Impact of self-phase modulation on coherently combined fiber chirped-pulse amplifiers

Shifeng Jiang, Marc Hanna,* Frédéric Druon, and Patrick Georges

Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique, RD 128, 91127 Palaiseau Cedex, France
Corresponding author: marc.hanna@institutoptique.fr

Received January 26, 2010; revised March 11, 2010; accepted March 12, 2010;
posted March 18, 2010 (Doc. ID 123352); published April 15, 2010

The impact of self-phase modulation on coherently combined ultrafast fiber-based chirped-pulse amplifiers (CPA) is studied. We point out that, in nonlinear CPA regime, the nonlinear phase accumulated in each fiber amplifier can significantly differ from one to another, resulting in serious efficiency degradation of coherent combining. A test bench based on picosecond pulses, and a single fiber amplifier is developed to experimentally demonstrate the effect. The effects that can lead to this nonlinear phase deviation and the induced system limitations are discussed and analyzed. © 2010 Optical Society of America

OCIS codes: 060.2320, 140.3510.

Fiber-based chirped-pulse amplification (CPA) systems, offering a number of advantages such as excellent output beam quality, high efficiency, and large surface area to volume ratio that results in large heat dissipation capacity, are currently one of the best technical solutions to generate ultrashort pulses at high average power. Recently, a fiber-CPA system delivering 640 fs pulses at an average power of 830 W and a repetition rate of 78 MHz has been demonstrated [1]. The energy per pulse that individual fiber CPA can deliver remains, however, modest compared to their bulk counterpart and is ultimately limited by two factors: the achievable physical size of the bulk compressor (which limits the temporal width of stretched pulses), and the peak pulse power that optical fibers can withstand. Since, typically, the former is of the order of 1 m and the latter is about 4 MW (corresponding to the critical power for self-focusing in silica glass) [2], a limit of a few millijoules can be found.

To further scale up the energy per pulse, active coherent beam combining is a promising solution [3]. Widely studied for cw laser systems, this technique consists in separating and distributing a single laser source into an actively phase-locked array of fiber amplifiers and then combining the amplified beams into a single one. Excellent results have been obtained in the cw regime. For the pulsed regime, it has been proposed and discussed as a solution for inertial fusion laser driver [4] and a first demonstration has been performed in the nanosecond regime [5]. In this Letter, we discuss a phenomenon that arises in short-pulse coherently combined fiber CPAs: the amount of self-phase modulation (SPM) accumulated in each fiber amplifier can significantly deviate from one another, leading to coherence degradation for beam combining. In what follows, we first bring out the issue by using a test experiment and then discuss further system aspects of this issue in real coherently combined fiber CPAs, outlining the factors leading to this nonlinear phase deviation, the induced limitations and possible solutions to overcome the problem.

To demonstrate the impact of SPM deviation on coherent combining, we have carried out an experiment based on picosecond (ps)-pulses and one single-fiber amplifier. Although interested in femtosecond (fs) CPAs, we have chosen to use ps pulses for two reasons. First of all, we need both high peak power and a relatively high repetition rate in this demonstration. This translates into an average power too high to be practical for fs CPAs. Second, the high peak power of ps pulses in our experiment is similar to that of stretched fs pulses in high-energy CPAs, which results in, approximately, the same amount of maximum SPM. For this to hold true, the temporal duration of the ps pulse should not change, which has been checked in our experiment. Moreover, it is shown in the second part of the Letter that, for fs CPAs, the time-varying nonlinear phase deviations of stretched pulses will finally translate into almost constant phase shifts for the recompressed pulses.

A schematic of the experimental setup is shown in Fig. 1 and bears some similarities with [6]. The pulsed source is a diode-pumped passively mode-locked $Nd:YVO_4$ laser operating at 1064 nm and delivering 11 ps pulses at an average power of 1.5 W and a repetition rate of 125 MHz. It is further reduced to 1.25 MHz by using an acousto-optic modulator. At the output of the laser source, a free-space

