# Polymer Fly's Eye Light Integrator Lens Arrays for Digital Projectors

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## *Abstract*

*Polymer Fly's Eye light integrators are now available as an alternative to glass. While the appropriate material is highly dependent on the specifics of the application, plastic integrators offer measurable advantages in certain situations. Key design considerations include weight, performance, cost, birefringence, and temperature resistance. This paper explores each of these design considerations, and presents some guidelines to aid optical engineers in material selection.*

## 1. Introduction

In any projection system, from a 35mm slide projector to a state of the art digital LCD projector, designers seek to optimize the degree of uniformity of projected light over the entire imaging screen. In LCD projectors, this begins with the light source upstream from the image plane. Light from the bulb filament is conditioned by the lamp reflector and optics between the bulb and the LCD. Rod integrators and fly's eye integrator arrays are typically employed to convert the bulb filament - a point or tiny line - into homogeneous illumination over the LCD [1-3]. The rod-type integrators can be physically long and heavy, and optically slow, which is fundamentally incompatible with today's trend toward smaller, lighter projectors. Fly's eye integrators are more compatible with this trend. Traditionally, fly's eye integrators have been made from molded glass, such as B270. Glass is popular because it has good temperature resistance and its performance is well understood.

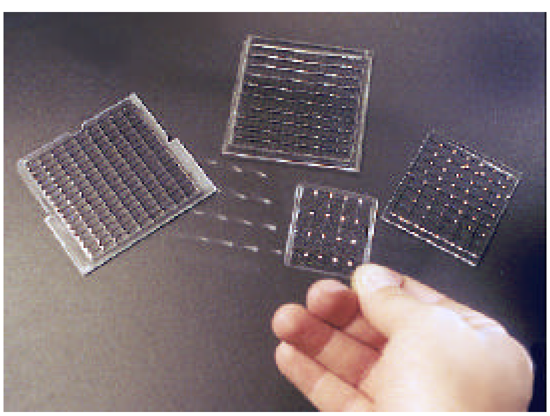

**Figure 1. Polymer Light Integrators**

Polymer integrators are now available (Figure 1), and have been included in numerous front and rear LCD projector applications. These lenses have been fabricated from acrylic (PMMA), polycarbonate (PC), and various high temperature thermoplastics. The potential advantages of a plastic light integrator in comparison to glass are lighter weight, lower cost, and better performance (higher transmissivity and overall uniformity). Resistance of plastic to continuous, high operating temperatures and birefringence in plastic parts are key concerns.

The goal of this paper is to explore these various design considerations, and to present relevant data comparing light integrators produced with various polymers to traditional glass. While preserving confidential aspects of customer designs and product specifications, the data presented in this paper is drawn from experience with front and rear projection systems in real world applications.

## 2. Temperature Considerations

Probably the most often mentioned reason why polymers are not used in projection optical trains is their low heat tolerance. Glass has a high melting temperature and low coefficient of thermal expansion, and therefore presents an excellent choice for high temperature applications.

Traditional optical polymers have well-known thermal limitations. General purpose acrylic must remain below 74°C (165°F) and polycarbonate must remain below 120°C (250ºF) to avoid deformation, warpage, or burning. However, these materials can still be used in light integration applications. We owe this partly to the continuing trend towards smaller/lighter projectors, which forces improved thermal management within the projector. Finite element analysis (FEA) software can be used to model thermal loads, air flows, and internal temperatures in a predictive manner, so that designs can be optimized more effectively. Today's innovative projector designs incorporate fairly sophisticated ventilation systems to keep critical areas cool and avoid hot spots.

In practice, we have successfully produced a matched pair of acrylic integrators for a light engine in a prototype rear projection system. We have also produced a pair consisting of polycarbonate (closest to

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the lamp) and acrylic used in a prototype portable front projection application.

However, when operating temperature requirements dictate that polycarbonate and acrylic will not suffice, there are new possibilities. New families of optical grade thermoplastic polymers (index ~1.5, Abbe value ~56) are now available, including cyclo-olefins which can survive continuous operating temperatures in the 120° to 150°C range. Arton[1], a new thermoplastic which can survive continuous operating temperatures of up to 150ºC (300ºF), is explored in greater detail in this paper.

## 3. Fidelity

Precision is a critical aspect of performance in any molded optic, be it glass or polymer. Assuming a precise mold, the degree of fidelity with which one can replicate the features of the mold into plastic will influence optical performance. Fidelity is most difficult to obtain when there are sharp features and/or discontinuities in the surface of the optic. Integrator arrays have discontinuities at the intersection of the lenslets.

