P-95: Fresnel Lenses in Rear Projection Displays

Arthur Davis, Robert C. Bush, John C. Harvey and Michael F. Foley, PhD
Fresnel Optics, Rochester, NY, USA

Abstract

A plastic Fresnel lens positioned just before the diffusion screen in a projection system can provide significantly superior corner illumination, enhancing overall display luminance uniformity. Fresnel lenses are also used within the light engine to collimate light through the LCD panel and focus light through the projection lens. Disadvantages include the added cost of the lenses, ghosting, printout of the Fresnel rings and moiré patterns. Birefringence is important to control in polarization-sensitive applications.

Without reduction of ghosting artifacts, Fresnel lenses will have limited application in text-based RP systems. Ghosting is described in some detail including how it is caused, quantified and reduced. Efforts to reduce cost and birefringence will also be discussed.

1. Introduction

Fresnel lenses are useful when large lenses are needed in the optical system. Lenses over 3 or 4 inches in diameter can have large costs associated with manufacturing of glass lenses for display applications. Another factor to worry about is the weight and space of these lenses. Fresnel Lenses, on the other hand, can be made essentially flat, are made of plastic, are lightweight and cost efficient.

Plastic Fresnel lenses cannot be used everywhere a large lens is needed. Because of the articulated surface of the Fresnel lens, and the thermal mechanical limitations of plastic, accuracy cannot be maintained for scientific pursuits such as astronomic equipment– a place where very large lenses are needed. However Fresnel lenses are a perfect match for display applications.

Fresnel Optics is a world leader in designing and manufacturing plastic Fresnel lenses for numerous applications. Some of these applications are outlined in Section 2.

2. Applications

A Fresnel lens can be incorporated into a projection lens system to reduce the number of components, weight, size, and cost. They are used as Field and Condenser lenses in single-panel LCD projectors to more efficiently direct light through the LCD. And they are very commonly used as part of the screen system in rear-projection monitors (RPMs) to provide a more uniform output: see Figure 1.

Overhead projection systems utilize Fresnels as Field and Condenser lenses. In photographic cameras, a Fresnel lens can be used as part of the focusing screen to dramatically increase brightness and resolution.

Fresnel lenses are used in a number of spots within a rear-projection television system. They are used as Field and Condenser lenses to pass light more efficiently through the LCD, and a large Fresnel lens is used as part of the screen system to provide a uniform output: see Figure 2.

Figure 1: Rear Projection Monitor

Figure 2: Rear Projection Television

Other applications include Fresnel lens arrays for Passive Infra Red (PIR) sensors that are used in motion detection systems and large Fresnel lens arrays which are used as solar collectors for high-concentration photovoltaic systems.

3. Rear Projection

Fresnel lenses have proved to be most useful in the collimation or collection of light in projection systems. Two examples are shown in Figure 3.

The advantage of Fresnels in these systems is to increase the overall display luminance by focusing or collimating light as needed. The bottom example of Figure 3 shows light coming from the illumination system (bulb, mirrors, integrators) towards the LCD display. The illuminating light will be diverging as it approaches the LCD panel. Without collimation, significant light would be lost as it goes through the panel and the display would have a visible hotspot and significantly lower corner luminance. Similarly, on the opposite side of the LCD panel, we must collect the light from the panel down into the projection lens. An example of the brightness gained by using a Fresnel lens before the viewing screen (as in the top portion of Figure 3) is plotted in Figure 4.

