Micro-optical modules fabricated by high-precision replication processes

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Abstract: Double-sided optical modules are fabricated by precision replication in glass-like, UV curable polymers. A wafer scale production process has been developed, which allows the fabrication of hundreds of thousands of optical components that pass strict environmental testing. Due to their competitive prices they are of great interest for datacom applications.

1. Introduction

Micro-optical components are already widely used as building blocks in many commercial applications. Most components include one- and two-dimensional diffraction gratings, subwavelength gratings, micro lenses, and micro prisms.

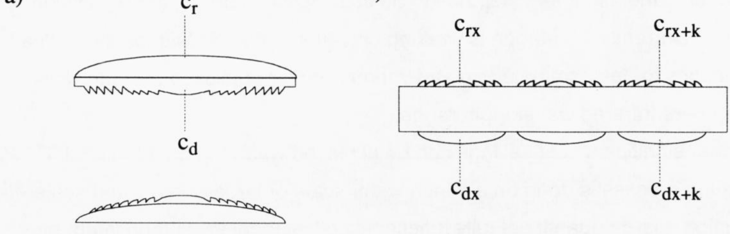


Fig. 1: Double-sided replicated optical modules: a) refractive/diffractive hybrid element with optically active surfaces either on opposite side or on top of each other; b) array of refractive/diffractive element combination.

These alone enable a large category of novel optical functions such as splitting a laser beam into almost arbitrary patterns of spots or transforming a Gaussian beam into top-hat profile, as well as replacing conventional optical systems with compact and lightweight planar solutions.

For many high-volume applications the most cost-effective fabrication technology is the replication of the optical function in polymer materials with techniques such as UV embossing, hot embossing, and injection molding. Because of the simple processing conditions, these techniques significantly reduce the cost in volume production in comparison to silicon-based etched components. Furthermore, functions like antireflection (AR) can be included with the generic replication technique via AR subwavelength gratings.

The introduction of double-sided components opens up a multitude of new applications since different optical functions can be realized by replicating on both sides of a supporting substrate. For example, beam splitter gratings on the front side can be combined with focusing micro lenses on the back surface (cf. Fig. 1b). In another example, the front surface can be a diffractive lens and the back surface a refractive lens. Such hybrid solutions can be designed to behave athermalized or achromatic, both useful properties in e.g. imaging in outdoor conditions (cf. Fig. 1a). Because one element in doubled-sided micro-optics replaces two elements, the need to carefully fix and align the two adjacent elements is eliminated. Naturally however, for double-sided components the alignment step has to be accomplished during the replication process. Currently, Heptagon is working on various projects with double-sided micro-optics for telecom/datacom and various sensor applications in the visible and the near infrared wavelength range.

Further significant cost savings can be achieved when the double-sided replication process is done on a 4 inch wafer scale or larger. In a wafer scale production a large quantity of fully functional optical modules is fabricated, by performing the replication process and all subsequent process steps like metallization or other coatings on the full wafer prior to dicing into the single optical components. Heptagon has developed proprietary processes that allow the production of double-sided optical components on a 4 inch wafer scale. With such a high volume production hundreds of thousands to million pieces can be produced, which makes the output of this process comparable or better than what is typically achieved with injection molding. When produced in millions the unit price of an optical component can be as small as a fraction of a dollar.

2. Fabrication by UV replication

All of the commercially available replication technologies such as injection molding, hot embossing, UV-embossing, have in common that the precision of the *microscopic* structures can be guaranteed even for high volume and low cost mass production. There are, however, certain limits which primarily consist of the aspect ratio of high resolution and sub-micron features. The list below shows some of the typical specifications for replicated micro-optical modules:

1. high profile fidelity for optical microstructures
2. flexibility in the substrate thickness for double sided replicas: 0.5 to 2.0 mm
3. 4 inch or larger replication area
4. accuracy of alignment (optical axes of front / back side): better than +/- 2 μm over replicated area (i.e. all pairs c_{dk} and c_{rk} for any k over the replicated area)
5. planarity of replication layers: better than +/- 5 μm (includes only deviations with low geometrical frequency like tilt and other bow)

For the type of structures discussed here the specifications 1. – 3. are fulfilled by all the standard replication techniques mentioned above. However, the differences in the replication methods manifest themselves in macroscopic characteristics such as planarity, dimensional accuracy, mechanical features and naturally the final element price. The specific demands for double-sided elements (as given in points 4. and 5.) are currently achieved by the UV-embossing technology as being used by Heptagon.

