Handbook of Plastic Optics

Edited by
Stefan Bäumer

2nd, revised and enlarged edition

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Handbook of Plastic Optics

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Various lenses used in optical pickup units by Penta HT Optics, Eindhoven

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1
Introduction

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Optics has been identified as one of the key technologies for the 21st century. Already now in our daily lives we come across optical technologies in several areas:

- at the supermarket most of the tills work in conjunction with bar code scanning;
- ink jet printers perform automatic calibration and media detection;
- most new mobile phones have an integrated camera;
- music and movies are available on CD and/or DVD players;
- computers store data on optical disks;
- blood sugar measurements are based upon optical technology; and
- LED illumination exists in several applications.

Looking at the examples above, it can be concluded that optical technologies are part of various market segments: consumer electronics, lighting, medical, automotive, sensors in general, security, and biometrics.

In order for these markets to further develop and emerge not only do smart inventions have to be made but also suitable manufacturing technologies have to be developed. For optical technology to really reach out and find applications in the mass market it is essential that optical components and systems can be manufactured in high volumes and at low prices. Many of the other components for high-volume applications as described above are based on silicon technology. Light sources such as LEDs and laser diodes can be manufactured using already developed silicon processing and manufacturing technology. The same holds for detectors such as photodiodes and CCD or CMOS cameras. These wafer-based technologies can cope with (very) high volumes and are of low cost. For integration of optical systems together with silicon devices in high-volume consumer optics, injection molding is the manufacturing method of choice. Once a design is cut into a tool and the proper processing for the application is developed, hundreds of thousand of virtually identical products can be made from that master. Injection molding of optics is known for showing very little part-to-part variation once the proper process is defined. Also, using multi-cavity molding, low prices per piece and a fast production cycle can be achieved. Using 8-cavity – and

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sometimes even 16-cavity – molding, production volumes of well above a hundred thousand parts per week can be achieved. These are the kinds of volumes needed to keep up with silicon manufacturing technologies, enabling the high-volume applications. For these lager volumes injection molded optics are highly cost effective. Compared to classic optics production with limited capital investment in machines and tooling, many parts can be produced. Furthermore the injection molding process can be automated and run with few operators.

As well as being cost effective in high-volume applications the other big advantage of injection molded optics is the possibility to also include mechanical features in the optics parts. This allows for cheaper, faster assembly. If reference marks are included in the optomechanical design, and the design is such that critical surfaces are referenced to each other through precision tooling, assembly can be done in a plug and play fashion. Parts can be stacked together without extra alignment of the components. There is even a possibility for (semi-) automated assembly. This is again a necessity for high-volume/low-cost production. Chapter 2 discusses various examples of integrated optomechanical design. By making use of combined optomechanical design, where in some cases the number of parts in a system can also be reduced. In particular, mounting rings and spacers can be eliminated quite easily. Although in some cases the price of the individual components might increase slightly by this integration, on the scale of the whole system costs can be reduced.

Injection molded optics is predestined for integration of functions – another advantage of optics produced by this process. Complex shapes can be realized using advanced tooling and molding. Mechanical functions can be combined with optical ones, and also electrical and chemical functions can be added. The last mentioned one is especially important for the emerging field of biosensing and biotechnology.

The overall drive for integration of functions is usually miniaturization. In classic manufacturing technology it can be fairly difficult to produce parts that are less than certain dimensions. Handling between polishing steps and working on front and back surfaces can become a problem. Molding these small parts can be of significant advantage, since fewer handling steps are involved.

Another advantage as regards injection molded optics is that packing of molded components can be made very effective. It is no problem to place molded optical components into a tape and reel package. The optical components can than be combined with silicon parts using standard pick and place machines, as they are common in the printed circuit board industry. Figure 1.1 shows a typical CMOS camera module in an exploded view and then packed in a tape.

