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Phase Screens for the Control of the Focal Irradiance of the Nova Laser

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ABSTRACT

We report on the design and fabrication of continuous contour (kinoform) phase plates for homogenizing the focal plane irradiance of high-power, inertial confinement fusion laser systems. These kinoform phase plates are designed using an iterative algorithm. They offer the flexibility of controlling the overall shape of the far-field irradiance profile and the ability to concentrate the energy within a central region of the focal profile. These properties make kinoforms superior to the conventional, binary random phase plates for many applications. Potential methods for fabrication of such kinoform phase plates are discussed.

2. INTRODUCTION

Binary random phase plates (RPP) have proven valuable in homogenizing the focal plane irradiance profiles of high energy laser systems used in inertial confinement fusion (ICF).[1-5] The binary random phase plates consist of a regular array of regions which are randomly selected to introduce either a 0 or π phase shift to the laser beam. This scrambles the phase coherence of a laser beam and produces a homogenous focal irradiation spot consisting of an overall envelope determined by a single phase plate element and a superimposed fine-scale speckle created by the interference of the fields generated by all the elements. We have made RPP's with good damage resistance by selectively etching away a layer of sol-gel material on a fused silica substate.[4,5] We can control the height of the phase step by controlling the thickness of the sol-gel layer, while we can control the steepness of the transition between the on-off regions somewhat by the choice of etching conditions. We have produced RPP's of various sizes up to 80 cm in diameter with a step height error less than 5% and transition regions on the order of 15 μm[5].

Although the binary RPP's are widely used in ICF applications world-wide, the focal plane intensity profiles produced by the RPP's have major limitations. Since the far-field envelope has a fixed profile (similar to an Airy pattern) determined by a single RPP element, the central maximum of such a profile contains only about 81-84% of the incident energy. This limitation arises from the abrupt, discrete nature of the phase steps. For ICF applications, energy concentrated outside of the central focal region results is lost and is not available for irradiating a target.

One approach to avoiding this type of energy loss is to create random phase patterns whose phase profiles do not contain abrupt, high spatial frequency steps. We refer to these smoothly varying phase screens as kinoforms. For random phase screens, the statistics of the phase variations governs the optical transfer function to the far field.[6] In particular, the behavior of the point spread function for phase screens with large phase variance implies that kinoforms with large phase variations governed by smooth, gaussian statistics would be useful in producing focal irradiances with smooth, gaussian profiles. A less mathematical, more intuitive picture of kinoforms involves picturing the phase screen as a series of wedges or prisms. Locally, these wedges steer the focal intensity away from the central optical axis. By properly choosing the distribution of these wedges, we can construct any given focal irradiance profile.

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In this paper we briefly discuss the design and fabrication of such kinoform phase plates for ICF applications. A robust, iterative design algorithm is discussed in the following section which allows us to construct the phase screen for producing any desired focal plane irradiance profile containing greater than 95% of the incident energy. Subsequent sections discuss our approaches to manufacturing and preliminary results.

