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Stray light analysis and testing of a MODE lens telescope

Youngsik Kim*[a], Marcos Esparza[a], Zichan Wang[a], Nicholas Brar[a], Heejoo Choi[a], Daewook Kim[a], Daniel Apai[b] and Tom D. Milster[a]
[a]Wyant College of Optical Sciences, 1630 E. University Blvd., Tucson, AZ, USA 85721,
[b]Department of Astronomy and Planetary Sciences, 933 N. Cherry Ave., Tucson, AZ, USA 85721

ABSTRACT

The stray light analysis and testing of multiple-order-diffraction engineered (MODE) lens telescope is an essential step in the evaluation of optical imaging performance of the telescope. The MODE primary lens has a multi-order diffractive (MOD) front surface and single-order (M = 1) diffractive Fresnel lens (DFL) rear surface. Both of MOD and DFL surfaces have four transitions between five annular zones. Stray light can be minimized to prevent unwanted photons from reaching the science instrument detectors. Stray light is evaluated on an optical testbed to test the polychromatic performance with a supercontinuum laser.

Keywords: Diffractive optical element, stray light, focal dispersion, polychromatic performance

1. INTRODUCTION

The multi-order diffractive engineered (MODE) lens telescope[1,2] is desirable in the application of space telescopes for exoplanet research[3], due to the transmissive optical path, ultralightweight, low sensitivity of alignment errors and large aperture without obscuration through easily replicated lens segments. The MODE primary lens has a multi-order diffractive (MOD) front surface and single-order (M = 1) diffractive Fresnel lens (DFL) rear surface. Our prototype MODE primary lens is a 240 mm aperture diameter, 1 m focal length lens designed for the astronomical R-band. It consists of one center segment and eight ring segments. Both MOD and DFL surfaces have four transitions between five annular zones of M = 2196 harmonic wavelengths of optical path difference. Stray light can be generated by the zonal transitions of MOD and DFL surfaces if not designed properly. Stray light should be minimized to prevent unwanted photons from reaching the science instrument detectors. In this paper, we discuss stray light analysis and testing of a MODE lens telescope. The stray light is analyzed on the nine segmented MODE primary lens with zonal transitions. It is controlled to maximize signal to noise ratio by effectively implementing the custom-shape back cuts on the zonal transitions and baffles in the lens tube. The stray light is evaluated on an optical testbed on which collimated light is focused by the telescope. Focused spot and resolution target images generated by a supercontinuum laser source are used to test polychromatic stray-light performance.

The following sections present an introduction to MODE lens primary design to minimize stray light, the prototype design, stray light analysis, stray light testing of MODE lens, and conclusions.

2. MODE LENS DESIGN TO MINIMIZE STRAY LIGHT

2.1 Segmentation design

Recently, multiple-order engineered (MODE) lens, as shown in Fig. 1 has been demonstrated, which is the combination of a large-M number multiple-order diffractive (MOD) front surface and single-order (M=1) diffractive Fresnel lens (DFL) rear surface lens.[4] Prototype MODE lens primary has 0.24-meter diameter and 1-meter focal length and consists of 5-zone and 9-segment and is designed to cover a 0.25˚ field of view. The 9-segmented MODE lens, as shown in Fig. 1(b), which consists of 1-center segment and 8-ring segment can be fabricated using two glass mold inserts where one is for center segment and the other for ring segment using a Ohara L-BSL7 glass. All segments of prototype MODE lens primary can be fabricated using a precision glass molding process and precisely aligned and assembled all together using kinematically-engaged yoke system (KEYS).[5] Even though all segments of MODE lens primary are UV bonded

* yskim@optics.arizona.edu ; phone 1 (520) 626-9096

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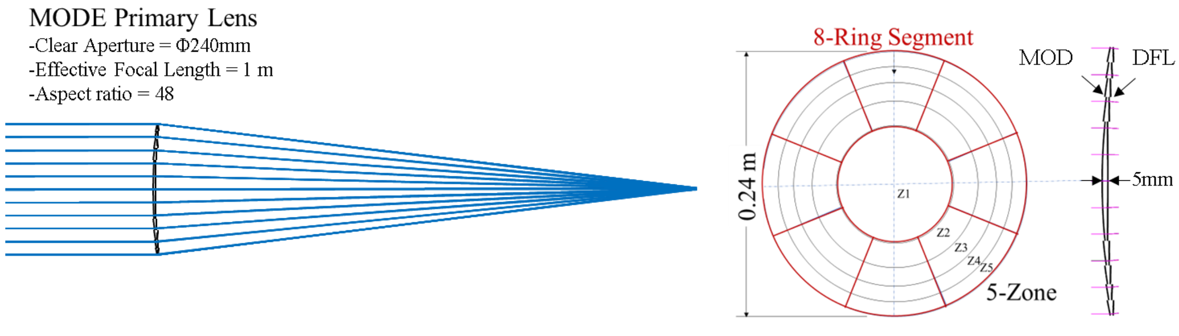
keeping the precise alignment, there might be some stray light induced by the bonded line. The narrow-bonded line can be coated with a light absorption material to minimize the stray light.



