

lecture 6

Rate-equation gain

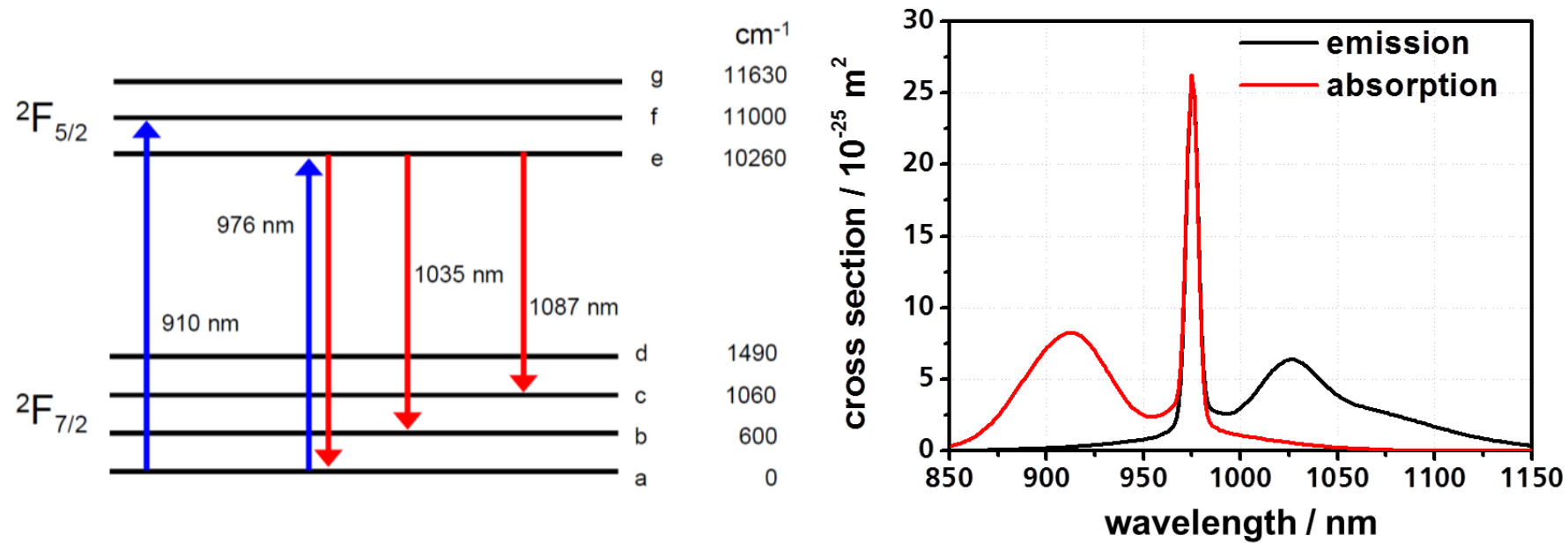
- (1) Background
- (2) Setup of the data array (field vs. power description)
- (3) Simple cw oscillators (power description)
- (4) Nonlinear fiber amplifiers (field description)
 - Gain Managed Nonlinear Amplification
 - Noisy cw amplifier (coming soon)



Lecture 6.1: Background

Rate-equation gain

Solution of stationary rate-equation (effectively two level system) to describe pump- and signal powers as well as inversion in lasers and amplifiers.



Lecture 6.1: Background

Rate-equation gain

Solution of stationary rate-equation (effectively two level system) to describe pump- and signal powers as well as inversion in lasers and amplifiers.

$$\frac{dP_{P/S}^{\pm}}{dz} = \pm \left(\sigma_{P/S}^{em} n_2 \mp \sigma_{P/S}^{abs} n_1 + \alpha_{P/S} \right) \cdot \Gamma_{P/S} \cdot P_{P/S}^{\pm} \mp \overbrace{\sigma_{P/S}^{em} n_2 \cdot 2 \cdot h\nu_{P/S} \cdot \Delta\nu}^{ASE}$$

$$n_2 = \frac{\sum_{i=P,S} \frac{\sigma_i^{abs} \cdot n_0}{h\nu_i} \Gamma_i P_i}{\sum_{i=P,S} \frac{(\sigma_i^{abs} + \sigma_i^{em}) \cdot n_0}{h\nu_i} \Gamma_i P_i + \frac{1}{\tau}}$$

$n_0 = n_1 + n_2$ is the sum of upper and lower population density

$\alpha_{P/S}$ is an additional loss (background loss)

τ as the upper state lifetime

assumed that the pump absorption can be described by a simple overlap factor Γ_p , which is the ratio of doped core area to pump core area.

Lecture 6.2: Setup

Setup of the field for rate equation simulations within the „power equation approximation“, that means, no coupling to the NLSE:

The rate equations alone **do not** need a field description, but power levels of the spectral bins. If only the rate equations are used, that means, they are not coupled to the nonlinear Schrödinger equations, nothing needs to be changed when creating a pulse. The spectrum is automatically converted to relative average power bins during the numerical calculations.

