

Replication of High Fidelity Surface Relief Structures

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There are several methods currently available for replicating high-quality patterned optical surfaces. This paper investigates the optical performance of replicated imaging quality diffraction gratings, interferometric encoders, and performance enhancing surface relief structures manufactured with ultraviolet curable photopolymers (UVPP) as an integral part of the replication process. Through the development of a UVPP replication process, fabrication times of the desired optical components are decreased while product quality is maintained, and in many cases increased. Attractive low cost replication based solutions to several optical manufacturing problems are discussed.

Review of Existing Technology

Replication technology employing embossing, molding, both injection and epoxy, and etching has been used for years in the production of surface relief optical components ranging from the visually pleasing, but low quality, credit card holograms to imaging quality diffraction gratings used in high resolution optical systems. Each of these technologies has provided cost-effective solutions for the production of multiple components from a single master optic. Depending on the desired component's requirements regarding cost, quality, production volume, substrate shape, etc., one technology would typically stand out as the obvious choice for manufacturing.

Embossing technology is typically used to produce relatively low quality surface relief structures in high volume at low cost.¹ Holograms such as those found on credit cards and software boxes are examples of the type of grating that can be manufactured using embossing.² Both the low cost and quality are due in part to the materials available for embossing. This technology applies heat and pressure to transfer surface relief microstructures from stamping rollers into a plastic substrate. Specifically, the substrate, which is typically a thermoplastic foil, is heated above its glass transition temperature

(T_g), pressed between embosser plates or rollers, and allowed to cool before release. Embossing is capable of producing submicron structures when properly designed equipment is used.

Due to the inherent limitations of thermoplastics, components produced by embossing lack the requirements necessary for imaging applications.³ Other issues arise in the macroscopic features of the component. Typically embossed structures are limited to flat surfaces that are used for non-imaging optical systems such as light control optics and visual displays.

Injection molding technology is typically used to produce moderate quality surface relief structures in high volume at low cost. Non-imaging Fresnel optics and compact discs are two examples of injection molded structures. Injection molding provides added flexibility as mounting tabs and other features can be designed directly into the component for easier assembly and alignment. The repeatability of the replicated part is contingent on the control of the injection molding process. Complex microstructures with high aspect ratios can be attainable if proper attention is paid to the thermodynamics of the mold.¹ The constraints on injection molding are similar to that of embossing, where one is limited to thermal polymers, which in many cases do not possess the quality characteristics necessary to produce high fidelity optical components. Moreover, due to the high cost of tooling associated with injection molding, the cost advantage over more conventional manufacturing processes does not become apparent until runs reach tens of thousands.

Conventional epoxy molding technology is typically used to produce moderate to high quality surface relief gratings in low volume at moderate to high cost. Spectrometer and monochromator gratings are two examples of epoxy molded structures. As with injection molding, epoxy molding provides added flexibility as mounting tabs and other features can be designed directly into the component for easier assembly and alignment. The repeatability of the replicated part is excellent when properly controlled processes are in place.

The major constraints on epoxy molding are the long processing times associated with it and the stress induced by the thermal curing cycle. Unlike injection molding where the cycle times can be well below one minute, epoxy curing cycles can run 6 hours

or longer. Long cycle times significantly impact the cost of the component produced. For both single component heat cured epoxy, and room temperature cured exothermic two part epoxy, the thermal stress induced can play a major role in the quality of the final product. Significant care must be taken to factor in the effects of thermal stress in order to produce high quality components.

The photolithography/etching process is typically used to produce high quality surface relief binary gratings in low volume and at high cost. Beam homogenizing⁴ and beam shaping diffractive optical elements⁵ (DOE) are two examples of binary gratings produced by the photolithography/etching process. This replication technology provides the designer with some freedom of substrate material choices, and is a process that produces good repeatability. With proper process control, feature errors of less than 5% can be achieved.⁶ With the use of gray scale masking it is possible to achieve structures that approximate continually curved structures rather than stepped. This technology is often used in the production of diffractive optics for variety of applications that require lightweight alternatives to refractive optics.

The drawbacks of this technology can be severe. Typically the replication process requires a significant number of tightly controlled etching steps in order to produce gratings with enough diffraction efficiency to be useful. Each additional step not only raises the cost of the associated part, but can also have a significant impact on grating quality due to mis-registration of the overlays.

