Pseudo-random phase plates

Steven M. Ebstein

Lexitek, Inc., Wellesley, MA

ABSTRACT

Well-characterized test conditions are essential for validating the engineering design of an adaptive optical system. A technique for fabricating high-resolution, well-characterized pseudo-random phase plates that addresses this need is described. Among other uses, these phase plates can be used to test adaptive optics systems under controlled conditions. Machining a surface whose relief height is proportional to the desired phase forms a pixellated phase plate. Using Lexitek's Near-Index-Match™ approach, a sandwich of two materials is formed that produces the desired phase. Phase plates with 20 micron pixels have been fabricated using a 4096x4096 pixel grid. Results are presented.

Keywords: adaptive optics, phase plates, atmospheric turbulence

1. INTRODUCTION

Validation of an engineering design is easily accomplished when the design is tested under controlled conditions. Adaptive optics systems are no exception. Detailed information about the response of a wavefront sensor (WFS) to a given input from an aberrated wavefront can be modeled and calculated, but confidence in its performance can only be gained by measuring its response to a known aberrated wavefront input.

This holds true for the spatial spectrum of the aberrations, i.e., what r_0[1] is for the wavefront, whether the spectrum is purely Kolmogorov[2], or whether the high or low spatial frequencies are modified from a strict power law. It also holds true for the temporal spectrum of the aberrations[3], i.e., whether the aberrations are spatially correlated in time (Taylor turbulence), are spatially uncorrelated (Mintzer turbulence), or whether the spectrum is partially correlated over times and scales of interest.

Similarly, the presence or absence of intensity scintillations in the aberrated input will affect the output of the WFS. Likewise, the effects of non-ideal wavefront compensators, deformable mirrors (DMs) and variable transmission phase elements, e.g., liquid crystal devices, are dependent on the details of the aberrated medium through which the compensated beam propagates. Confidence in the system design is most readily obtained by end-to-end testing under well-characterized conditions. For adaptive optics (AO) systems, this requires a well-characterized means of introducing aberrations or providing an inhomogeneous medium through which a compensated beam can propagate.

One way to simulate an inhomogeneous medium is with a series of phase plates. Lexitek, Inc. and its personnel have pioneered one means of fabricating well-characterized phase plates by a technique we call Near-Index-Match™ (NIM™) optics[4]. It turns out others have had this idea, and we give some of the published references[5]. As far as we know, we were the first to reduce this idea to practice, as well as to offer NIM™ phase plates commercially, which may be of interest to AO system designers.

2. PRINCIPLE

The principle behind NIM™ optics is illustrated in Figure 1. Two different materials with refractive indices n_1 and n_2 that are similar but unequal form a sandwich with the interfacial surface profile h(x). If the exterior surfaces of both materials are planar, then the optical path difference (OPD) impressed upon a plane wave incident on the optic is given by

$$\begin{aligned} OPD(x) &= h(x)(n_1(l) - n_2(l)) \\ &= h(x)\Delta n(l) \end{aligned} \quad . \tag{1}$$

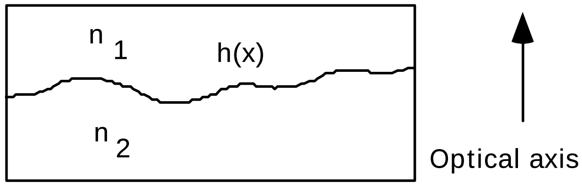

Figure 1. Schematic diagram of a Near-Index-Match™ phase plate consisting of a sandwich of 2 materials.

For materials with refractive index difference Δn of ~0.02, a relief height of ~50λ is required to produce an OPD of 1λ. For visible light (λ ~0.5 μm), this corresponds to 25 μm which can be machined fairly accurately with ordinary CNC machine tools. As we shall see, it is straightforward to machine relief profiles h(x) that realize phase surfaces of interest for AO systems.

3. DESIGN CONSTRAINTS

The principle limitations on the phase surface that can be produced are set by the choice of materials and the ability to machine a given phase surface. A limited set of index differences, Δn, is available in materials that are well characterized. The refractive index, as a function of wavelength and temperature, and thermal properties, such as coefficient of expansion and thermal conductivity, determine how an element will perform with polychromatic light and over different environmental conditions. The ease with which materials can be machined, cast, and/or bonded affects both the quality of the resulting phase plates and their cost to manufacture.

