Continuous Distributed Phase-Plate Advances for High-Energy Laser Systems

Introduction

The symmetric-direct-drive (SDD) and polar-direct-drive (PDD) configurations utilized in inertial confinement fusion[1,2] (ICF) driven by high-power lasers require target illumination that conforms to the design shape or objective with a high degree of fidelity. Nonuniformity in the lower spherical-harmonic ℓ 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.

This article describes a novel distributed phase plate (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 a <1% to 2% weighted σ_{rms} error of the far-field spot shape in a few minutes using a multicored personal computer with optional GPU accelerations.

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*'.

Zhizhoo' DPP Design Tool

The *MATLAB*-based tool *Zhizhoo*'[3,4] crafts continuous DPP's; the salient features of *Zhizhoo*' are as follows:

(a) Employs a 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 technique is novel in its approach and is very fast because of the feedback (which 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% σ_{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.

Zhizhoo' Intermediate NIF Polar-Direct-Drive Distributed Phase Plate Designs

The National Ignition Facility's (NIF's) 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 × 43-cm-sq–aperture intermediate NIF PDD design for one of the equatorial spots is shown in Fig. 146.19(a) along with the resultant speckled spot in Fig. 146.19(b). The effect of SMA is clearly observed in Fig. 146.19(b), where the over-the-horizon portion of the spot is occluded.

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's 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 beamline WFE was a weaker aberration than a 25-μm-rms (root-mean-square) MPE, setting the acceptable MPE tolerance to 25-μm rms.

During the NIF's 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 instrument.[11] Utilizing the phase-unwrapping algorithm from *Zhizhoo*' is a cost-effective alternative to procuring expensive interferometers. The algorithm is able to correct the phase errors from the intermediate energy scale up to the ignition-scale designs.

Steep-Profile, Low-Ripple, Flattoped Round Spots

Low-ripple, flattopped spots with steep profiles are additional design objectives compatible with the *Zhizhoo*' DPP design method. Traditionally, DPP's have had difficulty designing 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.

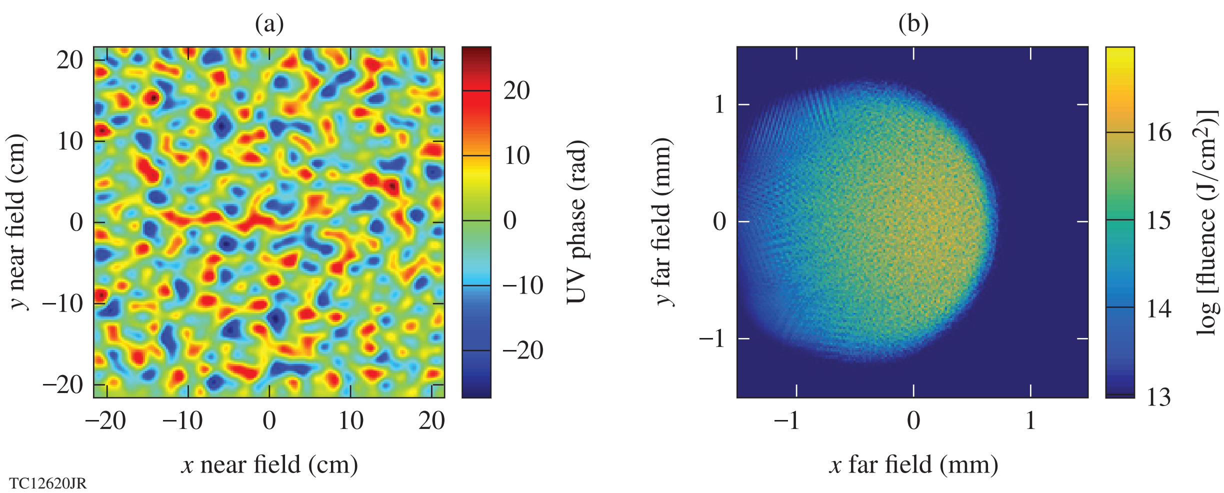

Figure 146.19
The intermediate NIF polar-direct-drive (PDD) distributed phase plate (DPP) design crafted for (a) an equatorial beam profile and (b) the resultant speckled spot. The speckled image on the log scale demonstrates the remarkable speckle rejection and smooth profile at low intensity not obtainable using other methods. Note that the design objective function and the extracted envelope are nearly indistinguishable at a <1% rms (root-mean-square) error.

