

Technical Advances in Microstructured Plastic Optics for Display Applications

M. Foley

Fresnel Optics, Rochester, NY and Apolda, Germany

Abstract

This paper will present recent technological advances in the field of replicated, microstructured plastic optics, and their applications in display optics. A number of technology areas will be discussed, including moth-eye Antireflective Microstructure™, High Precision Molding (HPM), high temperature polymers, and one-piece, diffusive imaging screens. Applications discussed will include field lenses, condenser lenses, microlens arrays, and light integrators for LCD Projection systems, specialized optics for microdisplay applications, and imaging screens for photographic and rear projection systems.

Introduction

Microstructured optics are a family of essentially flat devices which manage light through small precise features on one or both surfaces. Microstructured optics include Fresnels, prisms, lenticulars, beam splitters, lens arrays, and corner cubes. The benefits of microstructured optics are typically:

- more efficient use of energy and light
- almost unlimited flexibility in optical design, including aspheres, indexed planar surfaces, and discontinuous surfaces
- reduction in thickness and weight
- ease in manufacturing high aperture elements and large area components.

The objective of this paper is to present recent technological advances in the field of microstructured plastic optics, and their applications in display optics.

“Moth-eye” Antireflective Microstructure™

It has been noted that the moth has a unique anti-reflecting surface on its cornea¹, consisting of microscopic raised protruberances which are roughly 200nm in height and spaced in a hexagonal pattern with centers approximately 300nm apart. This sub-wavelength, surface relief profile is a low reflectance interface for light. From a theoretical standpoint, performance can be modeled as a modulated graded-index, which reflects very little light because there are no abrupt index changes from air into the material.

Moth-eye Antireflective Microstructure™ can now be produced and replicated in a cost effective manner.

Master tools with the moth-eye pattern are produced in photoresist using laser writing or holography. The surface geometry can be customized somewhat to optimize performance at various wavelengths and incidence angles.

Using electroforming technology it is possible to accurately replicate the master tool down several generations into a cost effective “stamper tool”. Stamper tools are the consumable tools used in high-volume plastic manufacturing processes. Figure 1 shows a 4th generation replicate of a moth-eye master, molded in plastic from a metal tool. While some inhomogeneity is visible, the structure is still effective as a low reflectance interface. Figure 2 shows a variety of reflectance spectra, representing the range of results we have obtained to date. Current research efforts are focused on increasing the overall homogeneity of the replicated tools, and further improving the broad-band antireflective properties for various applications.

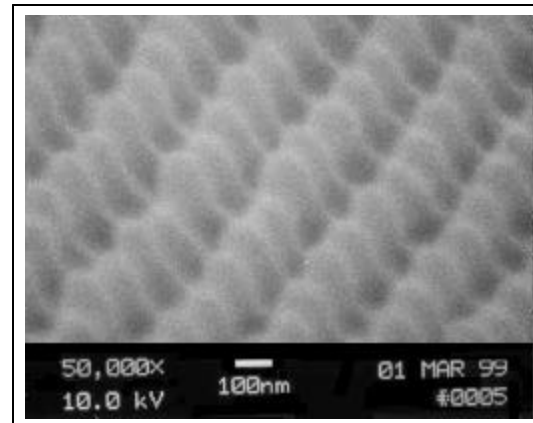


Figure 1: SEM, Moth-eye 4th Generation Replicate (in plastic)

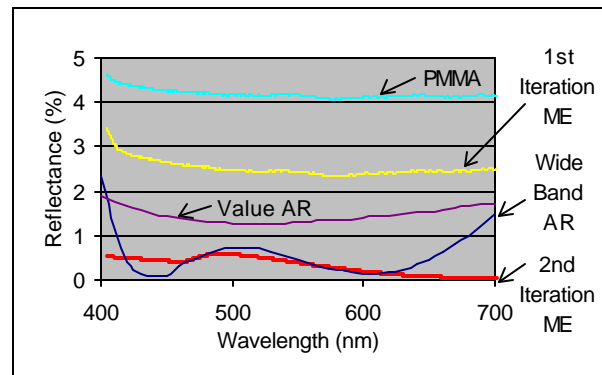


Figure 2: Single Surface Reflectance vs. Wavelength, Normal Incidence

When replicated in plastic, moth-eye Antireflective Microstructure™ provides a cost effective and more durable alternative to thin film AR coatings. While patterning moth-eye on 3D surfaces is theoretically possible, at present we are limited to plano surfaces only.