By creating a field with the dialog you only need to ensure the right spectral coverage and number of data point.

Pulse Profile and Data Array

Half
Intervall

10

ps +/-

ps

FWHM

0

ps +/-

ps

TempShi

0

ps +/-

ps

phase

0

rac +/-

rad

Size

1k (2^10)

Type

Gauss

wavelength

1060

nm +/-

nm

2nd order
spectral

0

fs^2 +/-

fs^2

3rd order

0

fs^3 +/-

fs^2

energy

0

J +/-

J

average

0

W +/-

W

repetition rate

100e6

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

☐ create field in data array 2

☐ add field to data array 1

☐ add field to data array 2

OK

Apply

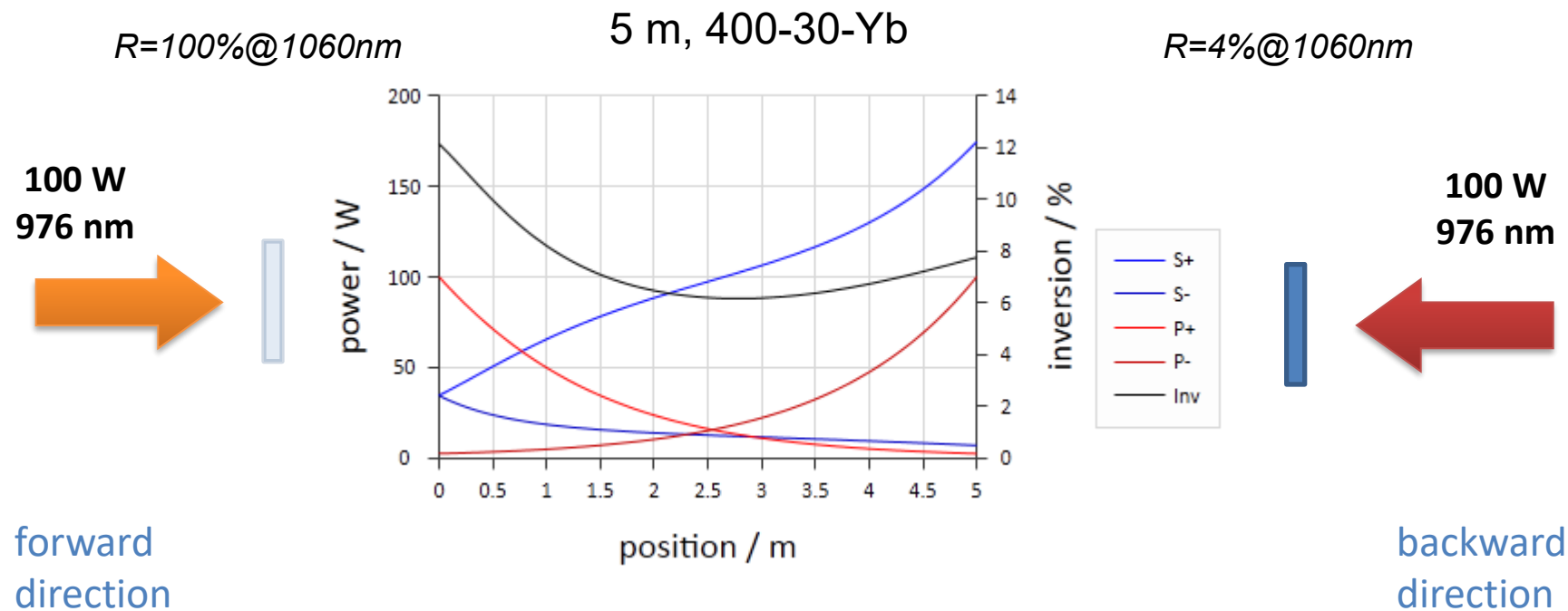
Cancel

reset



Lecture 6.3: Simple cw oscillators (power description)

For a **simple laser oscillator**, no external field (seed) is required. Thus, the field created by the dialog on the previous slide can be used. The following parameters will be set up in the following dialogs:



Lecture 6.3: Simple cw oscillators (power description)

The first property page sets up all relevant **numerical parameters**. Typical values are:

Longitudinal steps = 100, max. iterations = 100, convergency = $1e-7$

Ensure that the power equations are **NOT** coupled to the nonlinear Schrödinger equation (NLSE).

Rate Equation Setup

numerics pump signal RE-doping mirrors

fiber length 10 m
longitudinal steps along 100

use Power Equation forward ☒
use NLSE forward (instead of powers only) ☐

convergence
max. iterations 100
convergency 1e-07
deceleration* 0.99
*choose 0.999 or 1.0 for faster convergence, if no instability is observed

forward backward

use Power Equation backward ☒
use NLSE backward (instead of powers only) ☐

if field is written to file
☒ save backward propagating field as w...