(a) (b)

Figure 1. Prototype MODE lens primary and its segmentation. (a) Prototype MODE lens primary design (b) Prototype MODE lens primary consists of 5-zone and 9-segment, which has 1-center segment and 8-ring segment.

2.2 Zonal transition design

Prototype MODE lens primary, as shown in Fig. 1, consists of 5-zone radially, which may generate the stray lights. It is required to minimize the stray light through the zonal transition design using the truncated cone shape. The zonal transition can be designed efficiently through the three steps as follows, as shown in Fig. 2(a). Firstly, the incident ray into the outer radius(①) of MOD zone-1refracts to the outer radius(②) of DFL zone-1. Secondly, the zonal transition of DFL is tilted into a moldable angle (e.g. 5˚) from the MODE lens optical axis and define the inner radius(③) of DFL zone-2. Thirdly, find the incident ray into the inner radius(④) of MOD zone-2 which passes through the pre-determined inner radius(③) of DFL zone-2. The higher zonal transition can be designed following the same procedure as the 1st zonal transition design. The zonal transition can be described well as the conic surface equation.

$$z_0 - z_1 = \frac{y_1^2/R}{1+\sqrt{(1-(1+k)\,y_1^2/R^2)}}, \tag{1}$$

where k is the conic constant.

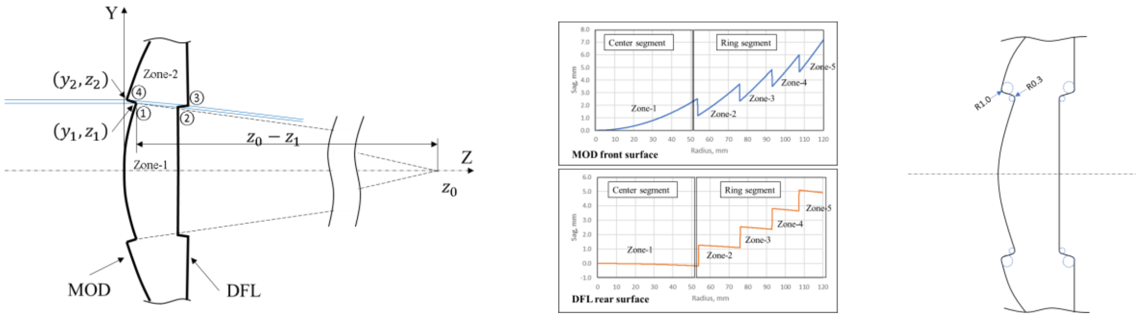
$$k = \frac{1-\left(\frac{y_1^2}{(R(z_o - z_1))} - 1\right)^2}{y_1^2/R^2} - 1, \tag{2}$$

The vertex position of cone can be calculated easily from the two points (①, ④) and (②, ③).

$$z_o = -\frac{b}{a}, \tag{3}$$

where $a = \frac{(y_2 - y_1)}{(z_2 - z_1)}$ and $b = y_1 - \frac{(y_2 - y_1)}{(z_2 - z_1)} z_1$.

Fig.2(b) shows the sag profile for MOD front surface and DFL rear surface of the prototype MODE lens primary which can be fabricated into the moldable glass. The zonal transitions between curved zonal regions should be designed to minimize the stray light for the incident light from the object and maximize the signal-to-noise ratio in the camera considering the fabrication of the segmented zonal MODE lens primary.



(a) (b) (c)

