Fiber Laser and Amplifier Simulations in FETI

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ABSTRACT Fiber lasers are displaying an increasing demand and a presence in the laser market since their power levels and robustness reached the performance of solid state lasers. This was made possible by using the latest optical fiber related developments like photonic crystal fibers and also by making careful system designs using the large variety of the fiber technology. The simulation of these systems is therefore indispensable to further optimize their performance and to maximize the required output parameters for certain applications. In Furukawa Electric Technológiai Intézet Kft., Budapest, Hungary (FETI), we can calculate continuous waves (CW) as well as pulsed fiber oscillators and amplifiers and our calculations are capable of using brute force, or simplex methods to optimize the system with an adequately defined merit function. Through the chromatic dispersion, we can calculate, the nonlinearity, the loss and the gain related effects. We combine the nonlinear Schrödinger equation and the rate equations in many different kind of solvers to obtain the pulse propagation in rare-earth doped optical fibers. Our algorithms make possible to satisfy the individual boundary conditions of linear or ring fiber oscillators and also of power amplifiers. In this paper, we present our models to achieve this task in different subsystems and also the calculation results which can pave the way for the design of more robust, ultra-high power fiber laser systems.

1. INTRODUCTION

At the end of the 90s the output power from a diffraction limited or nearly diffraction limited fiber laser (FL) was restricted to a few multiple of 10 W power level while recently this value is increased by three orders of magnitude as in the case of the Yb-doped fiber technology[1). This power level could be achieved, on one hand, by the introduction of double-clad rare-earth doped fibers[2) which made possible the use of high power multi-mode laser diodes (LD) as pump sources injected into the large area cladding, because single mode fiber lasers pumped with single mode pump diodes are featuring low output power. On the other hand, the work on such fiber designs which present an increased core area in order to reduce the nonlinear distortions of the propagating signal while keeping still a diffraction limited output field distribution contributed to the extension of the achievable power levels too[3),4). A big leap in the high quality, high energy laser outputs was achieved by the introduction of the large mode area (LMA) or large pitch (LP) fibers having photonic crystal cladding where the cladding filters out the higher order modes providing a nearly diffraction limited output[5). Aside from the mode instability[6), these type of fibers are theoretically infinitely single mode fibers[7). This mode scaling of the fiber core[8) and the application of the chirped pulse amplification (CPA) technique[9) can result in enormous output power levels from fiber lasers[10). The output level is comparable to the power levels of solid-state laser systems.

At FETI, we have been modeling nonlinear wave propagation in optical fibers for more than 10 years. We used our model successfully to predict the nonlinear compression of broad and ultra-short laser pulses in a small core area fiber[11). We also developed and verified amplifier models which are able to treat the rate equations in Ytterbium (Yb) or Erbium (Er) doped fiber amplifiers and consequently calculate the gain for the signal, pump and amplified spontaneous emission (ASE) fields in a wide wavelength range[12). We note also that these simulations can be extended to include the differential gain of the different core modes in case of few modes or multimode amplifiers[13). If one has an amplifier model that provide reliable calculation results in a certain parameter extent that model can be easily transfer to modeling fiber oscillators since the gain medium in both devices are identical and only the boundary conditions are distinct from the physical point of view. Of course, a fiber oscillator which can provide short laser pulses via Q-switching or mode-locking[14) is a bit more complex since additional optical elements such as saturable absorbers and also components with spectral filtering have to be modeled in the same time. We managed to concatenate these elements in a fiber ring oscillator and successfully modeled the mode-locked, output pulse properties of the oscillator at different parameter selections for the saturable absorb-

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er[15]. The simulation of continuous wave (CW) oscillators provide a different challenge at high power levels. We had to include the nonlinear effects in the calculations: they are crucial because a real CW laser has also finite bandwidth but the Fourier-transform of a finite bandwidth with constant phase will not be CW in the time domain. By introducing a phase-diffusion model, the connection between the spectral domain and the time domain can be established and the split-step Fourier method can be applied to add nonlinear and linear effects to the signal evaluation[16].

