Low Cost Anti-Reflection Technology For Automobile Displays

Bruce D. MacLeod, and Douglas S. Hobbs

Abstract— Light reflecting from instrument panel and center console automobile displays is distracting to drivers and necessitates overhanging dashboard designs that take up valuable interior space. A recent trend toward displaying increasing amounts of information with navigation and communication systems, has compounded the significance of light reflection. The conventional anti-reflection (AR) technique of coating the display cover with thin-films to reduce reflections, has generally not been employed due to cost, lifetime, and performance issues such as poor viewing angle, durability, and adhesion loss. Diffuse textured surfaces are sometimes used at the expense of image clarity.

TelAztec has addressed the reflection problem by incorporating micro-structured textures known as Motheye, directly into the window surface. The Motheye structure is an engineered surface texture that allows a gradual change in optical density as light travels from air into the display, resulting in minimal Fresnel reflection. In addition to performance that exceeds thin-film AR coatings, the primary advantage of exploiting Motheye surface textures is the ability to mass-produce product through the use of traditional plastic replication processes. Replication of tens of thousands of product parts from a single master results in a minimal increase in the production cost of the optical component.

***Index Terms*—motheye, antireflection, coatings, replication**

I. INTRODUCTION

The reflection of light from plastic display covers is a common problem. The everyday nuisance to cell phone users is a prime example, the display cannot be read at certain angles because of strong reflections. The same effect is seen with the new informational display systems in automobiles. The distracting reflection can delay response time when the user is multitasking on other functions, such as driving. A solution is desired which can address the problem at a cost model acceptable to the price sensitive automotive industry. The application of replicated surface structures for antireflection in automotive applications is discussed. The performance and fabrication of structures is reviewed in the context of the automotive industry.

II. BACKGROUND

The concept of using surface structures in lieu of multilayer thin film coatings to control reflections from optical surfaces has been discussed since the 1970s. The principle is derived from the work of Bernhard et al, who discovered that the eye of the night moth reflects very little light, due to the graded index nature of the moth's cornea [1], as shown in Figures 1 and 2. It was hypothesized that the low reflectivity surface of the moth's eye imparted a degree of stealth that protected the moth from its predators, primarily the owl. Wilson and Hutley fabricated the first artificial Motheye surfaces in photoresist using holographic lithography, and demonstrated the concept of motheye replication by electroforming [2]. Cowan advanced the fabrication of Motheye textures by closely matching the structure found in nature [3]. In the years since, there has been some interest in the Motheye antireflection principle, and several papers have been written discussing the optical properties and function of these graded index surfaces [4-7].

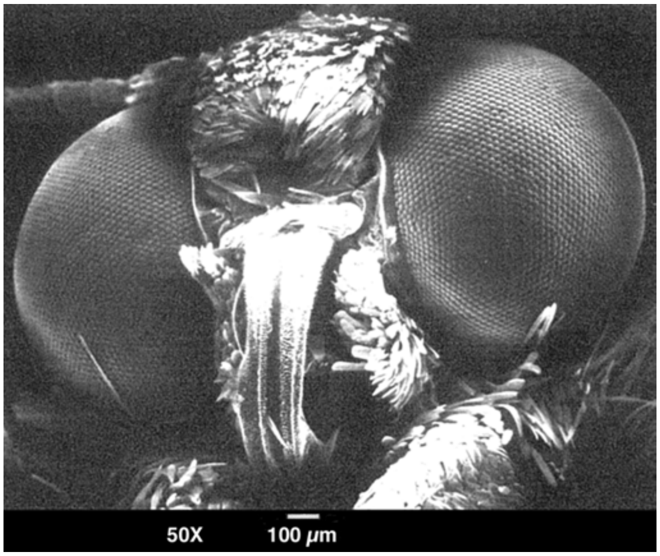

Fig. 1. The eyes of a night flying moth magnified 50 times. Note that each eye is composed of hundreds of lenslets arranged in a honeycomb pattern.

