Refractive index homogeneity TWE effect on large aperture optical systems

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ABSTRACT

Sapphire windows are routinely being used in demanding aerospace applications due to their high strength and desirable optical and material properties. Sapphire is particularly useful in addressing the increasing need for systems that provide a wider range of capabilities in a single package. In general, refractive index homogeneity of the component materials can have a significant impact on overall optical system performance. This leads to the need for a deeper understanding of the shape and magnitude of index inhomogeneity in large sapphire windows to ensure predictable, high quality operation. Thin, sapphire slices from a sapphire crystal boule grown via the Heat Exchanger Method (HEM) have been previously evaluated for refractive index homogeneity over a 25.4cm (10.0") aperture. The resultant transmitted wavefront error (TWE) from those measurements has now been used to model typical optical systems to quantify the effects on system-level performance attributed to representative amounts of index inhomogeneity in the sapphire window. The results of this modeling effort are presented in the following paper.

Keywords: sapphire, HEM, heat exchanger method, inhomogeneity, TWE, transmitted wavefront, optical systems

1. INTRODUCTION & PRIOR WORK

Sapphire crystal boules are being grown in the a-plane at II-VI Optical Systems (II-VI OS) via a process known as the Heat Exchanger Method (HEM). This process yields boules that are approximately 34cm (13.0") in diameter and 22cm (10") tall. The resulting crystal is then oriented via x-ray diffraction techniques for use in either the a-plane, c-plane, r-plane or m-plane. The large face of the boule is aligned to the a-plane, and the useable portion of the boule is sliced, resulting in blanks that are 34cm in diameter and typically 5.7mm thick for use in aerospace applications as windows.

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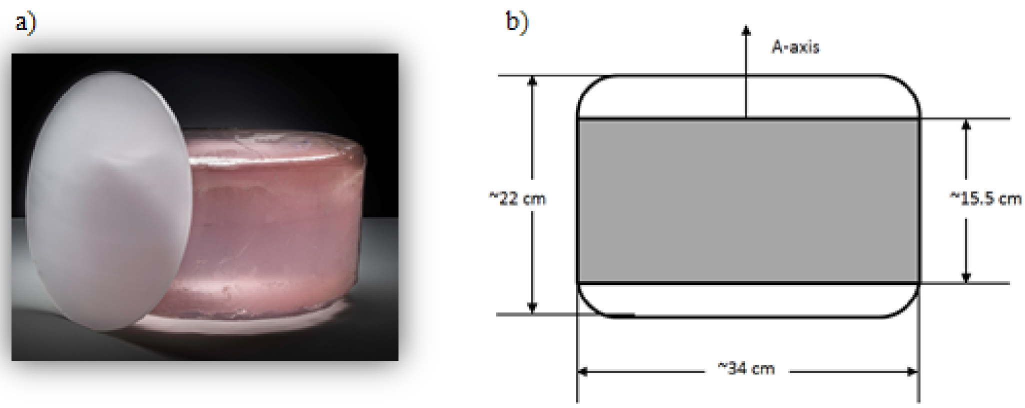

Figure 1: a) A typical boule produced from the HEM method with a representative blank; b) Typical dimensions of an as-grown HEM boule. The area shown in grey represents the portion of the boule which is considered optical quality.

Previously, II-VI OS characterized a HEM boule for refractive index inhomogeneity over a 25.4cm (10”) aperture. Samples were collected and evaluated at several locations through the useable thickness of a standard HEM boule. These measurements were made on a Zygo interferometer operating at a wavelength of 632.8 nm. Measurements were processed via the PHom (Polished Homogeneity) application, which subtracts cavity and surface influences from the transmitted wavefront (TWE) so that the resulting TWE is due to index inhomogeneity only [1].

The following paper is an expansion on the above described work. The optical systems that are being installed behind these windows are increasingly becoming more advanced, with higher capability, thus increasing the sensitivity of these systems to optical distortions imparted by the component materials. Inhomogeneity remains an important consideration for all optical components, however, a better understanding of not only the magnitude but the shape of this inhomogeneity is warranted, and ultimately, how the shape and magnitude of the inhomogeneity affects downstream system performance. The aim of this paper is to start answering these questions.

