
distance 0.2 m	Spectral	Temporal Propagation Spectral Propagation	inner space left	3	
adapõve 10-7 prm -	dDD control = 24 20 cm		inner space right inner space top	3	
		06.0	inner space boftom	3	
	Measured Graphs + 1	1001 × 1001			
	Ki - Padia current position				
	MD - Position Index * 100 v	E 0.120			
		ê asso			
		ă ă			
		000.0			
		000.0			
		0,000 <sup>1</sup> 140 0.70 0.00 0.73 1.40 0000 <sup>1</sup> 000 200 300 400 500			
		Time Inf. Exercise (Thir			
		inner jar inseparate insepar			
		Message Output *	×		
		Recretes is up to cate. No new version available.			
		OPED TOOL     OPED TOOL			
		waterier is to programmer to consist on the state state.			
		4			
fberdesk					UE NUM RE

Fig. 2.1: Graphical User Interface (GUI).

**fiberdesk** uses a ribbon menu (**Fehler! Verweisquelle konnte nicht gefunden werden.**) with advanced features and easier access to the command structure. It is explained in section 3.1.

Beside the main view, additionally information and parameter setups are displayed in four attachable windows (dockable panes). These four windows are:

7

- the propagation parameter pane
- the measured value pane
- the output pane
- graph pane

More details can be found in section 3.2.

## 2.1 File Menu



Fig. 2.2: The file menu.

The file menu (Fig. 2.2) includes all command to control data connected to a file.

## New

Creates a new project and sets most controls to standard values.

## **Load Project**

Opens an existing project that has been saved. When attempting to open a project file, the following dialog box will appear:



The *file* includes the *data array* that samples the electric field, as well as the element container (see File Description), propagation parameter, view definitions, and dialog parameters. You can choose which parameters to reload, allowing you to retain certain parameters that you have already set or need to reuse. This provides you with control over maintaining specific settings.

## Save / Save As ...

Saves the current project with all settings.

Load propagation parameters ...

Loads the propagation parameters from a specific file.

Export propagation parameters ...

Saves the propagation parameters to a specific file.

## Import spectrum (ANDO)

Imports an ANDO spectrum file and sets the phase to zero.

*Important for ASCII/ANDO imports:* The actual data array dimensions are kept constant, thus, be sure to provide enough datapoints and the right spectral range for the given file. This means, first "create a pulse" with the right bandwidth and central wavelength.

## Close

Closes the current document file.

Exit

ممطالالل

Quit fiberdesk.



## 2.2 Main

File	Main	Manipulatio	on I	Postproc	essing	Multi-Element Pro	opagation	View	Windows							
Field		lse energy ım noise	Undo	Redo	copy spec copy curr copy spec	trum (wavelength) ent view trogram (ASCII)	copy dispers T0 scramble sp	iion ectral phase	Start	parameter variation	RE Results	Plotter	I noise variation ↓ set z=0	Compress	Set Recall Swap	Clear display M+ M-
	Create					Edit						Propagat	ion			Memory

## 2.2.1. Create

## Field

This calls the main dialog for setting up a simple pulse and the corresponding temporal and spectral parameters for the simulations.

## Size (DP)

number of data points of the field

## Туре

shape of the temporal pulse intensity (Gauss, sech<sup>2</sup>, Parabolic, Rect) Additionally, one can select a specific spectral shape

**from file ..** select a specific field file that has been saved before (menu File>Save Field) in the \*.fieldx format.

## Half interval (HI)

Half of the temporal width of the complete field. The dwell time is therefore given by  $t_{DW} = 2 * HI / DP$ . Of course, this sets the spectral width and resolution due to Fourier theorem.

## Pulse duration (FWHM)

full width at half maximum of the pulse width

## TempShift

offset of the position of the pulse center  $\boldsymbol{\tau}$ 

## Double pulse separation $\tau_{\text{dp}}$

- Relative magnitude R
- Center wavelength: central wavelength of the pulse spectrum
- Chirp: linear spectral chirp in fs<sup>2</sup> with its definition:

ata arrav setup			
ata anaj setap	Size	2	rk (2^11) 🔹
array conter w	avelenath		1060.0 • * nm
undy center n	lf intorvall		2 *
vacuum length (full i	ntervall)		0.001199169832 m
vacuari tengar (rai t			
Type Gauss *			
pulse duration (FWHM)	0.1	÷	<ul> <li>ps (sets spectral width)</li> </ul>
TempShift	-1.5		* ps
phase	0	*	rad
,			• 100
wavelength	1060.0	٠	t nm
2nd order spectral phase	0		‡ fs²
3rd order	0	٣	
energy 🔽	1e-09	÷	¢ 0
average power	250	14	≎ w
repetition rate	2.5e+11		tHz ✓ cw
scramble spectral pha phase diffusion mode add quantum noise (r double pulsing separation 0 •	ase (random ell with given one photon p ps nag ps mag	pha line per s elati nitu	se) ewidth spectral node) ve 0 + e field in data array 2
add field to data array 1	a	dd f	ield to data array 2
52			



$$A(T) = \dots e^{-i\frac{C}{2}(\omega - \omega_0)^2 - i\frac{C_3}{6}(\omega - \omega_0)^6}$$

The double-pulse separation, temporal shift and relative magnitude is calculated from the complex single-pulse field amplitude A(T) by

$$A_{new}(T) = \frac{(1-R)A(T-\tau_{dp}+\tau) + (1+R)A(T+\tau_{dp}+\tau)}{2}$$

Scramble spectral phase (random phase)

It sets a random (uniform distribution) phase in the spectral domain, thus, the spectral lineshape is maintained, but the temporal domain does not contain pulse information anymore.

Phase diffusion modell with given linewidth

It randomizes the spectral phase according to Ref. 11.

Add Quantum Noise (one photon per spectral node)

Adds the energy of one photon in the spectral domain with random phase. Thus, energy might not be conserved due to the complex addition of the values.

## Change pulse energy

Changes the pulse energy of the current pulse.



## Add quantum noise

Adds one photon per spectral mode with random phase.

## Use second field

Enables or disables the second data array for a second field that can be coupled through the NLSE by XPM or birefringence.

Please ask webmaster@fiberdesk.com for details, currently not contained in commercial versions.

## 2.2.2. Edit

## Undo

Undo last change in the dataarray. The selected area is set to the full size of the dataarray.



## Redo

Restore last undo step.

## Copy spectrum (wavelength axis)

Copy spectrum to clipboard as ASCII. The wavelength axis is obtained by linear interpolation from the frequency axis.

## **Copy current view**

Copy current view to clipboard as enhanced metafile (EMF).

## **Copy spectrogram as ASCII matrix**

If spectrogram view is active, copy all values to clipboard as ASCII matrix.

## 2.2.3. Propagation

## Start

Start the propagation using the current settings.

## **Parameter variation**

Vary one or two parameters of a propagation using the dialog in Fig. 2.3.



## Fig. 2.3: Parameter Variation Dialog.

Depending on the parameter to vary, the field is create with the new parameter and propagated using the parameters set up so far. All measurements are done after propagation so that the results can be displayed without a new calculation.

The parameters are varied linearly or with equal logarithmic setup, if "log steps" is chosen.



