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Diffractive Optics for Compact Flat Panel Displays

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Diffraction Optics for Compact Flat Panel Displays

Introduction

Three years ago LLNL developed a practical method to dramatically reduce the chromatic aberration in single element diffractive imaging lenses. High efficiency, achromatic (i.e., color corrected) imaging lenses have been fabricated for human vision correction. This LDRD supported research in applying our new methods to develop a unique, diffraction-based optical interface with solid state, microelectronic imaging devices.

Advances in microelectronics have lead to smaller and more efficient components for optical systems. These include sources, (laser diodes and laser diode arrays), detectors, (small pixel, high-density CCD arrays) and displays (high-density, low-power flat panel displays). There have, however, been no equivalent advances in the imaging optics associated with these devices. With a few minor exceptions, light rays are still deflected by refraction or reflection from spherical surfaces. Although the state of the art has improved, the basic techniques are literally hundreds of years old. Typically, conventional spherical optics are configured as a system to correct field and chromatic aberrations. The optical designer must choose between a quality system that is large and bulky or a simple systems with poor optical quality. Either way, the optical system compromises the virtues of modern microelectronic devices.

The goal of this project was to replace the bulky, refractive optics in typical head-mounted displays with micro-thin diffractive optics to directly image flat-panel displays into the eye. To visualize the system think of the lenses of someone's eyeglasses becoming flat-panel displays. To realize this embodiment, we needed to solve the problems of large chromatic aberrations and low efficiency that are associated with diffraction.

We have developed a graceful tradeoff between chromatic aberrations and the diffractive optic thickness. It turns out that by doubling the thickness of a micro-thin diffractive lens we obtain nearly a two-times improvement in chromatic performance. Since the human eye will tolerate one diopter of chromatic aberration, we are able to achieve an achromatic image with a diffractive lens that is only 20 microns thick, versus 3 mm thickness for the comparable refractive lens. Molds for the diffractive lenses are diamond turned with sub-micron accuracy; the final lenses are cast from these molds using various polymers. The end result is that we retain both the micro-thin nature of the diffractive optics and the achromatic image quality of refractive optics. During the first year of funding we successfully extended our earlier technology from 1 cm diameter optics required for vision applications up to the 5 cm diameter optics required for this application.

Activities

During this project, we concentrated on solving the problem of chromatic aberrations associated with diffractive optics. We were able to:

1. Adapt existing optical design codes (e.g., Code V) to include out diffractive elements
2. Determined that these diffractive elements provide a sufficient number of degrees of freedom to allow simultaneous color correction over the entire field while maintaining a good impulse response.
3. Determine a strategy to minimize the number of elements in a given design
4. Characterize and control flare (or any type of unwanted optical scatter) from larger format diffractive lenses.
5. Specify optical tolerances for fabricating our diffractive optical systems.
6. Developed, fabricated, and tested a new compound diffractive optic that cancels underlying material dispersion.
7. Anti-reflection coated diffractive optical elements to avoid Fresnel insertion losses.
8. Applied a strategy to split diffractive surfaces for geometric aberration control
9. Acquired and modified color, flat-panel displays with video drivers for prototype demonstrations
10. Characterized the micro-structure of diffractive optic components using various diagnostics including atomic force microscopy.
11. Worked with Kaiser Electronics, a manufacturer of Helmet-Mounted Displays (HUDs), to incorporate our diffractive elements into their designs.
12. Fabricated diffractive elements to be used for color correction in an existing Kaiser HUD design.
13. Developed a novel zero-power, bi-Fresnel color-correction element.

Compound Diffractive Optic for Material Dispersion Correction

Previously, Sweeney and Sommargren[1,2], and independently Morris and Faklis[3] introduced a diffractive imaging lens for which the optical path-length transition between adjacent facets is an integer multiple m of the design wavelength. We will refer to this structure as a modulo- $m2\pi$ lens. Such a lens will have a diffraction-limited, common focus for a number of discrete wavelengths across the visible spectrum. At these specific wavelengths, 100% diffraction efficiency is obtained into a particular diffracted order. At intermediate wavelengths, multiple spherical waves are produced that are focused at axial locations other than the nominal focal plane. We refer to this fluctuation in axial focal position as the residual diffractive dispersion. This effect goes as P/m , where P is the nominal power of the element. Thus, this spread may be decreased by increasing m .