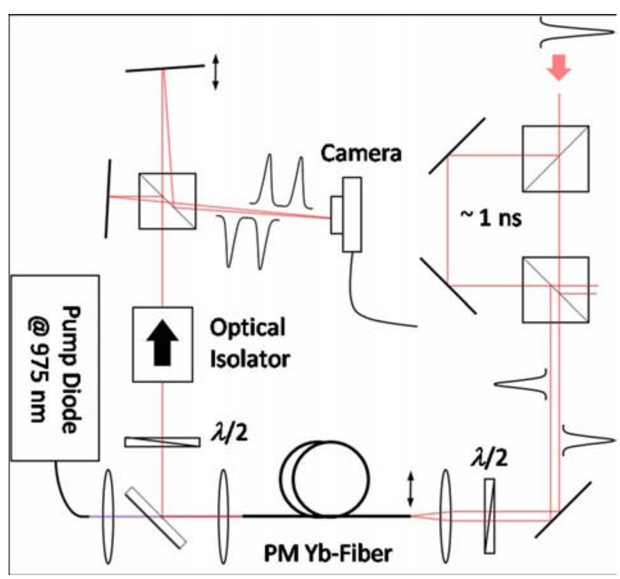

Fig. 1. (Color online) Schematic of the experiment setup.

Mach–Zehnder-type interferometer is used to prepare two time-shifted replicas of the same pulse with a fixed phase relationship at the amplifier input. The pulses are separated in time by about 1 ns to avoid the impact of environmental fluctuations, such as the mechanical and thermal fluctuations of fibers, whose characteristic time is far larger than 1 ns. The pulses are also slightly separated in space so that we can control the relative amplitudes of injected pulses by adjusting the position of the fiber input end. The amplifier is a 6-m-long polarization-maintaining double-clad (20/400 μm) ytterbium-doped fiber, which is counter pumped. The input power is 6 mW. The amplified signal is retrieved by using a dichroic mirror and then sent to a second interferometer, where the same time delay is introduced so that the two amplified pulses can interfere. The interference fringes are recorded on a CCD camera.

The fringes on Fig. 2(a) are recorded at an output average power of 0.5 W, which corresponds to a pulse energy of 0.2 μJ. The good visibility (46%, ideal value is 50%) suggests that the fixed phase relationship of the two pulses is conserved at the output of the amplifier, and that the relative intensity of the replicas is well balanced. When the output average power is scaled to 1.5 W, we observe a decrease of visibility (18%), as shown on Fig. 2(b). After slightly adjusting the position of fiber input end to balance the relative amplitudes of injected pulses, the visibility can be significantly improved [37%, see Fig. 2(c)]. Finally, as the output average power is scaled down to 0.5 W, the initial recorded visibility [see Fig. 2(d)] is recovered without readjusting the fiber input end. Figure 3 shows the measured fringe visibility evolutions, as a function of average output signal power, before and after our best adjustment of fiber input end for balancing the relative amplitudes of injected pulses at high power. The explanation of this experimental observation is as follows: at high output power, a small input amplitude imbalance of a few percents between the two replicas is turned into a large time-

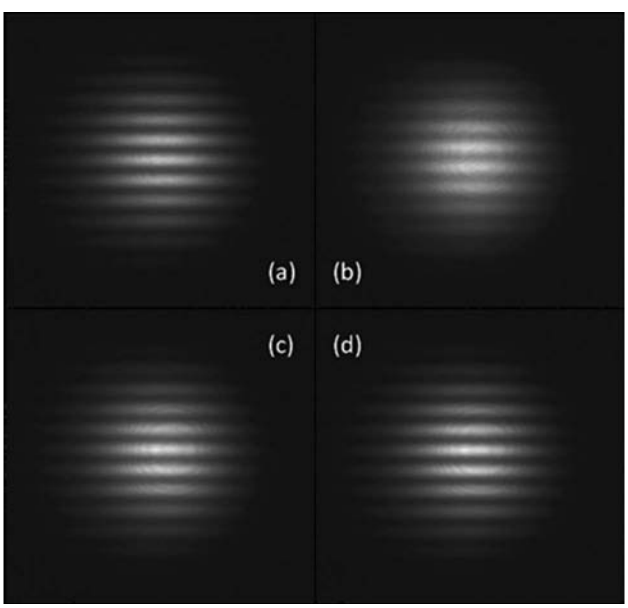

Fig. 2. Recorded interference fringes at the output.

