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The influence of the active gain medium on the spectral amplitude and phase of amplified, femtosecond pulses in a laser system is studied. Results from a 15-PW example based on Nd-doped mixed glasses show that gain-induced atomic phase shifts will distort the pulses, reducing their peak power. It is also shown that a phase compensation solution is possible and the corresponding coefficients are calculated.

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Petawatt (PW) laser pulses are vital for a variety of present and future scientific studies and projects such as high energy and attosecond science, particle acceleration, laser plasma interaction, relativistic physics, x-ray generation, and others [1]. Such pulses are produced today using the well-established technique of chirped-pulse amplification (CPA), which has been tremendously successful over the past 25 years [2].

To further increase the peak power, more energy and shorter pulses are needed. While the energy output of the laser is linked to the laser size, the pulse duration is related to the bandwidth that the system can amplify. Gain narrowing [3] is the dominant effect limiting the bandwidth of PW laser amplifiers today. To circumvent this shortcoming, three different approaches can be used. The *first* is through the use of optical parametric CPA amplifiers (OPCPAs) in hybrid laser system where part of the gain is shared with the parametric amplifier that does not suffer from gain narrowing. *Second* is to use multiple gain media to amplify sequential parts of the spectrum. The *third* approach is to use spectral filters to push down on the amplification near the peak wavelength and amplify more of the side wavelengths [4].

The last approach comes at the expense of the output energy. Nd:glass lasers are, however, very energetic and can easily produce more energy than what is needed for a 100-fs, 15-PW system. Shortly, an affordable loss in the output energy comes with the benefit of more bandwidth and, therefore, shorter pulses.

Other effects that shape the amplification in these PW lasers are gain saturation [3] and atomic phase shift (APS). The latter effect is also known for causing frequency pulling in high gain lasers. It also changes the phase of a pulse in a laser amplifier [5], and it can be potentially disruptive in CPA systems [6] that are very sensitive to small phase disturbances. However, even PW-level systems today marginally suffer from this effect, mainly because the bandwidth of these lasers is still small enough to overlap with the non-linear part of the phase shift. However, the APS will become important for large-bandwidth, high-gain systems and especially for those systems that utilize two (or more) different lasing materials to amplify more bandwidth [7]. Since generally these systems have low repetition rate, it is important to know the amount of phase that needs to be compensated.

In this letter, the consequences of the APS on the compressibility of the pulse are carefully investigated for a 15-PW laser that could potentially be built in the next few years. This is a Nd-doped glass laser utilizing two types of amplifiers, one based on phosphate glass and the other on silicate glass. The laser architecture is hybrid, with a front-end OPCPA and Nd:glass power amplifiers. This system uses all three of the above mentioned approaches to minimize gain narrowing.

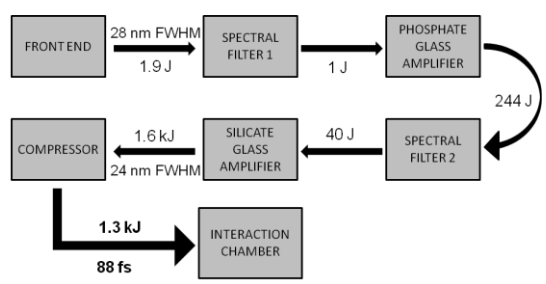

Figure 1. Main components of the 10-PW mixed-glass laser.

The components of the laser system studied here are shown in Fig 1. The front-end produces 60-fs, Gaussian, transform-limited pulses centered at 1069 nm having 1.9 Joules of energy. These numbers are comparable to those already demonstrated by the Texas Petawatt Laser [8]. Since high-fidelity and high-energy pump lasers for OPCPA systems are still under development, the pulses are here further amplified by Nd-glass amplifiers. The size, small signal gains and all other parameters used in this study are typical for disk amplifiers that are currently operating at the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory [9]. Each amplifier is made of two modules each containing two double-passed sets of disk amplifiers. The areas of the phosphate and silicate amplifiers are 63.6 cm^2 (9 cm diameter) and, respectively, 339.8 cm^2 (20.8 cm diameter). Before each power amplifier there are two spectral filters (see Fig. 1) to reduce gain narrowing, as described above in the 3rd approach. Finally, the chirped pulses are passed through the compressor in order to become femtosecond pulses.

