1756 OPTICS LETTERS / Vol. 31, No. 11 / June 1, 2006

Compensation of self-phase modulation in fiber-based chirped-pulse amplification systems

James van Howe, Guanghao Zhu, and Chris Xu

School of Applied and Engineering Physics, Cornell University, Ithaca, New York, 14853

Received January 6, 2006; revised March 22, 2006; accepted March 23, 2006; posted March 28, 2006 (Doc. ID 67089)

We demonstrate a simple, all-fiber technique for removing nonlinear phase due to self-phase modulation in fiber-based chirped-pulse amplification (CPA) systems. Using a $LiNbO_3$ electro-optic phase modulator to emulate a negative nonlinear index of refraction, we are able to remove 1.0π rad of self-phase modulation acquired by pulses during amplification and eliminate nearly all pulse distortion. Our technique is high speed, removes nonlinear phase on a pulse-to-pulse basis, and can be readily integrated into existing CPA systems. © 2006 Optical Society of America

OCIS codes: 320.7110, 320.5540, 230.0250.

Fiber-based amplifiers have generated great interest recently because of their ability to amplify ultrafast pulses to energies comparable with conventional bulk solid-state systems while offering significant practical advantages,[1] including compactness, reduction of complex components, and freedom from misalignment. However, the smaller beam confinement and larger interaction lengths render them $\sim 10^6$ times more sensitive to nonlinear effects than bulk solid-state amplifiers.[1] To avoid nonlinear effects, the dominant of which is self-phase modulation (SPM), it is necessary to employ chirped-pulse amplification (CPA), where pulses are stretched before amplification to reduce peak power and compressed afterward. However, even with the largest practical stretched pulse durations of ~ 1 ns, power must be scaled back so as to allow no more than 1 rad of nonlinear phase shift in the gain medium in order to prevent noticeable pulse distortion and broadening.[2]

Compensation of SPM therefore shows great promise in helping fiber-based CPA systems achieve pulses with larger energy. SPM compensation in CPA systems has been shown by using the negative nonlinear index (n_2) of semiconductor materials,[3] using a spatial light modulator (SLM) in a pulse-shaping configuration,[4,5] and by residual third-order dispersion (TOD).[6,7] However, the wavelength dependence of semiconductor parameters degrades the quality of compensation for pulses less than ~ 1 ps, and linear and two-photon absorption limit the thickness of the material and thus the amount of nonlinear phase that can be practically removed. The drawbacks to using SLMs are cost and complexity of compensation, which requires nontrivial free-space alignment as well as speed limitations of the SLM, which is physically limited to less than ~ 1 kHz. The use of residual TOD is practical to implement, but only partially compensates SPM at best. In this Letter, we demonstrate an all-fiber SPM compensation device for CPA based on a technique recently used for optical data streams in which an electro-optic phase modulator was used to emulate negative n_2.[8] We are able to successfully remove 1.0π rad of nonlinear phase on a pulse-to-pulse basis. Our technique is simple, high speed, capable of fully removing SPM and can readily be integrated into existing fiber CPA systems.

The concept of our compensation device is quite simple. Our goal is to remove the nonlinear phase due to SPM that a pulse accumulates during amplification in a fiber gain medium, $\varphi_{\mathrm{NL}} = n_2 k \int_0^L |E(z,t)|^2 \mathrm{d}z$, where $|E(z,t)|^2$ is the temporal profile of the intensity at a given point in the gain fiber. Because the total dispersion during stretching for a typical CPA system is much larger than the total dispersion in the amplifier, the interaction between nonlinearity and dispersion is negligible.[2] We can therefore treat nonlinearity as being lumped, in which case the nonlinear phase accumulated from SPM can be written as $\varphi_{\mathrm{NL}} = n_2 k |E_f(t)|^2 L_{\mathrm{eff}}$, where $|E_f(t)|^2$ is the temporal profile of the output intensity from the amplifier and L_{eff} is the effective length determined by the gain profile of the amplifier as a function of z. To cancel this phase, our compensation device makes use of a $LiNbO_3$ electro-optic phase modulator driven by a voltage that is proportional to the optical intensity of the amplifier output. The phase imparted to optical pulses by the phase modulator can be described by $\varphi_{\mathrm{PM}} = \pi V(t)/V_\pi$, where V_π is the voltage necessary to obtain a π phase shift. By applying $V(t) \propto -|E_f(t)|^2$, we effectively emulate negative n_2 and can use the phase modulator to compensate for the nonlinear phase. This technique differs from using true optical negative n_2, since electro-optic modulators have response times of the order of ~ 10 ps at best, and negative n_2 generally has a response of <1 ps. However, in our proposed and demonstrated compensation method we impose phase on pulses stretched to >100 ps. Therefore the ultrafast response associated with optical negative n_2 is not necessary, and our technique is ideally suited to a CPA system.

