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ABSTRACT

The initial testing of prototype multiple-order-diffraction engineered (MODE) lens telescope is essential process before the sky test to evaluate the optical imaging performance of a space object. Prototype MODE lens telescope consists of MODE primary lens which is a core component to correct secondary spectrum, a field lens and a double Gauss type color corrector and achieves a diffraction limited performance. The performance is tested on the diffraction efficiency with respect to supercontinuum laser wavelength on an optical testbed and evaluated on the polychromatic performance for prototype molded ring segment.

Keywords: Transmission telescope lens, diffractive optical element, secondary spectrum, polychromatic performance

1. INTRODUCTION

The multi-order diffractive engineered (MODE) lens telescope[1,2] is designed as a first step to verify MODE-lens design theory for eventual use in space telescopes for exoplanet research.[3] MODE lenses are desirable in this application, due to the transmissive optical path, ultralightweight, low sensitivity of alignment errors and large aperture through easily replicated lens segments. A MODE lens telescope consists of a MODE primary lens and a color corrector which consists of a Schupmann achromatic field lens and a double Gauss type color corrector which corrects refractive and diffractive dispersion induced from MODE primary in order to provide high quality, diffraction-limited imaging over a broadband wavelength. The MODE primary lens has a multi-order diffractive (MOD) front surface and single-order ($M = 1$) diffractive Fresnel lens (DFL) rear surface lens. The color corrector includes an Arizona total energy color corrector (AZTECC) for the Type 2 longitudinal chromatic aberration (LCA) correction[4]. In this paper, we discuss initial testing of the fabricated prototype MODE lens telescope. The performance is tested on the diffraction efficiency with respect to supercontinuum laser wavelength on an optical testbed and evaluated on the polychromatic performance for prototype molded ring segment. The following sections present an introduction to prototype MODE lens design and fabrication, MODE lens primary testing, MODE lens telescope testing, and conclusions.

2. PROTOTYPE MODE LENS DESIGN

Our prototype MODE primary lens is shown in Fig. 1, where a 0.24 m diameter (D) aperture, 1 m focal length lens designed for astronomical R-band (589 nm to 727 nm) is designed over a 0.25˚ field of view. It consists of one center-segment and eight ring-segments, The MOD surface has transitions between annular zones of $M = 2196$ harmonic wavelengths of optical path difference applying zonal field shift for an off-axis aberration free[5]. The color corrector has a double-Gauss-type lens structure with a AZTECC and DFL in a collimation beam region that corrects both refractive and diffractive dispersion induced from the MODE primary, and it is designed to achieve diffraction limited optical performance[6]. The zonal field shift, which is an off-axis aberration of high-harmonic diffractive lenses, was compensated by curving the surface of the zonal transitions like meniscus. AZTECC lens, which has a shape of circular staircase, removes high-harmonic wavefront steps of the MODE primary lens.

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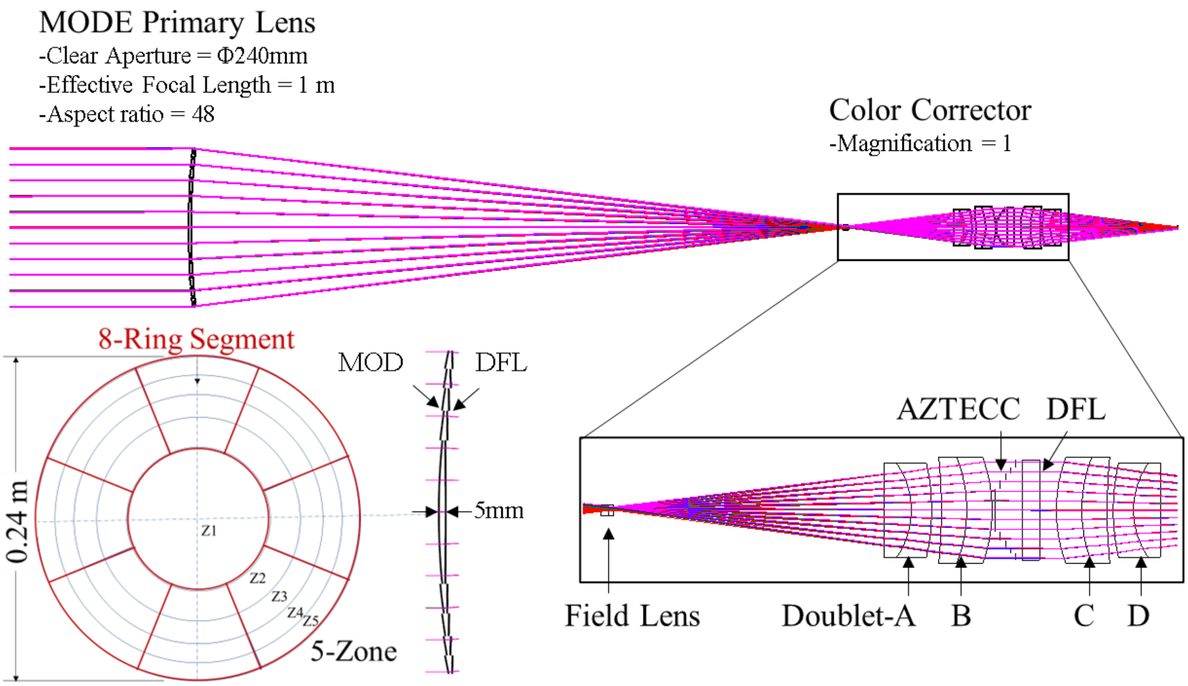


