Optical System Designs for Collimation of Large-aperture Phased Laser Array Elements

A dissertation submitted in partial satisfaction of the requirements for the degree

Bachelor of Science in Physics

by

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Committee in charge:

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The Dissertation of Jacob Raphael Erlikhman is approved.

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Abstract

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Directed energy propulsion for interstellar travel has been proposed as an ideal method for reaching appreciable speeds relative to the speed of light: $0.2c$. However, the amount of energy required necessitates a large aperture, on the order of kilometers, while mitigation of atmospheric perturbations requires a discretization of the aperture into many individual laser elements. The use of fiber lasers for these elements obligates mode-matching the fiber to the desired 10 cm aperture for a collimated beam. Various collimation systems were designed and compared. A 3-lens system with one achromat and two aspheric lenses, with two of the lenses used as a Keplerian telescope to achieve a system-shortening effect was analyzed. A similar system made with a plano-convex lens replacing the large-aperture aspheric lens with two additional compensating lenses was compared. A single diffractive optic operating at $F/7$ was likewise considered. The optical performance of these systems was compared, as was the cost-effectiveness. Scalability to millions of elements was required, so cost-per-system was a crucial consideration factor. Possible manufacturing processes for a diffractive system were investigated, and stamping processes for replication were analyzed to determine the possibility of replication of such an optic reliably, cheaply, and with acceptable results. Tolerancing for manufacturing of a diffractive system was likewise conducted. Overall, the diffractive system is best for scalability, though further investigation is needed to determine the ideal replication process for the proposed diffractive optics.
Chapter 1

Introduction

1.1 Phased Laser Array Design Idea for Interstellar Propulsion

A plan has been proposed for interstellar travel using an array of coherently combined laser elements. With sufficient power, size, and number of elements, this array can accelerate a light spacecraft attached to a reflective sail to 0.2c, allowing it to travel to Alpha Centauri within 20 years [1]. The projected number of elements required is on the order of $10^9$, so a cost-effective scheme must be developed to implement the components of the system [1]. Currently, a 10 km-class design is being investigated, where the full system will be made from a composite array of 1 m diameter sub-systems, which in turn consist of 91 10 cm diameter elements. Using a phase conjugation approach in a stochastic parallel gradient descent algorithm, the atmospheric perturbations can be corrected with a quasi closed-loop system for the entire array with individual element actuation [1, 2]. This approach allows the individual laser beams to remain diffraction-limited during flight. This suggests that the optics used should create near-diffraction-limited beams emitting from each laser element.
For each element, nominal 10 cm aperture diameters have been chosen to mitigate cost while still allowing atmospheric compensation. If smaller apertures are used, mitigation of the atmosphere is simpler, since an actuator for each element needs to eliminate smaller atmospheric perturbations—simply because the path of the laser occupies a smaller solid angle. However, the cost-per-element rises significantly, since each element requires its own amplifier [2]. As a nominal, balanced, and relatively easy to work with option, 10 cm apertures were chosen.

The primary cost of each laser element is the amplifier, actuator, and—if refractive optics are used—the optical elements. In order to achieve diffraction-limited performance, aspheric lenses are often used in short wavelength band imaging and laser applications. Although small-diameter aspheric lenses can be injection-molded, larger diameter—greater than 10mm—lenses must be CNC-machined or diamond-turned [3]. These processes increase the cost dramatically for high-quality, large-aperture aspheric lenses. Because of this, designs with plano-convex (PCX) lenses as well as achromatic lenses were investigated, in an attempt to reduce the cost of the optical elements of the system.

Diffractive optical elements (DOEs) can provide another possibility to avoid the high cost of conventional optics. Manufacturing of such optics is complicated, however, and has been traditionally realized through multi-step photolithographic processes[4]. Multi-step lithography is often costly, as it requires fabrication of several photomasks and the careful alignment of the photomasks to the substrate during patterning. This alignment and subsequent patterning process is time-consuming and requires expensive, state-of-the-art machinery[CITE SOURCE]. However, relatively recent developments in nanoimprinting lithography and thin-film replication provide ways to circumvent these issues, as a single, expensive master from which many cheaper replications are obtained could be manufactured.

Here will be presented refractive optic approaches to individual laser element collimation for a phased laser array system, contrasted with a DOE setup. Manufacturing considerations
for the DOE will be considered and evaluated, to allow for a path forward for manufacture of a test array system for further practical research.

