Polymer Micro-Optics via Injection Moulding

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A wide range of polymer micro optics are now used in technically functional applications. Injection moulded micro-lenses are used for miniature cameras in mobile phones, computer accessories, cars, and medical devices. CD/DVD pickup units, sensors, and fibre-optics utilise polymer micro lenses and diffraction gratings. Lightguides with moulded microdot structures or gratings are used for display back-lighting & front-lighting, and microstructured films for brightness enhancement and anti-glare applications are used in displays.

Introduction

Polymer micro-optics can be differentiated into refractive and diffractive optics.

In refractive optical design, light is considered to travel as particles along a straight line. This applies when the optical element is much larger than the wavelength of the light (wavelength of visible light is from 380 nm to 780 nm). An example of a refractive optical part would be a moulded aspheric camera lens.

Diffractive optics design considers that light travels as a wave in all directions. This applies when the optical element is comparable to the wavelength. An example of a diffractive optical part would be a diffraction grating or an anti-reflection component requiring sub-micron surface structuring. In diffraction gratings the period of the grating can be relatively large (tens of microns) but the height of the gratings is in the order of nano-meters. (See Figures 1 and 2)

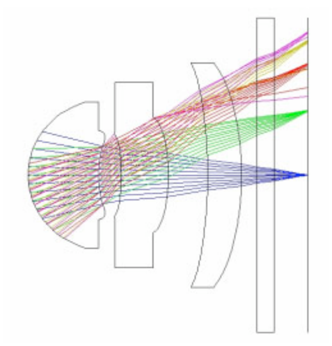

Fig 1: Sequential ray tracing through refractive optical lenses in a miniature camera design.

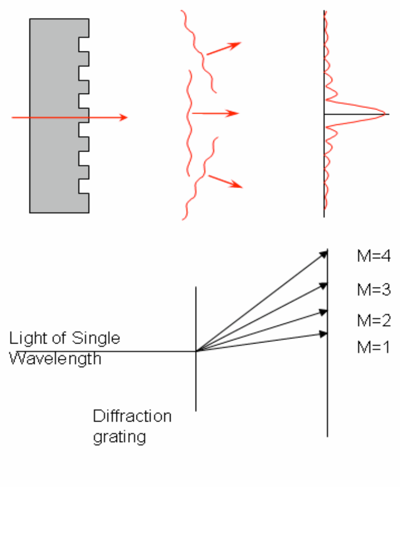

Fig 2: The principle of a diffraction grating. Light waves constructively and destructively interfere as they pass through the grating, forming a diffraction pattern. A single wavelength is split into diffractive orders of different amplitude, and a mixture of wavelengths (eg. white light) is split into different colours.

Polymer Optics versus Glass Optics

Polymer optics have several advantages over glass optics. However, they also have limitations. Understanding and recognising this is critical for an optical designer and part of the role of a good optical moulder is to educate designers in the best ways of using optical polymer materials.

Key advantages of polymer optics over glass include:

- **Low cost high volume production** — one mould makes many parts with no surface finishing required after moulding.
- **Design freedom** — aspheric lens surfaces are easily moulded, and mechanical features such as flanges and spacers can be integrated.
- **Consistent quality** — provided that the process is well controlled, the mould replicates the same shape each time.
- **Low weight** — the density of polymers is much lower than that of glass.

Balanced against these positive factors is the fact that polymers have a Coefficient of Thermal Expansion (CTE) in the order of 10 times higher than that of glasses, they have lower scratch resistance and are less environmentally stable, and they have limitations in terms of refractive index. Typical refractive index for polymers is in the order of 1.49 -1.59, whereas glass can have refractive indices up to 1.9. Stability of refractive index and other optical properties is less than with glasses, and because of the nature of moulded polymers, the refractive index can vary within the part causing birefringence.

An understanding of general polymer properties is also important. Polymers exhibit creep and stress relaxation, and their behaviour after moulding is dependent on their thermal and stress history. Changes in processing or in the environment can cause changes in the polymer which in turn alter the optics.

Table 1 shows properties that are important to the optical designer for some thermoplastic polymers used in optical moulding.

Property	**Polycarbonate**	**Acrylic**	**Polystyrene**	**Cyclo-olefinic copolymer (COC)**	**Cyclo-olefinic polymer (COP)**
Refractive Index					
486nm	1.593	1.497	1.604	1.54	1.537
589nm	1.586	1.491	1.590	1.53	1.53
651nm	1.576	1.489	1.584	1.526	1.527
Abbe no.	34.0	57.2	30.8	58.0	55.8
Transmission % (Visible spectrum, 3.174mm thickness).	85-91	92	87-92	92	92
CTE x10^{-5}/deg C @70 deg C	6.6-7	6.74	6.0-8.0	6.0-7.0	6.0-7.0
dN/dT x10^{-5}/deg C	-11.8 to -14.3	-8.5	-12.0	-10.1	-8.0
Max continuous service temperature (deg C)	124	92	82	130	160
Water absorption % (in water 73F for 24 hrs)	0.15	0.3	0.2	<0.01	<0.01

Table 1: Properties of commonly used optical thermoplastics. Materials such as COC and COP are available in a wide range of grades with different refractive indices and birefringence levels.

