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Differential Phase Measuring Deflectometry for On-Machine Metrology of Ultrafast Laser Stress Figuring

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ABSTRACT

Ultrafast laser stress figuring (ULSF) currently allows for the figuring of large aspect ratio fused silica mirrors with an accuracy of <20 nm RMS over 6 orders of Zernike polynomials. While similar technologies are capable of this accuracy, ULSF has the potential to be orders of magnitude faster. ULSF is an iterative process in which (1) an optic is figured, (2) optical metrology is used to measure the surface figure, and that measurement is used as feedback to repeat this closed-loop process and further figure the mirror until the mirror has reached the desired figure. We present an in-situ, on-machine optical metrology system that measures the mirror surface figure using differential phase measuring deflectometry (DPMD). After an absolute measurement of the surface figure is done using interferometry prior to any figuring, our differential deflectometry system can measure the change in surface figure after each laser stress figuring process. This eliminates the need to remove the mirror from its mounting, which can induce non-repeatable surface figure errors during the metrology step. The differential deflectometry system is also used to calibrate the ULSF process prior to the figuring of the mirror. We utilize and characterize the in-situ differential deflectometry system during the surface figuring of a 25.4 mm fused silica mirror and summarize the results in this proceeding.

Keywords: stress figuring, space optics, x-ray optics, on-machine metrology, flat optics

1. INTRODUCTION

1.1 Ultrafast Laser Stress Figuring

Ultrafast laser stress figuring (ULSF) is a method of accurately figuring lightweight, high aspect ratio, freeform mirrors. An ultrafast laser focuses pulses into fused silica and can produce either tensile or compressive stress (See Fig. 1). This method of stress figuring has been demonstrated on a 100 mm diameter, 1mm thick flat mirror with 10-20 nm RMS error. This is also done without impacting midspatial frequencies which is an issue that arises when using other lightweight figuring methods. (See Ref. 1 and Ref. 2 for more detailed information on the ULSF process. While the ULSF process has all these advantages, it is currently metrology limited to guide the fabrication process.

The figuring process is iterative. In the process described in Ref. 1, the mirror that is to be figured is first measured using a Fizeau interferometer, mounted in the ULSF setup and then figured. The mirror is unmounted and measured to determine if it has reached the desired shape or what further figuring must be done. If more figuring is needed, the mirror is again mounted in the ULSF setup and the process begins again. While this process has worked with 25.4 mm diameter, 1 mm thick fused silica mirrors, when figuring 100 mm diameter, 1mm thick fused silica mirrors, non-repeatable errors are observed. These non-repeatable errors are introduced while mounting and unmounting and moving the mirror from the interferometer to the ULSF setup (and vice versa). To achieve lower RMS errors, it would be appropriate to introduce an in-situ on-machine measurement system that would remove the need to move the mirror during the figuring process. We implement this in-situ on-machine measurement system using differential phase measuring deflectometry.

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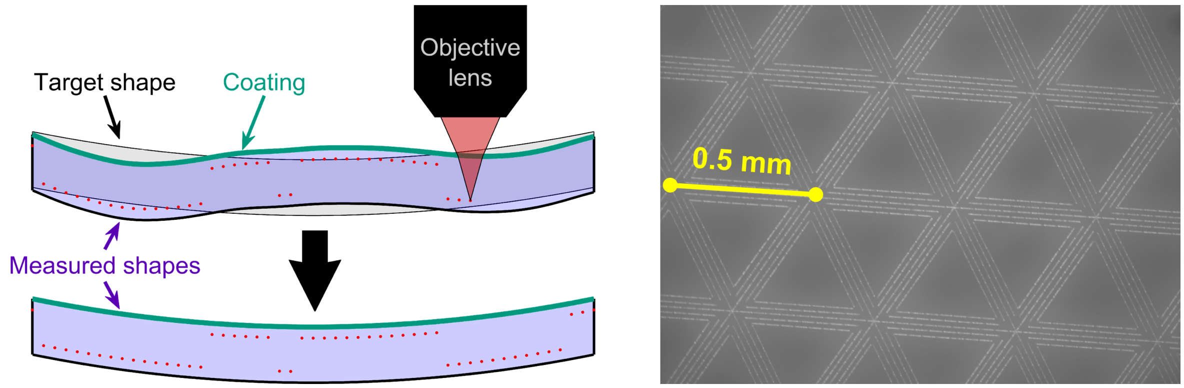