1.2 Methods of Investigation

1.2.1 The Point Spread Function

A theoretical ideal optical system has a focus that is of infinitesimal size; however, there does not exist a 1-1 transfer function that maps the input at the aperture stop of a real system to a point at the focus, due to diffraction. This is a result of the Rayleigh criterion, that two light sources will have an angular resolution of

$$\theta = 1.22 \frac{\lambda}{D}, \quad (1.1)$$

where $\lambda$ is the wavelength of the diffracted light and $D$ is the diameter of the aperture through which the two sources are being observed (and therefore diffracted). As it turns out, diffraction zones are theoretically predicted by Airy functions, with zeroes of the functions corresponding to the minima of the diffraction pattern. The value 1.22 corresponds to the location of the first zero of the model Airy function. Due to this fundamental limit, even point objects cannot be imaged down to a point. Instead, the function that provides this mapping into the image plane necessarily has a spread about the point—this is the point spread function (PSF). To gain some intuition, example PSFs are shown in Fig. 1.1, where 1.1a is the PSF for the optical system viewed along the optical axis, while 1.1b is the system viewed at about a milliradian off-axis, $0.06^\circ$. Both PSFs are normalized to the Strehl ratio, which is a measure of how close the optical system is to ideal. The image obtained from the measured optical system is compared to that from an identical system without any aberrations, and the ratio of the intensity of the light at the focus gives the Strehl ratio. As can be seen from the plots, the PSF has a width of about
10 μm, which corresponds to the diffraction-limited spot size chosen/expected for the system in question, suggesting that this system is diffraction-limited (and therefore not limited by any optical aberrations). Although it is not explicitly shown or used in the rest of this discussion, it is an essential ingredient in and necessary for understanding the modulation transfer function.

### 1.2.2 The Modulation Transfer Function

In order to adequately quantify and compare the performance of the optical designs that will be considered in the following chapters, a standard technique of modern optical analysis was employed. The modulation transfer function (MTF), gives modulation as a function of spatial frequency—this is essentially a measure of how blurry a set of horizontal or vertical lines will appear (modulation) as a function of how close the lines are to each other (spatial frequency: the number of lines per mm). See Fig. [1.2](#) for a pictorial example. The vertical bars a set distance apart set the spatial frequency, while the modulation is set by how "blurry" the image is relative to the object. This is more specifically a measure of how the PSFs for each point on each bar overlap (or do not) and whether or not they interfere. Greater overlap and interference causes a blurry image, as depicted on the right side of the figure. A perfect system would have an MTF of 1 for all spatial frequencies; of course, real systems can only get close to a value of 1 modulation for a range of spatial frequencies, with higher frequencies having less modulation. Again, diffraction creates a fundamental limit on the amount of modulation at high frequencies, as an image cannot be resolved by an optical system if its size approaches the theoretical angular diffraction limit (set by the Rayleigh criterion, Eq. [1.1](#)).

### 1.2.3 The Code V Optical Design Software

The designs mentioned in Section [1.1](#) were investigated using the commercial optical modeling software Code V. This program has the ability to model geometrical as well as physical
Figure 1.1: Example PSFs for a diffraction-limited system. The diffraction limit was chosen to be 11 µm, which is about the size of the PSFs shown above, suggesting that the system is diffraction-limited in both cases. (a) shows the PSF along the optical axis, while (b) shows the PSF at 0.06° ≈ 1 mrad away from the axis in the focal plane (as measured from the aperture stop).
optical systems in a variety of situations, including capabilities for tolerancing, optimization, Gaussian beam propagation, and fiber coupling. Surfaces are input into the program one-by-one, with appropriate input parameters, such as radius of curvature, size, refractive and material properties, and even diffractive structures. Rays are then propagated sequentially through the surfaces in the order they were defined. This limits the investigation to sequential systems—stray light or specular reflections that make it to later surfaces in the sequence without hitting prior surfaces are not taken into account, but this is sufficient for most optical systems, including those considered in this research.

In the investigation of these designs, built-in analyses in Code V were used such as the (diffraction) MTF, spot diagrams, PSFs, and simulated wavefronts (to determine wavefront aberration). Spot diagrams show—for a preset number of rays entering the aperture stop at a given field angle—where the rays hit the focal plane. These are usually overlaid with the first Airy disk, so that a (geometrical) determination of diffraction-limited performance for the optical system can be obtained. Simulated wavefronts are able to show the amount of aberration (though not the type) by measuring the largest distance along the optical axis between any two points on the wavefront. This tends to be the distance (along the optical axis) between points that are farthest from the optical axis in the perpendicular direction and those that are on or near
the optical axis. This gives the summed aberration value, or difference in optical path length (OPL), where a system is considered diffraction-limited if this length is \(< 0.4\lambda\), where \(\lambda\) is the wavelength in question. For multi-wavelength systems, MTFs and PSFs are more valuable metrics, as they can synthesize all system wavelengths into one function. Nonetheless, since the systems considered in this research are all single-wavelength, wavefront simulations were useful for further aberration analysis.

