Manufacturing methods for large microstructured optical components for non-imaging applications

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ABSTRACT

Various methods of manufacturing are reviewed for large area (6 inch diameter and greater) microstructured optical components (MOC's) that are used for light management in non-imaging applications. All of the manufacturing methods discussed will relate to the processing of various optical grade polymers. This paper will start with a review of the traditional methods used to make plastic Fresnel lenses over the past forty or more years. The evolution of precision compression molding will be analyzed. Quality / cost trade-offs of the various methods currently used to produce large-area, thin cross-section, microstructured optical components will be discussed. Examples of products made by compression molding, transfer molding, hot stamping, thermal and UV casting and other various processing methods will be discussed. The paper will conclude with a look into the future. Where is non-traditional, non-glass optical component manufacturing technology headed?

Keywords: Fresnel lenses, plastic optics, non-imaging optics, diffractive optics, compression molding, injection molding, polymer casting, microstructured optical components (MOC's)

1. INTRODUCTION

This paper is dedicated to a very small "niche" segment of the plastic optics market. Since Optics is considered a niche market, and Plastic Optics is considered a niche market within the optics market, *large microstructured components for non-imaging applications* must be such a small segment of the market that one may wonder if it really even exists. So, why write a paper on this subject?

Have you ever made or seen a presentation where an overhead projector (OHP) or a liquid crystal display (LCD) projector was used? Have you ever used a laptop computer? Have you ever watched a large screen television? Have you ever seen a reflective sign or cone as you drive through a road construction zone at night? All of these are very common examples of the use of *large area microstructured optical components for non-imaging applications.*

The "information highway" would not exist today if it were not for this *Management of Light*™ technology. Night time highway safety would not be possible with out this technology. The ability to manufacture large, high precision, microstructured optical components in high volumes at low costs appears not to be widely known or understood. The purpose of this paper is to introduce this little known and sometimes misunderstood niche in the optics industry to the reader.

The information presented in this paper will be limited to processes and products that require a fairly high degree of precision in the replication processes used and a relatively high aspect ratio profile (height/width >0.2). Thus, traditional lighting applications such as residential and commercial indoor and outdoor lighting, automotive head and tail lights, stage lighting, etc. will not be included in this paper. Also, low aspect ratio profile processes and products such as audio, video, and computer data compact discs, surface relief holograms and diffractive optical elements (DOE's) will not be included.

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2. THE BIRTH OF THE "MODERN DAY" FRESNEL LENS

The Eastman Kodak Company is credited with giving birth to the "modern day" plastic Fresnel lens. In 1946 Kodak developed a tooling and manufacturing process to mass produce plastic Fresnel lenses.[1] The circular Fresnel lenses made at this time had spiral grooves. The precision and geometry of these early plastic Fresnel lenses limited their usefulness in many emerging markets.

3. THE PLASTIC REVOLUTION OF THE 1960'S AND 1970'S

(from a microstructured optics point of view)

The demand for large area, light weight, high quality, low cost condenser and field lenses for products such as the overhead projector and microfilm readers led to a series of significant improvements in the tooling and molding processes for Fresnel lenses in the early 1960's. Almost all microstructured optical elements made in this period of time were called *Fresnel Lenses*. The term *Fresnel lens*, in its broadest sense, refers to any lens made up of a series of prismatic surfaces.[2] From the 1960's through today, many people include products such as micro-prism arrays, lenticulars, micro-beamsplitter arrays, etc. in this general product category called *Fresnel lenses*. As new applications and production processes emerge the generic term *Fresnel lens* is used less and less, but in the 1960's and 1970's almost any optical element that had microstructure was called a Fresnel lens.

The emergence of these new markets in the early to mid 1960's led to the establishment of several new companies. By the mid 1960's there were at least three small companies throughout the world specializing in the manufacture of *Fresnel lenses* (precision plastic microstructured optical components). The overhead projector was clearly the most significant contributor to this technology push. The plastic Fresnel lens, such as those found in any overhead projector today, has really been the seed for the entire niche market that we now call microstructured optical products (MOP's). The need for a high performance, low numerical aperture, light weight, low cost condenser lens led to significant improvements in the tooling and molding processes. Precision diamond machining and high volume compression molding processes were developed in the 1960's to satisfy the needs of this emerging market.

