Tutorial 6 - Rate-equation gain

- Background
- Setup of the data array (field vs. power description)
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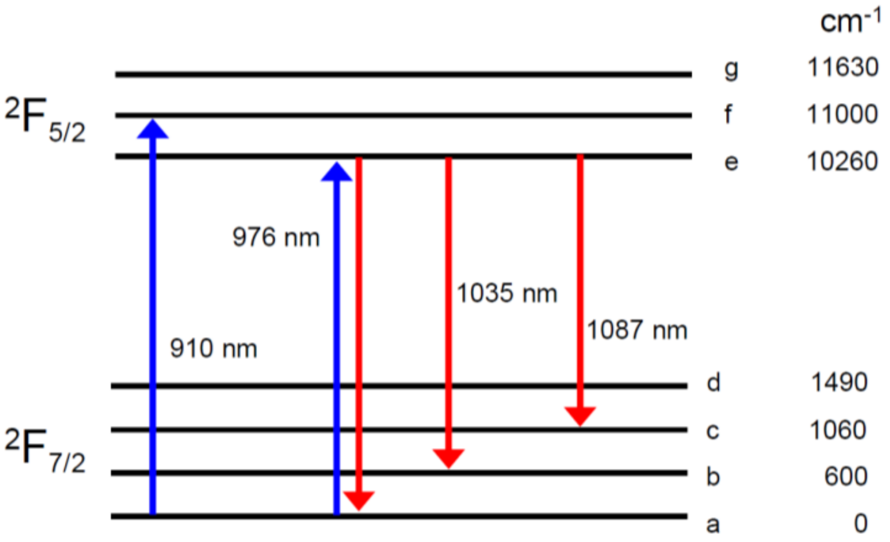
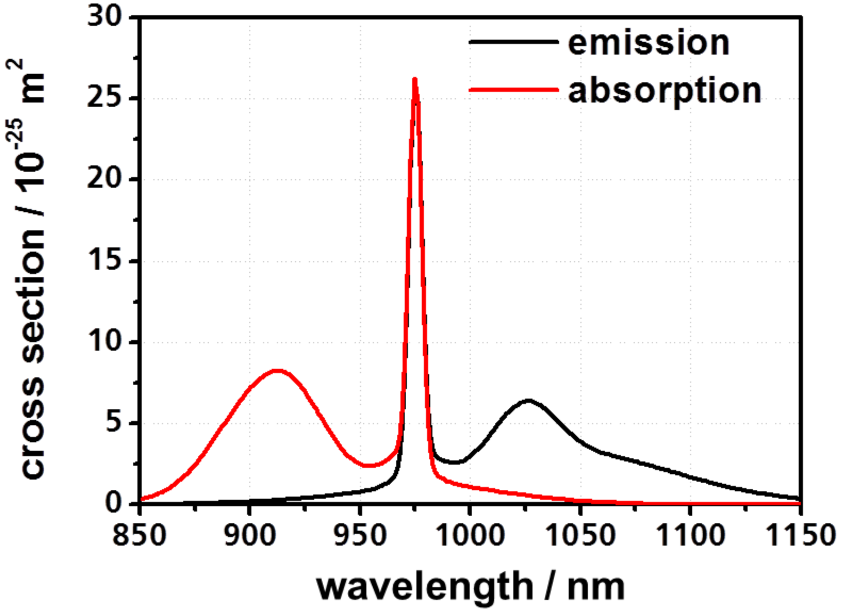
    - Gain Managed Nonlinear Amplification
    - Noisy cw amplifier (coming soon)

Tutorial 6 - Rate-equation gain

Background

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





Tutorial 6 - Rate-equation gain

Rate-equation gain

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

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

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

$n_0 = n_1 + n_2$ 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.

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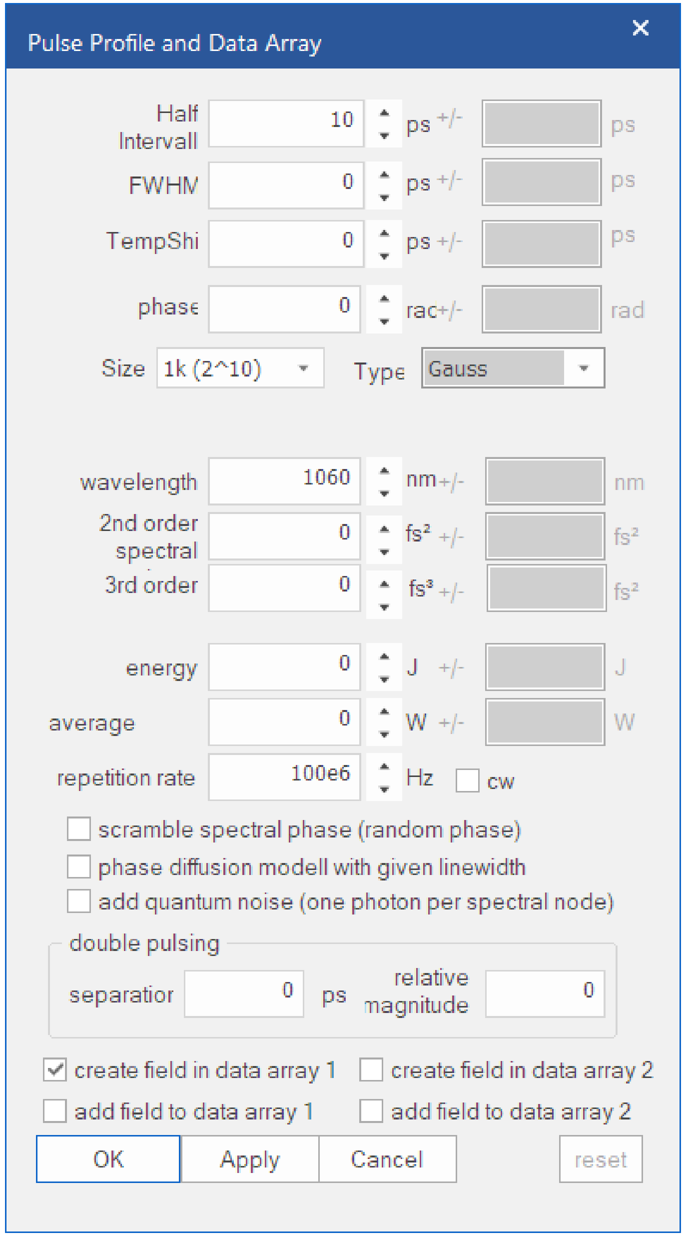
Setup of the field for rate equation simulations within the „power equation approximation“, that means, no coupling to the NLSE:

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.