Effective Medium Theory describes the surface textures as multiple layers composed of varying proportions of the substrate index and the incident medium index (typically air). The average index of refraction then increases gradually as the incident light propagates toward the substrate bulk [7].

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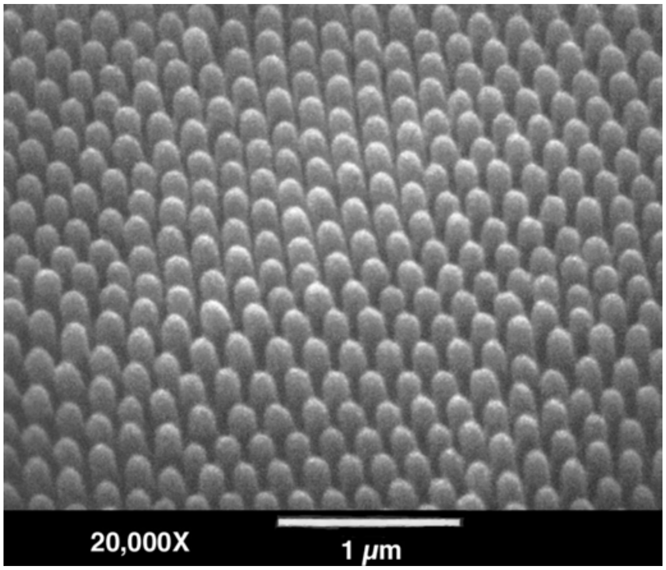

Fig. 2. Magnified image showing the surface structures found covering the eyes of night flying moths magnified 20,000 times. The texture consists of cone structures about 200nm high packed into a hexagonal array with a spacing of 200nm.

III. MODELING

Sophisticated computer models have been developed to guide the fabrication of, and predict the performance of our Motheye AR structures. Using a rigorous vector diffraction calculation, our software can predict the spectral reflectance and transmittance of light through a user defined three-dimensional surface texture composed of multiple structured and uniform materials. The model accounts for arbitrary polarization states and light incident angles. The ability to predict optical behavior and to analyze the impact of fabrication errors is essential to the development of Motheye textured products.

A. *Transmission at Normal Incidence*

A model showing the transmission through an acrylic sheet with Motheye texture on the two surfaces is shown in Figure 3. Absorption in the acrylic is assumed to be negligible. The motheye structures are modeled with a sinusoidal profile and a repeat period of 240 nanometers(nm). Transmission results are shown for 100nm, 200nm, and 300nm structure depth. There is a significant improvement when the Motheye depth is increased from 100nm to 200nm, but little improvement seen with a further depth increase to 300nm.

B. *Transmission at 30 degrees Angle of Incidence*

Changing the incident angle from normal to 30 degrees results in an average transmission loss for all three depths, primarily due to a shift in the wavelength at which free space diffractions occurs from the ultraviolet to 487nm, as shown in Figure 4. The effect is more severe for the shallow 100nm depth structures. This demonstrates the concept that Motheye can suppress reflections of light incident at large angles by increasing the structure depth. A further adjustment to the structure that increases angular acceptance is to decrease the Motheye period, as discussed in the next section.