## A second parameter can be varied if selected.

The resulting fields of the parameter variation propagation can be saved or reloaded by choosing a base file:

✓ save / load	save / load D:\OneDrive\Dokumente\fiberdesk wo code\test projects\2022 parameter variation\vary-base.pv-xml					
Reload	$\checkmark$ neglect saved plot content settings	reload propagation parameter globally	✓ load user defined measurements			

## The following files are saved for example:

Bibliothek "Doku	Bibliothek "Dokumente" manual	
inonau		Name
Name	Тур	base, all x at y=2.bpf
hace all vatur-1 hof	RDE-Datei	base - propagtion at x=9, y=2.bpf
	DF1-Datei	base - propagtion at x=7, y=2.bpf
base, all x at y=2.bpf	BPF-Datei	base - propagtion at x=0, y=2.bpf
base, all x at y=3.bpf	BPF-Datei	base - propagtion at x=4, y=2.bpf
base, all x at y=4.bpf	BPF-Datei	base - propagtion at x=3, y=2.bpf base - propagtion at x=2, y=2.bpf
base, all x at y=5.bpf	BPF-Datei	base - propagtion at x=1, y=2.bpf
base, all x at y=6.bpf	BPF-Datei	base, all x at y=1.bpf
base, all x at y=7.bpf	BPF-Datei	base - propagtion at x=9, y=1.bpf base - propagtion at x=8, y=1.bpf
base, all x at y=8.bpf	BPF-Datei	base - propagtion at x=7, y=1.bpf
base, all x at y=9.bpf	BPF-Datei	base - propagtion at x=5, y=1.bpf
base, all x at y=10.bpf	BPF-Datei	base - propagtion at x=4, y=1.bpf base - propagtion at x=3, y=1.bpf
👔 base.pvf	PVF-Datei	base - propagtion at x=2, y=1.bpf base - propagtion at x=1, y=1.bpf
	and the second second	

Fig. 2.4: File structure in the parameter variation dialog (left) without and (right) with individual propagation saved.

Each individual propagation can also be saved by combining the "save to file" option with the "write file" option in the general setup for the propagation parameter outside this dialog.

## Set z=0

Set propagation position to zero.

## include noise (deprecated, you should use the parameter variation tool)

Starts a propagation multiple times by adding specific noise sources on the initial pulse. The number of propagation is given by "Number of simulations".

- input phenomenological quantum noise: one photon with random phase is added per frequency intervall
- shot noise (each time intervall): Poisson noise on each temporal datapoint
- shot noise overall energy: poisson noise variation of the pulse energy

se		
Number of simulations	128	
input energy fluctuations	0	%
input phenomenological quantum	noise	
shot noise (each shot noise	time inter (total <mark>e</mark> ne	vall) 📃 ergy) 📃
		last clicas in haf



If the option "save last slice in bpf" is chosen, the result of each propagation is saved in a file for further processing and analysis, see menu "postprocessing". In combination with the usual "write file" option, each full propagation is saved in a file array.

## Plotter

The plotter allows to plot the measurement results in a more customized way. The x and y axis can be scripted and the design in detail configured.



## Compress

Minimizes the autocorrelation FWHM by a linear propagation (dispersion only) using the dispersion values given in the dialog.

	Initia	al Stepsize	0.05	m	
wavelengt	th	1060			
Beta2	0.2			ps²/m	
Beta3	0			ps³/m	
Beta4	0				
Gratin Compres	g ssor	Prism pa SF18	ir:		
OK		Cance			

## 2.3 Manipulation

File	Main	Manipulation	Postp	rocessing	Multi-Eleme	nt Propagation	Vie	ew	Windows	
$\bigwedge$ double $\bigwedge$ double $\bigwedge$ half te	e temporal v e temporal v mporal win	window by replica a window by zero filli dow	ddition ng	☆ double sp ☆ half spec	zero	zero outside selection	zero imag	zero real	zero phase	Broadening shift
		Data array resolut	ion			selected dat	a in curre	ent view	i .	Misc

## 2.3.1. Data array resolution

## double temporal window by replica addition

Doubles the number of points by increasing the temporal range and copies the field to that areas. Resets the selection as well.

## double temporal window by zero filling

Doubles the number of points by increasing the temporal range and set the new datapoints to zero. Resets the selection as well.

## Half temporal window

Halfs the temporal windows symmetrically.

Doubles the number of points by increasing the spectral range. Resets the selection as well.

## Double / half spec

Doubles / Halfs the number of points by decreasing the spectral range. Resets the selection as well.

## 2.3.2. selected data in current view

## Zero

Set field to zero for all data points inside the selection.

## Zero outside selection

Set field to zero for all data points outside the selection.

## Zero phase / real / imag

Set values to zero in the whole selection.

Panel: Misc

## exchange fields

If two fields are used, its content is exchanged.

merge fields

معملالالل



If two fields are used, its content is merged in the first field.

## 2.3.3. Misc

## shift

ممطالالس

Allows to shift the field in time.

Phase shifts		×
time shift		
OK	Cancel	



## 2.4 Postprocessing



## 2.4.1. Panel: Load

## single slice

Reload a previously saved slice from a beam propagation file. Choose the slice number by using the following slider control or manually type the requested slice:

select slice					×
	1	of	101	reload propagation	

During this slice selection, every view control (e.g. data selection and zoom) can be used. Use this function in prior to following visual post-procession tools (e.g. movie creation) or to check the slice from a long term propagation.

Reload propagation to recreate 2D propagation views.

Panel: Conversion to ...

## **AVI movie**

ممطالالس

The movie is created by using the current view. The following steps have to be done:

Select a previously saved propagation file.

Using the AVI creation dialog, one can specify the number of frames per second and an end delay, which shows the last frame for that time.

If the propagation is longer than required for the AVI use the option "force to stop at".

If a specific temporal window is given, the current selection is overwritten and the values of the dialog are used. This can be used to create an artificial co-moving time frame.

Choose a name for the AVI file, and then press OK to accept the settings. After the first screen is saved to the AVI file, select a compression scheme. The recommended scheme is "MS Video 1".



frames per s eno	econd 10 d delay 4	1/s sec	frames length	300 30	sec			
Force force t	to stop at	1 owing tempora	l window	m		Video Kom	o <mark>komprimierung</mark> primierer: e Finzelbilder (unkomprimie <del>v</del>	OK
start end	from -12 from -12	ps	to to	12 12	ps ps	Cine Inte Inte Inte Mici	apak Codec by Radius (4:2:0 Video V2:50 I Indeo(R) Video R3:2 I IYUV Codec rosoft RLE	Konfigurieren
Filename:	fiberdesk	ОК	Can	cel	.avi	Mice Mice Mice Mice Volle	osoft Video 1 rosoft H.263 Video Codec rosoft H.261 Video Codec rosoft MPEG-4 Video Codec V rosoft MPEG-4 Video Codec V e Einzelbilder (unkomprimiert)	

## **ASCII** matrix

Chose a previously saved propagation file. An ASCII copy of the temporal or spectral evolution is copied to the clipboard for further processing in other softwares, e.g. ORIGIN<sup>™</sup>. In the corresponding dialog, please chose the content, which is to copy and the dimensions of the ASCII matrix. Choose "normalize each slice" to do so.