An additional benefit of moth-eye Antireflective Microstructure™ is its performance at off-normal incidence angles. In today's compact, fast systems this is particularly advantageous. To demonstrate the practical benefits of this feature, the following test was performed. Many commercially available single panel LCD projectors contain 2 Fresnel lenses. The first lens collimates light into the LCD. The second Fresnel focuses light from the LCD into the projection lens. We tested a number combinations of coatings and moth-eye treatments to understand the actual measurable differences in light output from the LCD projector. The "1st Iteration Moth-eye" and the "Value AR" in Figure 2 above were used to coat both the field and condenser lenses used in this test series. Light measurements were made in accordance with ANSI IT7.228-1997 and ANSI IT7.204-1991. An example of the measurement method is included below in Table 1. Multiple samples were tested in each configuration.

Test #1, Sample 4		
No Treatments		
202		185
	261	
190		177
Field Sum 754		
Axis 261		
Field/Axis		
Ratio 72.2%		

Table 1: Light Measurement Method

Statistical results of the testing are shown in Table 2.

Test #	Lens Treatments		Avg Field Sum	Avg Axis	Field Axis Ratio
	Plano Side	Facet Side			
1	None	None	753.8	261.3	72.1%
2	ME	None	790.7	275.2	71.8%
3	ME	AR	812.8	284.6	71.4%
4	AR	AR	806.6	283.0	71.3%

ME = Moth-eye Antireflective Microstructure™
AR= Thin Film AR Coating

Table 2: Light Measurement Summary

From the data three things are empirically obvious:

- In comparison to no treatment, moth-eye Antireflective Microstructure™ enhances the efficiency of plastic lenses in projection systems

- The "1st Iteration Moth-eye" is comparable with "Value AR" coatings at normal incidence on axis, and appears to be slightly better at greater angles of incidence in the field.
- A combination of moth-eye and AR coatings possibly provides a "best of all worlds" solution with a good balance between total light transmission and Field/Axis performance.

Scale up of 2nd iteration moth-eye is underway.

High Precision Molding

A number of replication techniques are available for producing microstructured optics. These include embossing (flat bed, roller, and continuous), casting (UV and thermal cure), injection molding, coining, and compression molding. A more thorough discussion of these process can be found in [2].

Compression molding has been used most often in applications where high fidelity is required on deep or high aspect ratio structures. Aspect ratios of 4:1 and structures ranging in size from 100nm to 12mm are currently possible with compression molding. Compression molding has the additional benefit of producing optical components with very low internal stress, and thus low bi-refringence, which is particularly important in polarization sensitive applications. Finally, the cost of compression molding tooling is low compared to injection molding tooling.

Even though compression molding is now computer controlled and semi-automated, its primary disadvantage is its long cycle time (several minutes per part).

High Precision Molding is a new, patented process which produces parts with high fidelity and low internal stress, but without the long cycle times typical of compression molding. While not as fast as injection molding, HPM cycle times are measured in seconds, not minutes. HPM has fairly low tooling cost compared to typical injection molding. In addition, it is possible to mold microstructure on both sides of an optical element, and to accurately register features on opposing sides.

An example of a practical application for HPM is the single element (SE) lens, best known from low cost overhead projectors. The SE lens is shown in Figure 3. The SE lens performs similarly to a traditional dual element system, focusing the source into the projection lens. The benefit of the SE lens is cost reduction, the disadvantage is its limitations in very high NA systems. There has also been a manufacturing challenge in that

the centers of the two lenses must be precisely registered to avoid moiré interference between opposing facets. Because HPM allows for precise registration, single element production with a 1:1 facet ratio is now possible.