### 1.2.4 Zernike Polynomials and Surface Perturbations

Surface perturbations in optical substrates were also modeled using Code V, by inducing a surface profile defined by Zernike polynomials. These are a complete, orthonormal set of polynomials that are only normalized on the unit disk minus a ray extending out from the origin. For all intents and purposes, they can be assumed to be defined on the whole disk, due to the symmetric nature of the surfaces considered here. Each of these polynomials corresponds to a distinct optical aberration, so they are a natural basis for optical modeling and measurement. Due to the imperfect nature of fabrication, optical substrates often have some inherent surface imperfections that cause OPL changes in incoming rays of light. Once these changes are greater than a significant fraction of the wavelengths considered, aberrations are introduced.

Detailed analysis of the wavefront shape or the spot diagram can indicate which aberrations are present. For example, spherical aberration, an inherent OPL change for rays near the edge of a spherical optic compared to those at the center, is symmetric, so that rays in a spot diagram will appear symmetrically spread out farther from the center of the Airy disk. Aspheric lenses, which will be considered in Section 2.1, are manufactured in order to eliminate precisely this aberration. On the other hand, an aberration such as coma has inherent asymmetry, which can be observed by asymmetric deviations in a spot diagram. Thus, Zernike polynomials are especially useful for optical applications, as knowing the coefficients for a given system allows
one to determine which aberrations are present and whether or not they have a significant effect on the performance of the system. Furthermore, in theory, only a few are necessary to model simple systems. For example, a spherical lens which is otherwise perfect, would be almost ideally modeled by only a few out of the first 20 of these polynomials, which are those which correspond to several orders of spherical aberration.

### 1.3 Overview of System Requirements

Since the lasers considered are single-mode fiber lasers, for optimal combined power on target, the mode field diameter (MFD) of the fiber must be matched to the diffraction-limited spot size of the optical system at the laser wavelength. The MFDs of several suitable single-mode fibers are on the order of 11 µm, so this will be the nominal MFD considered. To a reasonable approximation the laser beams emitted from the fibers have a Gaussian intensity profile. Such beams have a theoretical beam waist, which corresponds to the idea of a diffraction-limited focus for normal light. By requiring the diffraction-limited spot size of the laser to match the fiber MFD, this is equivalent to the assertion that the Gaussian beam waist diameter match this MFD. The optimal clipping ratio for Gaussian beams is 90-91%, given to provide the greatest combining efficiency \[2\]. For a 10 cm clear aperture, this corresponds to a \(2\omega = 9\) cm \(1/e^2\) diameter of the Gaussian laser beam, the equation for \(2\omega_0\), set equal to the MFD, is given by

\[
2\omega = 2\omega_0 \sqrt{1 + \frac{f\lambda}{\pi \omega_0^2}},
\]

where \(f\) is the focal length of the optic and \(\lambda\) is the wavelength of the laser. Solving this for \(f\), we have

\[
f = \frac{\pi \omega_0^2}{\lambda} \sqrt{\frac{\omega^2}{\omega_0^2} - 1}.
\] (1.2)

Since the lasers are nominally Yb fiber lasers, which have affinity for coherent combination, the wavelength, \(\lambda\), is here 1064 nm. From this we can obtain that, for a nominal \(2\omega = 9.2\) cm
(assuming a clear aperture of 10 cm), $F = 7.1$, where $F \equiv \frac{f}{2\omega}$ is the F number. An $F/7.1$ system would require a nearly 0.71 m separation from the fiber to the collimating lens, which would increase the overall system length dramatically. Due to the weight of the large-aperture lenses as well as the fiber laser systems and the need to rotate the entire system to continuously track the target, the moment of inertia of the entire system may grow too large with a 0.71 m separation between the fiber and its collimator, possibly causing instability or other issues during rotation. This necessitates either reducing the mass of the optics (thereby reducing the system’s moment) or shortening the system length. One method of achieving the latter is using a Keplerian telescope composed of two refractive lenses to magnify the focal plane of a faster lens (here, $F/2$), to the desired 11 µm MFD. DOEs nominally eliminate this problem, since diffraction can be achieved with patterns that have heights of order microns. Thus, the substrate can be reduced to a thickness of 0.5 mm or less, eliminating much of the excess mass necessary for a refractive optic.

