

# PropSim v1.0: A Convenient Way to Model Light Propagation in Optical Fibers

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## 〈概要〉

本論文は、光ファイバ内の非線形伝搬に関連した旧知の研究課題を再考察し、既存の解法を見直すことで、さらに開発発展させるための新たなアイデアを提案するものである。このような開発のほとんどは、何年前に作られた光ファイバのパッケージ・ソフトの使い勝手に関するものであるが、光ファイバを扱う人々の間では、設定が容易なソフトウェアへの需要が高まっている。光ファイバ光学に基づいた装置を設計するためには、光ファイバに関連したシミュレーションが必要であることは言うまでもない。しかしながら、この目的のための市販光ファイバソフトウェアツールは、扱いが容易ではなく、また多くの場合、重要な機能に欠けている。パラメータ設定の影響を即時に認識しつつ光学部品を容易に設計に追加する、という我々のコンセプトは、このような欠落のあるソフトウェアツールにとって代わるものである。このプロジェクトは、昨年半ばにFETI社内の新規プロジェクトとして自発的に開始されたものである。現在、定められたデータ構造に対して十分に機能するコードの基盤技術を確立し、必要に応じてさらに複雑な特性をソフトウェアに追加することが可能となった。このソフトウェアのすべての要素が、広範囲にわたって試されることを期待している。

## 1. INTRODUCTION

Furukawa Electric Institute of Technology (FETI) Ltd. in Budapest, Hungary is a subsidiary and research laboratory of the Furukawa Electric Co. Ltd. (FEC) in Tokyo, Japan. Besides automotive, AI and material related research, many R&D projects in FETI are related to computer simulation. The type of these simulations are, for instance, the design and optimization of opto-electronic devices or the calculations of complex mechanical problems or coupled physical problems where thermal, mechanical and/or optical properties are treated at the same time. For many problems, we use commercially available finite element (FE) software or other type of software to speed up the design and optimization stage of the developments but there exists such situation when we must develop our own simulation code to be able to model a specific problem. This is the case with light propagation in optical fibers too. When the Simulation Group was established in FETI in 2000 the very first project was related to the calculations of nonlinear pulse propagation in telecommunication fibers with Wavelength Division Multiplexing (WDM) in that the multiplexed signal may reach the intensity level where self-phase modulation cannot be neglected anymore. This project at that time was a collaboration with FETI Photonics Lab. The calculations since that was developed in many directions: soliton propagation of modulated signals<sup>1)</sup> or compression of

ultra-short, low energy laser pulses in small core-area photonic crystal fibers<sup>2)</sup>, amplification and nonlinear propagation in optical fiber amplifiers<sup>3), 4)</sup> including multimode amplifier modeling<sup>5)</sup> in that not only one mode but many of them amplified at the same time and mode competition happens. Also, fiber oscillator<sup>6)</sup> and Raman amplification was modeled<sup>7)</sup> with the developed code, and many of these investigations were done together with our sister company: OFS Labs in Somerset, NJ. We have already reported these achievements and the diversity of the developed code in a 2016 paper in Furukawa Review<sup>8)</sup> but the written code was always in a state that could be used mostly by its developers only. The code was written in Matlab and any execution could be started by editing the parameter list at the beginning of a text file (Matlab file). Sometimes with careful selection of the parameter switches and setting certain parameters to one and others to zero in order to choose the right solvers for the intended task. This made the usage of the code difficult or completely impossible for others. Therefore, we decided last year that we develop a graphical user interface (GUI) around the existing solvers that can solve complex tasks and concatenate different components after each other easily. We can claim that this attempt was successful. In this review paper, we describe the basic concept of our development directions including the solvers as well as the GUI and also the possibilities that can be simulated easily by anybody using the propagation simulator that we named PropSim.