Figure 1. Prototype MODE lens telescope with color corrector

3. TESTING OF PROTOTYPE MOLDED RING SEGMENT

3.1 Prototype MODE lens telescope fabrication

A Prototype MODE primary lens with a 240mm diameter aperture and 1 m focal length is designed to operate over a 0.25° field of view and fabricated to the structure of 1-center segment and 8-ring segment. The color corrector for this prototype system consists of all spherical field-lens, all spherical four doublets (A, B, C, and D), AZTECC and a DFL. A field-lens forms a real image of the MODE primary lens upon the DFL inside four doublets for the Schupmann achromatic design. The AZTECC lens is a circular stepped surface that compensates the fast cyclic LCA.

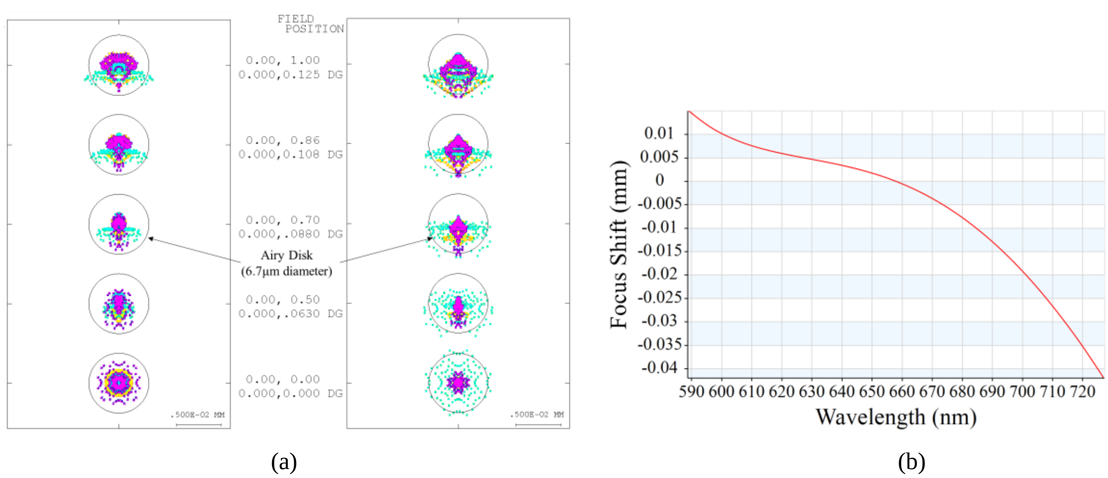


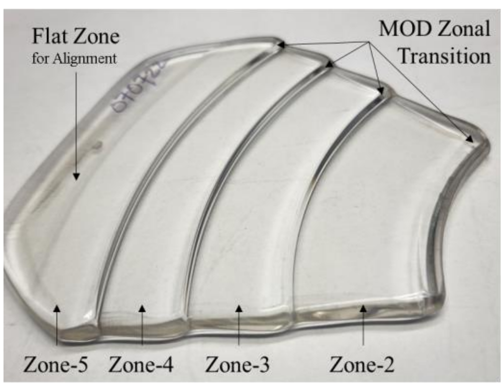
Figure 2. Performance of prototype MODE lens telescope. (a) Spot diagram within Airy disk of 6.7μm, where left is spots for design telescope lens and right is spots for the telescope with a fabrication error of a color corrector. (b) Chromatic focal shift over 589nm to 727nm shows about 56 μm.