2. MODELING APPROACH

The authors selected two of the measurements reported in the prior paper, *Homogeneity of material and optical properties in HEM grown sapphire,* for further analysis. The primary aberrations demonstrated by the inhomogeneity measurements previously performed were either power or astigmatism. As such, a window representing each error was modeled in Zemax. In the model, an ideal F/1.0 paraxial lens was placed behind the window and evaluated with a 25cm, 20cm, 15cm and 10cm sub-aperture, with the effective focal length scaled to F/1.0 for each sub-aperture. For each sub-aperture, we evaluated the uncompensated MTF performance of the paraxial lens against the theoretically perfect MTF performance without the window out to the Nyquist frequency of 1400 lp/mm. A paraxial lens was chosen to simulate an ideal optical system so that the analysis presented would represent the MTF loss from the window contribution alone. Each sub-aperture was evaluated at the center of each window. It was found that translating the sub-aperture made no significant difference in the performance results presented, with or without compensation. All results presented are for on-axis field of view.

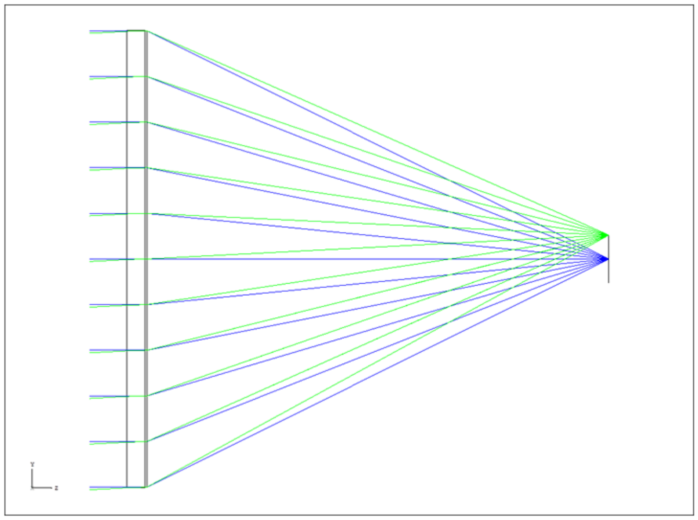

Figure 2: Model used for evaluation of MTF impact due to TWE of index inhomogeneity in a sapphire window. Model depicts sapphire window with a Zernike fringe on the rear surface and an ideal paraxial lens directly behind the window for image evaluation.

Henceforth, we will refer to these two windows as Window A and Window B. Window A measured an inhomogeneity of 63.2ppm RMS over a 25.4cm aperture, and the dominant aberration induced by the inhomogeneity is astigmatism. The simulated TWE for Window A is shown in Figure 3. Window B measured an inhomogeneity of 63.7ppm RMS over a 25.4cm aperture, and the dominant aberration induced by the inhomogeneity is power. The simulated TWE for Window B is shown in Figure 4. It is important to note that there is some contribution of surface irregularity in the inhomogeneity results for the two windows evaluated due to the nature of the measurement technique; therefore, the results presented herein should be considered conservative and worst-case.