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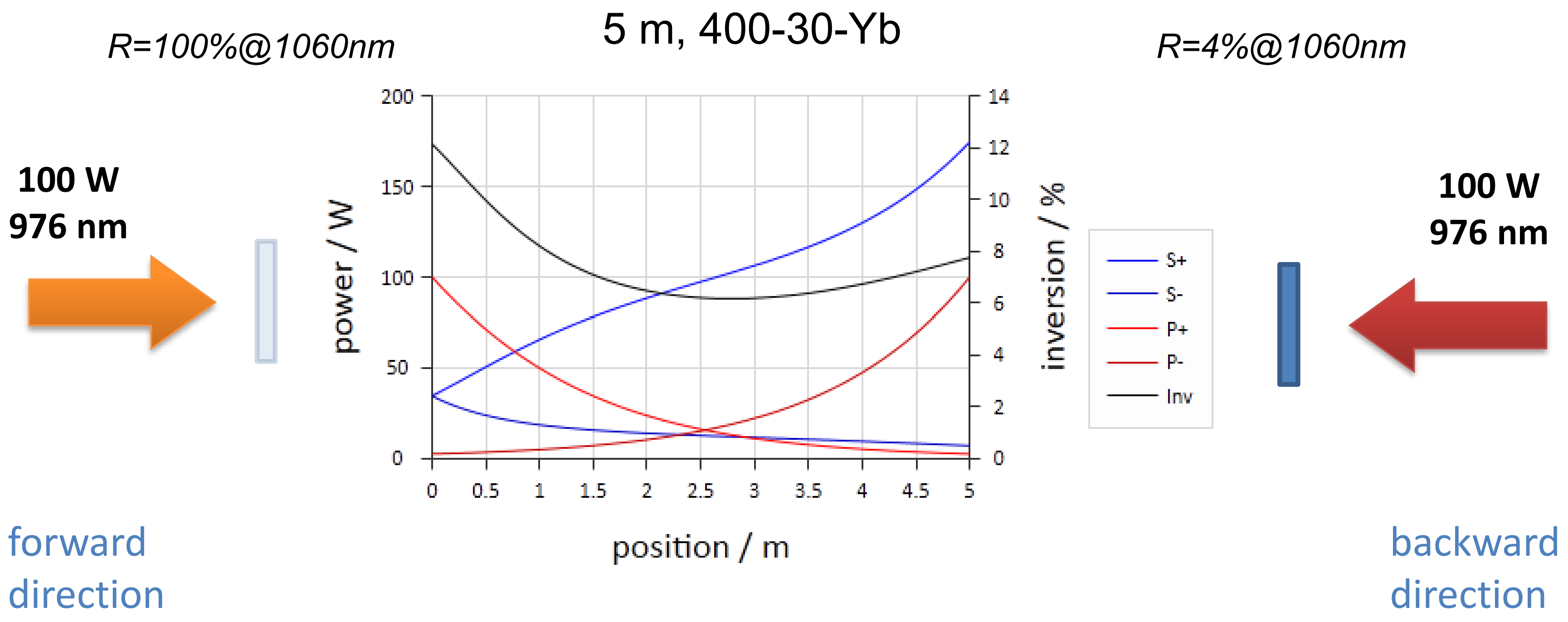
Tutorial 6 - Rate-equation gain

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:

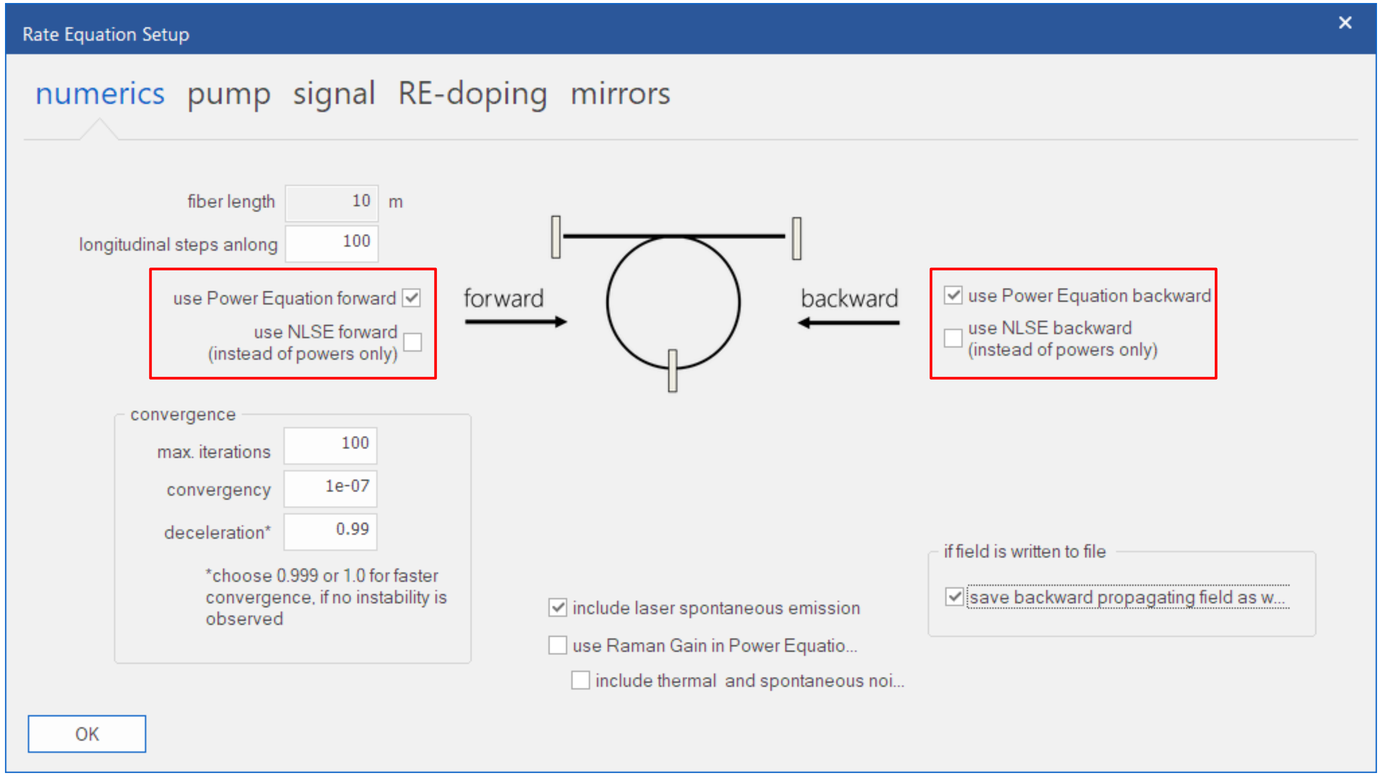


Tutorial 6 - Rate-equation gain

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

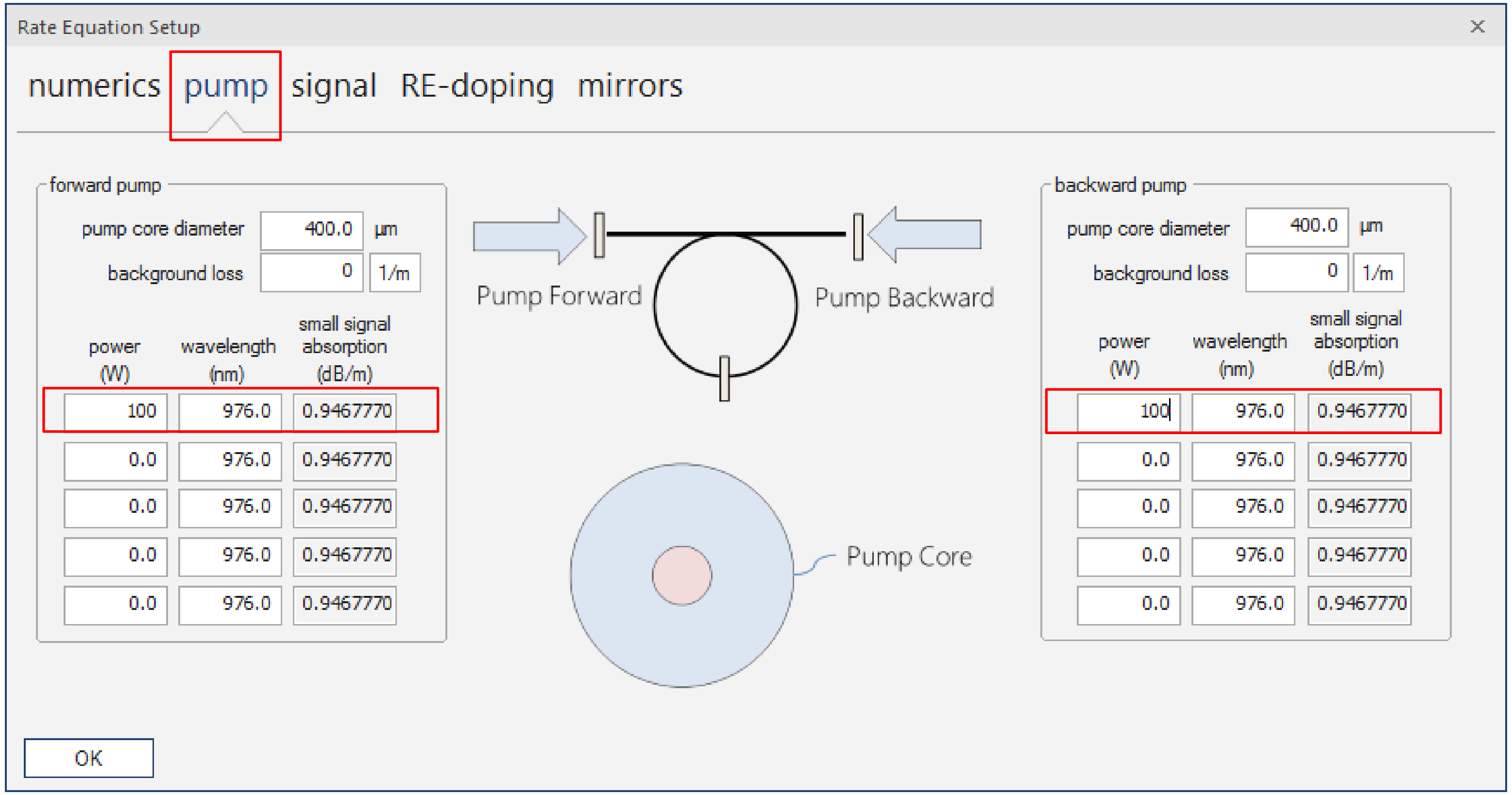
Longitudinal steps = 100, max. iterations = 100, convergency = 1e-7

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



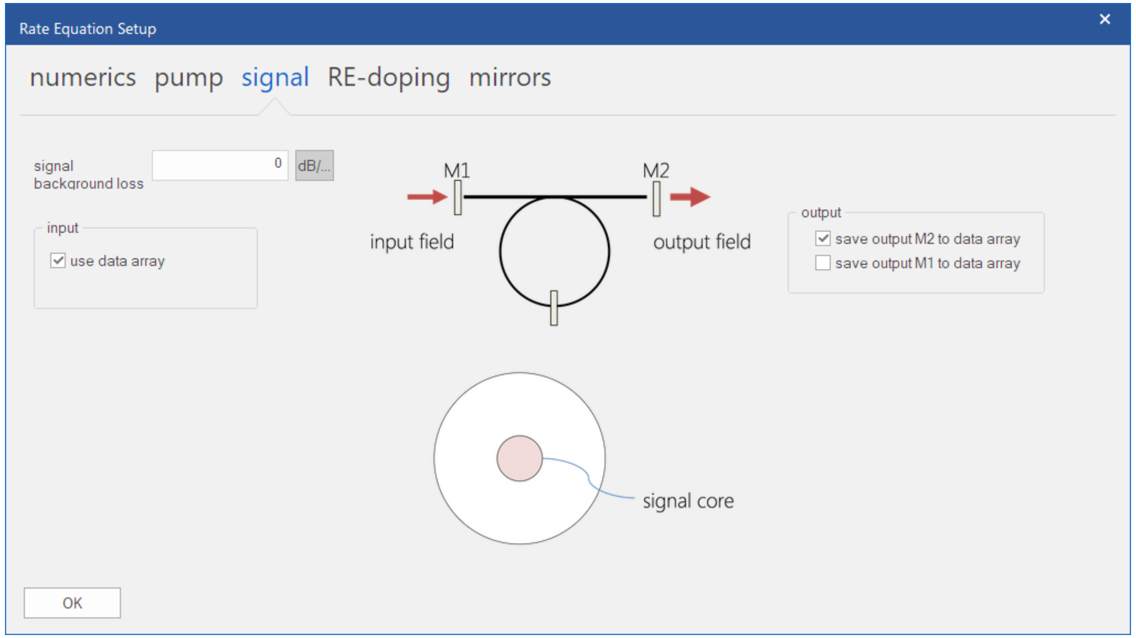
Tutorial 6 - Rate-equation gain

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.