Latest Advance in Replication Technology

State of the art replication technology developed recently at Holographix, Inc. as well as at other companies incorporates ultraviolet curable photopolymers (UVPP) as part of the replication process. This technology incorporates many of the positive aspects of the other major replication technologies without the associated drawbacks. This technology provides a cost-effective way to produce high quality surface relief structures in almost any volume at low cost. There are a number of very attractive attributes of this approach. Most importantly, the UVPP technology enables high-speed production of high quality replicated structures, such as the transmission grating shown in Figure 1. Each replica is produced using UVPPs, which cure within seconds, while at the same

time allowing the replica to stay at ambient temperature, which is why Holographix refers to this process as “cold” forming. Short cycle times mean lower cost, while ambient curing provides low thermal stress and thus high quality components can be attained. Another important attribute of this process is the flexibility it provides the systems designer. As with conventional epoxy replication, virtually any material can be used as the replica substrate; metal, glass, and plastic are all viable materials. Additionally, the process does not constrain the shape of the substrate. Therefore, components can be designed with almost any shape as well as with built in mounting tabs and other features. This flexibility allows for straightforward implementation of replicated structures into production systems. This paper describes the benefits of this replication technology by discussing case studies of three different types of surface relief structures that have been successfully manufactured using the technology.

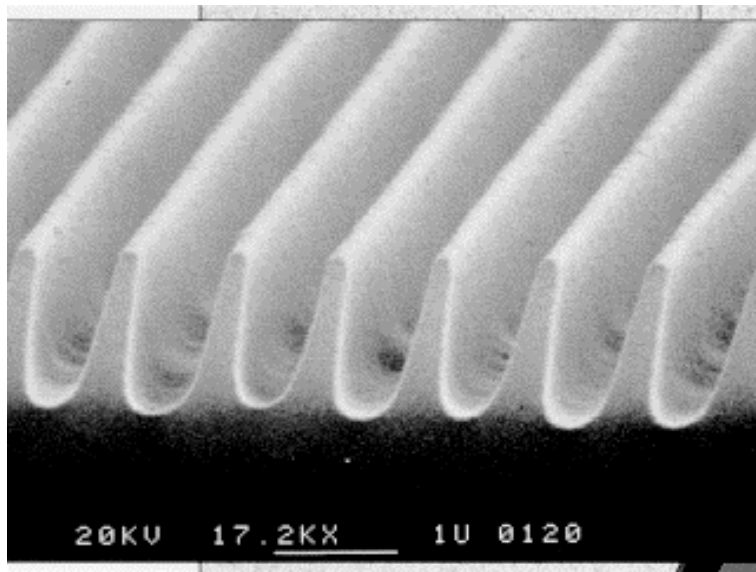


Figure 1 - Replicated Transmission Grating

Case Study #1: Diffraction Gratings For Imaging Applications

Nearly everyone is familiar with the colorful diffraction gratings (holograms) found on credit cards, cereal boxes and software etc. However, more than ever, optical system designers are finding diffraction gratings an attractive alternative to conventional optics for a variety of high quality imaging applications. Surface relief diffraction gratings are used in a variety of commercial devices including spectrometers,

holographic-based scanners, and pulse compression systems to name just a few. In most cases, these systems require high diffraction efficiency as well as preservation of the wavefront quality of the incident light beam. The use of original master ruled or holographically recorded gratings is attractive due to their high quality but is not generally economically feasible when production volumes of more than 5 or 10 units are required. The most economical solution for designs where production volumes are required is replication. However, for the replicated grating to function effectively in the system it must be a high fidelity copy of the original master grating.

Using UVPP technology, Holographix, Inc. manufactures a number of different transmission and reflection gratings for a variety of imaging applications (Figure 2). These gratings are replicated onto both high quality glass substrates and inexpensive polycarbonate substrates. The first step in the production of replicated gratings of this type involves the creation of the surface relief master and stamper tooling. The master can be formed in photoresist using holographic recording techniques or can be formed in aluminum or other suitable material using a high-resolution ruling engine. From the master grating, Holographix, Inc. can produce hundreds of stampers using proprietary stamper generation technology. These stampers are then used to produce hundreds, and in some cases, thousands, of high quality replicas. Thus, tens of thousands of high quality replicas can be made from one master (Figure 3).