The transmission of the compressor is assumed 86 % at all wavelengths. Other system losses (optics, diagnostics, etc.) are 5%.

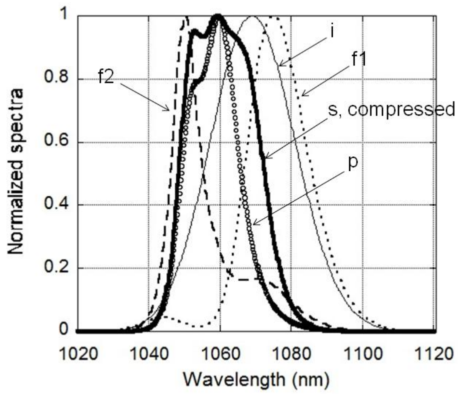

Figure 2 Normalized spectra of the laser pulse versus wavelength: i, initial 60 fs pulse, f1, after the first filter, p, after the phosphate amplifier, f2, after the 2nd filter, and s, after the silicate amplifier, also considered the compressed pulse spectrum which has a FWHM of 24 nm.

The operation of the laser has been studied with a 1-dimensional computer code that models the amplification, gain narrowing, saturation and APS. The optical properties of the laser glasses [10] were taken to be identical to those of Nd:Phosphate (APG-1, 27.8 nm linewidth), and Nd:Silicate (K-824, 38.2 nm linewidth). The stimulated emission cross sections were considered Lorentzian functions with the above-mentioned linewidths. The amplification of the phosphate and the silicate glasses peaks at 1053.9 nm and 1064.5 nm, respectively. To expedite the computer modeling, these glasses (operating at ambient temperature) are assumed to be homogeneous gain media [11].

The spectrum of the pulse is shaped by every module of amplification and filter. Figure 2 shows the evolution of the spectrum beginning with the initial 60-fs pulse and ending with the spectrum after the silicate amplifier which is also considered the final, compressed spectrum. This compressed spectrum has a full-width-at-half-maximum (FWHM) of 24 nm. A transform-limited pulse with this spectrum would be 86 fs long. However, due to the APS, the amplified pulse does not have a flat phase. Each amplifier contributes with a term in the total phase change $\Delta\phi$ as shown below in Eq. 1:

$$\Delta\phi(\omega) = \frac{\omega-\omega_p}{\Delta\omega_p}\ln(G_p(\omega)) + \frac{\omega-\omega_s}{\Delta\omega_s}\ln(G_s(\omega)) \quad (1)$$

Here ω_p, $\Delta\omega_p$ and ω_s, $\Delta\omega_s$ are the peak angular frequencies and linewidths of the phosphate and the silicate glasses, respectively. The power gain coefficients G_p and G_s, respectively, are functions of the frequency because of the Lorentzian lineshape and gain saturation. The phase change due to each amplifier as well as the sum of the two is shown in Fig. 3.

The influence of this phase on the compressibility of the pulse is presented in Fig. 4. Line i shows the shape of the initial, 60-fs pulse. With the phase accumulated during amplification (see total phase curve, Fig. 3) and same spectrum, this pulse would change to that shown by line ip. The difference between lines i and ip is just meant to show the effect (on the 60-fs pulse) of a pure phase distortion from flat to the APS.

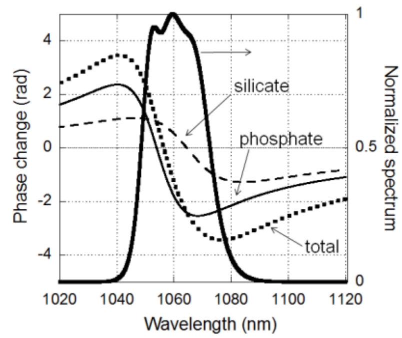

Figure 3. The APSs seen by the pulse in each of the glass amplifiers and their sum (total), left axis. The thick solid line, right axis, is a copy of the compressed spectrum that is shown just for visual overlapping with the phase curves.

