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Type 2 longitudinal chromatic aberration from a high-harmonic MODE lens and color corrector

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ABSTRACT

The longitudinal chromatic aberration (LCA) specific to a high-harmonic multi order diffractive engineered (MODE) lens designed for the astronomical R band (589nm to 727nm) is described and demonstrated. This Type 2 LCA is characterized by rapid changes of focal position versus wavelength over a focal range of f_0/M, where f_0 is the design focal length at 658nm and M=2196 is the harmonic order. Type 2 LCA effects on image performance and correction methods are also discussed and demonstrated.

Keywords: Diffractive optical element, high-harmonic lens, focal dispersion, color correction

1. INTRODUCTION

Multi-order diffractive (MOD) lenses have been discussed,[1,2] where an integer number M of wavelengths of optical path difference (OPD) defines transitions between zones in a focusing element. When M is a large number, say M > 250, both geometrical and physical optics considerations must be used to design and analyze the optical system. Recently, the combination of a large-M MOD front surface and single-order (M = 1) diffractive Fresnel lens (DFL) rear surface lens has been demonstrated, which is called a multiple-order-diffraction engineered (MODE) lens,[3,4] as shown in Figure 1. One motivation for developing these systems is application to large-aperture ultralightweight space telescopes.[5] Unlike simple diffractive lenses, the MODE telescope system with a color corrector provides high quality, diffraction-limited imaging over a broad bandwidth.[6] In this paper, we report on longitudinal chromatic aberration (LCA) of our prototype MODE lens telescope and various correction methods in order to extend the operational wavelength range and reduce size of the color corrector.

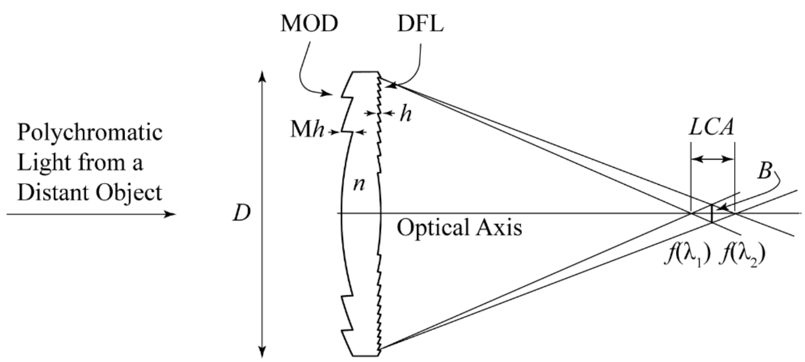

Fig. 1. Multiple-order-diffraction engineered (MODE) lens. The front surface is a multiple-order-diffraction (MOD) lens, and the back surface is a diffractive Fresnel lens (DFL). *h* is the glass thickness of refractive index *n* that produces one wave of optical path difference in transmission. Although reduced by the DFL, classical longitudinal chromatic aberration (Type 1 LCA) is still significant in the MODE lens, which causes blur when used for polychromatic imaging. *B* is the size of the blur circle due to LCA.

MOD lenses were introduced with relatively low M number in the 1990s by several authors.[1,2] The attraction for the MOD structure is that, although the focal point of any order moves toward the lens in the same manner as a single-order DFL, the diffraction efficiency of orders near the design focus change such that different orders have high diffraction efficiency in a limited axial range and thereby produce a relatively compact axial energy distribution over a broad bandwidth. In the paper by Faklis and Morris,[2] theory of MOD focal dispersion with wavelength is discussed, as well

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as introduction of an image quality metric for MOD lenses based on an optical transfer function that accounts for multiple orders and assumes a rectangular pupil. Results from an experiment were reported that used laser writing to fabricate an M = 2 lens. In the Sweeny and Sommargren paper,[1] a similar theoretical development was presented, and analysis of an M = 21 lens at a design wavelength of 550 nm was reported. A 6 mm diameter diamond-turned mold was used to fabricate a replicated acrylic lens with an optical power of 34.75 diopters at the design wavelength. A low-M (M = 45) MOD surface combined with a DFL on the same surface was also discussed.[7] Further diffraction and aberration analysis was reported by Hazra and Delisle.[8] More recently, a THz MOD lens was fabricated and tested.[9] A MOD-lens-based remote imaging system was also recently described that uses a combination of a thin MOD lens and advanced image processing to obtain high image quality.[10]