In this paper, we describe our physical and numerical models how we combine the rate equations associated with the gain effects with the nonlinear Schrödinger equation taking into account the dispersive and nonlinear effects during the light propagation. Using this extended numerical model, we present simulation results which intent is to optimize a high power CPA system using LMA or LP fibers as gain media. The aim of the optimization will be to determine the optimum applied chirp on the short pulses at the input end of the fiber to avoid any nonlinear distortion during the amplification process till the output end of the fiber.

2. THEORY

To model the gain properties of the doped optical fiber, we solve the coupled power evaluation equations of the different signals along with the steady-state, two-level rate equation[17]

$$\frac{dP^{\pm}{}_k}{dz} = u\,\Gamma C_d[N_2\sigma_e - N_1\sigma_a]P^{\pm}{}_k - u\,\alpha P^{\pm}{}_k \qquad (1)$$

$$N_2 = \frac{C_d\left[\sum_k \frac{P_k \Gamma \sigma_a}{\xi f_k}\right]}{[1+\sum_k P_k \Gamma(\sigma_e+\sigma_a)/\xi f_k]} \qquad (2)$$

where + and - in the superscript of P denote the forward and backward propagating signals, respectively and consequently u is 1 or -1 for forward and backward propagating signals. Γ is the overlap factor of the propagating mode with the doped region, C_d is the doping concentration, α is the so-called background loss of the fiber without the doping ions, σ_e and σ_a are the emission and absorption cross-sections of the doping ions in the particular host material. These cross-section values have to be measured in order to be used in this model[12]. N_2 and N_1 are the populations of the metastable and fundamental states, respectively. In Equation. (2), $\xi = \pi R_{eff} h/\tau$ where τ is the fluorescence lifetime of the doping ion, h is the Planck constant, R_{eff} is the effective radius of the doped region and f_k is the k^{th} frequency component. One has to add an amplified spontaneous emission (ASE) term to Equation (1) if the calculated signal is the forward or the backward ASE signal. This term has a form of $u\sigma_e \Gamma C_d N_2 n h f_k \Delta f$ where n is the number of the propagating modes and Δf is the ASE frequency resolution.

The dispersion and nonlinearity related effects are governed by the nonlinear Schrödinger equation[18]:

$$\frac{\partial A}{\partial z} = -\sum_{m=2}^{N} i^{m-1}\frac{\beta_m}{m!}\frac{\partial^m A}{\partial T^m} + \left(i\gamma\int_0^{\infty} R(T')|A(z,T-T')|^2 dT'\right)A + \frac{G}{2}A \qquad (3)$$

where A is the complex envelop function of the investigated pulse. The first term at the right-hand side of the equation takes into account the dispersion effects from the second order to the higher orders where β_m is the m^{th} order dispersion contribution of the fiber to the pulse evaluation and T is the time space in a frame of reference travelling with the pulse. The second term at the right-hand side is the term taking into account the nonlinear contribution to the pulse evaluation. Here, $R(t)$ is the nonlinear response function and γ is the nonlinear coefficient and they are discussed in details in References[8]. The third term could be the loss term but that is already included in Equation (1) therefore this term is kept for the gain in the fiber (negative loss). The frequency dependent G can be calculated from Equation (1) and Equation (2) using a small segment (Δz) of the fiber:

$$G = \ln\left(\frac{P(z,f_k)}{P(z+\Delta z,f_k)}\right)/\Delta z \qquad (4)$$

When solving Equation (1)-(3) with the help of Equation (4), one has to consider that the width of the temporal window, where we generate the complex envelope function, is not identical to the time range determined by the repetition rate of the pulse. Therefore, the spectral intensity during the calculations must be corrected accordingly.

The boundary conditions for Equation (1) in case of amplifier modeling are given in References[12] and for a linear fiber oscillator, it is described in References[16]. In order to treat the bidirectional propagation in the amplifier with great stability we apply a modified shooting method which is detailed in References[12].