The experimental setup is shown in Fig. 1. The pulsed source consisted of a mode-locked fiber laser (IMRA; Femtolite B-4-FC) producing 0.08 nJ, 370 fs pulses at a center wavelength of 1556 nm and a repetition rate of 50 MHz. The optical spectrum was approximately sech^2 in shape with a 3 dB bandwidth of

0146-9592/06/111756-3/$15.00

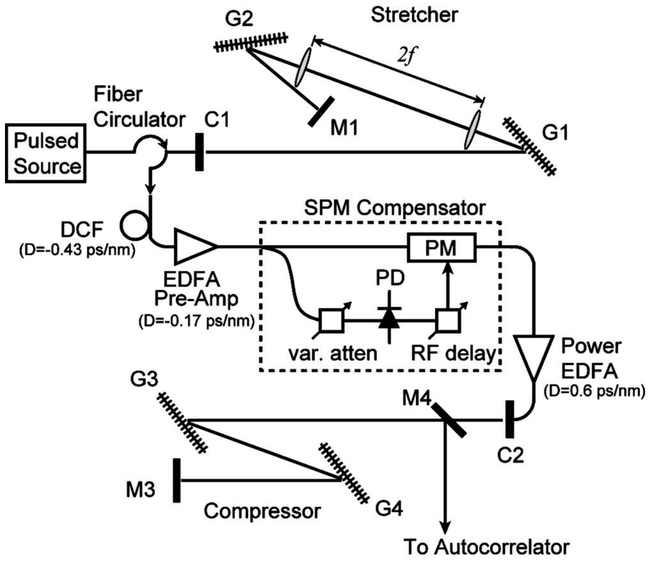

Fig. 1. Experimental setup. C, collimator; G, grating; M, mirror; PD, photodetector; PM, phase modulator; EDFA, erbium doped fiber amplifier; DCF, dispersion compensating fiber.

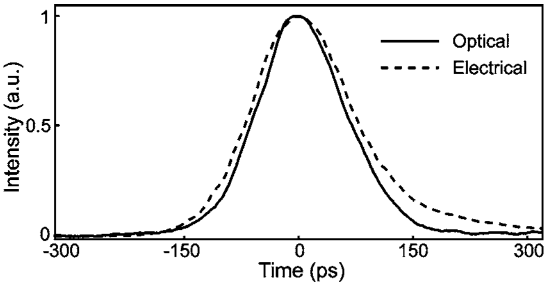

Fig. 2. Oscilloscope time trace of the stretched optical pulse (solid curve) and electrical signal (dashed curve) into the phase modulator. Pulse widths as measured by the 30 GHz sampling scope are 136 and 151 ps, respectively.

7.0 nm. Pulses were stretched to 136 ps (Fig. 2) by a grating stretcher, giving −20.0 ps/nm of total dispersion. They were then preamplified by an erbium-doped fiber amplifier (EDFA) to account for some of the loss through the stretcher and following SPM compensation device. Five meters of slope-matched dispersion-compensating fiber with a total dispersion of −0.43 ps/nm was placed before the preamplifier to compensate for dispersion from the power amplifier (0.6 ps/nm) and the preamp (−0.17 ps/nm). This allowed us to match the grating compressor to the stretcher and avoid nonnegligible effects from higher-order dispersion. The SPM compensator consists of a $\mathrm{LiNbO_3}$ phase modulator driven synchronously by the detected optical input signal. A variable attenuator was used to adjust the power into the 10 GHz high-speed photodetector (Discovery, DSC-R402) in order to adjust the magnitude of the compensation signal, and a variable rf delay was used to synchronize the electronic drive with the optical input. By choosing the correct sign and magnitude of the driving signal, the phase modulator precompensates each pulse with the desired amount of negative SPM. For proper compensation, the detector bandwidth and stretched pulse duration must both be large enough that the electronic signal into the phase modulator accurately follows the stretched optical signal. The oscilloscope time trace in Fig. 2 shows the excellent match between the optical pulse (solid curve) and electrical signal (dashed curve) in our system. The small deviation is expected as a result of the measured 63 ps impulse response of the detector and following rf components. Simulation shows that this deviation has no noticeable effect for precompensation in our system. After SPM precompensation, pulses were amplified from 0.02 to 30 nJ by a commercial, gain-flattened, two-stage EDFA (IPG, EAU-1-C), where they simultaneously acquire $\sim 1.0\pi$ of nonlinear phase from SPM. The total length of fiber inside the amplifier was ~ 26 m with an output fiber pigtail of ~ 1.25 m, giving a measured total dispersion of 0.6 ps/nm. The nonlinear coefficient of the fiber in the amplifier is close to that of SMF, $\gamma \sim 1.2\ \mathrm{W^{-1}\,km^{-1}}$, leading to the expected nonlinear phase shift of $\sim 1.0\pi$ obtained in our experiment. After amplification, pulses were compressed by a grating compressor providing 20 ps/nm of dispersion and then measured by a second-order autocorrelation.

