

High-Dynamic Range, High-Resolution Freeform Metrology with Optical Differentiation Wavefront Sensing

B. R. Swain¹, C. Dorrer², S. DeFisher³ and J. Qiao^{1,2,*}

¹Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623, USA

²Aktiwave LLC, 150 Lucius Gordon Dr., Rochester, NY 14586, USA

³OptiPro Systems, 6368 Dean Parkway, Ontario, NY 14519, USA

*qiao@cis.rit.edu

Abstract: Wavefront generated by freeform phase plate is measured with an optical differentiation wavefront sensor. Comparison of the measurement with a commercial scanning interferometer shows $\lambda/10$ ($\lambda=633$ nm) agreement, demonstrating its potential for metrology applications.

1. Introduction

Freeform optical components having no rotational symmetry allow diffraction limited performance over large field of view while enabling the imaging system to be less in volume. The high surface slope of freeforms require both high dynamic range and high-resolution metrology. Current metrology techniques are limited by dynamic range, resolution and measurement time. We demonstrate an accurate quantitative characterization of a freeform phase plate with an Optical Differentiation Wavefront Sensor (ODWS).

2. ODWS principle

Figure 1 shows the ODWS principle, where an optical field with phase profile $\varphi(x,y)$ is Fourier transformed by the first $4f$ lens. The far-field is modulated by a filter of which the transmission varies linearly from 0 to 100%, followed by a Fourier transform by the second $4f$ lens. The obtained near field fluence distribution F_x on camera renders wavefront slope information according to $\frac{\partial \varphi}{\partial x} = \frac{\pi W}{\lambda f} \left[2 \sqrt{\frac{F_x}{F_0}} - 1 \right]$, where W is width of the filter and F_0 is the fluence when far-field is not modulated [1]. Similarly, a vertical orientation of the filter will render the wavefront slope in orthogonal direction. The slope information in two orthogonal direction is then integrated to reconstruct full wavefront.

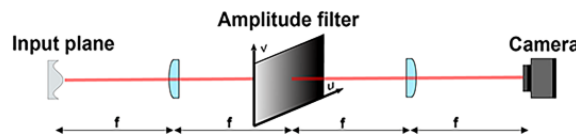


Fig. 1. ODWS principle. Adapted with permission from [5] © The Optical Society.

3. Experimental results

An experimental setup has been built allowing measurement of wavefront generated by freeform phase plates. The setup uses $\lambda = 633$ nm and $4f$ line of focal length 1m. The implemented transmission filter is of width $W = 10$ mm and has been realized by binary pixelated filter having transparent and opaque pixels of width $2.5 \mu\text{m}$ [2]. The dynamic range is $DR = W/(\lambda f) = [-8 +8]$ waves/mm. The spatial resolution of measurement is $26.7 \mu\text{m}$.

Two freeform phase plates were fabricated with an UltraForm machine [3] and their profile were characterized by using UltraSurf [4], a non-contact coordinate measurement system (OptiPro Systems). The phase plates have wavefront slopes in range $[-11.1 \ 3.7]$ waves/mm and $[-5.5 \ 19.3]$ waves/mm respectively; the wavefront slopes of first phase plate are either within or slightly exceeding the ODWS design baseline and that of second phase plate is higher than the design baseline.

Figure 2(a) and 2(b) show the wavefront maps of phase plate #1, measured by UltraSurf and ODWS respectively and Fig. 2(c) shows their difference. Piston, tip and tilt are removed from the measurement results. The ODWS measurement shows excellent agreement of $\lambda/10$ when compared with UltraSurf measurement. This difference contains inherent error in either measurements, imperfect registration and magnification. Figure 2(d) shows the far-field pattern that is well confined within the filter marked by white lines. Fig. 2(e) shows the fluence map in detection plane with the 20 mm measurement diameter marked by white circle.

Phase plate #2 that has higher slopes at the edge, and it exceed ODWS dynamic range. Therefore, it is expected that it will lead to measurement error. Figure 3(a) and 3(b) show wavefront measured by UltraSurf and ODWS respectively. Fig. 3(c) shows their difference in absolute form to emphasize the left edge which shows the highest

difference. The reason of this difference is because the slope at that location is much beyond ODWS measurement range and at the far-field, those high slope wavefront components fall beyond the edge of the filter and are clipped as shown in Fig. 3(d). This clipping results in a dark patch in fluence at detection plane as shown in Fig. 3(e), which in turn leads to inaccurate wavefront reconstruction in that region. However, upon avoiding this erroneous region, a wavefront comparison within 15 mm pupil shows an agreement of $\lambda/10$ between UltraSurf and ODWS.