💿 sp	ectrum nm				Matrix	
from	927.7	nm	to 1156	nm	dimx	1000
			s of		dimy	101
Osp	ectrum TH:	z			_	normalize
from	259.1	THz	to 323.1	THz		each slice
Ори	ılse					C

## 2.4.2. Panel: Noise evaluation

#### mean and variance

Especially, if the propagation file contains data from the noise variation simulation, this function helps you to calculate the mean (average value) and the variance of the data. Decide if the spectrum or temporal field should be used for the evaluation. The result is copied to the clipboard in a three-column ASCII format.

IberD	esk		1
?	Use spe	ctral instead of	temporal information
		·	

## min/max

The minimum and maximum values in the spectral or temporal domain are calculated from a previously saved propagation file. The result is copied to the clipboard in an ASCII format.

iberdesk

nonlinear pulse propagation

#### coherence

Calculates the coherence (see [4]) from a single propagation file according to the

following equation:  $|g_{12}(\lambda)| =$ 

$$= \frac{\left\langle E_{1}^{*}(\lambda)E_{2}(\lambda)\right\rangle}{\sqrt{\left\langle \left|E_{1}(\lambda)\right|^{2}\right\rangle \left\langle \left|E_{2}(\lambda)\right|^{2}\right\rangle}}$$

## **RF spectrum**

Calculates the radio frequency spectrum of a series of pulses  $S_i$  by taking the Fourier transform of the array  $|S_i|^2$ . The temporal spacing  $t_{i+1}$ - $t_i$  is given by the current repetition rate setting  $f_R$ , thus, the radio frequency range is  $-f_R/2...f_R/2$ . The result is copied to the clipboard in ASCII format.

#### <RIN> vs. z

Calculates the average relative intensity noise (RIN) along a previously saved propagation distance. A number of propagation files are required for this function. Each propagation file contains a single propagation. The propagations just differ in their noise properties.

## <Spectrum> vs. z

Calculates the average spectrum along a previously saved propagation distance. A number of propagation files are required for this function. Each propagation file contains a single propagation. The propagations just differ in their noise properties.

#### coherence vs. z

Calculates the coherence along a previously saved propagation distance. A number of propagation files are required for this function. Each propagation file contains a single propagation. The propagations just differ in their noise properties.

## Panel: Misc

ممطالالس

## **Measurement of BPF file**

This function measures all values along a previously calculated and saved propagation file (\*.bpf).



## 2.5 Multi-Element Propagation

File	L ▶ ₹ Main M	lanipulation	Postproces	sing	Multi-Ele	ment Pr	opagation	View	Windows		
Propagate Single Loop	Start Par Loop Va	ameter Sa riation single	ve hnf	Elemen 2 🗸	X It Element 3▼	Element 4 🔻	X t Element 5▼	Element Eler	¢ X nent Elemen ▼ 8 ▼	X t Elemen 9 V	X t Element 10 ▼
Propag	Propagat ation p	ion ar 🔻 4	× 1	Propagati Assign pr	e << hnf : opagation	>> file to e	lement	ntainer			
standard wavegui	propagation de	▼ Setup >		Save <<	nnf >> ward loop			n Out	gx		
loss	C	1/m		update af	ter forwar	d propa	gation		og y		
MFD	4.0512	2 μm	× 1	use in bac update af	ckward loo ter backw	op ard prop	bagation	-0.06	-0.04		-0.02
Esat	3.867	γμJ	~ 1	ave field	after back	ward pr	opagation				

Within this category previously saved propagation files can be assigned to a button (in the Element Container) for fast (or often required) propagations. Additionally, all propagation files can be used in a loop in "forward" and "forward and backward" direction. One can also directly load and save the assigned propagation parameter file. Use this panel for e.g. simulating short pulse resonators.

The buttons icon is changed to represent the possible usage:



Upper row:

- forward propagation,
- update after forward propagation
- save field after forward propagation

Lower row:

- backward propagation,
- update after backward propagation
- save field after backward propagation

## 2.5.1. Panel: Propagation

## Start Loop

Executes the loop propagation, type the number of loops and start by pressing "OK". The options "write to a propagation file" and "measure values" are switched off during a



loop propagation. After each round trip the field can be saved to a \*.bpf file with the option "write slice to bpf file".

oop propagation			Dialog					
switch off individual "live" s	ettings		forward	backward	filename	distance	L r	slices
write slice to bpf file	100	frames				0	m	0
maximum number of loops	1000					0	m	0
Automatic stop of loop		_: 				0	m	0
stop if converged						0	m	0
ondition	-					0	m	0
nimum change of 1e-006	_	ОК			5	sum of slices:	[	0
for at least 100	loops	Cancel			Cancel	Save	to BPF	file >>

#### save single loop

The propagation within one roundtrip can be saved to a file by using this panel entry. The corresponding dialog resembles the loop structure and one has to specify the slices belonging to each segment.

## 2.6 View

File Main Manipulation	Postprocessing Multi-Element F	Propagation <b>View</b> Windows	
	Calibri • A Select here or in the properties I •	show text panel	۵ ۵ ۵ ۵
single on top of side-by-side four each other		Text panel View options Setup	white color grey black focused
Arrangement	Graphs	Text Panel	App Look

This manages the configuration and presentation of the view.

However, the main setup is done using the attached window "View Properties" described in the next section.

#### 2.6.1. Panel: Arrangement

Select between one and four views simultaneous on the screen as indicated by the icons.

#### 2.6.2. Panel: Font

You can choose to display different main fonts and its relative size.

#### Panel: Text

Select "Text Panel" to show a summary of the main variables, like distance and energy.

#### **Text Panel options**

Select the information that should be shown in the "Text Panel".

## **View Setup**

Set up the measured variables for each view and other details.

## 2.7 Attached Windows

📂 💾 🗧	n 🦟 🛝 I	> ⇒				
File ✓ Message ✓ Propagat	Main Output ion Parameter	Manipulation Measuremen Watch	Postprocessing	Multi-Element Propagation	View	Windows
	Do	ocking Control Bars				

Each docking control bars can be switched on or off using the windows category. They are described in the following:

## 2.7.1. Propagation parameter

The propagation parameter window shows most parameters required to setup your simulation and are related to the equations that are numerically solved.

There are six different propagation methods available: "standard fiber", "saturable absorber", "pulse injection", "custom filter", "rate equation gain", "polarization manipulation" and "nonlinear loop mirror". They can be chosen within the propagation parameter window, see next figure.