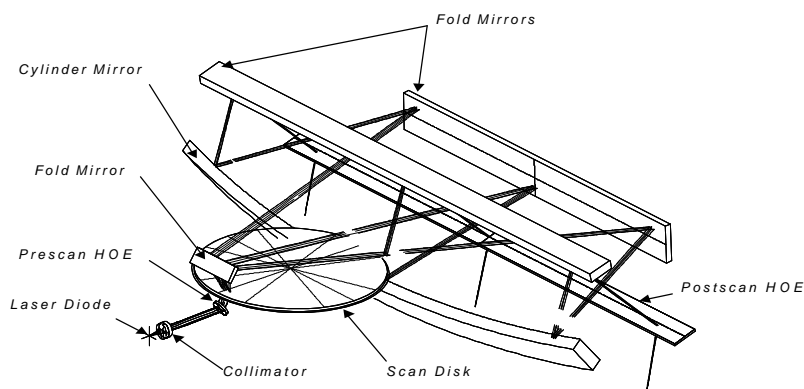


Figure 2 - Holographic Scanning System

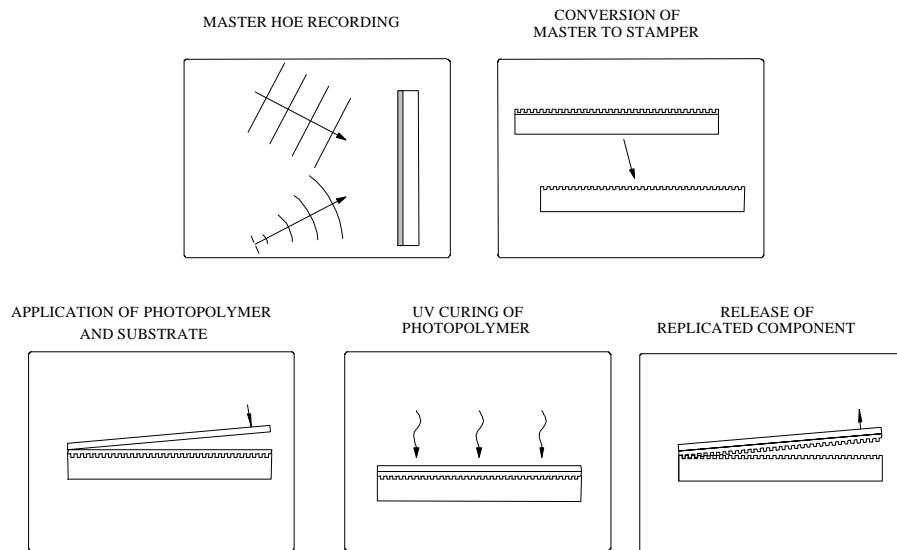


Figure 3 - Cold Form Replication Process

As with other manufacturing technologies, an important factor in the success of the replication approach is the repeatability of the components produced. With proper tooling and manufacturing processes in place, a very high degree of repeatability is virtually guaranteed using UVPP technology. Efficiency studies performed on gratings produced by Holographix, Inc. show that over the lifetime of a stamper, diffraction efficiency variations of less than 2% part to part can be expected (the efficiency is measured as the difference of the diffracted beam energy versus the incident beam energy) (Figure 4). Alignment and wavefront quality have also been shown to be very repeatable part to part. Numerous trials have shown that field replacement of gratings produced at Holographix, Inc. require no re-alignment in most cases to achieve the specified optical performance. This is quite different than that which is experienced when master gratings are used in each system. While master gratings provide comparable wavefront quality to that of the replica, they show more variation in diffraction efficiency from part to part and can be harder to align as they are not duplicates. Therefore, UVPP replication not only provided a significant cost savings, but it also enabled these products to be higher quality and easier to align.