The work described in this report considers correction for residual diffraction efficiency losses and focal position changes as a function of wavelength in MOD and MODE systems. Our previous work on MODE systems reported on fabrication and testing of a M = 1000, *f*/3.2 MODE prototype lens with a focal length of 150 mm at the design wavelength of 658 nm, along with analysis of MODE lenses with apertures up to 250 mm in diameter and focal lengths from 100 mm to 1000 mm.[3] Although performance of the prototype was satisfactory, the analysis indicated that correction of residual LCA in larger diameter and lower f-number systems can significantly improve performance. Since our long-range goal is application to large-aperture space telescopes, this color correction was necessary to understand. Design of a 240 mm aperture, M = 1000 system, reported several geometrical design considerations important in MODE systems with high M, where both refractive and diffractive design considerations must be used.[4] The concept of zonal field shift, which is an off-axis aberration characteristic of high-harmonic diffractive lenses, is corrected by curving the surface of the zonal transitions. Previous aberration analysis on harmonic lenses that are based on a thin-element model of the transmitted phase did not explain this effect.[8] We then reported on a color-corrected, 240 mm aperture, 1 m focal length, M = 2196 MODE system that uses an optical element we call an Arizona total energy color corrector (AZTECC) lens, which essentially removes harmonic steps in the MODE-lens wavefront.[6] A basic theoretical framework and understanding for LCA color correction using an AZTECC lens was also presented.[11]

The following sections present an introduction to longitudinal chromatic aberration in high-harmonic lenses, the prototype design, LCA measurements, discussion of color correction philosophies, and conclusions.

2. TYPE 1 AND TYPE 2 LONGITUDINAL CHROMATIC ABERRATIONS (LCA)

Longitudinal chromatic aberration (LCA) in diffractive lenses is a significant aberration that limits image quality. A refractive lens increases focal length as wavelength increases, which is called Type 1A LCA, as shown in Figure 2. For a single-harmonic diffractive Fresnel lens (DFL) with M = 1, the dispersion is in the opposite direction compared to the dispersion from a conventional refractive lens, and the change in focal length is much greater for a given change in wavelength as compared to a simple refractive lens, which is called Type 1B LCA. A MOD lens exhibits Type 1A LCA due to the change of refractive index of the lens material. It also exhibits short, cyclic changes in focus that are like Type 1B LCA, in that they change focus at the same rate versus wavelength, as explained in References 2 and 3. The cyclic variation is due to the high-harmonic surface transitions and zone spacings. The unusual character of the short cycle range of f_0/M, where f_0 is the design focal length, is labeled as a new type of aberration called Type 2 LCA. Minimization of Type 1 and Type 2 LCA is necessary for good color correction in high-harmonic diffractive lenses.

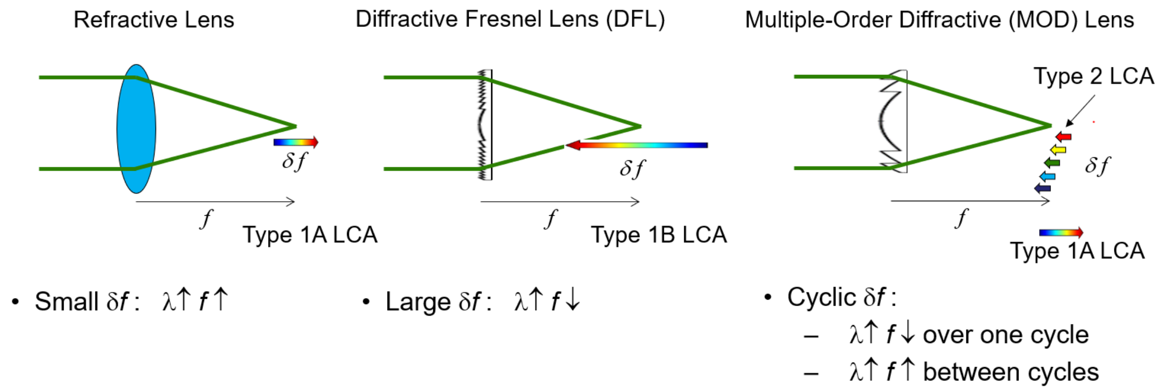


Fig. 2. Multiple-order-diffraction engineered (MODE) lens. The front surface is a multiple-order-diffraction (MOD) lens, and the back surface is a diffractive Fresnel lens (DFL). *h* is the glass thickness of refractive index *n* that produces one wave of optical path difference in transmission. Although reduced by DFL, longitudinal chromatic aberration (LCA) is still significant in MODE, which causes blur for polychromatic imaging.