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## 2. THEORY

The core of the software is the split-step Fourier (SSF) solver that can handle many different forms of the nonlinear Schrödinger equation. We show here an exact form of the equation that is the default settings of PropSim v1.0 in its present state<sup>9)</sup>

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A + \sum_{m=2}^N \frac{i^{m+1}\beta_m}{m!} \frac{\partial^m}{\partial T^m} A = i\gamma \left( |A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right) \quad (1)$$

where  $A$  denotes the complex envelope of the propagating field,  $z$  is a coordinate pointing to the direction of the propagation (parallel with the fiber axis),  $T$  is the temporal space,  $\alpha$  is the attenuation in the fiber in 1/m units,  $\beta_m$  is the  $m^{\text{th}}$  Taylor term of the dispersion,  $\gamma$  is the nonlinear coefficient and  $T_R$  is the Raman response time that is usually 2 fs for silica fibers.  $\omega_0$  is the center frequency,  $N$  is the number of the dispersion components that can be up to 14 Taylor components but most of the cases 6-8 dispersion parameters are enough to describe the dispersion property of most of the fibers with great accuracy on a 100-300 nm wavelength range.

For calculating the amplification, the power evaluation equations are combined with the rate-equation as it is described by Giles and Desurvire<sup>10)</sup>:

$$\frac{\partial P_k}{\partial z} = u_k \Gamma_k n_t (N_2 \sigma_{ek} - N_1 \sigma_{ak}) P_k + u_k \Gamma_k n_t N_2 \sigma_{ek} m h \nu_k \Delta \nu_k \quad (2)$$

where  $u_k$  can be -1 or +1 representing backward and forward signal directions, respectively. The  $k$  index denotes the  $k^{\text{th}}$  frequency component of the signal,  $\Gamma$  is the overlap factor of the propagating mode with the doping ions,  $n_t$  is the doping concentration of the fiber in 1/m<sup>3</sup> units,  $\sigma_e$  and  $\sigma_a$  are the emission and absorption cross-sections, respectively, in m<sup>2</sup> units,  $N_2$  is the ratio of the upper population while  $N_1=1-N_2$  is the ratio of the base population level,  $\nu$  is the frequency components of the amplified spontaneous emission (ASE),  $\Delta \nu_k$  is the width of the  $k^{\text{th}}$  frequency component and  $m$  is the number of the polarization states of ASE and  $h$  is the Planck constant.  $N_2$  and consequently  $N_1$  must be determined in every step of the calculations, and this is described by a two-level rate equation working well for Ytterbium and Erbium doped fibers. The inversion level from the rate equation in steady-state approximation ( $dN_2/dt = 0$ ) can be calculated as follows

$$N_2 = \frac{\sum_k \frac{P_k \Gamma_k n_t \sigma_{ak}}{h \nu_k \zeta}}{1 + \sum_k \frac{P_k \Gamma_k n_t (\sigma_{ek} + \sigma_{ak})}{h \nu_k \zeta}} \quad (3)$$

where  $\zeta = \pi R_{\text{eff}}^2 n_t / \tau$ , in that  $R_{\text{eff}}$  is the effective radius of the doped region and  $\tau$  is the fluorescence lifetime of the doping ion. For example,  $\tau$  is approximately 10 ms for Er-doped silica fibers while it is around 2 ms for Ytterbium doped ones.

The numerical solution of the nonlinear Schrödinger equation is done by the split-step Fourier algorithm that is a spectral method to solve nonlinear partial differential equations<sup>9)</sup>. The power evaluation equation however is handled by a 4<sup>th</sup> order Runge-Kutta method with great accuracy as we will show later. It is a question how the two equations can be coupled in a solver that simulate a gain amplifier with nonlinearity and dispersion related effects too. The answer is to add a gain term to the equation (1) that has a similar form than the loss term in that same equation. The frequency dependent gain coefficient can be calculated from the ratio of the output and input powers of every calculation segment. These power values are obtained from the solution of the equation (2) and (3). This is the method we use to model optical fiber amplifiers including not only gain but also the effects of dispersion and nonlinearity.