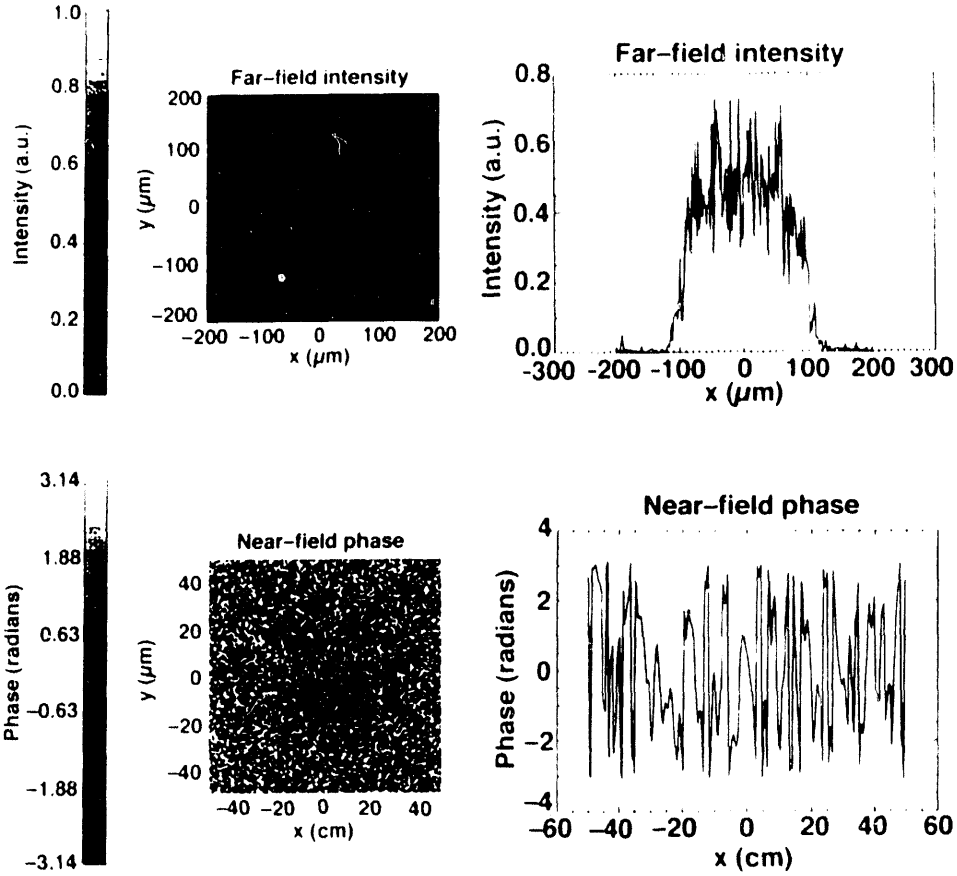


Figure 1. Far-field intensity profile (top) and the profile of the knioform phase plate (bottom) obtained using the iterative KPP design algorithm. Horizontal line-scans through the center of these profiles are shown on the right

3. SPECIFICATION OF THE CONTINUOUS PHASE PATTERN

In contrast to both the RPP[1] and lenslet[7] approaches to beam smoothing where the focal irradiance profile is largely governed by the shape of individual cells or lenslets, the kinoform approach relies on the proper statistical distribution of phase tilts to create the focal irradiance pattern. The difficulty arises in determining a phase screen which has the appropriate statistical properties. The basic question becomes: is it possible to construct a phase screen in the input plane which, for a given intensity distribution, produces the desired focal irradiance pattern? (For our purposes here, we are concerned primarily with the far-field intensity envelope. The details of the speckle pattern inside the envelope are not of interest.) It seems that no general mathematical proof exists of the existence and/or uniqueness of the solution to this problem. However, we can pose the problem such that an iterative solution can be found which satisfies our requirements. Iterative algorithms have been developed to construct solutions for a wide range of problems in image recovery and synthesis, speckle interferometry, beam profile manipulation for microwave plasma heating, designing diffractive optical elements, etc. We have implemented such an iterative algorithm for constructing kinoforms for tailoring the focal intensity distribution of the Nova beam.

The iterative algorithm we use for designing kinoforms consists of repeatedly Fourier transforming between the near-field and far-field profiles of a beam with constraints on the qualities of the profiles imposed at each step. Since we are not interested in the phase distribution of the focal spot, we can leave this as a free parameter. Thus, we transform between the near-field and far-field, keeping the values of the phase which were calculated by the FFT and constraining the intensity to have the desired profile. We repeat the iteration until the focal irradiance profile meets our requirements for the amount of energy concentrated in the focal region. We have implemented this algorithm using FFT techniques on a 256 x 256 grid. We tested the effect of the limited grid size by imbedding the resultant pattern on a 512 x 512 grid and comparing the performance of the kinoform.