As an example, figure 1 shows a (theoretical) power versus wavelength plot for an $f/5$, 100 mm focal length modulo- $m2\pi$ diffractive lens with $m=45$, fabricated in a material with $n_d=1.492$ and an Abbe V-number of 57.4. A linear fit of the focal shift data is also shown in the figure. The negative slope of this line reveals the underlying material

dispersion of these lenses. Note the similarity to the dispersion characteristics of a conventional refractive singlet. In this paper we describe a technique for cancelling the material dispersion of the modulo- $m2\pi$ diffractive lens. Only the residual diffractive dispersion remains after achromatization.

Figure 1 - Theoretical focal length variation for an $f/5$, 100 mm nominal focal length, modulo- $m2\pi$ diffractive lens with $m=45$. Lens material has $n_d=1.492$ and $V=57.4$. The dashed, linear fit line shows the underlying material dispersion of the lens.

The material dispersion of the modulo- $m2\pi$ lens may be canceled by utilizing the concepts developed for hybrid (combination refractive and diffractive) achromatic optical elements. The negative dispersion of a diffractive element is used to balance the positive dispersion of the refractive component. Generally, these refractive hybrid lenses consist of a convex refracting surface possessing most of the optical power, and a planar surface on which the weaker diffractive structure has been patterned. Just as with the conventional hybrid elements, a modulo- 2π ($m=1$) diffractive structure may be combined with the modulo- $m2\pi$ harmonic diffractive lens to cancel its material dispersion. However, rather than placing the diffractive element on the opposite face of the element, it can be imbedded directly into the harmonic lens structure. We were able to design, fabricate, and test a compound lens of this sort.

There are various ways to design the desired compound diffractive optical elements. Rather than utilizing analytic design techniques found in the literature, we found it helpful to use commercially available computer-based optical design packages. This approach provided for better design flexibility and aberration control. The modulo- $m2\pi$ lens is modeled as a Fresnel lens. The so-called Fresnel surface in the computational code deviates rays at an interface according to a refraction equation. Basically, the model simulates microscopically-patterned surfaces as macroscopically smooth surfaces. In this

configuration, the codes do not include the effects of diffraction from the facets so the treatment is rigorously correct only at the resonant wavelengths shown in figure 1. To a good approximation, however, a design optimized in this way is corrected for all wavelengths except for the superimposed residual diffractive dispersion described above. The modulo- 2π element is modeled as a binary diffractive element or holographic optical element. These two optical elements are modeled as having zero separation and zero thickness. The impact of neglecting the finite sag of the modulo- $m2\pi$ lens has been modeled in more detailed analyses and has also been found to be negligible.

In the following, we present an example design for an $f/5$, eight-degree full-field, 100 mm focal length achromat over the visible spectrum. The lens material is acrylic ($n_d=1.492$, $V=57.4$). The effective surface sag (i.e., the sag used to generate the refraction equation) is given by

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4, \quad (1)$$

where c is the base radius of curvature, k is the conic constant, and α_1 and α_2 are the aspheric coefficient terms. The modulo- 2π lens is modeled as a phase surface of the form,

$$\phi = Ar^2 + Br^4, \quad (2)$$

with ϕ in radians, and A and B respectively being the second and fourth order polynomial expansion coefficients.

The various coefficients are determined by the optimization package of the design code. The radial thickness profiles of the final design for the modulo- $m2\pi$ surface can be described as,

$$t(r)_{2m\pi} = \text{MOD}(z(r), S_{2m\pi}), \quad (3)$$

where

$$S_{2m\pi} = \frac{m\lambda}{\Delta n}$$

and $z(r)$ is given by eqn. 1. The radial thickness profile of the modulo- 2π surface can be described as,

$$t(r)_{2\pi} = MOD(z(r)_{2\pi}, S_{2\pi})$$

where

$$z(r)_{2\pi} = A' r^2 + B' r^4,$$

$$A' = A * [\lambda / (2 \pi \Delta n)],$$

$$B' = B * [\lambda / (2 \pi \Delta n)], \quad (4)$$

and

$$S_{2\pi} = \frac{\lambda}{\Delta n}.$$

For equations 3 and 4, $\Delta n = n_d - 1$, and λ corresponds to the sodium d-line at 587 nm. Radial thickness profiles for sections of these two surfaces are shown in figure 2a and 2b. Although not explicitly shown in figure 2b, the minimum facet separation at the edge of the lens aperture is about 100 μm .

Rather than separating these two surface structures on opposite faces of a planar substrate, they can be superimposed onto a single compound surface. This operation can be represented mathematically simply by adding the radial thickness profiles of the two surfaces as given in equations 3 and 4. Figure 2c shows a radial profile of the compound surface.