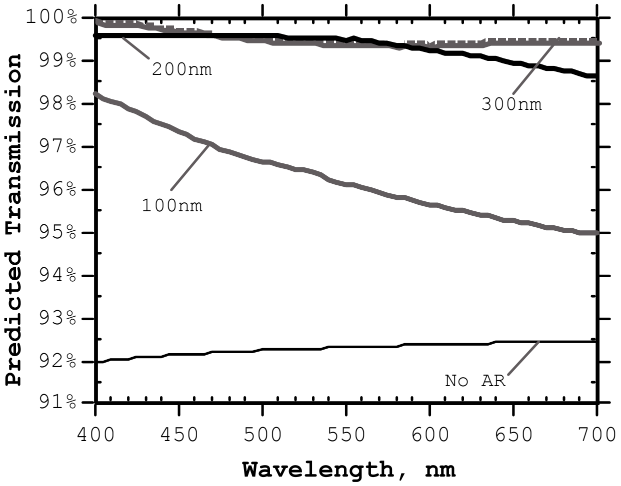

Fig. 3. Predicted on-axis transmission of visible light through an acrylic sheet with Motheye textures in both surfaces. The cone structures in the Motheye texture were modeled with sinusoidal profiles and a grid spacing of 240nm. Three curves are shown illustrating the effect of the structure height on performance. A fourth curve shows the on-axis transmission through an acrylic sheet with no AR treatment.

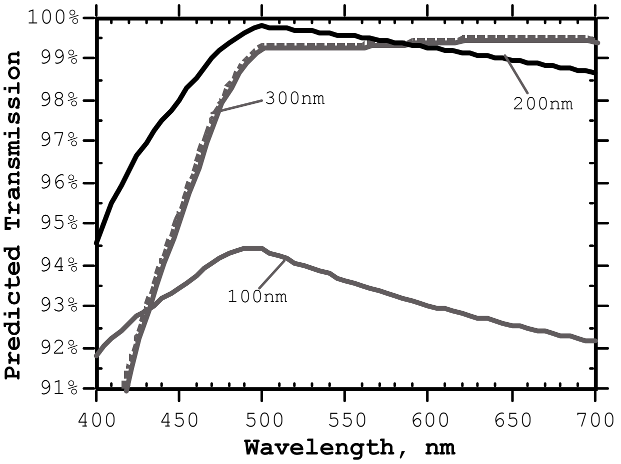

Fig. 4. Predicted off-axis transmission of visible light through an acrylic sheet with Motheye textures in both surfaces. Light incident at 30° off the normal to the sheet was modeled. The cone structures in the Motheye texture were again modeled with sinusoidal profiles and a grid spacing of 240nm. Three curves are shown illustrating the effect of the structure height on performance.

C. *Shifting the pattern period to address angle of incidence*

For full spectrum off-axis AR performance in automotive applications, the Motheye structure must satisfy the following equation-

$$\Lambda < \lambda / (n_{sub} + \sin\theta)$$

where Λ is the Motheye period, n_{sub} is the index of refraction of the substrate, and θ is the angle of incidence as measured from the surface normal. Changing the Motheye structure in acrylic to shift the diffraction out of the visible region and into the UV range, for light incident at 30 degrees, necessitates decreasing the pattern period to 200nm. Figure 5 shows a modeling comparison of Motheye structure function for 200nm and 240nm period, both with 200nm depth, at an angle of incidence of 30 degrees.

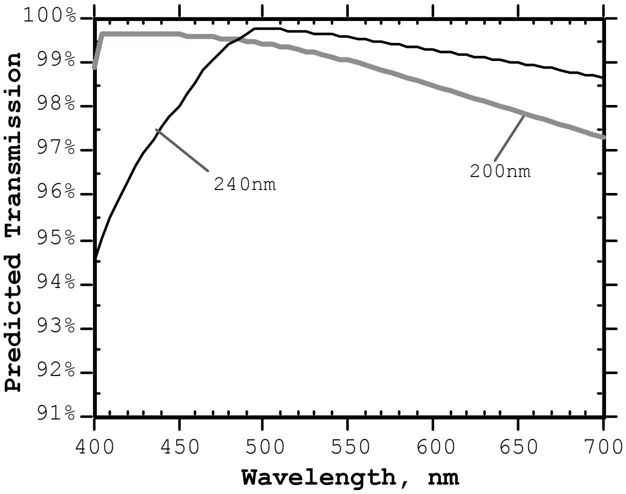

Fig. 5. Predicted off-axis transmission of visible light through an acrylic sheet with Motheye textures in both surfaces. Light incident at 30° off the normal to the sheet was modeled. The cone structures in the Motheye texture were sinusoidal profiles with a structure height of 200nm. Two curves are shown illustrating the effect of the structure spacing on performance.