3. PROTOTYPE MODE TELESCOPE DESIGN

An example system design is shown in Figure 3,[6] where a 5-zone MODE primary lens with a 240mm diameter aperture and 1 m focal length is designed to operate over a 0.25° field of view. The color corrector for this system consists of four doublets (A, B, C, and D) and a DFL that reimage the focal point onto the image sensor. The Arizona total energy color corrector (AZTECC) lens is a stepped surface that compensates Type 2 LCA. In this design, the primary MODE lens is made from moldable glass, which is L-BSL7 from Ohara Corporation. The AZTECC lens is diamond-tuned PMMA that is fabricated at The Ohio State University in Professor Allen Yi's group.

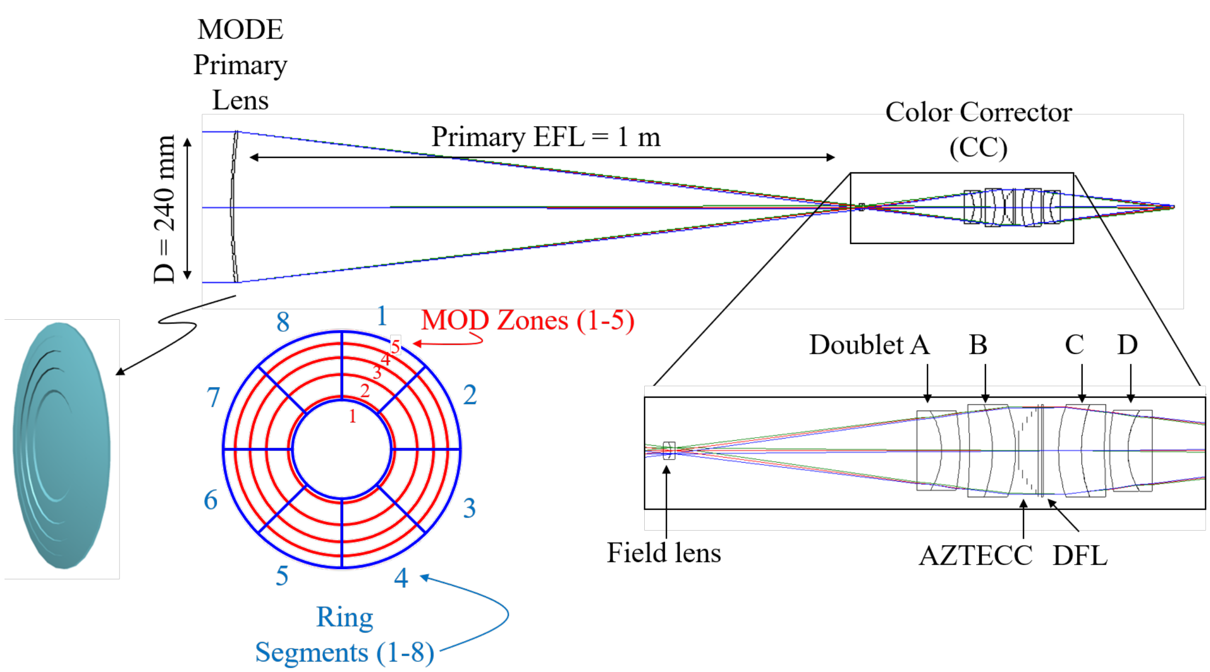


Fig. 3. The prototype MODE-lens telescope with color corrector.[7]

Correction of Type 1 LCA follows well-known design rules. In this case, a combination of high-positive-dispersion refractive elements and a negative-dispersive DFL adequately produces apochromatic focusing. Type 2 LCA is corrected with the AZTECC lens near a conjugate plane to the primary that compensates for the stepped wavefront produced by the MOD surface.

Figure 4 shows the longitudinal chromatic aberration of a MODE lens design before and after correction. The solid blue line on the left is Type 1 LCA that follows from conventional color geometrical correction, where the combination of the refractive focusing from each MOD zone is corrected to an achromatic secondary spectrum with the back-surface DFL. Diffraction due to the high-harmonic MOD transitions presents an additional variation in the focal dispersion that is shown in the detail inset as a rapidly varying blue line, where magnitude of the focal dispersion is ~ f_0/M, the wavelength period is ~ λ_0/M, f_0 is the design focal length and λ_0 is the design or center wavelength. The dotted lines in the left figure show the range of Type 2 LCA as a function of wavelength. Corrected LCA, which is shown as the green line in the left figure, is nearly prefect. The right portion of Figure 4 shows the relative PSFs, with the uncorrected system exhibiting a Strehl ratio (SR) ~ 0.12, Type 1 correction SR ~ 0.2 and fully corrected SR ~ 0.95.