Fabricating the achromatic element as a compound surface has numerous advantages over separating the two surfaces. First, a single fabrication process (for example, diamond turning) may be utilized. Second, by using only one surface of the element for chromatic correction, the "unused" surface potentially could be utilized for additional aberration balancing, or to provide additional power. Lastly, the compound surface eliminates the need for tight alignment tolerances for casting or embossing replication procedures.

Figure 2 - Radial thickness profiles for the central 5 mm of the computer-designed(a) modulo- $m2\pi$ surface from eqn. 3, with $m=45$, (b) the modulo- $2\bullet$ surface from eqn. 4, and (c) the superimposed compound surface.

Precision diamond turning was utilized to fabricate the surface shown in figure 2c. The surface was turned in oxygen-free copper on the Precision Engineering Research Lathe here at the Lawrence Livermore National Laboratory. This machine has a resolution of 125 Angstroms and an overall absolute accuracy of better than 0.1 microns. The target surface roughness on our curved parts is on the order of 50 Angstroms RMS with an eight micrometer radius diamond tool.

Lenses are replicated from the diamond-turned mold using a two-step process. A first-generation silicone mold is cast from the diamond-turned part. The silicone mold is then used to cast a second-generation replica in a commercially available uv-setting photopolymer, SK9. The replicated lenses have no measurable height or lateral shrinkage, as compared to the master mold. Root mean square roughness for the replicated lenses are typically 7-8 nm, as measured by atomic force microscopy. Figure 3

shows a scanning electron micrograph of a cross-sectional view of a freestanding SK9 replicated lens. Note the steep sidewalls, and smooth surfaces. Maximum depths for the modulo- $m2\pi$ facets were 50 μm . Maximum depths for the modulo- 2π facets were 1.2 μm . These depths correspond closely to the specified depths on the diamond turned mold.

Figure 3 - Scanning electron micrograph of a cross-section of a freestanding SK9 compound achromatic lens.

Before proceeding with a discussion of the optical performance, a brief statement regarding the SK9 is necessary. The lens was originally designed with the assumption that SK9 has the same optical characteristics as acrylic with $n_d=1.492$, and $V=57.4$. However, recent characterization of SK9 shows that it actually has $n_d=1.501$, and $V=45$. The small discrepancy in refractive index simply causes a slight shift in the nominal focal length. However, the error between the assumed V-number and the actual V-number for the lens that was fabricated is important. Since the material used for the fabricated lens

was actually more dispersive ($V=45$) than how we had modelled it ($V=57.4$), the end result is that we have undercorrected the *actual* material dispersion of the lens.

Figure 4 shows the measured optical power as a function of wavelength for the replicated lens. Measurements were taken every 2 nm. The bandwidth of the light was 0.8 nm. The uncertainty in the focal positions was about ± 0.01 D (± 0.10 mm). From the linear fit to the measured data, we can calculate an effective V-number ($P/\Delta P = V_{\text{eff}}$) for this lens of 250. This is about 5.6 times higher, and thus less dispersive, than a similar lens without the superimposed modulo- 2π diffractive lens (see figure 1).

Figure 4 - Measured focal length variation as a function of wavelength, for the replicated compound lens. The linear fit to the measured data gives an indication of the remaining material dispersion in the element.

Using a standard optical setup for resolution testing with an Air Force resolution test chart, the replicated lens was found to have a resolution of 120 lp/mm when illuminated with 2 nm bandwidth light centered at 550 nm.

We thus have successfully demonstrated a planar, microthin achromatic compound diffractive optic by superimposing a modulo- 2π diffractive element on top of a modulo- $m2\pi$ harmonic diffractive lens.

Kaiser Electronics

Kaiser Electronics is a manufacturer of HUDs. Until recently, they have been concerned mainly with monochrome displays. However, newer generations of HUD devices are beginning to incorporate color displays. By using achromatized diffractive elements, we hoped to provide wideband chromatic performance without the usual bulk of conventional achromatized optics.

Kaiser started with a monochromatic, doubly telecentric lens system. The design had two aspheric and toric mirrors and three lenses, with six highly aspheric lens surfaces. Before attempting color correction, we simplified this design. After a lot of time spent in carefully managed slow progress, we were able to reduce the number of higher-order terms in the six aspheric lens surfaces and simplify the design bit-by-bit. The result is seen below in Fig. 5, which instead of six aspheric surfaces has only one! The performance is essentially identical to the original design. The two mirrors are still aspheric torics.