IV. FABRICATION OF MOTHEYE MASTERS

A. Interference Lithography.

Interference lithography [10, 11] is the preferred technique for patterning sub-micron features such as Motheye patterns. The technique is inherently maskless, using multiple coherent beams overlapping in a three-dimensional exposure volume to generate the Motheye patterns. The technique allows the patterning of non-planar surfaces, and is ideal for patterning large field sizes in a single rapid exposure. Highly uniform Motheye textures have been fabricated over 8-inch diameter wafers and larger. An interference lithography configuration is shown in Figure 6. The typical process begins with coating a substrate with a photosensitive material used in the semiconductor industry, known as photoresist. An exposure produces a latent image of the interference pattern in the photoresist layer, as described in Figure 7. A standard wet development step delineates the image as a surface relief texture in the photoresist. A completed Motheye surface in photoresist is shown in Figure 8.

The Motheye repeat period is determined by the laser wavelength and the angle between the exposure beams. Pattern depth is modified by adjusting the exposure dose and development time.

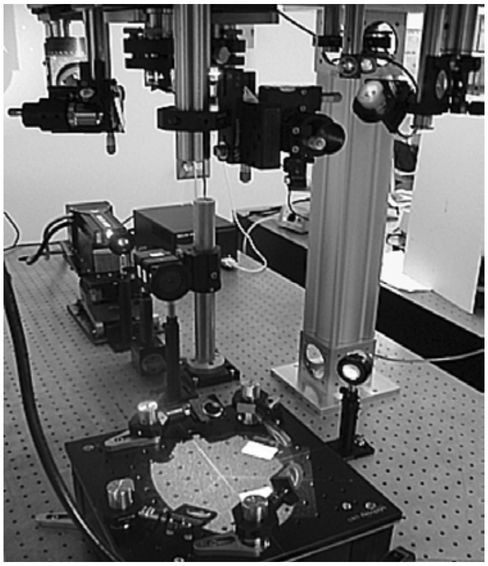

Fig. 6. An interference lithography system. The recording stage, shown at the bottom center, is illuminated by three expanded beams derived from the solid-state laser seen just left of center.

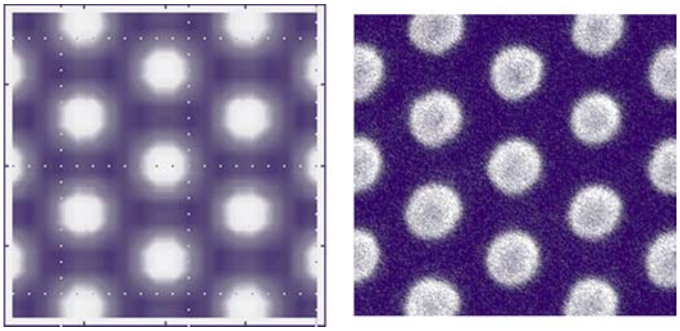

Fig. 7. *Left*: Gray scale image showing the calculated intensity distribution of the interference pattern generated by a three-beam holographic lithography system. *Right:* Scanning electron microscope image of the resulting surface texture recorded in a photoresist layer after exposure to the interference pattern.