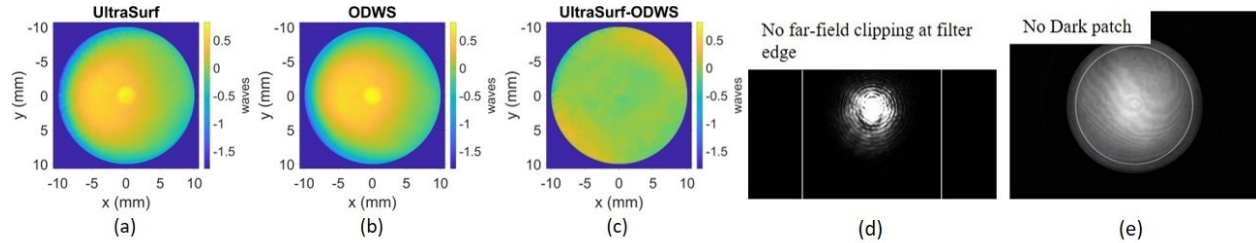


Fig. 2. Wavefront of phase plate #1: (a) UltraSurf measurement: Root Mean Square (RMS) 0.38λ , Peak to Valley (PV) 2.58λ , (b) ODWS measurement: RMS 0.39λ , PV 2.28λ , (c) Difference RMS 0.1λ , (d) Fluence at far-field, (e) Fluence at detection plane. Adapted with permission from [5] © The Optical Society.

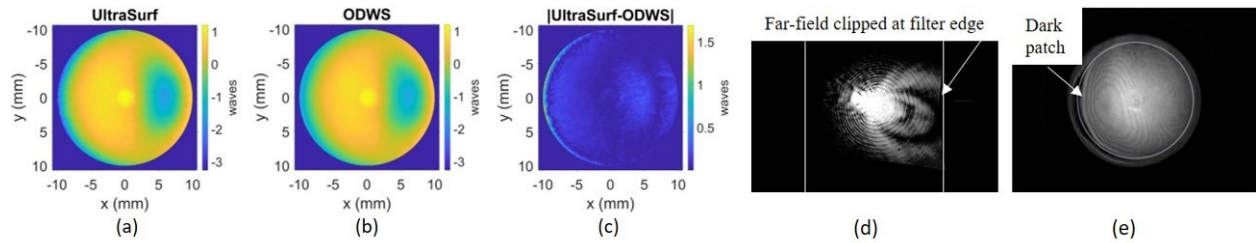


Fig. 3. Wavefront of phase plate #2: (a) UltraSurf measurement: Root Mean Square (RMS) 0.69λ , Peak to Valley (PV) 4.44λ , (b) ODWS measurement: RMS 0.6λ , PV 2.8λ , (c) Absolute difference RMS 0.16λ , (d) Fluence at far-field, (e) Fluence at detection plane. Adapted with permission from [5] © The Optical Society.

Results from Figs. 2 and 3 confirm that ODWS measurement dynamic range is effectively limited by filter width. One way to improve is to increase the filter width and another way is to decrease the far-field feature size below the filter width by decreasing focal length of the $4f$ system. However, the latter case needs to have filter with smaller pixel size to provide enough sampling to far-field for good measurement accuracy [1].

4. Conclusion

We have demonstrated a high-performance optical differentiation wavefront sensor that uses binary pixelated filters [5]. Its performance in freeform wavefront measurement matches excellently with that of a commercial instrument. It also enables single-shot ability. We experimentally showed that dynamic range can be improved by tailoring filter width or focal length of the imaging system. This high-resolution, high-dynamic-range wavefront sensing technology will allow characterization of complex shaped freeform optics. Demonstration of stronger freeform measurements with increased filter width will be presented.

We acknowledge funding support from the US National Science Foundation (EPMD 1711669).

References

- [1] J. Qiao, Z. Mulhollan, and C. Dorrer, "Optical differentiation wavefront sensing with binary pixelated transmission filters," *Opt. Express* 24(9), 9266–9279 (2016).
- [2] C. Dorrer and J. D. Zuegel, "Design and analysis of binary beam shapers using error diffusion," *J. Opt. Soc. Am. B* 24(6), 1268–1275 (2007).
- [3] J. Tiersen, E. Fess, and G. Matthews, "Developments in precision asphere manufacturing," in *Optifab 2015*, (International Society for Optics and Photonics, 2015), 96330H.
- [4] K. Medicus, S. DeFisher, M. Bauza, and P. Dumas, Round-robin measurements of toroidal window, *SPIE Optifab* (SPIE, 2013), Vol. 8884.
- [5] B. R. Swain, C. Dorrer and J. Qiao, "High-performance optical differentiation wavefront sensing towards freeform metrology," *Opt. Express* 27(25), 36297–36310 (2019).