The low-ripple (2.5%) resultant extracted envelope is shown in Fig. 146.20(a). The equivalent free-space back-propagation was determined to be 6 m, which drove the DPP design to use large feature sizes to minimize near-field modulations [see Fig. 146.20(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, which also increased local phase gradients.

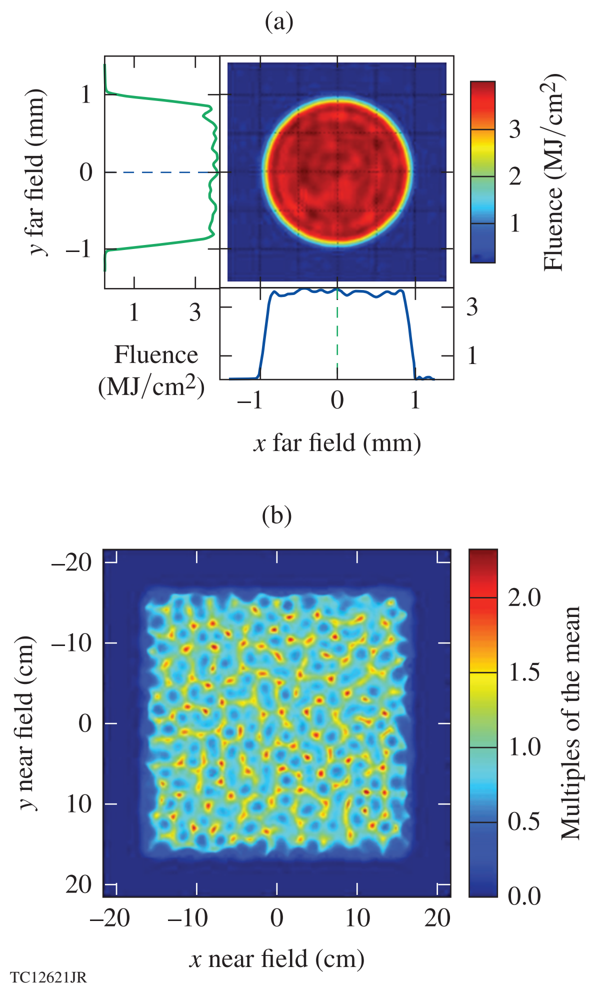

Figure 146.20
(a) The OMEGA EP low-ripple, 1.8-mm-wide far-field extracted envelope. (b) The resulting near-field low-level modulation from a retroreflection is indicative of the large DPP feature sizes.

The Dynamic Compression Sector (DCS) laser also required a low-ripple, flattopped spot but with two additional attributes: decreased mid-range spectrum (high pass) and a flexible spot shape via dispersion control. The high-pass DPP design procedure, similar to the method reported in Ref. 3, successfully reduced the power in the long- to mid-wavelength modes, even in the presence of predicted DCS WFE (see Fig. 146.21). 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, multi-FM smoothing by spectral dispersion system.[12]

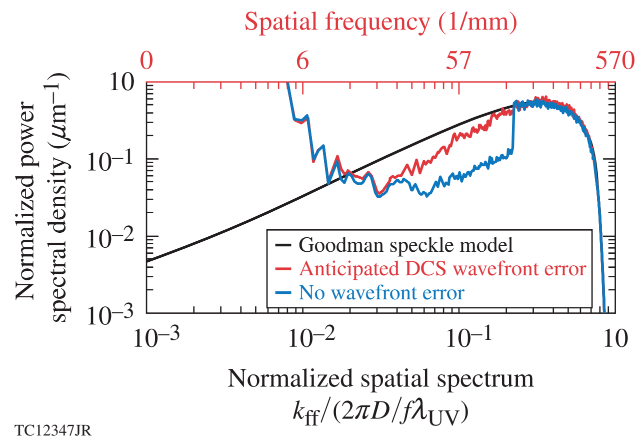

Figure 146.21
The far-field speckled spot spectrum for the DCS Laser System. The Goodman speckle model is shown as a reference to indicate the ability of the high-pass DPP design to modify the far-field spot's spectrum (blue curve). In the presence of predicted DCS laser WFE, the high-pass DPP design still maintains a decreased spectrum over the spectral band (red curve). DCS: Dynamic Compression Sector; WFE: wavefront error.

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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