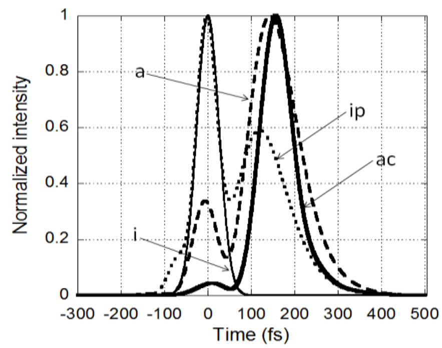

Figure 4. Compressed, FFT-reconstructed pulse profiles: i, initial 60-fs pulse with no distortions; ip, initial spectrum and APS; a, amplified spectrum and APS; ac, amplified spectrum with APS and compensated phase.

However, the spectrum of the amplified pulse changes too, to the one shown previously in Fig. 2, line s. An FFT reconstruction from this spectrum and the APS is shown in Fig. 4 by line a. This is the temporal profile of the amplified pulse. This pulse is distorted and broken in two parts, with a significant part of the energy in the early part. To recover the pulse shape and increase the peak power, a phase modulator could be used. Using just a 4th order polynomial fit to the total phase shown in Fig. 3, the 2nd, 3rd and 4th order compensation coefficients were found. Applying the phase compensation according to these coefficients (-2.7×10^3 fs^2, 2.4×10^5 fs^3, and 1×10^7 fs^4, respectively), the pulse shape improves significantly with 96.6% of the energy concentrated in a single pulse, as shown by line ac in Fig. 4. The FWHM of this pulse is 88 fs, which is 2 fs more than a transform-limited pulse. The peak power for this pulse is 15 PW, which is 61% larger than the peak power of the uncompensated pulse. If plotted on a logarithmic scale (not shown), a contrast of 10^{-12} is reached by the leading edge at about -1 ps and by the trailing edge at +2.5 ps. The width of the pulse at 10^{-3} level is 532 fs and at 10^{-6} level is 1198 fs. Overall, if the OPCPA provides a high-quality, strong seeding pulse [12], the contrast should be good enough for the majority of high energy density experiments.

Another consequence of the APS is a delay of the peak of the pulse [13]. That can be inferred from Fig. 4 where the phase compensated pulse "arrives" later by 160 fs than any flat-phase pulse such as the initial 60-fs pulse. This fact could be important in single shot experiments where a low energy probe pulse derived before amplification is used for pump-probe measurements.

The phase of the pulse can also be affected by the self-phase modulation process [6]. The peak value of the nonlinear phase, also called the "B-integral," was calculated after each pass of amplification. The nonlinear indexes of refraction were $n_2 = 1.13\times10^{-13}$ esu and $n_2 = 3.44\times10^{-13}$ esu for phosphate and silicate glasses, respectively [10]. A stretching factor of 385 ps/nm, typically provided by a double-pass, Offner-type stretcher [9], was also used in this calculation to determine the intensity of the pulse as a function of frequency.

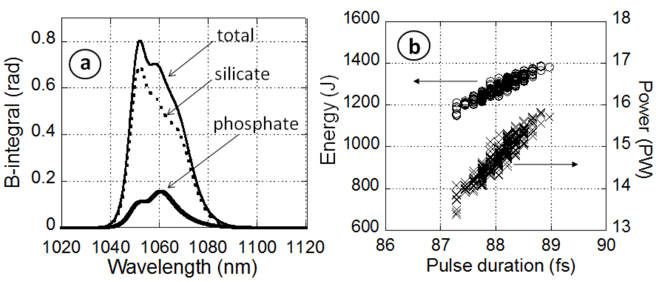

Figure 5. The B-integral values accumulated by the stretched pulse in the phosphate and silicate amplifiers, and their sum (total), a. Output energy and power versus the pulse duration for 300 test shots with 1% noise rms in the small signal gain, b.

