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**Synthesis of Fully Continuous Phase Screens for Tailoring
the Focal Plane Irradiance Profiles**

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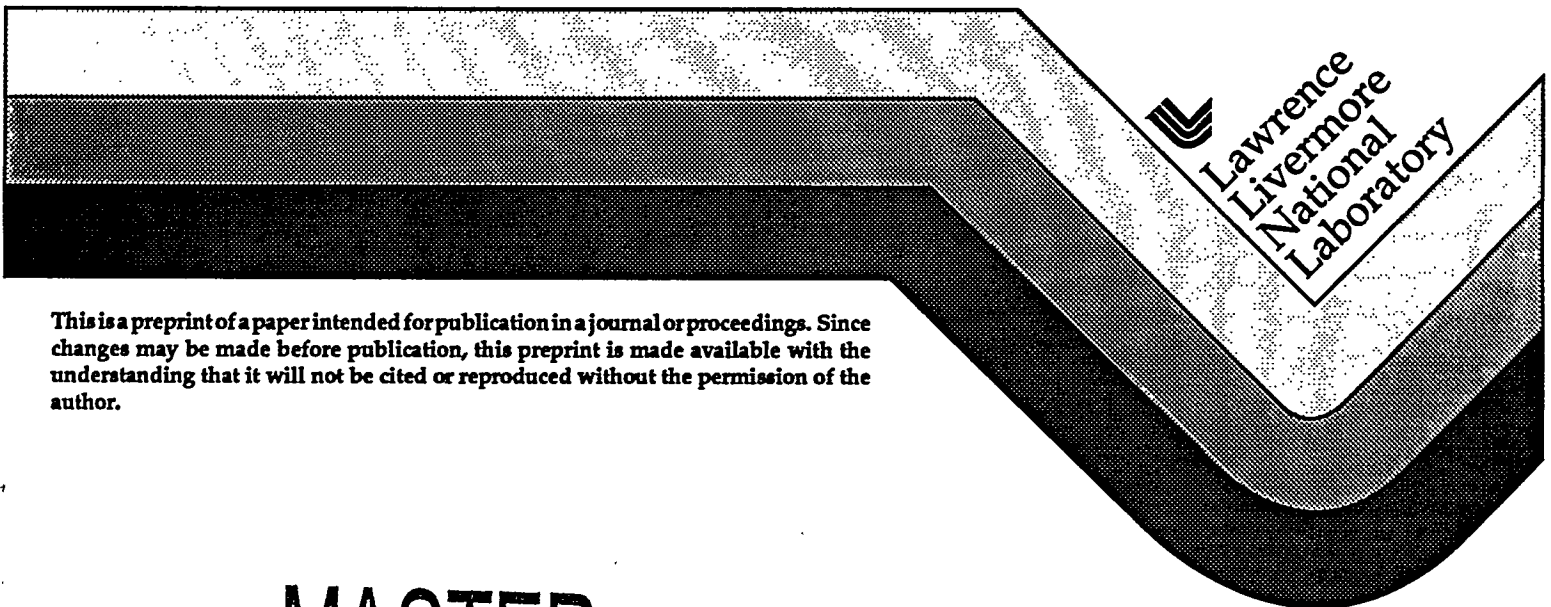
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**Synthesis of fully continuous phase screens for tailoring the focal plane
irradiance profiles**

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ABSTRACT

We present an iterative procedure for constructing fully continuous phase screens for tailoring the focal plane intensity distributions. This algorithm alleviates the stagnations experienced in the application of the Gerchberg-Saxton algorithm with a random initial phase screen and leads to efficient distribution of the incident energy into the desired focal plane profile.

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In laser driven inertial confinement fusion systems, it is desirable to produce smooth focal plane intensity profiles [1]. Traditionally, binary random phase plates (RPPs) have been used to produce a focal plane irradiance profile which consists of a smooth Airy function shaped envelope and a superimposed fine scale speckle pattern. The speckle is smoothed by conduction smoothing in the laser produced plasma and/or by externally imposed temporal smoothing methods. Although easy to fabricate and use, the RPPs have very limited flexibility in producing arbitrary shaped irradiance profiles. In addition, the secondary maxima of the Airy profile lead to a 15% loss of the energy from the desired region in the focal plane. This loss of the laser energy requires the operation of the fusion lasers at higher energies thereby increasing their cost of operation. Additionally the scattered energy could also cause optical damage to detection equipment near the target.

In order to overcome these limitations of the RPPs, we have recently proposed [2] new phase plate designs for producing arbitrary shaped focal plane intensity profiles which contain greater than 95% of the incident energy. We presented a robust, iterative algorithm based on the phase retrieval algorithms for generating the appropriate phase screens (called kinoform phase plates or KPPs) for producing quite complex intensity profiles in the focal plane. In this procedure, an initial random phase screen is systematically improved upon by repeatedly transforming the complex electric fields between the near-field and the far-field planes and applying appropriately chosen constraints in each plane. The process was successfully

applied to design KPPs that produce complex far-field profiles such as the logo of our Laboratory.