Along with these many advantages, the challenges for plastic optical components lie mainly in the area of environmental resistance and durability. Plastic optical components have a limited temperature range in which they can operate. Water absorption, thermal expansion, and change of refractive index with temperature are other problems one encounters while working with injection molded optical components. Chapters 5 and 6 describe these problems in detail and also

Figure 1.1 left: exploded view of a COMS camera module, right: tape of CMOS camera modules[3]

ways to circumvent some of them. However, in most cases the benefits of using injection molded optics by far out weight the disadvantages.

Many advances in injection molded optics have been made, which started to really penetrate into the market with the advent of CD players. Besides defining ever more applications, research and development has been taking place in the following areas:

- molding machine development;
- tooling for optical inserts and molds;
- materials;
- coatings; and
- processes.

Taking all these developments into account it should become clear to the reader that injection molding of optical components is state-of-the-art manufacturing technology for high-volume optics. Precision and quality of molded optical components is at a level comparable to glass optics and certainly way beyond the level of toy-like applications.

This book attempts to give a coherent overview of the current status of injection molded optics. Since injection molded optics is a subject with many facets, it was decided to ask several experts in their fields to contribute to this book. This way the specific disciplines are covered in sufficient depth. Also, since injection molding is a manufacturing technology, all of the contributors either work in or have very close links to the industry. Therefore this book reflects practical molding experience rather than theoretical reflections. After going through the book, the reader should have a basic understanding of injection molded optics in all of the relevant areas. He or she should be able to enter a detailed and specific discussion about his/her application with an injection molding company. Also, engineers working in a specific area of injection molded optics can use the book for broadening their knowledge in other areas of injection molding. A designer can learn more about metrology and a tooling engineer more about materials. By sharing experiences and knowledge the whole industry should profit and advance to the next level.

The basic idea that serves as a guideline throughout the book is the thought that all products have to go through a Design – Build – Test cycle. This idea has also been kept in the second edition of the book. Therefore, all the chapters of the first edition have been kept. Chapters 2, 3, and 5 have gone through some minor revisions and corrections. Chapters 4 and 6 have been substantially revised and updated. In order to make the book even more complete, three new chapters have been added: Process and Molding Equipment, Cost Modeling, and Applications. All the new chapters contain topics that are vital when talking about plastic optics, and deserve more attention than previously. With these additions and revisions of the previous chapter, this book is on its way to become more of a true handbook and reference for injection-molded optics.

Chapter 2, the first chapter after this introduction is devoted to optomechanic design of injection-molded optics. The unique opportunities in injection-molded optics to combine mechanical and optical features in one component are described. Special attention is paid to the thermal properties of the optical plastics and the proper design with these.

In Chapter 3 the building part of the cycle is covered. During the past few years immense advances in precision engineering and especially single-point diamond turning of optical surfaces have been made. The advances in tooling capability are essential for modern injection molded optics. While designing in glass gives the designer a freedom of material with preferably spherical forms, the designer of injection molded optics is left with very few materials but with freedom of form. However, in order to utilize fully the potential of free and aspherical forms optical tooling needs to be at a level such that these forms can be manufactured. In addition to advanced optical tooling, the whole variety of mold design and tooling is described. This ranges from prototype molding to multi-cavity series molds.

In Chapter 4 an overview of current state-of-the-art metrology is given. As in all of the other chapters the subtleties of injection molding are emphasized. A few generic metrology technologies are discussed and the conflict between these generic methods and custom metrology setups is described. Also the need for high-volume inspection is discussed.

Chapter 5 is devoted to materials. If currently or in the future there is one area that is or will be important for injection molded optics, then it is materials. At present it is very difficult to get reliable and coherent data on optical plastics. In the chapter an attempt is made to provide these data for the most common optical polymers. The most relevant properties of many optical plastics are listed and described. This chapter can serve as a reference for properties like refractive index, Abbe number, thermal expansion, etc.