Figure 1. (left) Diagram of the ULSF process in which an ultrafast laser is pulsed into the top and bottom of a mirror in order to figure the thin mirror's surface shape. (right) The patterns seen after multiple figuring runs.[1]

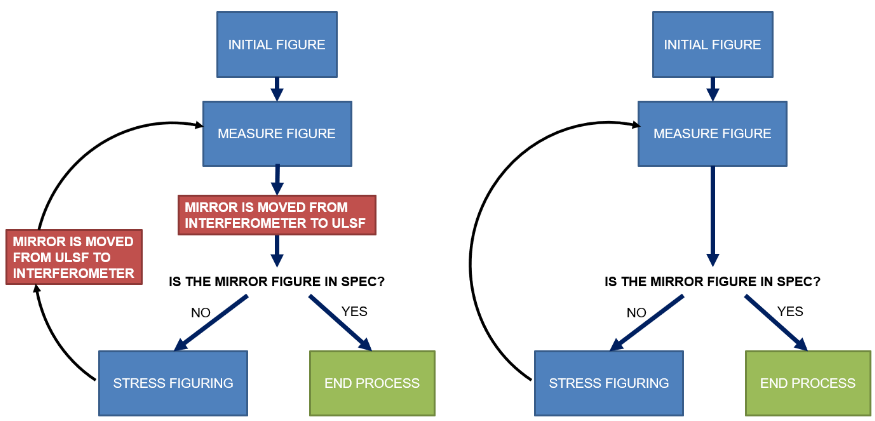

Figure 2. (left) A diagram showing the previous figuring process in which an interferometer was used and the mirror needed to be moved between the ULSF setup and the interferometer. (right) A diagram showing the improved figuring process using an in-situ on-machine measurement method.

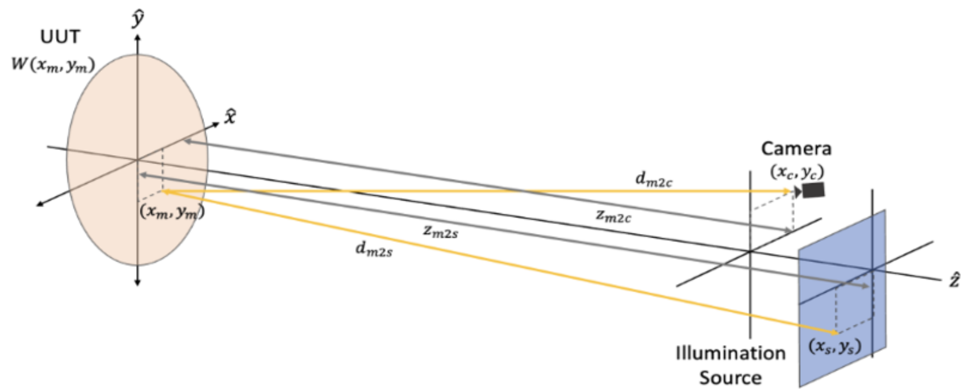

Figure 3. A diagram showing the elements of a phase measuring deflectometry metrology system.[3]

1.2 ULSF In-situ On-machine Metrology Method

1.2.1 Phase Measuring Deflectometry

Phase measuring deflectometry is a metrology method used to measure specular surfaces and is often described as a reverse Hartmann Test. This method utilizes an illumination source that displays a pattern (in this case, a fringe pattern), the unit under test (UUT) and a camera that captures the reflection of the pattern off the UUT (see Fig 3). The camera is focused on the UUT (not the fringes). For the ULSF metrology system, fringe patterns at multiple phases in both the horizontal and vertical direction are displayed and captured. Using the reflected images captured on the camera, pixels on the illuminations source can then be correlated with pixels on the camera and points on the UUT. Using the location information of these pixels and points, the local surface slope of the UUT at a point can be calculated. Eq. 1 gives the equation that is used to determine the slope at a point on the UUT in the y-direction. In Eq. 1 y_m, y_s, and y_c are the y-coordinate of the UUT, illumination source and camera respectively and z_{m2s} and z_{m2c} are the distances from the UUT to the illumination source and the distance from the UUT to the camera.[3] An equivalent equation is used to find the slope in the x-direction using the x-coordinates for the UUT, illumination source, and camera.

$$S_y \approx \frac{1}{2}(\frac{y_m - y_s}{z_{m2s}} + \frac{y_m - y_c}{z_{m2c}}) \tag{1}$$

This slope information can then be integrated in order to calculate the surface height map with nanometer level precision.[4] While phase measuring deflectometry does have the precision and the elements are simple enough to be incorporated into the ULSF setup, it has strict tolerances on the position information of the UUT, illumination source and camera. However, these tolerances can be made less stringent by utilizing differential phase measuring deflectometry.