Propagation parameter	×		
🗁 Load 💌 🔚 Save 💌			
🗞 standard propagation 🔹 Setup	>		
general			
define free parameters			
measure and parse 100 write file	>		
waveguide			
loss 0.0 - 1/	m		
gain 0 - 1/	m		
mode diameter 10.0 👻 µm	ı	Propagation parameter	×
gamma 0.0024150943 1/(W n	n)		
effects		🗁 Load 🔻 🔚 Save 💌	
Raman		standard propagation • Setup >	
self-steepening		🖎 standard propagation	
		A saturable absorber	
numerica		y pulse injection	
stens 100 *			
stensize 0.01 m			
distance 1.0 - m		🗼 rate equation gain	
		field manipulation	
local error		▼ 1/m	
		× polarization element	
		p nonlinear loop mirror 1/(W m)	

## **Standard Propagation**

This propagation is based on solving the nonlinear Schrödinger equation. If all effects are considered, it has the following form:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A + \int_{-\infty}^{\infty} \frac{g(\omega)}{2} \widetilde{A}(\omega) e^{-i\omega\tau} d\omega + \sum_{n\geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial \tau^n} A + i\gamma \cdot \left(1 + i\tau_{shock} \frac{\partial}{\partial \tau}\right) \left(A(\tau) \int_{-\infty}^{\infty} R(\tau) |A(\tau-\tau)|^2 d\tau\right)$$
 2.1

The normalized functional form R(t) includes the vibrational contribution of the delayed Raman responds to a fraction of  $f_R$  and the instantaneous electronical contribution to a fraction of (1- $f_R$ ).

$$R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$$

معطااالس

The shock term is described by a single time scale  $\tau_{\text{shock}}$ , which is defined as [6]:

$$\tau_{shock} \cong \tau_0 + \tau_A = \frac{1}{\omega_0} - \left[\frac{1}{n_{eff}} \frac{dn_{eff}(\omega)}{d\omega}\right]_{\omega_0} - \left[\frac{1}{A_{eff}} \frac{dA_{eff}(\omega)}{d\omega}\right]_{\omega_0}$$





The parameter  $\tau_A$  can be changed in the "self-steepening" dialog, see below.

To change the parameters in this equation, the propagation parameter window is usually used.

There you can directly edit the following parameters as they appear directly or indirectly:

## linear loss / gain

معلالالل

waveguide		
loss	0.0 👻	1/m
gain	0 👻	1/m

- in [1/m] or [dB/m], Click on the unit to change it.
- Click the button [gain] to choose:

orofile										-su			
	gain pro	1060		Width	40	nm	add sec	ond peak	nm	Width	40	nm	
	shape	const					shape	const	•				
	TAB)	SCII file fo	or gain i	pronie give		,	5.						
	TAB)	SCII file fo	or gain			,		file					
	TAB)	SCII file fo	or gain					file	•				

gain profile: The gain profile can also be an addition of two different profiles.

The profiles have the following analytical forms, which are normalized and multiplied by the gain value. The parameters are converted to frequency domain for the calculation (center wavelength~  $v_c$ , width~ $\Delta v$ ).



Lorentz	$\frac{1}{\pi} \frac{\Delta v}{\Delta v^2 + (v - v_c)}$
Parabolic	Positive values of $1 - 2\left(\frac{\nu - \nu_C}{\Delta \nu}\right)^2$
N-th order Gauss (supergauss2: N=2)	$4 \cdot \ln(2) \left( \frac{(\nu - \nu_C)^2}{\Delta \nu^2} \right)^N$
Asymmetric sech (reverse frequency axis for Asymmetric Lorentz)	$v < \mathbb{P}c: \frac{\cosh\left(\frac{v - v_c}{0.45 \cdot \Delta v / 2.041475}\right)^{-1}}{\left(1 + \frac{2 v - v_c }{0.55 \cdot 3.5 \cdot \Delta v}\right)^{-2}}$

Select a gain profile from file, an ASCII file, created by yourself in a separated dialog.

The ASCII file has to have the structure: <wavelength in nm> [TAB] <positive gain in 1/m>, e.g.

1000	0
1010	0.5
1020	0.6
1030	0.4
1040	0

- It includes setting *total* **gain saturation** check this to simulate gain saturation effects.
- Alternatively, choose **temp gain saturation** check this to approximately simulate the temporal gain saturation effects meaning that the front depletes the gain and is amplified more than the pulse trail. This can be observed for long pulses with a pulse energy close to the saturation energy of the fiber Esat, which is calculated automatically (for details see [2]).

MFD



mode diameter 10.0 👻 µm

Sets the mode field diameter of the propagation mode in [µm]. It is used to calculate the nonlinear coefficient g by γ=ω/c\*n<sub>2</sub>/A<sub>eff</sub> with A<sub>eff</sub>=π\*MFD. Also it determines the saturation energy E<sub>sat</sub> (see also [temp gain sat] below and [2]). The parameter n<sub>2</sub> can be changed in the "fiber parameter" dialog. For an advanced setup, especially using die mode diameter setup for simultaneous Gauss BPM simulation, see below.

#### Gauss Beam Propagation (Multi-Pass-Cell)

and the state	10.0				DDM		
mode diameter	10.0	٣	μm	converts to	using BPM	μm	if selected
				0011011310		-	11 30100100

• click the "mode diameter button" to access the dialog. See tutorial on Multi-Pass-Cell for more information.



#### SPM

• check this to use the SPM term in the NLSE.

## self steepening

- check this to simulate the self-steepening effect.
- it includes the (linear) dependence of the effective area with wavelength though an **additional shock term**, please see Ref. 6 for details.



term self steepening		
$\frac{\partial A}{\partial z} = \dots + i\gamma \left(1 + i\tau_{\rm s}\right)$	$\frac{\partial}{\partial T}\bigg)\bigg(A(T)$	$\int_{-\infty}^{\infty} R(\tau)  A(T-\tau) ^2 d\tau \right)$
$\tau_{\rm shock} = \tau_0 + \tau_A = \frac{1}{\omega_0}$	$-\left[\frac{1}{n_{\rm eff}}\frac{dn_{\rm eff}}{d\omega}\right]$	$\frac{\omega)}{\omega_0} - \left[\frac{1}{A_{\rm eff}} \frac{dA_{\rm eff}(\omega)}{d\omega}\right]_{\omega_0}$
additional shock time	0.0	fs
$\checkmark$ use self steepening term		* exclude self steepening

## Raman response

- check this to simulate the delayed Raman response.
- The dialog allows for a detailed setup of the function h(t) or scripting your own.



## steps, stepsize, distance

 Set the distance to propagate and the corresponding stepsize by these values. It determines the accuracy of the Split-Step algorithm. Even if the adaptive step size option help to avoid numerical errors, decrease the step size to ensure the numerical result.

## stepsize adaption

ممللالليس

Options: none/rough/normal/precise/accurate – This determines the adaptive stepsize control by means of the local error. The stepsize is reduced until the local error is below the given value. The smallest stepsize is 1 µm and therefor the highest precision used by the software. Set the stepsize adaption to "none" to control stepsizes smaller than 1 µm.



## Measure and parse

Select this option to measure and parse strings that you might have set variable during propagation. It will reinitialize the parameter of the NLSE. Set also the number of how many times you want to update these during the propagation.

#### write file

ممطالالل

Select this option to write a specific number of slices of the propagation to a propagation file (\*.bpfx). Use



this to write files that are required for most post-processing functions. If no filename is given, a fallback filename in the %APPDATA% directory is taken.