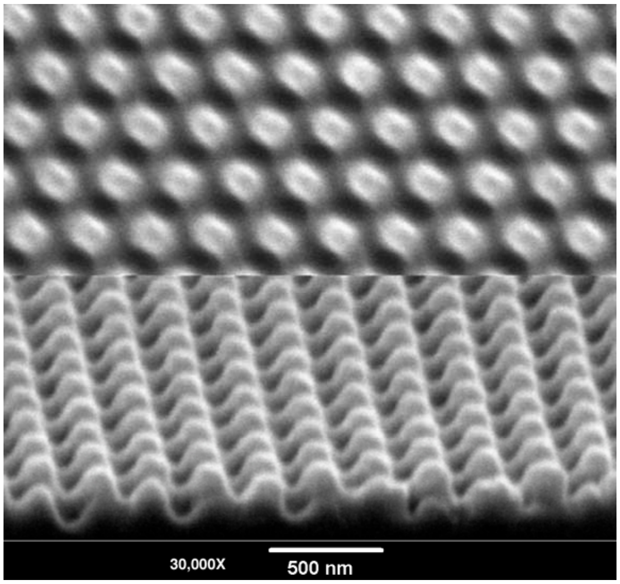

Fig. 8. Scanning electron microscope (SEM) images of an artificial Motheye texture recorded in a photoresist layer on a glass plate. Both overhead and elevation views are shown.

B. Replication

The photoresist master is not sufficiently durable for high volume replication, so a copy of the photoresist master is made in a metal foil called an electroform or replication tool. The process starts with cross-linking the photoresist master with a hardening process. A thin metal layer is then deposited on the resist as a conductive seed layer for electroplating. Typically nickel or nickel alloy solutions are used for the plating material due to their mechanical durability. Electroplating parameters are chosen for tool density and release compatibility with the resist master. The final plating thickness is application defined. For roller embossing, a thickness of 1-2 mils may be sufficient, while for compression molding, a thickness of 5 mils or greater is employed. An electroformed lens master is shown in Figure 9.

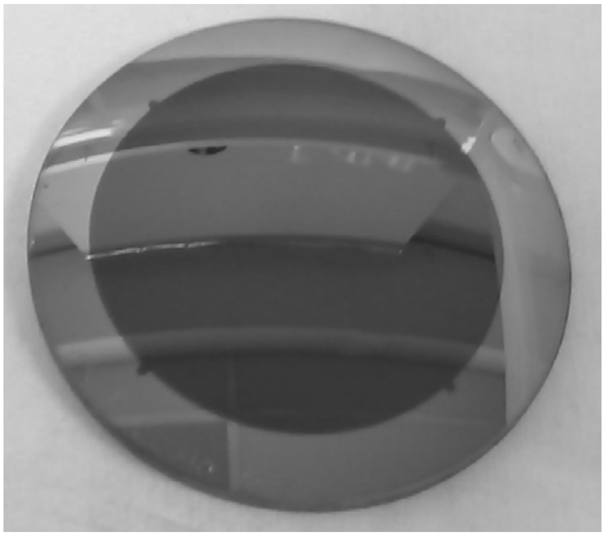

Fig. 9. An 80mm diameter electroform used as a master mold to replicate plastic eyeglasses. The central 65mm diameter area has been textured with Motheye structures.

V. EXPERIMENTAL RESULTS

A. Motheye in Acrylic

Replication processes such as roller embossing and compression molding can be used with metal electroforms to replicate Motheye structures into polymer materials. A shorter route to defining the resist master quality, is to use an ultraviolet curing system with the resist master itself and fabricate Motheye structures into hard acrylic samples. Figure 10 shows a 65mm diameter Motheye pattern replicated into acrylic. The overhead and edge view microstructure of the pattern is shown in Figure 11. The structure uniformity is excellent with few defects, a result that is due to the fundamental advantages of the IL technique. Patterning defects of 270nm or larger size will result in scattering in the visible spectrum.

B. Reflectance Measurements

Reflectance measurements were made using a fiber coupled grating spectrometer with a measurement range of 410nm to 1000nm. Reference traces of closed beam and untreated sheet acrylic were made as a control. Figure 12 shows the reflectance from the Motheye surface in acrylic of sample R4 from Figure 11. The sample backside was roughened and painted black to eliminate backside reflection. The measured reflectance remains below 0.5% across the visible spectrum, performing as well or better than expensive, conventional multi-layer thin film AR coatings.