Figure 5. The improved design for the Kaiser helmet-mounted display. This design has only one aspheric lens surface.

We were able to add color correction to this design using a diffractive element. The diffractive surface was placed on a separate parallel plate made of acrylic. The lens tilts and decenters were allowed to vary, although this is probably not important. The rms spot size over the field was optimized over a 21 mm pupil. This optimization tends to give "tails" on the aberration curves. The monochromatic rms spot size over the field of this new design is similar to the original design. With further optimization, the "tails" on the aberration curves could be reduced. In the worst case, some aspheric surfaces could be reintroduced.

In Fig. 6, we see the ray-intercept curves for the original design, and the new design incorporating the diffractive element. For this field point, their design has better monochromatic tangential rays than ours, but worse sagittal rays. For both designs the in-plane field points are better than the out-of-plane field points, and the two designs have almost identical performance in the out-of-plane direction. Further optimization is possible to maximize the performance of the new design, but even in its present state the diffractive color-corrected system is clearly superior to the original design.

Figure 6. Ray-intercept curves for (a) the original design and (b) the new diffractive design.

Diffractive Elements for Chromatic Correction

One of the simplest ways to extend the wavelength range of an optical system using diffractive elements is to use the high chromatic aberration of a standard diffractive lens. Diffractive lenses have about one diopter of chromatic aberration for every three diopters of optical power, making them much more dispersive than normal refractive elements. We can therefore add fair amounts of correcting chromatic dispersion without adding overly large amounts of negative optical power.

We designed and fabricated a chromatic-correcting element in acrylic to increase the spectral bandwidth of one of Kaiser's existing HUD designs. The lens had an active radius of over 14 mm (rather large for a diffractive lens) and an optical power of 0.36 diopters. One of the concerns for a lens of this type is that scattering from the diffractive cuts in the lens would lead to an unacceptable veiling glare. For military-type applications such as HUDs, the acceptable amount of such glare is extremely small. We made an estimate of the amount of glare by calculating the amount of surface area covered by the diffractive cuts on the lens. We assumed that the cuts were 4 microns wide, the width of the cutting surface of the diamond tool. We found that for this lens, only 2.5% of the surface was covered with the diffractive cuts, thus we expected only about 2% of scattered light.

This element was fabricated as an acrylic lens. The lens had 5.5 nm rms surface roughness (measured with a 5 micron resolution over one square millimeter of area), and a 0.042 wave (26 nm) rms deviation from a perfect lens as measured over the whole surface. We measured the efficiency and scatter by using the lens to focus a laser beam, and then measuring the amount of power incident on the lens, power in the focal spot, and scattered power. We found that the lens was very efficient, with less than 2% of the light being scattered. Thus the lens is suitable for use as a color-correcting element in a HUD system.

Bi-Fresnel Element

We also developed a unique, zero-power bi-Fresnel element for color correction. The element consists of two flat surfaces on the outside and two Fresnel surfaces (acrylic and styrene) cemented on the inside. It acts like a parallel plate with a strong power "buried" Fresnel surface inside.

The main color problem in conventional eyepieces is lateral chromatic aberration. Fixing it requires a large increase in the system weight, and also cuts down substantially on both eye relief and working distance to the image. The Erfle eyepiece is a good example of that. Lateral color becomes a particularly troublesome problem with wide-angle eyepieces, or those with a large eye-relief – as we required. It requires putting in strong

negative power of a flint glass. That then requires a big increase in the power of the positive lenses, to compensate. That makes everything much thicker and heavier. It also forces the negative power further away from where it has the most effect. More negative power is needed still, and that feeds back into the bad cycle just described. Steep curves that result from this lateral color correction process can limit the field angle and/or working distance to less than is required. Because of this, lateral color correction is often quite bad in order not to adversely impact the system weight, field angle, etc.

However, Fresnel lenses don't have the thickness and weight problems of conventional lenses. In particular, a strong Fresnel negative lens and a strong Fresnel positive lens can be right against each other without causing the substantial ray height changes that would occur in a conventional lens equivalent. That turns out to have the unexpected benefit of making it much easier to correct lateral color.

This element has an index difference of only 0.10 at the interface. Therefore, reflection losses (due to steep Fresnel prism faces with high incidence angles), total internal reflection effects, groove shadowing, etc. are greatly reduced. Angle accuracy of the Fresnel facets on both of the sandwich components of this element is loosened up, since there is only a small index break across the buried Fresnel surface inside the sandwich. Centration tolerance of the element is also improved, as there are now no steep ray angle changes going through the element.

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