During the replication by UV-embossing the microstructures are transferred into a thin film of UV-curable epoxy resin (cf. Fig. 2) on top of a substrate. The substrate typically consists of a standard glass wafer as well as high-precision machined refractive optical elements such as prisms and lenses. The thickness and uniformity of the replicated epoxy film can be controlled to form an overall surface planarity of fractions of a micron over areas of some millimeters, thus being comparable to the quality of etched components in fused silica. Heptagon has developed a semi-automated UV-replication process that allows mass production of aligned, double-sided components on a wafer scale.

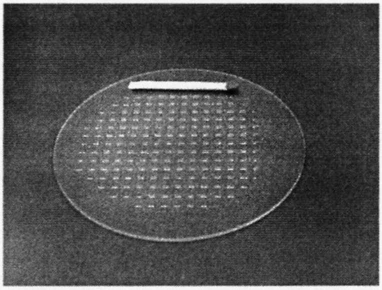
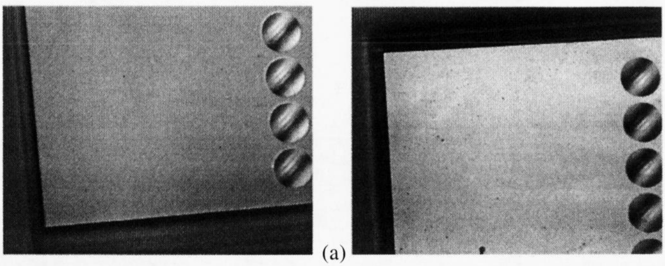


Fig. 2: Double-sided micro optical components on a 4 inch glass wafer.

During the UV embossing process double-sided micro-optical components are obtained either by a simultaneous replication process on both sides of the substrate or by processing the two sides subsequently. In both schemes the alignment of front- and backside structures is achieved with alignment marks. It is mandatory that they can be detected and analyzed with sub-micron resolution even through substrates with a thickness for several mm's. In order to achieve a high yield in the fabrication of high volumes of micro-optical modules, this fabrication process needs to meet very high standards of accuracy and reproducibility. This requires extremely stable and rigid mechanical holders for replication tools and substrates. Since the two replication tools itself still can shift during the replication process (most likely during the mold separation), an on-line control of the alignment and a high-accuracy off-line measurement of the alignment accuracy have been established.

3. Materials and Processing

The materials used in this work are those currently employed by Heptagon in commercial products, as well as new materials under investigation. For any application in the telecom/datacom area, the elements have to meet strict environmental specifications. These specifications typically include testing at 85 % relative humidity at 85°C for 1000 hours and 1000 thermal shock test from -40°C to +100°C, with no change in adhesion of the epoxy layer and in the optical performance. Most of the commercially available UV-curable polymer materials do not withstand such conditions completely. Especially the presence of an anti-reflection coating leads to failures in some of the environmental tests. This material combination has shown to be vulnerable to high humidity, thermal shocks, and to mechanical stress as occurring during the final dicing procedure along the dicing edge. However, Heptagon identified materials and developed processes that allow a wafer scale fabrication of double-sided components that meet and even surpass the environmental specifications mentioned above (Fig. 3).



(a) (b)

Fig. 3: Micro lens array with AR coating after 1000 hrs at 85°C, 85 % R.H. (a) and after 1000 thermal shocks -40°C to 100°C (b)

4. Conclusions

A high-quality, high volume replication method for micro-optical modules in glass-like materials has been developed based on a UV embossing process. The double-sided components fabricated with this process pass typical environmental testing for telecom and datacom applications and meet Telcordia specifications. Heptagon's process has the following competitive advantages over other fabrication methods:

(i) Double sided diffractive optical elements fabricated by a wafer-scale replication process combine the high alignment and positioning accuracy of photolithographic processes with the low fabrication costs of injection molding.

(ii) Most of the current products are based on refractive micro-optical elements in fused silica, the fixed index of refraction and thermal expansion coefficient is a major obstacle in the overall system design. In the replication process the substrate material can be chosen to be compatible with other materials and processes in the whole opto-electronic system.

(iii) The double-sided optical elements meet the standards required to pass demanding environmental tests.