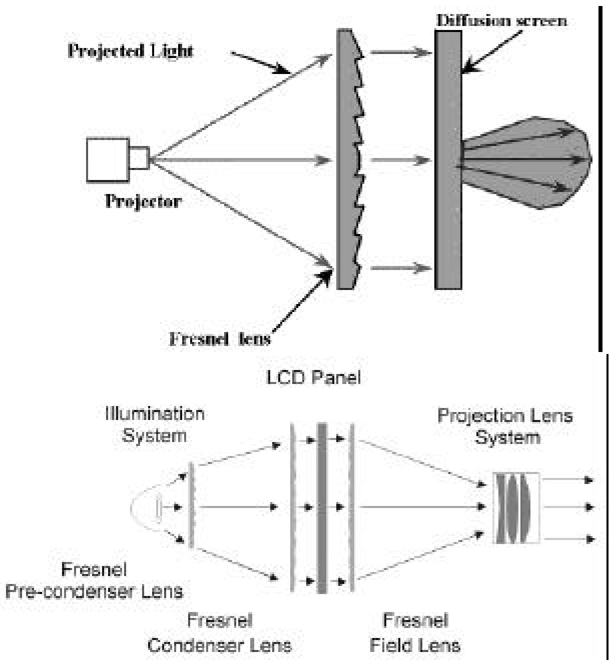

Figure 3: Fresnel Lenses used in Rear Projection

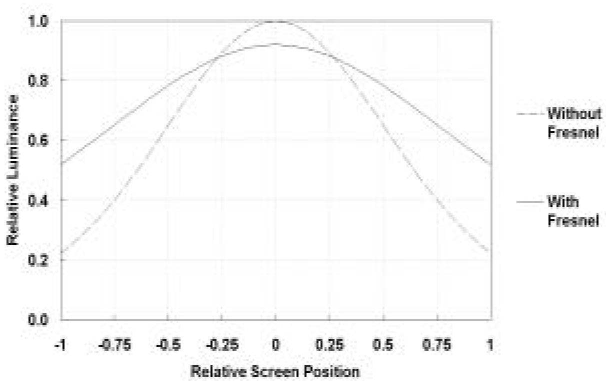

Figure 4: Luminance enhancement using Fresnel Lens

4. Fresnel Lenses

4.1 Background

The Fresnel lens is a periodic refractive structure of concentric prisms. The surfaces of these prisms are designed to refract light by collapsing the surface curvature of a conventional lens nearly into a plane. In this way the lens thickness is greatly reduced [1], [2]. See Figure 5.

The constituent refractive surfaces of the concentric prisms are called slopes and drafts. The slopes are the actual surface which is

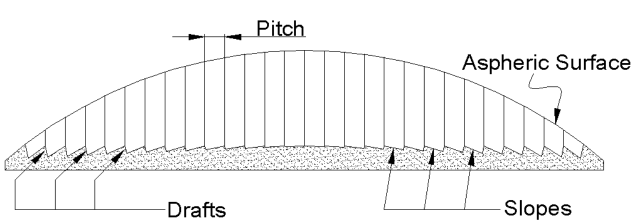

Figure 5: Schematic of Fresnel Lens

used to approximate the curvature of the aspheric conventional lens. Ideally, all refraction should occur at the slopes. In order to collapse the thickness of a lens, the drafts are the necessary discontinuities between the slopes to return the curvature back to a plane. Light incident on draft surfaces is lost from the image plane and can manifest other problems besides a drop in efficiency (eg. stray light, ghosting). With a judicious choice of draft design and proper Fresnel lens orientation, draft loss can be minimized. See Figure 6 for a chart of how the efficiency of an Acrylic lens varies with f/# in a collimation/display application.

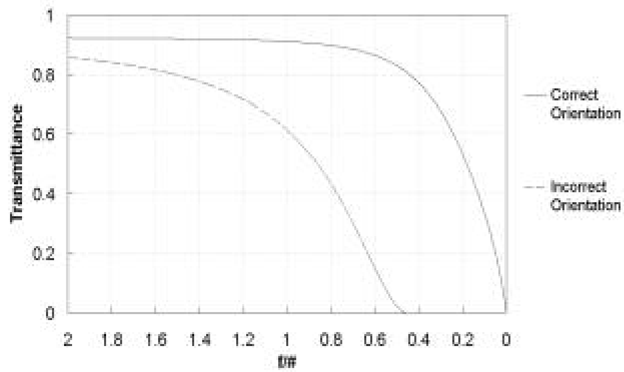

Figure 6: Acrylic Fresnel Lens transmission vs. f-number

When collimating light, it is essential that the Fresnel lens facets face the infinite conjugate. This way, the draft angles can be designed to not interfere with the light rays. Figure 6 demonstrates how much less efficient the lens is when used in the incorrect orientation.

