Optimization of ultrafast Yb-doped fiber amplifiers to achieve high-quality compressed-pulses

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Abstract: We both theoretically and experimentally study the performance of nonlinear Yb-doped fiber amplifiers, and demonstrate that there exists an optimum *negative* pre-chirp that produces the best-quality compressed pulses.

Yb-doped fiber amplifiers (YDFAs) feature superior power scalability, high electrical-to-optical conversion efficiency, large single-pass gain (~30 dB), excellent beam quality, as well as robustness and compactness. To avoid detrimental effects from fiber nonlinearities (e.g., self-phase modulation, stimulated Raman scattering etc.), YDFAs normally operate in a low-nonlinearity regime such that the spectral bandwidth of the amplified pulse only changes slightly during the amplification. For some applications, YDFAs are required to operate in a high-nonlinearity regime, in which the amplified pulse acquires substantial extra bandwidth, and therefore can be compressed to much shorter pulse duration. However, the relatively narrow gain bandwidth (~40 nm) and the gain narrowing effect during the power amplification usually generate compressed pulses >100-fs with considerable pedestal. In this paper, we both theoretically and experimentally investigate the dependence of the compressed pulse quality on the pre-chirp of the pulse to be amplified. It is found that there exists an optimum *negative* pre-chirp that produces the best-quality pulses.

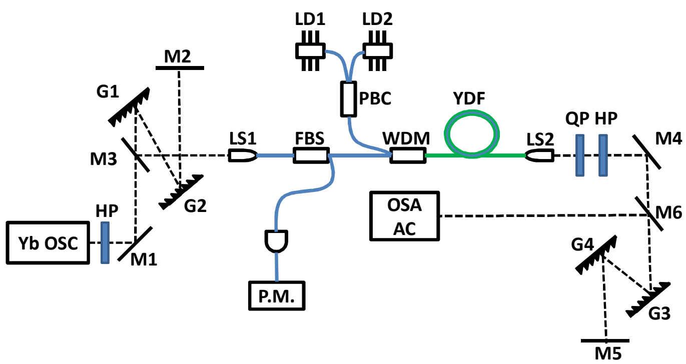

Fig. 1. Experimental set-up, OSC: oscillator, HP: half waveplate. M: mirror, G: Grating, LS: lense, FBS: fiber beam splitter, LD: laser diode, PBC: polarization beam combiner, WDM: wavelength division multiplexer, YDF: Yb doped fiber, QP: quarter waveplate, OSA: optical spectrum analyzer, AC: attocorrelator, P.M.: power meter.

Figure 1 schematically illustrates the experimental setup. It consists of an Yb-fiber oscillator (repetition rate of 280 MHz) served as a seed source, a grating pair to adjust pulse's pre-chirp, an YDFA to amplify the pulse and broaden its spectrum, and finally another grating pair to dechirp the amplified pulse. The oscillator was passively mode-locked with a saturable Bragg reflector; the cavity dispersion is managed by highly dispersive mirrors. Exhibiting a positive chirp, the output pulse has a duration of 2.1 ps with ~6 nm (FWHM) spectral bandwidth centered at 1030 nm. Since the pulse is positively chirped, use of a grating pair (600 grooves/mm)—which provides negative chirp—allows us, by changing the separation between two gratings, to set negative or positive pre-chirp for the pulse entering the YDFA. The pre-chirp adjustable pulses are coupled into the YDFA with >60 % efficiency. The 10 % tap from the splitter monitors the seed power into the YDFA which is constructed from 2-m, low doped Yb fiber pumped by two laser diodes combined with a polarization beam combiner. The amplified pulses are dechirped by the second grating to the shortest pulse duartion measured by an autocorrelator. The average power after the grating pair with ~50% transmission is ~300 mW.

With the input power fixed at 20 mW, we achieved amplified pulse trains of 600-mW average power at 1-W pump power. We vary the pre-chirp by changing the separation of the first grating pair and then adjust the second grating pair to compress the amplified pulses to its shortest duration as measured by the autocorrelator. We also record the amplified pulse spectra corresponding to the varied pre-chirp; the root-mean-square (RMS) duration of the transform-limited pulses calculated from these spectra are plotted in Fig. 2(a) as a function of pre-chirp. As the pulse pre-chirp becomes negative, the spectral bandwidth increases which can be explained by spectral broadening due to the nonlinear effects in the YDFA. Figure 2(b) plots the input pulse spectrum (black curve) and three spectra corresponding to different pre-chirp values: -0.063 ps^2 (blue curve), -0.018 ps^2 (green curve), and 0.01 ps^2 (red curve). For all three cases, the input spectrum is broadened from ~6 nm to >20 nm. However, the shape of the amplified pulse spectra varies subtantially with different pre-chirp, which in turn supports different transform-limited pulse duration. The black, scatter curve shows that the minimum duration is achieved at negative pre-chirp of -0.063 ps^2. Also plotted in Fig. 2(a) are the three autocorrelation traces for the three compressed pulses at different pre-chirp value : -0.063 ps^2, -0.018 ps^2, and 0.01 ps^2; the FWHM of these autocorrelation traces are 134 fs, 149 fs, and 169 fs, respectively. Apparently, the best compression quality occurs at a pre-chirp of -0.063 ps^2 with a measured autocorrelation trace of 134-fs, suggesting a de-convolved pulse of ~100-fs. Deviation from this optimum pre-chirp leads to deterioration of compression quality lengthening the autocorrelation trace via an increased pedestal. The spectra in Fig. 2(b) reveal that, as we vary the pre-chirp from -0.063 ps^2 to 0.01 ps^2, the corresponding spectra develop sharper edges, which leads to the pedestal for the compressed pulses. More experiments suggest that optimizing other parameters leads to even better compressed pulse in which the optimum pre-chirp is different.