1.2.2 Differential Phase Measuring Deflectometry

Differential Phase Measuring Deflectometry (DPMD) is a metrology technique developed to attain the benefits of high sensitivity, comparable to phase shifting interferometry, without the need for complex equipment. Typical phase measuring deflectometry requires very accurate knowledge of the location and orientation of each component but if one only needs to obtain a differential height data, looser tolerances can be used. This can be seen by comparing the slope with error of an absolute measurement (Eq. 2) and the slope with error of a differential measurement (Eq. 3).[5]

$$S_y \approx \frac{1}{2}(\frac{(y_m + \epsilon_{y,m}) - (y_s + \epsilon_{y,s})}{z_{m2s} + \epsilon_{z,m2s}} + \frac{(y_m + \epsilon_{y,m}) - (y_c + \epsilon_{y,c})}{z_{m2c} + \epsilon_{z,m2c}}) \tag{2}$$

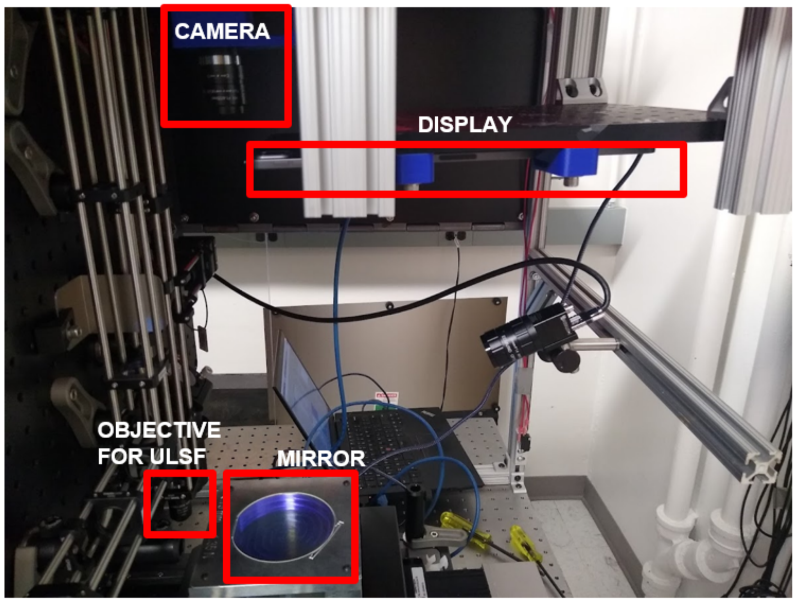

Figure 4. The DPMD setup used in the ULSF process (note that in the results reported in this paper, we used a 25.4-mm, not the 100-mm seen in the photo).

$$\begin{aligned}\Delta S_y &= S_y - S_y' \\ &\approx \frac{1}{2}\left(\frac{(y_m+\epsilon_{y,m})-(y_s+\epsilon_{y,s})}{z_{m2s}+\epsilon_{z,m2s}} + \frac{(y_m+\epsilon_{y,m})-(y_c+\epsilon_{y,c})}{z_{m2c}+\epsilon_{z,m2c}}\right) \\ &- \frac{1}{2}\left(\frac{(y_m'+\epsilon_{y,m})-(y_s'+\epsilon_{y,s})}{z_{m2s}'+\epsilon_{z,m2s}} + \frac{(y_m'+\epsilon_{y,m})-(y_c'+\epsilon_{y,c})}{z_{m2c}'+\epsilon_{z,m2c}}\right) \\ &\approx \frac{1}{2}\frac{y_s'-y_s}{z_{m2s}+\epsilon_{z,m2s}}\end{aligned} \tag{3}$$

It is clear that differential measurement is only affected by the error in distance from the UUT to the screen and camera. Because of its tolerance to alignment error and ease of installation and use, DPMD was used as the metrology method for the in-situ on-machine ULSF figuring process.