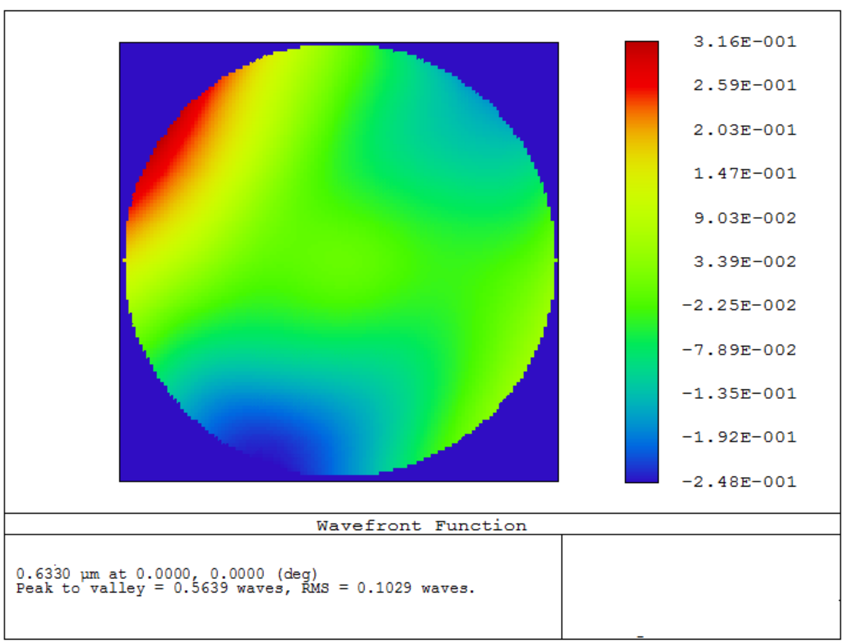

Figure 3: Simulated TWE for sapphire Window A. Primary aberration due to inhomogeneity is astigmatism.

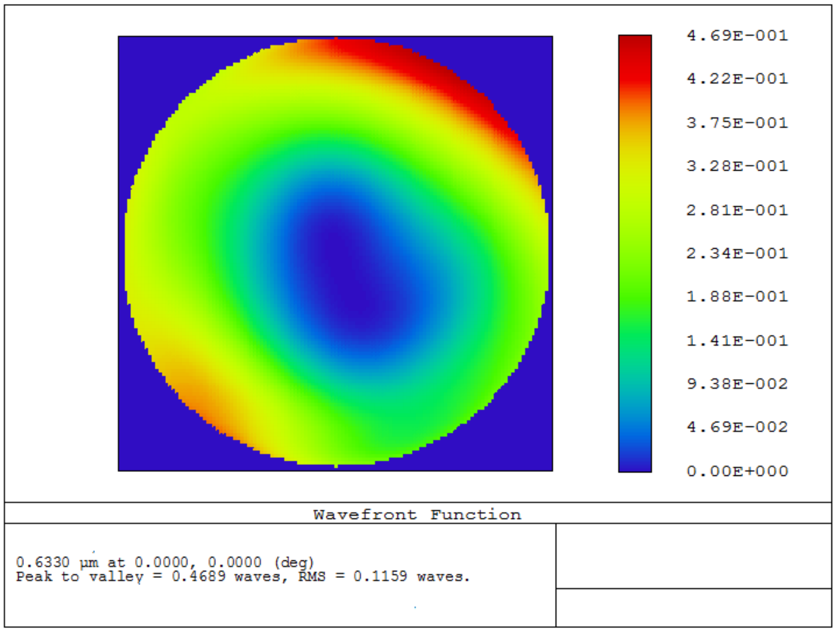

Figure 4: Simulated TWE for sapphire Window B. Primary aberration due to inhomogeneity is power.

3. RESULTS

3.1 Window A

Given that the dominant aberration of Window A is astigmatism, focus compensation provides negligible improvement in the overall performance of each evaluated sub-aperture. Therefore, the results shown in the Figure 5 are for the uncompensated performance of the system due to the inhomogeneity of the window. The most significant impact to system performance is realized by the largest aperture evaluated, 25cm, with an approximate 15% reduction in MTF compared to the diffraction limit. For each smaller sub-aperture, the MTF performance is improved, and for the 15cm and 10cm sub-aperture, the effect of this inhomogeneity has a nearly undetectable impact on system performance.