4.2 Fresnel Lens Detriments

4.2.1 Ghosting

A problem with the application of Fresnel lenses in display systems (particularly in fast display systems) is the existence of Ghosting. Ghosting is a highly undesirable artifact visible as a displaced replica of the image on the screen. It is most noticeable in the display of high contrast images and is consequently extremely objectionable in text display applications.

Ghosting is caused by internal reflections at the slopes of the Fresnel lens microstructure. Light will reflect off the slopes, totally internally reflect (TIR) across the plano side of the lens, and then exit the lens in the wrong location either via the slopes or the drafts as diagrammed by the optical path in Figure 7. Although the draft angles are designed so that the draft facets do not interrupt any of the direct path of the light, light caused by ghost reflections will still inevitably be incident on the drafts.

Internal reflections range from 3.9% for normal incidence in Acrylic to more than 10% at low f/# portions of the lens. In normal video applications, this is typically unnoticeable. But as soon as sharp edges and high contrast areas are displayed (such as text display), the ghost image becomes evident and bothersome. Additionally, multiple bounces inside the Fresnel lens can lead to multiple ghost images.

There are various techniques for minimizing the visibility of a ghost image. One very effective method is to tint the lens material. Because the ghost rays have longer optical path contained within the lens media than the image rays, by Beer's Law, they will be attenuated more. The drawback is a loss in

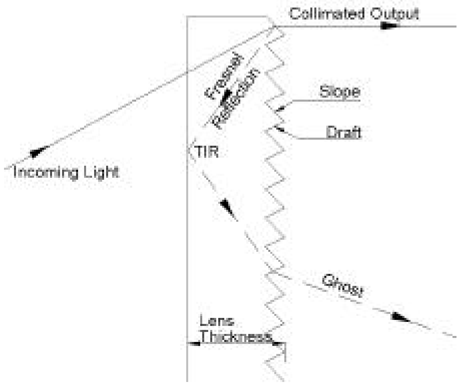

Figure 7: Cause of Ghost Image in Fresnel Lens

transmission through the screen. This is unacceptable in rear projection applications where maximizing the observed luminance is paramount.

Another technique that has shown experimental success in eliminating ghost images has been "draft blackening". Though difficult, it is possible to coat the draft portion only with a black absorbing material. Since most of the ghost intensity is transmitted through the drafts, this effectively eliminates the ghost.

In principal, applying a broadband anti-reflection (AR) coating to the Fresnel facets could reduce the ghost image with the added benefit of increased transmission efficiency. Applying the coating however has not been successful because the functional angle of the AR coating needs to be adjusted with radial distance from the Fresnel center as the facet angle varies.

Using proprietary processes and designs, Fresnel Optics has successfully produced Fresnel lenses for RPM applications which demonstrate that it is possible to achieve the benefits of a Fresnel lens (brightness uniformity) with negligible ghosting. This is the worst case application because the systems are optically fast and the resolution requirements are high. Through our USDC [3] program, we are developing a cost effective domestic manufacturing capability to produce these lenses.

4.2.2 Moiré

Moiré patterns are apparent whenever two periodic structures containing varying light intensities are overlapped. In the case of rear projection displays, serious artifacts may be visible when the pitch of the pixelated image forming element is projected onto the screen which consists of a Fresnel lens and commonly a lenticular diffuser, each with their own periodic microstructure. As a result, the designs of the Fresnel lens and the diffuser screen need to be carefully considered in conjunction with the pixel pitch of the display element in the system. An example of a moiré pattern generated by the stripes of a lenticular and the circular rings of a Fresnel are given in Figure 8. A pixelated image on top could make it even worse.