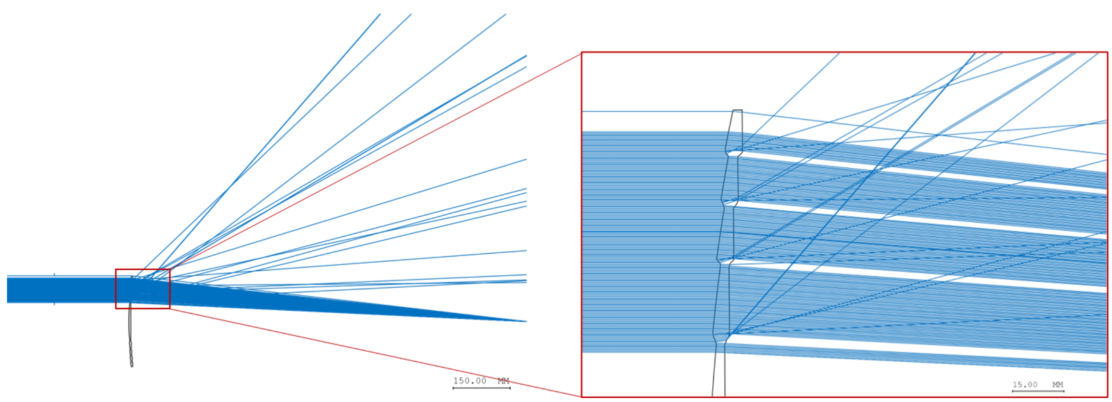
Figure 2. Prototype zonal transition design. (a) Zonal transition diagram to minimize the stray light, (b) MODE primary lens sag and zonal transition for MOD and DFL surface and (c) Zonal transition corner rounding

Prototype MODE lens primary ring segment is glass molded using a MOD and DFL mold inserts which can be diamond turned on the copper-nickel alloys. The diamond tool-tip wear depends on the cutting speed, feed rate, depth of cut and tool-nose radius. The combination of high cutting speed, low feed rate and a large tool radius should be used to achieve a high surface finish with minimal tool wear. The sharp edge condition in the mold inserts limit the mold life and can ne difficult to manufacture. This rounded edge also effects on the stray light for the incident light, so that the rounding radius should be considered carefully. The edges of the zonal transitions for the prototype MODE lens primary ring segment are rounded to 0.3 mm radius for the concave side and 1.0 mm radius for the convex corner, as shown in the Fig. 2(c).

3. STRAY LIGHT ANALYSIS

3.1 Stray light ray tracing through transition

The prototype MODE lens primary consists of 5-zone radially which connected with the zonal transitions discussed in the section 2.2. The incident light into each zone of MOD front surface refracts properly in the MOD and DFL surface made of Ohara L-BSL7 molded glass and constructs the achromatic focus with the focal length of 1 meter. The light incident into the zonal transition region of MOD surface generates the stray light as shown in Fig. 3, but it is deviated a lot from the optical axis of MODE lens primary after refracting at the zone and zonal transition of DFL rear surface. The refracted light from the rounding edge of the MOD zonal transitions diffract in the DFL zones or refract in the DFL zonal transitions to deviate a lot from the camera located on the optical axis of the MODE lens primary.



(a) (b)

Figure 3. Stray light ray tracing. (a)Zonal transition generates mainly stray lights which deviates far away from the camera and (b)Enlarged view of zonal transition region

3.2 Stray light simulation using hemisphere receiver

The light incident into the prototype MODE lens primary refracts at MOD front surface and refract again at the DFL rear surface. The incident light into the zones of MOD front surface refracts into the zones of DFL rear surface and focuses on the focal point of MODE lens primary, but the incident light into the zonal transition region of MOD front surface refracts into the zonal transition or zone of DFL rear surface and refracts far away from the MODE lens optical axis.

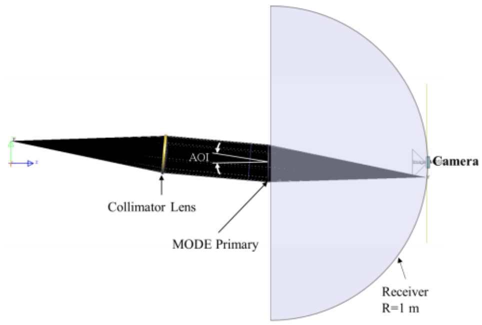
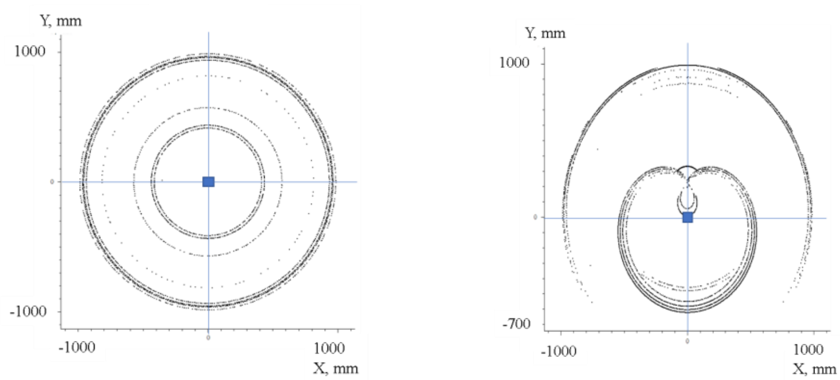