As robust as the algorithm is, it suffers from one serious limitation: if one launches the iterative process using a random phase screen as an initial guess, the algorithm stagnates at the positions of the intensity zeros in the near-field and phase vortices are introduced at these points. Further iterations are unable to remove these vortices. These vortices lead to $\sim 2:1$ intensity modulations immediately following the phase screen and also to a few percent scattering loss of energy in the focal plane. The inherent singularities at these vortices also make it impossible to unwrap the phase screen into a continuous phase profile.

Continuously varying phase screens offer several advantages over those containing 2π discontinuities. One important advantage is that the propagated field past such a KPP exhibits a low level of intensity modulation. This should minimize the damage threat to the downstream optics. Since the phase appears continuous for the fundamental and harmonic wavelengths as well, the intensity modulations remain small at these wavelengths and hence the unconverted laser light also does not experience any significantly increased level of intensity modulation because of the KPP. The absence of 2π jumps also eliminates the large angle scattering losses from these edges and increases the energy concentration inside the central spot. Phase screens without 2π discontinuities are also useful when fabrication techniques such as ion exchange methods or volume holographic methods are used.

In spite of the advantages of continuous phase screens, the problem of designing such phase screens has eluded us for some time. Typically, smoothly varying phase screens lead to Gaussian envelopes in the far-field whose size is related to the correlation length and the variance of the phase profile. Recent attempts [3] to improve on the iterative algorithm have been unsuccessful where the authors used a continuous phase as a starting point in an iterative algorithm and concluded that the 2π line discontinuities crept in after only two iterations.

We have developed an iterative procedure for constructing fully continuous phase profiles for producing arbitrary focal plane intensity profiles. While continuous phase screens can be easily designed in simpler situations such as circularly symmetric phase profiles and x-y separable phase profiles, the new algorithm is applicable to fully two-dimensional non-

separable situation. The algorithm is launched with a continuous phase profile as an initial guess. The continuous nature of the phase is maintained throughout the iteration cycles by a careful application of the constraints in the near-field and the far-field. The details of the procedure will be presented during the presentation.

We have applied this new algorithm to generate continuous phase profiles for producing superGaussian focal plane intensity distributions. The converged phase continuous phase screen and its corresponding far-field intensity profile are shown in figure 1. The azimuthally averaged far-field profile corresponds to an approximately 12th power superGaussian and contains greater than 98% of the incident energy inside it. We have also applied the algorithm to generate complex far-field profiles. The results will be presented.

This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References:

- [1] J. D. Lindl et al *Physics Today* 45 32 (1992)
- [2] S. N. Dixit et al *Opt Lett* 19 417 (1994)
- [3] Y. Lin et al *Opt. Lett.* 20 764 (1995).

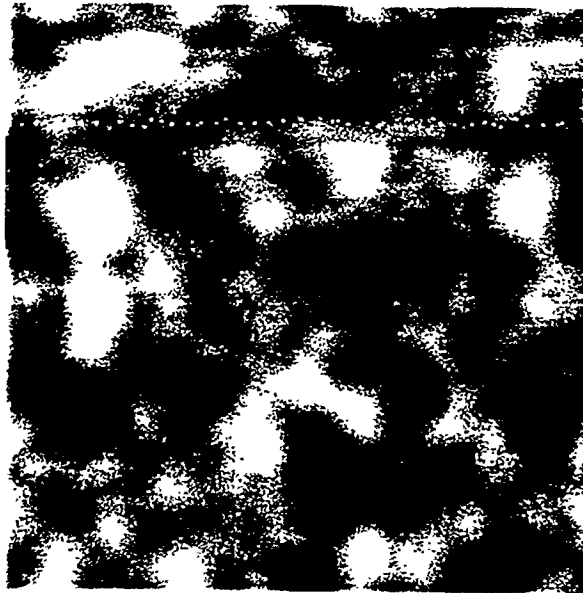


Figure 1a. Continuous phase screen for producing a superGaussian focal plane intensity profile. The phase values range from 0 (black) to 43 radians (white). The gray scale is linear between black and white.

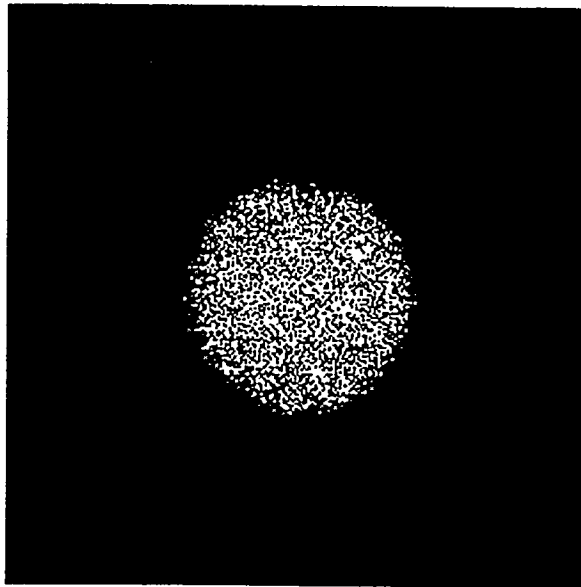


Figure 1b. Far-field intensity distribution produced by the phase screen shown in figure 1a. The far-field has an approximately 12th power superGaussian profile and contains 98% of the incident energy inside it.