In principle, any one or two dimensional phase surface can be realized with a very fine cutting tool and a machining system with the appropriate degrees of freedom. In practice, the cutting tool, machining time required, tool lifetime, choice of materials, and machine tool precision all impose constraints on the surfaces that can be fabricated.

One of the most important design constraints is the index difference, Δn, as a function of wavelength. If the difference is very small, the required surface relief to produce a meaningful OPD can become quite large. If the difference is too large, the precision of the machine tool may limit the accuracy of the OPD. For machine tools with accuracies of several microns or a couple of tenths of a mil, i.e., 0.0002”, we have found that Δn in the range 0.02-0.06 works well for wavelengths in the 0.5-1.5 μm range.

The choice of materials is also affected by the wavelength, environmental parameters, and other optical specifications for the phase plate. For visible wavelengths through 1.6 μm, optical plastics and castable polymers are inexpensive and reasonably transparent, and the plastics can readily be machined or molded with the required surface relief. For longer or shorter wavelengths, plastics and castable polymers do not have good transmission. The materials that are transparent are typically more expensive and cannot be fabricated as easily with ordinary machining operations.

The required operating temperature range can play a role, especially because a NIM™ optic is a sandwich of two different materials. Mechanical stresses induced by temperature changes can affect the optical figure of a rigidly mounted optic and can cause a rigid sandwich to separate. These stresses are obviously greater for dissimilar materials, i.e., glass and polymers. In addition, differential changes in refractive index of the two materials with temperature can change the OPD as a function of temperature.

We have found that a combination of factors generally favor fabricating the NIM™ sandwich out of acrylic and a castable optical cement. This results in a solid sandwich, as opposed to having one of the materials be a liquid, eliminating the need to make a sealed cell. It also means that the sandwich materials have similar thermal and mechanical properties, so the sandwich is less sensitive to thermal stresses than if dissimilar materials were used.

The exterior (optical finish) surfaces have a significant impact on the performance of the phase plates. Any figure on the surface will change the transmitted wavefront from the designed OPD given by equation 1. It is difficult to polish plastic and achieve a finish better than a few waves per inch. Many of the castable polymers we use are very difficult to polish. Consequently, we have developed techniques for finishing the exterior surfaces by replicating an optical surface. Alternatively, optical windows that are bonded to the NIM™ sandwich can provide the exterior surfaces.

This latter construction, where the NIM™ phase plate is sandwiched between two optical quality substrates, has another advantage. While numerous coating houses now offer anti-reflection (AR) coatings on plastics, usually with an ion-assisted deposition, the availability and cost of these coatings are still less favorable than for glass optics. If AR coatings are required, and the application can tolerate the thickness of a double sandwich, using off-the-shelf with one side AR coated is a cost-effective way of providing AR coated external surfaces.

One must use a tool that has finite size in order to machine the surface in an economical time period. The tool cannot be too delicate or it will wear quickly and will not last. We have had good success using ball end mills to machine the pseudorandom surfaces. The size of the ball determines both the lateral spatial scale and the slopes that can be accurately reproduced in the relief surface.

As with any machine program to reproduce a contoured surface, there are different tool paths that can be used to machine the contours. Two features of pseudo-random surfaces influence the design of machine programs to fabricate the relief surface. First, the pseudo-random surface is almost always defined on a grid of points. Second, because the surface is so irregular, there is little value in generating a tool path that follows a given contour height. Consequently, a raster scan of the surface is straightforward to program and results in a program that does not take much longer than the shortest program that could be written. The grid for the raster scan of the surface is typically identical to the grid for the pseudo-random phase function and is chosen along with the size of the ball end mill to accurately reproduce the phase surface.

Along with the precision of the machine tool, the fidelity with which the raster scan can reproduce a flat surface gives a measure of the maximum accuracy of the phase surface. If a tool of radius r is scanned with a raster step l, a scallop of height h is produced where the quantities are related as follows:

$$h = \left(r - \sqrt{r^2 - \left(\frac{l}{2}\right)^2} \right) \tag{2}$$

and

$$l = 2\sqrt{h(2r-h)} \ . \tag{3}$$

Together with the index difference, Δn, this sets one limit on the accuracy of the NIM™ phase plate. Another limit on the accuracy is set by the surface finish of the machined substrate. If the surface is rough, this adds noise to the surface profile. In addition, a rough surface can often cause greatly increased scatter at the interface surface. We have sometimes found it helpful to very lightly polish the machined plastic surface before casting the second material.