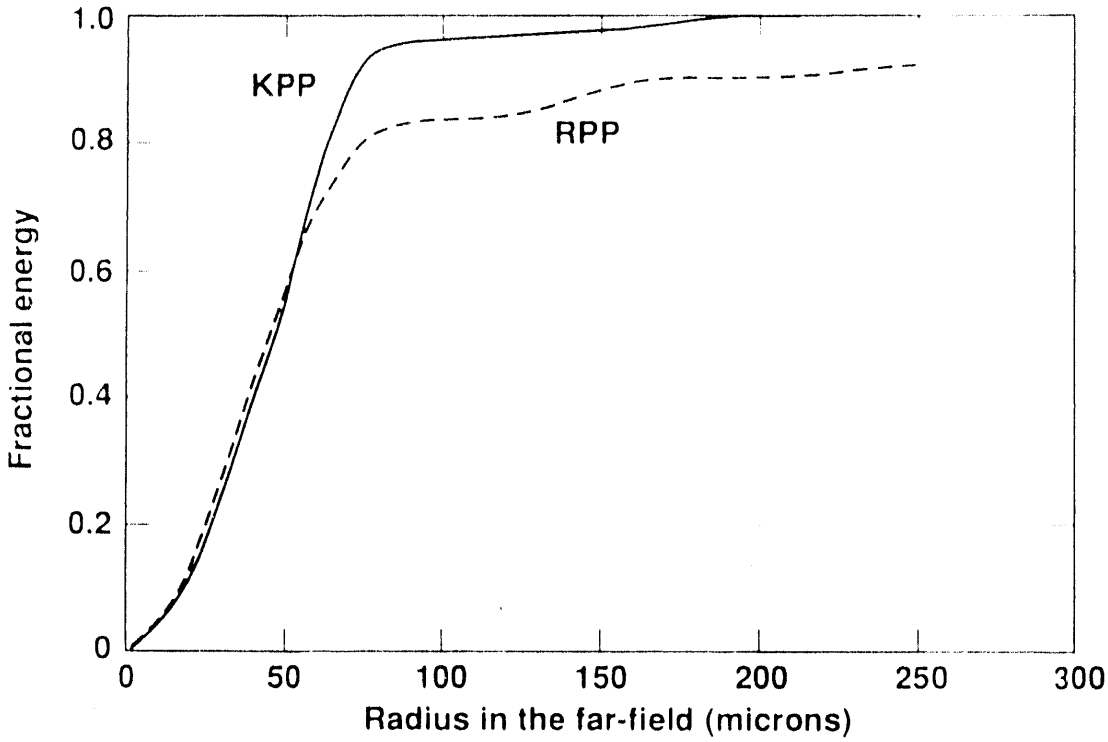


Figure 2. Comparison of the energy contained inside a circle of a given radius in the far-field pattern produced by a KPP and by an RPP. The RPP cell size was chosen so as to give the same size central spot as that produced by the KPP.

We have determined phase screens which produce supergaussian focal irradiance profiles when illuminated by an uniform supergaussian input beam(Fig. 1). Our simulations indicate that the dominant part of the convergence is achieved after only a few iterations of the algorithm. The resulting phase screen is fairly smooth except for the 2π discontinuities which arise from the numerical nature of the algorithm. Currently, we are working on unwrapping these jumps in phase. These discontinuities place more stringent requirements on the fabrications of phase gradients than we believe is necessary. Figure 2 compares the energy contained within a circle of a given radius for the kinoform phase plates and for binary random phase plates that produce a far-field spot with the same diameter as the kinoform phase plate. The focal profiles produced by the KPP contain over 95% of the beam's intensity inside the central focal region and therefore demonstrate the superiority of the KPP's over the RPP's.

We have also tested the effect of typical beam aberrations on the performance of a specified kinoform. The focal plane field distribution of the kinoform in the presence of intensity and phase aberrations is the convolution of the focal spot arising from the aberrated beam with the focal spot produced by illuminating the kinoform with a perfect beam. When the beam aberrations result in a focal spot which is considerably smaller than that produced by the KPP in the absence of beam aberrations, the overall spot size and the energy content therein remain approximately same as for the unaberrated beam. In this case, the focal irradiance profile is essentially determined by the phase structures present in the phase screen. However, the intensity distribution within the far-field spot becomes more modulated ("speckly").