3. RESULTS

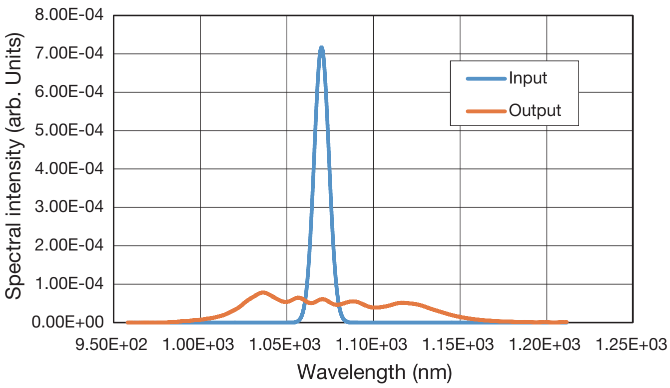
We model an Yb-doped, LMA amplifier to amplify 1 μJ Gaussian pulses at around 1070 nm originating from a 1 MHz fiber oscillator and a pre-amplifier system which amplified the pulse to the 1 W power level (1 μJ·1 MHz). This pulse is amplified further in the LMA fiber having an effective core area (ECA) of 4000 μm^2. Although this core size is large enough to present low nonlinearity, the mentioned power level will be too large to propagate without significant spectral broadening if the transform limited pulse duration with its high peak power is the input signal. Fig. 1 shows that even after 10 cm of propagation the spectral bandwidth is broadened more than 10 times compared to the original full width at half maximum (FWHM). The used dispersion parameters are the dispersion values of the silica glass at around 1070 nm (no waveguide contribution at large core sizes). Linear dispersion: D = -28.4366 ps/(nm km), dispersion slope: S =

0.3146 ps/(nm^2 km), third order dispersion: T = -7.2853·10^{-4} ps/(nm^3 km) and fourth order dispersion: F = 4.6057·10^{-6} ps/(nm^4 km).

Though the doping ions will modify the dispersion of a silica fiber, its small contribution to the above dispersion values will not alter the calculation results significantly. Therefore, we calculate with these dispersion values throughout this paper. Conversely, the nonlinear refractive index of the fiber is the nonlinear refractive index of the silica glass which is n_2=2.6·10^{-20} m^2/W.

Figure 1 (b) shows not only the changes of the spectral FWHM but also the broadening of the temporal width which extends to 465 fs from the initial 170 fs during 10 cm of propagation due to the dispersion contribution of the fiber. Due to the higher order dispersions, the modulated spectra becomes slightly asymmetric (Figure 1 (a)).

(a) SPECTRA



(b) TEMPORAL AND SPECTRA FWHM ALONG THE FIBER

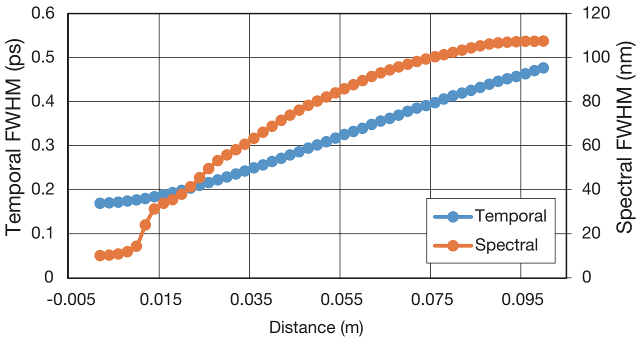


Figure 1 **(a) Input and output spectra before and after a 10 cm LMA fiber amplifier and (b) Temporal and spectral FWHM evaluations along the fiber without any amplification.**