Manufacture of Optical Inserts for Micro Moulds and Micro-Embossing Dies

Processes used for the manufacture of micro-optics in polymers include hot embossing, UV embossing, and injection moulding. All of these processes require some kind of form tool — either a mould or embossing die — to form the shape of the optical part.

Micro-structured inserts for moulds or embossing tools can be produced by a variety of methods. One way to create optical inserts for moulding or embossing is via single-point diamond cutting. This can be used to cut aspheric form accuracies on metals of <100nm and achieve surface roughness of 1nm Ra. The traditional single point diamond turning (SPDT) technology has now evolved into micro-milling using diamond tools. Freeform diamond machining centres can be used to cut complex optical surfaces with sub-micron accuracy.

Many of the methods used for finer micro-optical details require the manufacture of a nickel electroformed surface which accurately copies the inverse of a master pattern. The nickel form is used as the surface of the embossing tool or mould tool. The master pattern itself can be produced by an ultra-precision process such as a lithographic method, laser patterning, electron beam machining, or focussed ion-beam. The surface structure shown in figure 3 was produced by electron beam machining and nickel replication.

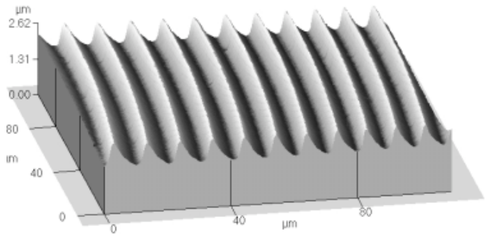

Fig 3: Section of optical insert micro-structure showing features <1µm in height.

Forming the Plastic Micro-Optical Surface

In hot embossing, the thermoplastic polymer substrate is heated to beyond its glass transition temperature and the form tool is pressed into it to form the required shape. In UV embossing, a UV-curable polymer is coated onto a glass or plastic substrate. The polymer is embossed, and cured using UV light prior to releasing from the embossing tool. Proprietary processes based on these embossing methods are used by various companies. Very fine optical structures can be produced including micro-lens arrays and diffraction gratings.

Injection moulding is probably the longest established and most familiar of the above processes, and is widely used for mass-production of lenses and lightguides for many applications. Lenses for mobile-phone camera modules are mass produced in eight cavity moulds of traditional design on high precision electric injection moulding machines. Larger optics with sub-5 micron form accuracy are now moulded in 32 cavity moulds with fully closed loop control. However, for high accuracy in micro-optics below 1g shot weight, the best results are achieved using a dedicated micro-moulding machine where the feed system to the cavities is as short as possible, and the precise amount of polymer required is injected into the cavity in each shot.

Using recently developed micro-EDM and micro-machining technology, micro-injection moulds can be run reliably in production that include 0.2mm diameter through-holes as long as 1.5mm (eg for optical fibre location) and injection gates less than 0.06mm diameter. Gates of this size facilitate automatic demoulding of micro-components with minimum gate vestige.

The micro fresnel lens shown in figure 4 was injection moulded in acrylic material in a 4-cavity mould. It is shown tinted with yellow for visualisation. The picture shows four lenses and the runner/gating system. Next to the lenses is one of the optical mould inserts. The cycle time for this mould is less than 6 seconds.

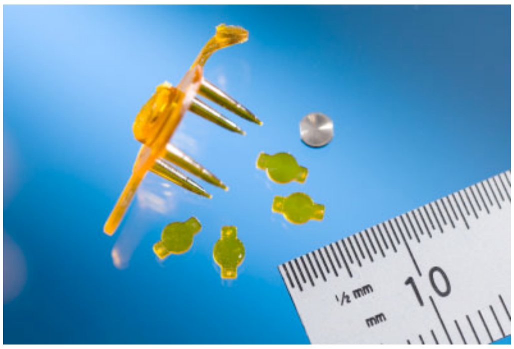

Fig 4: Micro lenses and feed system pictured next to mm scale. The silver-coloured part is a nickel mould insert with the surface structure partly shown in Fig 3.

Application Examples

Interconnects for optical networks.

Connectors with integral moulded lenses are used to connect optical networking devices such as trancievers and optical fibres. A collimating lens can be used to collect and reshape the beam emerging from a laser diode in order to improve coupling efficiency into an optical fibre.

An example of this type of component, injection moulded in polyetherimide, is shown in figure 5. This includes an internal lens, approximately 1.5mm diameter, moulded from a diamond-cut mould insert. Although collimating optics do not have to be as accurate as imaging optics, these parts are challenging to mould because of the tooling accuracy and moulding control needed to control the fibre alignment and barrel diameter tolerances.

