Replication Technology for Holograms and Diffractive Optical Elements*

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Replication technologies such as embossing, molding and casting are highly attractive for the fabrication of surface relief hologram and diffractive optical element (DOE) microstructures. They have very high resolution, typically in the nanometer range, and allow the fabrication of a large area, complex microstructure by low cost, high volume industrial production processes. Their use is already well established for gratings, white light holograms, and diffractive foil with typical relief structure shallower than 1 μm and the extension to the fabrication of deeper and higher aspect ratio microstructure is underway. The combination of replication technology with other processes such as dry etching and thin film coating can also offer new possibilities in the design of DOEs suitable for mass production. Replication is expected to become a key technology for the microfabrication of a wide range of DOEs in the future. We review the major hologram and DOE replication techniques and describe recent work and results.

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Introduction

The replication of surface relief microstructure by techniques such as embossing, molding, and casting is well established for the mass production of a wide variety of elements. The technologies are capable of reproducing micrometer and nanometer sized features over areas of many squared centimeters at very low cost. Examples of high resolution microstructure routinely produced in this way include spectroscopic gratings (casting), holographic security features and diffractive foil (hot embossing), and compact disks (injection molding).

In the second section of this paper, we review the origination and major replication technologies for surface-relief holograms and diffractive optical elements (DOEs). The term DOE is taken to cover the complete range of diffractive elements fabricated by a wide variety of microfabrication techniques, including the more familiar holograms fabricated by holographic interference techniques. Elements of interest include simple patterned grating diffractive foil,[1] rainbow holograms,[1] binary optical DOEs (multilevel relief microstructures),[2] continuous-relief DOEs such as Fresnel lenslets[2,3] and buried grating microstructures.[4] The justification for using the replication approach is almost always economic—the technologies allow the generation of multiple, low cost copies from a single original, which itself may be relatively complicated and expensive to fabricate, and present recent results. Details and recent results for individual replication technologies are given and then summarized.

Surface relief, reflection rainbow holograms for security and display applications are today routinely produced by hot embossing. Such holograms typically have relief microstructure with periodicities down to about 1μm and amplitude up to about 300 nm. The application of replication technology to the production of DOEs in general involves the extension of the technology to deeper or higher aspect ratio (feature depth to width ratio) microstructures, without sacrificing replication speed or fidelity. Binary optical elements and continuous-relief Fresnel lenslets, for example, can have relief amplitudes of many micrometers. An additional consideration is the maintenance of large area surface quality for elements for which the optical performance can be strongly affected by the optical flatness. This can be achieved by combining a replicated film with a rigid element such as a planar glass substrate or lens element. Replicated holograms and diffractive foil have long been present in the marketplace. Replicated DOEs are now beginning to appear and replication is expected to become a key technology for the low cost, mass production of DOEs in the future.

Overview of Replication Technology

Figure 1 illustrates the manufacturing path for replicated holograms and DOEs. Three basic steps are involved.

Origination. The original surface relief microstructure is fabricated by one or a combination of techniques. Examples include holographic exposure of photoresist[1] for grating and hologram microstructure, direct laser writing[3,5] for Fresnel lenses and kinoforms, direct e-beam writing[5,6,7] for binary and continuous-relief DOEs, lithography and dry etching[2,8] for binary optical DOEs, and diamond turning[9] for Fresnel lenslets. The product of the origination is a surface relief element in photoresist, quartz, metal, or other material used in the fabrication technique.

Replication Tool Fabrication. The replication tool is the workpiece used in the replication machine. If the origination is directly in metal or another hard material (as in diamond turning, for example), this can be used directly as the replication tool. Tools can also be fabricated by casting epoxy copies on rigid substrates (submasters) from the original relief. These approaches have the advantage of being able to maintain the optical form (planarity or curvature) of the original, which can be essential for some elements.

The most widely used approach, however, is to electroform the original to produce a nickel foil (shim) or plate

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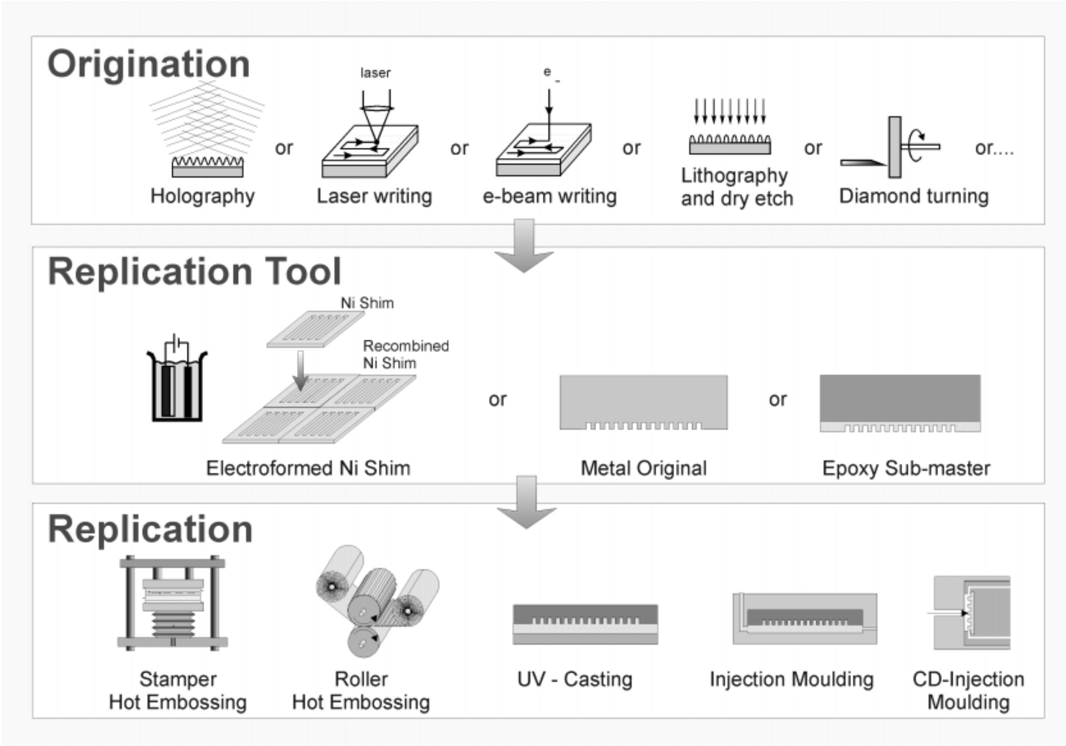


Figure 1. Overview of the manufacturing path for replicated DOEs. The original DOE microrelief is fabricated by one or a combination of high resolution lithographic processes. A replication tool is then generated, usually by electroforming. The major replication technologies in use today are hot embossing, injection molding and casting or UV embossing.