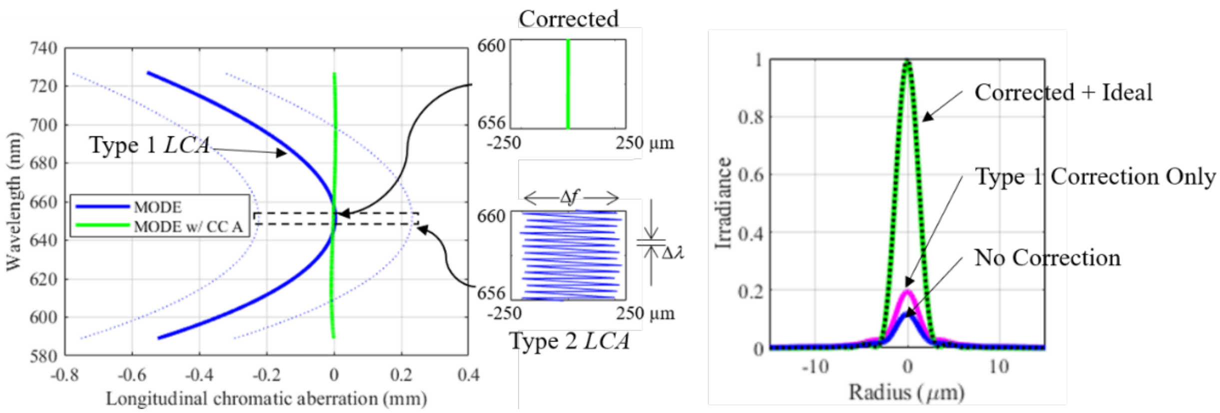


Fig. 4. LEFT: LCA plot of a MODE lens before (blue line) and after (green line) color correction for a M = 2196, 1 m focal length and 240 mm aperture operating over the astronomical R-Band.[7] The color-corrected result shows more than 10 times less Type 1 LCA and almost no Type 2 LCA compared to before correction. RIGHT: Point-spread functions (PSFs). "CC A" refers to a specific color-corrector design specified in Reference 6.

4. EXPERIMENTAL MEASUREMENTS

This section reports on experimental measurements from one of the molded glass ring segments designed for the prototype telescope. Measurements include Type 2 LCA of the color corrector and diffraction efficiency of the DFL.

4.1 Experimental setup

An experimental testbed composed of a collimated laser beam from an off-axis parabola (OAP) is used to measure Type 2 LCA from a fabricated MODE-lens segment. A frequency tunable laser diode (New Focus Velocity 6300) is coupled into a fiber with free-space optics and the output of the fiber is adjusted at the focus of the OAP. Due to a file conversion error, the MODE primary lens was not used to measure Type 2 LCA. Instead, Type 2 LCA from the color corrector, which has the opposite sense of Type 2 LCA compared to the MODE primary shown in Figure 4, is reported. The OAP is aligned with an alignment telescope and a shear plate in order to assure a collimated beam incident onto the color corrector. An aspheric achromatic doublet (Edmund Optics) is used to focus light into the field lens of the color corrector in order to simulate focusing of the MODE primary. Light is refocused by the color corrector, which includes the AZTECC lens onto a CMOS image sensor (Thorlabs CS235CU) that is moved to the minimum spot radius for best focus as a function of wavelength.

4.2 Results

Figure 5 shows the result of the Type 2 LCA experiment, where the small inset of Figure 4, which shows the theoretical Type 2 LCA of the MODE lens, is enlarged (left) and compared to measurements with the AZTECC lens (right). AZTECC lens measurements show the opposite slope from the theoretical curve, and the magnitude of the ~ 0.45 mm focal shift and the ~ 0.3 nm wavelength cycle range are approximately the same as the theory. Therefore, the AZTECC lens should compensate the Type 2 LCA of the MODE lens.