☒ include laser spontaneous emission
☐ use Raman Gain in Power Equatio...
☐ include thermal and spontaneous noi...

OK

Lecture 6.3: Simple cw oscillators (power description)

The property page „**pump**“ defines up to 5 pump wavelength and it's power levels. It also shows the small signal absorption, that is defined by the effective cross sections and the doping level in the property page „RE-doping“ scaled by the pump overlap factor.

Rate Equation Setup

numerics **pump** signal RE-doping mirrors

forward pump

pump core diameter400.0 μm

background loss0 1/m

power (W)	wavelength (nm)	small signal absorption (dB/m)
100	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770

Pump Forward

Pump Backward

Pump Core

backward pump

pump core diameter400.0 μm

background loss0 1/m

power (W)	wavelength (nm)	small signal absorption (dB/m)
100	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770
0.0	976.0	0.9467770

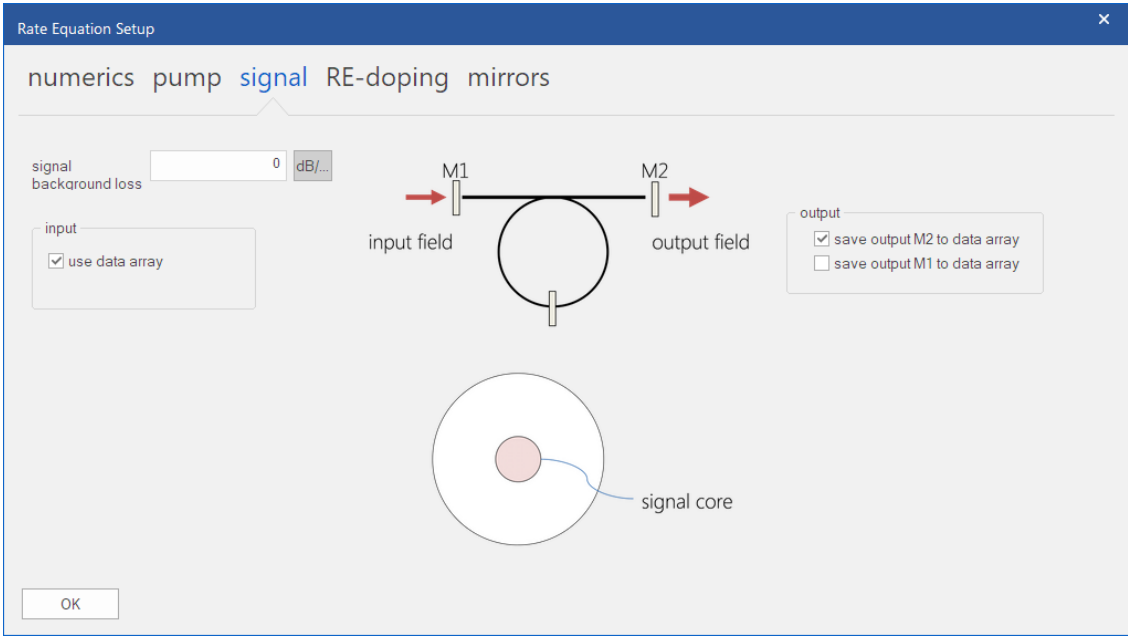
OK

fiberdesk
nonlinear pulse propagation

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Lecture 6.3: Simple cw oscillators (power description)

The property page „**signal**“ defines, how the current field and the results of the simulation are treated. Choose a data array as **input**, if you need this field as a seed. Otherwise, the field definitions of spectral width and datapoints are used with an empty field. The result can be saved as the output after M2 (even if not set), e.g. for single-pass amplifiers. For double pass amplifiers, the output should be M1.



Lecture 6.3: Simple cw oscillators (power description)

The property page „**RE-doping**“ defines the doping level and effective cross section as well as fluorescence lifetime of the upper level and the doped core diameter. Click the cross section button to choose or define different values.

Rate Equation Setup

numerics pump signal RE-doping mirrors

ion mass

5870

ppm

molecular

1

mol%

host material

2200

kg/m³

ion

5.25997366597003e+25

1/m³

Yb2O3

Er2O3

Tm2O3

atomic mass

173.04

u

molecul

0.39408

kg/mo

M1

M2

signal core

doped core

available fibers ...