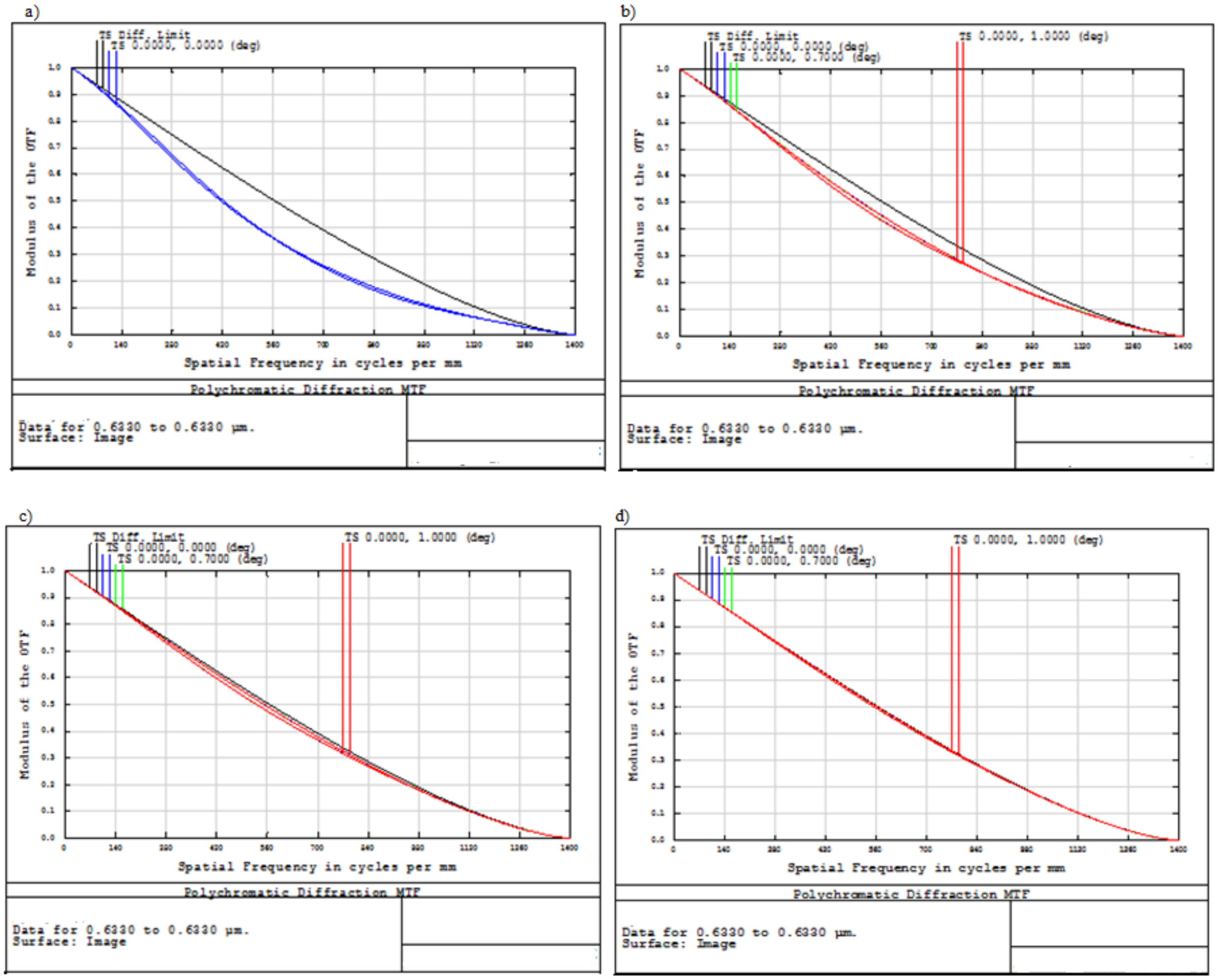

Figure 5: a) Uncompensated system performance of an F/1.0 paraxial lens with a 25cm aperture behind Window A. System MTF is reduced by 15% at 700 lp/mm. b) Uncompensated system performance of an F/1.0 paraxial lens with a 20cm aperture behind Window A. System MTF is slightly impacted by approximately 5% at 700 lp/mm. c) Uncompensated system performance of an F/1.0 paraxial lens with a 15cm aperture behind Window A. System MTF is essentially unaffected and shows nearly diffraction limited performance. d) Uncompensated system performance of an F/1.0 paraxial lens with a 10cm aperture behind Window A. System demonstrates diffraction limited performance.