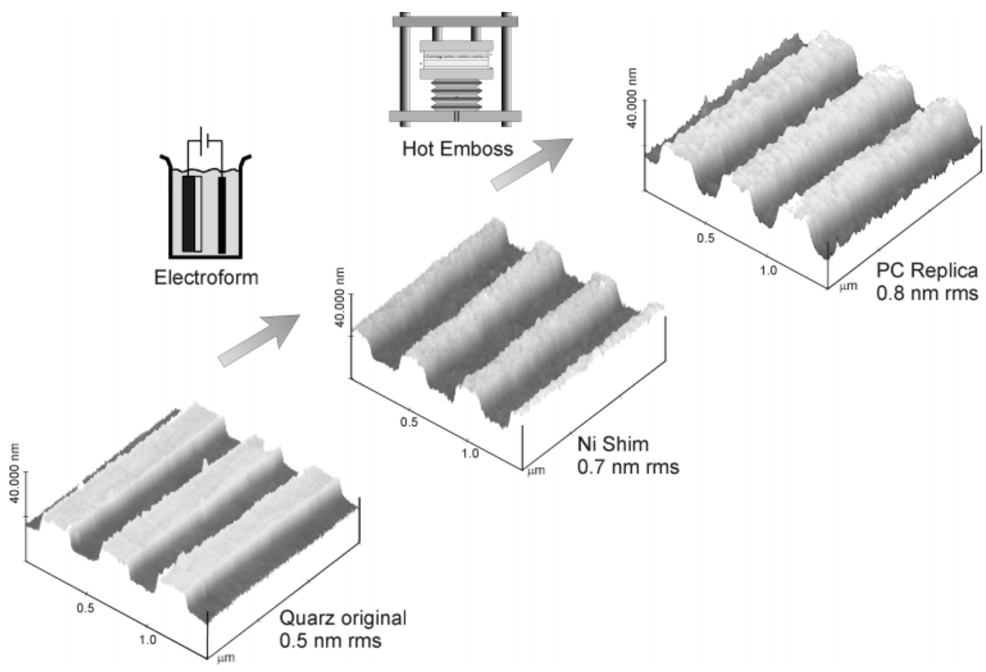


Figure 2. Surface roughness increase during steps in the replication process. AFM measurements on a shallow grating (400-nm period, 10-nm relief depth) fabricated in a quartz substrate, the electroformed Ni shim and a replica hot embossed into polycarbonate foil. The measured rms roughness values along the top of a grating line are shown for each step.

(stamper). This technique is routinely used for the production of holograms and diffractive foil,[1,10] as well as in the production of Compact Discs (CDs). A first Ni shim fabricated from an original recording, often in photoresist, can be recombined to form a larger shim with multiple copies of the element.[10] The optical planarity or form is generally lost in this process, so that it is mainly used for elements in which this is of no consequence. Typical flexible shims used for hot embossing have a thickness of about 100 μm, whereas the stampers used for injection molding elements, e.g., CD molding, are typically about 0.5 to 1 mm thick.

The resolution and fidelity of the electroforming process is typically on the nanometer scale. Lateral dimensions are held to better than about 0.5% and are reproducible for a given process, so that precompensation is possible if required for a given application. Measurements on surface roughness show an absolute increase of about 0.5-nm rms over the original for the master shim and less than 0.2-nm increase per subsequent shim generation, as well as for embossed replicas in polycarbonate. Figure 2 shows atomic force microscope (AFM) measurements of an electroformed and replicated (by hot embossing into polycarbonate foil) grating of about 400-nm period and 10-nm depth.

Replication. The major replication technologies are as follows.

Hot Embossing. Stamping, roller, or reciprocating systems are used for the hot embossing of surface relief microstructure into thermoplastic foil. Hot embossing technology is routinely used for reproducing diffractive optical microstructures such as holograms and submicron grating patterns for diffractive foil.[1] Commercial roll embossing systems achieve embossing speeds of up to 1 m/s in polymer foil of up to 2 m in width; typical polymers include poly(vinyl chloride) (PVC) and polycarbonate (PC), usually, but not necessarily, precoated with a thin metal film. Typical costs for hot embossed foil are below $0.001/cm^2. Although commercial roller systems are fully capable of submicron resolution, microstructure with relief amplitudes in excess of about 1 μm require customising the system and embossing conditions.

Injection Molding. Injection molding is standard replication technology for fabricating CDs with micron pit relief structures and is being investigated by various groups for applications in micro-optics. Customized injection molding equipment has been developed for fabricating poly(methyl methacrylate) (PMMA) and polycarbonate (PC) microstructures.[10] Injection molded replicas are of higher cost than those fabricated by hot embossing (typical CD fabrication costs are ~$0.01/cm^2), but the technology has the potential of producing higher quality, deeper microrelief structures in stable, thick (>1 mm) PMMA or PC substrates.

Casting and UV Embossing. Casting techniques have long been used for producing very high fidelity replicated spectroscopic gratings in epoxy materials. Of particular interest is the replication into a thin film of UV-curable material coated onto a rigid substrate such as glass. A related technology is the replication using a roller press into a UV-curable film on a plastic substrate film, with rapid curing at the contact stage or shortly afterwards (so-called UV embossing). Such techniques have the advantage of producing a replicated film that can be highly resistant to a subsequent solvent coating step. They are particularly suited to the replication of deep or high aspect ratio microstructures. Casting or UV embossing is also suitable for replicating a DOE microstructure onto a glass or polymer refractive lens to produce a hybrid lenslet.