Figure 5a shows the accumulated (a sum over all four passes in each amplifier) B-integral values in the phosphate and silicate glasses. Also shown is the overall value which is the sum of the two and has a peak value of 0.8 near 1052 nm. Such a low value is the result of the relatively long stretched pulse (9.24 ns for the 24 nm bandwidth) that lowers the intensity. Therefore, it can be concluded that the self-phase modulation of the stretched pulse will not affect its compressibility. It should be also noted that the maximum fluences in the phosphate and silicate amplifiers is 3.8 J/cm^2 and 4.7 J/cm^2, respectively. For this 9.24 ns stretched pulse, both numbers are smaller than the damage threshold for high-quality, inclusion-free glass [14].

Small fluctuations in the laser gain, typical to pulse systems, could change the spectrum and the APS value. This can adversely affect the amplified spectrum and the phase of the pulse. Assuming a 1% variation (standard deviation/mean value) in the initial small signal gain of every amplifier in the laser, a statistical study of 300 shots was performed. The output energy and pulse duration were calculated for all shots with only *one* set of phase compensation factors, precisely, the ones used to compensate the pulse in Fig. 4.

The results of the study are shown in Fig. 5b. The variations of the output energy, power, bandwidth and pulse duration are: 3.6%, 3.1%, 0.67%, and 0.38%, respectively. Therefore, fluctuations in the small signal gain will produce minimal changes in the laser output.

In conclusion, the atomic phase shift effect is large enough to distort the compressed pulse of a CPA-type, Nd:glass laser based on a dual gain medium. The pulse shape can be improved and the peak power increased 61% if a phase modulator is used. The pulse duration would then be 88 fs and the peak power approximately 15 PW. These results are important since they show that gain-related issues such as gain narrowing and gain dephasing can be overcome and intense, sub-100 fs pulses can be generated in a single beam by a moderate size laser. Given the large bandwidth of the amplified pulses, a well-aligned, tiled-grating compressor is needed. The repetition rate can also be improved if modern amplifier cooling designs are utilized. The ultimate limiting factors for the peak power of these systems remain the B-integral and the damage threshold of optics.

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References

1. Science of Extreme Light Infrastructure, Toshiki Tajima, et. al., AIP Conf. Proc. 1228, 11 (2010), DOI:10.1063/1.3426041
2. D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
3. C. Le Blanc, P. Curley, F. Salin, Opt. Commun. **131**, 391 (1996).
4. C. P. J. Barty, C. L. Gordon III, and B. E. Lemoff, Opt. Lett. **19**, 1442 (1994).
5. Siegman, E. A., *Lasers*, (University Science Books, 1986) p. 468.
6 . S. Backus, C. G. Durfee III, M. M. Murnane, and H. C. Kapteyn, Rev. Sci. Instrum. **69**, 1207 (1998).
7. R. Danielius, A. Piskarskas, D. Podenas, A. Varanavicius, Opt. Commun. **84**, 343 (1991)
8. E. Gaul, M. Martinez, J. Blakeney, A. Jochmann, M. Ringuette, D. Hammond, T. Borger, R. Escamilla, S. Douglas, W. Henderson, G. Dyer, A. Erlandson, R. Cross, J. Caird, C. Ebbers, and T. Ditmire, Appl. Opt. **49**, 1676 (2010).
9. B. Stuart, J. Bonlie, J. Britten, J. Caird, R. Cross, C. Ebbers, M. Eckart, A. Erlandson, W. Molander, A. Ng, P. Patel, and D. Price, "The Titan Laser at LLNL," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science* Conference and Photonic Applications Systems Technologies, Technical Digest (CD) (Optical Society of America, 2006), paper JTuG3.
10. S. E. Stokowski, R. A. Saroyan, and M. J. Weber, "Nd:doped laser glass spectroscopic and physical properties," Lawrence Livermore National Laboratories, Rep. M-095, 2nd revision, 1981.
11. D. Hall, W. Hagen, M. Weber, IEEE Quantum Electron. **22**, 793 (1986)
12. J. Itatani, J. Faure, M. Nantel, G. Mourou, S. Watanabe, Opt. Commun. **148**, 70 (1998).
13. L. Casperson and A. Yariv, "Pulse Propagation in a High-Gain Medium," Phys. Rev. Lett. 26, 293–295 (1971)
14. F. Trager, *Springer handbook of lasers and optics*, (Springer 2007), page 299.