## 3. INTRODUCTION OF THE SOFTWARE

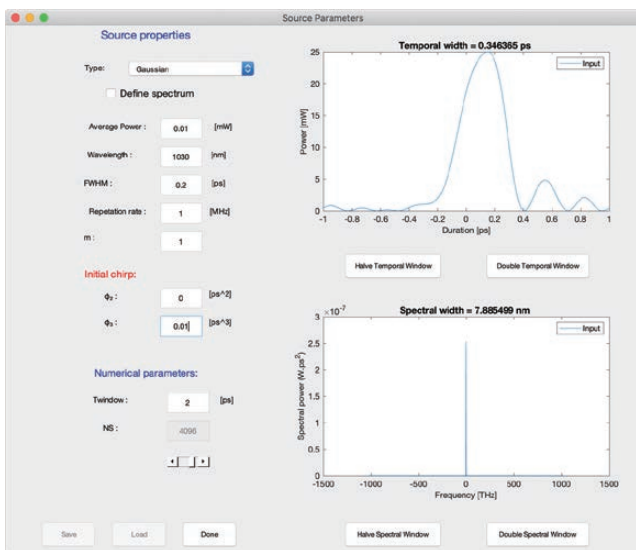
Opening PropSim software and creating a new component arrangement that is intended to be simulated can be done by opening the *Device Management* menu and clicking on the *Create Device* menu item. This will place a light source, a passive fiber and a diagnostic element to the user interface and small + signs appear between them. Clicking on any plus sign will allow us to add additional components to the existing ones. This is the way how we can build up a complete system. In Figure 1, we show the main GUI window of the software using a few components to model. Clicking on any of the component will open the corresponding dialogue window to set up its parameters. By clicking with the right button of the mouse on any component, a dialogue menu will open that will allow us to delete the actual component or shift



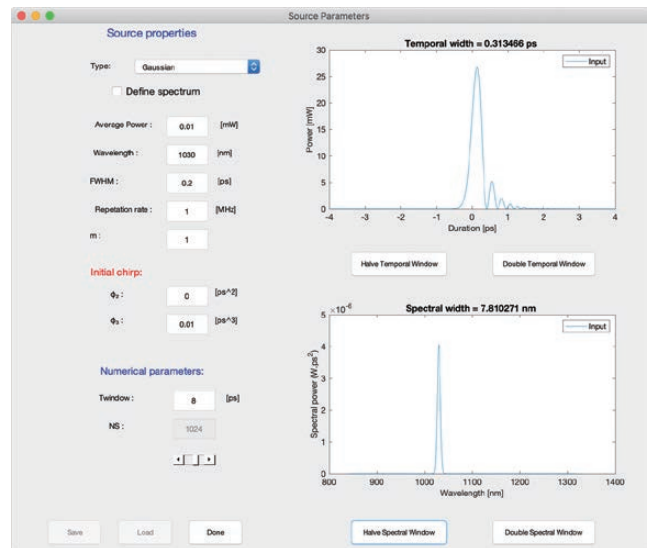
**Figure 1** The main GUI window of PropSim with a few additional components compared to the initial state. From left to right the components are the followings: light source, a passive fiber, Ytterbium doped fiber, band-pass filter, passive optical fiber and diagnostic tool.

to the right or shift to the left. Clicking on the Start button will start the simulation and the results are plotted in separate windows finally.

The basic concept of the software which interweaves the whole design of it is that the user can recognize immediately what he or she is doing. This is apparent on the parameter setting dialogue of the light source, for example. After clicking on the light source icon on the main GUI (most left icon in Figure 1), one can get the settings dialogue of the light source as it is shown in Figure 2. We selected a Gaussian pulse, and we define it in the temporal space though the opportunity to characterize the source with its spectrum is given by clicking on the *Define Spectrum* checkbox. Now, in Figure 2, one can see a distorted pulse shape due to the fact that the user has just typed a third order chirp value that causes an asymmetric broadening in a too large extent and the temporal window is too narrow to be able to include the pulse, therefore it is sticking out of the range. That is crucial to make a simulation with a well characterized signal not affected by the edge of the available space. Another issue what we can recognize in Figure 2 that the user defines such broad spectral range that the shape of the spectrum cannot be perceived, and the central wavelength cannot be seen. If the spectrum is broader than that can be visualized in wavelength units, the graph switches to the relative frequency range where the zero frequency corresponds to the central wavelength of the pulse defined here as 1030 nm. To overcome these issues can be done by simply clicking on the *Double Temporal Window* button and *Halve Spectral Window* button a few times. In Figure 3, we show the result of adjusting the temporal and spectral space this way.



