LLNL-CONF-491416

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July 27, 2011

Ultrafast Optics 2011
Monterey, CA, United States
September 26, 2011 through September 30, 2011

Spectral amplitude and phase evolution in multi-petawatt laser pulses

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Abstract: 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 case study of a 15-petawatt laser based on Nd-doped mixed glasses are presented.

I. INTRODUCTION

Petawatt (PW) laser pulses are produced today using the chirped-pulse amplification (CPA) technique. Two CPA systems have shown significant potential. The first is based on Ti:Sapphire crystals and can generate PW pulses with durations below 30fs. The second is based on Nd-doped glass and can produce 440 fs pulses with 660 J of energy [1]. Using a combination of two different glasses in the amplifier, more bandwidth can be generated in glass systems and PW pulses as short as 167 fs have been produced [2]. Shorter and more intense pulses could be generated using this approach and therefore it is important to study the gain-induced phenomena that can potentially limit the peak power of the amplified pulses.

II. LASER SYSTEM

The test laser system 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 (optical parametric CPA) and Nd:glass power amplifiers. The laser architecture is simple and based on already demonstrated concepts and techniques. Its components are shown in Fig 1.

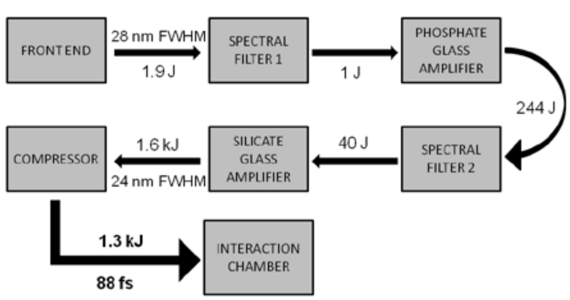

Fig. 1. Main components of the 15-PW mixed-glass laser.

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 [2]. This design incorporates three approaches to fight gain narrowing. First, the front-end OPCPA maintains the necessary bandwidth while reducing the amount of gain needed to achieve multi-PW levels of power. Second, two gain media distribute the gain across the pulse bandwidth during amplification. Third, spectral filters "push the spectrum around" to minimize gain narrowing in the power amplifiers. All these efforts culminate with the generation of 1.3 kJ pulses with enough bandwidth to be compressed to 88 fs.

III. SPECTRUM AND PHASE EVOLUTION

The energy obtained after every amplifier is shown in Fig. 1. A one-dimensional code that accounts for the energy and gain in the glass for each frequency in the stretched pulse is used to model the amplification. The spectrum of the pulse is shaped by every module of amplification and filtering.

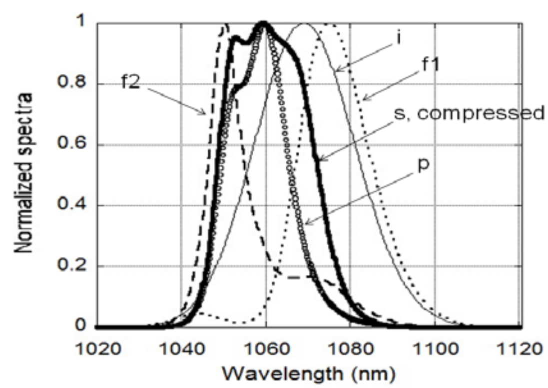

Fig. 2. Normalized spectra of the laser pulse versus wavelength: (i) initial 60 fs pulse, (f1) after the first filter, (p) after the phosphate amplifier, (f2) after the 2nd filter, and (s) after the silicate amplifier, also assumed to be the final, compressed pulse spectrum with a FWHM of 24 nm.

Figure 2 shows the evolution of the spectrum starting with the initial 60-fs pulse and ending with the spectrum after the silicate amplifier which is also considered the final, compressed spectrum. This 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 gain-induced dispersion, the amplified-and-compressed 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:

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

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.

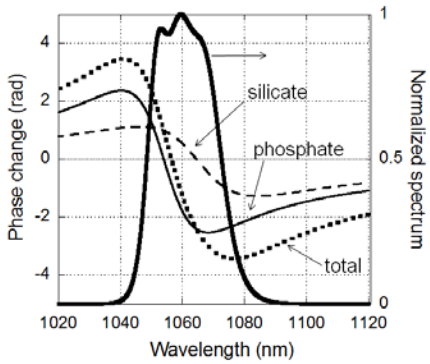

Fig. 3. (left axis) The phase change APS experienced by the pulse in each of the glass amplifiers and their sum (total). (right axis) For comparison, the compressed spectrum from Fig. 2 is also shown (thick solid line).

IV. COMPRESSIBILITY

The influence of this phase change, called APS (atomic phase shift [3]), on the compressibility of the pulse is presented in Fig. 4.

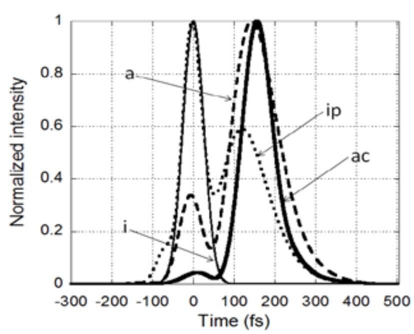

Fig. 4. FFT-reconstructed pulse profiles: (i) initial 60-fs pulse with no distortions, (ip) initial spectrum and APS, (a) amplified spectrum and APS, (ac) amplified spectrum with APS and compensated phase.

The line (i) shows the shape of the initial, 60-fs pulse. Due to the APS accumulated during amplification (see total phase curve, Fig. 3) and assuming the same spectrum, the initial pulse shape would change to that shown by line (ip). The difference between lines (i) and (ip) in Fig. 4 is only meant to point out the effect (on the 60-fs pulse) of a pure phase distortion from flat to the APS. However, the spectrum of the amplified pulse changes as well, as previously shown in Fig. 2, line (s). An FFT reconstruction from this spectrum and the APS is presented 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 can be used. Applying the phase compensation that minimizes the pulse duration, 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 only 2 fs longer than that of the transform-limited pulse. The peak power of this pulse is 15 PW and exceeds the peak power of the uncompensated pulse by 61%.

The value of the "B-integral," was also calculated after each pass of amplification. Its maximum value was found to be 0.8 rad, below the level of concern for the pulse compressibility.

V. CONCLUSIONS

In conclusion, the atomic phase shift effect or gain-induced dispersion 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 by 61% with a phase modulator. The pulse duration would then be 88 fs and the peak power approximately 15 PW.

ACKNOWLEDGMENTS

This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

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