Continuous distributed phase-plate advances for high-energy laser systems

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Abstract. The distributed phase plate (DPP) design code Zhizhoo’ has been used to design full-aperture, continuous near-field transmission optics for a wide variety of high-fidelity focal-spot shapes for high-energy laser systems: OMEGA EP, Dynamic Compression Sector (DCS), and the National Ignition Facility (NIF). The envelope shape, or profile, of the focal spot affects the hydrodynamics of directly driven targets in these laser systems. Controlling the envelope shape to a high degree of fidelity impacts the quality of the ablatively driven implosions. The code Zhizhoo’ not only produces DPP’s with great control of the envelope shape, but also spectral and gradient control as well as robustness from near-field phase aberrations. The focal-spot shapes can take on almost any profile from symmetric to irregular patterns and with high fidelity relative to the objective function over many decades of intensity. The control over the near-field phase spectrum and phase gradients offer greater manufacturability of the full-aperture continuous surface-relief pattern. The flexibility and speed of the DPP design code Zhizhoo’ will be demonstrated by showing the wide variety of successful designs that have been made and those that are in progress.

1. Introduction
The symmetric-direct-drive (SDD) and polar-direct-drive (PDD) configurations utilized in inertial confinement fusion [1,2] (ICF) driven by high-powered lasers require target illumination that conforms to the design shape or objective with a high degree of fidelity. Nonuniformity in the lower spherical-harmonic $\ell$ modes can have a significant impact on ICF-target performance since these modes imprint for the longest period of time and are the most difficult to smooth.

Continuous phase plates are used in SDD and PDD ICF applications because they offer control of the far-field intensity envelope in the presence of typical laser system phase aberrations. The resultant time-averaged, far-field spot intensity has a well-controlled shape. The goal is to design phase-dislocation-free continuous phase plates that produce a speckled far field whose envelope and spectrum are controlled, unaffected by system aberrations and speckle that can be smoothed.

The following report describes a novel DPP design process that achieves higher fidelity to the design objectives relative to existing methods. The novel DPP design code is called Zhizhoo’ and is capable of producing a continuous phase-dislocation–free DPP with low near-field modulation that achieves <1 to 2% weighted $\sigma_{rms}$ error of the far-field spot shape in a few minutes on a multicored personal computer with optional GPU accelerations.

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The versatility of the Zhizhoo’ design technique is evident in its ability to craft far-field envelopes from simple super-Gaussian to rather arbitrary shapes [3]. The phase-plate design techniques presented here can be applied to phase plates with or without constraining the far-field power spectrum to lower spectral power in the long-wavelength band. The ability of this technique to calculate phase-dislocation-free continuous phase plates is closely linked to maintaining a correlation with the speckle pattern and minimizing the phase gradient [3]. Various phase-plate designs will be presented for a few high-power laser systems that highlight the various capabilities of Zhizhoo’.

2. Zhizhoo’ DPP design tool

The MATLAB-based tool Zhizhoo’ [3,4] crafts continuous DPP’s; the salient features are outlined here:

(a) Employs feedback loop: Unlike other methods currently in use, Zhizhoo’ employs a novel feedback technique as a fundamental tool to generate DPP profiles with tight control of the resultant far-field spot shape and phase plate; e.g., far-field shape, arbitrary azimuthal and radial variations, DPP phase gradient, DPP phase spectral control, and phase anomaly-free designs [3]. The algorithm employs a highly modified Fienup-type algorithm as part of the whole feedback loop [5,6]. The overall novel technique is unique in its approach and it is very fast due to the feedback (that distinguishes Zhizhoo’ as it hastens convergence via augmentation) and the FFTW-based methods [7]. In addition, a robust phase-unwrapping algorithm is employed that solves Poisson’s equation in the least squares sense (algorithm adapted from Ref. [8]).

(b) Designs far-field envelopes from simple super-Gaussian to rather arbitrary shapes: Simple or exotic far-field envelope shapes are effortlessly handled with Zhizhoo’. Wide design objectives and/or steep profiles will require correspondingly higher surface or phase gradients in the DPP. Zhizhoo’ can maintain envelope control even down to the ~1% $\sigma_{\text{rms}}$ level.

(c) Uses an optimal filter: An important aspect of the Zhizhoo’ feedback-loop is the Wiener or optimal filter [3]. The Wiener filter employs the well-known speckle statistics from Goodman [9,10] to model the speckle “noise” to create an optimal filter that accurately extracts the true envelope shape.

3. Zhizhoo’ intermediate NIF polar-direct-drive distributed phase-plate designs

The NIF PDD asymmetric far-field spot design objective is an ideal candidate to test the shape control capabilities of Zhizhoo’. The NIF PDD asymmetric spot shape is a composite spot consisting of a primary super-Gaussian plus an offset secondary ellipse that is modulated by an offset aperturing function referred to as “spot-masking apodization” (SMA). The asymmetric far-field spot objective for NIF PDD cannot be considered an ellipse nor can it be accurately represented as a distorted ellipse. The 43 $\times$ 43-cm sq-aperture intermediate NIF PDD design for one of the equatorial spots is shown figure 1(a) and the resultant speckled spot in figure 1(b). The effect of SMA is clearly observed in figure 1(b), where the over-the-horizon portion of the spot is occluded.