Chapter 6 deals with coatings on polymers. Proper coatings can add value to injection molded optics. Besides that, coatings can enlarge the areas of application of polymer optics. Coatings can be used not only to enhance the optical performance of injection molded components but also make them more able to withstand a larger range of environments. In this way some of the traditional shortcomings of injection molded optics can be compensated for. The chapter gives an overview of the current state-of-the-art of coatings on plastics. Also, the challenges of working with plastics are illustrated.

Chapter 7 is devoted to injection-molding equipment and processes. Besides proper design and tooling, suitable processes for the parts at hand are necessary as well. The processes used go mostly together with the injection-molding equipment available. Therefore, Chapter 7 gives a good overview on both: some of the most common equipment and on injection molding processes. Since processes are usually a core competence of the injection molding companies, this chapter gives an overview on basic principles; not recipes to follow.

A reoccurring topic in injection molding is costs. When it is cost effective to start molding? What are initial costs involved? These are only two of several common questions asked. Chapter 8 shines some light on cost modeling for injection molding. The chapter gives a review on several of the most important parameters that determine the cost of injection molding parts and products. As the other chapters of the book, this chapter can also be used and read from various perspectives: engineer, purchasing, and general interest.

The last chapter that was added to the second revision is a chapter on Applications. Sometimes in can be very useful and illustrative to see, how certain problems have been solved and how some of the solutions look like. In Chapter 9, several authors of companies and institutes have been willing to lift the tip of the veil and share their solutions with the reader. This chapter is intended more as an inspiration and food for thoughts on what is possible using injection-molded optics.

2
Optomechanics of Plastic Optical Components

Michael Pfeffer (Optical Engineering, FH Ravensburg-Weingarten, Germany)

2.1
Introduction

Citing Dan Vukobratovic, Willey and Parks [1] defined optomechanics “as the science, engineering, and/or art of maintaining the proper shapes and positions of the functional elements of an optical system so that the system performance requirements are satisfied.” With respect to mechanical engineering this also implies “that the emphasis is on strain or deformation rather than stress.”

Starting from this point of view, several new aspects arise when considering plastic optics, all of which have their origin in two fundamental differences. First, in comparison to glasses or metals, optical plastics have quite different material properties. Second, plastic optical parts and components are typically fabricated by methods and processes different from those applied to classic optics.

As a consequence, this gives rise to, on the one hand, various new possibilities such as:

- high-volume production capability and low relative manufacturing cost;
- freedom with respect to design, shaping, and structuring optically active surfaces, including aspheric, micro-optical refractive, and diffractive features;
- reduction of weight due to both smaller densities of plastic optical materials and facile realization of lightweight structures;
- higher shatter resistance due to the elastic behavior of most plastic optical materials; and
- implementation of cost-saving mounting methods for optical elements such as snapping, screwing, and welding techniques when dealing with thermoplastic resins.

The aspect with the highest overall impact with respect to the issues listed above is probably the monolithic integration of several optical, mechanical, or even electrical features.

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On the other hand, there are also some optomechanical challenges [2]:

- Compared to glass, optical plastics show much higher photoelastic birefringence, which requires very careful study of both fabrication- and mounting-induced stress.
- Higher thermal expansion coefficients and lower thermal capacity and conductivity may cause important dimensional deformations. Therefore, athermalization becomes an important issue.
- Since service temperatures of almost all optical plastics are lower than those of glasses and metals, thermal management on a systems level has to be considered.
- Due to low mechanical hardness plastic optical materials are quite sensitive to scratching. This can be addressed by the use of hard, scratch-resistant surface coatings.
- Outgassing limits the use of plastic optical components in ultrahigh vacuum (UHV), since most polymers contain lubricants, colorants, and stabilizers, which may outgas.
- Another characteristic property of plastic optical materials is water absorption, which causes both dimensional changes by swelling and changes in the refractive index.
- Shrinkage due to cooling in an injection molding process is rather complicated to predict.
- When exposed to ionizing radiation, plastic optical materials show some fluorescence or even discoloration by polymer chain cross-linking.

All these items have to be taken into account when optimizing plastic optical parts and systems.