1.4 Permissions and Attributions

1. The content of Chapter 2 and parts of Chapter 3 has previously appeared in the SPIE Proceedings [6].
Chapter 2

Conventional Optics Approaches

2.1 Aspheric Lens Option

As mentioned in Chapter 1, the use of a single lens for mode-matching the fiber is not desirable. For a shorter system, a Keplerian telescope can be used. Noting that the length of the telescope can be made to be on the order of 50 cm, a fast collimating lens is desirable. Therefore, an $F/2$ aspheric lens from Thorlabs was chosen. Its clear aperture given on their website is 92 mm, providing an ideal $1/e^2$ diameter of 82.8 mm. Setting $2\omega = 82.8\text{ mm}$ and $f = 200\text{ mm}$, the spot size diameter of this lens is $2\omega_0 = 3.3\mu\text{m}$ at 1064 nm, necessitating a $\sim3.3\times$ magnification with the telescope system. From elementary optics it is known that the ratio of the focal lengths of the lenses used in the telescope will provide the desired magnification of the beam waist. 30 mm focal length and 100 mm focal length lenses were chosen to create the desired magnifying effect. The system was analyzed, and the distances between the different lenses were optimized by the optimization feature in Code V to correct for the thin-lens approximation used for the nominal analysis. Accordingly, a composite $F/8$ system was obtained—according to the Code V analysis, which was the goal. Analysis of this system yields the following results.
Conventional Optics Approaches

2.1.1 Analysis

Since the single $F/2$ aspheric collimator is diffraction-limited, if the Keplerian telescope is also, then the system will remain diffraction-limited. An optimal 216.8 mm separation is given by Code V between the primary asphere and the first lens of the Keplerian telescope (30 mm focal length asphere). Since the next lens has $f = 100$ mm, an achromat was chosen to again mitigate costs. No noticeable difference in optical performance was seen between the use of an asphere and an achromat for this lens, since it is a relatively slow lens. The MTF and spot diagram are shown in Figs. 2.1 and 2.2 for the composite system.
2.2 PCX and Achromatic Lens Attempts

Although PCX and achromatic lenses are generally not diffraction-limited even for much slower (> F/5) lenses, the idea of using a compensating lens to correct for the spherical aberrations was investigated using Code V. A nominal F/2 PCX lens was chosen from Edmunds Optics as a possible primary collimating optic, assuming a clear aperture of 100 mm. This provides an ideal 2\(\omega = 90\) mm, and an 2\(\omega_0 = 3.0\ \mu m\) using Eq. [1.2]. Again, this necessitates a 3.5\(\times\) magnification, though the same lenses have been used as in Section 2.1 (giving a final MFD of only 10\(\mu m\)). A global optimization was run in Code V to optimize the transverse ray aberrations for this lens with a variable lens (nominal N-BK7 glass) inserted between this lens and its focal plane. No solutions were found. However, with two variable lenses, several solutions were found with near-diffraction-limited performance. The chosen ideal solution can be seen in Fig. 2.3. Since the compensating lenses are touching, this system should ideally be easy to assemble. Furthermore, the system performs as well or better than that in Section 2.1, see the following section. Similar attempts were made with an achromatic lens as the primary optic, with the thought being that the achromat may have enough spherical aberration correction that a single compensating lens would be sufficient to create a diffraction-limited beam.
2.2.1 PCX System Analysis

For near-field focusing of the system, up to a milliradian actuation in the focal plane is desired. Therefore, field angles from $0^\circ - 0.05^\circ$ were chosen in $0.01^\circ$ steps, where $1 \text{ mrad} \approx 0.057^\circ$. Although some field curvature is present at the final field, as is evident from Fig. 2.4, the system remains diffraction-limited at all fields—see Fig. 2.5. Moreover, Strehl ratios of over 97% are given by Code V for the performance of the system at all fields, as shown in Fig. 2.6.

Optical performance notwithstanding, the cost of the system—combined with the added complexity of two additional lenses—does not make it inherently better or more useful than the aspheric system presented in Section 2.1. The cost of manufacturing the custom lenses to the desired specifications is on the order of hundreds of dollars per lens, which—in addition to the requisite opto-mechanics necessary to hold and align them—will likely rival the cost of the single, $1250, aspheric primary optic. Because of these reasons, this design was abandoned.
Figure 2.4: Wavefront aberration for the final field (0.05°) of the PCX aberration-corrected system. Note the scale of 0.2λ, suggesting that this field remains diffraction limited since the total wavefront is less than 0.5λ tall. Field curvature is easily evident here.
Figure 2.5: Spot diagram for the PCX system, with spots given for each field in degrees. The first Airy disk at 1064nm is overlaid over each diagram. The system appears to remain diffraction limited at all fields.
Conventional Optics Approaches

Chapter 2

Table 2.6: Strehl ratios for the PCX system at all fields. The composite best focus optimization done by Code V allows the given Strehl ratios in the right-most column to be achieved simultaneously for each field. The individual best focus—which will not be used—allows only one field’s ideal Strehl, given in the other Strehl column, to be achieved at a time.