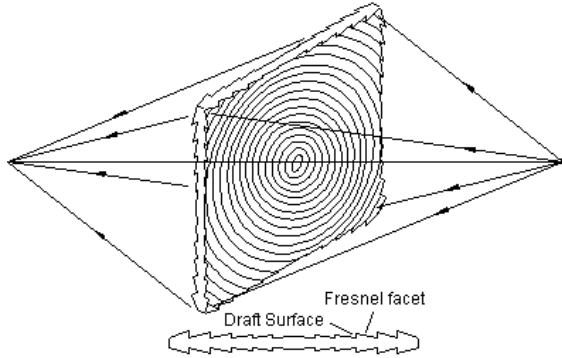


Figure 3: Single element lens made on HPM

The applications for HPM in display optics are perhaps too numerous to mention. HPM can be used to produce field and condenser lenses, lens arrays (Figure 4), novel backlight architectures, and the light integrators and one piece collimating/diffusive elements described later in this paper.



Figure 4: Plastic Microlens Array

One-Piece Diffusive Imaging Screens

A new family of integrated, one-piece diffusive imaging screens has been developed. These screens, which are described schematically in Figure 5, are the subject of several US patents. The one-piece integrated system consists of a Fresnel lens on one side and a surface relief diffuser on the other side. The Fresnel facets gather/collimate incoming light. The microstructure on the output side is designed to spread light into a predetermined gain distribution. An example of the surface geometry of a high-gain, symmetric diffuser is shown in Figure 6. Various horizontal and vertical gain profiles (both symmetric and asymmetric) are possible,

and contrast and peak gain can be balanced using neutral density contrast enhancing tints in the material. Two key quality criteria to minimize in a surface relief diffuser are “graininess” and also any periodicity that creates interference with a pixelated image.

In comparison to a traditional two-piece screen design, the advantage of molding the Fresnel directly into the same optical element is not only cost reduction and durability, but also the reduction, or potential elimination, of “ghosting artifacts.”

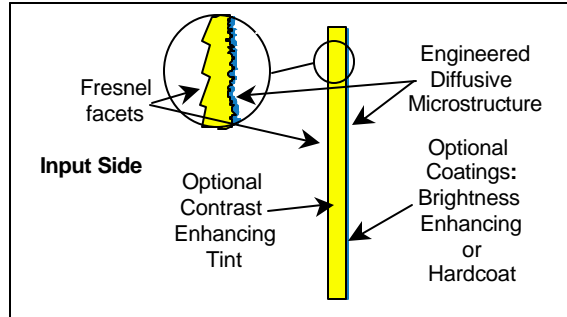


Figure 5: One piece, diffusive imaging screen

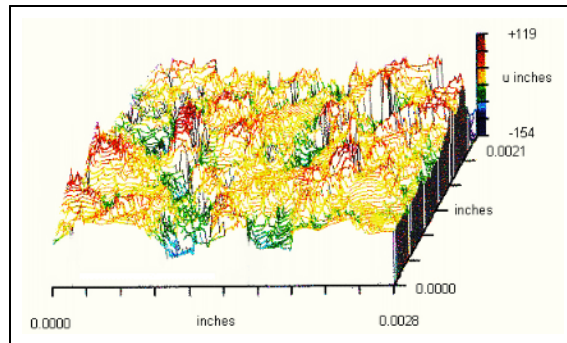


Figure 6: Surface Relief of Engineered Diffusive Microstructure

There are several practical considerations to the successful application of this type of architecture. One is the size of the surface relief diffuser master tooling that is currently available. This is the focus of a great deal of effort in the industry, and a 50”-60” diagonal seamless screen (3:4:5 format) should be possible in a 1-2 year time frame. Due to size limitations, current applications of this architecture are focusing screens for cameras, collimating diffusers for certain backlit displays, and imaging screens for smaller rear projection systems such as desktop monitors.