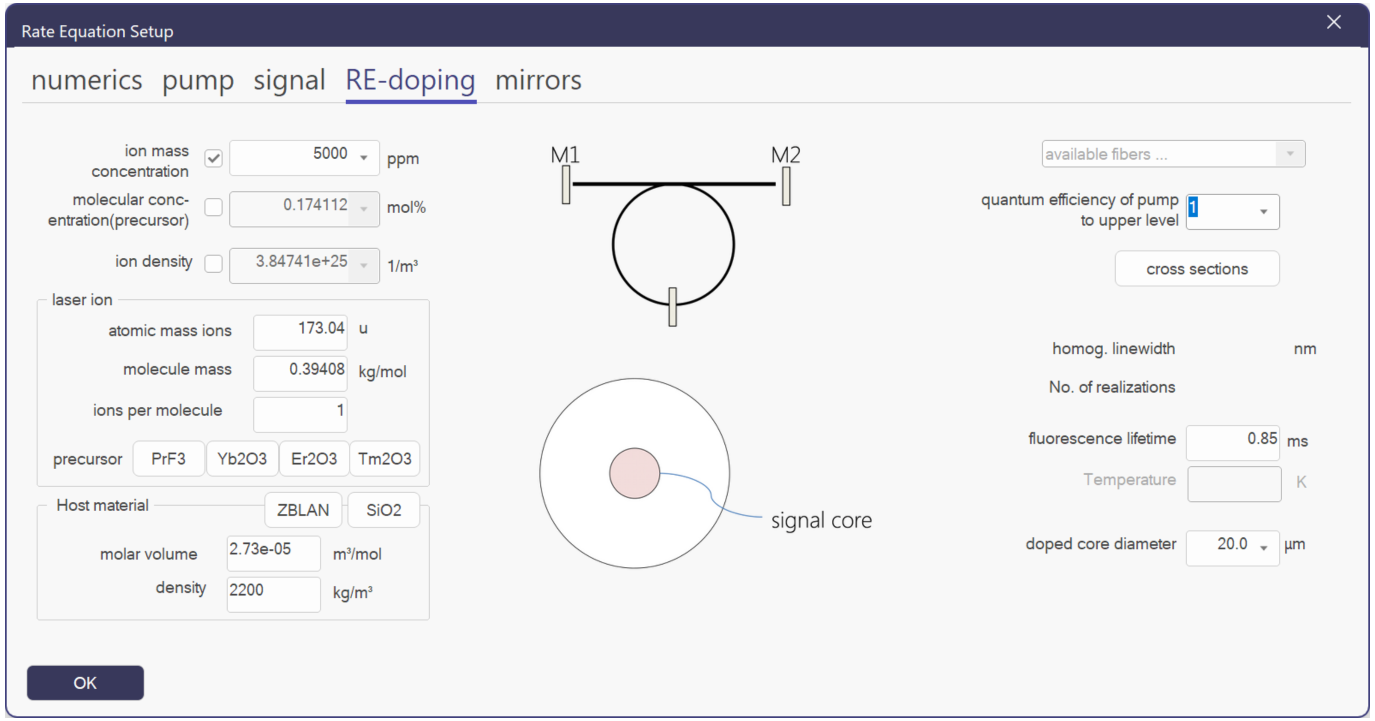
Tutorial 6 - Rate-equation gain

The property page „**signal**“ defines, how the current field and the results of the simulation are threated. 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.