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<th>FOCUS (Hatr)</th>
<th>RMS</th>
<th>STREHL</th>
<th>SHIFT (WAVE)</th>
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Conventional Optics Approaches

Chapter 2

2.2.2 Achromatic Primary Lens Attempts

An achromatic lens of 100 mm diameter was not available as a stock item from the primary optics manufacturers. However, in order to investigate the possibility of using an achromat in this system (and perhaps having it custom-made), a stock 75 mm diameter lens was chosen from Edmunds Optics. However, this lens likewise required four surfaces or two additional lenses to compensate for its spherical aberration, suggesting that the only simple solution with conventional lenses must be the aspheric one. See Fig. 2.7 for the MTF given after optimization. Although the system is diffraction-limited, the need to have the aspheric lens as well as the compensating lenses custom-made in addition to the added overall complexity of the system is outweighed by the ease-of-use and relative cost of the aspheric system. Investigation of magnifying the spot size of this lens to match the MFD of the fiber was not conducted.
Chapter 3

Diffractive Optical Elements

3.1 Introduction

Diffractive optical elements (DOEs) have been investigated for some time as an alternative to conventional, refractive optics. They are used today as lenses in projectors and lighthouses, often made of plastic. Since their method of action is diffractive in nature, the thickness of the optic needs to be no greater than a few wavelengths, rather than the millimeters or tens of millimeters that are required for the action of a refractive lens. Furthermore, their ability to be made out of plastic, such as projector lenses are, allows a significant reduction in mass in addition to that obtained from the reduced thickness. This reduction implies that the rotational moment of the phased array system will be significantly reduced compared to the same system with refractive optics. This allows the elimination of the Keplerian telescope discussed previously, and the use of a single, slow ($\sim F/7$) diffractive optic as the entire collimation system. Currently, small-aperture—on the order of millimeters—DOEs are used in many applications, such as medical imaging, and regularly achieve diffraction-limited performance even in a small wavelength band, rather than at a specific wavelength [7]. However, DOEs with exceptional optical performance that are much larger than a few centimeters in diameter are not currently
Due to their diffractive nature, DOEs are usually inadequate when used for imaging applications, as they are highly wavelength dependent. The feature height is ideally (for diffraction into the first order)

\[ t = \frac{\lambda}{n - 1}, \]  

(3.1)

where \( n \) is the index of refraction of the material, with a 1% diffraction efficiency degradation for every 5% difference in the thickness from the ideal for a given wavelength [4]. However, for a narrow line-width laser as is suggested for directed energy propulsion, these optics can be ideal if they can achieve similar performance as an aspheric optic at a single wavelength, as DOEs are relatively insensitive to small variations in feature heights, as indicated by Eq. 3.1.

An example surface profile is shown in Fig. 3.1. A lithographically etched surface profile is obtained after several subsequent etching steps, which finally give the profile in (d). These are generally called phase levels, with a greater number of levels achieving a closer approximation to the ideal, blazed structure. Generally, 8 phase levels is enough to achieve >90% diffraction efficiency, with 16 levels being the ideal. Adding more levels beyond this is often not necessary. Another approach to manufacturing DOEs is greyscale lithography, which etches away just the right amount of resist to obtain the blazed structure nearly perfectly. This is a recently developed process which has been very successful and is another option for manufacture of DOEs. It is similar in idea to diamond turning.

The only known example of extremely large-aperture DOEs that were manufactured for diffraction limited performance (albeit at very slow stops—\( F/40 \) to \( F/50 \)) is the DARPA MOIRE program. This program requested a 1 m aperture DOE manufactured by the diamond turning group at Lawrence-Livermore National Laboratory (LLNL). This lens was successfully manufactured, and—although the program was cancelled—the lens achieved 55% diffraction efficiency with only 4 phase levels [5]. If a 4 phase level design was successfully implemented
Figure 3.1: The traditional photolithographic etching process for a DOE which is to focus as the lens in (a). The ideal structure is given in (b), while the iterative process is given in (c) and (d), where a binary profile is obtained after one etching step in (c), giving a theoretical diffraction efficiency of $\eta = 40.5\%$. 4 phase levels, pictured in (d), provide $\eta = 81\%$ (according to scalar diffraction theory) [4].

at the meter-class level, then an 8 or 16 phase level design is possible at the 0.1 m-class. Furthermore, the minimum feature sizes for the MOIRE program’s 4 phase level design are on the order of $1\,\mu m$, while the minimum feature sizes of the 8 phase level optic proposed in the following section would be on the order of $1.9\,\mu m$, corresponding to a theoretical diffraction efficiency of 94%. Noting that the MOIRE program used diamond turning rather than lithography to create their lens is key, however, as lithographic methods may be inadequate for even modest 10 cm lenses. On the other hand, as mentioned previously, greyscale (maskless) lithography is an alternative fabrication method that eliminates the need for several masks and for a several-step lithographic process. This has been extensively studied and tested, achieving sub-micron resolutions on $>10$ cm scales [9].

