Dispersion management in the Vulcan OPCPA petawatt laser using a grating-prism compressor

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Abstract

The residual dispersion of femtosecond petawatt lasers can limit their output pulse duration and temporal contrast. We design a pulse stretcher and a grating-prism compressor based on transmission gratings to control the residual dispersion in the VOPPEL CPA system up to the fifth order.

Background

Since their first demonstration in 1999 [1], femtosecond petawatt laser systems have attracted significant attention due to their applications in plasma physics, the generation of bright X-rays or γ-rays, and for compact particle accelerators [2-4]. New petawatt laser facilities have recently been constructed to develop applications in nuclear physics and material science [5]. These applications require extremely high pulse irradiance ($> 10^{21}$ W/m^2) and high temporal contrast ($> 10^{10}$). A challenge for achieving high contrast few-cycle pulses is minimizing the residual dispersion of the CPA system.

There are two common approaches to dispersion management in petawatt lasers up to the fourth order. The first one is based on three degrees of freedom in the pulse stretcher design: the separation distance, the incidence angle and the line density of the gratings [6]. This approach has the drawback of tight tolerance of the amount material dispersion that can be compensated for by fine tuning the stretcher parameters. The second approach overcomes this limitation by matching the dispersions of the pulse stretcher and the main compressor. The residual material dispersion is then compensated for using an additional pulse compressor based on diffraction gratings and prisms [5]. The latter approach has not been demonstrated so far using transmission gratings, which can improve the output temporal contrast of a CPA system when used in the stretcher [7]. Commercially available transmission gratings reach high diffraction efficiency across broad spectral bandwidth only when having a large line density and operating them close to the Littrow angle. A problem is that the comparatively small material dispersion then imposes impractically small distances between the optical components in the additional compressor.

In this report we combine these approaches by designing a pulse stretcher and an additional grating-prism compressor both based on transmission gratings for the Vulcan OPCPA petawatt laser [8]. The additional compressor has four times the GDD of the material dispersion. The sum of their dispersion is then compensated for by fine tuning the stretcher grating line density, incidence angle and separation distance. The calculated CPA output pulse duration of 16 fs and temporal contrast are not affected by the residual dispersion.

Design work

We use Zemax OpticStudio to calculate the overall dispersion of the CPA system by dividing it into modules and calculating their dispersion at central wavelength of 888 nm (Fig. 1). The dispersion of the ps OPCPA, the ns OPCPA and the main compressor dispersion is considered as fixed. Our goal is to design the Öffner stretcher and the additional compressor, so that the residual dispersion has negligible effect on the CPA output pulse duration and temporal contrast.

The optimized parameters of the transmission gratings in the stretcher and the additional compressor are the same: line density of 1113 lines/mm and incidence angle of 29.56°. The line density is close to the effective line density of the gratings in the main compressor: 1117 lines/mm taking into account the out-of-plane angle of 10°. The incidence angle is close to the Littrow angle for the central wavelength and close to the incidence angle in the main compressor. The diffraction efficiency calculated by the grating manufacturer is high and smooth across the operational spectral range between 780 nm and 990 nm (Fig. 2).

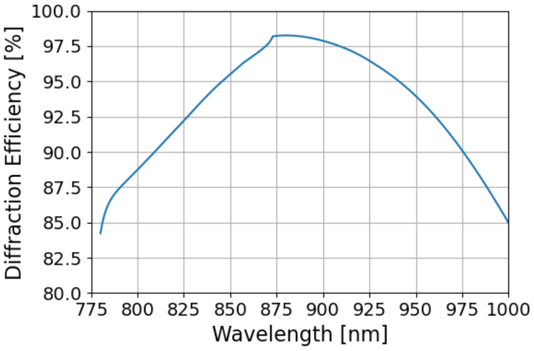

Fig. 2: Diffraction efficiency as function of wavelength calculated by the grating manufacturer

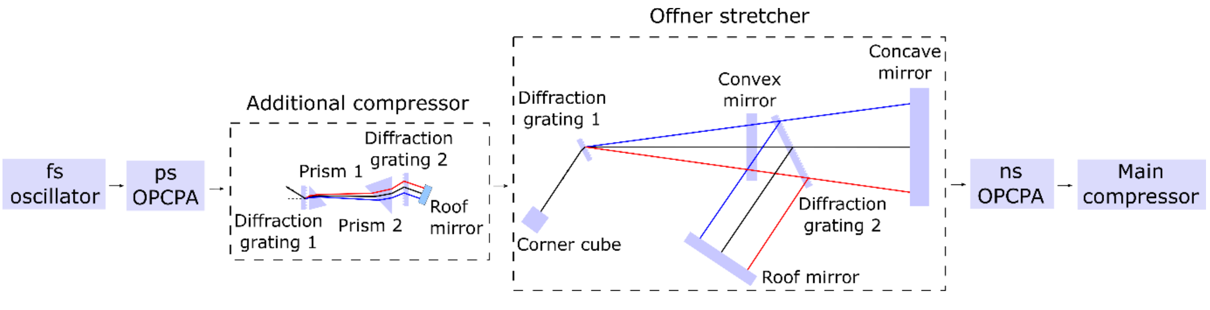

Fig. 1: Vulcan OPCPA petawatt laser system: block diagram

The radii of curvature of the concave mirror and the convex mirror are 1600 mm and -800 mm, respectively. They are large enough to minimize the effect of the aberrations on the residual angular dispersion and the residual spatial chirp. The grating separation distance is 998 mm along the central wavelength beam. A corner cube is used for a second pass through the stretcher. Thus, the effective grating separation of 1996 mm is close to the one in the main compressor.