QE pump to upper

1

cross sections

fluorescence

0.85

ms

Temperature

K

20.0

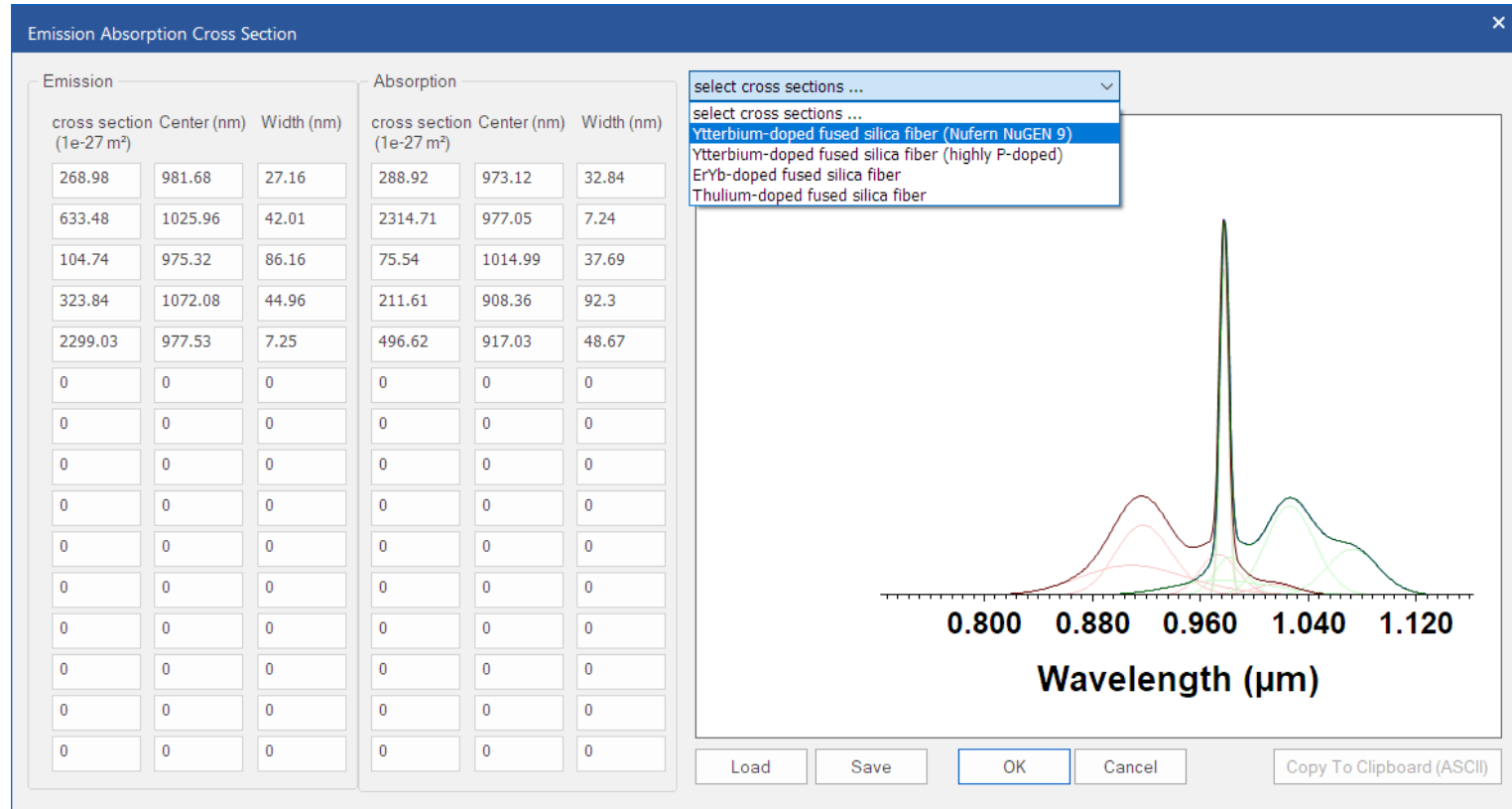
µm

OK



Lecture 6.3: Simple cw oscillators (power description)