**Figure 2** Setting dialogue of the light source. Graphs immediately show the effect of changing any parameter of the source properties in the temporal as well as in the spectral space.



**Figure 3** Corrected signal parameters for better resolution of the spectral and temporal shapes.

The software can use Gaussian or sech-hyperbolic pulses ( $m$  is the order of the Gaussian shape in Figure 2 and in Figure 3), continuous wave signals and frequency combs as possible inputs for the simulations.

1030 nm signals can be amplified well by Ytterbium doped fiber amplifiers (YDFA), this is the reason that the setup in Figure 1 contains an YDFA though the software is prepared for calculating with Erbium doped fiber amplifiers (EDFA) if necessary, at around the telecommunication wavelengths. The component list contains also YDFA and EDFA at the present state of the code they can be set by clicking on their icons in the main GUI. The pop-up dialogue as shown in Figure 4 is sectioned according to the parameters of a fiber that can be simulated with our present models. This includes polarization related effects, dispersion, nonlinearity, loss and gain related parameters. Clicking on any of the button representing the given set of parameters will make available the corresponding parameter set. For example, clicking on the *Dispersion* button will open the window shown in Figure 5. Again, this element of the GUI is designed the way that the user can immediately check the effect of his or her parameter input. Changing any parameter including the axis limits will take effect immediately after hitting enter or clicking out from the edit-box. The available tools at the upper right corner of the graph appear when the pointer is moved above the graph and can be used for further analysis. For example, in Figure 5, the user has just used the *data tips* tool to check the zero-dispersion wavelength of the curve defined by the dispersion parameters.

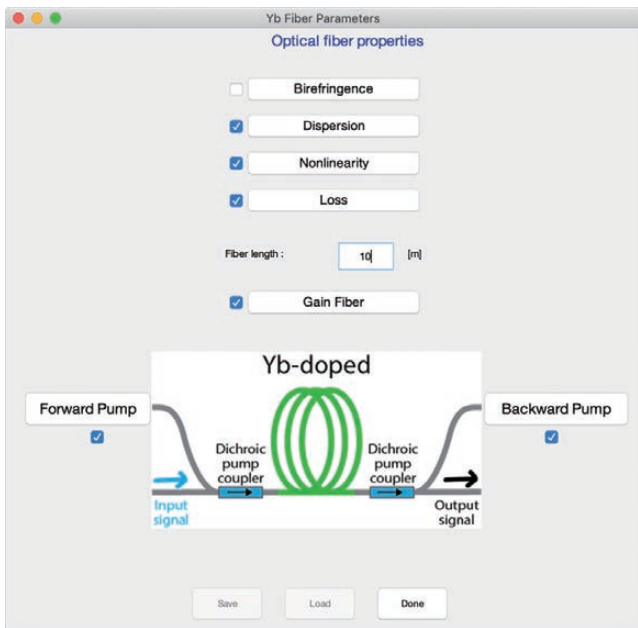


Figure 4 Parameter settings dialogue for the Ytterbium doped fiber amplifier.

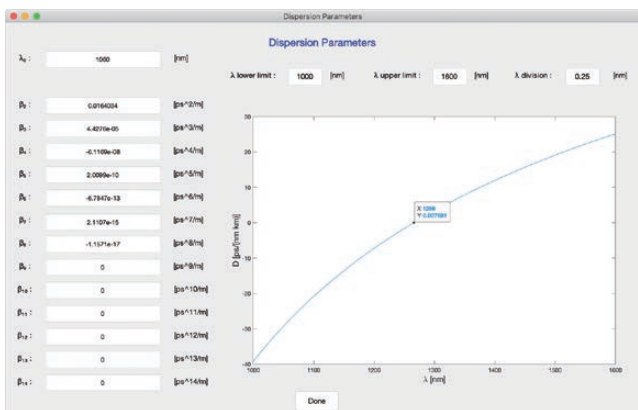


Figure 5 Dispersion parameter setting dialogue for optical fiber components including amplifiers.