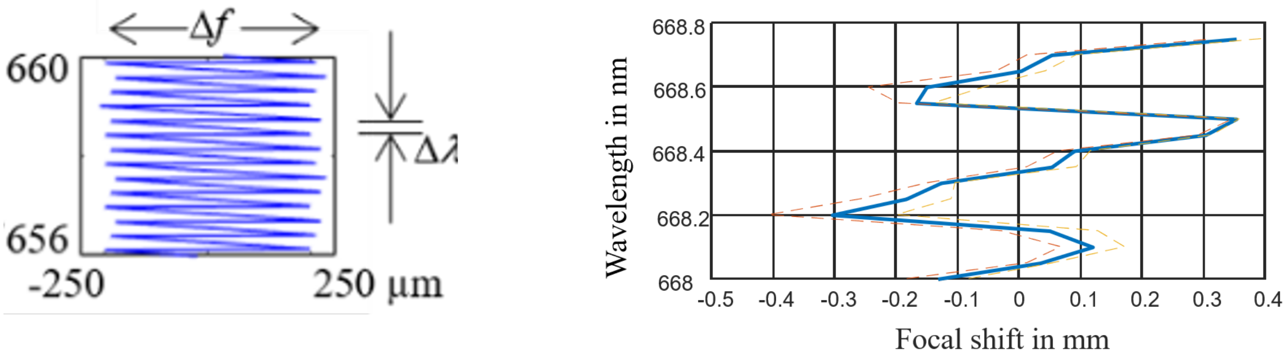


Fig. 5. Type 2 LCA theory (left) showing the MODE primary focal shift; and (right) showing measurement of the Type 2 LCA of the AZTECC lens in the color corrector.

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.[6] Performance of the fabricated DFL 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. The amount of light in even focal orders was not measurable in our setup.

Even though DE of the primary MODE ring is not perfect, light from focal orders other than the design order are far out of focus from the design focus. For example, the +3rd order focused is 61.2 mm from the design focus, and the -1 order is focused -69.8 mm from the design focus. Higher +/- focal orders are much further from the design focus. With an f/4.2 focus cone, diameters of the blur circles from these orders at the field lens would be about 14.6 mm and 16.6 mm, respectively. The field lens is only 6.2 mm in diameter, so somewhere between 10% and 20% of these low-power beams would even make it to the detector, and they would be similarly out of focus in that plane with similar image blur diameters. For example, at 658 nm, the +3 focal order at most would contain 0.2*1.6% = 0.32% of the incident light as background over a blur circle diameter of about 14.6 mm.

5. COLOR CORRECTION PHILOSPHIES FOR LARGE APERTURE AND WIDE BANDWIDTH MODE TELESCOPES

As discussed in Section 2, the MODE telescope simultaneously exhibits different types of LCA. An effective correction philosophy is to correct both Type 1 and Type 2 LCA separately, as used in the Prototype MODE telescope described in Section 3. However, the long-range goal of the Nautilus project is to develop very large aperture devices, up to 8 m in diameter, and operate over wide optical bandwidths. In terms of large-aperture telescopes, the proportional diameter of the color corrector must be reduced substantially compared that used in the prototype MODE telescope, in order to maintain the weight advantage of the primary MODE lens. For example, if a reasonable diameter of a color corrector lens is 0.2 m when used with an 8 m primary, the diameter of the primary divided by the diameter of the color corrector is a factor of 40. In addition, the optical bandwidth must be increased substantially compared to the prototype described in Section 3. Solutions to these requirements are not straightforward nor are they common in optical design. The following paragraphs review basic concepts that could provide pathways to solutions for this engineering challenge.

5.1 LCA Type 1 correction

In order to provide diffraction-limited imaging over broad optical bandwidths, Type 1 LCA must be corrected to be apochromatic (three wavelengths with no focal shift). Like discussed in Section 3 with the protype MODE telescope, this condition is achieved with the achromatic focal shift (two wavelengths with no focal shift) of the MODE primary lens cancelling the nearly opposite achromatic focal shift of the color corrector. A limiting factor in this design is the limited optical bandwidth of the DFL on the back side of the primary lens. The MOD surface itself has a very wide optical bandwidth. If the DFL is fixed to the back surface of the single-element primary, the entire telescope has a limited bandwidth. However, the DFL can be moved to a different location in the system, and different DFLs can be designed to cover different optical bandwidths. Alternatively, a negative refractive lens can be used near the primary focus to make the primary and second lens an achromatic pair. The following paragraphs discuss these possibilities and some tradeoffs associated with them. For convenience, we illustrate examples with standard visible bandwidths, Abbe numbers, and refractive index values.

5.1.1 Basic Theory for LCA Type 1 correction

Basic paraxial, thin-lens theory for color correction is given by Kingslake.[12] For a system of k thin optical elements, the paraxial LCA in image space with collimated input light is given by

$$\mathrm{LCA} = -\frac{1}{u'_k}\sum \frac{y^2}{f\,V} \quad , \tag{1}$$

where u'_k is the image-space marginal angle, f is the focal length of the element, y is the marginal ray height at the element, and V is the Abbe number of the element.