Figure 6 shows another type of connector, used to locate 0.2mm diameter plastic optical fibres. This is moulded in liquid crystal polymer, and includes 0.2mm diameter cored holes throughout the full 1.5mm thickness.

Fig 5: Tranceiver barrels with integrated collimating lens (polyetherimide).

Fig 6: Optical micro-connector (moulded in liquid crystal polymer).

Lightguides for displays.

Liquid crystal displays (LCDs) need to be illuminated in a dark environment as they do not emit any light of their own. This is achieved by coupling the light from LEDs into a plastic lightguide which carries the light across the display and uniformly scatters it to create the illumination. To scatter the light uniformly, a graduated density of micro-features is needed on the surface. These features can be dots, or gratings, typically with a depth of 5-20µm. The microfeatures are often created in nickel inserts, or etched into steel by a lithographic technique. *(See Figure 7)*

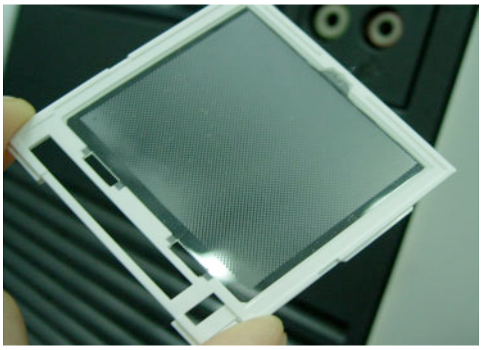

Fig 7: Moulded polycarbonate lightguide for backlighting an LED display. The mirco-dot pattern can be seen on the surface. The dots are in the order of 20-150µm diameter. Dot quality, size, and pattern design are critical to the performance.

Miniature imaging lenses and LED optics.

Camera modules used in applications such as mobile phones typically include up to three plastic moulded lenses assembled together. In addition to customising the lens geometry, the optical designer now has access to special grades of material developed for this type of application. These have different refractive indices and birefringence levels. The designer needs to design the optics to cut out optical aberrations and create the best focus, and these new materials give more scope to vary the design.

Lenses for miniature imaging applications are typically highly aspheric and have to be very accurate in terms of form error. The mould inserts may need to be cut and recut several times in order to compensate for the material shrinkage during moulding and achieve moulded lens form errors in the order of 1 micron. *(See Figure 8)*

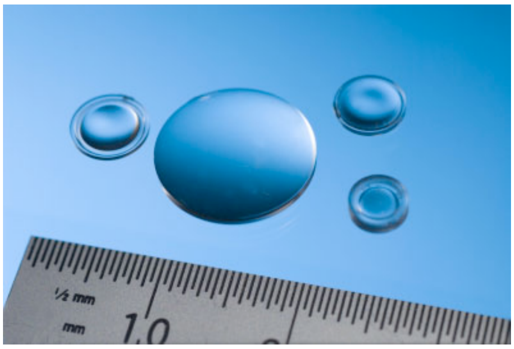

Fig 8: Moulded imaging lenses. The small lenses are for mobile-phone camera modules and require maximum form errors in the order of 1 micron.

With the increasing use of solid state lighting (light emitting diodes / LEDs) there is an accompanying need for optics to manage and distribute the light output. Because of the need to minimise the height of many optical parts, LED optics are now sometimes created by using types of fresnel lens (a lens made up of concentric rings) with very steep angled fresnel structures. For example, moulded fresnel lenses are now frequently used in LED flash optics for mobile 'phones. The evenness of the light output is important for picture quality, and any radius on the angular fresnel gratings will reduce the quality of the flash. For this reason, the target for the maximum radius of the peaks and valleys between the rings is typically about 10 microns. *(See Figure 9)*

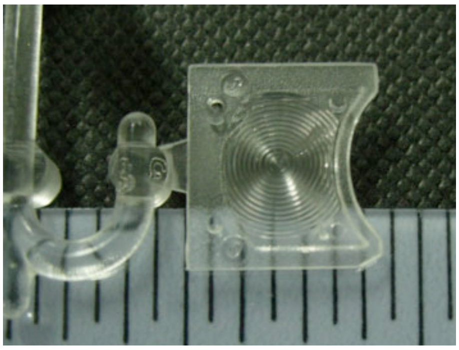

Fig 9: Moulded fresnel-style lens for an LED flash application.

Conclusion

The use of polymers in micro-optics is expanding and is expected to continue to grow as opto-electronics become more and more widely applied in everyday life. Injection moulding is a long-established technology, which through developments and innovations in process know-how has continued to lead the way in producing these types of advanced components. Glasses and other specialised materials will always be needed in certain applications, but the correct injection moulding process combined with accurate high quality tooling remains the most viable way forward for producing many micro polymer-optics.

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