The MOIRE program was interested in an ultra low-mass final optic for space applications, and they contracted Nexolve to replicate their DOEs using their proprietary thin-film replication process. Purportedly, this was successful, and the resultant films retained excellent total thickness variation (TTV) and bow/warp when mounted well. The films were of order microns to tens of microns thick [8]. Thin-film replication, if scaled appropriately, is a path forward to low-cost mass-manufacturing of DOEs, which would be required for the implementation of a several-array system.
3.2 DOE Design in Code V

A DOE was designed in Code V using its built-in physical optics capabilities. DOEs in Code V are modeled according to a phase polynomial, which is a function, \( \varphi(x, y) = \sum_m \sum_n C_{m,n} x^m y^n \), of the coordinate on the surface of the DOE, whose value is the phase change applied to incoming photons at that point on the surface. Although this can generally be a function of the two spatial coordinates, \( \varphi(x, y) \), since the DOE is to function as a lens, no asymmetry is needed. Therefore, a radially symmetric phase polynomial was chosen: 
\[
\varphi(r) = \sum_{j=1}^{10} C_j r^{2j}
\]
(only up to 20th order is supported). Although a phase polynomial including odd powers of \( r \) can be used in Code V, the chosen phase profile with only even powers was sufficient for this design.

The quadratic phase coefficient, \( C_1 \), determines the focal length of the optic by 
\[
f = \frac{-1}{2C_1}.
\]
Since a target aperture of 10 cm is desired, this optic will likely be patterned on a standard 4" or 100 mm wafer. However, mass-production considerations may require a master that is patterned on a larger substrate to allow for easy replication. Generally, 3 mm of the edge of the wafer/active area are not patterned well, so the clear aperture would be on the order of 97 mm. Using this and Eq. [1.2] we obtain \( 2\omega = 87.3 \) mm and \( f = 710 \) mm for a \( 2\omega_0 = 11.0 \) \( \mu \)m. The quadratic coefficient was entirely determined from the choice of \( f = 710 \) mm. The other phase polynomial coefficients were set to 0. The thickness of the optic was nominally chosen as 6 mm, due to manufacturing constraints of the greyscale lithography machine. Optimization of the optic at various thicknesses shows that this metric does not have an appreciable effect on the optical performance, as long as the optimization is performed at the manufactured thickness. Likewise, the glass was chosen as fused silica and the desired diffraction order as the first. An optimization was conducted on the \( C_2 \) coefficient, which—assuming 100% diffraction efficiency—provided diffraction-limited performance at up to a milliradian off-axis, see Fig. 3.2. Due to this almost ideal performance, no further optimization
Figure 3.2: The MTF for the optimized DOE after optimization of the quartic order phase polynomial coefficient. All fields are almost ideally diffraction-limited, suggesting that the only limiting factor of optical performance is diffraction efficiency, assuming an ideal substrate.

was conducted on the higher order coefficients.

Code V has implemented both scalar diffraction theory and the same extended theory into their code. These theories provided theoretical diffraction efficiencies of 94% for an 8 phase level DOE, 80% for 4 levels, and 40% for a binary design. Moreover, the program outputs a surface profile—height as a function of radius—for the optic assuming perfect fidelity to the desired structure (i.e. \( \infty \) phase levels), see Fig. 3.3. Discretization of the smallest feature into 8 steps provides a minimum feature size of 2.1 \( \mu \text{m} \), requiring precision photolithography for manufacture.

3.3 DOE Manufacturing Tolerancing and Processes

Since a DOE would be manufactured lithographically on a likely quartz substrate, an understanding of imperfections in such substrates is necessary, to ensure that the finished product will behave as desired. These imperfections are normally divided into three areas: surface roughness, bow/warp, and total thickness variation. Surface roughness figures are generally on the order of tens of nanometers, so this metric is not going to be an issue on manufactured substrates. This is due to diffraction being a phenomenon that occurs on the scale of the size
Figure 3.3: DOE surface profiles given by Code V for a 10 cm diameter, circular, radially symmetric DOE. The profile shown here gives sag as a function of radius; this profile would be revolved around the vertical (i.e. optical) axis to obtain the three-dimensional surface profile, looking something like (d), which is a view from above—along the optical axis. As can be seen in (c), the steps have much less length in the radial direction near the edge of the optic than in the center. This minimal distance is of order 15 µm.
of the wavelength of light of interest. Hence, in order to better understand the tolerances of a manufactured DOE, only effects of bow/warp and TTV on the optical performance of the optic need to be investigated. Code V supports surfaces modeled by Zernike polynomials, so an attempt to model possible imperfections using these polynomials was made. Mathematica was used to induce a pre-defined amplitude perturbation onto the unit disk, and Zernike coefficients were then obtained by means of a fit to the disk. Code V supports only a low number of input coefficients—37, so the fit was necessarily poor. High frequency perturbations could not be reliably fit using only 37 Zernike polynomials. Furthermore, differences in the definitions and numbering of the polynomials in Mathematica and Code V—which diverged significantly after the 20\textsuperscript{th} polynomial—limited the effective number of usable polynomials to 20. No appreciable change was seen when attempting to use 40 coefficients (from Mathematica’s definitions), however.