Tutorial 6 - Rate-equation gain

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



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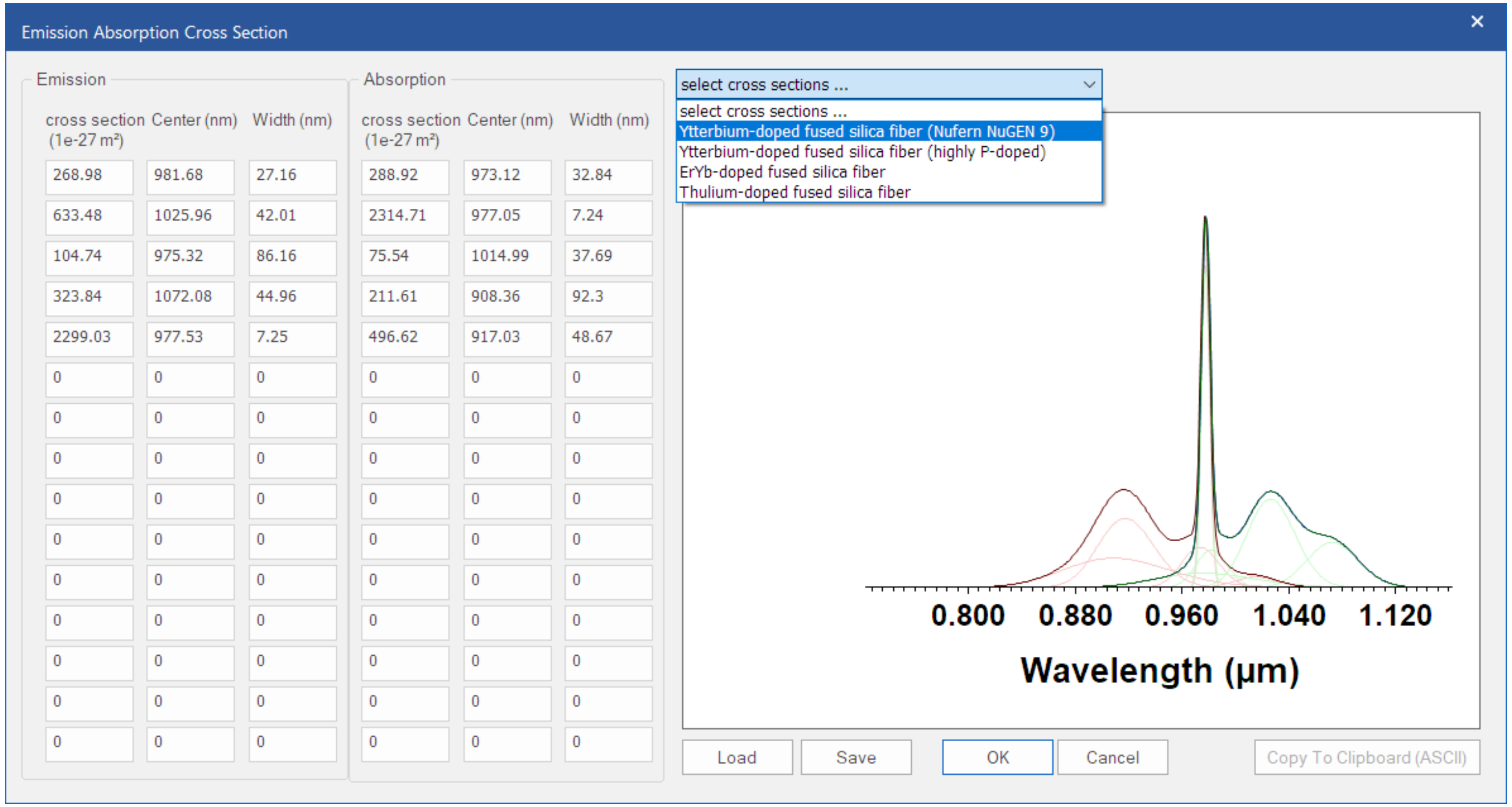
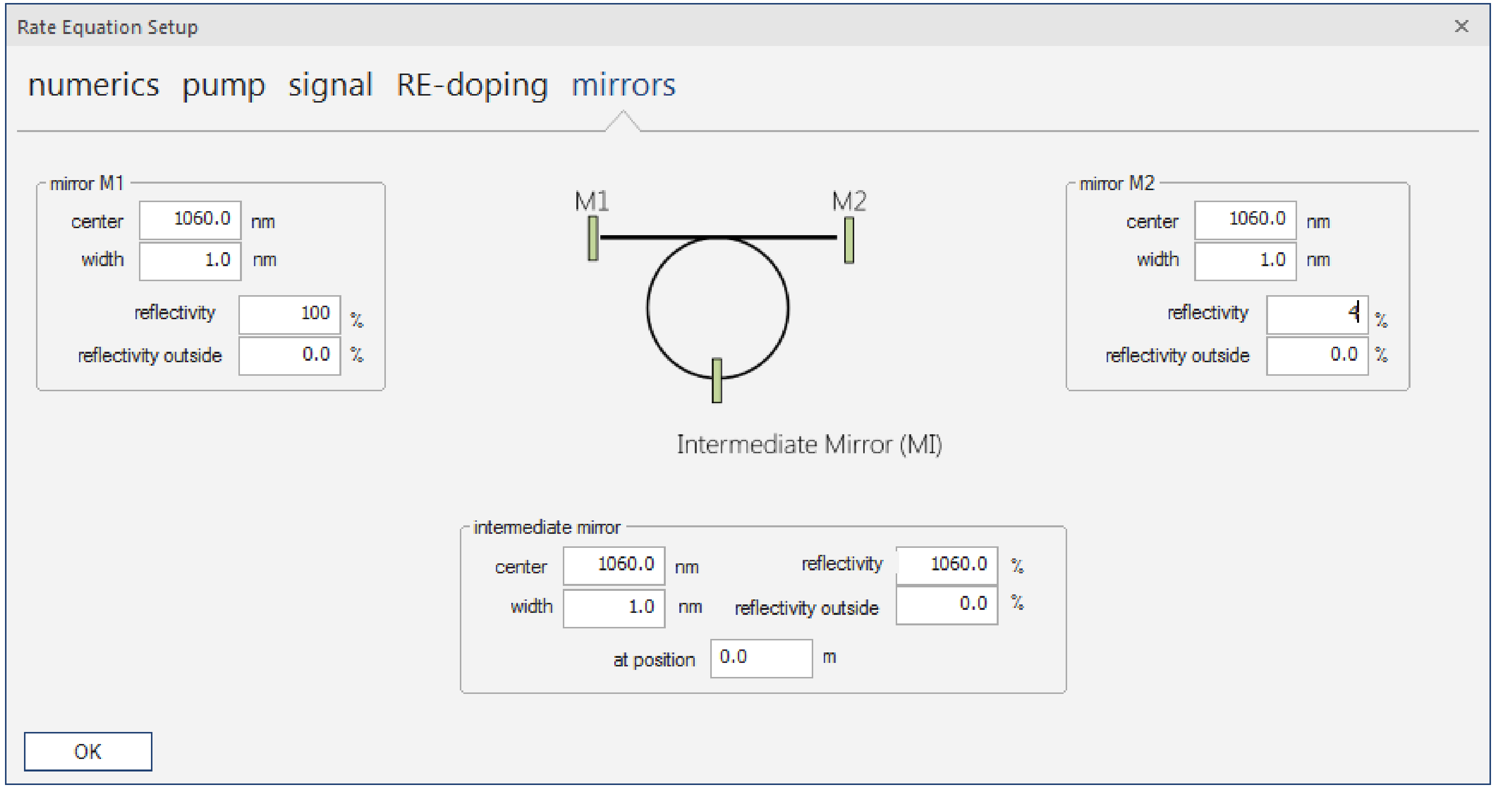
The cross sections are set by a multi-Gaussian peak fit. Some fibers are predefined.



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.