Figure 1. The intermediate NIF polar-direct-drive (PDD) DPP design crafted for (a) an equatorial beam profile and (b) the resultant speckled. The speckled image on the log scale demonstrates the remarkable speckle rejection and smooth profile at low intensity not obtainable using other methods. Note that the design objective function and the extracted envelope are nearly indistinguishable at <1% rms (root mean square) error.
It is crucial to the success of NIF PDD experiments that the DPP design prepared for the manufacturing process be as close as possible to the design objective. Otherwise, the far-field spot integrity severely degrades in the presence of both manufacturing phase error (MPE) and near-field wavefront error (WFE). A DPP design that initially has the highest integrity level will remain more intact, relative to an insufficient design. NIF’s WFE was measured and imposed upon the DPP’s for a worst-case analysis via DRACO hydrodynamic simulations. The strongest NIF WFE was a weaker aberration than a 25-µm-rms MPE that set the acceptable MPE tolerance to 25-µm rms.

During the NIF PDD (intermediate and ignition-scale) DPP design process, a potential manufacturing problem surfaced. The issue was the result of a combination of interferometric measurements and the machine’s internal phase-unwrapping algorithms. The resulting unwrapped phase would produce areas of phase dropouts and occasionally large regions of π discontinuities. However, the phase-unwrapping procedure incorporated within Zhizhoo’ is designed to be immune to areas of noise and regions of π discontinuities. It was demonstrated that the phase-unwrapping algorithm was more than capable of removing and correcting the corrupted phase data from the instrument11. Utilizing the phase-unwrapping algorithm from Zhizhoo’ is a cost-effective remedy to procuring expensive interferometers. The algorithm is able to correct the phase errors from the intermediate energy-scale up to the ignition-scale designs.

4. Steep-profile, low-ripple flattop round spots
Low-ripple, flat-topped spots with steep profiles are additional design objectives compatible with the Zhizhoo’ DPP design method. Traditionally, DPP’s have difficulty designing for low-ripple, flattopped spots because the designs tended to ring as the spot shape rolls off to zero. In contrast, Zhizhoo’-crafted DPP’s tend not to suffer the same fate because of the feedback control with augmentation of the design profile.

The OMEGA EP laser required a redesign for its 1.8-mm-wide spot because of damage that the turning mirror suffered from high-level modulation caused by a retroreflection back through the focusing lens. The close proximity of the turning mirror posed a design challenge for Zhizhoo’ by mandating wavelength control of the DPP’s feature size. The design for the far-field envelope demanded a large flat area with a fast roll-off. The low-ripple (2.5%) resultant extracted envelope is shown in figure 2(a). The equivalent free-space back-propagation was determined to be 6m, which drove the DPP design to use large feature sizes to minimize near-field modulations; see figure 2(b). The larger feature sizes had the side effect of driving up the peak-to-peak phase depth of the DPP because of the smaller bandwidth distribution of the phase that also increases local phase gradients.

Figure 2. (a) The OMEGA EP low-ripple, 1.8-mm-wide far-field extracted envelope. (b) The resulting near-field low-level modulation from a retroreflection is indicative of the large DPP feature sizes.

The Dynamic Compression Sector (DCS) laser also required a low-ripple, flattopped spot, but with two additional attributes: decreased mid-range wavelength control (high pass) and flexible spot-shape control via dispersion control. The high-pass DPP design procedure was similar to the method
reported in Ref. [3] and successfully reduced the power in the long- to mid-wavelength modes, even in the presence of predicted DCS WFE [see figure 3]. The DCS DPP design provides a trade-off among several smoothing attributes, including spot shape and intensity on target by adjusting a differential grating that changes the dispersion experienced by the 1-D, mFM SSD system [12].

Figure 3. The far-field speckled spot spectrum for the DCS Laser System. The Goodman speckle model is shown as a reference to indicate the ability of the high-pass DPP design to modify the far-field spot’s spectrum (blue trace). In the presence of predicted DCS laser WFE, the high-pass DPP design still maintains a decreased spectrum over the spectral band (red trace). DCS: Dynamic Compression Sector; WFE: wavefront error.

5. Conclusion
The continuous phase-plate design code Zhizhoo’ is capable of crafting DPP’s for a variety of high-power laser systems, each having different design constraints. Zhizhoo’ designs continuous DPP’s with simple envelope shapes or exotic shapes with asymmetry. The code Zhizhoo’ crafts DPP’s with a high degree of fidelity to the design objective. A higher-fidelity DPP design results in a more-faithful representation of the desired objective function when the DPP is subjected to WFE and MPE. The flexibility of the Zhizhoo’ design code makes it easy to create multiple designs, even when the design requirements change, because Zhizhoo’ can respond in a short period of time or produce multiple realizations to improve beam-overlap nonuniformity reduction.

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