A number of other replication techniques are also used commercially in the fabrication of certain plastic foil and sheet products. Solvent evaporation, in which a solution of the polymer is poured onto the replication shim and allowed to dry before separation, can produce very high quality replicas and is often used in the preparation of samples with subnanometer resolution for electron microscopy. The calendering process, in which molten polymer is squeezed between two rollers, one of which contains the surface relief structure, is used for the mass production of surface relief patterned plastic foil.

Further details, examples and recent results of these replication approaches are given in the following sections.

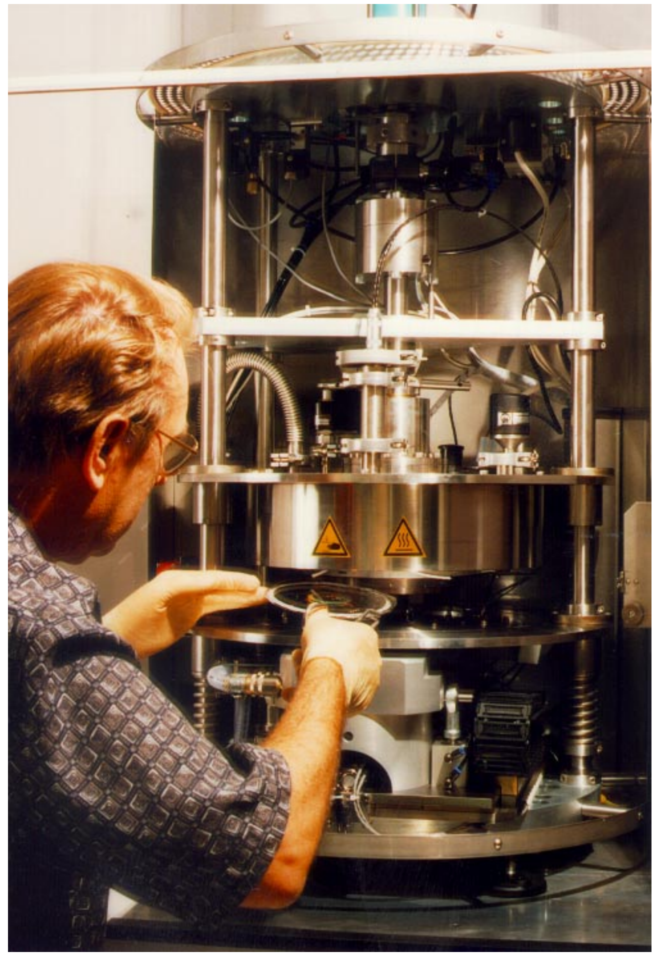
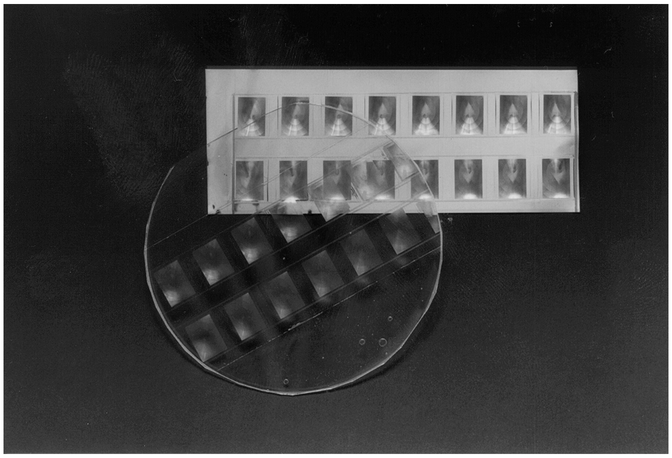


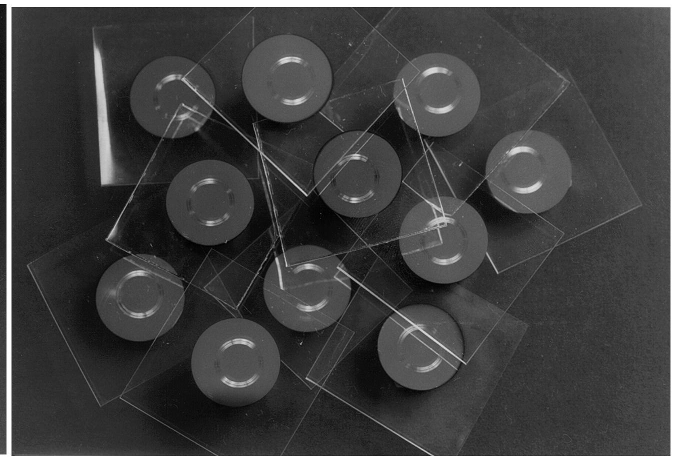
Figure 3. Hot stamping press at PSI for the replication of DOEs in polycarbonate foil.

Hot Embossing

Stamping, roller, and reciprocating hot embossing systems are routinely used for reproducing diffractive optical microstructures such as holograms and submicron grating patterns for diffractive foil.[10] Figure 3 shows a hot stamping press (constructed by Jenoptik, Jena, Germany), which is used at PSI Zurich for laboratory research and development and for small scale fabrication runs of up to about 100 pieces. The plastic sheet is sandwiched between the Ni shim and an optically smooth backing plate. After applying pressure, typically ~5 kN, the whole sandwich is cycled to above the softening temperature T_g, held for some minutes and cooled again before release of pressure and separation. DOEs such as continuous relief Fresnel microlenses and binary optical elements in arrays with a maximum area of 120 mm diam are routinely fabricated with this press. Submicron feature resolution can be replicated with aspect ratios in excess of 5:1. The cycle time depends on the depth and aspect ration of the DOE microstructure, and is typically 20 to 30 min. Polycarbonate (T_g ~ 150 °C) is used for most replication work since it combines very good optical quality and transmission in the visible and near IR with excellent mechanical properties. Figures 4(a) and 4(b) show examples of DOEs fabricated using this system. No significant degradation of the optical properties or stray light are measurable for the replicated elements, except for those properties dependent on the overall optical flatness of the element. The approach



(a)



(b)

Figure 4. (a) Replicated DOEs (Fresnel elements) in polycarbonate foil and Ni embossing shim; and (b) replicated DOEs—diffractive encoder elements with submicron grating microstructure for a rotary encoder microsystem (courtesy of Baumer Electric AG, Frauenfeld, Switzerland).