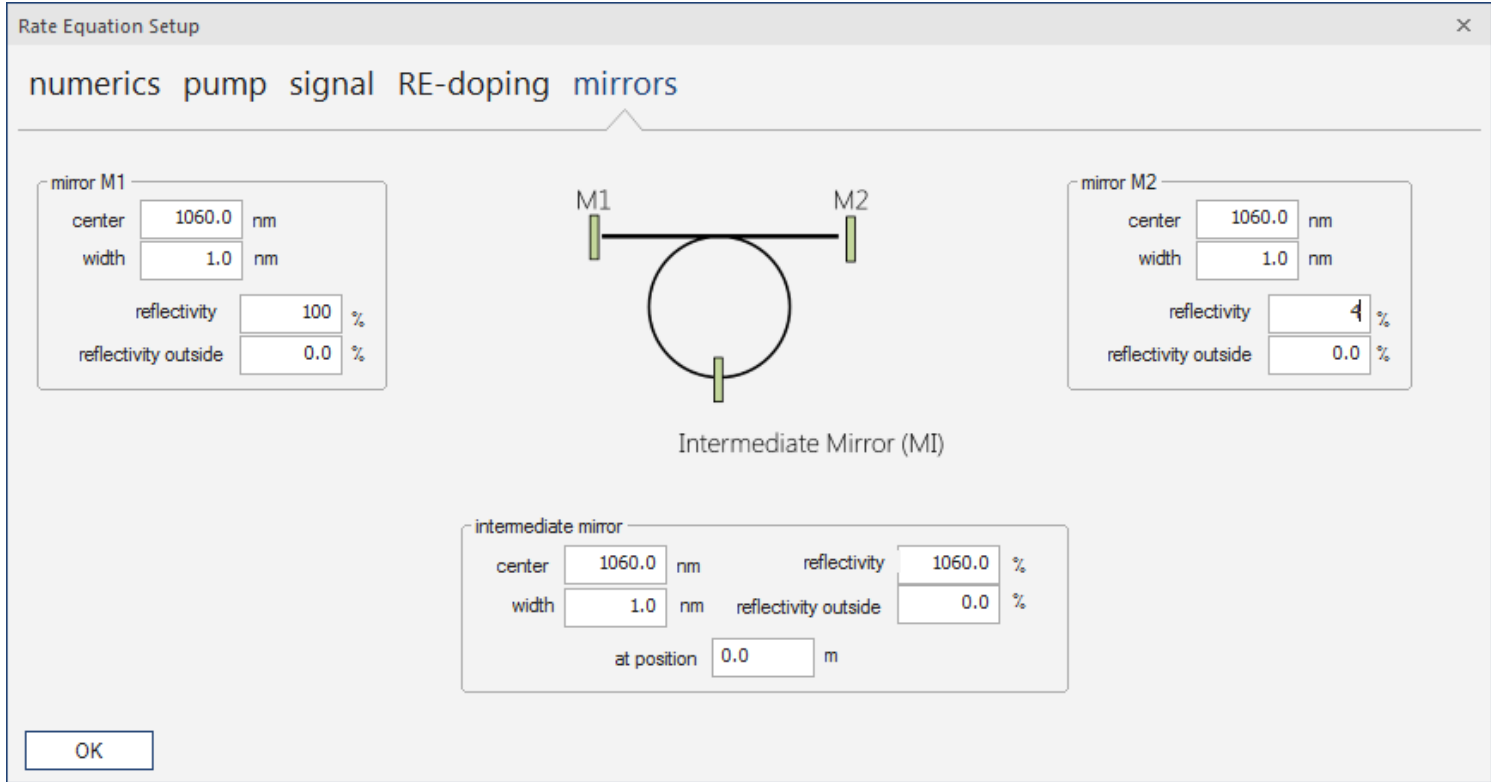
The cross sections are set by a multi-Gaussian peak fit. Some fibers are predefined.



Hint: If you have a certain pump absorption given by a vendors fiber and know approximately the cross sections, choose the doping concentration to a level that the small signal pump absorption in the „pump“ property sheet“ matched those values.

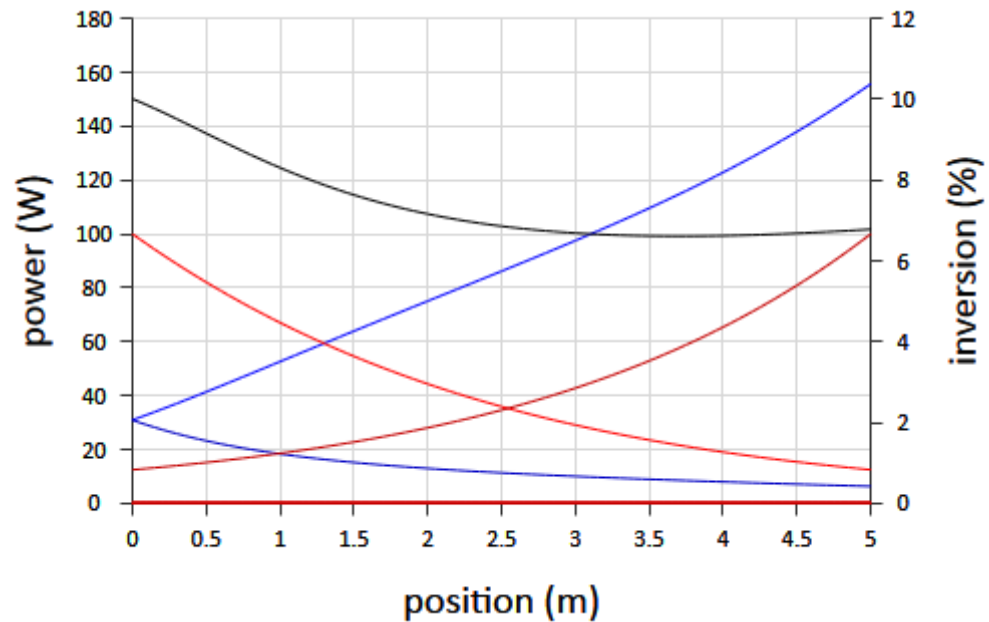
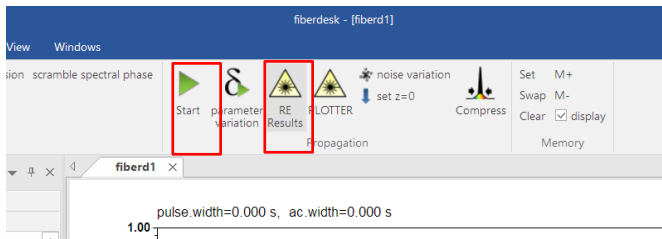
Lecture 6.3: Simple cw oscillators (power description)

The last property page „**mirrors**“ defines the spectral reflectivity of M1, M2 or an intermediate mirror. For amplifiers, these values have zero reflectivity.