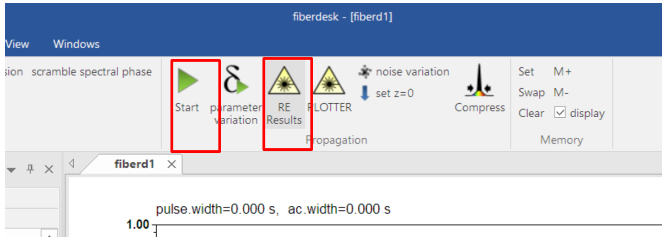
Tutorial 6 - Rate-equation gain

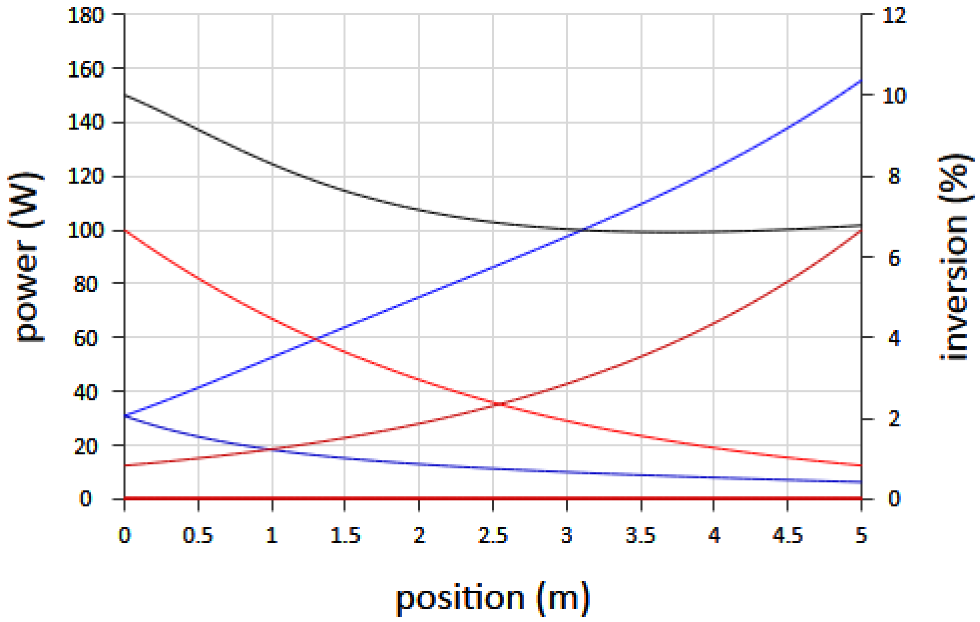
The last property page „**mirrors**“ defines the spectral reflectivity or M1, M2 or an intermediate mirror. For amplifiers, these values have zero reflectivity.



Tutorial 6 - Rate-equation gain

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.





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Tutorial 6 - Rate-equation gain

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.

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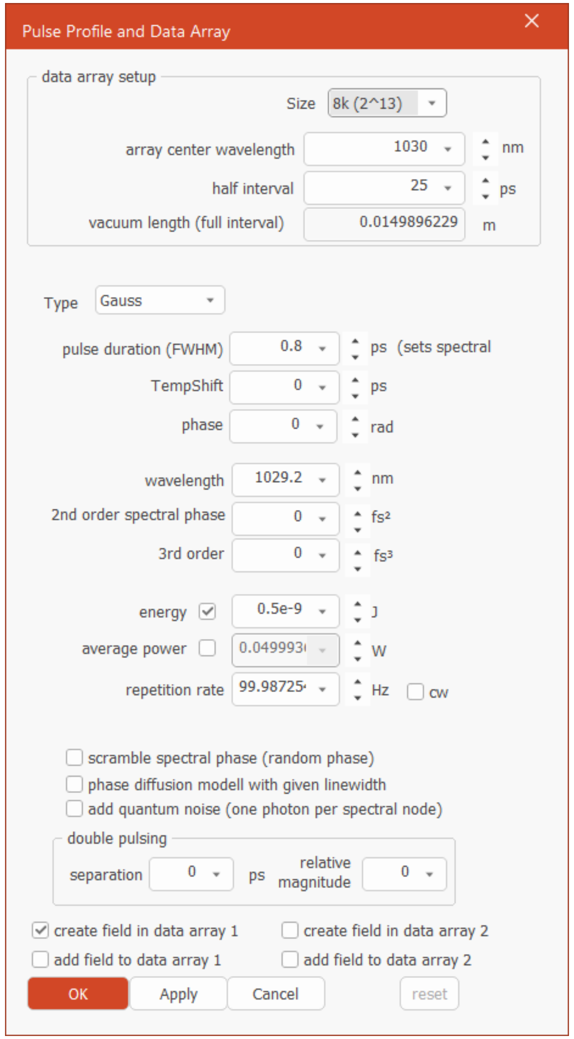
The following example is similar to the published results in:

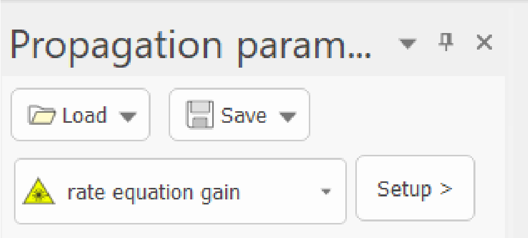
(1) Pavel Sidorenko, Walter Fu, and Frank Wise, "Nonlinear ultrafast fiber amplifiers beyond the gain-narrowing limit," Optica 6, 1328-1333 (2019).

(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.

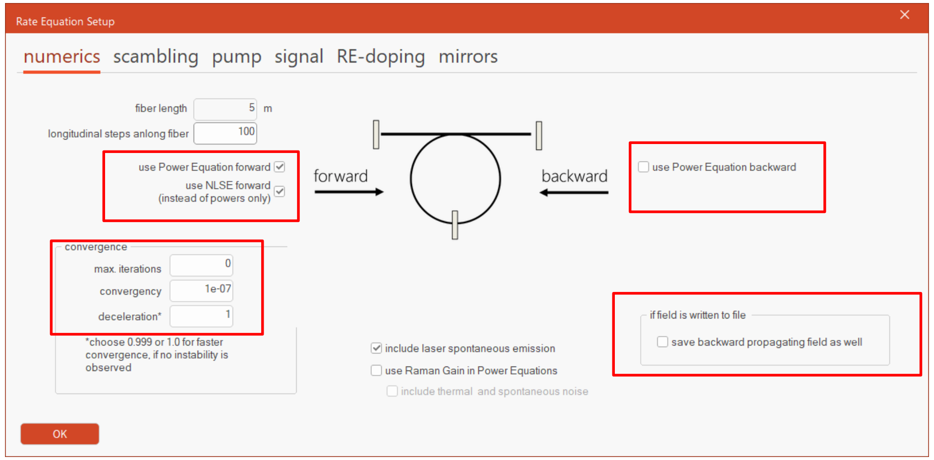


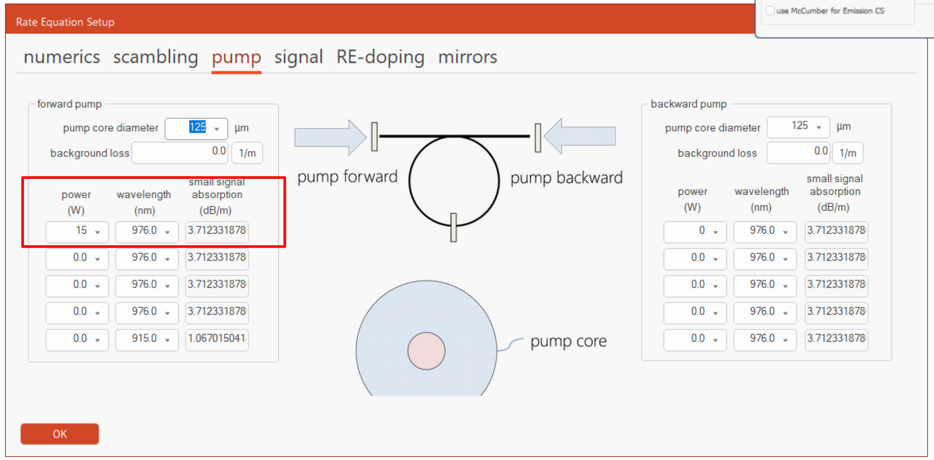
The propagation is set to rate equation gain.