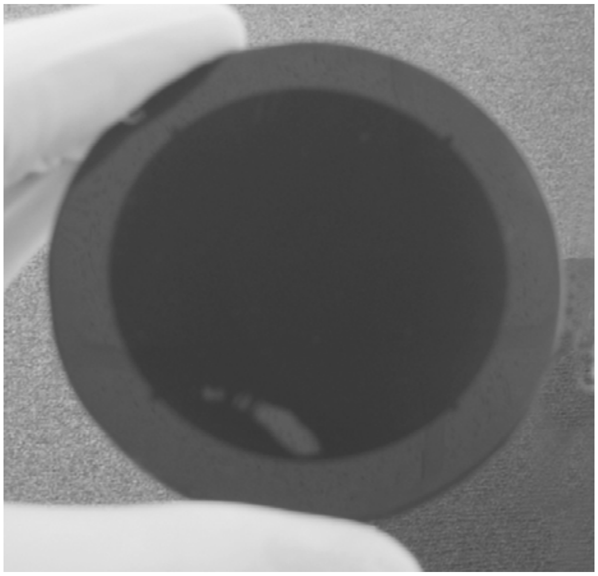

Fig. 10. A 75mm diameter cast acrylic window with a Motheye texture in the central 65mm diameter area. The untreated backside of the sheet is painted black to prevent reflections.

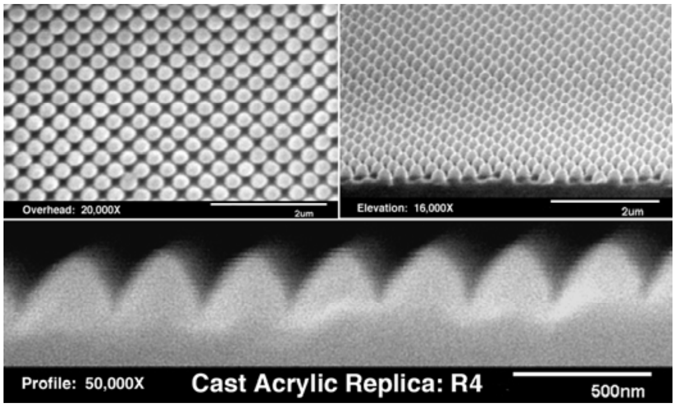

Fig. 11. SEM images of a cast acrylic Motheye texture similar to the Motheye textured window shown in Figure 10.

C. Transmission Measurements

Transmission measurements were taken on a second sample replicated with a similar UV curing system. The sample is a glass substrate with a Motheye surface impressed into thin acrylic films on each side of the substrate. The textured acrylic is index matched to the glass to eliminate internal reflections. The Motheye structure has a period of 265nm and an approximate depth of 180nm. Transmission results are shown in Figure 13, where the measured data falls just below the model performance of the 200nm depth structure, suggesting a slightly shallower texture.

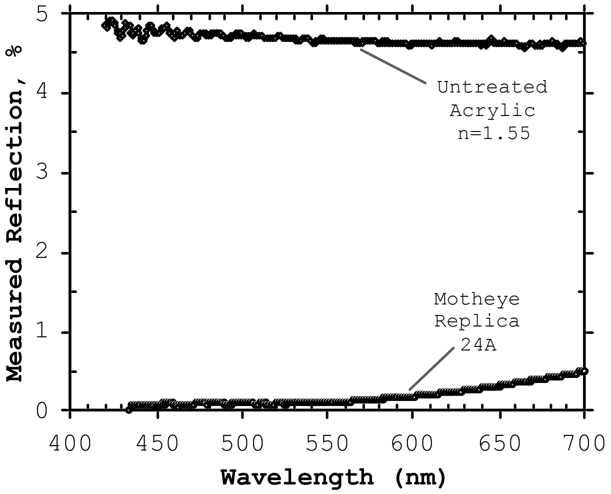

Fig. 12. Measured reflectance from a single surface of cast acrylic with and without Motheye texturing. Note that the Motheye replica data was collected from the sample shown in Figure 10.