There are also several dialogs available to change additional parameters:

## Dispersion

• is changed in the "Dispersion dialog" by using the following options:



• Taylor expansion series

It is specified by the coefficients  $\beta_n$  according to the following equation (Taylor series expansion):



Taylor S	Series (	1060	nm	prede	fined	more		*
Beta1			0 ps/m	compensate at:		80	0 nm	
Beta2		-0.011	85 ps²/m	D	19.86585179	12 ps/(nm*km	)	
Beta3		7.995	e-5 ps3/m	s s	0.1872	13 ps/(nm <sup>2*kn</sup>	ו)	
Beta4		-1.00392e-	07	Touton				
Beta5		1.21005e-	10	from	0	nm to	20000	nm
Beta6		4.0347e-	14					
Beta7			0					
Beta8			0					
Beta9			0					
eta10			0	force rel	tarded time fra	ame (beta0=bet	a1=0)	
eta11			0					
eta12			0					
eta13			0					
eta14			0					
						co	py dispersio	n
gratin	g compresso	or >>		Save		([nm],D[p	s/nm/km],b2	2[ps²/m])
3						and the second se		1 I

The center wavelength/frequency of this Taylor series expansion  $\omega_0$  is also required. Specify a trust region. It determines in which wavelength range the Taylor series generates values, which are physically right. Outside this region, the dispersion is set to zero. If the range is set to zero, the full range is used for evaluating the Taylor series.

Additionally, it is possible to select several fibers from the pre-settings as well as to save or load the dispersion settings.

Automatically, the parameters of  $\beta_2$  and  $\beta_3$  are converted to the dispersion parameter D and its slope S=dD/d $\lambda$  according to:



$$D = -\frac{2\pi c}{\lambda^2} \beta_2$$
$$S = -\frac{2\omega^3}{(2\pi c)^2} \beta_2 + \frac{\omega^4}{(2\pi c)^2} \beta_3$$

If the center wavelength of the current spectral domain does not correspond to the Taylor series expansion wavelength of the dispersion, the Taylor series is automatically recalculated (internal). During this operation, a group delay (and fast varying amplitude due to the offset frequency) usually appears at the center wavelength of the pulse. To compensate for that, the option "always use retarded time frame" is used to set both values to zero ( $\beta_0^{new}=\beta_1^{new}=0$ ). Thus, the retarded time frame is always at the center wavelength of the spectral domain and the most slowly varying amplitude envelope is used.

- grating compressor
- In the Taylor series expansion dialog, the dispersion of a typical grating compressor in single pass can be calculated. The drawing in the dialog visualizes the parameters (m = diffraction order).
- The dispersion is calculated according to:



$$\sin(\alpha_c) + \sin(\alpha_i) = m \frac{\lambda}{\Lambda}$$
$$\beta_2 = -\frac{1}{c} \frac{m^2}{\omega^3} \left(\frac{2\pi c}{\Lambda}\right)^2 \frac{1}{\cos(\alpha_c)^3}$$
$$\beta_3 = -3\beta_2 f \quad \text{with} \quad f = \frac{1}{\omega} + \frac{m}{\omega^2} \frac{2\pi c}{\Lambda} \frac{\sin(\alpha_c)}{\cos(\alpha_c)^2}$$
$$\beta_4 = \beta_2 \left(12f^2 + 3\frac{m^2}{\omega^4} \left(\frac{2\pi c}{\Lambda}\right)^2 \frac{1}{\cos(\alpha_c)^4}\right)$$

• **fused silica photonic crystal fiber:** By specifying the hole to hole distance (pitch) and the hole diameter, the dispersion of a one missing hole solid core photonic crystal fiber can be used. The background material is assumed to be fused silica. Please see [3] for details.

PCF Parameter							×
	pitch L 50 hole diameter d 0.5 d/L 0.1	μm	Ma	aterial dispersion $n = \sqrt{A + \frac{B_{1}}{\lambda^2}}$	$\frac{\lambda^2}{C_1} +$	$\frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_2\lambda^2}{\lambda^2}$	$\frac{1}{2_3\lambda^2}$ - $C_3$
	Get V over lam	nbda/pitch=02		predefined material:	more	ə	•
d	Get n_eff over la	mbda/pitch=02	А	1			
-414	Get D[ps/nm/km] o	over lambda/L=02	B1	0.696166	C1	0.00467915	μm²
			B2	0.407943	C2	0.0135121	μm²
ОК			В3	0.897479	C3	97.934	μm²

- Sellmeier coefficients
- The well-known Sellmeier coefficients can also be used to describe the dispersion of a material. Several predefined materials are available. Please take a look at <u>http://refractiveindex.info</u> for more material data.
- Please also keep in mind that there are other definitions of the sellmeier equation, which might explain differences for coefficients.

Dielec	tric dispersive medi	ium		×
n	$= \sqrt{A + \frac{B_1 \lambda^2}{\lambda^2 - \alpha}}$	$\frac{1}{z_1} + \frac{1}{z_2}$	$\frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_2}{\lambda^2}$	$\frac{C_3\lambda^2}{-C_3}$
	predefined	more	•••	v
A	1			
B1	0.696166	C1	0.00467915	µm²
B2	0.407943	C2	0.0135121	µm²
B3	0.897479	C3	97.934	µm²
	ОК			

## **Rate Equation gain**

The propagation solves the NLSE similarly to "standard fiber" but includes the gain by solving the stationary rate equations. This can be used to model cw and quasi-cw amplification including ASE.

**Background:** The theoretical description of the laser process in fiber amplifiers is done by combining the local rate equation for the laser process and the power flow (propagation equation) for the fields along the fiber. They have been developed to predict and optimize Erbium-doped fiber amplifiers used for telecommunication application [7].

The local rate equation describes the dynamic of the emission and absorption processes of the rare earth ion within its host material by using its spectroscopic properties. A simple model for the energy level system for the Ytterbium-ion is shown in Figure 2.1 and shows some of the most important emission and absorption lines, which result from the Stark splitting of the upper and lower energy lines. It has been argued that for Erbium and Ytterbium fibers, a reduced two level model for the emission and absorption cross section include the population density and cross section values [7, 8]. As an example, the effective cross sections of a typical Yb-doped fiber is shown in Figure 2.2.



ممطااالس

Figure 2.1: Energy level model for Ytterbium-ion in fused silica.



Figure 2.2: Typical emission and absorption cross section of an Yb-doped fiber.

The approximated system used in fiberdesk leads to the following equations for the forward (+) and backward (-) propagating signal (S) and pump powers (P) including spontaneous emission  $(SE)^2$ 

$$\frac{dP_{S/P}^{\pm}}{dz} = \Gamma^{S/P} \left( \pm \sigma_{\rm em}^{S/P} N_2 \mp \sigma_{\rm abs}^{S/P} N_1 + \alpha_{S/P} \right) P_{S/P}^{\pm} + SE_S$$
2.2

with

$$SE_S = \pm 2 \cdot h\nu \cdot \Delta\nu \cdot \sigma_{\rm em}^S N_2$$

where the total ion density  $n_0=n_1+n_2$  is the sum of upper and lower population density and  $\alpha_{P/S}$  is an additional loss (background loss) for the fields. It is assumed that the pump absorption can be described by a simple overlap factor  $\Gamma_p$ , which is the ratio of doped core area to pump core area. The upper population density for steady-state conditions is

$$n_2(z) = n_0 \frac{\sum_{k=S,P} \frac{\sigma_{abs}^k}{hv_k} \Gamma^k \frac{P^k(z)}{A_c}}{\sum_{k=S,P} \frac{\sigma_{abs}^k + \sigma_{em}^k}{hv_k} \Gamma^k \frac{P^k(z)}{A_c} + \frac{1}{\tau}}$$
2.3

with  $\tau$  as the upper state lifetime and the total power at a given position  $P(z)=P^+(z)+P^-(z)$ . The inversion level is defined as  $n_2/n_0$ . The solution of Eq. 2.2 and 2.3 and can be made

<sup>&</sup>lt;sup>2</sup> for the signal only



for fiber amplifier but also for laser, if the boundary conditions at the laser mirrors (typically z=0, L) are included in the description for forward and backward propagating fields.