One of the larger sources of inaccuracy in a NIM™ phase plate is the precision with which Δn is known, since the castable materials are less reproducible than an optical glass. Variations of ~0.002 in Δn are common, and this can cause a 10% uncertainty in the phase scale. If tracking the phase strength to greater than this accuracy is required, it is possible to add a calibration portion to a phase screen that has a well-defined phase difference. An example of a test piece illustrating this is shown in Figure 2. Aside from this effect, the strength of a NIM™ phase plate is set by the height of the relief surface, which can be accurately machined.

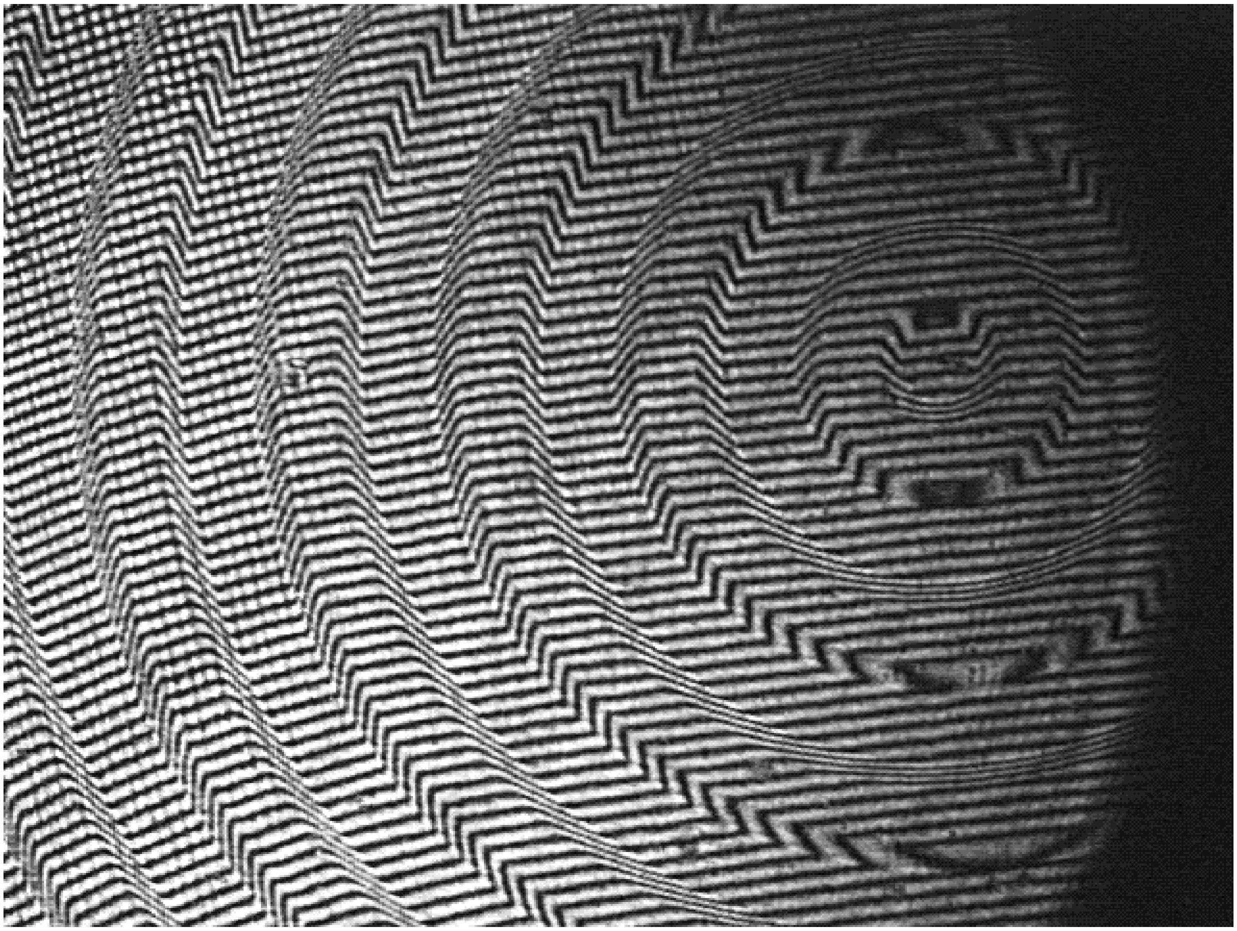

Figure 2.	Interferogram of a NIM™ optic test piece used for calibrating Δn. Note that the phase step from region to region can be gauged by tracking fringe offsets.