Lecture 6.3: Simple cw oscillators (power description)

After setup, run the simulation. The results can be accessed by „RE results“, the output field in the main window or the measurements or saved field , if you have chosen those options. In version 6, you can also use the plotter to show the results.



Lecture 6.4: Nonlinear fiber amplifiers (field description)

Coupling of nonlinear propagations with Rate Equation Gain

The main difference to the power equation based solutions discussed before to a coupling to the nonlinear Schrödinger equation is that the field need to set up correctly in order **to match the time domain peak powers and average powers** that the rate equation requires.

For pulsed systems this is easy, as the repetition rate defines this scaling. For cw systems, no repetition rate is available, but you can then choose the „cw“ option, directly beside the repetition rate setup in the pulse create dialog. It then will ensure that the temporal window matched the repetition rate and in this way, the average peak power and average power is equal.

For combined cw and pulsed system (a rare case) the temporal window needs to match the repetition rate.



Lecture 6.4: Nonlinear fiber amplifiers (field description)

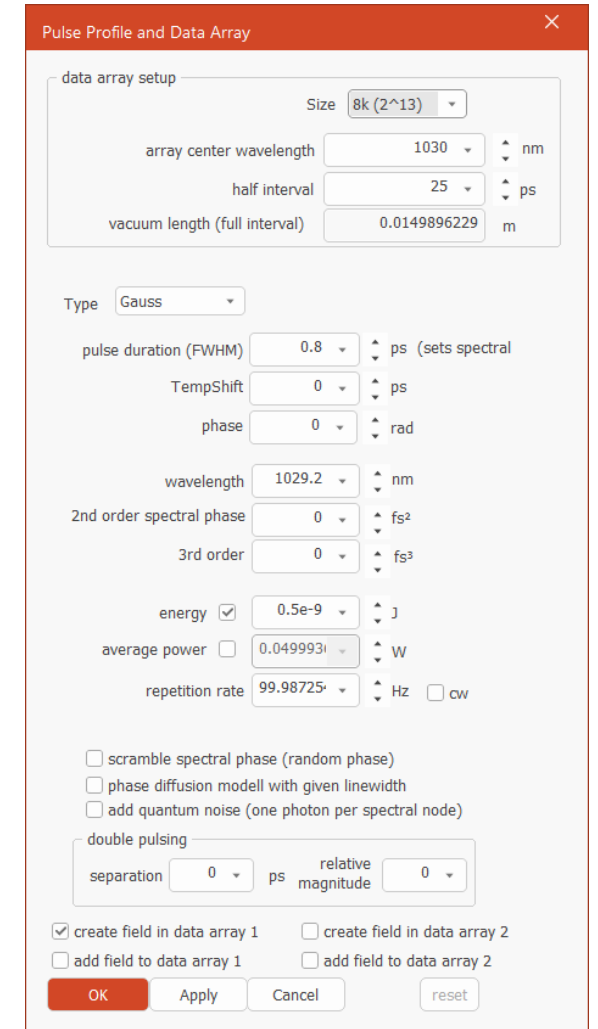
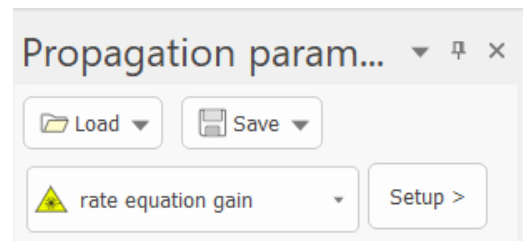
Gain managed nonlinear amplification

The following example is similar to the published results in:

- (1) Pavel Sidorenko, Walter Fu, and Frank Wise, "Nonlinear ultrafast fiber amplifiers beyond the gain-narrowing limit," *Optica* 6, 1328-1333 (2019).
- (2) Tomaszewska-Rolla, D., Lindberg, R., Pasiskevicius, V. *et al.* A comparative study of an Yb-doped fiber gain-managed nonlinear amplifier seeded by femtosecond fiber lasers. *Sci Rep* 12, 404 (2022).

We set up a low power pulse with a duration of 800 fs and 50 mW (0.5 nJ) at 100 MHz repetition rate. Importantly, the center wavelength is at ~1030 nm as the gain dynamics will extend the spectrum toward longer wavelength.