For ultra-short pulse propagation, the rate equations are combined with the nonlinear Schrödinger equation (Eq. 2.1) by calculation the spectral gain  $g(\omega,z)=dP(\omega)/dz^*1/P(\omega)$  with the results of the rate equation and then propagating the NLSE with that gain. However, the spontaneous term is added to the complex field by photons of random phase in that case.

In the main dialog, all parameters are set in various tabbed property pages including:

• Numerics

e Equation Setup				×
numerics pump s	signal RE-dopi	ng mirrors		
fiber length	0.12 m 100 Forwa	ard Backward		
use f (instead of	NLSE forward powers only)		use NLSE backward (instead of powers only)	
max iterations	100			
convergenci	1e-007	include A.		
deceleration	0.99			

## • Pump

ard pump			1		backward pur	ηp		
iump core	-	400.0 µm			pump core		100.0	μm
backgr	ound	0 1/m	Pump Forward	Pump Backward	backgrou	nd	0	1/m
power (W)	wavelength (nm)	absorption (dB/m)		- P	power (W)	wavelength (nm)	abs (d	orption B/m)
0.0	976.0	2.3669425			10.0	976.0	2.3	69425
0.0	976.0	2.3669425			0.0	976.0	2.3	69425
0.0	976.0	2.3669425		Pump Core	0.0	976.0	2.3	69425
0.0	976.0	2.3669425			0.0	976.0	2.3	69425
0.0	976.0	2.3669425			0.0	976.0	2.3	69425

Signal





• Doping, with its sub-menu for cross section setup. There, the cross sections can be included using a simple multi-Gaussian peak fit.

	pump sig	Inal KE-dopi	ng mino	15				_
mass iost material	4600 2200	ppm kg/m <sup>s</sup>		M2		available fibers	·	
density	3.52196198885912	e+025 1/mª				QE pump to up	ber	
nic mass	173.04 u Yb Er		$( \circ$	Signal Core		fluorescence Temperatu	0.85 ms	
			$\sim$		doped c	core	0.1 μm	
ОК								
ок ision Ab	sorption Cros	s Section						
ок ision Ab: imission	sorption Cros	s Section	Absorptic	n		Ť		
ок sion Ab mission ross sec 1e-27 m <sup>2</sup>	sorption Cros	s Section m) Width (nm)	Absorptio cross sec (1e-27 m <sup>2</sup>	n tion Center (nm)	Width (nm)			
ок sion Ab mission ross sec 1e-27 m <sup>2</sup> 2325	tion Center (nr ) 975	s Section m) Width (nm)	Absorptic cross sec (1e-27 m <sup>2</sup> 180	n tion Center (nm) ) 950	Width (nm)			
ok mission Ab mission ross sec 1e-27 m <sup>2</sup> 2325	tion Center (ni 975 978	s Section m) Width (nm) 4 12	Absorptic cross sec (1e-27 m <sup>2</sup> 180 360	tion Center (nm) 9 950 895	Width (nm) 70 24			
ок sion Ab mission ross sec 1e-27 m <sup>2</sup> 2325 160 340	tion Center (nr 975 978 1025	x Section m) Width (nm) 4 12 20	- Absorptio cross sec (1e-27 m <sup>2</sup> 180 360 510	tion Center (nm) 950 895 918	Width (nm) 70 24 22			
ok sion Ab mission ross sec 1e-27 m <sup>2</sup> 2325 160 340 175	tion Center (nr 975 978 1025 1050	s Section m) Width (nm) 4 12 20 60	Absorptic cross sec (1e-27 m <sup>2</sup> 180 360 510 160	on tion Center (nm) 950 895 918 971	Width (nm) 70 24 22 12			
ок sion Ab mission ross sec 1e-27 m <sup>2</sup> 2325 160 340 175 150	sorption Cross tion Center (n) 975 978 1025 1050 1030	s Section Width (nm) 4 12 20 60 90	Absorptic cross sec (1e-27 m <sup>2</sup> 180 360 510 160 2325	tion Center (nm) 950 895 918 971 975	Width (nm) 70 24 22 12 4			
ok ssion Ab Emission ross sec (1e-27 m <sup>2</sup> 2325 160 340 175 150 0	tion Center (m 975 977 978 1025 1050 1030 0	s Section Width (nm) 4 12 20 60 90 0	Absorptio cross sec (1e-27 m <sup>2</sup> 180 360 510 160 2325 0	on Center (nm) 950 895 918 971 975 0	Width (nm) 70 24 22 12 4 0		0 840 0 910	
ok sion Ab mission ross sec 1e-27 m <sup>2</sup> 2325 160 340 175 150 0 0	sorption Cross tion Center (n) 975 978 1025 1050 1030 0 0	<ul> <li>s Section</li> <li>Width (nm)</li> <li>4</li> <li>12</li> <li>20</li> <li>60</li> <li>90</li> <li>0</li> <li>0</li> <li>0</li> </ul>	Absorptio cross sec (1e-27 m <sup>2</sup> 180 360 510 160 2325 0 0	on tion Center (nm) 950 895 918 971 975 0 0 0	Width (nm) 70 24 22 12 4 0 0		0.840 0.910 Way	0.980 1.050 1.120 1.190 elength (µm)
ok ssion Ab: mission ross sec 1e-27 m <sup>2</sup> 2325 160 340 175 150 0 0 0	sorption Cross tion Center (n) 975 978 1025 1050 1030 0 0 0	s Section           m)         Width (nm)           4         12           20         60           90         0           0         0           0         0	Absorptio cross sec (1e-27 m <sup>2</sup> 180 360 510 160 2325 0 0 0	bin Center (nm) 550 250 895 918 917 971 975 0 0 0 0 0	Width (nm) 70 24 22 12 4 0 0 0		0.840 0.910 Wav	0.980 1.050 1.120 1.190 elength (µm)

The equation for the cross-section fit is:

$$\sigma(v) = \sum_{j} \sigma_{j} e^{-\frac{1}{2} \left(\frac{v - v_{0}}{\Delta v}\right)^{2}}$$

With v as the frequency,  $v_0$  the center frequency of the cross-section peak, both expressed as wavelength ( $v = c/\lambda$ ) as well as  $\Delta v$  given by

 $\Delta v = 1.0/(2*\operatorname{sqrt}(2.0 * \log(2))*|c/(v_0 + \Delta\lambda/2) - c/(v_0 - \Delta\lambda/2)|$ 

- where  $\Delta\lambda$  is the FWHM of the contributing peak.
- Mirrors

معدالاللا

	cs pui	mp	signal	RE-doping	mirr	ors								
rror M1				N	1		147				mirror M2			
enter	1060.0	nm		Ĩ	<u> </u>	_					center	1060.0	nm	
width	1.0	nm			1		) "				width	1.0	nm	
,	eflectivity		0.0 %				)				reß	ectivity	0.0	%
reflectiv	ity	-	0.0 %			┢					reflectivity		0.0	%
				/- intermediar	e mirror									
				intermedia center	e mirror 1060.0	nm	re	flectivity	0.0	%				
				intermedial center width	e mirror 1060.0 1.0	nm nm	reflectivity	flectivity	0.0	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~				
				intermedial center width	e mirror 1060.0 1.0 at	nm nm	reflectivity 0.0	effectivity / m	0.0 0.0	%				



After propagation, the total powers and inversion can be accessed in the "main" section, "propagation"->"RE Results".