If we switch on the gain lunching cladding pumps in forward and backward directions in the LMA fiber and we use at least one meter length of it in order to achieve a noticeable gain, the temporal and spectral distortions will be more significant. Therefore, we will use a brute-force optimization on the system by adding a linear chirp to the input pulse to broaden the pulse-width and decrease the peak power sufficiently. At the output, we will compress the amplified pulse applying linear and second-order chirps to compensate the phase on the pulse. The merit-function (MF) of the CPA system is to achieve maximum compression at the output but simultaneously the highest pulse quality after the compression. We define the quality of the pulse as a ratio of stored energy in the main peak and the total pulse energy (References 11)). Since we wish to obtain the best possible quality pulses at the shortest possible duration, we found that a proper merit function considering the pulse quality to a greater weight should have the form of

$$MF = \frac{\Delta\tau}{QF^x} \tag{5}$$

where $\Delta\tau$ is the FWHM of the compressed pulse and QF is the obtained quality factor of the compressed pulse (a number between 0 and 1) and x is an exponential factor. We found that the exponential factor should be larger than 3 to obtain a reliable optimum (high quality compressed outputs).

We will minimize MF in Equation (5) and to do this, we use the following setup of the arrangement: the gain fiber is 1 m long having a core diameter of 88 μm and a cladding diameter for the pump of 200 μm[8]. This fiber has an ECA of 4000 μm^2. The ratio of the core and cladding area determines the overlap factor of the cladding pump with the doping ions in the core[12),13)] and this way we have Γ=0.1936. The doping concentration is set to 10^{26} 1/m^3 and the fluorescence lifetime of Ytterbium is set to 2.3 ms. Both pumps (forward, backward) have 4 nm spectral bandwidth and 80 W CW output power injected into the fiber cladding. The input signal has a 10 nm initial bandwidth and 1 W power level which corresponds to 170 fs transform limited pulse duration at around 1070 nm and 5.6 MW peak power. To avoid nonlinear distortions, we are looking for the optimum input chirp on the input signal that way to obtain a minimum for Equation (5).

The shortest pulse width and the possible highest quality factor is found to be at 6.65 ps^2 linear, input chirp scanning the input chirp values in hundred steps between 3 and 8 ps^2 repeating the calculations with each pulses. The corresponding FWHM and QF using a range of compression chirps can be seen in Figure 2. where that is obvious that the shortest pulse duration does not always meet with the highest quality factor of the pulse which makes necessary to introduce Equation (5) the way we did. Fig. 3 shows the steady-state inversion level in the gain fiber along with the gain of the signal at the center frequency. Figure 4 (a) and (b) show the power evolution of the propagating signals as well as the temporal and spectral FWHM along the fiber during this amplification process. Finally, the temporal and spectral shape of the pulse are shown in Figure 5 (a) and (b).

One can see that the first step to amplify high power pulses is stretching them and the added 6.65 ps^2 input chirp will broaden the pulse to an FWHM of 109.4 ps (See Figure 4 (b)) corresponding to a reduced peak power of

8.6 kW. During the amplification and propagation, the pulse width becomes 111.3 ps and due to the gain the peak power will reach a little more than 1 MW. During this process, the spectral width is increased only by 0.6 nm (Figure 4(b)) which small broadening adumbrates a good quality compression. The best compression is achieved at -6.46 ps^2 compression chirp and 0.004 ps^3 third order chirp (Figure 2 and Figure 5 (a)). The obtained FWHM of the compressed pulse we got is 522 fs with a pulse peak power of 148.1 MW (Figure 5 (a)).