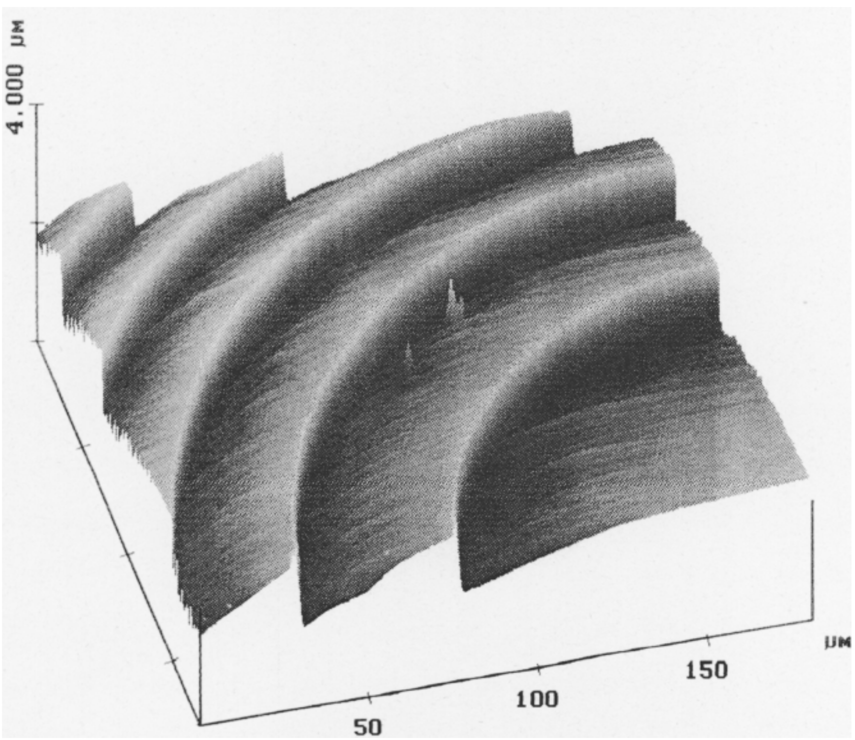


Figure 5. AFM image of a DOE microstructure (section of a continuous relief Fresnel lenslet) embossed in polycarbonate foil.

is thus most suited for applications such as nonimaging lenslets, e.g., illumination and light control micro-optics, and grating microstructure for nonimaging optical microsystems, e.g., encoder scales for metrology, see Fig. 4(b). An AFM characterization of the surface of a hot embossed DOE is shown in Fig. 5.

The hot embossing of very deep grating microstructure has been demonstrated within the LIGA technology development[11] of high aspect ratio microstructure for mechanical and optical microsystems. Figure 6 shows a schematic and enlargement of the grating microstructure in a replicated LIGA miniature spectrometer with a grating of about 2-µm periodicity, ~300-nm groove depth and about 100-µm groove height.[12] The hot embossing is carried out using a press similar to that shown in Fig. 3. Such replicated miniature spectrometers are now available as commercial products.

Considerably faster replication can be achieved by roller hot embossing systems. Figure 7 shows a schematic of the basic technique, in which replication speeds in excess of 1 m/s are achieved industrially for the production of diffractive foil with submicron, but relatively shallow (<< 1 µm), grating microstructure. Similar systems are used for the production of high quality holograms for security feature applications.[1] The continuous hot embossing of squarewave grating microstructure with period <400 nm has been developed by PSI Zurich and Hologram. Industries (Paris) for new security feature DOEs.[4] Customized hot embossing systems can be used for the replication of DOE microstructure such as Fresnel lenslets.

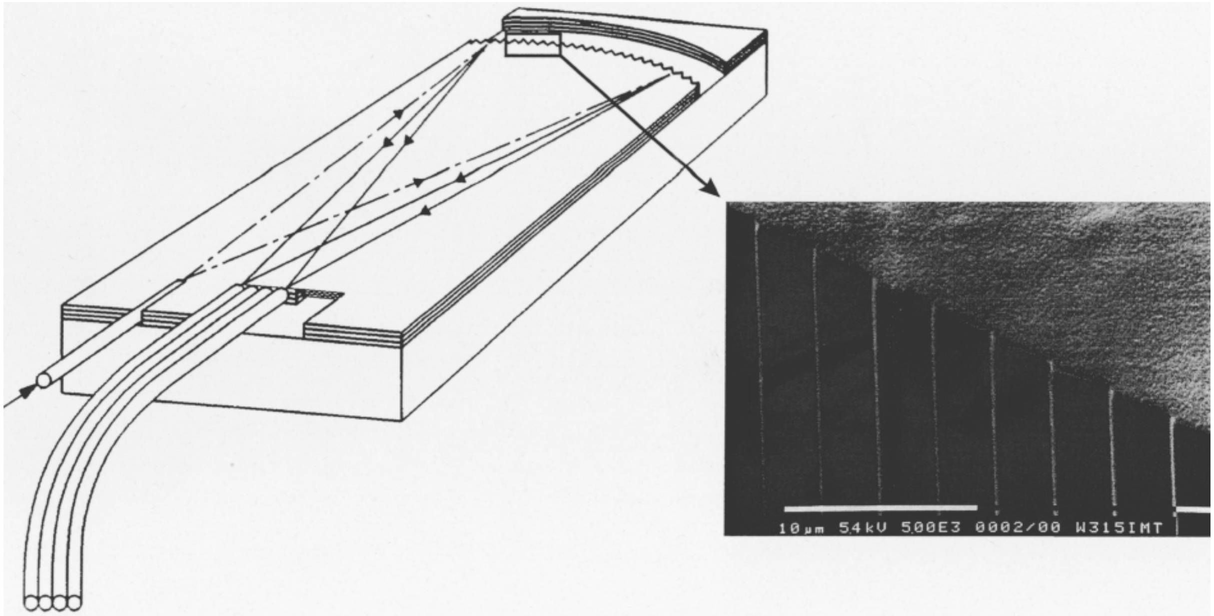


Figure 6. Miniature LIGA spectrometer produced by hot embossing: schematic and enlargement of submicron grating microstructure of about 100-µm groove height (courtesy of Forschungszentrum Karlsruhe, see Refs. 9 and 11).