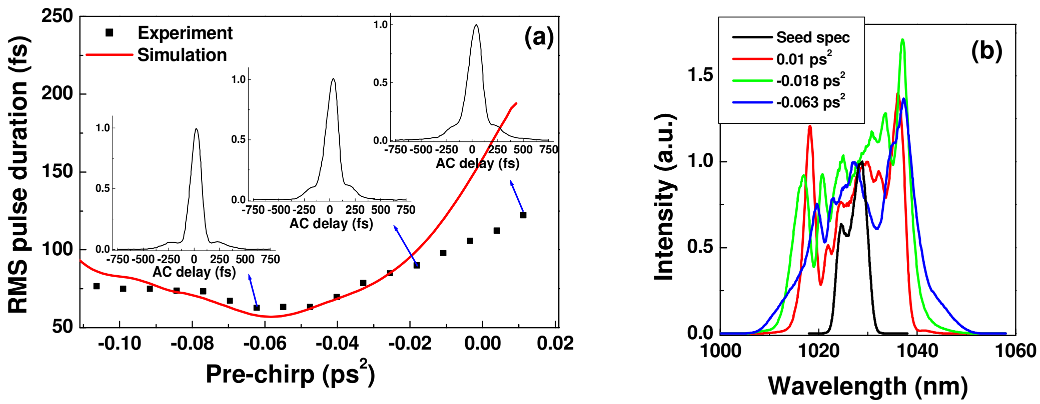

Fig. 2. a) RMS pulse duaration from experement (black scattered) and simulated curve. The shortest autocorrelation (AC) trace is achieved at the lowest RMS pulse duration. τ_{AC} (FWHM) =134 fs for -0.063 ps^2 , . τ_{AC} (FWHM) =149 fs for -0.018 ps^2, and τ_{AC} (FWHM) =169 fs for 0.01 ps^2 respectively. b) The spectra corresponding to AC traces. The pulse has widest spectral bandwidth with smoother edges at -0.063 ps^2.

A thorough understanding and optimization of the system requires numerical modeling. To date, optimization of fiber amplifiers are mostly modeled using a generalized nonlinear Schrödinger equation (GNLSE) [1] or more accurately the Maxwell-Bloch equations [2], both assuming constant small signal gain, a given gain profile, saturation energy, and pump absorption. Here we combine steady-state propagation-rate equations [3, 4] and the GNLSE to model our system with no need for above *a priori* assumptions. In the modeling, we only need to make the following justified assumptions: (1) the amplified-pulse energy is much lower than the saturation energy (~10-μJ for a typical single-mode fiber), (2) the inverse of pulse's repetition-rate is much shorter than the relaxation time of the upper level (~1 ms), and (3) negligible amplified spontaneous emission. The nonlinear propagation of the pulse inside the YDFA is governed by the standard GNLSE which takes into account gain, dispersion, self-steepening, self-phase modulation, and stimulated Raman scattering. The red curve in Fig. 2(a) plots the RMS duration of the transform-limited pulses—predicted by the model—as a function of pre-chirp. It can be seen that the modeling and experimental measurements agree well at the negative pre-chirp region. The deviation at positive pre-chirp may be caused by the fact that we used a hyperbolic secant spectrum of 6-nm as the input rather than feed the measured spectrum into the model. Nevertheless, the model predicts the overall tendency of the measurements: there exists an optimum, negative pre-chirp that results in the shortest compressed pulse.

Due to the limited space, we only show here the effect of input-pulse pre-chirp on compressed pulse quality. Indeed, a thorough optimization requires an exploration of other important parameters (such as input pulse power, center wavelength, Yb-fiber doping concentration, Yb-fiber length and mode-field-diameter, etc.) as well. Currently, we are using this model to optimize all the parameters numerically, which will allow us to further improve the performance of the experimental system. After the optimum condition is found, the free space grating-pairs will be replaced by either fiber Brag gratings or hollow-core photonic crystal fibers such that an all-fiber format can be implemented.

References

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