2.2 Configuration of Plastic Optical Elements

In general, an optical element has not only to fulfill optical functions but also mechanical and sometimes even electronic functions.

From a functional point of view optical elements generally can be divided into two groups: imaging and non-imaging optical devices. Of these two device groups, each may work with surfaces having refractive, reflective, diffractive, or stop functions.

Optical devices must also be considered as mechanical parts, which have to be mechanically aligned, centered, fixed, mounted, and assembled.

In some cases optical elements even must be considered as electric or electronic devices. For example, when using the surfaces of an optical element as substrate for integrated or printed circuits or in the case of electromagnetic compatibility (EMC), the electronic function aspect of such primarily optical devices may become an issue.

The following discussion starts with the configuration of single-function elements such as lenses and elements with integrated fixation features. This is followed by the consideration of some examples of plastic optical elements with high functional integration.

2.2.1
Single-Function Elements

Apart from plano window elements, the simplest plastic optical element is a lens with an integrated mounting flange, whether with a protrusion (Figure 2.1, top) or a flat (Figure 2.1, bottom) for both gating and orientation with respect to the mounting position.

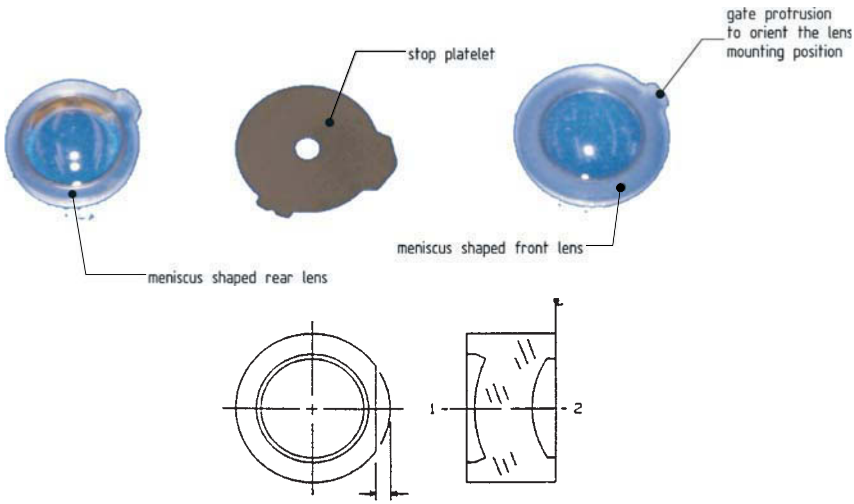

Figure 2.1 Top: components of the objective lens system of a single-use camera consisting of a meniscus-shaped rear lens, a stop platelet made of steel, and a meniscus-shaped front lens. Note the mounting flange and the gate protrusion to orient the lens mounting position. Bottom: meniscus lens with gate flat from Ref. [21]. Note the edge configuration serving for both lens centering and as a spacer with respect to other lens elements or the mounting barrel.

Particular attention has to be paid to the edge configuration. Higher stress levels at the edge of the optic cause birefringence and surface irregularities, the so-called "edge effect" [3]. Consequently, for standard-size lenses the effective aperture should be at least 1–2 mm beyond the clear aperture, i.e., the edge between flange and optical surface. To allow injection of molten plastic into the lens cavity, any increase in lens diameter should be accompanied by a proportional edge thickness increase. Typically the edge thickness varies between 1 and 3 mm.

Another feature to consider when designing edge configurations is the integral use of the flange as spacer requiring no additional spacers. If no flanges are incorporated, the same airspace may result in a spacer requirement that is too thin, particularly for robotic assembly (Figure 2.2, left). Extending the flange beyond the surface vertex of a convex surface protects the surface from damage when the lens is placed on a table or in a tray [21]. However, integrating flanges around a lens for mounting purposes requires thick flange walls designed with chamfers and radii that do not degrade the quality of the optics [3].