Figures 2 and 3 are photomicrographs of Reprosil®[2] impressions of typical glass and acrylic intersections, respectively. In the figures, the dark areas correspond to the glass/acrylic, and the lighter areas are the dental casting material. The scale is such that the width of the micrographs are approximately 0.2mm.

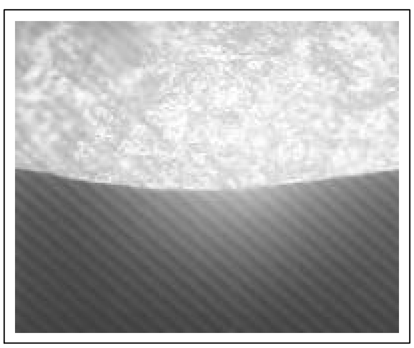

**Figure 2. Cross sectional photomicrograph of lenslet intersect in glass array**

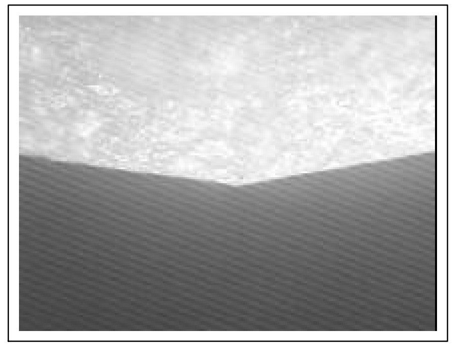

**Figure 3. Cross sectional photomicrograph of lenslet intersect in plastic array**

Note the presence of the large fillet in the glass intersection. The fillet is about 50µm across, and has a radius of curvature on the order of a millimeter. Presumably, light striking the fillet will be misfocussed and will manifest itself as stray light.

The acrylic part was produced with the High Precision Molding [4] process, which achieves high fidelity replication. Figure 3 illustrates the sharp intersection on the acrylic part, much closer to the ideal design. Compression molding would achieve similar fidelity. It would be expected that injection molding would produce lower fidelity. Replication fidelity appears to be a fundamental benefit of plastic integrators produced with HPM. As shown in measurements presented later in the paper, we believe this translates to improved performance.

## 4. Birefringence

In polarization-sensitive applications, the optical engineer desires to use optical components that will not perturb the polarization of the light being transmitted

[1] Arton is a trade name of Japan Synthetic Rubber Co., Ltd.

[2] Reprosil® is a registered trademark of Dentsply International, Inc. Reprosil® is a material for making dental impressions.

through the optical system. Birefringent optics are those components whose refractive index is not isotropic, and can therefore change the polarization state of the light. In projection optics (particularly those which employ liquid crystals), this is generally a serious and undesirable effect.

In plastic molding processes, various levels of stress are created when the liquid plastic flows and solidifies under pressure. These stresses are manifested as direction-dependent variations in refractive index. Stress is influenced by geometry, cycle time, plastic flow direction, and temperature gradients. A light integrator is most susceptible to stress at the lens intersections, and, in the case of injection molding, near the mold gate.

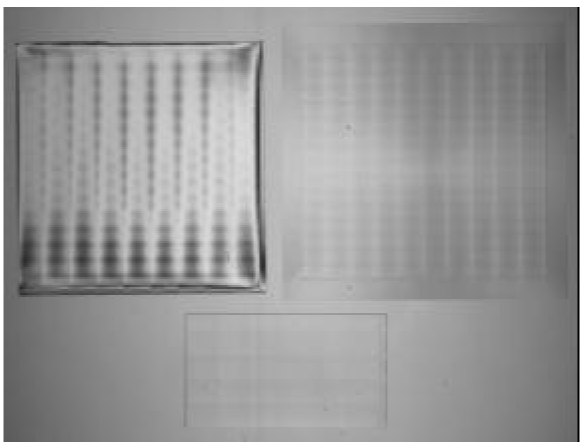

**Figure 4: Internal stress in (clockwise from upper left) PC, PMMA, and glass**

We evaluated the birefringence of three sample integrating lens arrays in the PS-100 Polarimeter from Strainoptic Technologies, Inc. This instrument can yield a moderate degree of quantitative information, but the qualitative results can be much more informative. Figure 4 shows the three arrays within the polarimeter. From the depth of the fringes, we estimate that the glass array had approximately 25nm of stress, the acrylic array had ~50nm, and the polycarbonate array had ~250nm of stress. We excluded samples made of Arton from Figure 4 due to the proprietary nature of the designs. However, the measured stress in Arton was ~50nm. The amount of stress in the plastic parts is relatively low because a low stress process (HPM) was used to mold the plastic. If the parts had been injection molded, stress levels would have been much more significant (a factor of 10 to 100 times higher). Note once again that the suitability of birefringent parts within a projection system depends largely upon how the parts are used and where they are used (i.e., in a polarization sensitive area such as between the polarizers, or elsewhere, such as within the projection lens).