2. MATERIALS AND METHODS

The DPMD experimental setup consists of a 12.9" iPad Pro as the illumination screen source, a Point Grey monochrome camera (FL3-U3-13Y3) with a 25-mm focal length lens, and a 25.4 mm diameter, 1 mm thick fused silica wafer with a dielectric Bragg mirror for high reflectivity around 633 nm. The mirror is mounted on a precision Aerotech stage (PlanarDL-200XY) that can move the mirror from the ULSF figuring position to a position in which it can be measured by the DPMD setup (see Fig. **??**). The camera and display are mounted using 80/20 framing, an optical breadboard and custom 3D printed brackets. The equipment used for the ULSF process was an Trumpf TruMicro 2030 ultrafast laser with 1030 nm wavelength, 350 fs pulse duration, 0.59 µJ pulse energy. The ultrafast laser is focused using a 0.4 NA objective lens.

3. RESULTS

3.1 Comparing DPMD with Interferometry

The DPMD system was initially tested by comparing it to Fizeau interferometry measurements during calibration runs on a 25.4-mm diameter, 1-mm thick fused silica mirror. Calibration is done by writing laser spots along six

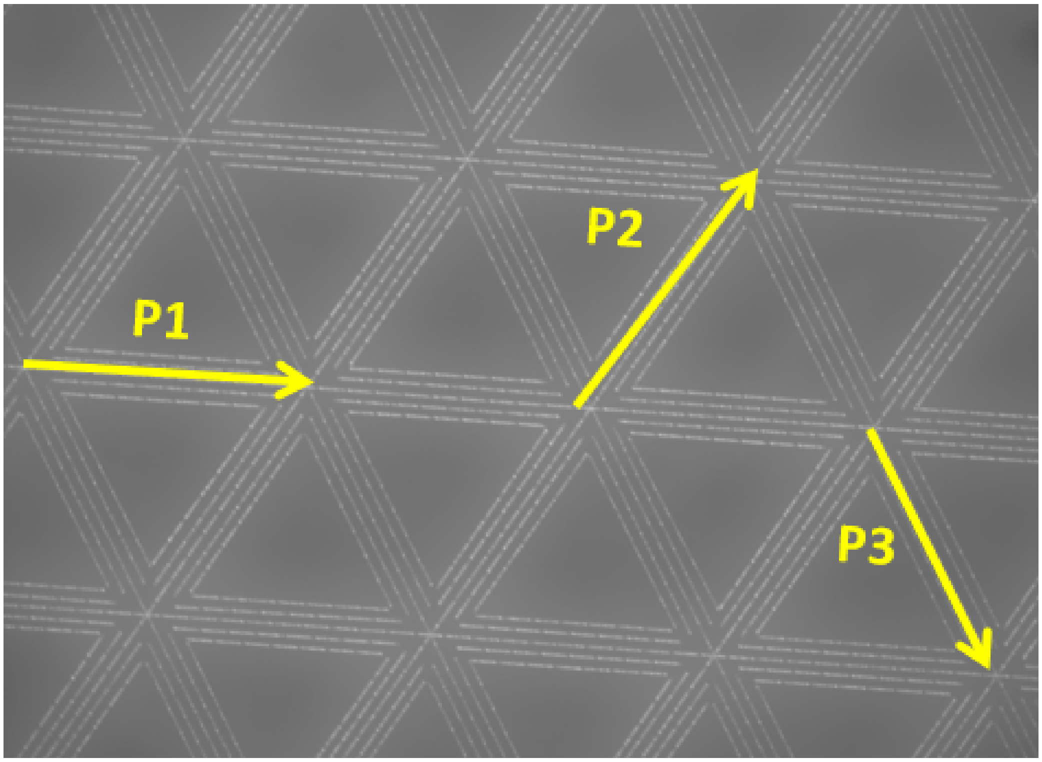

Figure 5. Microscope image of the mirror after it has been figured with the calibration runs. The orientation of paths 1-3 can be seen. Paths 4-6 are written at a different depth but have similar orientations.

different paths (three at two different depths). The orientation of paths 1-3 can be seen in Fig. 5. Differential calibration measurements were taken by measuring the mirror before and after writing each calibration path with both the Fizeau interferometer and the DPMD system. As seen in Fig. 6, it is clear that the measurements are qualitatively similar but the deflectometry measurement is scaled by a constant. By looking at the low order Zernike terms of the surface measurements, as seen in Table. 1, it can be seen that the deflectometry measurements are different from the interferometry measurements by a factor of 0.55 (Zernike terms are labeled using Noll ordering). While this is not ideal, this factor of 0.55 is consistent enough to be used in the iterative figuring process. Also, this can be eventually calibrated out after careful investigation of any potential systematic error sources.