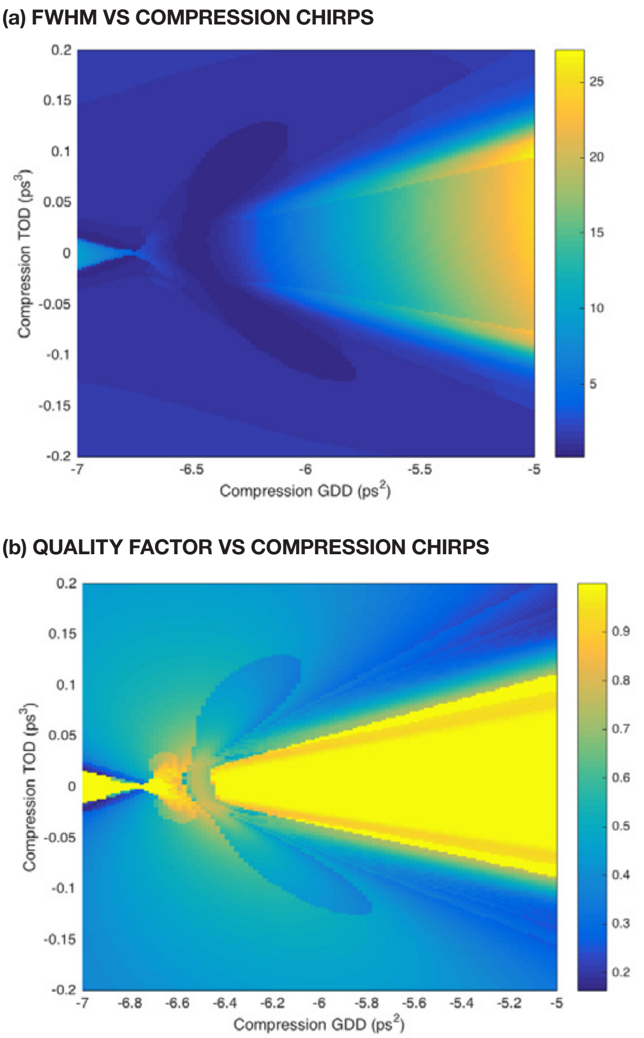


Figure 2 (a) FWHM. (b) QF as functions of compression group-delay dispersion (GDD) and compression third-order dispersion (TOD). Color is showing the magnitude of FWHM and QF in pico-seconds and in proportion, respectively.

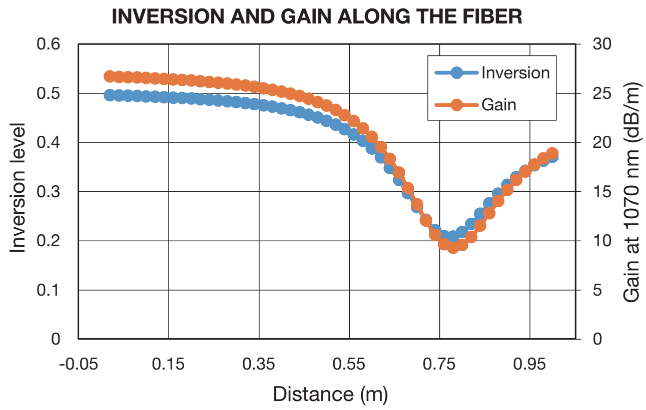


Figure 3 Inversion level and gain along the 1m long amplifier.