Example perturbations are shown in Fig. 3.4 which were obtained by choosing a single frequency (i.e. single number) in frequency space and then performing a discrete Fourier transform to transfer it to position space. How well these kinds of perturbations correspond to real bow/warp or TTV perturbations in substrates is unclear, and modeling of such perturbations cannot be achieved in Code V using this method.

Several model perturbations were chosen, see Fig. 3.5. The Zernike coefficients obtained from the fits were then linearly scaled to be normalized over a 50 mm radius disk rather than the unit (i.e. 1 mm) disk for which they were fit. The peak-to-peak amplitude was then varied to test the optical performance of the DOE system.

Upon investigation, TTV values were found to be relevant on the order of hundreds of nanometers, while bow/warp amplitudes on the order of tens of microns. These were implemented into Code V by adding the Zernike coefficient perturbations to only one surface—TTV—or to both surfaces—bow/warp. Figs. 3.6, 3.7, and 3.8 show the degradation in optical performance of the DOE system as the TTV peak-to-peak amplitude is increased. These sim-
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Figure 3.4: An actual perturbation (a) with a chosen frequency of 4 peaks over the surface of the unit disk. This is not fit well by only 20 Zernike polynomials (b) using Mathematica’s built-in fit functions. Thus, perturbations had to be chosen that provided appreciably different fits, as only these fits could be input into the Code V software. As a glance at Fig. 3.3 will show, the shape of (b) is not too different from the half-frequency fit in that figure. Hence, only a few frequencies produce noticeably different resultant fits.

Simulations suggest that no greater than $\lambda/4 \approx 250$ nm peak-to-peak TTV amplitudes can be tolerated. Noting that in Fig. 3.7b there is already a significant decrease in system performance, 250 nm may still be too large, depending on how realistically the simulated perturbations approximate real surface variations on substrates. However, the system is not nearly as sensitive to bow/warp.

Figs. 3.9, 3.10, and 3.11 give MTFs for the DOE system with bow/warp perturbations of 30$\mu$m, 40$\mu$m, and 50$\mu$m, respectively. These were chosen as they are near the limit of acceptable performance for the optical system, as can be seen from Fig. 3.11 where significant degradation is present in Figs. 3.11a and 3.11b corresponding to Strehl ratios less than 80%. Moreover, in general, fused silica and quartz wafer bow/warp tolerances are often much less than 10$\mu$m, so that these requirements are not stringent. Thus, simulations were not conducted for even larger amplitude bow/warp perturbations.
Figure 3.5: Chosen perturbations (after fitting) for modeling TTV and bow/warp in Code V. These all have 100 nm peak-to-peak amplitudes. As was found after comparison, bow/warp amplitudes can be tens of microns without appreciably affecting optical performance, while TTV amplitudes were required to be of order $\lambda/10$, or $\sim 100 \mu$m peak-to-peak.

3.4 DOE Replication Processes

3.4.1 Nanoimprinting Lithography

Generally, high-performance DOEs are made with multi-level, expensive photolithographic processes [10, 7]. A possible method of circumventing this process in the mass-production of identical DOEs is nanoimprint lithography of a master made with traditional photolithography. Photolithographic techniques can regularly achieve sub-micron feature sizes with ease, sug-
Figure 3.6: MTFs for the three different perturbation types considered with 100 nm TTV. Note that all three types remain diffraction-limited at all fields.
Figure 3.7: MTFs for the three different perturbation types considered with 250 nm TTV. Note that although (a) and (c) appear to remain (nearly) diffraction-limited at all fields, (b) has a significant degradation in performance. This degradation is not tolerable, so, for real systems, careful testing must be done to determine whether 250 nm peak-to-peak TTV is tolerable or not.
Figure 3.8: Here, significant degradation is seen for each case, with even (c) having a Strehl ratio of less than 80% when optimized to perform at the fields given (simultaneously). This implies that 300 nm perturbations are certainly unacceptable.
Figure 3.9: MTFs for bow/warp with 30 µm peak-to-peak amplitudes. Although some degradation in optical performance can be seen in (a), the optic does remain diffraction-limited at all fields. This is certainly true for (b) and (c), already suggesting that DOEs are less sensitive to bow/warp than TTV.
Figure 3.10: As in Fig. 3.9, the most degradation in performance is in (a), but this is still within the diffraction-limit (though just barely—the Strehl ratio is 85%). Generally, bow/warp perturbations on non-optical quality substrates are <20 µm, so these tolerances are already non-issue. They were however taken out as far as possible—see Fig. 3.11.
Figure 3.11: In (a), we finally pass the diffraction-limit, obtaining a Strehl ratio of 78%. (b) has a Strehl ratio of 85%, suggesting that bow/warp perturbations much greater than these will cause significant degradation in image quality.
suggesting that — although it may be an expensive one-time cost — the master could be made without significant process development. The possibility of success of imprinting it is unclear. Nanoimprinting of 3\(\mu\)m features has already been achieved for diffractive optic replication in PDMS, but much more precise nanoimprinting has been conducted for other purposes — on the order of 100 nm with the use of Nanonex machines as early as 2004 [10, 11]. This suggests that a nanoimprinting process for DOEs with \(~1\mu\)m feature sizes may be viable, though the literature does not provide evidence of this.

