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Distributed nonlinear fiber chirped-pulse amplifier system

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Abstract: A two-stage fiber-based femtosecond amplification system is presented, based on chirped-pulse amplification in highly nonlinear regime. The amount of self-phase modulation is separately adjusted in each stage selecting the proper stretching ratio in order to compensate gain narrowing. Analytical design rules are validated using numerical simulations. Our experimental implementation leads to the generation of high temporal quality 20 µJ 202 fs pulses at repetition rate of 200 kHz, a record duration at this energy level.

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OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (190.5530) Pulse propagation and temporal solitons; (320.7090) Ultrafast lasers.

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1. Introduction

Ytterbium-doped femtosecond fiber amplifiers appear as a promising alternative technique compared to bulk systems, in particular in terms of efficiency and average power handling. Numerous systems and strategies have been developed to improve the performances of these amplifiers. However, bulk systems retain several advantages over fiber systems. One of the

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main limitations of the fiber technology is the achievable amplified pulse energy. Harmful nonlinear effects and damage thresholds are reached sooner than in bulk amplifiers because the mode-field area in the fiber is limited in order to retain a good beam quality, and the interaction length with the medium is large. Another limitation of fiber amplifiers is the achievable pulse duration. The ytterbium ion in glass exhibits a gain bandwidth of approximately 40 nm, well below the value of titanium-doped sapphire systems. Moreover, fiber amplifiers typically exhibit very high gain values, on the order of 100 or higher, which tend to enhance the amount of gain narrowing (GN) experienced in such systems. This explains that the output pulsewidth obtained in fiber-based chirped-pulse amplification systems is usually greater than 300 fs, and increases as the output energy is scaled up [1-3].

Two types of solutions have been investigated to reach shorter pulsewidths from fiber amplifier systems. One is based on the use of long pulses from the fiber amplifier to feed an additional stage that provides pulse compression, and possibly added features such as wavelength conversion. These stages can be based on nonlinear broadening in a gas or dense medium [4,5] or on optical parametric amplification seeded by a continuum [6]. Although providing compression ratios on the order of 10, these solutions suffer from a limited efficiency (generally below 50%), added complexity, and possible degradation of the spatial quality of the beam.

Other solutions consist in exploiting nonlinear effects inside the fiber amplifier rather than after it, which can be seen as a nonlinear broadening stage embedded in the amplifiers. This concept has the advantage of requiring simpler setups and taking full advantage of the output power available from the amplifier. However, it was until recently limited to stretcher-free setups, in the framework of the self-similar or parabolic propagation regime [7]. This concept has been used with current large mode area (LMA) fibers to generate output pulse energies around 1 µJ with a pulsewidth of 70 fs, but the energy cannot be further scaled due to damage and self-focusing thresholds.

We have recently proposed to use the same idea of exploiting self-phase modulation in the amplifier to compensate the gain narrowing experienced in the context of a CPA system, thereby allowing the scaling of the output energy [8]. We showed that the pulse spectral width can be retained by adjusting the stretching ratio to set the nonlinear phase at a value that continuously regenerates the frequency lost through GN. This was demonstrated on a single amplifying stage as a proof-of principle. Here, we extend this idea to several stages, thereby distributing the nonlinearity over the stages, and limiting the gain necessary in the final amplifier. This leads to a system where nonlinearity is managed and distributed over the amplification stages in order to maintain the pulse bandwidth, while minimizing the detrimental impact of accumulated nonlinear phase on the compressed pulse quality. We demonstrate the generation of high temporal quality 20 µJ 202 fs pulses at a repetition rate of 200 kHz.

2. Theory: analysis and simulations

We consider a two-stage femtosecond fiber amplifier setup that conserves the spectral bandwidth at each stage using SPM, by adjusting the stretched pulse duration. The problem we are considering is the following: for a fixed overall gain, how should we distribute it over the stages to maximize the output pulse quality? Let us first try to give an analytical response by calculating the accumulated nonlinear phase as a function of the gain distribution.