Synthesis of fully continuous phase screens for tailoring focal plane irradiance profiles



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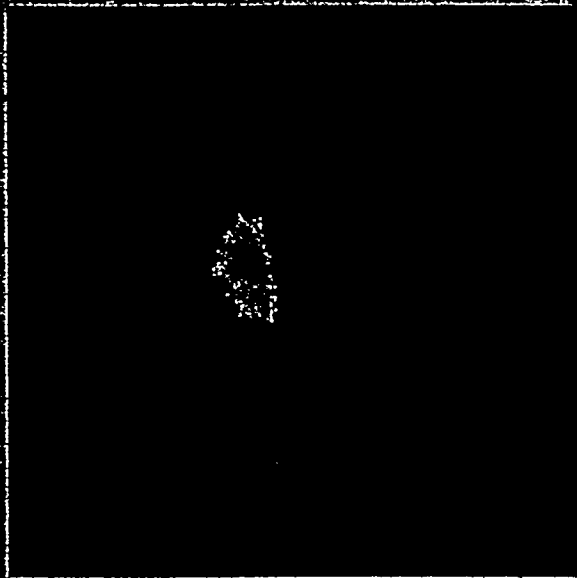
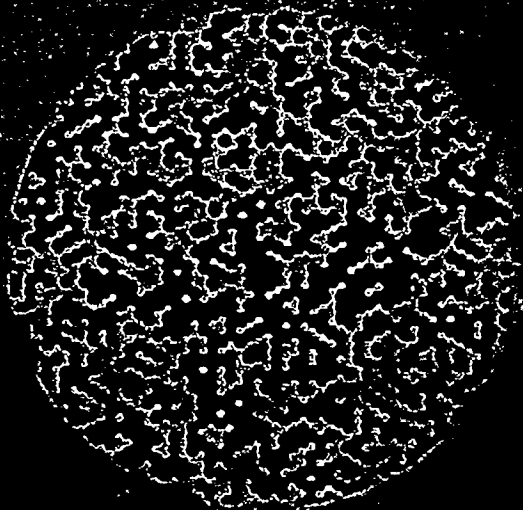
Outline



- Random phase plates for spatial beam smoothing and their limitations
- Kinoform phase plates, interactive Gerschberg-Saxton algorithm
- Limitations of KPPs containing 2π branch cuts
- Modification of the GS algorithm
- Numerical results

Random phase plates (RPP) produce spatial beam smoothing—a "uniform" focal spot with fine-scale speckle

Random and/or phase elements

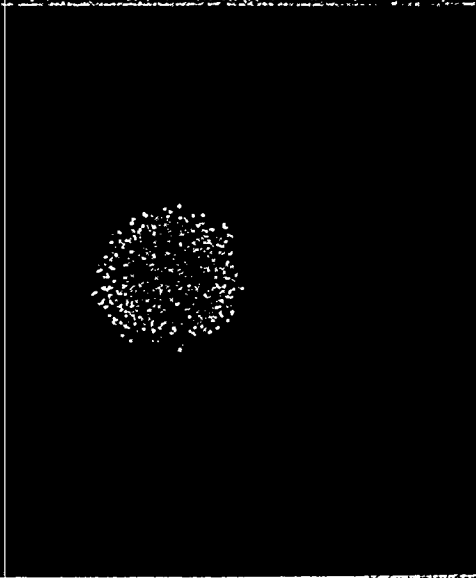


No RPP
20, best focus

Deposited SiO_2



SiO_2 substrate

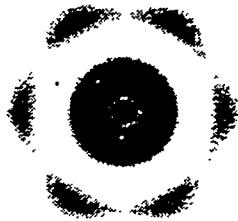


RPP
20, 7 μm
hexagonal

Binary phase plates have limited flexibility in controlling the focal plane irradiance distribution



- Far-field envelope is essentially limited to an Airy pattern
- ~ 15% of the incident energy is scattered outside the central spot in the focal plane