## 5. Uniformity

From a functional standpoint, the fundamental purpose of a light integrator is to provide uniform illumination by homogenizing light from a lamp source. We investigated the uniformity of the light in the focal plane of the integrating array's output lens. Using a 12-bit digital camera to capture focal plane images, we found that the light in the acrylic integrating lens system varied ±10.0% (from 5% to 95% of the peak intensity) about its average value. In this test we excluded the upper and lower 5% of the intensities (i.e., the tails of the intensity histogram) so that test artifacts such as noise and imaging screen grain would not affect the results. Under the same conditions we found that the glass integrating assembly had ±14.9% variations about its mean, and the polycarbonate ±8.9%. We feel that the differences in variations are not due to the test setup, and are indeed representative of the performance of the three systems.

## 6. Transmissivity

In the transmissivity test setup (see Figure 5), collimated light (from a high quality regulated lamp) was incident on the first integrating lens array, and the second array was placed at the focal point of the lenslets of the first array. A glass focussing lens was placed immediately after the second array. The illuminance of the collimated light incident on the first array was measured (Plane #1), and then multiplied by the area of the array to give the input lumens. Next the illuminance of the output light was measured in the output focal plane (Plane #2), and this number was multiplied by the area of the rectangularly shaped spot, and the output lumens was found. The transmissivity is simply the output lumens divided by the input lumens. The test was repeated for glass integrating arrays, acrylic, and polycarbonate.

After accounting for the loss of light at the focussing lens, the glass integrating lens array system transmitted 73% of the light, the acrylic system transmitted 78%, and the polycarbonate system transmitted 76%. The high transmissivity of the acrylic is especially interesting because it was not antireflective coated, whereas the glass arrays were. This suggests that even more significant improvements in light throughput can be achieved with an A/R coating on a polymer array.

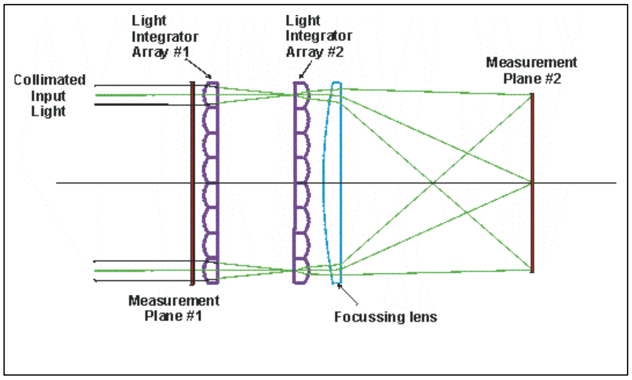


**Figure 5. Experimental set-up, tranmissivity measurements**

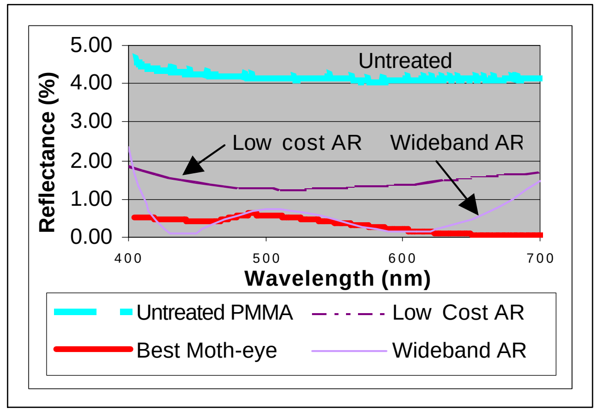


**Figure 6. Comparison of single surface reflectance with AR coatings and Moth-eye Antireflective Microstructure®**

## 7. Weight

Because polymers have roughly half the density of glass, polymer lens arrays can be significantly lighter in weight. Specifically, a typical glass density is 2.5grams/cm$^3$, whereas acrylic and polycarbonate are each 1.19g/cm$^3$, and the polyolefin's (such as Arton) are roughly 1.05g/cm$^3$. In additional, because plastic is less brittle than glass, it can be molded thinner. A glass lens array measuring 3 x 52 x 55mm weighs 22 grams (0.78oz), whereas the same array (except being only 2mm thick) made of polycarbonate would weigh only 7 grams (0.25oz). Since there are two lens arrays in a projector, the savings in weight is 30 grams (1oz). In a world where projectors under 5 lbs. are increasingly common, plastic does present a measurable weight saving opportunity.