## 4. RESULTS

We tested the solvers from many aspects including typical dispersion and nonlinearity related solutions of analytically solvable forms of the nonlinear Schrödinger equation. Those solutions can be found in the Agrawal book<sup>9)</sup>, for instance. We also executed simulations that calculates super-continuum generation and good agreement was obtained with published results. These tests are available in the form of regular research reports. Therefore, we think that the code can handle well the effects described by the nonlinear Schrödinger equation. The forthcoming task is to test the optical fiber amplifier related calculations. An extensive test is still to come but a possible test opportunity is presented in Figure 6. In this test case, we compare the solution of a basic arrangement, for example, in this case a signal and a forward pump situation solved with two different numerical methods. Basically, we want to use a fourth order Runge-Kutta method to handle the power evaluation equations corresponds to gain fibers, but we wrote another finite difference solver and compare the two to each other. This is useful for testing purposes. If the two different numerical scheme provides the same result, we can claim that the solutions are accurate with great probability. The Euler method is a first order numerical method to solve differential equations. Therefore, the solution of the power evaluation equation is quite unstable with it at low resolution in the longitudinal direction. This is shown in Figure 6 (a) where the 10 m long amplifier was calculated only in ten steps. But surprisingly the Runge-Kutta solver provides a stable solution even in this case at such a low resolution for the longitudinal coordinate. This accuracy is apparent checking the results in Figure 6 (b) where the discretization is done in 100 steps. In this case, the Euler method provides the same solution than the Runge-Kutta solver and this fact indicate that our solution can be considered appropriate. Figure 6 (c) shows the convergence of the two methods using different number of numerical steps in the solutions. The Runge-Kutta solver for this problem is very stable. The difference between solutions with high and low resolutions are apparent only in the third or fourth digits of the power values. The parameters of these calculations

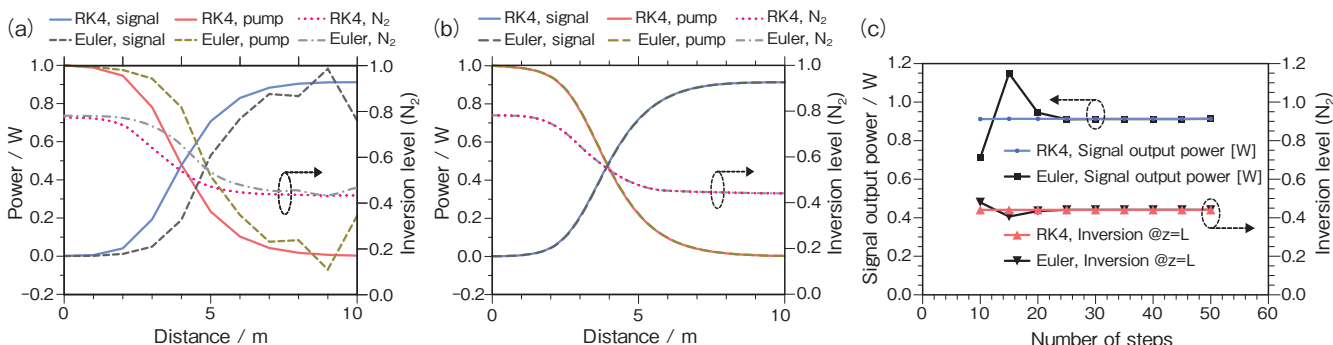


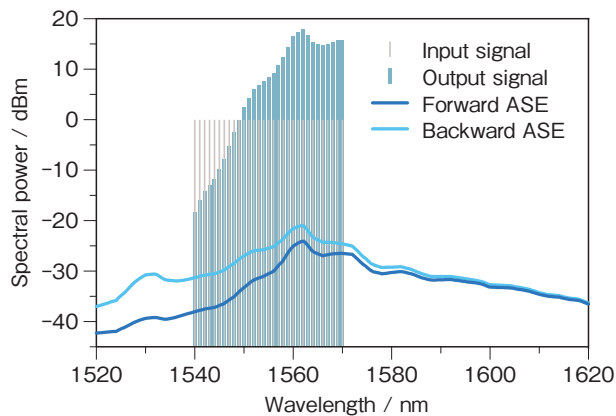
Figure 6 Comparison of the RK4 and Euler methods. (a) low resolution calculations with 10 steps, (b) high resolution calculations with 100 steps and (c) convergence of the two methods as function of the step size.

are collected in Table 1 that are essentially the same as for the forthcoming simulation example.