3.2 Window B

The dominant aberration of Window B is power, which induces a focus shift of the paraxial lens system behind the window. Figure 6 show MTF performance before focus compensation. The most significant impact to MTF is again realized by the largest aperture evaluated, 25cm, and the impact is reduced with each smaller sub-aperture. The 25cm sub-aperture shows a 30% reduction in MTF at 570 lp/mm. Again, as was the case for Window A, for the 15cm and 10cm sub-aperture, the effect of this inhomogeneity has an insignificant impact on system performance.

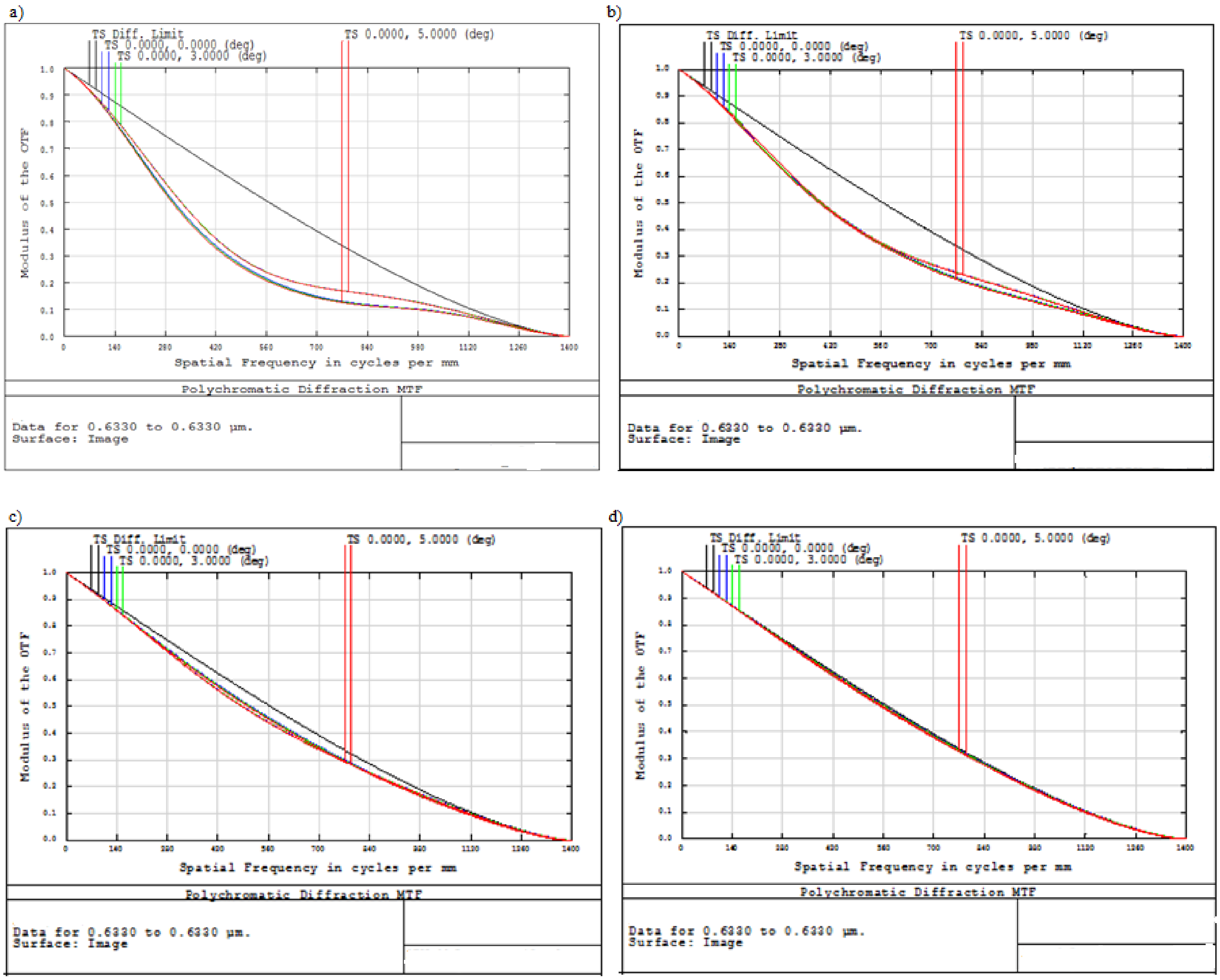

Figure 6: a) Uncompensated system performance of an F/1.0 paraxial lens with a 25cm aperture behind Window B. System MTF takes a significant hit by 30% at 570 lp/mm before focus compensation due to power caused by the inhomogeneity of Window B. b) Uncompensated system performance of an F/1.0 paraxial lens with a 20cm aperture behind Window B. System MTF is impacted by 15% at 570 lp/mm. c) Uncompensated system performance of an F/1.0 paraxial lens with a 15cm aperture behind Window B. System MTF is slightly reduced by <5% due the power caused by the inhomogeneity of Window B. d) Uncompensated system performance of an F/1.0 paraxial lens with a 10cm aperture. System demonstrates near diffraction limited performance.

After focus compensation is applied, the MTF losses are significantly reduced. For the 25cm sub-aperture, the MTF impact to reduced from 30% at 570 lp/mm to a maximum of 5%. The 20cm and 15cm sub-aperture performance returns to near diffraction limited performance, while there is essentially zero change in the performance of the 10cm aperture, which was already diffraction limited even before focus compensation. The MTF performance after focus compensation is shown in Figure 7. Focus was adjusted -2.5µm for the 25cm sub-aperture.