We first recall that the stretched pulse duration that satisfies the SPM/ GN compensation criterion is given by [8]

$$\Delta t = \sqrt{\frac{2\gamma E_{in} \exp(g_0 z)}{g_0 \left(\Delta\omega_{in} - \Delta\omega_{out}\right)}}, \tag{1}$$

where γ is the fiber nonlinear parameter, E_{in} is the input energy, g_0 is the spectral peak value of the gain, z is the fiber length, $\Delta\omega_{in}$ is the input spectral width, and $\Delta\omega_{out}$ is the reduced

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output bandwidth obtained in the case of purely linear propagation linear case. If we consider all the spectral shapes to be Gaussian, this output bandwidth can be written as:

$$\Delta\omega_{out} = \sqrt{\frac{\Delta\omega_{in}^{2}\Delta\Omega_{GN}^{2}}{\Delta\omega_{in}^{2}+\Delta\Omega_{GN}^{2}}}\,, \tag{2}$$

with $\Delta\Omega_{GN}^{2} = \Delta\omega^{2}\ln\left[g_0 z/(g_0 z-1)\right]$, where Δω is the lineic gain bandwidth of the fiber. We can now use the stretching ratio defined in Eq. (1) in each amplifier stage and calculate the amount of nonlinear phase experienced in each stage as $\phi_{NL} = E_{in}(G-1)/(\Delta t\gamma z\ln G)$. We use parameters that fit the experiment presented hereafter, with an overall gain in the amplifiers of 47 dB, and a coupling between the stages of 25% to account for the acousto-optic modulator, isolator, stretcher and additional optics losses. The gain bandwidth is taken equal to 40 nm centered at 1030 nm, the fiber lengths in the first and second sections are 1.9 m and 1.7 m respectively, the nonlinear coefficient γ is equal to 2.7×10^{-4} $W^{-1}.m^{-1}$, corresponding to a mode field diameter of 30 µm, and the input pulse is Fourier-transform limited with 100 fs pulsewidth and 5 nJ energy.

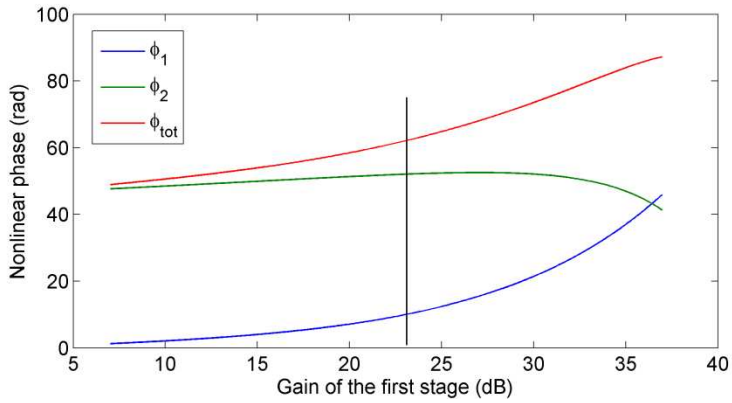

Fig. 1. Accumulated nonlinear phase in each stage and overall as a function of gain in the first amplifier stage, for a fixed overall gain of 47 dB. The black line represents the experimental operation point.

Figure 1 shows the accumulated nonlinear phase in each stage and the total amount of nonlinear phase. The stretched pulse duration in each stage is constrained by our rule to keep the optical bandwidth constant in both stages, in accord with Eq. (1). The result fits with the intuition that in order to keep the B-integral low, the gain should be mostly set at the second stage, so that the area under the curve power vs. distance along the fiber is minimized. However, this gain distribution goes against the minimization of ASE noise and efficient energy extraction. The experimental operation point in terms of gain distribution between the stages therefore corresponds to a tradeoff between these trends. Because the accumulated nonlinear phase does not vary greatly between 5 and 25 dB gain in the first stage, we chose to operate around 23 dB in the first stage to minimize ASE noise generation in the power amplifier while retaining a nonlinear phase close to the minimum for this set of constraints. It remains that the nonlinear phase is high (around 60 rad), and simulations must be performed to find out whether or not a good quality pulse can be obtained in this highly nonlinear regime.

Indeed, although the analysis above gives some insight in multi-stage bandwidth preserving fiber amplifier design, they are solely based on the amount of accumulated B-integral and do not take into account considerations effects related to the pulse shaping mechanisms. In order to see such effects, we have run simulations of the propagation based on

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the split-step Fourier algorithm. The second- and third-order dispersion coefficients of the fiber were taken equal to the values for pure silica. We present results that use parameters close to the experiment, i. e. a gain distribution among the stages of 23 dB in the preamplifier, and 21 dB in the power amplifier. The stretched pulsewidths in the first and second stages are 6 ps and 150 ps respectively, and the other parameters are the same as above. In the simulation the pulses are stretched and compressed using 1600 l/mm grating pairs to fit the experiment.