### 3.5 DOE Testing and Manufacturing

Due to the high cost of manufacturing an 8 phase level diffractive profile, a binary one was chosen to be made first. This allows cheaply testing the optical qualities of the pattern and substrate, as the only degradation due to less phase levels is in diffraction efficiency. The only way this would manifest in tests of the optic is less power in the central spot—not in a degraded focus. Thus, testing of substrates as well as the pattern itself can be obtained through this relatively cheap method, for which a single mask costs only several hundreds of dollars. Standard processes in photomask manufacturing require a properly designed profile in the appropriate computer file format. Python was used to design such a profile in the GDSII format, which is pictured in Fig. 3.12. All units are in microns, so that in Fig. 3.12c, one can see the minimum feature size to be 8.5\(\mu\)m, or about half of the nominal 17\(\mu\)m \(\approx\) 15\(\mu\)m. Fig. 3.12b shows the central several mm of the optic, where one can clearly see the ring pattern (not obvious from 3.12a). The red regions correspond to regions that will not be opaque on the photomask, so that the resultant profile is a negative of the one that will be etched into a chosen substrate.

Since the photomask is a binary pattern, there actually should be no difference whether it is the negative or the positive version, as the diffraction of the light will not be affected by this
Figure 3.12: Snapshots of the GDSII file created for production of a binary pattern photomask for DOE manufacture.
orientation. Thus, assuming the photomask substrate itself is transparent at 1064 nm, then it can be used for initial testing of the DOE pattern and substrate surface perturbations. Since it should focus light just as the aspheric lenses discussed in Section 2.1, a setup where laser light emitted from an 11 µm MFD fiber is collimated by the asphere system discussed in that section can then be refocused using this DOE to determine the perturbations introduced from the fidelity of the patterning as well as from substrate imperfections. This was performed, and no significant degradation was found due to substrate imperfections, suggesting that the soda lime plate substrate on which the photomask was patterned had perturbations that did not have a significant effect on the OPLs of the incoming rays. Although the bow/warp specifications for this substrate were within the simulation requirements for diffraction-limited performance, the TTV specifications were not, suggesting that there is a discrepancy between either the simulation, or—more likely—between the kinds of perturbations considered in Section 3.3 and those that actually appear on real substrates. The immediate next step is to use a Zygo interferometer or similar full-surface profilometer to obtain the actual surface profile on the substrate used. A Zygo approach would be especially useful, as these interferometers can give the Zernike coefficients corresponding to the measured surface and hence be used as a way to input the surface profile into Code V for further simulation of substrates. However, Zygo interferometers are expensive, and our group nor UCSB has one on-hand that can be used. Because of this lack, a profilometer from the nanofab that can profile on small-scales (i.e. not the entire surface) will be used to determine at least small-scale variations in total thickness and bow/warp.
Chapter 4

Conclusion and Future Work

Several designs were investigated and compared to determine the ideal collimation system for laser elements in an array, from the standpoint of optical performance as well as cost- and mass-efficiency. An aspheric design is likely the best option for optical performance, as these were shown to be diffraction-limited with lenses chosen from stock options from common lens manufacturers. However, a DOE system can theoretically be made to perform just as well, with only a few percent losses in intensity due to a $\lesssim 100\%$ diffraction efficiency. Preliminary experimental tests with possible substrates show that the sensitivity of optical performance of DOEs predicted by the simulations in Section 3.3 are not as stringent as initially thought. This initial experimental development is promising, as it suggests that non-specialty substrates are sufficient to obtain relatively diffraction-limited performance after patterning. This suggests that cheap replication may be feasible, but more testing is required of different replication techniques, such as those mentioned earlier.
Bibliography