The propagation is set to rate equation gain.



Lecture 6.4: Nonlinear fiber amplifiers (field description)

Gain managed nonlinear amplification

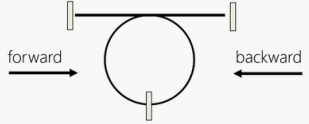
In the rate equation setup dialog, please set the following parameter:

Rate Equation Setup

numerics scrambling pump signal RE-doping mirrors

fiber length 5 m
longitudinal steps along fiber 100

use Power Equation forward ☒
use NLSE forward (instead of powers only) ☒

forward  backward

use Power Equation backward ☐

convergence
max. iterations 0
convergence 1e-07
deceleration 1

*choose 0.999 or 1.0 for faster convergence, if no instability is observed

☒ include laser spontaneous emission
☐ use Raman Gain in Power Equations
☐ include thermal and spontaneous noise

if field is written to file
☐ save backward propagating field as well

OK

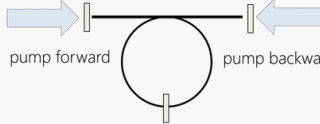
Rate Equation Setup

numerics pump signal RE-doping mirrors

forward pump
pump core diameter 125 μm
background loss 0.0 1/m

power (W) wavelength (nm) small signal absorption (dB/m)

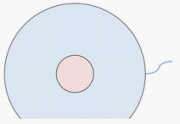
15	976.0	3.712331878
0.0	976.0	3.712331878
0.0	976.0	3.712331878
0.0	976.0	3.712331878
0.0	915.0	1.067015041

pump forward  pump backward

backward pump
pump core diameter 125 μm
background loss 0.0 1/m

power (W) wavelength (nm) small signal absorption (dB/m)

0	976.0	3.712331878
0.0	976.0	3.712331878
0.0	976.0	3.712331878
0.0	976.0	3.712331878
0.0	976.0	3.712331878

 pump core

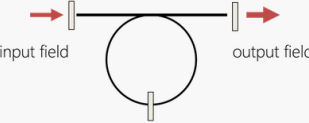
OK

Rate Equation Setup

numerics pump signal RE-doping mirrors

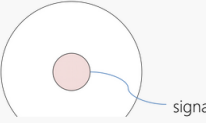
signal background loss 0 1/m

input
☒ use data array

M1  M2

output field

☒ save output M2 to data array
☐ save output M1 to data array

 signal core

OK

Rate Equation Setup

numerics pump signal RE-doping mirrors

ion mass concentration ☒ 13500 ppm

molecular concentration 0.23714 mol%

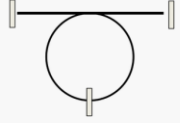
ion density 1.03362e+26 1/m³

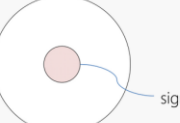
host material density 2200 kg/m³

atomic mass ions 173.04 u

molecule mass 0.39408 kg/mol

Yb2O3 Er2O3 Tm2O3

M1  M2

 signal core

available fibers ...

quantum efficiency of pump to upper level 1

cross sections

homog. linewidth nm

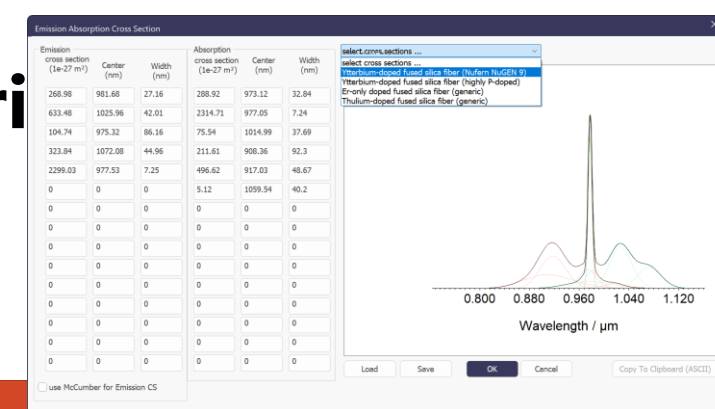
No. of realizations

fluorescence lifetime 0.85 ms

Temperature K

doped core diameter 5 μm

OK



Lecture 6.4: Nonlinear fiber amplifiers (field description)

Gain managed nonlinear amplification

The nonlinear Schrödinger equation parameter are:

dispersion term

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

☐ beta 0
☐ beta 1
☐ beta 2
☒ D

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

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

☒ Use dispersion
☐ do not use dispersion
☐ auto y

Dielectric dispersive medium

predefined

A 1
B1 0.6961663
B2 0.4079426
B3 0.8974794

more...

more...
fused silica
CaF2
Schott BK7
Schott SF6
Zerodur
Si (crystalline silicon)
Diamond
Germanium
LiNbO3 (o)
LiNbO3 (e)

self phase modulation / two photon absorption term

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

n2 3.2e-20 m²/W

f R 0.18

TPA 0.0 m/W

TPA is experimental so far ...
☐ saturate SPM
saturation power density 1.0 GW/cm²