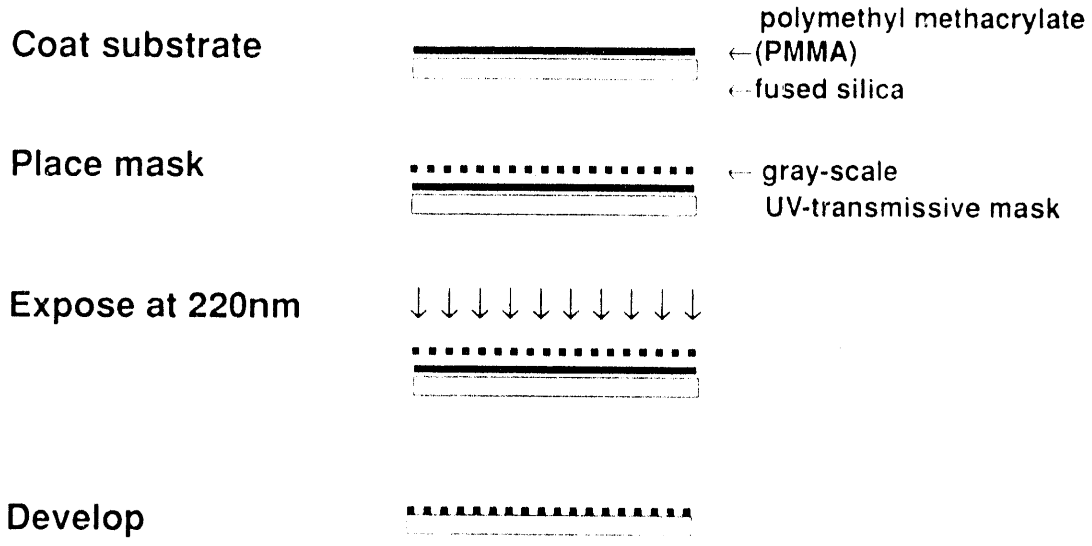


Figure 3. Schematic diagram of the photolithographic process for recording the phase pattern into a thin layer of poly-methyl methacrylate (PMMA) polymer coating.

4. APPROACH TO MANUFACTURING

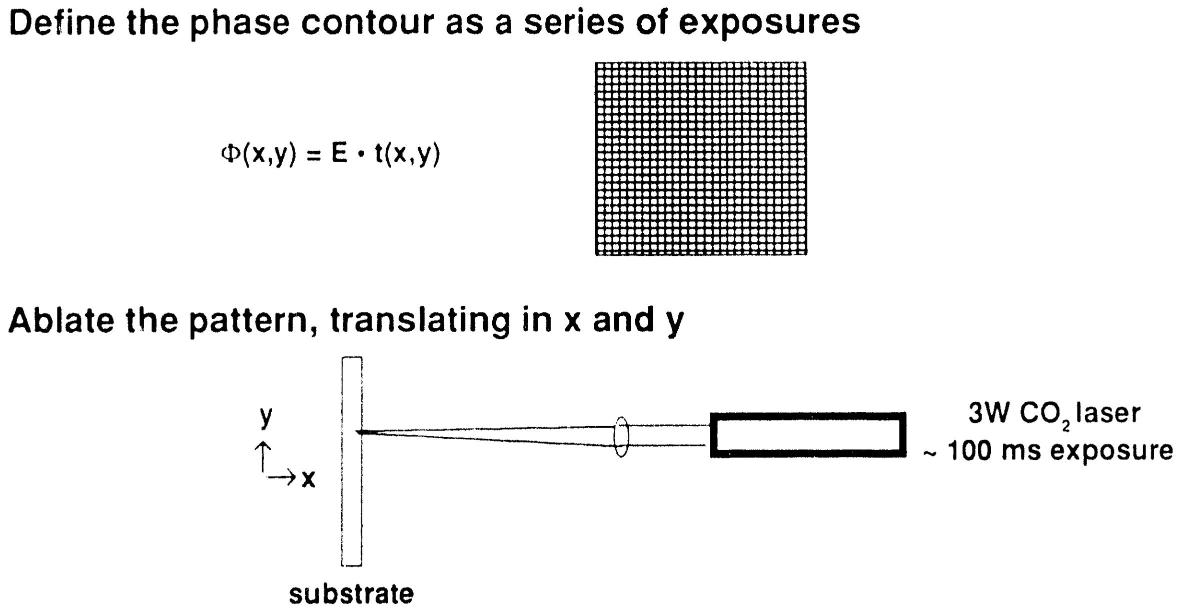
Kinoforms have been manufactured on small optics for a variety of applications, but do not have the damage resistance required for high energy applications. The technique which we have used[5] to create high damage threshold, binary patterns cannot be readily applied to this problem partly due to the rapid etch rate of the sol-gel. We have developed new relatively low-cost approaches which have the potential for producing high damage resistance kinoforms.