To demonstrate the concept of the device, we measured autocorrelation traces with and without SPM compensation for the highest power obtainable from the amplifier and therefore the largest amount of SPM. This corresponded to 1.5 W and 1.0π, respectively. For both cases, the grating stretcher and compressor were left in a matched configuration in which the compressor length was optimized by maximizing the two-photon photocurrent of a silicon diode for low power out of the power amplifier (20 mW) and therefore negligible nonlinearity. Figure 3(a) shows the high-power trace without compensation, and Fig. 3(b)

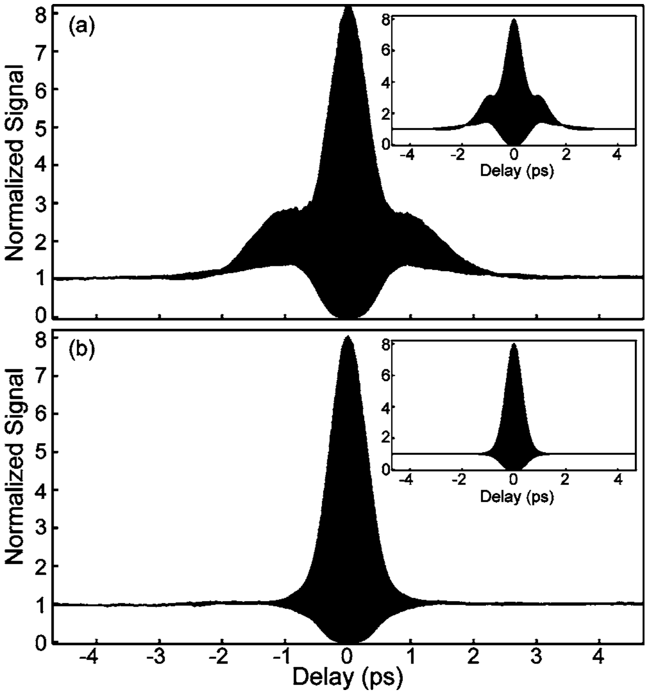

Fig. 3. Autocorrelation traces. (a) without compensation for a nonlinear phase shift of 1.0π rad, (b) with 1.0π rad of compensation. Insets, simulated traces.

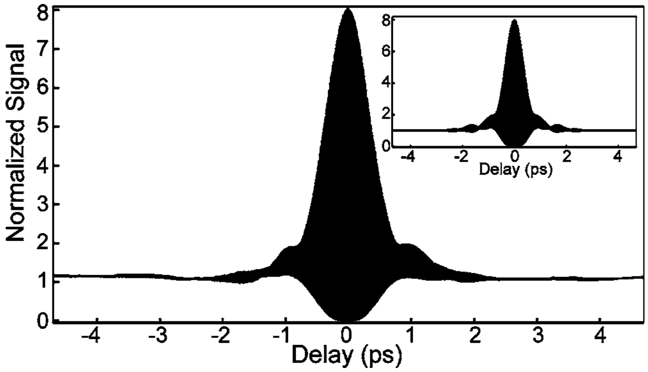

Fig. 4. Autocorrelation trace for a nonlinear phase shift of 1.0π rad and an optimally mismatched grating compressor. Inset, simulated trace.

shows the trace for 1.0π compensation (~5.0 V peak-to-peak signal into the phase modulator). Calculated results from the simulation are shown in the insets of each figure. We model the amplifier by using the standard split-step Fourier method and take into account dispersion, SPM, stimulated Raman scattering, and third-order dispersion, of which the latter two have negligible effects given our pulse energy and bandwidth. The significant reduction in pulse broadening and distortion shown in Fig. 3(b) demonstrates the effectiveness of the compensation technique. Furthermore, the excellent match between simulated and measured autocorrelation traces demonstrates the accuracy with which we are able to remove SPM. Taking into account the deconvolution factor, the final compensated intensity pulse width corresponds to 418 fs, which is only 13% beyond the transform limit of 370 fs. The reason we do not exactly recover the transform limit is a small amount of nonlinearity in the 2 m of fiber between the source and the stretcher, ~0.5 rad of SPM.