In this section, the DFL on the back side of the primary is removed, so it can be placed downstream in the smaller-diameter sections of the optical system. Our first design task is to make an achromatic focus from the primary lens by using much smaller lenses near the primary focus.

In our case, we start with two elements, as shown in Figure 6, in order to make an achromatic focus for the primary lens. The first element is the MODE primary, and the second element is for color correction. In our case, the MODE primary lens is designed for minimum aberration at three wavelengths, and focus compensation at each wavelength is allowed to vary. The color corrector is not considered in the design of the primary. The ratio y_1/y_2 should be as large as possible with f_1 and V_1 fixed. Application of Eq. (1) with LCA = 0 yields an achromatic system with

$$f_2 = -\left(\frac{y_2}{y_1}\right)^2 f_1 \frac{V_1}{V_2} \quad . \tag{2}$$

Note that typical achromat designs have $y_1 \approx y_2$, so the focal length of the second element is primarily determined by the ratio of the Abbe numbers and the focal length of the first element. However, large-aperture designs require very small y_2/y_1 values, so the focal length of the second element becomes very small.

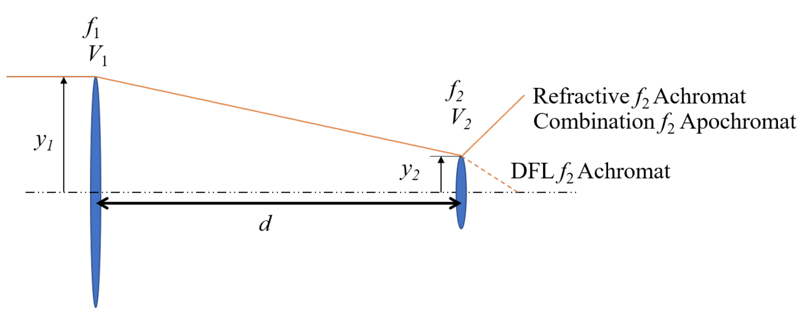


Fig. 6. Type 1 LCA theory layout to produce an achromatic focus from the primary lens.

The secondary spectrum (SS) of an achromat with zero focal shift at wavelengths *F* (0.4861μm) and *C* (0.6563 μm) is the residual LCA between a wavelength in the center of the optical band and one of the two co-focal wavelengths, *F* and *C*. According to Kingslake[12],

$$\mathrm{SS} = -\frac{1}{u_k'}\sum \frac{P\,y^2}{f\,V} \quad , \tag{3}$$

where partial dispersion *P* is given by

$$P = \frac{n_\lambda - n_F}{n_F - n_C}, \tag{4}$$

and refractive indices *n* are specified at wavelengths *F*, *C* and *λ*, which is the wavelength exhibiting the maximum residual LCA. *P* is computed for each element in the sum. For the system shown in Figure 6,

$$\mathrm{SS} = \frac{f_{sys}\left(1-k\right)}{V_1\left(1-k\right)-V_2}\left(P_2 - P_1\right) \ , \tag{5}$$

where $k = d/f_1$ and f_{sys} is the system focal length.

5.2 Dialyte achromat

A Dialyte achromat uses a refractive lens for the second element that is separated from the first element. Refractive lenses have positive Abbe numbers. With f_1 = 1 m and V_1 = 64.1 (L-BSL7), a 10x size reduction for y_2/y_1 = 1/10 yields a focal length for f_2 of $f_2 = -\frac{64.1}{100}\frac{1}{V_2}$, which is negative. This relationship implies that V_2 should be as small as possible in order for f_2 to be as large as possible. One choice is N-SF6, which has V_2 = 25.36, and yields f_2=-25.3 mm. With y_2 = 120/10 = 12 mm, according to the design of the prototype telescope, the second element design is almost a divergent f/1. This low and divergent f/# would result in a highly divergent virtual focus and would make engineering the remaining portions of the optical system challenging. As the f/# of the primary decreases, these difficulties get worse. Note that a Schupmann system is defined with $V_1 = V_2$, which makes the focal length of the second element even shorter. Therefore, *a refractive singlet in the configuration of Figure 6 is not a good solution to producing an achromatic focus for the primary*. For this example, if λ = 0.5876 μm, P_1 = -0.7010, P_2 = -0.7134. and *k* = 0.9 and f_{sys} = -0.339 m, which yields SS ~ - 22.2 μm.