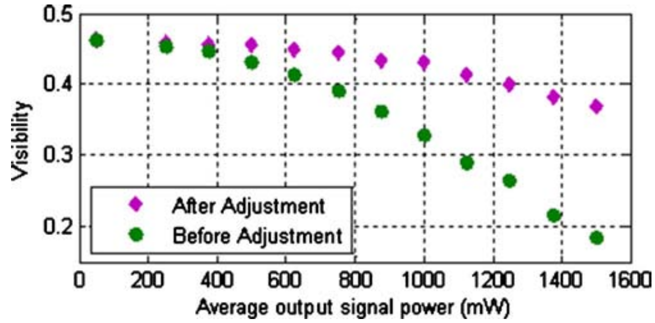

Fig. 3. (Color online) Measured fringe visibility evolutions, as a function of average output signal power, before and after the adjustment of fiber input end.

dependent phase deviation through SPM, which reduces the fringes contrast. Indeed, since the B-integral in our experiment is about 10π (estimated by measuring the spectral broadening compared with numerical simulation) for an average power of 1.5 W, an input amplitude deviation of only a few percents can result in an output phase deviation of several radians. This phenomenon leads to a very high sensitivity of the system to amplitude imbalances and fluctuations and to a degradation of the performances of a coherent combining system. Note that even when the power balance was adjusted as best as we could in this test experiment, the visibility of the fringes decreases at high power. This nonlinear sensitivity is not due to thermal or transverse spatial effects, which have been carefully ruled out by using a single-mode fiber to filter the output beam (not shown in Fig. 1 for clarity), but probably related to relative beam pointing instabilities between both arms of the splitting interferometer and increased sensitivity to the time overlap of the pulses in the recombining interferometer.

In order to quantitatively analyze the impact of the SPM deviation on the efficiency of coherent combining CPAs, we assume that the SPM deviations just lead to temporally constant phase deviations between the final compressed pulses, and these deviations take the value of B-integral deviations. This assumption has been numerically verified for several pulse shapes, such as Gaussian, super-Gaussian, first-order soliton, and spectrally modulated Gaussian pulses. Figure 4 shows an example: two 100 fs Gaussian Fourier-transform limited pulses are stretched with second-order dispersion to 1 ns; then, a nonlinear phase with a peak value of, respectively, 20 and 21 rad is introduced for each pulse (values corresponding to the nonlinearity of one amplification stage in a FCPA system described in [7]); finally, they are both compressed by the same compressor, with second-order dispersion, to about 210 fs. From Fig. 4, we see clearly that, during the main part of the compressed pulses, the deviation between their phases is about 0.8 rad and is quasi-constant, which means that a piston correction of the phase is sufficient to compensate it. Now, if we assume the phase deviation $\Delta\phi_{NL}$ is a Gaussian random variable with a variance of σ_Δ^2, we can estimate the coherent combining efficiency (ratio of obtained peak power compared to the ideal in-phase case) for a large number of am-

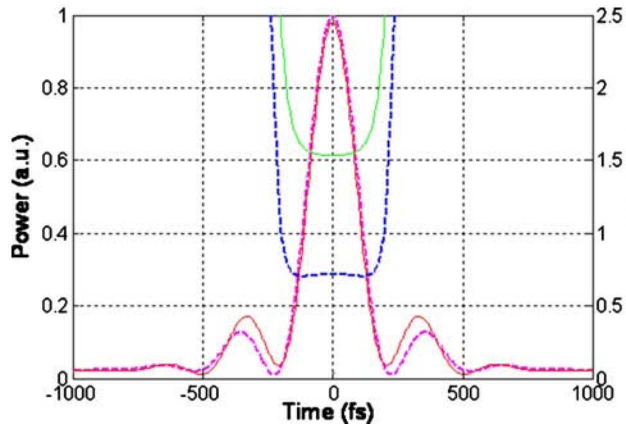

Fig. 4. (Color online) Intensity and phase of the two compressed pulses: the peak values of nonlinear phase before compression are 20 and 21 rad.

plifiers to be $\exp(-\sigma_\Delta^2/2)$. For the efficiency to be above 90%, we must have $\sigma_\Delta < 0.46$. If the average B-integral is 25, this translates into a relative deviation of B-integral among the amplifiers that should be less than 2%.