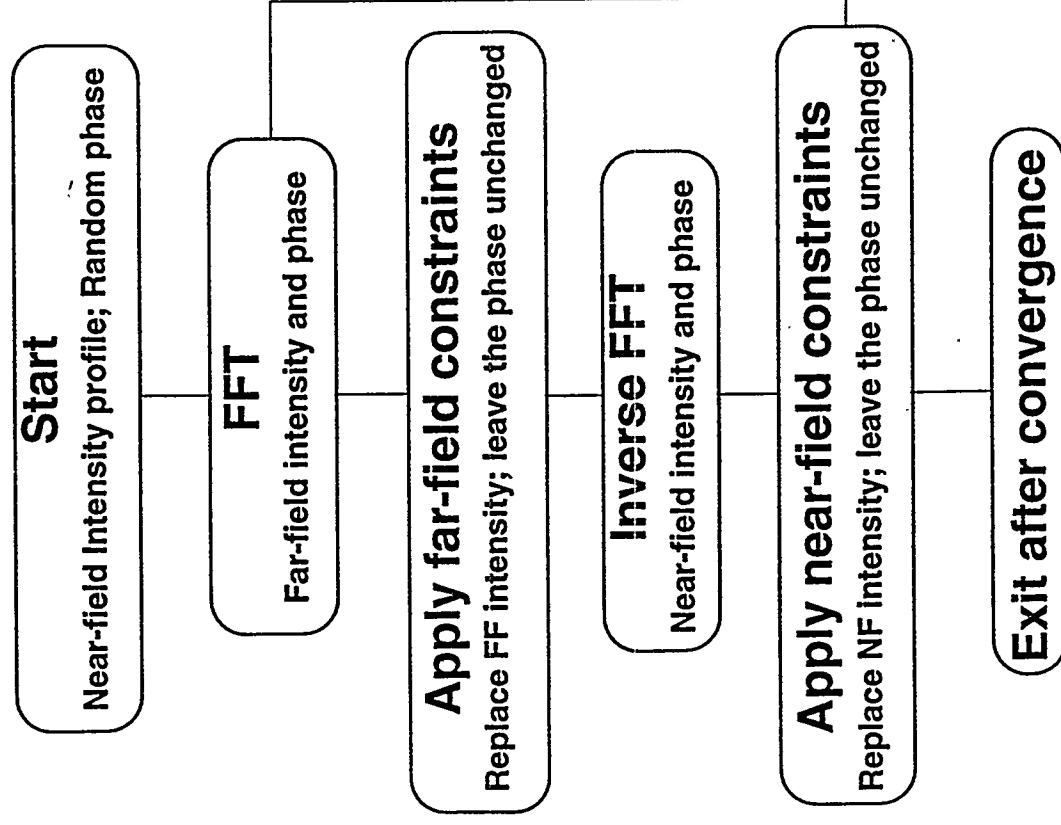


Solution: Relax the binary phase approximation

Design and fabricate continuously varying phase profiles
We call such phase plates kinoform phase plates or KPPs

KPPs offer complete flexibility in tailoring the focal plane irradiance profile and the energy content within it

An iterative algorithm is used to design the KPP phase screens

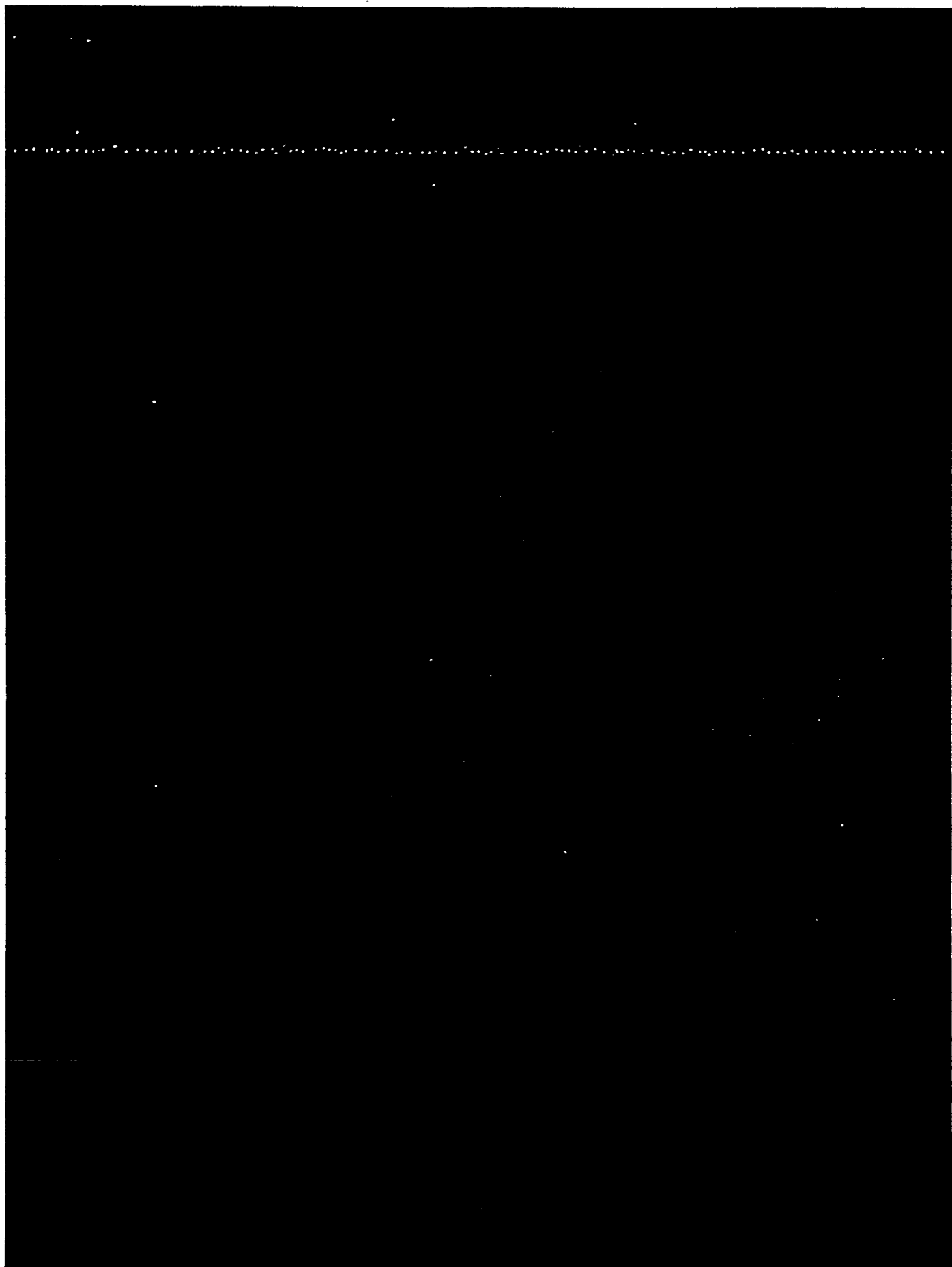


References:

- S. N. Dixit et al. Opt. Lett 19 417 (1994)
R. W. Gerschberg and W. O. Saxton,
Optik 35 237 (1972)

Features:

- Robust
- Rapidly convergent
- Arbitrary NF and FF profiles
- High energy concentration

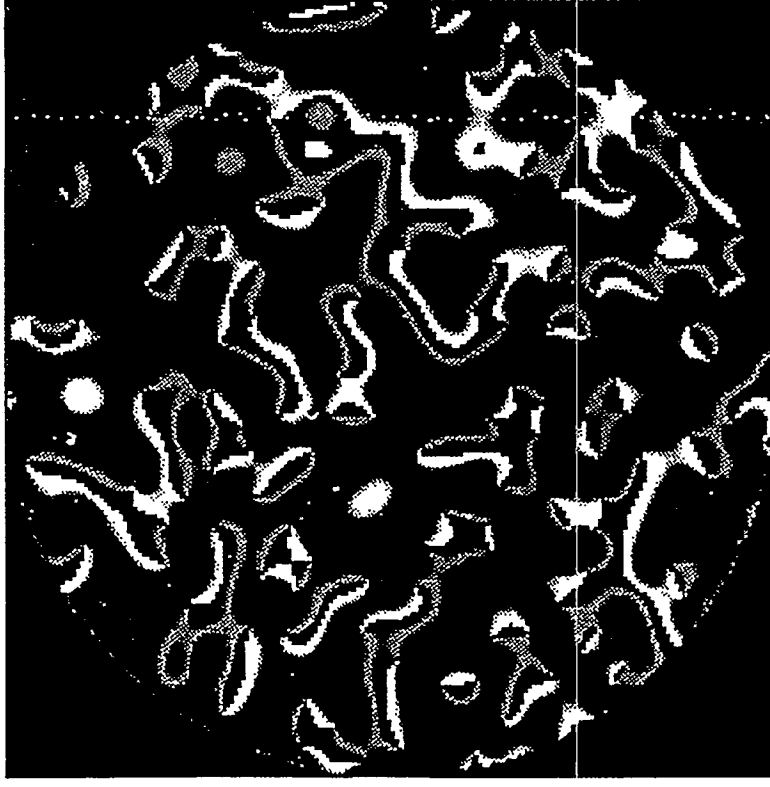


Iterative design launched with a random phase screen leads to many 2π - line discontinuities



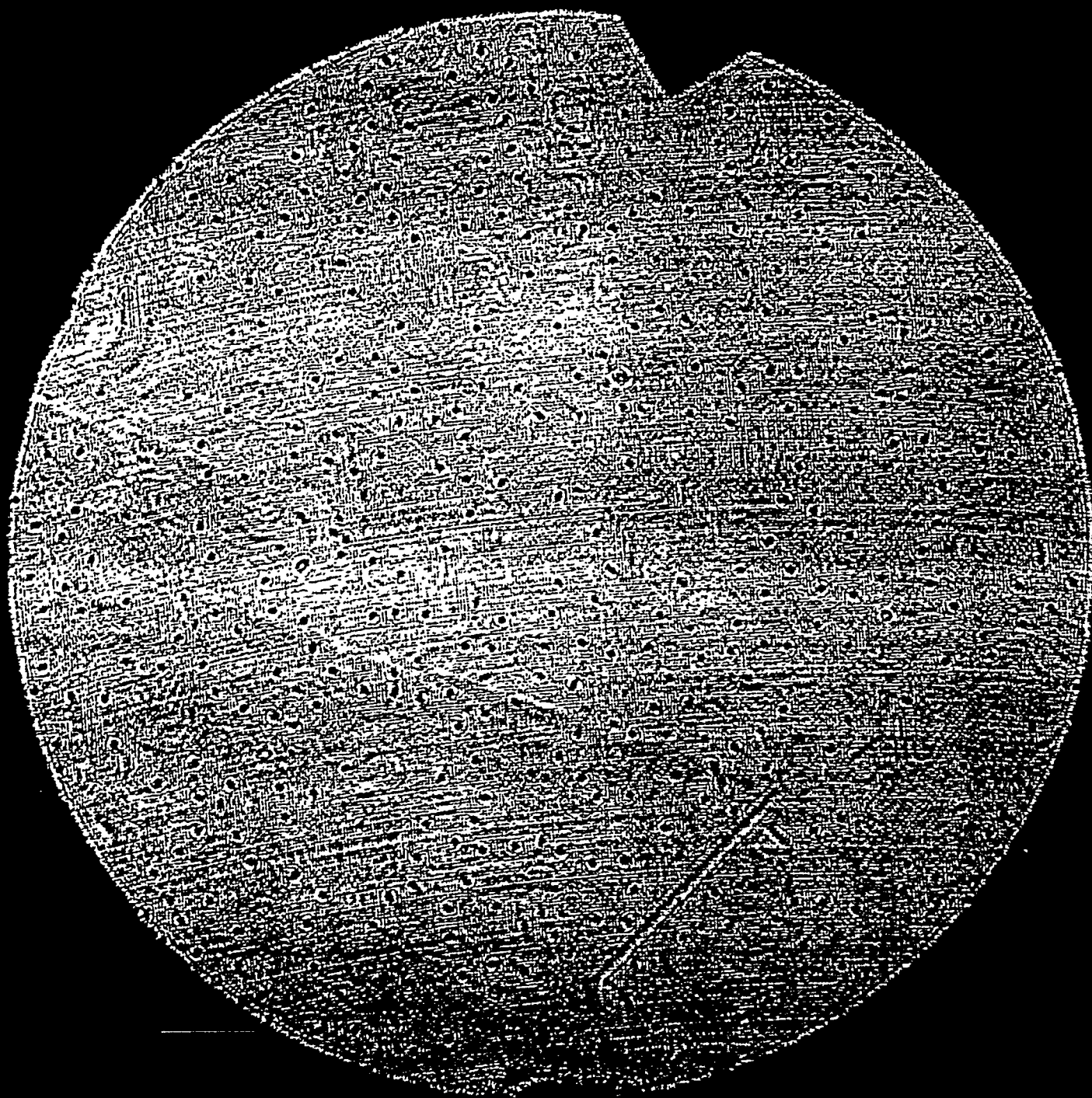
Consequences of the open-line 2π jumps:

- These cannot be unwrapped
- Ends of the lines cause zeros in the propagated intensity pattern following the KPP and lead to wide angle scattering in the far-field
- The 2π jumps induce ~3:1 intensity variations in the immediate vicinity ($\sim 10\ \mu\text{m}$) of the KPP



Example of a KPP phase screen;
Boundaries between black and white
represent 2π phase jumps

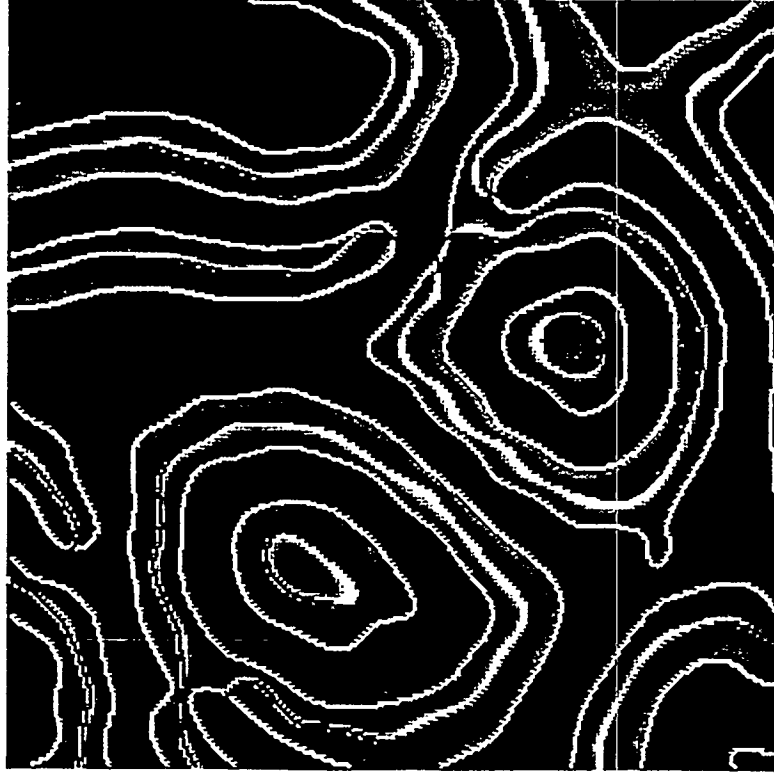
Highly efficient KPP designs require continuous phase screens



3 - 14

69.6 cm

Ends of 2π branch cuts correspond to intensity zeros and lead to speckle



Color picture:

A phase screen containing 2π branch cuts; color scale corresponds to phase values ranging from 0 (black) to 2π (white)

Black contours:

zeros of the imaginary part of the electric field

White contours:

zeros of the real part of the electric field

Notice the crossing of the zero value contours of the real and the imaginary part of the electric field at the ends of the 2π branch cuts

Speckle cannot be eliminated simultaneously in both the near-field and the far-field



Zel'dovich* has shown that the number of intensity zeros is ~ the number of times diffraction limited the beam is



If the near-field and the far-field are many times diffraction limited, then it is impossible to eliminate speckle in both planes simultaneously

Hence,

The best that can be done is to move the speckle in one plane

- for continuous phase screens, we need to move all the speckle to the far-field

The continuous phase plate design problem can be redefined as:
"Start from and maintain a speckle free intensity distribution in the near-field plane"

Speckle-free nature of the near-field can be preserved by adiabatically applying the far-field constraints