3.2 Measurement Stability and Repeatability

To determine the stability of the DPMD metrology system, a 25.4 mm diameter, 1 mm thick fused silica mirror was measured 30 times using the DPMD system. The piston, tip and tilt were removed from all measurements. The average of the 30 surface height maps was labeled the "TRUE" map. Then, N measurements were randomly selected. The"TRUE" map was then subtracted from each of these randomly selected height maps. The RMS of this difference map is then calculated, and the average and standard deviation was then determined. The standard deviation is the uncertainty of the RMS. This was done for $N = [1, 2, ..., 29, 30]$.[6] This was also done to test the repeatability by performing the same procedure except the mirror and stage were moved from the measurement point to the figuring point between measurements (no figuring was done). As seen in Fig. 7, both the stability and repeatability RMS uncertainty decreases at a similar rate with an increasing number of measurements. This indicates that moving the stage does not meaningfully affect the measurements, which highlights the highly robust and stable manufacturing platform of ULSF.

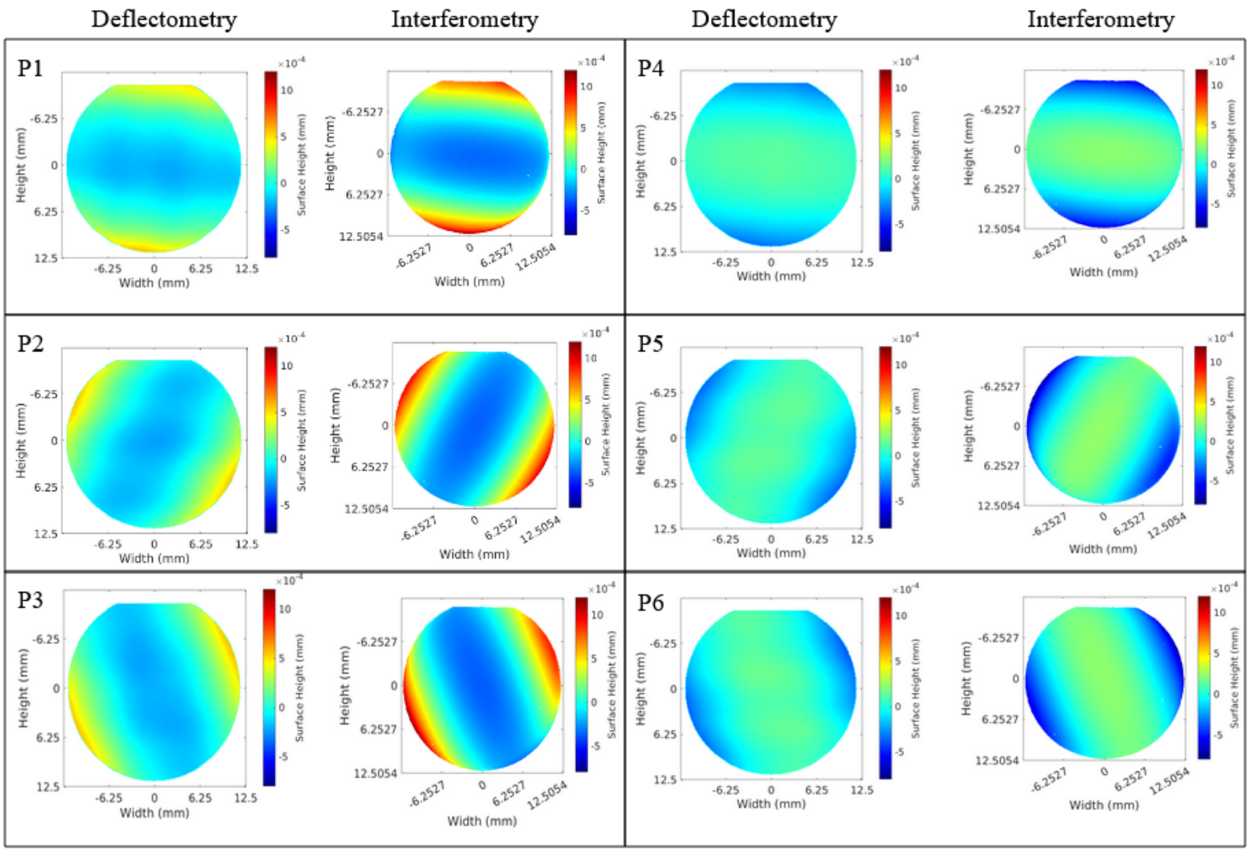

Figure 6. Comparison of the surface height measurement of the Fizeau interferometer and the DPMD system after each of the six calibration passes.