5.3 DFL-Dialyte achromat

Instead of a refractive lens for the second element, it is useful to consider using a single-order DFL. In this case, V_2 = -3.45, and for y_2/y_1 = 1/10, f_2 = 185 mm and f_{sys} = 650 mm. The positive system focal length presents a real image conjugate, as shown in Figure 6. Calculation of Eq. (5) with P_2 = -0.5964 yields SS = 690 μm. The f/# in image space is reduced about a factor of 0.6. In consideration of DFL fabrication, the minimum zone width would be about Λ = 2*(0.5876 μm)*(f/# of the DFL) ~ 9 μm for a 24 mm diameter secondary. Although this small period can be fabricated with good fidelity, it requires special equipment. As the diameter of the secondary increases with decreasing f/# of the primary, the minimum zone width reduces further, making *DFL fabrication impractical for a single-harmonic-order device used with low f/# primaries*.

5.4 Considerations for an apochromat

Now consider Eq. (1) again with three elements, where the primary lens is a MOD element, *k* = 0.9 and the second element is now a combination of a DFL and a refractive lens. The LCA expression becomes

$$\mathrm{LCA} = -\frac{y_1^2}{u_k'}\left(\frac{1}{f_1 V_1} + \frac{1}{100 f_2 V_2} + \frac{1}{100 f_3 V_3}\right) \ , \tag{6}$$

with a similar expression for the total SS from Eq. (3). The challenge is to make LCA = SS = 0. Given the large reduction in effectiveness of each element produced by the size reduction $(y_2/y_1)^2$, design of an apochromat involves challenges similar to the achromat design. Solution to LCA = SS = 0 with the paraxial equations can be found with a relatively simple computer program. However, the output values must be modified in a real ray-trace design program to get a physical solution, due to the paraxial limitations of the equations. Nevertheless, a solution is found for an apochromat using a DFL combined with a negative N-SF6 lens for element 2 in Figure 6. The residual focal shift is only 6 µm. However, like with the Dialyte solution discussed in Section 5.2, the divergence of the output cone is large, at f/1 for y_2 = 120/10 = 12 mm.

5.5 Cascaded correctors

The discussion outlined in Sections 5.2 through 5.4 indicate that it is very difficult to design for an achromatic or apochromatic focus with only one element or doublet in the converging cone of the primary. Although significant reduction in the range of the chromatic focal shift is possible with a single color corrector, *it is better to divide the color correction task between cascaded correctors*.

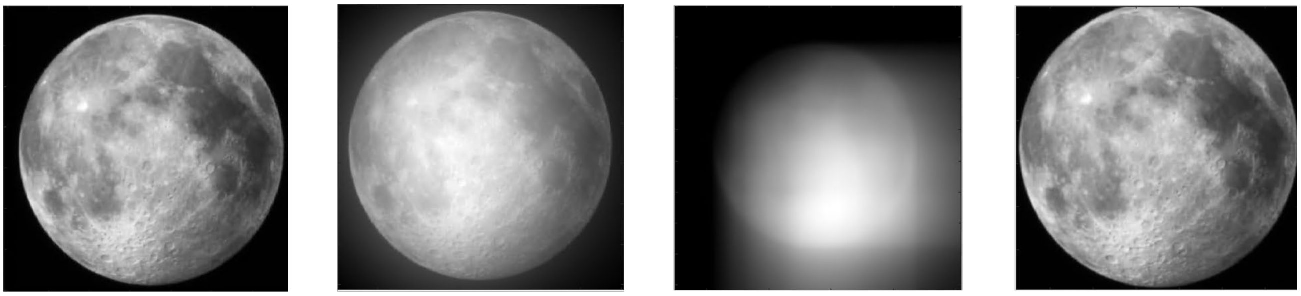
5.6 Advanced image processing

Given the Type 1 LCA achromatic focusing properties of the MODE lens combined with a small Type 2 LCA focal shift, it may be possible to avoid color correction with advanced image processing. An example of this technique using a MOD-only lens is reported by Nikonorov *et al*.[10] In that work, an M = 13 MOD lens with 150 mm and 300 mm focal lengths at λ_0 = 550 nm were fabricated by a gray-scale process in photoresist. Advanced image processing is used to process raw images into impressive RGB reconstructions. The first image processing step is to perform pixel-by-pixel color correction, based on a polynomial representation between the original and distorted colors. Next, a convolutional neural network (CNN), which is trained with truth images, reconstructs the blue and red channels, and regularized deconvolution with an approximated point-spread function (PSF) is used to reconstruct the green channel. With the MODE design's reduced Type 1 LCA focal shift and high-M that produces low values of Type 2 LCA focal shift, *a similar advanced image processing technique has the potential to reconstruct very high-quality images from a MODE telescope without the need for a color corrector*.