4.3 Metrology

To quantify the performance of Fresnel lenses in display applications, new metrology needed to be developed for measuring both ghosting and moiré.

For the measurement of ghosting, a CCD camera is aimed at the Fresnel under test. A high intensity light source of sufficiently fast f-number is aimed at the center of the Fresnel lens and an opaque

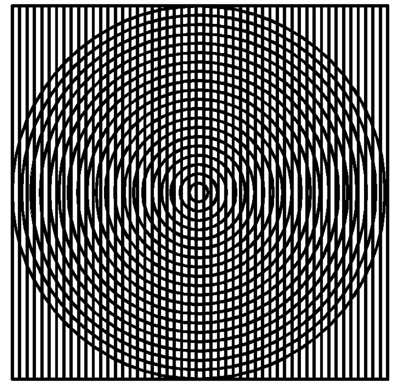

Figure 8: A moiré pattern

mask with a small hole punched in it is placed in front of the lens. The effective f-number of the measurement is determined by the location of the hole along the diameter of the Fresnel lens (from Figure 9: f/#=f/d). The camera can then be scanned in angle to record the intensity of the bright spot on the diffuser and the ratio of the ghost(s) intensity to it. See Figure 9 for a schematic of the layout and for an example image capture showing many ghost images.

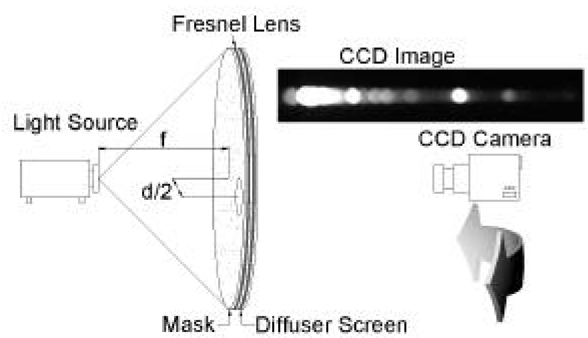

Figure 9: Test setup to measure ghosting

To measure moiré, Fresnel Optics currently uses a method of illuminating the Fresnel lens and lenticular diffuser with uniform white light. The setup is similar to the ghost measurement setup in Figure 9 except there is no mask present. Any moiré generated is captured with a CCD array and contrast can be determined by taking the ratio of dark to bright fringes. This technique will likely be further expanded to include moiré effects caused by the pixelated image by projecting an appropriately scaled grid pattern onto the test screen and measuring the resultant fringes.

5. Manufacturing

Fresnel tooling can be produced using processes such as diamond turning, laser writing, lithography, and e-beam writing. These and other mastering processes are discussed in more detail in [4]. Master tooling can be replicated using electroforming processes [5].

From a master tool, a number of processes can be used to replicate a polymeric Fresnel Lens. These include the following: injection molding, compression molding, injection compression molding

Table 1: Various Fresnel replication processes

	Compression Molding	Injection Molding	HPM	Coining-Standard/DVD	Casting-Discrete/ Continuous	Embossing-Discrete/ Continuous
Precision	Very High	Low	High	Medium/High	High	High
High Aspect Ratios	Easiest	Difficult	Easy	Difficult	Moderate[1]	Moderate
Replication Fidelity	Very High	Low	High	Low/High	Very High	High
Tooling Cost	Low	High [2]	Medium	High	High	Medium
Unit Cost	High	Low	Medium	Medium/Low	High/Low	High/Medium
Internal Stress	Very Low	High	Low	Medium/Low	Medium	Low

(also called coining), cell casting, continuous casting, discrete embossing, continuous embossing and high precision molding (HPM).

High Precision Molding is a hybrid process described in [6]. Coining is an injection molding process where the clamp is closed at the end of the cycle [4]. Specialized versions of the coining process are used to make DVD's and Laser Disks.

