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Chirped Pulse Amplification with Narrowband Pulses

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We demonstrate a compact hyper-dispersion stretcher and compressor pair which enables chirped-pulse amplification in Nd:YAG. We generate 750 mJ, 0.2 nm FWHM, 10 Hz pulses recompressed to 8 ps near transform limited duration. The dispersion matched pulse compressor and stretcher impart a chirp of 7300 ps/nm, in a 3 m x 1 m footprint.

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Chirped pulse amplification (CPA) enables generation of highly energetic picosecond and femtosecond pulses [1]. Pulse bandwidth and applied dispersion determine the duration of the chirped pulse. For applications requiring high energy, subnanometer bandwidth pulses, traditional two-grating stretchers and compressors cannot provide adequate dispersion in a table-top footprint. Here, we present novel, meter-scale stretcher and compressor that achieve 10x greater dispersion than comparable footprint two-grating designs. We employ the hyperdispersion stretcher and compressor pair for CPA in Nd:YAG and generate 750 mJ pulses at 1064 nm with 0.2 nm bandwidth, compressed to near transform limited pulse duration of 8 ps.

The motivation for CPA with narrowband pulses is two-fold. First, hyper-dispersion allows CPA with commercially available Nd:YAG or Nd:YLF amplifier which are relatively inexpensive and have a high signal gain. Second, nominally 10 picosecond duration, near transform limited, joule scale laser pulses are well suited for generation of high flux monoenergetic γ-rays in Compton-scattering based light sources [2]. Previously, D. Fittinghoff, *et. al.* suggested hyper-dispersion compressor arrangements [3]. F. J. Duarte described a conceptually similar hyper-dispersion arrangements for a prism-based compressor [4].

The hyper-dispersion stretcher and compressor described here have been deployed on the interaction laser for the Compton scattering gamma-ray source at Lawrence Livermore National lab [2]. Initially, we utilized a chirped fiber bragg grating (CFBG) stretcher in place of a bulk stretcher. However, the CFBG imparts a large group delay ripple on the chirped pulse. Resulting pulse recompression fidelity is poor, with 80% of the energy scattered into a wide pedestal outside the main peak. We replaced the CFBG with a bulk stretcher, which has a smooth group delay profile and enables high fidelity recompression.

The compressor design is shown in Fig. 1. The compressor consists of two 40x20 cm multi-layer dielectric (MLD) gratings arranged anti-parallel to each other, a vertical roof mirror (RM), and a 6-mirror assembly. The anti-parallel arrangement enables angular dispersion,

$\frac{d\theta}{d\lambda}$, which is greater than possible with a single grating. The 6-mirror assembly, conceptually 3 periscopes, sets the height and position of the reflected beam on the gratings and inverts the beam in the plane of diffraction. A single retro-reflector could replace the 6-mirror assembly. The beam is incident at Littrow-3 degrees (64.8^o) on the 1740 grooves/mm gratings. Unfolded, the compressor would consist of 4 gratings. The 6-mirror assembly allows to fold the compressor and eliminate two of the gratings. We double pass the compressor with the roof-mirror. The beam undergoes a total of 8 grating reflections and 16 mirror reflections in the compressor. The first grating angularly disperses the incident collimated beam; the second grating, then, additionally chirps the dispersed beam. After the 6 mirror-assembly, the third and fourth grating reflections remove the angular but not the spatial chirp. After the roof mirror, the beam undergoes four more grating reflections, which produce a collimated, spatially de-chirped beam at the compressor output. The total beam path of the central ray is 22 m. MLD gratings in this compressor have diffraction efficiency above 97%, enabling an overall compressor throughput efficiency of 60%.

The hyper dispersion stretcher design, conceptually similar to the compressor, is shown in Fig. 2. We use two 1740 grooves/mm MLD gratings, with footprints of 20x10 cm and 35x15 cm. The two gratings are also arranged anti-parallel to each other in hyper-dispersion configuration. The key difference, here, is a 175 mm diameter, $f = 3099$ mm lens to impart a positive frequency chirp onto the pulse. Similar to a Martinez stretcher, the hyper-stretcher contains a $2f$ telescope: the retro-mirror is f away from the lens and folds the stretcher [5]. The beam height changes through off-center incidence on the lens, eliminating the six-mirror assembly. Two 45^0 mirrors fold the beam path, rendering a more compact footprint. The beam is first incident on gratings 1 and 2 at Littrow - 3^0 (64.8^0). The beam then refracts through the lens and back reflects from a retro-mirror. After two more grating reflections, a spatially dispersed beam becomes collimated at the roof mirror. After four more grating reflections the beam recollimates and spatially de-chirps at the output. The distance between the lens and grating 2 determines the magnitude and the sign of the dispersion. Beam clipping prevents a sufficiently short distance between the lens and grating 1 to match the compressor dispersion in a single pass. The beam at the output is retro-reflected for a second pass through the system, undergoing a total of 16 grating reflections. The input and the output to the stretcher is fiber coupled, and we use the same fiber port for coupling in and out of the stretcher. We measured 30 dB loss between the input and the output signal. The loss is mainly due to the poor recoupling efficiency.