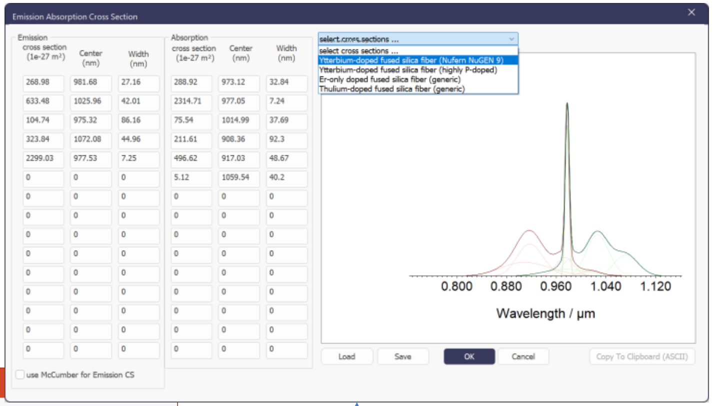


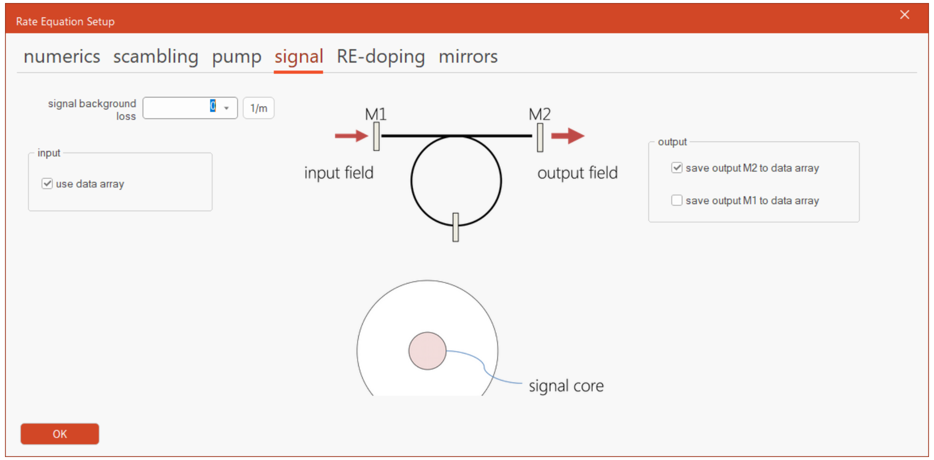
Tutorial 6 - Rate-equation gain

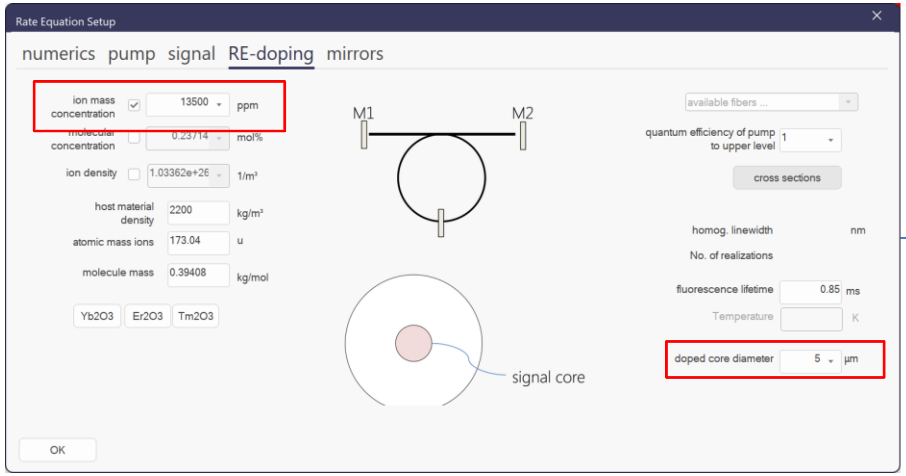
In the rate equation setup dialog, please set the following parameter:











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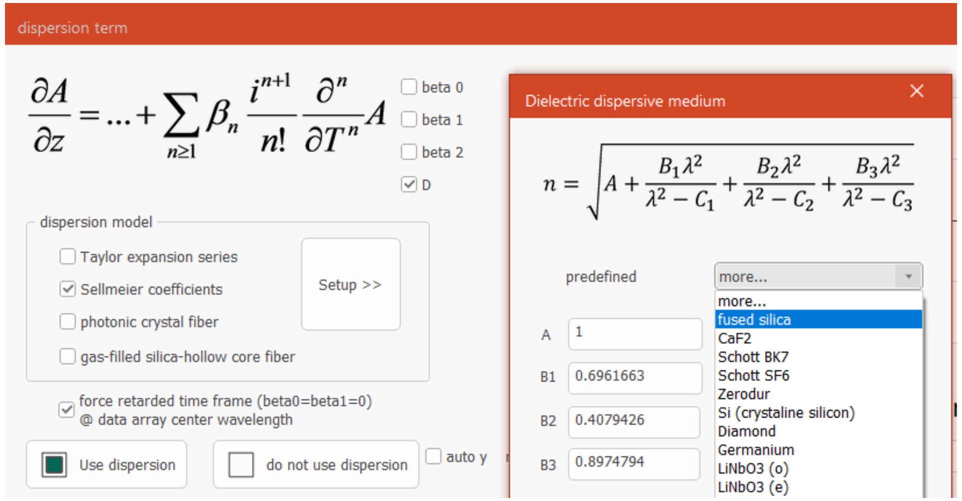
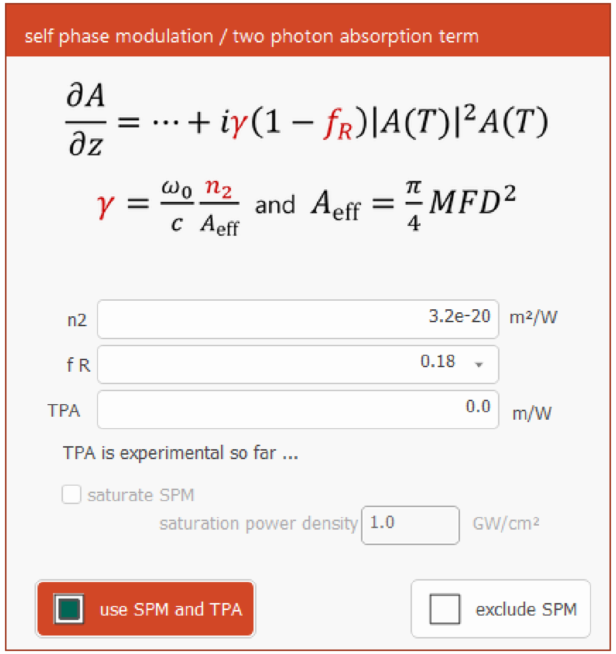
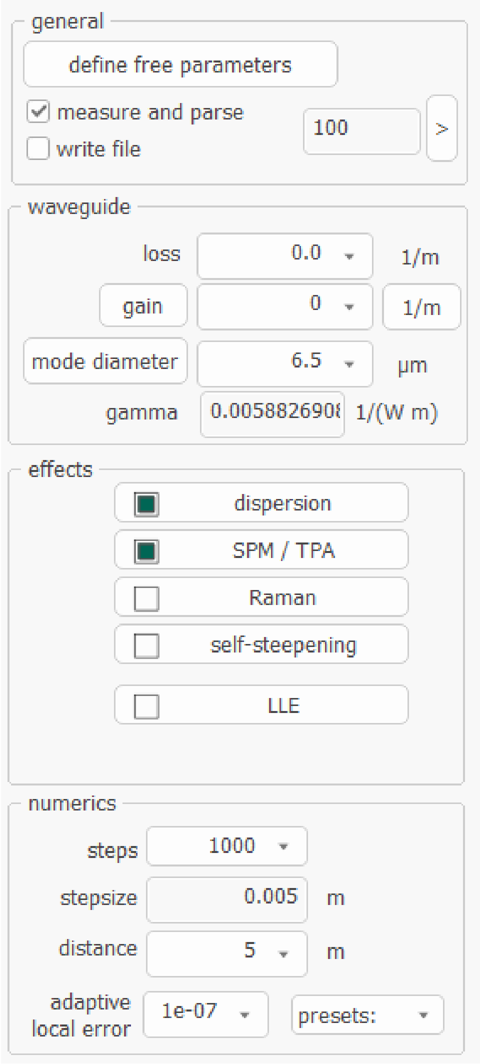
The nonlinear Schrödinger equation parameter are:







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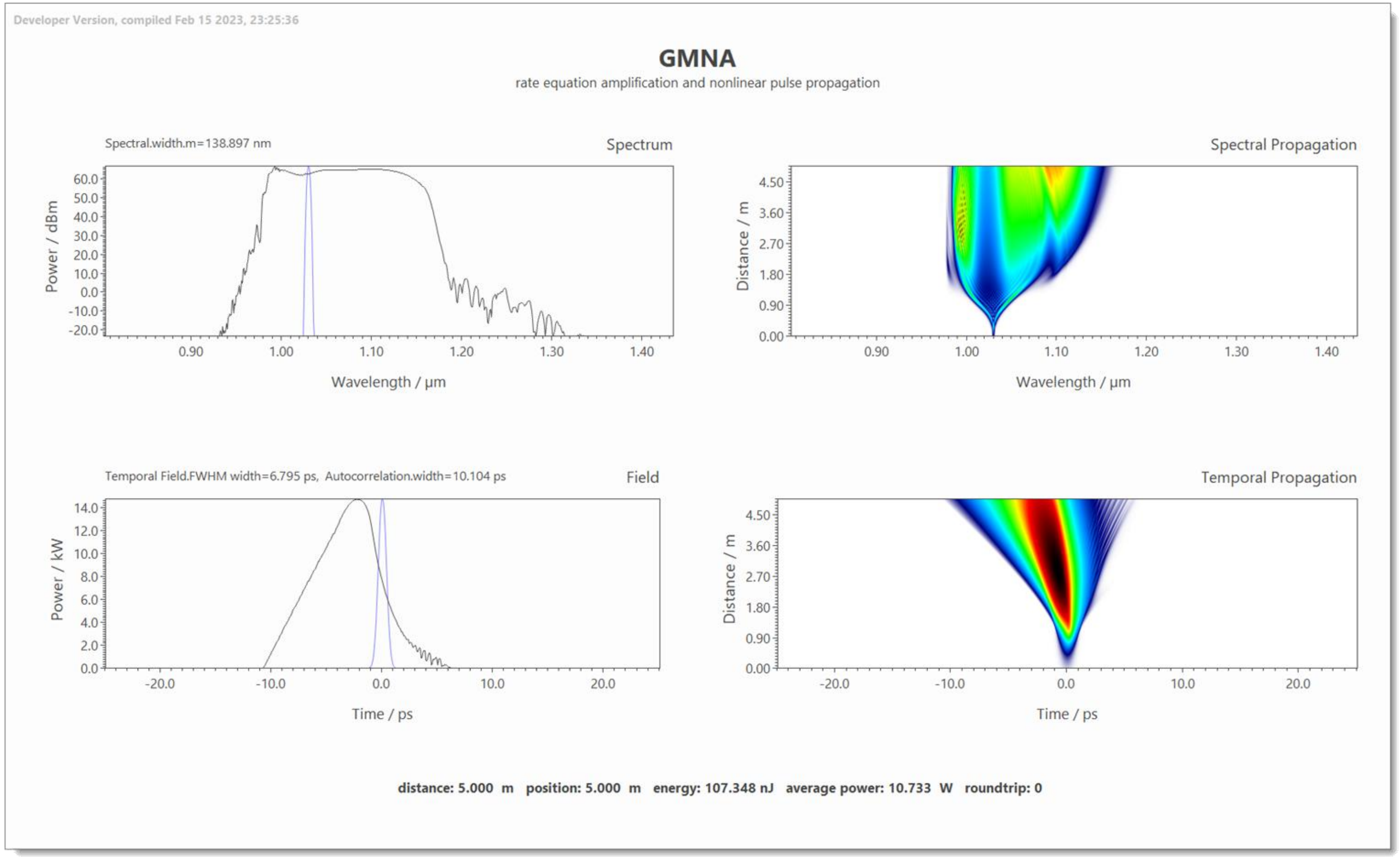
After propagation, the result looks like this:



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.. Soon ..