Prescan Replica Efficiencies

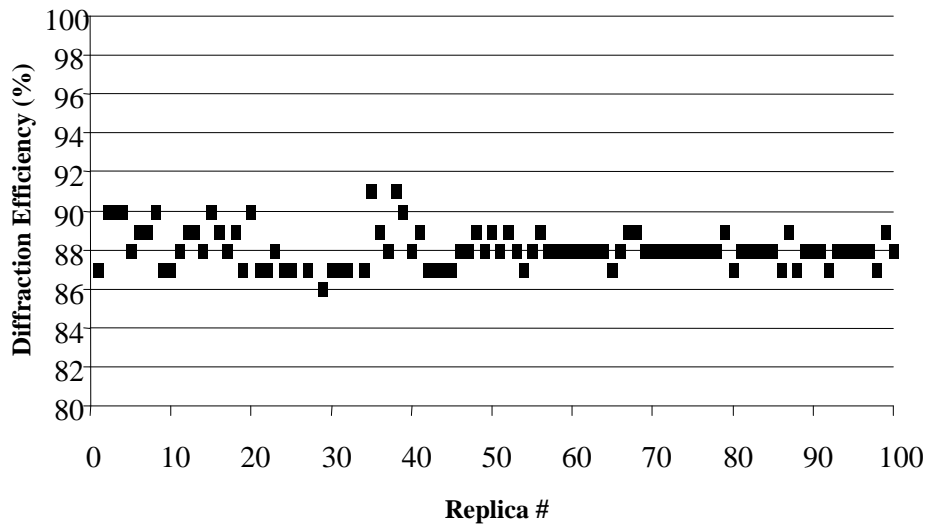


Figure 4 - Replica Efficiency Repeatability

Case Study #2: Interferometric Encoders

A new application for surface relief diffraction gratings has emerged for the precision motion control and measurement markets. In the past, the chrome-on-glass type encoder was the technology of choice to provide position feedback for both linear and rotary motion devices. These encoders are manufactured using photolithography and etching. For very high-end precision motion control, for applications such as semiconductor and metrology devices, Michelson-type interferometers replaced chrome-on-glass encoders to provide the resolution required. Today, a single device called the interferometric encoder (Figure 5) is rapidly replacing these two approaches. This device provides the compactness of the chrome-on-glass encoder with the resolution capabilities of the rather bulky Michelson interferometer.

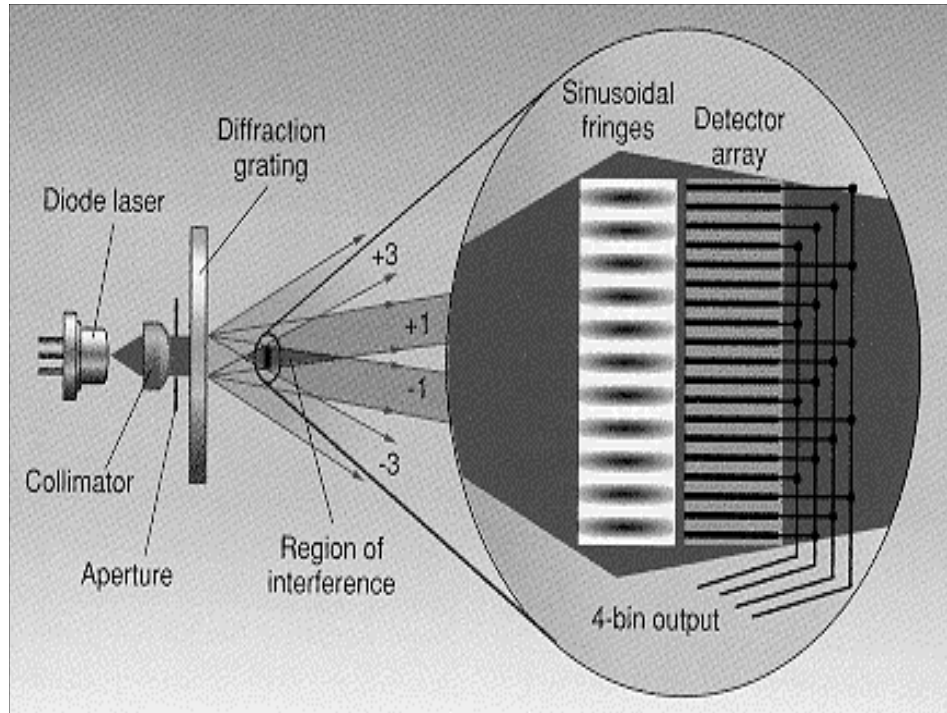


Figure 5 - Interferometric Encoder Assembly (Courtesy of MicroE)

For these encoders to meet the requirements of this demanding application, they must be fabricated to exacting tolerances. The grating's depth and pitch must be rigorously controlled during manufacturing. Errors in the range of 10's of nanometers can cause significant degradation in the encoder's performance. Imperfections in the gratings are also problematic as they can cause dead zones in the encoder where position can not be read. Imperfections on the order of 0.1 mm or greater are generally not tolerated.

Until approximately one year ago, all interferometer encoders were individually manufactured as master gratings. Due to the large number of variables, the mastering process leads to non-repeatability from part to part. This in turn reduces yield and increases the time required to assemble and align the grating into the encoder assembly. Since early 1998, Holographix, Inc. has been successfully using UVPP technology to replicate in a variety of different types of interferometer encoders, both linear and rotary. Holographix and its customers are enjoying high production yields of >95% in most cases for these products. Also, because each master is capable of producing >150 replicas and each replicated grating is an exact duplicate of the master, alignment time of

these gratings into systems has been reduced compared to the alignment of master gratings. Again, going to UVPP replication technology not only provided a more cost effective approach to making the gratings, but it also provided a more repeatable and thus higher quality product than was possible with master gratings.