Step 1: start with a continuous phase screen in the near-field

Step 2: go to far-field by a FFT

Step 3: apply constraints in the far-field

$$F' = G(F) = GF \quad (\text{multiplicative constraint for discussion})$$

Step 4: go to near-field

$$F'^{-1} = G^{-1} * F^{-1}$$

If the extent of G^{-1} is small F^{-1} is only slightly modified and no crossings are introduced

If G^{-1} has a large extent then speckle is introduced in the near-field



Modify the far-field slowly to maintain the speckle-free near-field

The new iterative algorithm



- 1) Start with a continuous near-field phase screen**
- 2) Apply adiabatic far-field constraints**
- 3) Iterate with a replacement constraint in the near-field**

Numerical simulations

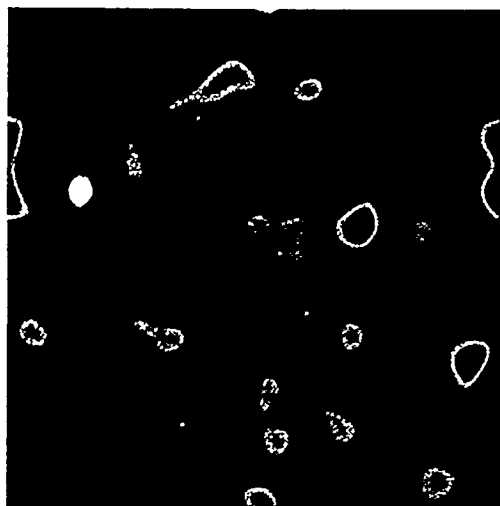


Objective: Generate a continuous phase screen that produces a high order super-Gaussian far-field

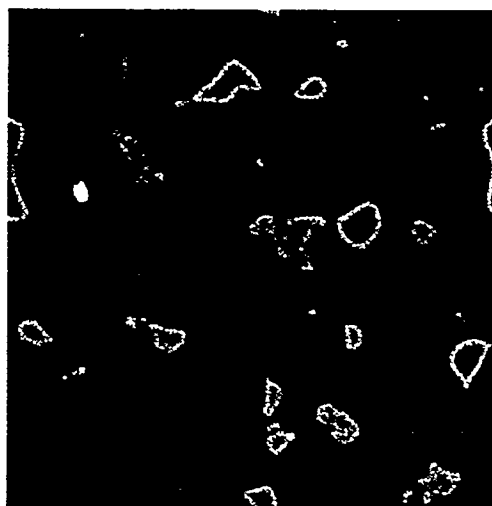
Parameters:	Near-field size	50 cm
	Far-field size (desired)	500 μm diameter
	Far-field shape	8th power or higher superGaussian
	Energy efficiency	>95% inside 500 μm circle
	Lens focal length	7 m
	Light wavelength	351 nm
FFT grid size		256 x 256

Note: these parameters correspond to KPP performance requirements for the National Ignition Facility (NIF).
See the following poster for fabrication and performance of the KPP)

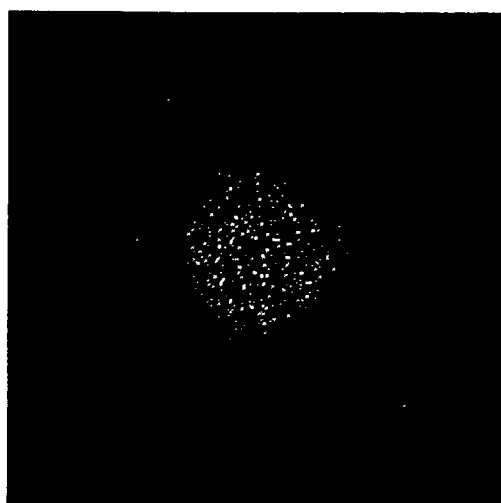
Initial phase screen



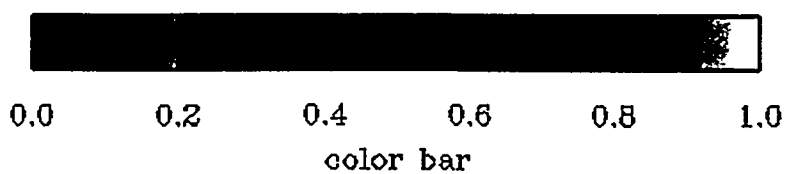
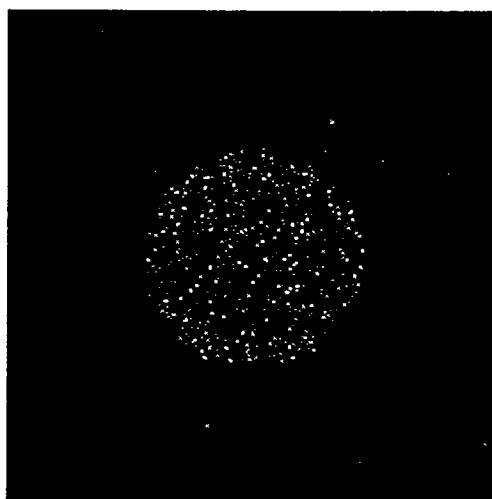
Iterated phase screen