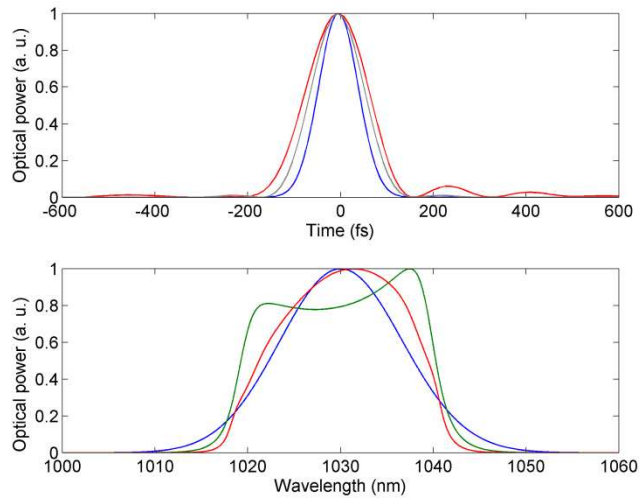

Fig. 2. Numerical simulations of the two-stage amplification. Top: temporal profiles, input (blue) output (red), Fourier-transform-limited ouput (grey). Bottom: spectra: input (blue), intermediate (green), output (red).

Figure 2 shows the temporal and spectral profiles obtained at the input and output, and the spectrum between the stages. Although the accumulated nonlinear phase is high, the compressed pulse exhibits a good temporal quality with low asymmetrical wings mostly due to uncompensated 3rd order spectral phase acquired during the nonlinear propagation because the stretcher 3rd order dispersion induces an asymmetric temporal profile. The spectral reshaping induces a more platykurtic spectrum with sharper edges than a Gaussian. This results in compressed pulse duration of 154 fs, with a time-bandwidth product of 0.8, to be compared with an ideal value of 0.69 for this spectral shape with a flat spectral phase (130 fs pulse duration). This good quality despite the high B-integral stems from the spectral shaping, towards a flat top profile at the intermediate stage, and a parabolic profile at the output. Because the nonlinear spectral phase is proportional to the spectral profile in CPA systems [9], these shapes induce a spectral phase which is mostly either constant or parabolic, and can be well compensated at the output. These simulations hint at the possibility of accumulating a large amount of nonlinear phase while retaining a good temporal pulse quality.

3. Experimental setup and results

The experimental implementation of the distributed two-stages CPA setup is depicted in Fig. 3. The oscillator is based on a diode-pumped Yb:$CaGdAlO_4$ bulk crystal [10], delivering 20 nJ, 100 fs pulses at 27 MHz and centered at 1040 nm, with a bandwidth of 13 nm. The repetition rate is reduced to 200 kHz using an acousto-optic modulator and about 5 nJ pulses are seeded into the first fiber amplifier, after stretching to 6 ps. A second stretcher (150 ps)

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and amplification stage are used to further amplify the pulses, before final compression. The first and second fiber amplifiers are pumped in a counterpropagating geometry with 25 W and 35 W 100 µm fiber-coupled diodes. The major role of the second acousto-optic modulator is to suppress amplified spontaneous emission from the first stage. The stretchers / compressor are based on 1600 l/mm transmission gratings set at Littrow angle in a standard arrangement. The fiber used in the first and second stages have core/cladding diameters of 40/200 µm and 40/170, with respective length of 1.9 and 1.7 m. The pulses are amplified to 1 µJ in the first amplifier stage. The pulse energy fed to the power amplifier is 240 nJ, and maximum output energy is 30 µJ, which results in 20 µJ compressed output pulses (4W average power).

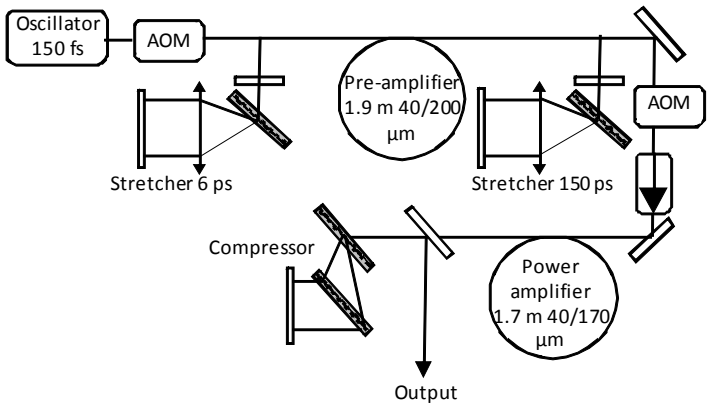

Fig. 3. Experimental setup.