4. RESULTS

We have used the approach outlined above to fabricate pseudo-random phase plates for adaptive optics. One of the more challenging applications was fabrication of a ~80 mm diameter phase screen. This screen was defined on a 4096x4096 pixel grid and was fabricated with a 1/32" diameter ball end mill with the grid spacing ~20 microns. A picture of the machined surface is shown in Figure 3.

We recorded an interferogram of a test piece of that phase screen that is pictured in Figure 4. This phase screen was designed for use at 1.55 μm, and the interferogram is recorded at 633 nm. An interferogram of another phase screen is shown in Figure 5. Although both phase screens nominally have Kolmogorov statistics, they differ as to their strength and how the low spatial frequency content was treated. Low frequency components such as focus and tilt are often treated with separate sensors and correctors in adaptive optics systems, so their representation in a pseudo-random test plate will vary for different applications.

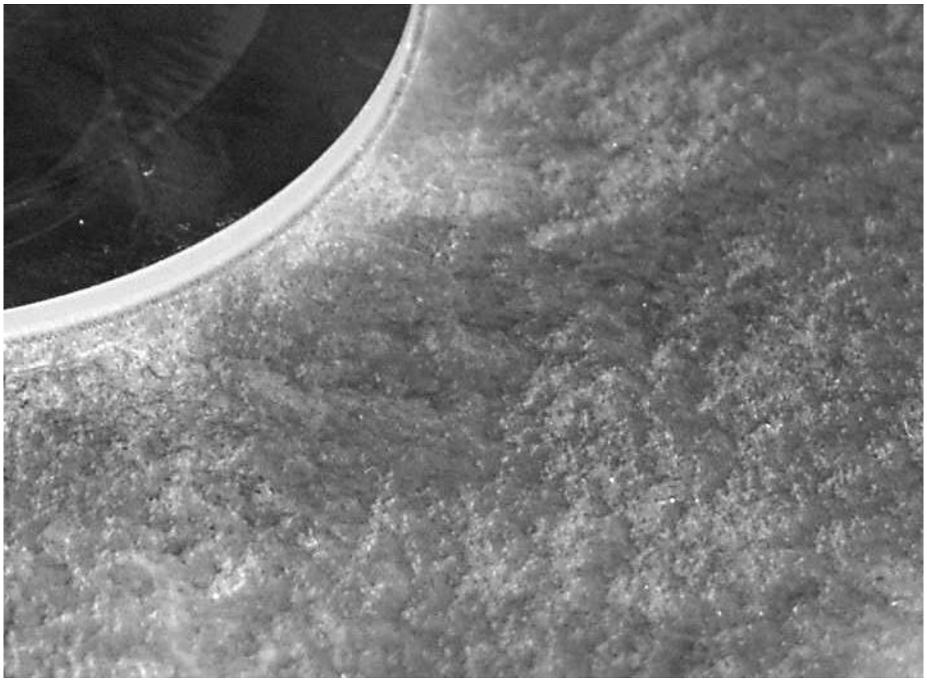

Figure 3. Picture of a machined substrate for a Near-Index-Match™ phase plate before the 2nd material was cast. The hub of the annular phase screen is visible at the upper left.

