Multi-wavelength Characterization of Multi-Order Diffractive Lenslet Arrays

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**Abstract:** Multi-order diffractive (MOD) lenslet arrays were characterized for Strehl ratio, f/#, and efficiency at multiple wavelengths. The focal ratios as a function of wavelength were deduced from analysis of images of illuminated lenslets.

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# Introduction

The Shack-Hartmann wavefront sensor (WFS) is a technology widely used for aberration characterization, particularly for adaptive optics. At the heart of the sensor is a lenslet array that divides the optical system’s pupil into discrete regions over which the local geometric tilts of incoming wavefronts are measured. Tailoring the WFS to the requirements of a particular optical system often means that a custom lenslet array must be used. These components are generally expensive and require significant manufacturing lead time. We are exploring instead the use of multi-order diffractive lenslet arrays manufactured via maskless photolithography. The process offers rapid turn-around from initial design to completed part and is cost effective. Furthermore, multiple components of the same design may be easily and quickly replicated in cast epoxy from a single mold made by photolithography. In this paper we describe the manufacture and test of three variants of the multi-order diffractive lenslet array.

# Manufacture

Our motivation is to develop inexpensive lenslet arrays for use in experiments to demonstrate the utility of tomographic wavefront sensing from an imaging Shack-Hartmann sensor for terrestrial applications [1]. The lenslet array requirements are listed in Table 1.

Table 1. Lenslet array requirements.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Lenslet diameter | 0.75 mm |
| Focal ratio | f/19 |
| Waveband of operation | 500 – 750 nm |
| Array size | 20 x 20 lenslets |
| Fill factor | >95% |

Three lenslet arrays were designed and manufactured in-house by our group. They were made on BK7 substrates 25.4 mm in diameter and 6 mm in thickness. The array is designed to be 15 x 15 mm. The 400 subapertures are etched into photoresist on the substrate [2]. The arrays are designed at a center wavelength of 650 nm. Each aperture is a multi-order diffractive lens (MOD), which features concentric Fresnel zones.

The lenslet arrays and the phase plates were fabricated using the Maskless Lithography Tool (MLT) at the University of Arizona, a direct-write laser lithography writer. The exposure wavelength of the MLT is 365nm and the spot diameter of the focused writing beam is 2.1µm. The beam is modulated using an acousto-optic modulator (AOM) and a scanline is generated with a rotating polygon mirror on an air bearing spindle. Samples are placed on a set of motorized X, Y, and Z stages. During exposure, the beam scans along the X direction while the Y stage provides the other degree of motion. Exposure occurs pixel by pixel based on data input in the form of bitmap files with 8-bit depth. Modulation is synchronized with stage position and the start of each scanline. The resist used for fabrication was Fujifilm AP2210B Polyimide. Using a calibration print, the nonlinear responses of the AOM and photoresist are measured and accounted for allowing for linear surface relief of specific depths to be fabricated.

The three lenslets are differentiated by whether one, two, or three passes of photolithographic writing onto the photoresist were made [3]. The shapes of individual lenses, measured by white-light interferometry, are shown in

Figure 1. 1-Wave lenses Figure 2. 2-Wave lenses



Figure 3. 3-Wave lenses



The use of more than one pass allows deeper profiles to cut, reducing the number of zones in each lenslet. In principle, this will improve the diffraction efficiency of the lenslet. In practice, the diffraction efficiency may suffer because of artifacts introduced by misregistration of the lenslet array under the photolithographic writing head between passes.

# Testing

The 1-wave, 2-wave, and 3-wave lenslets were assessed to confirm their focal ratios, Strehl ratios, and efficiencies at 3 different wavelengths as well as physical features such as the dead space between apertures and the diameter of each lenslet. The efficiency is simply defined as the fraction of light incident on each subaperture that appears in the corresponding diffraction pattern. The focal ratios, Strehl ratios, and efficiencies are determined through analysis of PSFs of the lenslets measured on a Point Grey Flea3 CMOS camera with the arrays illuminated by a collimated laser light source. A supercontinuum laser is to be used with a monochrometer to do a sweep through visible wavelengths. Custom MATLAB scripts perform the analysis. The programs crop individual PSFs in a 30 x 30 pixel square and fit the point spread function (PSF) of each individual subaperture of the array to an expected PSF from a square aperture, which is calculated based on the relation of the PSF to the Fourier transform *F* of the aperture function *A*,

( 1 )

( 2 )

where *L* is the linear size of each lenslet, (*x,y*) are coordinates in the pupil plane, and (**) are coordinates in the focal plane. Equation (3) gives the relationship to convert from spatial frequency back to units of length at a wavelength ** for a lens of focal length *f*.

( 3 )



Because a CMOS detector is used for imaging, we measure the power of the wave, not the field, so we must square Equation 2. Making the substitutions and noting that , we get Equation (4).

( 4 )



This gives us the expected shape of each lenslets’ PSF. If we then fit the image of the PSF with Equation 5 we find that with a similar result for . Thus, the expression determined to fit the images to is given by equation (5).

( 5 )

In Equation 5, and are simply for convenience so that any decenter of the image is compensated for in the fit. From there, the focal length in each direction is found by knowing the lenslet pitch.

As of this writing, the three lenslets have been assessed only at 628 nm. Measurements at other wavelengths are in progress. The estimated Strehl ratios are very high, with the 2- and 3-wave arrays exhibiting values indistinguishable from 1 given the uncertainty in modeling the distribution of energy in the focal plane. The focal ratios are consistently slightly higher than predicted which is likely attributable to uncertainty in the refractive index of the resist material at this wavelength. Future lenslet arrays manufactured in this way can take this result into account. The efficiencies are also satisfactorily high, with no evidence that there is a trend toward either higher or lower efficiency with the number of photolithographic passes.

Table 2. Results of measurement analysis on the three lenslet arrays.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Wavelength** | **Array** | **Strehl value** | **f/# (x-direction)** | **f/# (y-direction)** | **Correlation** | **diff in x-y** | **Normalized Eff (%)** |
| **628 nm** | 1 Wave | 0.97 | 22.034 | 21.801 | 0.99 | 0.23 | 96.12 |
| 2 Wave | ≈1 | 20.982 | 22.643 | 0.98 | 2.411 | 97.36 |
| 3 Wave | ≈1 | 19.719 | 19.762 | 0.98 | 0.49 | 96.4 |

# Discussion

Preliminary testing has confirmed that our photolithography method for fabrication of MOD lenslet arrays is effective. The most notable feature of the data taken thus far is the difference in the x and y-direction focal ratios of the 2-wave lenslet. This array had an average difference of 2.4 while the 1-wave and 3-wave had average differences of 0.23 and 0.71, respectively. The y-direction focal ratios were consistently greater than those in the x-direction on the 2-wave array. This is possibly due to an isolated error during fabrication of the array, likely a small translation along one of the principal axes. Given this finding, the 2-wave array may be excluded from the remaining testing at different wavelengths. Once all measurements are completed, the behavior of the focal ratio with respect to wavelength will be used to refine the design of further lenslet arrays.

# References

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