Many of the manufacturing processes used in this time frame to make *Fresnel lenses* had their origins in the record industry. Once a master tool was created the replication of that tool, either in metal or plastic, used technologies that had been developed to make records (those things we used to distribute music on before we had the CD). The size, volume, and cost objectives to make records were all very similar to those of the Fresnel lens manufacturers. Remnants of this record industry origin of the processes used to make optical microstructured elements (MOE's) can still be seen today. At the same time, as early as the late 1960's the optical product performance demands caused this industry to modify existing processes and develop new processes to meet the unique optical requirements of the parts that were being produced. In addition to the obvious need for an optically clear material, microstructures with much more depth, steeper slopes, and sharper peaks and valleys than those needed in the record industry resulted in the development of specialized manufacturing processes. The best example of this is compression molding. The term compression molding is used to describe many different and highly specialized molding techniques. The compression molding process used to make printed circuit boards is not the same as the compression molding process that was used to make records. The compression molding process used in the 1960's and 1970's to make *Fresnel lenses* was a highly specialized process that had been developed to make precision optical microstructured products.

In the late 1960's and through out the 1970's further specialization occurred as the need for circular, linear, and crossed linear optical structures grew. By the end of the 1970's there were special processes developed for making specific shapes and sizes of optical microstructured products. Compression molding, transfer molding, casting, extrusion embossing, and injection molding were all used to produce various microstructured optical products during this period of time. Compression molding was considered to be one of the slowest, but most precise methods of manufacturing plastic microstructured optical products.

Some of the unique products developed in the 1970's that required precision microstructured optical components include:

- the SX-70 Polaroid camera (an ultra-thin Fresnel field mirror made by compression molding)
- rear projection television systems (Fresnel field lens and projection lenses made by compression molding)
- photovoltaic concentrator arrays (an array of circular Fresnel lenses made by compression molding)
- infrared motion detection devises (an array of circular Fresnel lenses made by transfer molding and compression molding)
- *Press-On™* temporary correction ophthalmic lenses (micro-prisms and Fresnel lenses made by compression molding)
- portable [reflective] overhead projectors (an ultra-thin Fresnel mirror made by compression molding)
- *Vangard™* wide angle safety lenses for the automotive and recreation vehicle market (made by compression molding)
- numerous night safety products incorporating micro-corner cube retroreflector technology (ultra-thin, high efficiency retroreflectors made by compression molding, transfer molding, injection molding and precision casting).

The above is a very impressive list of products that all depended on a precision microstructured optical element to exist. Many of these products not only still exist today, but the markets for these products continue to expand. Also, it is easy to see the significant role that compression molding has had in the success of this niche area of optics.

Plastic diffractive optics and holographic optics also had their origins in the 1970's The marriage of these two technologies with the traditional "Fresnel lenses" will be discussed later in this paper.

4. THE COMPUTER EXPLOSION OF THE 1980'S AND 1990'S

(from a user and a supplier point of view)

The development of "micro-computers" has had two very profound impacts on this niche optical industry. There has been a dramatic improvement in manufacturing process technologies that are used to produce large microstructured optical components. At the same time, there has been an explosion in the number and size of the markets that require some type of precision microstructured optical component.

Let's explore a few specific markets served by this niche optical industry as they have evolved over the past 15 years. We can use the overhead projector (OHP) as an example of an established product and the flat panel display (FPD) as an example of a new or emerging product (in relative terms). Both of these products depend on precision microstructured optical components for their very survival. Each of these products can be used to trace the changes that have taken place in the manufacturing processes, as well as the changes in the performance specifications of the microstructured optical components over the past 15 years. The dramatic changes that have taken place in the computer industry in the 1980's and the 1990's have driven both the manufacturing process changes and the performance and volume demands of MOC's.

It seems likely that engine that drives the information highway (the computer) will continue to have a dramatic influence on both the production of and use of MOC's as we move into the 21st century.

In the early 1980's the overhead projector (OHP) market was a sleepy little business that had been around for more than 20 years. Everyone seemed to predict the death of the OHP each year, but it just kept rolling along at a stable level of sales. Sales slowly began to clime in the mid 1980's as the availability of the color copier expanded and as the costs of a color transparency came down. The widespread use of color transparencies gave new life to the overhead projector. At the same time, the use of the OHP for projecting spreadsheet data and full color graphics created a demand for brighter, higher resolution projectors that were lighter and easier to carry on an airplane. This caused the projector manufacturers to demand new and improved optical systems. The performance requirements of the Fresnel condenser lenses were increased significantly. The availability and affordability of computers enabled special optical design programs to be developed for Fresnel lenses. Computer controls were added to diamond turning machines that enabled manufacturers to significantly increase the flexibility they had to make master tools. Computers were introduced to compression molding processes to improve the quality and consistency of these operations.