Previous methods of producing kinoforms generally involve exposure of a photoresist coating applied to a substrate. Development of the photoresist leaves a layer of material whose thickness varies inversely proportional to the exposure fluence. This layer of material serves either as the phase pattern or as a resist for subsequent reactive ion etching into the substrate. Phase patterns based on the developed resist suffer from absorption and subsequent damage when irradiated with high energy, ultraviolet (UV) light. Phase patterns based on reactive ion etching may be an option in producing high-damage threshold KPP's, but facilities are not readily available with the large, extremely uniform ion etching chamber required for the production of large optics.

We have currently focused on two simple techniques which are designed to give high damage resistance, even at UV wavelengths, at a modest cost and with the capability for large aperture optics.

The first technique we are attempting involves recording a phase pattern into a polymer coating. Tests of micron thick poly-methyl methacrylate (PMMA) polymer coatings on fused silica have demonstrated damage thresholds of up to 5 J/cm^2 for 1 ns, 350 nm light. These polymeric materials act as deep-UV photoresists for exposure with $\lambda < 220$ nm.[8,9]

The phase pattern can be recorded into the polymer coating using either contact-printing techniques with UV-transmissive masks or direct-writing techniques using excimer lasers. We are concentrating on the contact mask approach to deep-UV photolithography (Fig. 3). In this approach, we coat a substrate with a thin layer of PMMA. We then expose the polymer layer to deep-UV light through a gray-scale mask. Photo-chemical reactions take place that change the density in the regions exposed to the radiation. A subsequent development in the appropriate solvent results in a differential removal rate between the exposed and unexposed regions. Proper selection of a gray-scale mask then results in the desired phase contours.


Define the phase contour as a series of exposures

Ablate the pattern, translating in x and y

Figure 4. Schematic diagram of the CO$_2$ ablation process for recording the phase pattern directly into the fused silica substrate.

In the second technique, rather than applying a layer of varying thickness to a substrate, we remove a portion of the substrate in order to produce a phase pattern. We have explored this approach (figure 4) using CO$_2$ radiation to ablate fused silica in a controlled fashion. The 10.6 μm radiation is absorbed on the surface of the substrate, rapidly heating the material above the volatilization point.[10,11] If a small volume of material is removed, recondensation is not a serious problem. The hole left behind is in the characteristic shape of the irradiating spot and is generally free from both surface cracks and contaminants. As a result, the pattern demonstrates high optical quality and comparable damage resistance to the rest of the substrate. The depth of the ablation can be controlled by limiting exposure times. Thus, using a direct-writing method, arbitrary phase patterns can be constructed.

5. EXPERIMENTAL RESULTS

In order to demonstrate deep-UV photolithography, a coating of 1.0 μm optical depth of PMMA was deposited onto a fused silica substrate. Sections of the coating were masked by a metal mask and the optic was exposed to light from a xenon-mercury arc lamp. A significant portion of the light from such a source falls in the 185-250 nm wavelength region. The results are encouraging. After development in a methyl isobuthyl ketone solution, the height of the remaining PMMA was inversely proportional to the exposure fluence. The height was measured by both a phase-stepping interferometer and a contact profilometer. The PMMA exhibits excellent patterning resolution. Binary patterns could be easily resolved down to 50 line pairs per mm without special care in the illumination angles and coupling of the mask and substrate.

Currently, we are developing methods of producing variable density masks which will transmit the deep-UV required for exposures. Conventional gelatins used in photographic films and plates are not useful due to their strong absorption of wavelengths less than 250 nm. Substitution of a different type of emulsion should result in a usable deep-UV mask.

We have also demonstrated the production of a phase pattern on a fused silica substrate by focusing the output of a low-power (5 watt) CO_2 laser onto the substrate (Fig. 4). Focal spot sizes used ranged from 25 to 600 μm in diameter. The amount of material removed was controlled by limiting the exposure time. (Exposures are typically on the order of milliseconds.) This produced pit depths which varied linearly with exposure. Currently, we are developing procedures for producing complex phase patterns using the ablation technique. We are studying the consequences of writing the continuous contours as a series of discrete exposures. Care must be taken in order that the spatial frequency associated with the spacing of the multiple exposures does not appear in the finished contour, or alternately, does not result in a significant portion of the energy of the beam being diffracted away from the central focal region.

6. ACKNOWLEDGMENT

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