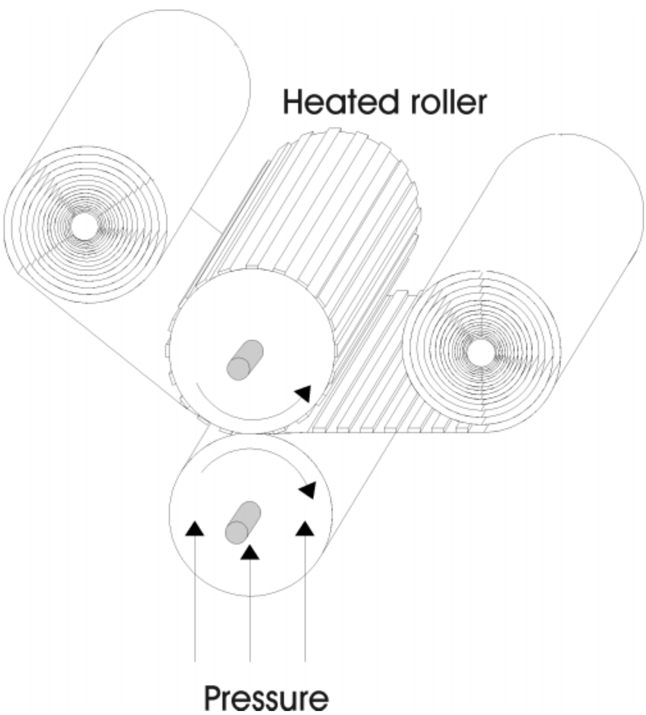


Figure 7. Roller hot embossing system for the high speed replication of diffractive microstructure.

Figure 8(a) shows a roller for the mounting of DOE shims in a hot embossing machine by 3D Ltd. (Unterägeri, Switzerland). Figure 8(b) shows a Ni shim and the replicated roll of DOEs fabricated in 60-µm-thick polycarbonate foil. Under conditions optimized for the hot embossing of such DOEs, with typical relief depths of 2 to 3 µm, a replication speed of about 1 cm/s was achieved.

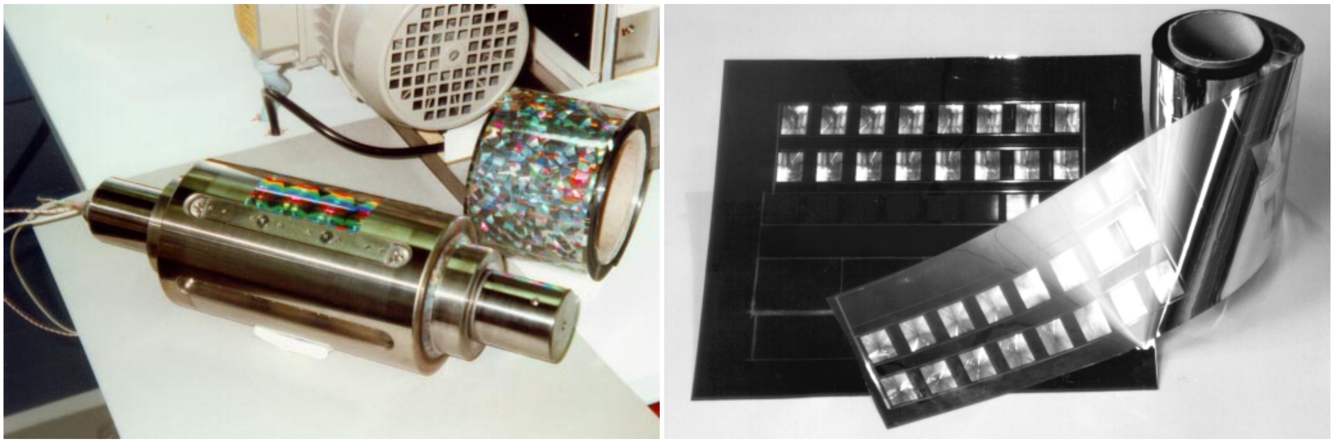
Injection Molding

Injection molding is widely used for the production of plastic components. The injection molding of CDs, and more recently Digital Video Discs (DVDs), with micrometer relief structure is also standard technology today. A pioneer in the injection molding of DOE microstructure was PLASMON Data Ltd. In the mid 1980s, it modified the CD injection molding process for optical data storage write once, read multiple (WORM) disks based on 250-nm period "moth-eye" microstructure.[13] Figure 9 shows a view of the molding equipment and an enlargement of the molded DOE microstructure.

DOE test microstructure has been replicated for PSI Zurich by a standard CD molding process. Figure 10 shows the stamper (Ni master) and polycarbonate replicas with various test DOEs. Typical cycle times for modern CD production are in the order of seconds. Injection moulded replicas are of higher cost than those fabricated by hot embossing (typical CDs cost about $0.5 to produce in quantity), but the technology has the potential of producing higher quality, deeper microrelief structures in stable, thick (>1 mm) PMMA or PC substrates. Tests have shown that the reproduction of high aspect ratio (>1:1) microstructure can present problems for the standard CD molding process and work is underway to address this problem. Injection molding using a customized press and molding tool can give better results, although the tooling cost is significantly higher and must be justified by higher volume runs (or by additional structure such as mounting or housing features that can significantly lower the cost of an assembled microsystem). Examples and results for injection molded DOEs have been described by Te Kolste et al.[14] and by Sweeney and Sommargren.[15] The industrial production technology for the injection molding of DOEs is currently being developed by a number of companies worldwide.

Casting

High quality replicas can be produced by casting using thermal or UV-curable epoxy materials. The replication is usually into a thin film of the epoxy on a solid substrate blank. The main disadvantage of thermally cured materials is the long curing time, typically many hours. Blough and Morris have described results of UV embossing for the



(a) (b)

Figure 8. (a) Custom roller for mounting DOE shims in a roller hot press system (courtesy of 3D Ltd., Unterägeri, Switzerland); and (b) Ni shim and replicated roll of DOEs fabricated in 60-μm-thick metalized polycarbonate foil.