Another limitation lies in the use of a collimating Fresnel with facets facing the input side of the projector. In this configuration, there is a tradeoff between the speed of the system and the efficiency of the Fresnel. As the f/# decreases, there is increased amount of vignetting at the

corners of the screen due to light hitting the draft surfaces of the Fresnel.

In fast systems ($f/\# < 1$), for optimal results the Fresnel must be a separate element with facets facing the audience. Although more expensive, such dual element systems may still offer performance benefits in many applications.

High Temperature Polymers

A factor limiting the application of plastic optics has been their relatively low resistance to continuous high operating temperatures. New families of optical grade thermoplastic polymers (Index ~ 1.5 , Abbe value ~ 0.56) are now available, including cyclo-olefins (brandnames include Arton, Zeonex, and Topas) which can survive operating temperatures in the 120° to 150° C range. This enables plastic optics to be considered in applications formerly restricted to glass for temperature reasons. These applications include light integrators³ in LCD projectors, and condenser lenses close to light sources in projection systems. Plastic integrators (see Figure 7) are now possible.

There are a few hurdles to overcome with these new materials. They are currently an order of magnitude more expensive on a per pound basis than polycarbonate and acrylic. This is expected to change as usage increases. Like polycarbonate, they also tend to be slightly yellow. However, they do offer an exciting new degree of freedom to optical designers interested in using plastic optics in high temperature systems.

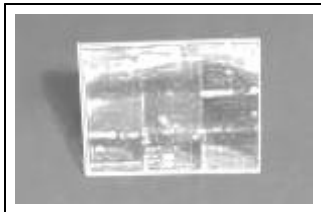


Figure 7: Plastic Light Integrator Array

Microstructured Optics for Microdisplays

There is a new family of transmissive and reflective microdisplays⁴ which present a whole new set of applications for microstructured optics. Depending on the application, light from an LED or other source is distributed over the display using a miniature backlight or frontlight architecture or a collimating diffuser. In many applications (cell phones, cameras, etc.) the display must be magnified, but size and weight of the optical system must be minimized. Further, light is often

polarization sensitive, which means that birefringence is undesirable. Specialized coatings (incl. mirrors and AR treatments) are also often required. For all of these reasons, a new family of custom microstructured optics is now in development.

One example is a very fine pitched ($\sim 0.1\text{mm}$), high quality Fresnel objective lens suitable for microdisplay magnification is shown in Figure 8. This lens is aspherically corrected for minimal distortion.

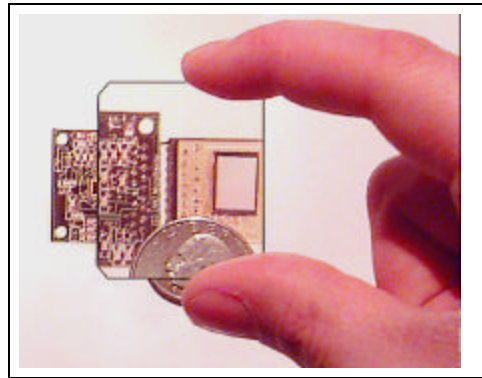


Figure 8: Fresnel objective lens magnifying a microdisplay

Conclusions

Microstructured optics continue to evolve at a rapid pace. New processes such as HPM, new materials such as high temperature thermoplastics, and new optical elements such as Antireflective MicrostructureTM and one-piece imaging screens provide Optical Designers and Systems Engineers with new degrees of freedom and flexibility in display applications.

References

- 1) C. G. Berhard, "Endeavor", Vol. 26, pp. 79-84, 1967.
- 2) Gale, M. T., and Rossi, M., Diffractive Optics for Industrial and Commercial Applications, ISBN 3-05-501733-1, 1997.
- 3) Honguh, Y., "SID Digest", Volume XXIX, pp. 113-116, 1998.
- 4) McLaughlin, C., "Information Display", Vol 14. No. 9, pp. 14-17, 1998.

Acknowledgements

SEM Data in Fig. 1 supplied courtesy of Holographic Lithography Systems, Bedford, MA.