The grating-prism additional compressor has a flexible dispersion due to its degrees of freedom such as prism material, prism apex angle and the prism separation distance. We choose these parameters to be fused silica, 46° and 40 mm along the beam, respectively, so that the residual dispersion in the CPA system is minimum (Table 1 and Fig. 3). The GDD magnitude of the grating-prism compressor is around four times the one of the material dispersion. This allows for more practicable distances between the optical components in the additional compressor. The tolerance of material dispersion of ±100%, significantly larger than the expected error during the CPA design process.

Table 1: Calculation of the residual 2nd, 3rd, 4th and 5th order dispersion in the CPA laser system

Dispersion source	**GDD [fs^2]**	**TOD [fs^3]**	**FOD [fs^4]**	**FiOD [fs^5]**
Optical material	$6.5 * 10^4$	$5.6 * 10^4$	$-1.5 * 10^4$	$7.5 * 10^4$
Main compressor	$-7.74 * 10^6$	$1.78 * 10^7$	$-6.15 * 10^7$	$3.01 * 10^8$
Stretcher	$7.93 * 10^6$	$-1.82 * 10^7$	$6.25 * 10^7$	$-3.04 * 10^8$
Grating-prism compressor	$-2.51 * 10^5$	$2.94 * 10^5$	$-9.95 * 10^5$	$3.45 * 10^6$
Residual	120	-25	$-5.6 * 10^4$	$2.2 * 10^5$
|Residual: required|	< 150	$< 2 * 10^3$	$< 10^5$	$< 2 * 10^6$

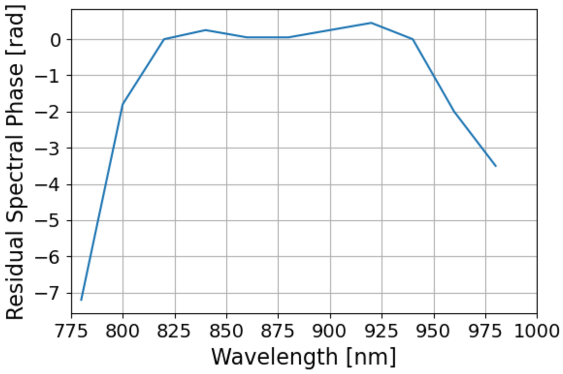

Fig. 3: Residual spectral phase as function of wavelength

The calculated temporal contrast and pulse duration of the CPA output is not affected by the residual dispersion (Fig. 4). The pulse duration is 16 fs at FWHM, corresponding to five optical cycles at the central wavelength.

Conclusions

In conclusion, we minimize the residual dispersion of the VOPPEL CPA system up to the fifth order, not affecting the output pulse duration of 16 fs and the temporal contrast. We use an additional grating-prism compressor whose flexible dispersion increases the tolerance of material dispersion to ±100%. We expect the transmission gratings used in both the stretcher and the additional compressor to further improve the temporal contrast. The gratings have high diffraction efficiency across the operational spectral range due to their large enough line density and Littrow incidence angle.

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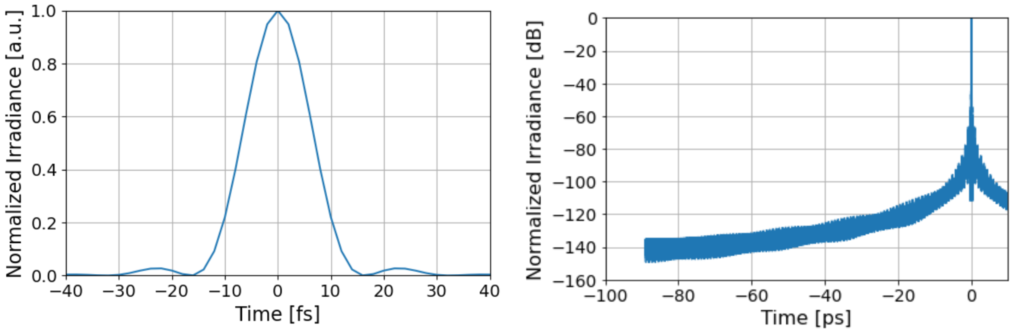

Fig. 4: Calculated output pulse duration (left) and temporal contrast (right)