5.7 Bicubic phase plate

A simple technique introduced by Cathy *et al*. in the early 2000's is meant to extend the depth of focus in optical systems by using an asymmetric phase plate in the pupil plane of the optical system.[13] After acquiring an image, post processing is used to reconstruct an extended-depth-of-field result. Similar techniques have been introduced by others. If the Type 2 LCA for a MODE lens has a focal shift cycle range that is within a reasonable factor of the depth of focus of the MODE lens, these techniques could provide high-quality imaging without the need for an AZTECC in the color corrector. The penalty is that post processing of the raw image data is required. For the prototype telescope, the Type 2 LCA focal shift range is approximately f_0/M = 455 µm, and classical depth of focus is about $2\lambda_0 \times f/\#^2$ = 23.2 µm. The ratio of these values is 455/23.2 = 19.6.

In order to test the possibility of this techique for MODE lens Type 2 LCA color correction, a commerically available moon image is used as an object.[14] The raw image is filtered with a point spread function corresponding to an f/4.2 camera and a ¼° full field of view, as shown in Figure 7(a). (Note: The actual subtense of the moon is ~1/2°, but the size was reduced here to more closely represent the field of view of the prototype telescope.) A simulated image with three defocus planes at the short (589 nm), center (658 nm) and long (727 nm) wavelentghs of the astronomical R band is shown in Figure 7(b) with the appropriate defocus from Type 2 LCA at each of the threee wavelengths. This image is degraded with respect to Figure 7(a). Figure 7(c) shows a simulated raw image using a bicubic phase plate (BCP) with about 30 waves of peak phase. This image is shown at a slightly reduced transverse scale in order to show that the BCP signficantly affects the raw image and extends energy in the image well beyond the geometrical image area due to the asymmetry and area of the BCP point spread function. However, when appropriate post processing is applied to the raw BCP image data, a striking reconstruction is obtained, as shown in Figure 7(d). That is, *simulations indicate that the presence of a BCP in the protoype telescope system could eliminate the need for an AZTECC lens*.



(a) F/4.2 Image (b) Image with Type 2 LCA (c) BCP Image (d) BCP Reconstruction

Fig. 7. Image processing fro chromatic correction with a bicubic phase plate (BCP): a) Simulated camera image with a perfect f/4.2 imaging system; b) Simulated image with Type 2 LCA of the prototype telescope; c) Simulated raw image with Type 2 LCA of the prototype telescope and a BCP in the pupil of the imaging system; and d) Image reconstruction from (c). Note that (a) and (c) are nearly identical.

5.8 Consideration of the science case

There are two primary applications under consideration for application of MODE space telescopes. The first is direct imaging, and the second is spectroscopy. Optical system requirements are different in each application. Generally, direct imaging is observed in multiple experiments over different wavelength bands, and these systems target near-diffraction-limited imaging. Spectroscopic applications do not necessarily require diffraction-limited imaging, but they benefit from extremely wide optical bandwidth.

In future MODE space telescope systems, it would be straightforward to have direct imaging requirements met with different color correctors, which could be separated with chromatic beam splitters for parallel measurements or rotated on a wheel for serial measurements. The test segment analyzed in this work displays high measured diffraction efficiency over a 20% bandwidth, and separating the DFL from the primary into the color corrector allows for fabricating a reduced diameter DFL following Nakai, which is shown to operate over a 50% bandwidth.[15] Accounting for Type 2 LCA could be completed with an AZTECC lens or post-processing with convolutional neural networks and/or custom diffractive elements in the pupil.

Spectroscopic applications require large bandwidths, so the tradeoff of not correcting for Type 2 LCA may be acceptable, and 50% or larger bandwidth DFLs could be placed in parallel channels with wide-bandwidth chromatic beam splitters. Although these systems may be less complicated in terms of imaging performance, they require other optical elements, like spectroscopic gratings, in the science instrument package. Alternatively, the spectroscopic grating could be incorporated into a single-lens-group color corrector with a wide-bandwidth DFL in order to minimize the total optical system footprint.

6. CONCLUSIONS

The feasibility of using an AZTECC lens for correcting Type 2 LCA is shown with experimental measurements using an AZTECC that is designed to correct for the Type 2 LCA of an M = 2196 high-harmonic MODE lens. The slope of the focal position versus wavelength is opposite to that of the design for the MODE lens, and the variation occurs over the designed wavelength cycle range and focal shift magnitude.

In addition, several color correction techniques are explored conceptually that could lead to simplification of the color correction system for both Type 1 LCA and Type 2 LCA in a large-aperture space telescope.

7. ACKNOWLEDGEMENTS

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