## 8. Coatings and Surface Treatments

A variety of coatings and surface treatments are available. Traditional thin film AR coatings (see Figure 6) can be applied to either surface of the integrator to decrease reflectance losses. We have successfully applied a number of AR coatings to PMMA, PC, and Arton.

In addition, Moth-eye Antireflective Microstructure® [4,5] can also be applied to one or both surfaces of a plastic integrator. Figure 7 shows moth eye on the curved surface of an integrator lens. Note that the use of Moth-eye on light integrators is the source of numerous Patent applications.

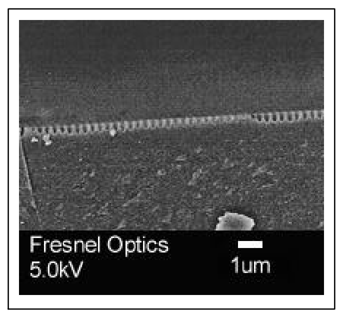


**Figure 7. Cross section of Moth-eye Antireflective Microstructure® on curved lens surface**

In the case of the curved surface, there are some important considerations in using Moth-eye. First, the cost of tooling is higher because a custom, dedicated tool must be generated for each integrator design. Second, since Moth-eye begins in photoresist, one must account for the presence of the photoresist layer and the effect it will have on the final part shape. Careful control of the photoresist coating process is required.

Hot mirror coatings have also successfully been applied to plastic lenses. Figure 8 describes the infrared rejection properties of the Balzers Calflex™ C hot mirror coating on Arton.

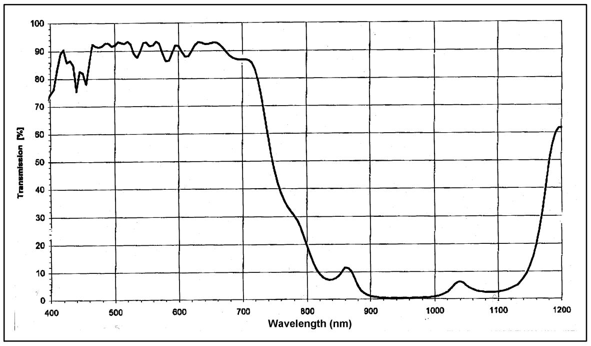


**Figure 8. Hot mirror (IR reflecting) coating on Arton**

Note that UV inhibitors can be also added to various polymeric materials in order to block UV and eliminate the need for additional optical filtering elsewhere in the system.

## 9. Cost

The cost of the plastic lenses varies greatly depending on the raw material used to make the lens. Arton has very attractive thermal properties, but the raw material is presently more than an order of magnitude more expensive than acrylic.

The presence of coatings also influences cost. Thin film AR coatings can improve transmission, but there is a cost penalty. Moth-eye Antireflective Microstructure® is a more cost effective alternative. Relative costs of various options are presented in Table 1 below. We assumed HPM was used to produce all polymer lenses.

We also assumed a 75mm by 75mm part and that tooling was amortized over 1,000 sets a month. Note that a hybrid solution of AR on the structured side of the integrator and Moth-eye on the plano side is possible. This hybrid may be the most cost effective alternative in low volumes, since the tooling cost for Moth-eye on the lens side of the integrator can be high.

| | No Coating | AR | Moth-Eye |
|---|---|---|---|
| Acrylic | +++ | + | ++ |
| Polycarbonate | ++ | equal | + |
| Arton | - | --- | -- |

**Table 1: Relative cost compared to Glass w/AR on both sides (+ is more cost effective)**

Note also that with innovative tooling design, it is possible to combine the function of upstream and downstream optical elements into the lens arrays. For instance, prisms or condensors can be integrated into the plano side of the integrator, to reduce part count and increase cost effectiveness.

## 10. Conclusions

Plastic light integrators are now available as an alternative to glass. Plastic light integrators offer the potential advantages of better performance, lighter weight and lower cost. There are design considerations related to temperature and birefringence which must be carefully considered in selecting plastic over glass. In the end, plastic provides optical engineers with another degree of freedom in projector design, and in the proper applications they are a superior choice.

## 11. References

[1] US Patent 5,098,184.
[2] US Patent 5,418,583.
[3] US Patent 5,959,778.
[4] M. Foley, "SID Digest", Volume XXX, pp. 1106-1109, 1999.
[5] H. Jänchen, U. Schulz, A. Gombert, SPIE EUROPTO Vol. 3738, 1999.

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