Gaussian far-field



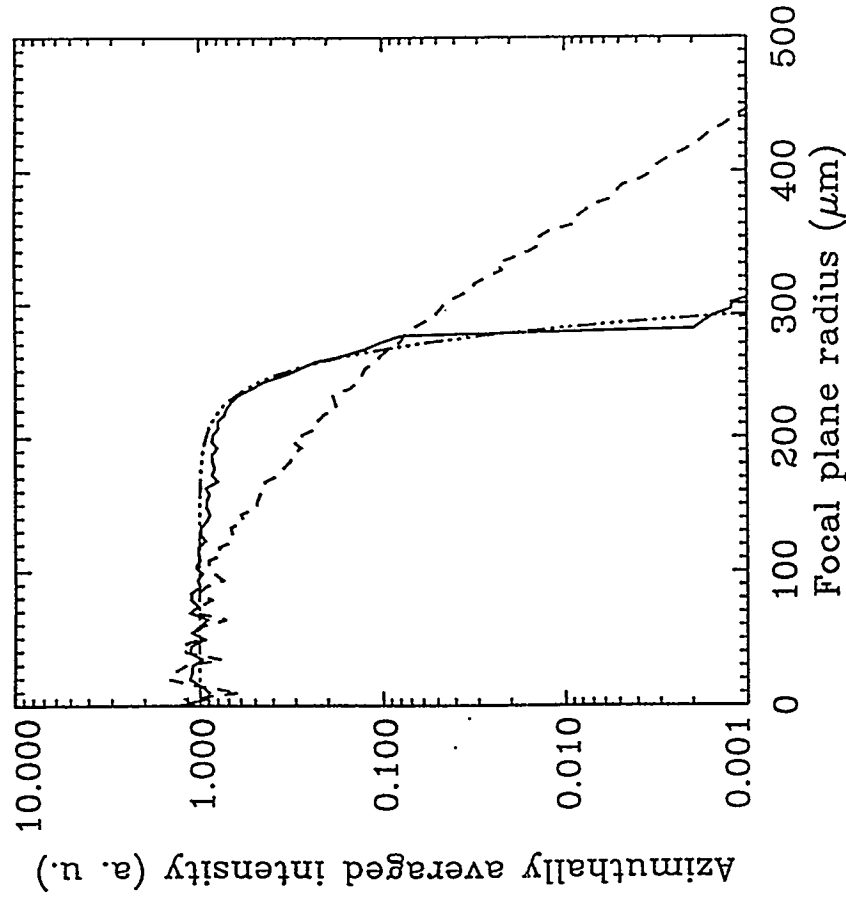
Super-Gaussian far-field



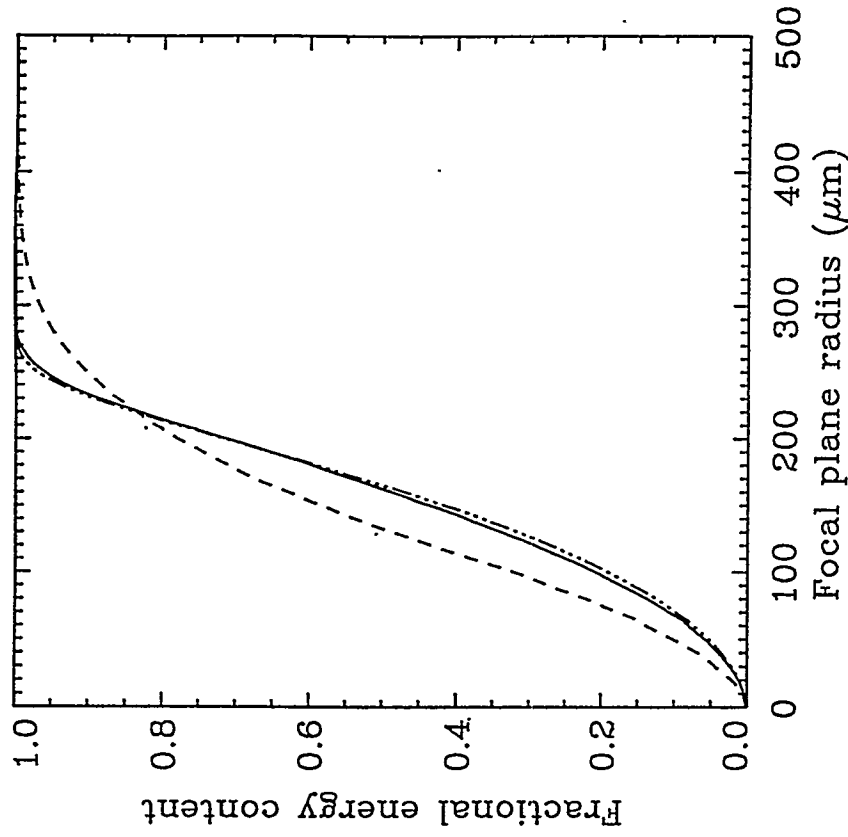
Continuous KPP has a good envelope profile and a high energy concentration



Azimuthally averaged profile



Far-field energy concentration



Summary



- We have developed an iterative algorithm for generating fully continuous phase screens for tailoring far-field profiles
- Key step is to start with a continuous near-field phase and adiabatically modify the far-field to maintain a fully continuous near-field phase
- We applied the procedure to generate fully continuous phase screens for producing super-Gaussian far-field profiles

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