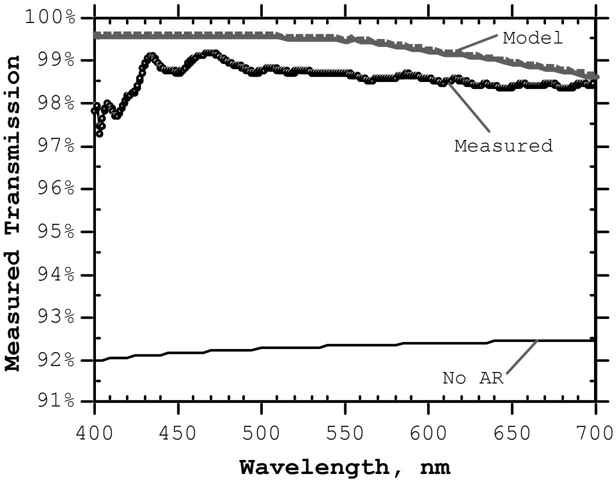

Fig. 13. Measured transmission through the Motheye textured window shown in Figure 11. The theoretical performance of a 200nm deep, sinusoidal profile Motheye texture in an acrylic sheet is shown for comparison. Note the significant improvement over an untreated window.

D. *Enhanced Display Viewability*

The suppression of external reflections from a protective display cover can have a dramatic impact on the driver's ability to view an automotive display in the presence of varying lighting conditions. Sunlight reflections in daylight and reflections from headlights and interior lighting at night, can produce superimposed images on the instrument or navigational displays leading to unsafe conditions. Figure 14 illustrates how the superior off-axis performance of Motheye AR textures allows the clear observation of the display or object behind a protective cover. The image of an overhead lighting fixture completely obscures the evergreen plant behind the untreated window areas outside the central Motheye textured area.

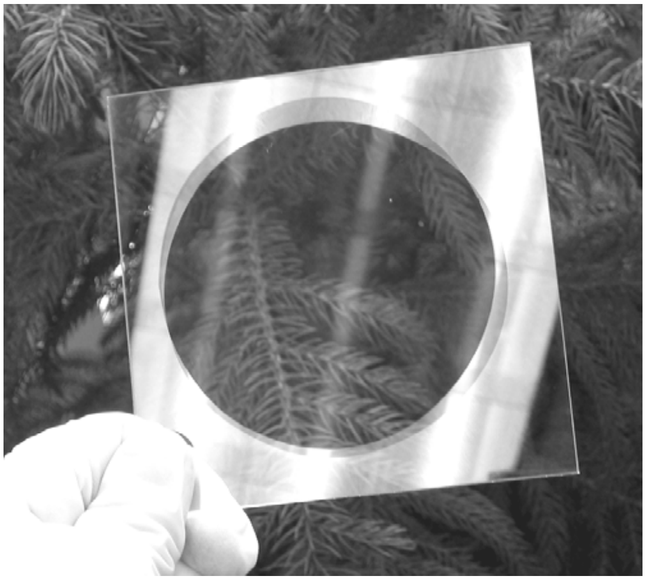

Fig. 14. A 100mm square glass window with Motheye textures replicated into an acrylic layer coated on both sides. The Motheye texture, which covers the central 80mm diameter area, effectively eliminates reflections from an overhead light fixture.

VI. DISCUSSION

A. *Durability*

The durability of Motheye structures can be hard to define in quantitative terms. Sharp tipped AR structures for high index infrared materials in space-based applications are considered more resistant to thermal shock and radiation effects than multilayer thin film AR coatings. The structures typically do not have abrasion resistance specifications as they are protected by system enclosures. For abrasive environments, such as atmospheric rain and sand impacts, blunt tip or hole structures are a better choice. Therefore, with each application, structure period and profile must be considered in terms of the durability of substrate material and the environment of use.