For demonstration of the practicality of this technique, we compare the configuration of a matched stretcher–compressor with SPM compensation versus the typical configuration in which a deliberately mismatched grating compressor providing anomalous dispersion is used to mitigate the effects of SPM.[9] Figure 4 shows the autocorrelation trace for the system with 1.0π rad of SPM and an optimally mismatched grating compressor (by decreasing the grating distance of the compressor until the two-photon current was maximized). Calculated results from the simulation are shown in the inset. Not only is the pulse width for this configuration 23% larger than that with SPM compensation and in a matched stretcher–compressor system [Fig. 3(b)], but there also resides a significant amount of energy in incompressible sidelobes. As the nonlinear phase increases, the technique of using residual dispersion from a mismatched compressor becomes even less effective. Pulses become broader and more distorted. Using SPM compensation in a matched stretcher–compressor as demonstrated in this work, however, can ideally return pulses to the transform limit regardless of increasing nonlinearity.

The practical limit for which our technique can compensate for SPM depends on the interaction between dispersion and SPM in the amplifier. Our simulation shows that for our large amplifier dispersion of 0.6 ps/nm there is no noticeable distortion of the pulse intensity for compensating up to 10π rad of SPM. Decreasing the amount of dispersion in the power amplifier will make SPM compensation more robust, allowing for compensation of even larger nonlinear phase shifts.

In summary we demonstrate the removal of 1.0π rad of nonlinear phase shift on a pulse-to-pulse basis for fiber-based CPA by using an electro-optic modulator to emulate negative n_2. Our compensator is all-fiber, high speed, and can readily be integrated into existing systems. Though we demonstrate SPM compensation for a wavelength of 1550 nm, our technique can work at any other wavelength for which integrated electro-optic phase modulators can be manufactured, such as 1.3 μm, 1.06 μm, and 850 nm. In fact the V_π for integrated modulators scales superlinearly with wavelength, making our compensation technique even more powerful for shorter-wavelength sources. Larger magnitude of compensation can also be achieved by using higher-power rf amplifiers. Furthermore, for a completely periodic pulse train, waveform synthesis of the electronic drive could allow compensation of at least 4–5 times as much SPM[10] as demonstrated in this work by using cost-effective narrowband rf amplifiers. Though grating pairs were used for stretching and compressing of optical pulses in this experiment, we foresee this compensator's being integrated into systems that use other fiber-based dispersive devices, such as fiber Bragg gratings and photonic bandgap fiber,[11] to achieve compact, all-fiber, high-energy pulse generation.

The authors gratefully acknowledge Martin Fermann of IMRA America for loaning the fiber laser source, as well as Frank Wise, Shian Zhou, and Lyuba Kuznetsova of Cornell University for their insightful discussions.

References

1. A. Galvanauskas, IEEE J. Sel. Top. Quantum Electron. **7**, 504 (2001).
2. M. D. Perry, T. Ditmire, and B. C. Stuart, Opt. Lett. **19**, 2149 (1994).
3. O. A. Konoplev and D. D. Meyerhofer, IEEE J. Sel. Top. Quantum Electron. **4**, 459 (1998).
4. A. Braun, S. Kane, and T. Norris, Opt. Lett. **22**, 615 (1997).
5. A. Effimov, M. D. Moores, B. Mei, J. L. Krause, C. W. Siders, and D. H. Reitze, Appl. Phys. B **70**, S133 (2000).
6. L. Shah, Z. Liu, I. Hartl, G. Imeshev, G. Cho, and E. Fermann, Opt. Express **13**, 4717 (2005).
7. S. Zhou, L. Kuznetsova, A. Chong, and F. Wise, Opt. Express **13**, 4869 (2005).
8. J. Hansryd, J. van Howe, and C. Xu, IEEE Photon. Technol. Lett. **17**, 232 (2005).
9. F. Cattani, D. Anderson, A. Berntson, and M. Lisak, J. Opt. Soc. Am. B **16**, 1874 (1999).
10. C. Xu, L. Mollenauer, and X. Liu, Electron. Lett. **38**, 1578 (2002).
11. G. Imeshev, I. Hartl, and E. Fermann, Opt. Express **12**, 6508 (2004).