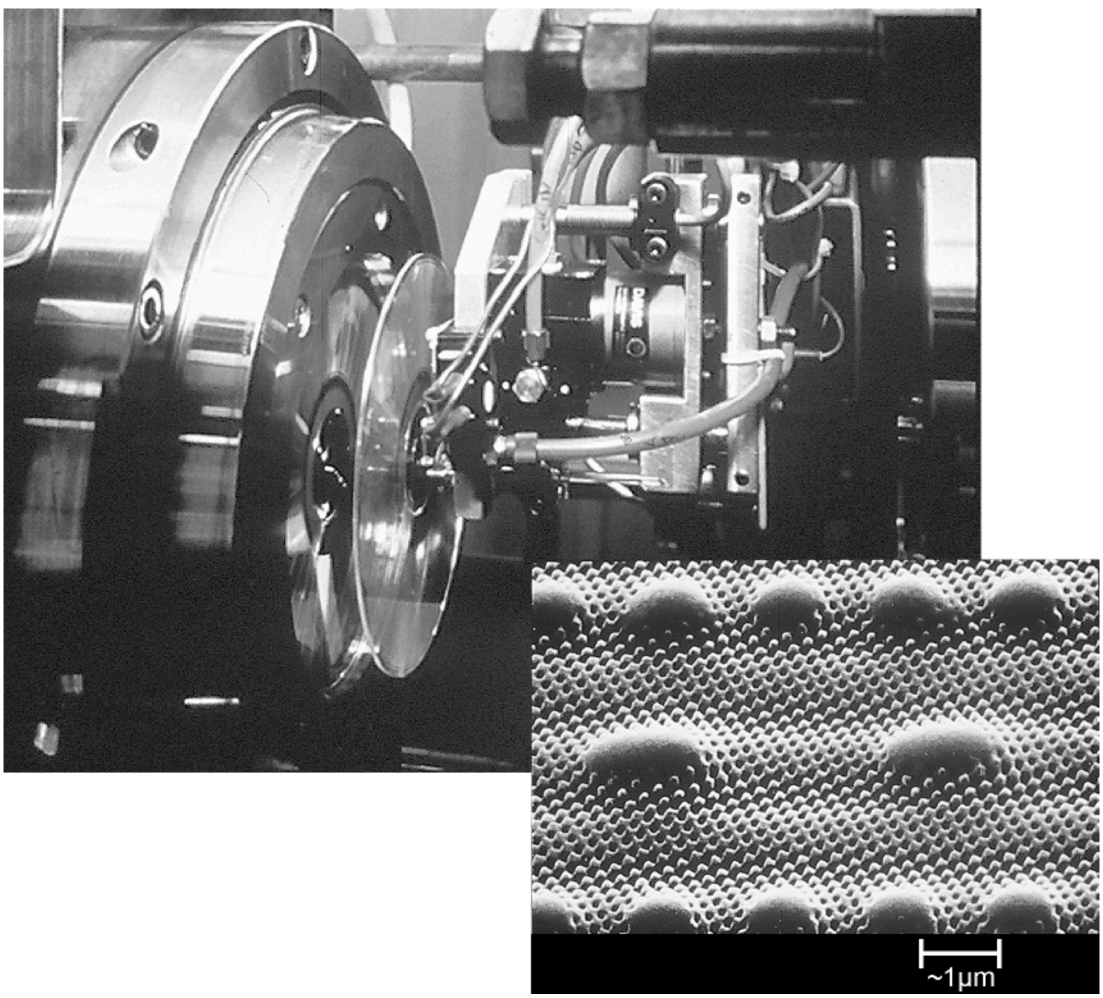


Figure 9. Injection molding of DOE “moth-eye” microstructure for an optical disk application (from Ref. 13, courtesy of Plasmon Data Ltd., Melbourn, England).

Figure 10. Ni stamper (master) and injection molded CDs with test DOE microstructures.

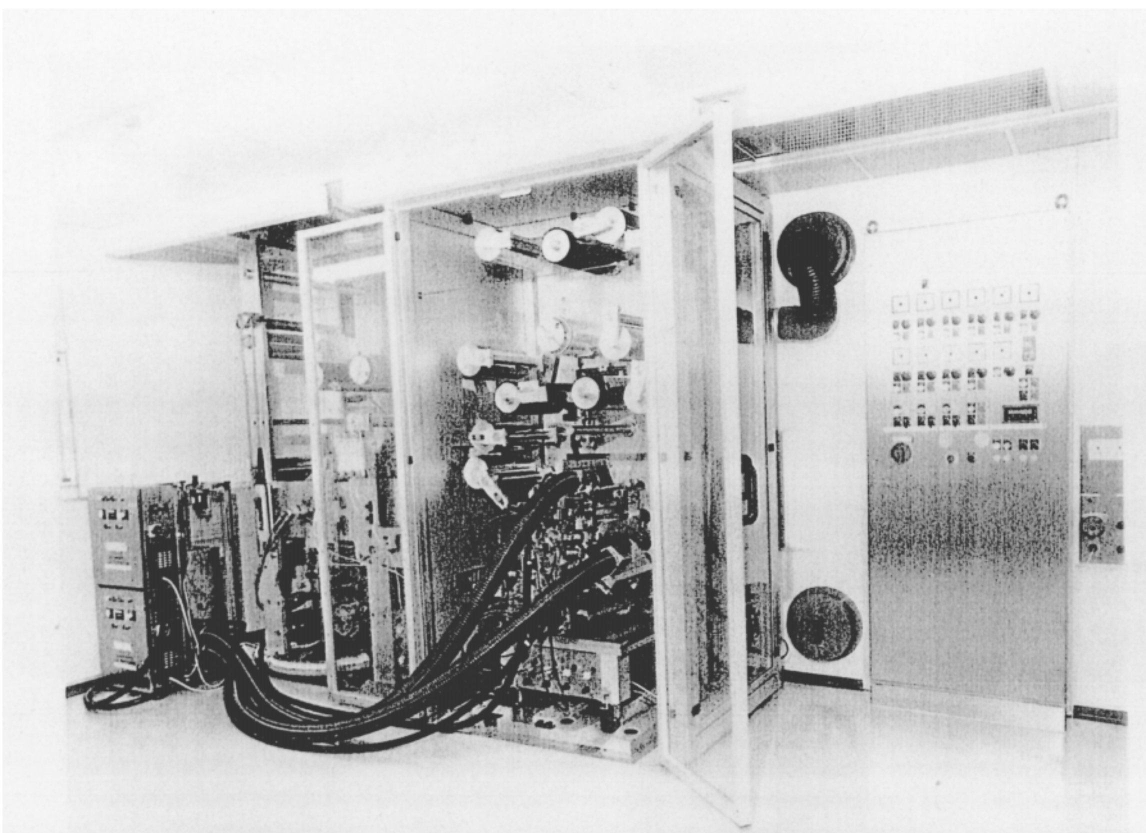


Figure 11. Commercial roller UV embossing system (from Ref. 10, courtesy of Epigem Ltd. Wilton, England).