In the particular case of automotive displays, there is typically one panel surface exposed to the car interior and its occupants, while one surface faces the display or instruments. High performance Motheye structures on both sides of the panel would decrease total reflection from approximately 8% to 1%. An alternative design could include demanding AR specifications for the protected inside surface, with average reflection in the visible < 0.5%. The exposed panel surface may be designed shallower for increased durability at the expense of performance, with reflection specified less than 1.5%. This combination would give a total panel reflectance of < 2%, compared to an untreated reflection of around 8%. A more conservative approach would be to incorporate Motheye only on the inside of the panel, decreasing reflection from greater than 8% to less than 4.5%.

B. *Cleaning Motheye structures*

The performance of Motheye structures, like expensive thin-film AR coatings, will show degradation when oil and debris come in contact with the surface. Oils on thin-film coatings have a particularly negative impact on the AR properties, as they can increase local reflections and performance non-uniformity drastically. Oil on Motheye surfaces tends to decrease performance less significantly, with the worse case likely to still perform better than no surface texture, as the oil becomes part of, or is repelled by, the surface structures. Cleaning our acrylic Motheye replica parts has not been a problem. A simple soap and water bath or isopropyl (rubbing) alcohol rinse removes dirt and oils, leaving no visual residue. Again, the effect will be somewhat different for various structure depths and substrate materials.

C. *Cost and Pricing of Replicated Motheye Products*

The facilities and equipment costs of fabricating Motheye masters is significant. Expenses include clean-room and exposure system costs, as well as consumables such as substrates and photoresist. There are process yield issues to contend with in fabrication, as samples can fail criteria for performance or defects. TelAztec has invested heavily in the tools and fabrication process development required to produce high-quality Motheye masters suitable for high-volume manufacturing.

The electroforming step is a maturing technology for microstructures, and should have a reasonable fixed cost.

The replication process with proper tooling, should have a minimal added cost per part. It is envisioned that a license arrangement with a fixed cost per master and a minimal royalty per replicated part will be the working model for Motheye products. An encrypted signature is included within the Motheye structure to prevent product piracy.

VII. CONCLUSION

The problematic reflection from automotive display covers can be suppressed through the incorporation of micro-structured textures known as Motheye, directly into the window surface. Motheye structures in acrylic have been modeled and fabricated to perform to stringent antireflection performance requirements. A further advantage of exploiting Motheye surface textures is the ability to mass-produce product through the use of traditional plastic replication processes. Replication of tens of thousands of product parts from a single original master will result in a minimal increase in the production cost of the optical component.

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Bruce D. MacLeod has 19 years experience in the field of infrared detectors and optical microstructures. He holds a bachelor’s degree in ceramic engineering from Alfred University

For the past year Mr. MacLeod has worked on a successful Air Force contract aimed at developing microstructures capable of narrow-band filtering in the mid- and long-wave infrared. Mr. MacLeod joined TelAztec in 2003 as a consultant on its Motheye surfacing efforts. From 1986 thru 1995 Mr. MacLeod worked as a scientist at Raytheon Research Division developing crystal growth and fabrication processes for advanced infrared detectors. After Raytheon, Mr. MacLeod moved to Lockheed Martin as a Principle Production Engineer from 1994 to 1997. At Lockheed he was responsible for R&D and production line maintenance of IR detector material surface passivation. From 1997 thru 2003, Mr. MacLeod worked at Holographic Lithography Systems (HLS), and HLS’s successor Optical Switch Corporation (OSC) where he gained extensive experience related to the proposed effort. Mr. MacLeod’s duties at OSC included development and direction of the company’s Motheye and optical micro-structuring technology. The OSC micro-structuring effort included delivery of high performance visible Motheye products to many different industries, including opthalmalic, automotive, PDA, and telecommunications.

Mr. MacLeod is co-inventor on three U.S. Patents and has 8 journal publications.