Figure 4 (left) shows the input and output spectra at the power amplifier stage that provides a gain of 21 dB. Because the stretching ratios are not perfectly set to compensate GN, the preamplifier slightly broadens the spectrum and the power amplifier introduces a moderate amount of gain narrowing. During the amplification process in this highly nonlinear regime, the pulse spectrum is modified and some nonlinear spectral phase is accumulated. The output pulses, characterized using a frequency-resolved optical gating (FROG) setup, can be recompressed to 202 fs, a record value at this energy level, as shown in Fig. 4 (right). Although the spectral FWHM is 8 nm, the spectrum extends significantly over the long wavelength range, covering more than 20 nm. This assymetrical spectrum is due to the oscillator central wavelength of 1040 nm, whereas the maximum of the gain in the fiber is located around 1030 nm. The time-bandwidth product is 0.44. The obtained peak power calculated from the retrieved temporal profile is 88 MW. This value corresponds to a temporal Strehl ratio (defined as the ratio between the actual peak power and the peak power of the corresponding Fourier-transform-limited pulse) of 0.89, which confirms the excellent temporal quality of this pulse despite the highly nonlinear regime.

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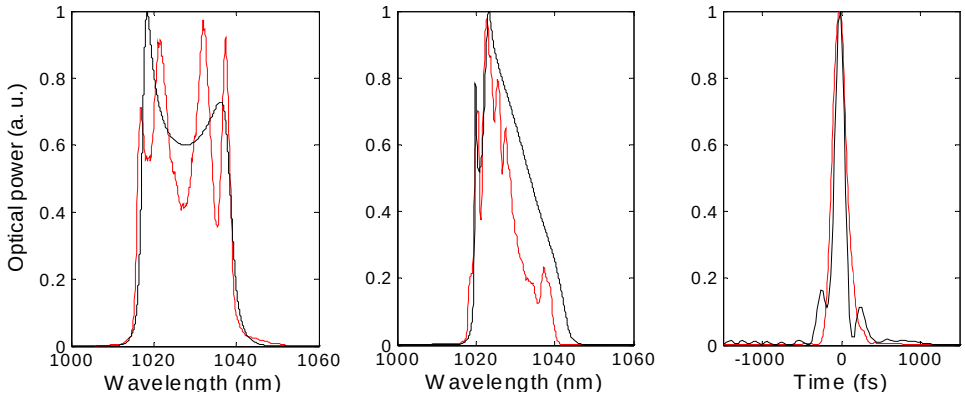

Fig. 4. Left: Simulation (black) and experimental (red) between the amplifier stages. Middle: Simulation (black) and experimental (red) at the output of the system. Right: Simulation (black) and experimental (red) output temporal pulse intensity retrieved by FROG (FROG error is 46×10^{-4} on a 256×256 grid).

The pulse characteristics are well predicted by simulations that use the same parameters as the experiment, now including the mismatch between the oscillator and fiber gain central wavelength. The simulations do not reproduce the oscillations in the spectrum at the intermediate stage that might be caused by nonlinear polarization rotation. Also, the simulated output spectrum is broader than the experimental one, resulting in output pulsewidth of 150 fs. This is probably due to the approximation of a 40 nm broad Gaussian bandwidth for the spectral gain shape in the simulation, which deviates from the real gain curve. Based on these simulations, the estimated nonlinear phase accumulated in the first and second stage are 21 and 26 rad. Despite these high values, we did not observe in the experiment the transfer of energy to satellite pulses due to high nonlinearity, as reported in reference [11]. This probably results from the large amount of spectral reshaping that prevents this resonant phenomenon of energy transfer. Indeed this analysis was made in the context of constant spectral shape as in the case of quasi linear CPA systems.

4. Conclusion

We have reported on a two-stage nonlinear fiber CPA systems where SPM is used to compensate for gain narrowing, resulting in the generation of 202 fs, 20 µJ pulses. We theoretically and experimentally demonstrated that the distribution of gain and nonlinearity on both stages allows a minimum impact of SPM on the pulse quality. With an obtained peak power of 88 MW, this work represents a step forward for the design of simple, compact, and efficient fiber-based sources for high field physics experiments at high repetition rates.

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