In choosing the appropriate manufacturing process for a particular Fresnel lens, considerations include: fidelity (feature sharpness and aspect ratios possible), tooling cost, per piece cost, process cycle times, and control of internal stress/birefringence.

These can be interrelated. Figures 10 and 11 demonstrate the relative fidelity of a Fresnel structure replicated using compression molding, in comparison to a similar tool replicated using injection molding. Because the plastic flow front freezes as it fills the mold, sharp features are not replicated in an injection molded part (Figure 10). Also, internal stress is created, which can be undesirable in polarization sensitive applications. A compression molded Fresnel has sharper features, and much lower internal stress. The penalty is cycle time and per piece cost.

HPM combines the attractive features of both processes.

Table 1 above presents, in qualitative format, the relative performance and attributes of the various Fresnel replication processes.

6. Conclusion

Careful understanding of the complete optical system allows for Fresnel lenses to be designed without ghosting and moiré artifacts that limit the effectiveness of the lenses in display applications. With correct design, modern manufacturing methods, and new proprietary processes, Fresnel lenses are being successfully incorporated in new high definition rear projection systems.

7. References

[1] Miller, O.E, McLeod, J.H, and Sherwood, W.T., Thin Sheet Plastic Fresnel Lenses of High Aperture, Journal of the Optical Society of America, Vol. 41, Num. 11, pp. 807-815 (Nov. 1951).

[2] Egger, John R., Use of Fresnel lenses in optical systems: some advantages and limitations, Proceedings of SPIE, Vol. 193 Optical Systems Engineering, pp. 63-68 (1979).

[3] USDC Press Release. http://www.usdc.org.synapta.net/FresnelOpticsPR.htm

[4] M.T. Gale and M. Rossi, Diffractive Optics, ISBN 3-05-501733-1, p. 105, (1997).

[5] Lowenheim, F.A. ed., "Modern Electroplating", Wiley and Sons, pp. 287-341, (1942).

[6] M. Foley, "SID Digest", Volume XXX, pp. 1106-1109, (1999)

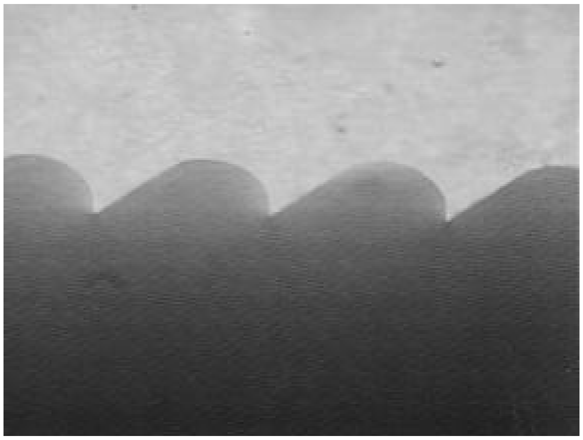

Figure 10: Cross section of injection molded fresnel

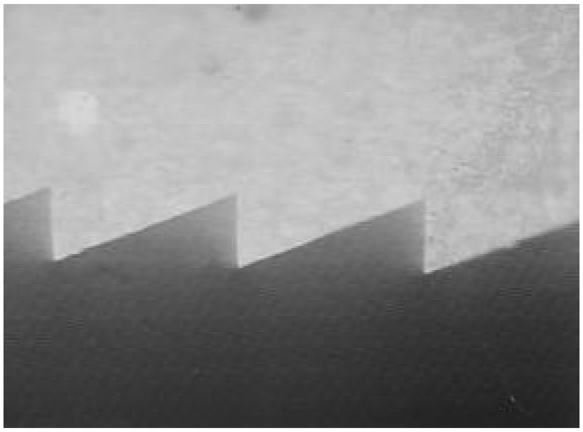

Figure 11: Cross section of compression molded fresnel

[1] High aspect ratios are possible but in UV cured casting systems there are practical limitations on feature size due to shrinkage.

[2] Tooling cost can be minimized using MUD mold base, but is in general high.