Figure 4. Optical layout to analyze the stray light from the primary MODE lens

The stray light generated mainly from the zonal transitions of the MODE lens primary can be analyzed in the hemisphere receiver with 1 m radius located in the focus of the MODE primary lens, as shown in Fig. 4. We assume the camera is located in the focal position of the MODE primary lens. The angle of incidence (AOI) for the collimated light which is incident into the MOD front surface of the MODE lens primary changes with the stray light analysis on the hemisphere receiver and camera. Fig. 5 shows the scatter chart to analyze the stray light from the zonal transitions of the MODE primary lens. For the incident angle of 0.0˚ into the MODE primary lens, the total stray light ratio is 1.39 % for the incident light. The total stray light ratio to the incident light with an incident angle of 12.55˚ is 2.05 %, which is no stray light incident into the camera with the active area of 13.3 mm x 13.3 mm. If the field lens is located in near the focus of the MODE primary, which has a very small clear aperture (i.e. 6 mm aperture diameter), the allowable incident angle of the incident beam into the MODE primary lens increases a lot more without the stray light into the camera.

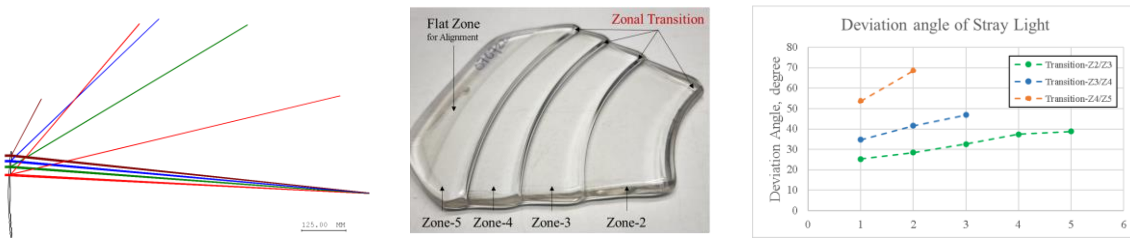


(a) (b)

Figure 5. Scatter chart to analyze the stray light from the primary MODE lens. (a) Scatter chart for incident angle of 0.0˚ with total stray light ratio of 1.39% and (b) Scatter chart for incident angle of 12.55˚ with stray light ratio of 2.05% without stray light incident into camera with active area of 13.3 mm x 13,3 mm.

4. STRAY LIGHT TESTING OF MODE LENS PRIMARY

Fig. 6 (a) shows the ray trace through the zonal transitions between the zones 1-5 of the prototype MODE lens primary. The narrow beam illuminated into the zonal transitions of the MOD front surface refracts into the DFL rear surface zones and zonal transitions, and deviates from the optical axis of the MODE primary lens. The deviation angle of the ray increases and the number of the deviated ray decreases as the zone number increases.



(a) (b) (c)

Figure 6. Transmitted light distribution (a) Ray trace through the zonal transitions between zone 1-5 when illuminating narrow beam, (b) Prototype molded MODE primary lens ring segment, and (c) Measured ray distribution from the narrow beam of HeNe laser illuminated into the zonal transitions. The ray deviation angle from the optical axis of the MODE primary lens increases and the number of the deviated beam decreases as the zone number increases.

As shown in Fig. 6 (b), Prototype molded ring segment of the MODE lens primary consists of zone 2-5 and zonal transitions between them. The flat zone outside of zon-5 can be used to align the prototype molded ring segment to test the stray light distribution induced by the narrow beam illuminated into the zonal transitions. Fig. 6 (c) show the experimental results for the deviated beam distribution when illuminating the HeNe laser into the narrow zonal transitions between MOD front zones 2-5. The deviation angle of the illuminated beam increases and the number of the deviated beam decreases as the zone number increases, as the ray trace through the zonal transitions, as shown in Fig. 6 (a).

5. CONCLUSIONS

The stray light distribution is analyzed from the ray trace angle through the zonal transitions between zones 2-5 and the ray distribution on the hemisphere receiver in the focal position of the MODE lens primary. For the incident ray with the incident angle of 0.0˚ into the MODE primary lens, the total stray light ratio is 1.39 % for the incident light. The total stray light ratio to the incident light with an incident angle of 12.55˚ is 2.05 %, which is no stray light incident into the camera with the active area of 13.3 mm x 13.3 mm. The experimental results for the deviated beam angle passing through the zonal transitions of the molded ring segment sample shows the similar results as the ray trace analysis. The zonal transition structure enables to minimize the stray light effect and maximize the signal-to-ratio of the MODE telescope system.

6. ACKNOWLEDGEMENTS

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