In this prototype telescope, the primary MODE lens is made of moldable glass, which is L-BSL7 from Ohara Corporation. The field-lens and four doublets (A, B, C, and D) are precisely fabricated at Optimax Systems, Inc. The AZTECC and DFL lens is diamond tuned on PMMA at the Ohio State University.

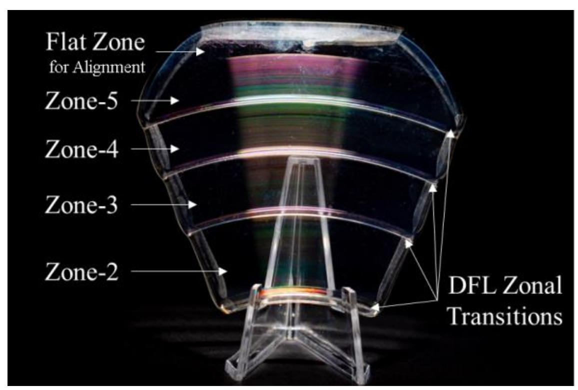
During the molding process of the ring segment, there might be some error in the thickness and wedge angle of the molded ring segment. The thickness is over due to the mold inserts not completely compressed together, which is about 0.6 mm. In addition, the wedge angle appears to the molded ring segment because the molding guide pins tilts into a very slight angle due to the over constraints in the mold assembly, which give a radial wedge of 0.21˚ and a tangential wedge of 0.08˚. The manufacturing tolerance for all spherical field lens and all spherical four doublets (A, B, C, and D) is precision level, which is the diameter of +0.000/-0.025mm, center thickness of ±0.050mm, radius of ±0.025% or 1 fr., irregularity of 0.05 wave PV.[7] Fig. 2 shows the performance of prototype MODE lens telescope. The spot diagram for the MODE telescope lens with a fabrication error of a MODE primary lens and a color corrector is still within the Airy disk diameter of 6.7 μm, and the chromatic focal shift over 589nm to 727nm shows about 56 μm.

3.2 MODE lens ring segment measurement

Prototype ring segment of MODE lens primary of 240 mm aperture diameter and 1 m focal length with a 0.125˚ half field angle, which is designed to minimize zonal field shift that is characteristic of segmented lens by curving front intercepts of zonal transitions, is molded from moldable glass, which is L-BSL7 from Ohara Corporation. This segment is one of eight ring segments fabricated for the prototype telescope. As shown in Fig. 3, glass molded prototype ring segment has a MOD front surface and a DFL rear surface. MOD surface as shown in Fig. 3(a) consists of MOD zones 2-5, flat zone for alignment, and MOD zonal transitions between zones and a DFL rear surface as shown in Fig. 3(b) consists of DFL zones 2-5, flat zone for alignment, and DFL zonal transitions. MOD zonal transitions and DFL transitions are properly designed and molded to minimize the stray light.



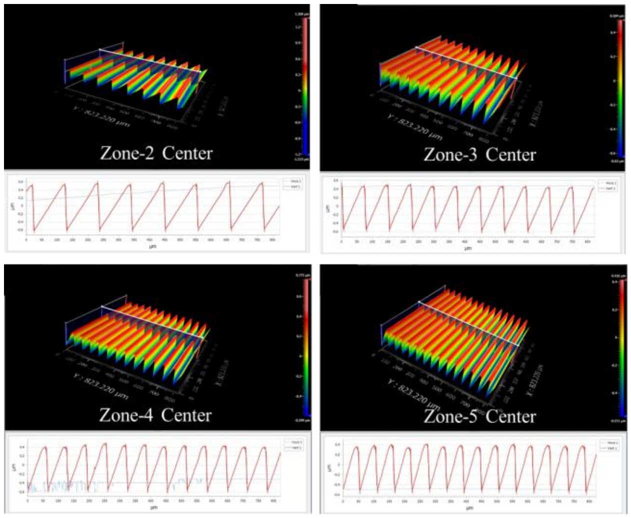
(a)