Case Study #3: Performance Enhancing Surface Relief Structures

Performance enhancing surface relief structures are finding their way into numerous applications ranging from flat panel display manufacturing to broadband anti-reflection surfaces. This is in part due to the recent advances in the production of complex surface relief structures over large areas. Since UVPP technology is capable of producing feature quality and depth equal to or greater than that of etched components at a fraction of the cost, it is in most cases the better choice for production quantities of high quality performance enhancing surface relief structures. Relative to other replication approaches, UVPP provides an important benefit in its capability to function over a wide range of environmental conditions without degradation. This is particularly important for certain applications such as diffusers used with high-energy light sources or holographic anti-reflection (motheye) structures (Figure 6) working under harsh environmental conditions.

Holographix, Inc. replicates a number of different custom structures for a variety of customers using UVPP technology. Applications for these structures include diffusers, both holographic and conventional, LCD alignment wells for flat panel display manufacturing, and motheye structures. Structures ranging in pitch and depth from <100 nm to >100 microns have been successfully produced.

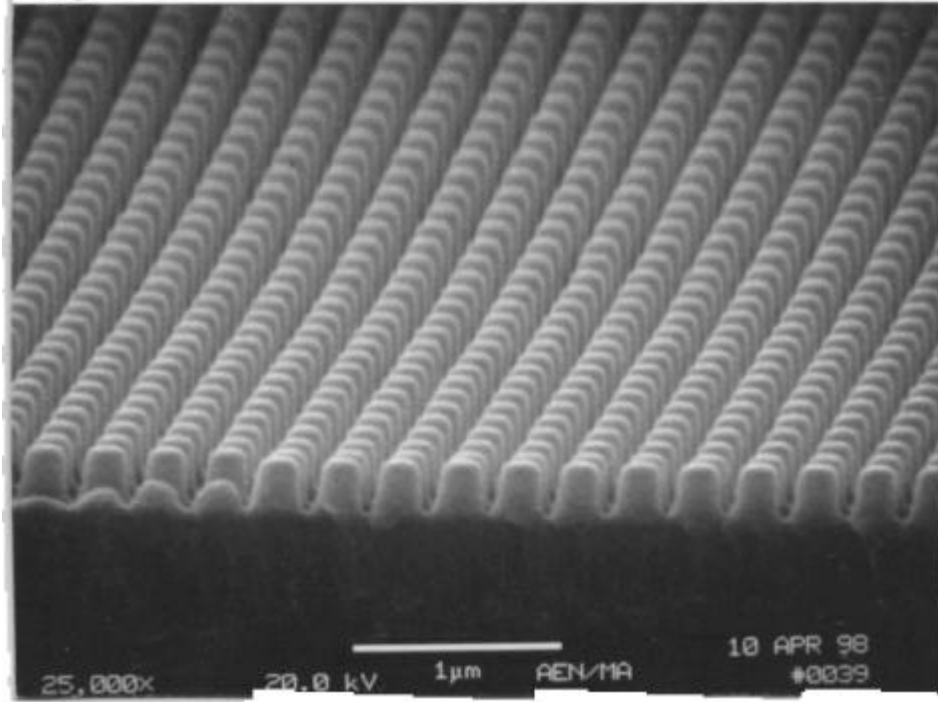


Figure 6 – Replicated Motheye Structure (Courtesy of HLS, Inc.)

Conclusions

As detailed above, there are numerous proven technologies to choose from when selecting a replication approach. However, only UVPP replication technology is capable of producing a wide range of high quality, robust surface relief structures at low cost. This combination makes UVPP technology a very attractive alternative to other more conventional replication technologies. Based on the advantages of UVPP technology, the authors believe that it is the best choice for many applications.

¹ M.T. Gale, Replication Technology for Diffractive Optical Elements, Proc. SPIE 3010 (1997) 111-121.

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³ Jon Nisper Diffractive Optics: Plastics Make the Grade, Phot. Spectra, Jul. (1997) 115-122.

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⁵ A. Kathman, E. Johnson, Binary Optics: A valuable part of the designers tool kit, Photonics Design and Application handbook, 1996 pp. H-368-372.

⁶ W. Däschner, P. Ling, R. Sein, C. Wu, S.H. Lee, Cost Effective mass fabrication of multilevel diffractive optical elements by use of a single optical exposure with a gray-scale mask on high-energy beam sensitive glass, Appl. Opt. **36**, 20, **1997** pp 1-6.