Proper pulse recompression requires balanced system dispersion. We derive an analytical formula (Eq. 1) for group delay dispersion (GDD) as a function of wavelength for the compressor using Kostenbauder formalism [6, 7].

$$GDD = -\frac{\lambda}{\pi c^2}\frac{\left[\sin(\phi)+\sin(\psi)\right]^2}{\cos^4(\phi)} \times \left[2L_1\cos^2(\phi) + L_2\left[\cos(\phi)+\cos(\psi)\right]^2\right] \quad (1)$$

Here ψ and ϕ are, respectively, the angles of incidence and diffraction of the central ray of wavelength λ at the first grating measured from grating normal; L_1 is the slant distance from grating 1 to grating 2, and L_2 is the total path traveled by the central ray from grating 2 through the 6-mirror assembly and back to grating 2. We assume that the groove density of gratings 1 and 2 is the same. When L_2=0, the GDD formula reduces to that of a standard two-grating Treacy compressor [8]. The separation of the two gratings in the standard Treacy compressor with the same GDD would be 32 m. Noting that ϕ is a function of wavelength, higher order dispersion terms can be derived. Modifying Eq. 1 by setting $L_2=2(L_f-f)$, where L_f is the distance from grating 2 to the lens and f is the focal length of the lens, computes GDD of the aberration free hyper stretcher. Note, that for a stretcher L_2 is negative and sufficiently large to produce an overall positive GDD.

Chromatic and geometric lens aberrations modify higher order dispersion terms in the stretcher, requiring raytracing for more accurate computation. We use a commercial raytracing software to compute ray paths in the stretcher and in the compressor [9]. Experimentally, we also measure compressor and stretcher dispersion using a recently developed dispersion diagnostic [10]. This device measures group delay as a function of wavelength with subpicosecond accuracy.

The results of the analytical calculation, raytracing, and experimental measurement are summarized in Fig. 3, where GDD is plotted vs wavelength. We calculate the experimental group delay dispersion by first fitting a 4^{th} order polynomial to the group delay data and then taking a 1^{st} derivative of the fitted polynomial. From raytrace analaysis, the GDD for the stretcher is 4300 ps^2/rad, and the TOD/GDD ratio is -115 fs, at the 1064 nm central wavelength; for the compressor, the TOD/GDD ratio is -84 fs. The TOD mismatch would result in a 3% reduction in the temporal Strehl ratio of the compressed pulse. We can match the GDD and the TOD of the stretcher/compressor pair by a 1^o increase of the angle of incidence on gratings 1 and 2 in the stretcher.

The details of our high energy laser system are described separately [11]. The pulses from a mode-locked oscillator are stretched to nominally 5 ns and then amplified to 20 μJ in a chain of Yb^{3+} fiber amplifiers. A commercial Q-switched bulk Nd:YAG laser heads amplify pulses from the fiber chain to 1.3 J, with 800 mJ remaining after pulse recompression. We characterize the compressed pulse temporal profile using multi-shot 2^{nd} harmonic FROG [12, 13]. We use a scanning background free autocorrelator and a 0.01 nm resolution 1 m spectrometer (McPherson Model 2061) to resolve the gain narrowed pulse spectrum. The measured field of the FROG spectrogram is shown in Fig. 4(a). Numerical processing then symmetrizes the trace and removes spurious background and noise. Analysis of the processed trace produces the temporal profile shown in Fig. 4(b). The pulse is slightly asymmetric and contains a small pre-pulse, caused by a small residual TOD mismatch. We calculate that the FWHM is 8.3 ps, with 84% of the pulse energy contained in the 20 ps wide bin indicated by the dashed box, and the temporal strehl ratio is 0.78.

Fig. 5(a) indicates good agreement between the IR pulse spectrum measured by the spectrometer and that obtained from FROG analysis. We calculate the associated spectral phase (Fig. 5(b) after numerically filtering out any pre and post pulses outside a 100 ps window. This eliminates high frequency spectral phase ripple caused by beating of the main pulse with small scale (<1% of peak intensity) satellite pulses. The resulting group delay curve exhibits slow scale modulation which scatters $\approx 16\%$ of the energy in a wide pedestal outside the main peak.