3.3 ULSF Results

With the calibration done using the DPMD metrology system, a 25.4 mm diameter, 1 mm thick fused silica mirror was then figured to have 1.0 wave (at 633 nm) of astigmatism (Z6), 0.5 wave of trefoil (Z8), and 0.5 wave of coma (Z10). As seen in Fig. 8, the ULSF and DPMD figuring process was successful in achieving this arbitrary surface figure. Decomposing the difference map of these two surface figures into Zernike terms, it was found that the lower order Zernike terms (Z4-Z15) of this difference map had a residual error of 18.9 nm RMS and the higher order terms (Z16-Z32) had a residual error of 15.8 nm RMS. The root sum square (RSS) error of all these Zernike terms (Z4-Z32) was 24.8 nm. It is clear that the DPMD metrology system can be used along with ULSF to figure high aspect ratio mirrors with a precision of better than $\lambda/20$ at 633 nm.

Table 1. Comparison of the low-order Zernike terms (Z4-Z6) of the Fizeau interferometer and the DPMD system after each of the six calibration passes.

Zernike Term	Interferometry (nm)	DPMD (nm)	DPMD/Interferometry
PASS #1			
Z4	110	211	0.520
Z5	32.4	58.4	0.555
Z6	-127	-235	0.541
PASS #2			
Z4	129	234	0.552
Z5	-119	-219	0.546
Z6	61.7	125	0.492
PASS #3			
Z4	135	240	0.564
Z5	113	201	0.564
Z6	98.5	172	0.573
PASS #4			
Z4	-71.8	-128	0.559
Z5	-16.0	-31.2	0.512
Z6	80.6	140	0.575
PASS #5			
Z4	-83.3	-150	0.554
Z5	76.6	139	0.549
Z6	-45.8	-82.5	0.555
PASS #6			
Z4	-85.8	-150	0.574
Z5	-66.4	-117	0.566
Z6	-68.3	-113	0.602

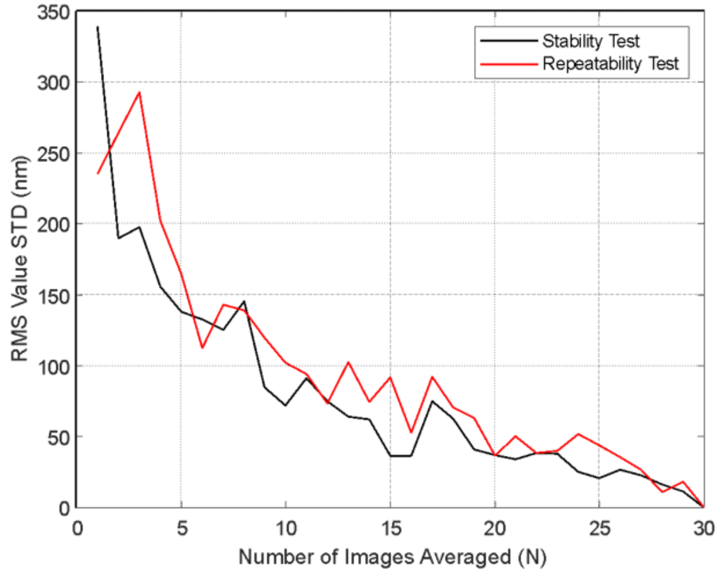

Figure 7. Stability and repeatability RMS uncertainty as a function of number of measurements.