☒ use SPM and TPA
☐ exclude SPM

general

define free parameters

☒ measure and parse 100
☐ write file

waveguide

loss 0.0 1/m

gain 0 1/m

mode diameter 6.5 μm

gamma 0.005882690 1/(W m)

effects

☒ dispersion

☒ SPM / TPA

☐ Raman

☐ self-steepening

☐ LLE

numerics

steps 1000

stepsize 0.005 m

distance 5 m

adaptive local error 1e-07 presets:

fiberdesk
nonlinear pulse propagation

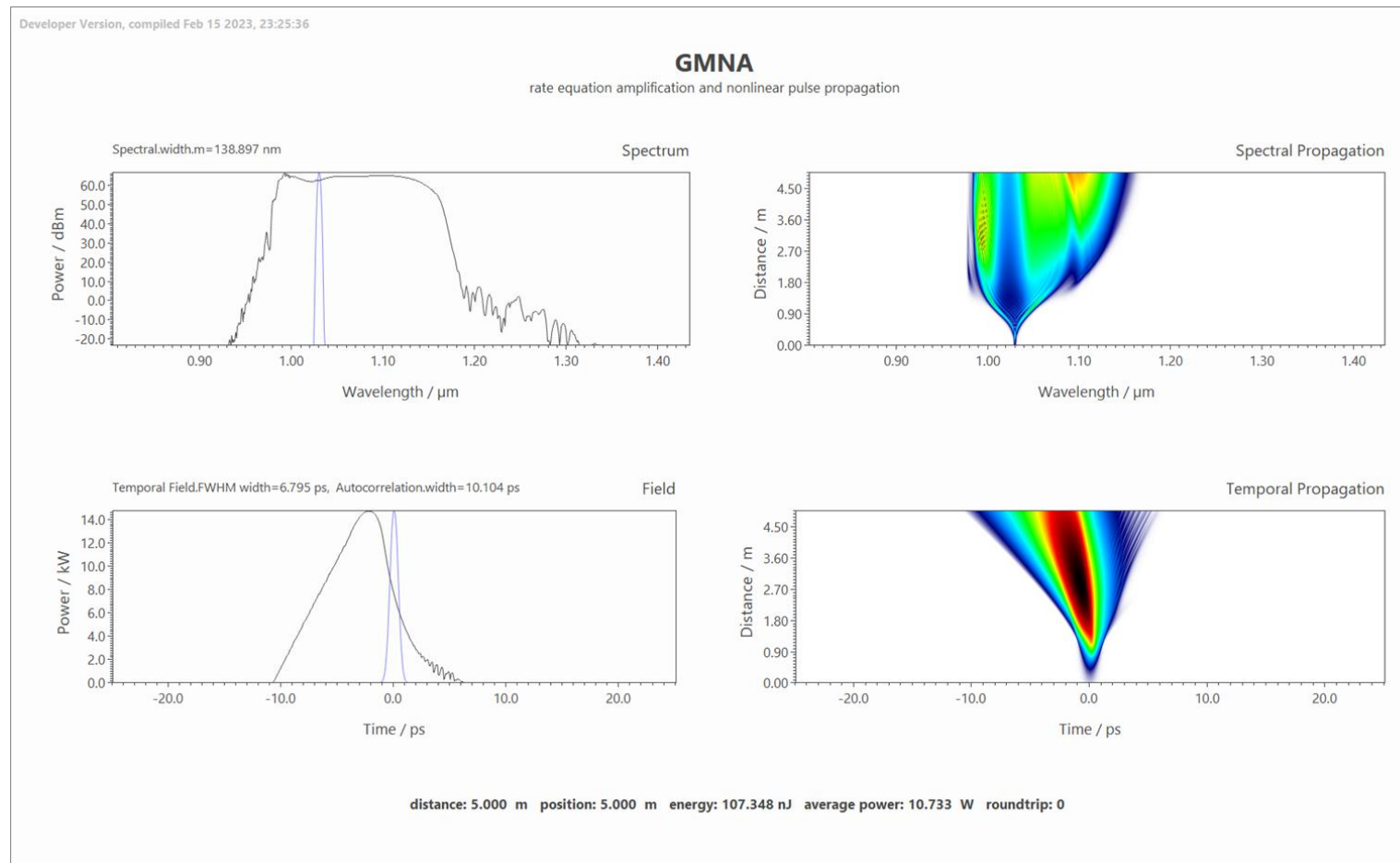
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Lecture 6.4: Nonlinear fiber amplifiers (field description)

Gain managed nonlinear amplification

After propagation, the result looks like this:



Lecture 6.4: Nonlinear fiber amplifiers (field description)

Noisy cw amplification

.. Soon ..