In conclusion, we demonstrated chirped pulse amplification with 0.2 nm bandwidth pulses in Nd:YAG gain medium. Utilizing a novel technique of hyper-stretching and hyper-compression, we generated 750 mJ of 0.2 nm bandwidth pulses compressed to 8 ps. High energy, few picosecond laser systems based on hyper-dispersion allow generation of high brightness, monoenergetic gamma-ray radiation in Compton scattering light sources.

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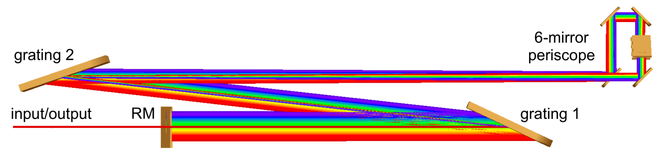


Fig. 1. The compact hyper-dispersion compressor consisting of two 1740 grooves/mm gratings has a footprint of 3 x 0.7 m. Utilizing anti-parallel grating arrangement and path folding, group delay dispersion is -4300 ps^2/rad.

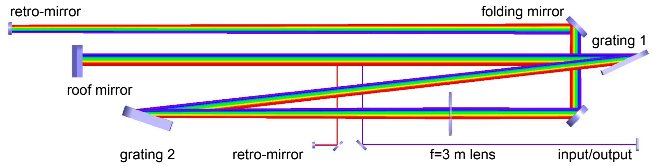


Fig. 2. The compact hyper-dispersion stretcher has the same footprint and grating arrangement as the compressor. The GDD is matched to the compressor by adjusting the distance between grating 2 and the lens.

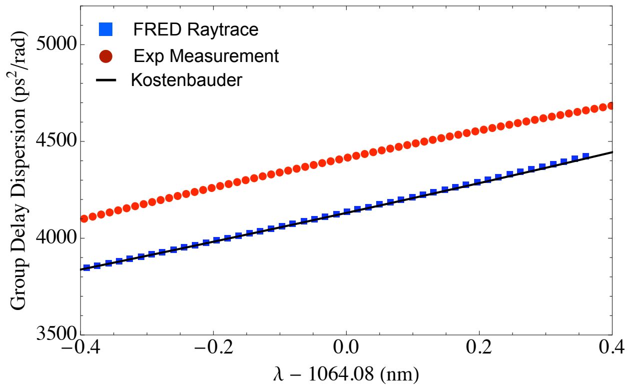
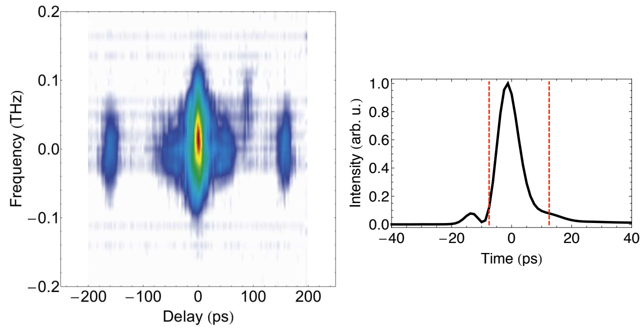


Fig. 3. Group delay dispersion of the stretcher vs wavelength - 1064 nm. Good agreement is shown between Kostenbauder based analytical calculations (black line), raytracing (squares) and the mean of 3 experimental measurements with the group delay diagnostic (circles).



(a) (b)

Fig. 4. Experimental measurement of the 800 mJ pulse duation. (a) Field of the FROG spectrogram. (b) Temporal pulse intensity obtained by analyzing a numerically processed FROG spectrogram. FWHM of the pulse duration is 8.3 ps, and 84% of the energy is contained in the 20 ps bin (dashed box).

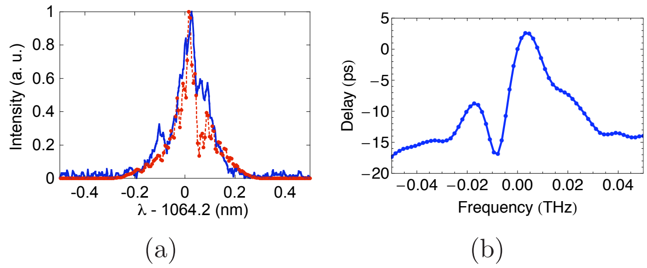


Fig. 5. (a) Pulse spectrum from FROG (red dots) and spectrometer (solid line) measurements. (b) Group delay vs pulse frequency calculated after numerically applying a 100 ps FWHM supergaussian filter.