fabrication of hybrid DOEs, in which a thin diffractive element is replicated onto a refractive glass singlet. A hybrid achromat was produced by replicating a diamond turned DOE relief onto a plano-convex BK7 glass singlet.[16] Diffraction efficiencies in excess of 97% were achieved for such replicated hybrid DOEs, which can offer significant advantages in weight, size, and design flexibility. Diffraction efficiency measurements and a summary of the technology of single point diamond turning and replication by thermal and UV-cured epoxy have been described by Blough et al.,[9] showing that the measured and predicted efficiencies for DOE lenses studied were typically within about 5%.

UV embossing, the replication into UV-curable material on a glass or polymer substrate, is very attractive for

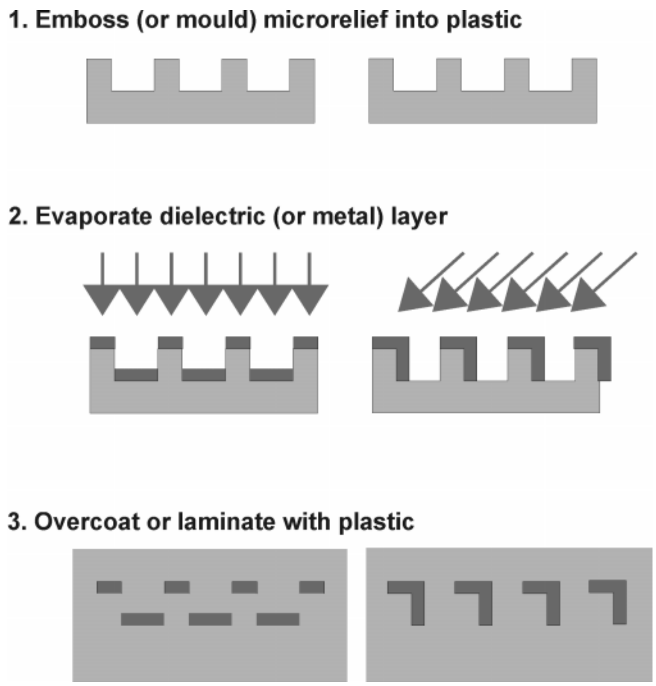


Figure 12. Fabrication of microstructured thin film DOEs by embossing and deposition processes.

the high speed replication of DOEs, in particular deep or high aspect ratio microstructures. Micro-optical elements, for example lenslet arrays for enhancing the fill factor in CCD imagers and for Shack-Hartmann wavefront sensors, are routinely fabricated at PSI using this technology.[3] DuPont has developed a dry photopolymer film for UV replication.[17] Epigem has developed UV embossing onto glass substrates for micro-optical elements such as lenslet arrays[18] and, for large volume mass production, the use of a roller press to replicate into a UV-curable film on a plastic substrate film, with rapid curing at the contact stage or shortly afterwards.[10] Figure 11 shows a commercial roller UV embossing system capable of replicating a wide range of DOE microstructures.

New Developments—Microstructured Thin Films

An interesting development with considerable potential for the mass production of certain DOE microstructure is the combination of surface relief replication and thin film deposition technology. The basic idea, illustrated in Fig. 12, is to use the replicated microrelief to influence and structure a thin film deposited by direction evaporation (or other deposition technique) onto the surface. Since both replication and evaporation technologies are low cost, mass production processes, the approach is highly suited to the production of grating-like DOE microstructure.

This approach has been pursued at PSI Zurich for a number of applications. Novel DOE security features based on an overcoated submicron grating microstructure have been developed and the roll-to-roll mass production demonstrated.[4] A unique visual and machine-readable optical characteristic is achieved using a buried, high index grating. Figure 13 shows a roll of replicated and overcoated DOE microstructure with feature linewidths below 200 nm, together with the embossing shim and a card with the laminated security feature strip. A similar coated submicron grating structure has been developed for application as a broadband antireflection layer for solar energy applications.[19]

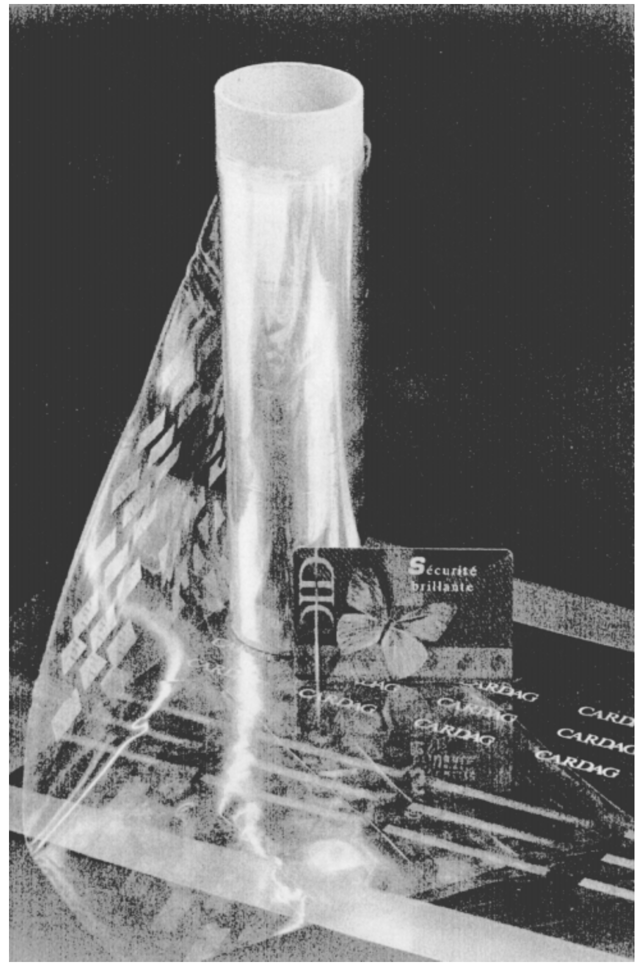


Figure 13. Roll of DOE buried grating DOE microstructure mass produced by industrial embossing and evaporation technology. Applications in advanced optical security features are being investigated.[4]