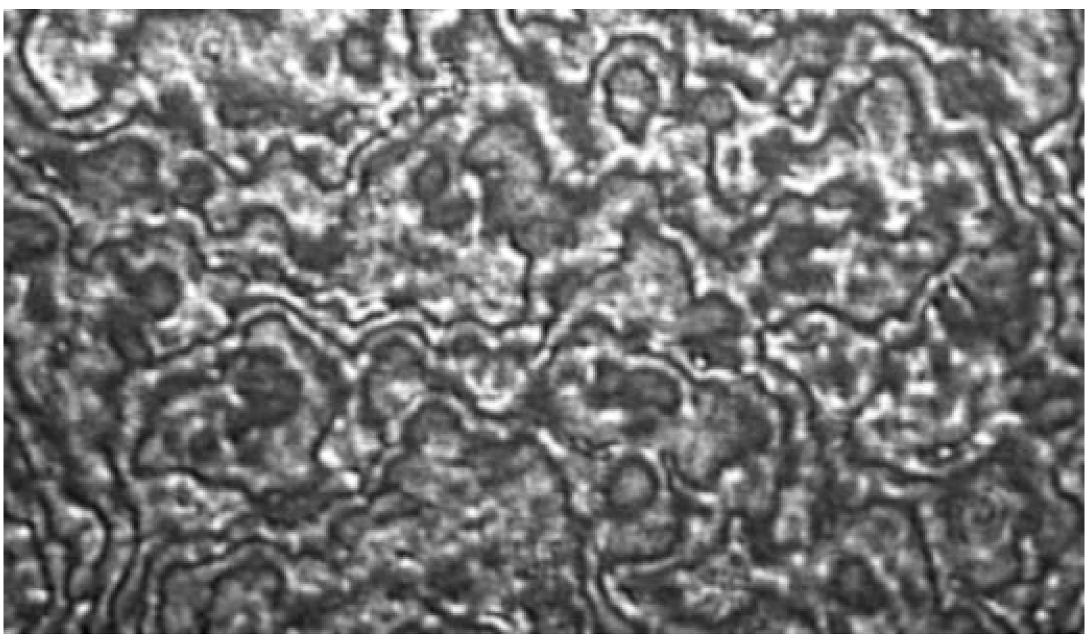

Figure 4. Interferogram of a finished Near-Index-Match™ phase plate corresponding to Figure 3.

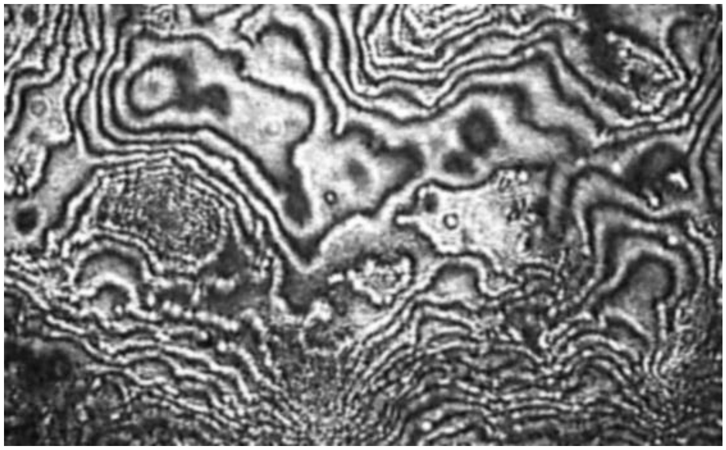

Figure 5. Interferogram of a Near-Index-Match™ phase plate with different strength than that of Figure 4.

6. CONCLUSION

We have described an approach for producing pseudo-random phase plates using NIM™ phase plates and shown examples we have fabricated. These pseudo-random phase plates can be generated with large numbers of pixels and can serve as a well-defined stimulus for testing adaptive optical systems.

REFERENCES

1. Fried, D.L.; “Optical Resolution through a Randomly Inhomogeneous Medium for Very Long and Very Short exposures;” J. Opt. Soc. Am , 56 No:10, pp. 1372-1379.October 1966.
2. V. I. Tatarskii, The effects of the turbulent atmosphere on wave propagation, Israel Program for Scientific Translations, Jerusalem 1971, ISBN 07065-0680-4.
3. Barakat R., Nisenson P. ``Influence of the wave-front correlation function and deterministic wavefront aberrations on the speckle image reconstruction problem in the high-light level regime" J. Opt. Soc. Am. 71, 1390-1405 (1981).
4. Ebstein, S.M., "Method and Apparatus for Changing the Focal Length of an Optical System," U.S. Patent No. 5,091,801 (1992); Ebstein, S.M., "Nearly-index-matched optics for aspherical, diffractive, and achromatic-phase diffractive elements," *Optics Letters* **21**, 1454-1456 (1996); Ebstein, S.M., "Achromatic Diffractive Optic," U.S. Patent No. 5,734,502 (1998).
5. Deve, C. (1954). Optical workshop principles. Adam Hilger, London, p. 322: “If a layer of some thickness of a cement of too high or too low an index were interposed between two lenses, the equivalent of an uncalculated three lens combination would be realized instead of the calculated two lens combination…”; Hercher, M., “An automated method for the manufacture of optical correction plates,” Opt. Eng. 21, No. 3, SR-064 (May/June 1982); Naffarate, A.B., “Aspheric lenses: an easier way,” Appl. Opt. 22, No. 16, pp. 2400-2401 (1983).