By the end of the 1980's many of the process steps involved with the fabrication of a Fresnel lens were controlled by a computer. In this same time frame, the color copier had become common place and a new technology called LCD panels was causing a second explosion in the (once thought to be dying) overhead projector market. The OHP was used as a light source for the LCD panel. As the LCD panel moved from black and white to color the demand for OHP's became even larger. Because the transmission through a color LCD was less than 10% the requirement for brighter and brighter OHP's continued to grow. This demand for increased brightness again trickled down to the optical manufacturers of Fresnel lenses. The requirements for improved uniformity of illumination, improved resolution, and improved transmission created another round of refinements in the manufacturing processes used to make Fresnel lenses. The addition of a requirement for little or no stress (birefringence) in a 300 mm square part added additional demands on the molding process. Without the ability to utilize micro-computers in the compression molding process, the demands of the LCD panel users could have never been achieved.

Today, a computer controlled, semi-automated compression molding process is used to manufacture most of the Fresnel lenses used in overhead projectors. This process is used to produce hundreds of thousands to millions of 300 mm (12") square lenses per year. An assembly of two of these lenses sells for less than $ 20.00 in quantities of thousands per year. If you stop to consider all of the technology that goes into making such a lens assembly, this is an impressive accomplishment.

A similar picture can be painted for the flat panel display market. Fresnel lens arrays were used in the 1970's as magnifiers for linear LED arrays used in the early hand held calculators. These small area microstructured optical components quickly lost out to injection molded linear arrays of conventional aspheric lenses as volumes jumped into the multi-millions and cost pressures pushed prices for a typical calculator array below the 10 cent level. Slower, labor intensive compression molding techniques that were required to produce high quality Fresnel lens arrays simply could not compete as the volume demand for these products increased. In the 1980's and 1990's MOC's found new opportunities in the larger (two dimensional) LCD arrays. Illumination systems were needed for LCD's that were being used in both direct view and projection applications. State of the art compression molding and other "traditional" microstructured optical component manufacturing techniques were able to satisfy the performance, volume, and cost demands of this emerging market in the 1980's and the early 1990's. As the volumes continue to increase and the performance demands rise, current "state of the art" MOC production technologies may not be able to keep pace with this dynamic and demanding market.

Today, many patents exist that specify the use of unique microstructured optical components to improve the efficiency of illuminating LCD's in direct viewing and projection applications. This market has become one of the fastest growing markets for MOC's. The challenge that faces all of the companies involved with the production of microstructured optical components for the flat panel display market is to find manufacturing methods that are suitable for very high volume / low cost production runs without lowering the performance standards achieved with slower / more costly methods of production. The financial rewards for those companies that are successful in finding ways to meet the cost / volume / performance demands of the flat panel display market are creating another revolution in the manufacturing methods used to produce microstructured optical components.

5. TAKING A RIDE ON THE INFORMATION HIGHWAY INTO THE 21ST CENTURY

The examples used in section 4.0 are very representative of what is happening in most, if not all, of the microstructured optical component markets today. Many of these markets are driven directly or indirectly by the phenomena that we call "the information highway". The impact of this "highway" on the manufacturing processes used to produce MOC's will be extraordinary. Also, the new opportunities for using microstructured optical components in the 21st century will only be limited by our ability to develop cost effective precision manufacturing processes. Rear projection television screens, infrared devises and night safety devises are just a few additional examples of markets that will continue to push the state of the art of microstructured optical components. The marriage of diffractive, holographic, and refractive MOC's has already started. This powerful combination of physical and geometrical optics will play a major role in shaping the future for all of us. The manufacturing technologies that will be possible in the 21st century will marry the strengths of today's processing methods with the power and speed of the computer to create precision and efficiencies that we can not even imagine today.

A simple, but powerful, example of what is happening can be demonstrated by continuing the story of compression molding. Injection compression molding (ICM) is more than 20 years old. It is finally on the verge of having a major role in the production of microstructured optical components. The computer power necessary to design strange looking, but outstanding performing, MOC's is finally available. This same computer power is also available to develop special molds and mold bases for ICM and to monitor, and control all of the critical process variables necessary for ICM to work properly. The computer revolution of the 1990's has helped to create the process capabilities necessary to produce high volume, precision MOC's in a cost effective manner. At the same time, these same advances in computer technologies are creating new markets that require the use of MOC's in extremely high volumes. The marriage of compression molding and injection molding to cost effectively produce microstructured optical components has been going on for many years. The recent work done by people like George Galic and Steve Maus of Galic Maus Ventures and Dale M. Grove of Optimum Systems Technologies Inc. moves this marriage one step closer to reality.[5]

We really are living in the middle of a revolution in technology that is more fundamental than anything ever experienced before. It is exciting to be a part of this technology revolution. Now, if we could only get the optics community to recognize that there really is a microstructured optics industry!

6. REFERENCES

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