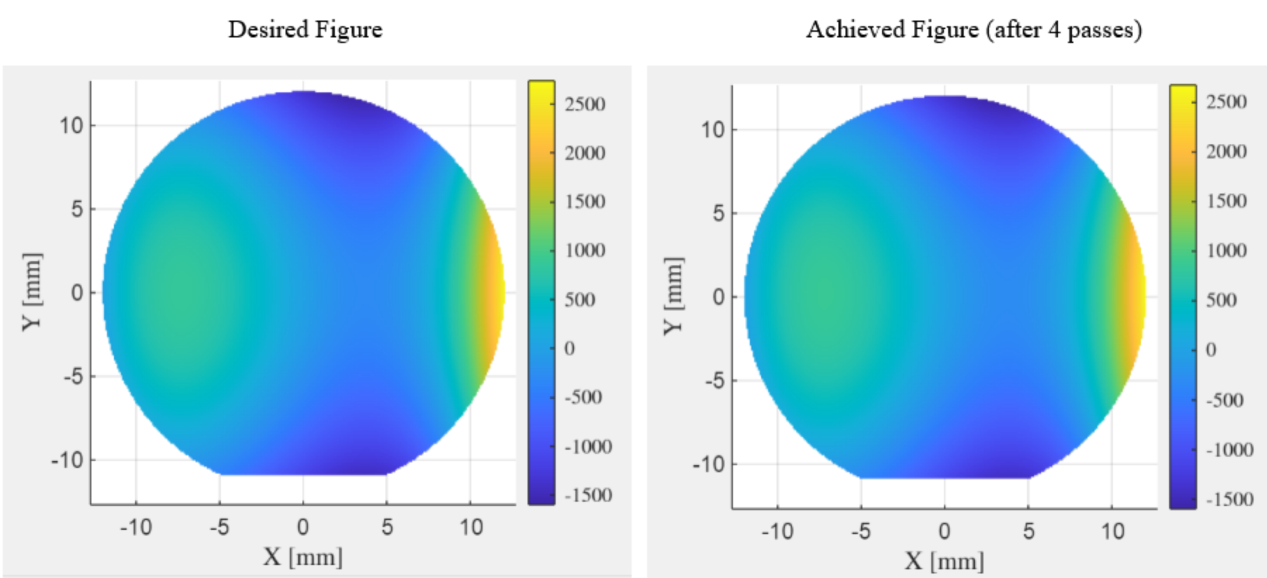

Figure 8. (left) The desired target figure. (right) The achieved figure after 4 iterative ULSF passes.

4. CONCLUSION AND FUTURE WORK

Initial tests using differential phase measuring deflectometry with the ultrafast laser stress figuring process were successful and a 25.4 mm diameter, 1 mm thick fused silica mirror was figured with 24.8 nm RMS residual error. Our team will work to determine the factor of 0.55 systematic discrepency between differential deflectometry and differential interferometry measurements so it doesn't necessarily need to be accounted for in the iterative figuring process. Future improvements and calibration can also be made by reducing noise by averaging more deflectometry measurements. Differential PMD also has the potential be used as an in-*process* metrology method for ULSF by embedding phase information into different wavelengths of light.[3]

REFERENCES

[1] Chalifoux, B. D., Laverty, K. A., and Arnold, I. J., "Ultrafast laser stress figuring for accurate deformation of thin mirrors," *Opt. Express* **30**, 17767–17780 (May 2022).

[2] Laverty, K., Esparza, M., Kim, D., and Chalifoux, B., "Strategies for Improving Ultrafast Laser Stress Figuring Range and Resolution," in [*Optical Manufacturing and Testing XIV*], International Society for Optics and Photonics, SPIE (2022).

[3] Trumper, I., Choi, H., and Kim, D. W., "Instantaneous phase shifting deflectometry," *Opt. Express* **24**, 27993–28007 (Nov 2016).

[4] Su, P., Parks, R. E., Wang, L., Angel, R. P., and Burge, J. H., "Software configurable optical test system: a computerized reverse Hartmann test," *Appl. Opt.* **49**, 4404–4412 (Aug 2010).

[5] Quach, H., Kang, H., Sirsi, S., Chandra, A., Choi, H., Esparza, M., Karrfalt, K., Berkson, J., Takashima, Y., Palisoc, A., Arenberg, J. W., Walker, C., d'Aubigny, C. D., and Kim, D., "Surface measurement of a large inflatable reflector in cryogenic vacuum," *Photonics* **9**(1) (2022).

[6] Cai, W., Kim, D. W., Zhou, P., Parks, R. E., and Burge, J. H., "Interferometer calibration using the random ball test," in [*International Optical Design Conference and Optical Fabrication and Testing*], *International Optical Design Conference and Optical Fabrication and Testing* , OMA7, Optica Publishing Group (2010).