The options "live" is disabled during the calculation. However, you can "write to a propagation file" and measure or display afterwards ("Post Processing").

## Saturable Absorber

You can choose between an instantaneous saturation and a saturable element.

The first action of this element is to center the field temporally.

You can choose between an instantaneous saturation and a saturable element with a saturation that is decaying with a specific time constant.

Fas	st saturable los	s	-				
R0	70 •	%	R = R	$_{0} + \Delta R -$	$\Delta R$	C	ж
dR	30	%			$1 + \frac{ A(T) }{2}$		
PA	1	w			$P_A$	Car	ncel
🔽 sa	turable absorbe	er m	irror with tir	ne constant	s		
vnsat sat	turable absorbe urated reflectiv urable reflectiv iration fluence	er m /ity /ity 8/	irror with tir 60 30 0	ne constant % % µJ/cm²	s temporal response A	0.2	

The instantaneous saturation modifies the field intensity I(T) according to (A is the "field amplitude" with the unit of  $J^{1/2}$ ):

$$I(T) = I(T) \cdot \left( R_{unsat} + \Delta R \left( 1 - \left[ 1 + \frac{|A(T)|^2}{\tau_{dw} P_{sat}} \right]^{-1} \right) \right)$$

The unsaturable  $R_{\mbox{\tiny unsat}}$  and saturable reflectivity  $\Delta R$  as well as the saturation power can be controlled.

The time dependent saturable absorber modifies the field according the following rate equation with the notations  $q_0 = \Delta R$  and the reflectivity  $R = R_{unsat} + (\Delta R - q(t))$ :

$$\frac{dq}{dt} = -\frac{q - q_0}{T_1} - \frac{|A(t)|^2}{E_{sat}}q$$

with:

مععدالالليس

 $q_0$  – saturable reflectivity

 $E_{sat}$  – saturation energy

A(t) – field envelope in [J<sup>1/2</sup>]

q(t) – response of SESAM

The unsaturable and saturable reflectivity can be controlled directly in the dialog. The saturation energy  $E_{sat}$  is controlled by controlling the focal spot and the saturation fluence (as known from semiconductor saturable absorber mirrors).



## **Pulse Injection**

This method adds a pulse to the current data array, causing interference with the existing field. You must set a transmission parameter and phase.

The parameters can vary randomly based on the uncertainty parameter set in the setup dialog.

Tip: For an interference-free pulse, use multi-element propagation. You can either add a high loss before this element to zero out the existing array and then inject a pulse, or achieve absolute zero by multiplying with zero using "manipulation" propagation.

## **Custom Filter**

مطلالا

This allows to select an ASCII file with a custom defined transmission T( $\omega$ ) for the spectral intensity and an additional spectral phase  $\varphi(\omega)$ . It is combined with the spectral field amplitude as follows:  $\widetilde{A}(\omega) \rightarrow \sqrt{T(\omega)} \cdot \widetilde{A}(\omega) \cdot e^{i\varphi(\omega)}$ 

The ASCII file has to contain three columns with the values of the wavelength in nm, the transmission T and the phase in rad. The values have to be separated by "TAB" or ",".

The imported data are displayed in the main view (normalized).



E.O. evicting fic	ld la data					EC			
E_in - defined	a in data			transn	hission I	50	1.0	*	%
E_out - interfering				phas	e phi_0	0.	0	÷	rad
Type Gau	55	~							
FWHH	0.1	- 1	ps	+/-		0	ps		
TempShif	0.0	- 1	ps	+/-		0	ps		
	1060.0	* r	nm	+/-		0	nm		
wavelength							1		
wavelength Chirp	0.0	* f	fs <sup>2</sup>	+/-		0	ts2		

custom filter from	n ASCII file	
(wavelength in n	m TAB multiplier intensity TAB additio	nal phase)
C: Users \Schre	iber\Desktop\filter.txt	file



## **Nonlinear Loop Mirror**

This allows to define a nonlinear loop mirror consisting of several elements that are previously saved as ppfx files. The current field is the input and the output is the coherent superposition of the results of the left and right clockwise propagating field. See tutorial 8 for details and examples.

Dialog					×
2nd outpu input outpu 2nd inpu	t	coupler	R I-R	1	2 3
element 1	C:\Users\tsch	\Downloads\Fiber-o	desk laser sir	mulation	select>>
element 2					select>>
element 3				][	select>>
element 4					select >>
element 5					select >>
✓ use outp □ use 2nd	out port output port	if both options to put the outp	are choose out in both fie	n, it's tried Ids	
ОК	cancel	R =	0.1	with 0.5	= 50:50



## 2.7.2. Measurements

The current dataarray is analysed almost after each modification. The results are displayed in this separate window. SI units are used. The description is usually intuitive and displayed in the bottom of the windows when clicked on a specific measurement. To keep it short, here is a description for some of the values:

- datapoints number of datapoints in current data array
- position current propagation position
- FWHM full width at half maximum
- rms root mean square (second momentum)
- ac. values belonging to the autocorrelation
- pulse. values belonging to the temporal field intensity
- spec. values belonging to the spectral field intensity
- theory. parameters of the current propagation according to usually used normalization parameters (change is by "menu->manipulation->change T0")
- t.b. product time-bandwidth product
- Q quality factor in time and spectral domain (FWHM/RMS/2.0) [1]
- (for more information ask webmaster @ fiberdesk.com)

To see a description for other parameters, click the parameter and a description is shown in the information window at the bottom of the control:

Measurements	×
user defined measurements >>	
Position	
(M0) index = 0	
(M1) current position = 0.000 m	
(M2) accumulated distance = 0.000 m	
Data Array	
(M3) datapoints = 256	
(M17) center wavelength = 1.060 µm	
Temporal Field	
(M4) energy = 0.000 J	
(M5) avg_power = 0.000 W	
(M6) repetition rate = 100.000 MHz	
(M7) center offset shift = -7.843 fs	
(M8) FWHM width = 0.000 s	
(M9) RMS width = 0.000 s	
(M10) skewness = 0.000	
(M11) kurtosis = 0.000	
(M12) max-phase = 0.000 rad	
(M13) peak power = 0.000 W	
(M14) peak power = 0.000 W	
(M15) peak power = 0.000 W	
(M16) peak power = 0.000 W	
(M78) time-bandwidth product = 0.000	
Spectral	
(M18) center.offest = 466.866 pm	
(M19) number of photons = 0.000	
(M20) width.Hz = 0.000 Hz	
(M21) width.m = 0.000 m	
(M22) width_rms.m = 0.000 m	
(M23) width_rms.Hz = 0.000 Hz	
(M24) skewness = 0.000	
(M25) kurtosis = 0.000	
(M77) max-phase = 0.000 rad	
Autocorrelation	
(M26) width = 0.000 s	
(M27) Wath.ms = 0.000 s	
Beam Propagation	
(M28) diameter = 0.000 m	
Rate Equation	
(M29) signal.forward = 0.000	
(M30) signal.backward = 0.000	
(M31) pump.1.forward = 0.000	
(M32) pump. 1.backward = 0.000	
(M33) pump.2.forward = 0.000	
(M35) pump 2 forward = 0.000 (M35) pump 2 forward = 0.000	
(M36) pump 3 backward = 0.000	
(M37) pump 4 fopvard = 0.000	
(M38) pump 4 backward = 0.000	
(M30) pump 5 fopward = 0.000	
(M40) pump 5 backward = 0.000	
(M41) pump power forward at M1 = 0.000	
(M42) nump power backward at M1 = 0.000	Ŧ

Spectral	
(M20) center.offest = 466.866 pm	
(M21) number of photons = 0.000	
(M22) width.Hz = 0.000 Hz	
(M23) width.m = 0.000 m	
(M24) width_rms.m = 0.000 m	•
spectral width as second central momentum (deviation) giver in dimensions of a wavelength difference	ı

## 2.7.3. Measurement graphs

If the measurement is switch on (see propagation parameter window) during propagation, all measured value from the measurement result window are show with respect to the propagation distance in the "Graph" window.





Use the buttons on top to copy the content of the current graph to the clipboard in ASCII or BMP format or save it to a file. Zoom in to the values by moving to mouse onto the data and click left. Zoom out by the button on top.

## 2.7.4. Output

Several important information or results of the propagation are displayed in the output window.





## 2.8 View interface

## 2.8.1. View

ممطلالل

The general view can contain different views of the current electric field: the temporal field, its Fourier transformation as the spectral field and the autocorrelation. The number of views can be chosen in the ribbon menu (see ribbon control "View").



The control of the view is done in the view setup pane and is related to the selected view (e.g. simply by clicking into the view) In the bottom of the pane, a description of each property item is displayed – click on a specific item to read its description.

🗘 Load View 👻 🚨 Sav	ve View 👻	
Search		1
A VIEW	Manu 1	
Centent	View I	
Content		
show the		
Tuno	Time	
start (no)	2 000077	
start (ps)	-2.000977	
stop (ps)	1.999023	
a data scaling		
normalized values on y-axis		
logantnmic		
auto scale	0.000000	
from minimum (%)	0.000000	
to maximum (%)	100.00000	
additional data		
show real		
snow imag		
snow phase		
Misc	100	
text size zoom (%)	100	
title space	15	
honzontal split top	50	
honzontal split bottom	50	
vertical split left	50	
vertical split right	50	
outter space	3	
inner space left	3	
inner space right	3	
inner space top	3	
inner space bottom	3	
View		

There it is possible to select up to three different measured values displayed in the view for a quick access.

If the option "colored wavelength" is chosen, each wavelength is colored individually. The colors are controlled by the options "only VIS" to highlight the visible wavelength (otherwise the whole current spectral range is used) and the option "Fade to white ..." to choose the colors of the wavelength that are out of the visible region.

Additionally, a fast algorithm is implemented to visualize the temporal position of the spectral components (chirp).

ممطالالل

M8Temporal Field.FW V M26Autocorr		ation.w ~	none		~
Spectral domain measurer	nent diplay				
M21Spectral.width.m \vee	none	~	none		~
Style					
line thickness rectangle	thin	*			
line thickness ticks	thin	*			
Colour fill					
Colored wavelength		Vis	sualize chi	irp	
Only VIS		re	solution	0.2	ps
✓ Fade to white inste	ad of black				
stretching 01		0	NK	Can	col

## 2.8.2. Spectrographic content

The spectrographic view shows a spectrally (wavelength) resolved temporal map of the electric field. This view is well known from the measurement technique of ultrashort pulse known as frequency resolved optical gating (FROG) [5]. It is calculated by the following equation:

$$S(t,\lambda) = \left| \int_{-\infty}^{\infty} e^{-iC_{\lambda}^{\tau}} e^{-i(\tau-t)^{2}/T_{BW}^{2}} A(z,\tau) d\tau \right|^{2}$$

If the axis of the spectrum in the normal view is set to any of the frequency axis, the spectrogram is also calculated in time-frequency domain.



In the view properties pane, the temporal resolution  $T_{\mbox{\tiny BW}}$  can be chosen.

## 2.9 References

مععدالالليس

[1] K. Tamura and M. Nakazawa, "Pulse compression by nonlinear pulse evolution with reduced optical wave breaking in erbium-doped fiber amplifers," Opt. Lett. 21, 1, 68 (1996).

[2] Govind P. Agrawal, "Optical pulse propagation in doped fiber amplifiers ", Phys. Rev. A 44, 7493 - 7501 (1991))

[3] K. Saitoh and M. Koshiba, "Empirical relations for simple design of photonic crystal fibers," Opt. Express 13, 267-274 (2005).

[4] J. Dudley and S. Coen, "Coherence properties of supercontinuum spectra generated in photonic crystal and tapered optical fibers," Opt. Lett. 27, 1180-1182 (2002).

[5] Rick Trebino, Kenneth W. DeLong, David N. Fittinghoff, John N. Sweetser, Marco
A. Krumbügel, Bruce A. Richman, Daniel J. Kane, "Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating," Rev. Sci. Instrum.
68, 3277 (1997)

[6] B. Kibler, J. M. Dudley, and S. Coen, "Supercontinuum generation and nonlinear pulse propagation in photonic crystal fiber: influence of the frequency-dependent effective mode area," Appl. Phys. B 81, 337–342 (2005).

[7] Giles, C.R.; Desurvire, E.; , "Modeling erbium-doped fiber amplifiers," Lightwave Technology, Journal of , vol.9, no.2, pp.271-283, Feb 1991

[8] R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers", IEEE J. Quantum Electron. 33 (7), 1049 (1997).

[9] Lindberg, R., Zeil, P., Malmström, M. *et al*. Accurate modeling of high-repetition rate ultrashort pulse amplification in optical fibers. *Sci Rep* **6**, 34742 (2016).

[10] Marc Hanna, Nour Daher, Florent Guichard, Xavier Délen, and Patrick Georges, "Hybrid pulse propagation model and quasi-phase-matched four-wave mixing in multipass cells," J. Opt. Soc. Am. B 37, 2982-2988 (2020)

[11] Michael H. Frosz, "Validation of input-noise model for simulations of supercontinuum generation and rogue waves," Opt. Express 18, 14778-14787 (2010).