If the deposited dielectric film is of sufficient quality to be a low loss waveguide, then this approach opens the way to the mass production of low cost integrated optical elements and related DOEs such as grating couplers (Fig. 14). Grating coupler sensors fabricated in this way at PSI have been shown to have excellent sensitivity and the simultaneous fabrication of the grating coupler DOEs and channel waveguides on the same substrate is of considerable interest for realizing low cost integrated optics.[20,21]

Conclusions

Replication technology for DOEs is well established for certain types of holograms and diffractive foil, as well as diffractive lenslets and lenslet arrays. Industrial replication technology such as hot embossing is currently best suited to high resolution, shallow microstructures with lateral feature sizes down to about 300 nm and relief depths up to about 1 μm, provided that the aspect ratio is not greater than about 1:1. Deeper, higher aspect ratio DOE microstructure can be replicated by a casting and UV embossing technique. The choice of technology for a given DOE has to be carefully studied. Factors such as optical flatness, microstructure dimensions and aspect ration, cost and volume must all be considered to find the best approach.

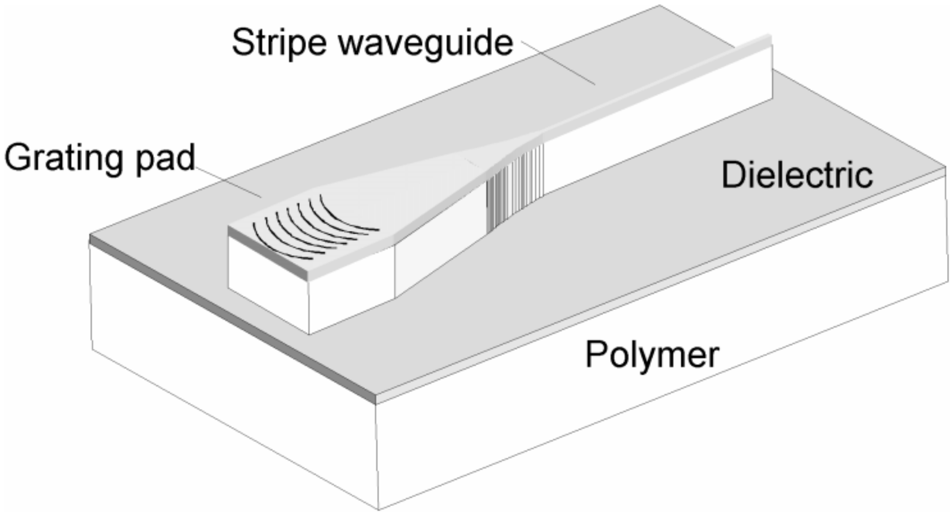


Figure 14. A DOE grating coupler and channel waveguide can be fabricated by replicating a surface microrelief and evaporating a thin waveguide dielectric coating onto the surface. The technology is being investigated for applications in low cost optical sensors.[21]

TABLE I. Summary of Replication Technologies

Technology	Typical micro-optical elements	Strengths	Weaknesses	References [10] and
Hot embossing: flat bed	DOEs in general, Fresnel elements, integrated optical microstructures	Good replication for high resolution and deep microstructures	Slow (typical cycle times of minutes)	[22]
Hot embossing: reciprocating press	DOEs, Fresnel elements	Faster than flat bed (typical cycle times of seconds)	Resolution & aspect ratio generally inferior to flat bed embossing	[1]
Hot embossing: rotary press	Holograms	Established technology, high speed, continuous, roll-to-roll.	Limited depth (max. ~ 1 μm at present) and aspect ratio	[1]
Hot embossing: LIGA press	High aspect ratio microstructures	Demonstrated technology for LIGA microstructures such as microspectrometer	Slow (typical cycle times ~ tens of minutes)	[23,24]
Injection molding: CD type	CDs, shallow DOEs and grating microstructure	Established technology, with automated production lines, High speed (cycle time ~ 5 s)	Limited aspect ration and depth (~ 1 μm)	[13]
Injection molding	Micro-optical lenses LIGA microstructures, DOEs, integrated optical microstructures	High aspect ratios. Simultaneous molding of alignments and housing features	High cost of mold (typically 50 to 100 k$)	[25]
Casting	Spectroscopic gratings	High resolution and aspect ratios possible, good dimensional stability	Slow (typical curing times ~ hours), expensive	[26]
UV embossing	DOEs, Fresnel microlenses, integrated optical microstructures	High resolution and aspect ratios, high speed potential	Cost (more expensive than hot embossing)	[17,18,25]

The electroforming of microstructure to produce the mold or tool for a replication process is also well established. For most applications, resolution is more than adequate and presents no significant problems. The maintenance of the large area optical form, however, is nontrivial and in general not yet satisfactorily achieved. Significant deviations (many wavelengths) from the desired flatness or optical form is already present in the electroformed shim or tool after separation from the original and is then transferred to the replica. For many applications (such as display holograms), this is of no consequence. In other applications (such as high resolution, imaging DOEs) however, the resulting aberrations in the optical wavefront are unacceptable. Such DOEs must currently be replicated directly from an original in metal or quartz, or from epoxy copies of the original, avoiding the electroforming step completely.

Table I (adapted from Ref. 10) gives an overview of the main replication processes and a summary of their features. The potential of replication technology for high resolution and low cost production is enormous, and it will play an increasingly significant role in the future production technology for DOEs.

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