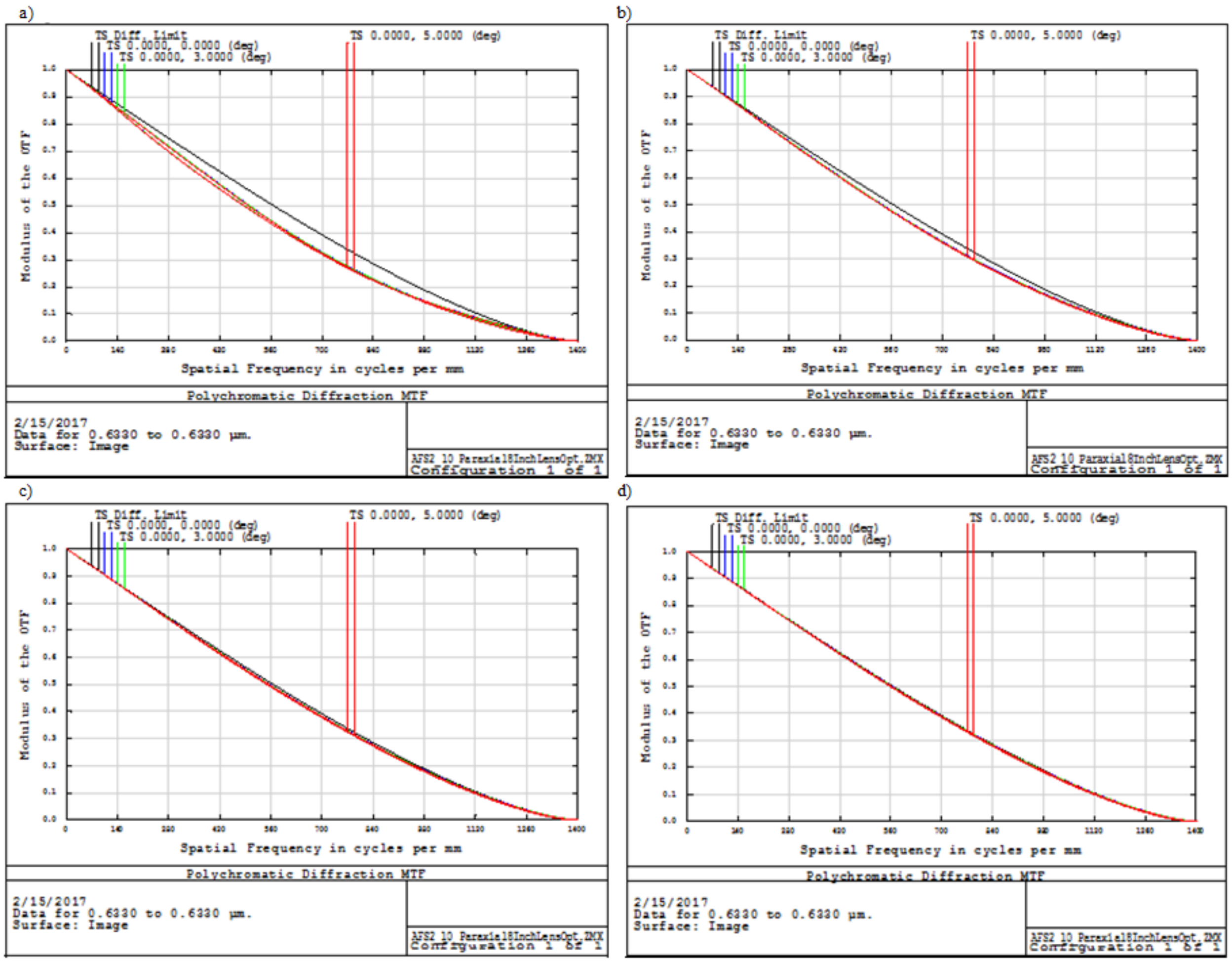

Figure 7: Compensated system performance of an F/1.0 paraxial lens behind Window B. System MTF losses can be focus compensated. a) 25cm aperture, b) 20cm aperture, c) 15cm aperture and d) 10cm aperture.

4. DISCUSSION

The results indicate what one would expect given that the errors created by the inhomogeneity in the sapphire windows evaluated are smooth errors. In both cases, the largest sub-aperture evaluated was most affected by the inhomogeneity errors in the windows, and the 15cm and 10cm sub-apertures were essentially unaffected. In the case of Window A, in which the primary aberration is astigmatism, focus compensation could not be utilized to provide an improvement in image quality. However, in Window B, in which the primary aberration is power, focus compensation significantly improved the performance of the system evaluated, improving the MTF performance by more than 80% for the 25cm sub-aperture.

The results presented here emphasize the ongoing need to develop better understanding of index inhomogeneity, specifically how inhomogeneity contributes to the final transmitted wavefront of a finished window for practical aperture sizes. HEM sapphire inhomogeneity has been previously reported by others for 2 inch apertures [2, 3] but the findings presented here indicate that such data are insufficient when larger sub-apertures are considered that are more representative of the size of systems that are being installed behind sapphire windows. By increasing our understanding and establishing realistic expectations of sapphire window performance, we can expect to be able to design more capable optical systems at reduced cost.

5. CONCLUSION

Two representative sapphire windows were evaluated for index inhomogeneity over a 25.4cm aperture [1]. The resultant TWE due to the index inhomogeneity was used to model the performance impact of an optical system placed behind each window. The dominant aberration in Window A was astigmatism and the dominant aberration in Window B was power. In both cases, the MTF performance impact is most significant for the largest aperture evaluated. For the 20cm aperture, there is a moderate to low impact, and for the smallest aperture evaluated, 15cm and 10cm, the inhomogeneity error did not impact image quality. Further, for Window B, focus compensation was taken into account and reduced errors imparted by index inhomogeneity by more than 80% for the largest sub-aperture evaluated. As the need for complex systems with increasing capabilities in a single package grows, so does our need for understanding how to specify component materials and their impact in final performance. In the case of sapphire windows, the magnitude and shape of index inhomogeneity over a specific and representative aperture size is warranted to ensure reliable and consistent performance at a reduced cost. The work presented in this paper demonstrates that when the index inhomogeneity errors are known and quantified, in some cases they can be compensated for, as was the case with Window B. More importantly, for small apertures relative to the size of the window, index inhomogeneity of the window can essentially be ignored, as there is little to no meaningful impact on system performance.

6. REFERENCES

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