The SPM deviation can be induced by input signal power deviation, as demonstrated in our experiment. In a real coherent combing fiber-CPA system, it might have less impact than suggested by our demonstration, because the fiber amplifiers are generally operating in the regime of saturation, which reduces the intensity variations at the output and therefore the phase deviation. However, in a real system, the SPM deviation can also come from pump power deviation. We can use the following equation to evaluate the impact of the relative deviations of the signal and pump powers on the relative SPM deviation:

$$\frac{\Delta\phi_{NL}}{\bar{\phi}_{NL}} = \eta_s \frac{\Delta P_{s0}}{\bar{P}_{s0}} + \eta_p \frac{\Delta P_{p0}}{\bar{P}_{p0}}, \tag{1}$$

where $\Delta P_{s0}/\bar{P}_{s0}$ and $\Delta P_{p0}/\bar{P}_{p0}$ is the relative input power deviations for, respectively, the signal and pump, and

$$\eta_s = P_{s0}\frac{\partial \ln \phi_{NL}}{\partial P_{s0}}, \quad \eta_p = P_{p0}\frac{\partial \ln \phi_{NL}}{\partial P_{p0}} \tag{2}$$

are two coefficients that characterize the sensitivity of SPM deviation to the relative power deviations. We have numerically calculated these two parameters by using the parameters of the fiber used in our experiment and with a pump power of 10 W. The results are shown on Fig. 5, where we can clearly see that the SPM deviation is generally much more sensitive to the pump power deviation. With an average input signal power of 1 mW, for example, we found that 1% pump power deviation can lead to 1.3% SPM deviation, whereas it is less than 0.1% for signal. As mentioned above, this is because the amplifier is rapidly saturated with the increase in input signal power. Moreover, it is worth noting that the deviation of fiber Kerr nonlinear coefficient, inversely proportional to the fiber mode area, can also be translated into a nonlinear phase deviation. The tolerance for the core diameter of commercialized large mode area fibers can be as large as 10%, which can result in a relative SPM deviation as large of 20%.

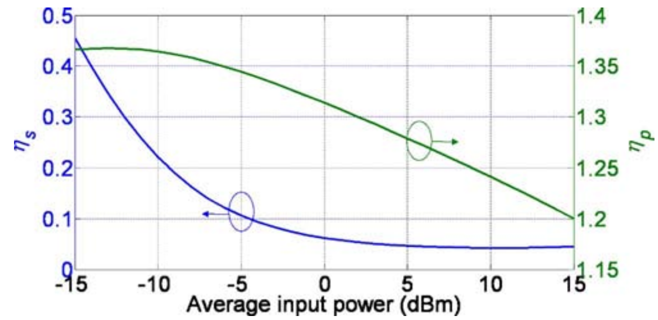

Fig. 5. (Color online) Simulated sensitivities of relative SPM deviation to the relative input signal and pump power deviations (η_s and η_p, respectively), as a function of average input signal power.

As shown above, the phase deviation $\Delta\phi_{NL}$ can be considered as a constant during the compressed pulse, though it is time varying for stretched pulses. Therefore, by performing the relative phase measurement after compression, one may retrieve the nonlinear phase-deviations and correct them actively. The precise mechanism at the origin of phase deviation, i.e., pump and input signal intensity fluctuations and fiber nonlinearity deviation, will determine the frequency range of the nonlinear phase noise and the possibility to correct for it.

To conclude, we present the first analysis to our knowledge of the impact of nonlinear effects in pulsed CPA fiber combining systems. An experiment is presented to identify the limiting effect, and further analysis of induced limitations is carried out. It is shown that, for highly stretched CPAs, the phase deviations induced through SPM by multiplicative intensity deviations can still be corrected, since they are essentially constant in the compressed pulse. However, as nonlinearities induce an increased sensitivity to fluctuations that is quantified in this Letter, future combined CPA systems are likely to work in a quasi-linear regime.

We acknowledge funding for this work from the ANR program CAN.

References

1. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, Opt. Lett. **35**, 94 (2010).
2. C. B. Schaffer, A. Brodeur, and E. Mazur, Meas. Sci. Technol. **12**, 1784 (2001).
3. T. Y. Fan, IEEE J. Sel. Top. Quantum Electron. **11**, 567 (2005).
4. C. Labaune, D. Hulin, A. Galvanauskas, and G. A. Mourou, Opt. Commun. **281**, 4075 (2008).
5. E. C. Cheung, M. Weber and R. R. Rice, in *Advanced Solid-State Photonics*, Technical Digest (Optical Society of America, 2008), paper WA2.
6. M. Hanna, H. Porte, J.-P. Goedgebuer, and W. T. Rhodes, IEEE J. Quantum Electron. **36**, 1333 (2000).
7. M. Hanna, D. Papadopoulos, F. Druon, and P. Georges, Opt. Express **17**, 10835 (2009).