(b)

Figure 3. Prototype molded ring segment. (a) High-harmonic MOD zones and (b) Single-harmonic DFL zones

Fig. 4 shows DFL rear surface profiles in zones 2-5, that are measured using Zygo NewView 3D optical surface profiler. The half tool radius of 0.5mm is used to cut the DFL surface profile on the DFL mold insert in the diamond turning process. This induces the peak rounding in the DFL profiles, which looks larger radius because the DFL pitch decreases as the DFL zone number increases. The required DFL height can be calculated from a single-harmonic height, $h=\lambda/(n-1)$ where λ = 658 nm and n = 1.5138 for L-BSL7 moldable glass from Ohara, which is 1.28 μm. The DFL height deceases as the zone number increases and the DFL pitch decreases at the same time. The DFL height effects on the diffraction efficiency of DFL surface mainly.

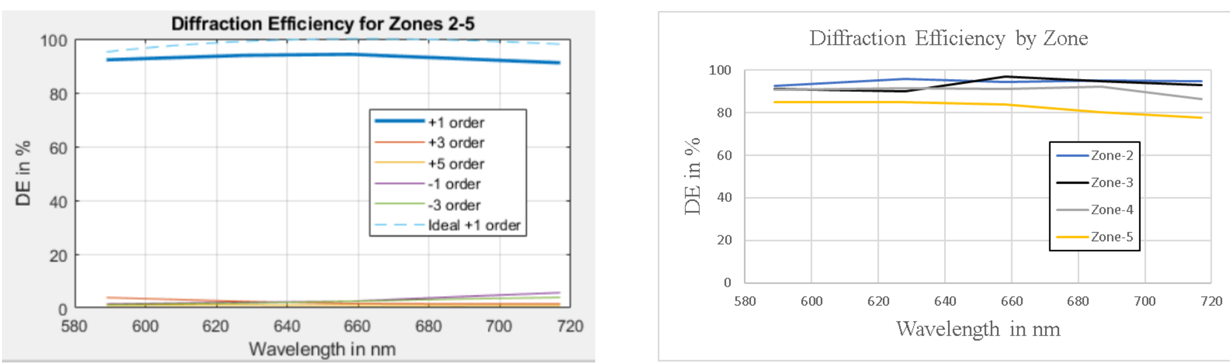


DFL Zone	Pitch	Height
-	μm	μm
2	109.42	1.14
3	73.74	1.04
4	63.95	1.04
5	58.73	1.06

Figure 4. Single-harmonic DFL profiles measurement using Zygo NewView 3D optical surface prolier

The MODE primary Lens of the prototype telescope is designed with a diffractive Fresnel lens (DFL) on its image-side surface. A different DFL design is used in each zone. Measured diffraction efficiency versus wavelength is shown in Fig. 5, where DE is defined as

$$\mathrm{DE} = \frac{\text{Measured power in a focal order}}{\text{Total transmitted power}} \times 100\%$$



(a) (b)

Figure 5. Measured diffraction efficiency (DE) of the test molded ring segment. The +1 order is the design order. (a) Diffraction efficiency over all wavelengths averaged for zone 2-5 and (b) Diffraction efficiency by zone 2-5 for the +1 design order.

Performance of the fabricated DFLs is excellent, with diffraction efficiency of the +1 design order at well above 90% for all wavelengths using zones 2-5 transmitting through rectangular measurement aperture. The measured diffraction efficiency of the +1 design order is slightly lower than the ideal values, due to small fabrication errors in the measured profiles shown in previous paragraph. The diffraction efficiency by zone for the +1 design order is slightly different with respect to zone number because the DFL heights are different from the ideal designed height of 1.28 μm mainly.

4. CONCLUSIONS

The performance for the prototype MODE lens telescope using the measured errors of the molded ring segment and the color corrector is estimated within the Airy disk diameter in the spot diagram and almost no degraded in the chromatic focal shift. The measured diffraction efficiency for the +1 design order of the DFL on the image-side surface of the glass molded MODE primary ring segment is slightly lower than the ideal design values due to the small fabrication error in the measured profiles and especially in the higher zone with the small pitches.

5. ACKNOWLEDGEMENTS

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