**Table 1** Parameter list of the test simulations in an EDFA system calculating with only forward direction signal and pump.

Parameter name	Parameter value	Units
Signal input power	1	mW
Signal wavelength	1550	nm
Overlap factor of the signal	0.6	—
Emission cross-section @1550 nm	3.602	$\times 10^{-25} \text{ m}^2$
Absorption cross-section @1550 nm	2.848	$\times 10^{-25} \text{ m}^2$
Forward pump power	1	W
Forward pump wavelength	1475	nm
Overlap factor of the forward pump	0.63	—
Emission cross-section @1475 nm	0.6076	$\times 10^{-25} \text{ m}^2$
Absorption cross-section @1475 nm	2.213	$\times 10^{-25} \text{ m}^2$
Fiber length	10	m
Effective radius of the doped region	3.45	$\mu\text{m}$
Er-concentration in the glass	$15 \times 10^{24}$	$1/\text{m}^3$
Fluorescence lifetime	10.8	ms
Number of steps	10 – 100	

In Figure 7, we show a typical computation example or usage of an EDFA simulation with input signals having equally spaced spectral spikes (frequency combs). The length of the fiber is 10 m and a forward and backward pump are injected both ends of the fiber. The backward pump is a 400 mW CW light source at 1475 nm and the forward pump is a 250 mW CW light at the same wavelength. The doping concentration is selected to be  $15 \cdot 10^{24} \text{ 1/m}^3$  and the emission and absorption cross-sections are the cross-section values of a typical  $\text{Er}^{3+}$ -doped Aluminum-Phosphate fiber (Shown also in Table 1). Results looks reasonable, for example, the spectral features of the signal channels follow the spectral properties of the forward and backward ASE, but we note that this setting is too complicate to test with analytical solution. The next step in our amplifier development plan to make an extensive test for the amplifier gain simulations that one can done the easiest way by using literature data.



**Figure 7** Modeling the spectral behavior of an EDFA around 1555 nm wavelength range using bidirectional pumping at 1475 nm.

## 5. CONCLUSION

We developed here in FETI within the framework of an IHIA project (project# 211009) a software tool named PropSim that can be used for general optical fiber related investigations including telecommunication related tasks or laser science related researches. The software is easy to handle and indicates the effect of the selected parameters instantaneously. Additional modules and components can be added to the code due to the well-designed data structure behind the scenes that can make PropSim a versatile fiber optics simulator. At the moment, the non-linear Schrödinger equation and the power evaluation equations for gain fibers are treated by the code reliably but some tests are still needed.

We must note that this is not the first software tool with high versatility developed in FETI. The software named CRTD is a complex laser diode simulation tool used for the design of DFB and DBR based lasers and also SOA applications. In connection with this development a know-how was made recently titled “CRTD simulation tool to design and optimize wavelength tunable laser diodes for telecom applications”.

Another inhouse developed software is called OptiCo. OptiCo is a software tool, that was developed for laser-to-fiber coupling simulations. The core is based on the so called “wave propagation method” that is more accurate for non-paraxial systems than most beam propagation method (BPM) based software and requires less resources than full-wave solvers. Thanks to its modularity and graphical user interface, it became a frequently used design tool for micro-optics modules at multiple locations of the Furukawa Electric Group.

Now, PropSim could also become a software tool that can be used in FEC and OFS, despite the non-user-friendly version of it existed and used for long time. If we have the opportunity to make further developments on the PropSim code, this software may become an even more mature and essential tool to design state-of-the-art fiber optic devices.

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