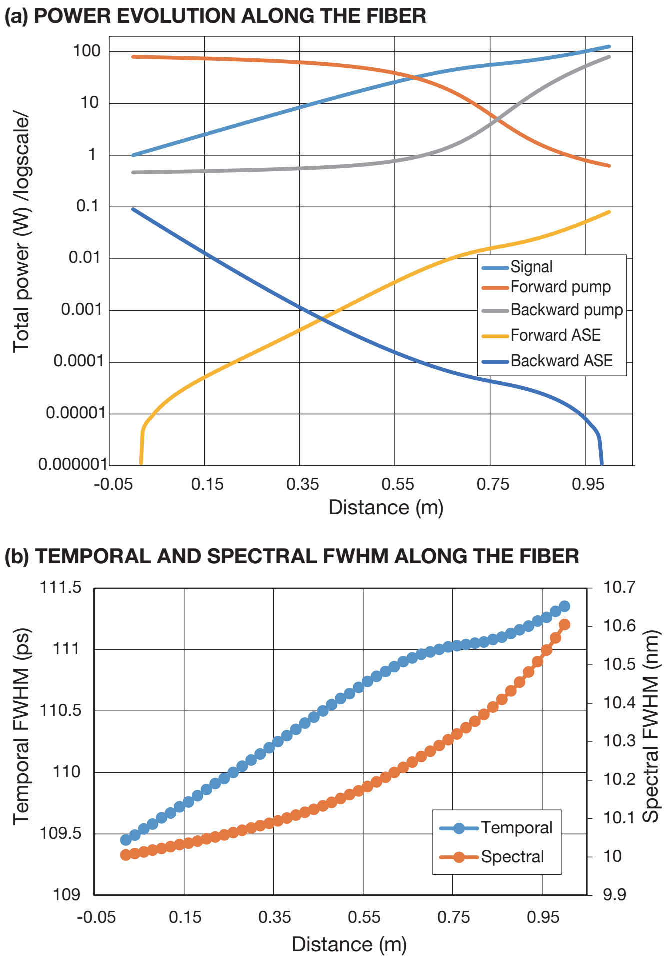
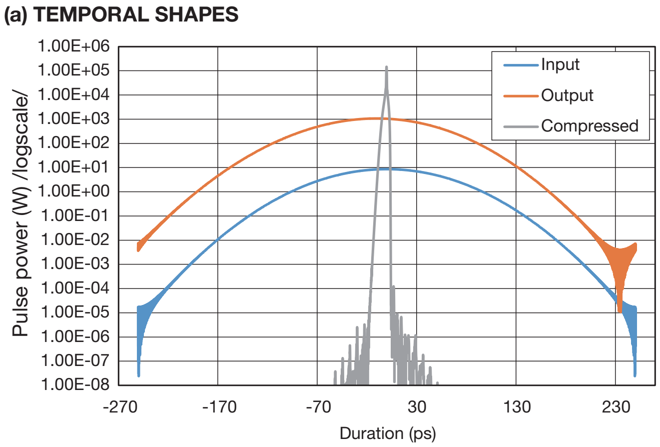


Figure 4 (a) Power evolution of the ASE signals, cladding pumps and the amplified pulse.
(b) Temporal and spectral FWHM of the amplified pulse along the fiber due to the dispersion and nonlinear effects.

4. CONCLUSION

We showed in this paper that our developed software that calculates the pulse amplification and the nonlinear, dispersive propagation can be used in connection with high power LMA fibers in CPA systems. Our calculations are based on a signal having 10 nm bandwidth as an input for a 1 m long LMA amplifier with 4000 μm^2 ECA. The signal had 1 W input power and 1 MHz repetition rate. Using sufficient amount of chirp on the input pulse, we managed to amplify it without significant spectral and temporal distortion to 126.4 W average power level that corresponds to 148.1 MW peak power and 522 fs pulse duration after ideal chirp compensation at the output of the amplifier.



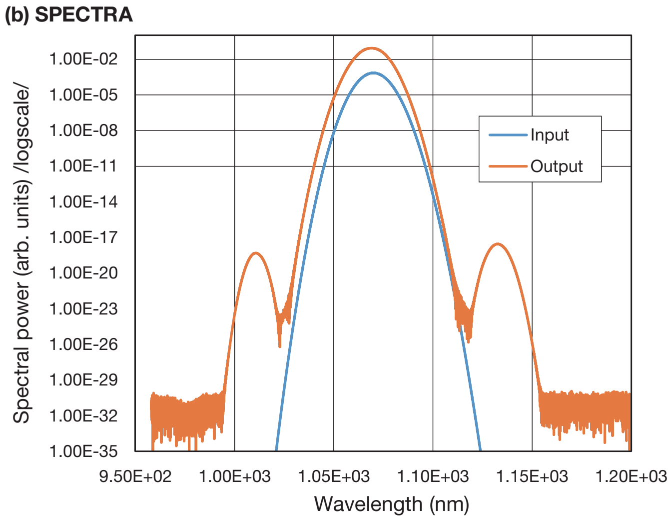


Figure 5 (a) Input, output and optimally compressed pulse shapes.
(b) The slightly broadened and significantly amplified spectra.

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