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Numerical Study and Validation of Ultra-short Pulse Amplification in Fiber Amplifiers at High Repetition Rates

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Abstract: We present a numerical method for studying fiber-based ultra-short pulse amplification at high repetition rates. Validation of the simulations, by comparison with experimental results, are also presented.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators, (060.7140) Ultrafast processes in fibers

1. Introduction

The applications for high-power ultrafast laser sources range from pump sources in nonlinear frequency conversion schemes to metrology and material processing. Depending on the specific application, the design and complexity of the laser system varies greatly. However, efficient heat removal is a key concern for any system dealing with high power lasers. This makes fiber-based power amplifiers especially interesting. Furthermore, fibers also provide large gain, small foot-print and robustness as well as excellent beam quality. Nonetheless, the long interaction lengths in fiber amplifiers increase the impact of dispersive, nonlinear and gain asymmetric effects that the pulses experience.

The simplest and most widely used method for studying ultra-short pulse amplification in fibers is to assume a constant gain along the fiber and solving the generalized nonlinear Schrödinger equation (GNLSE). Although accounting for dispersive and nonlinear effects, this approach neglects the specific dopants' and the pump configuration's impact on the gain, which are described by the rate equations (RE).

Approaches based on including additional terms in the GNLSE [1], solving the GNLSE and the RE sequentially in between the pulses [2] and extracting gain parameters from the RE to be used in the GNLSE [3] have been investigated to account for a non-constant gain. In contrast, the model presented here jointly solves the RE and the GNLSE, in the case of a high repetition rate seed, and thus directly includes the interplay between dispersive, nonlinear and pump related effects. A similar approach was used in [4] to optimize chirped-pulse fiber amplifier design. However, the model presented here provides greater generality by allowing for arbitrary end-pumping configurations as well as including amplified spontaneous emission (ASE), gain saturation and using the inversion at each position to determine the gain for the GNLSE.

2. The algorithm

The launched pump and seed together with reflections at the fiber end facets constitute a boundary value problem. In our approach, we use an iterative shooting-method for double clad fibers, outlined in [5], to reduce the boundary value problem to initial value problems. This method solves the equations iteratively going back and forth between the fiber ends and imposing boundary conditions upon reaching them.

Fig. 1 Schematic illustration of how the boundary conditions (BC) are combined with the propagation scheme from the end where the seed is launched (blue box) and the one in the opposite direction (green box). The red arrows indicate where the algorithm is initiated for co-, counter propagating and bi-directionally pumped configurations.

The algorithm is based on two propagation schemes, one from the end where the signal is launched to the other end of the fiber and one in the opposite direction. The pump, the ASE and the pulse at each step along the fiber are used in the RE to equate the inversion, which is then used to propagate these signals. A schematic block diagram of the algorithm is shown in Fig. 1.

3. Results and discussion

To validate the model, we set up and characterized a 5.2 m long counter propagating Yb-doped fiber amplifier. It was seeded by a 170 fs 217 MHz Yb:KYW oscillator, centered around 1040 nm, mode-locked using a QW-SESAM. As evident from Fig. 2, our model successfully predicts the output powers, the shift in central wavelength of the amplified pulses, due to gain asymmetry, and the more pronounced self-phase modulation at longer wavelengths. The slight discrepancies in some of the spectral features as well as the systematic offset of the pulse durations are attributed to using tabulated values for parameters such as the dispersion, the fluorescence lifetime and the nonlinear parameter.

Fig. 2 Comparison of measured (red crosses/lines) and simulated (blue lines) a) output powers, b) Autocorrelation widths and spectra at (measured/simulated output powers) c) 2.61/2.50 W and d) 9.72/9.79 W.

As a second evaluation of the model, data on the Yb-doped amplifier chain from [6] was used to numerically investigate amplification of non-transform-limited seed pulses through three amplification stages. The reported time-bandwidth product of the nominal sech pulses was 0.37, i.e. the seed pulses were slightly chirped. The reported development of the pulse spectra in the amplifier chain (blue dashed lines in Fig. 3) suggests that the seed pulses were predominantly positively chirped. In order to illustrate the effect of the chirp on the evolution of the pulse spectrum, negatively and positively chirped sech pulses with a time-bandwidth product of 0.37 were propagated through two preamplifiers, one with co-propagating and one with counter-propagating pump, and one main amplifier pumped in a counter-propagating geometry. Fig. 3 shows the numerically generated spectra from linearly chirped pulses compared to the experimental results at output powers where no transverse modal instabilities were present in the experiments, as the model used in this work assumes single-mode operation. The modeling results clearly show stark difference in the spectral evolution of the negatively (red solid lines in Fig. 3) and positively (green solid lines in Fig. 3) chirped pulses, the latter showing close similarity to the experimental data.

Fig. 3 Comparison of measured (dashed blue lines) and simulated spectra in a) the first preamplifier, b) the second preamplifier and the main amplifier at c) 25 W d) 75 W and e) 100 W of output power. Red and green lines correspond, respectively, to positively and negatively chirped seed pulses.

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