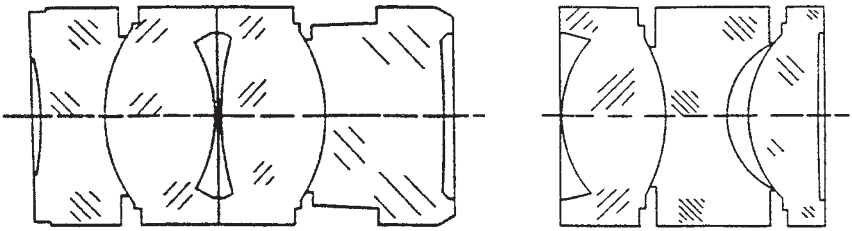

Figure 2.2 Edge configurations of plastic optical lenses. Left: flange spaced lenses; right: edge contact assembly (both from Ref. [20]). Note the possibility of achieving small airspace and protection of convex optical surfaces by extending the integrated flanges beyond the vertex (left).

Finally, plastic optical elements can often be designed to nest with one another, allowing the parts to be centered without the use of expensive mount designs (see Figure 2.2).

2.2.2
Elements with Integrated Fixation Features

Apart from simple flanges around lenses, there is a large variety of integral mounting and fastening features. In cases where a complete flange around a lens element is not possible, e.g., mounting/assembly problems or stress-induced birefringence, fastening pads with slots and holes can be applied (Figure 2.3, left). This is particularly the case for rotationally non-symmetric prismatic elements (Figure 2.3, center and right).

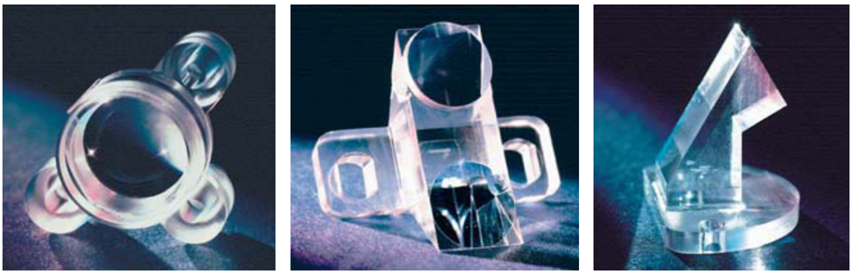

Figure 2.3 Plastic optical elements with integrated mounting slots and flanges. Left: lens assembly with three single slots; center: Small porro prism with two slotted mounting flanges; right: small prism with one-side cut circular flange and two fixation slots [4].

Generally, slots with an open end are preferred over mounting holes. This is because slots create less optical distortion during molding due to local shrinkage-induced deformation [3].

2.2.3
High Functional Integration

Deliberately integrating several optical, mechanical, and electrical features into one monolithic device could replace several discrete optical elements in an instrument. This, in turn, would decrease costs due to easier assembly and alignment, and lead to more reliable products, where in the case of failure the whole integrated module could be replaced. Thus, higher integrated optical devices would be of interest to many manufacturers dealing with optical assemblies.

Because of fabrication difficulties, until recently in classic glass optics it was difficult to integrate several optical and mechanical functions into one monolithic device. However, because of the totally different fabrication process, injection-molded optics offers an enormous variety of surface shapes and structures, easily allowing the implementation of several optical, mechanical, and electrical features.

Therefore, when dealing with plastic optics designers should aim for a high degree of feature integration. Here, it is important to resist the urge to emulate glass-based optomechanical design approaches. A fully optimized polymeric optical system not only makes use of aspheric technology and integrally molded features in the optical elements but also embodies an extension of this design philosophy into the lens housing concept and assembly strategy.

The best way to show the variety and the potential of functional and geometric integration of plastic optic elements is done through examples. In following some examples of highly integrated monolithic plastic optical elements for both imaging and non-imaging purposes are considered.

Figure 2.4 Monolithic plastic optical assembly made of poly(methyl methacrylate) (PMMA). The device is about 50 mm high and integrates a spherical and an aspherical lens, sensor alignment holes and locating ledges for sensors at the focal point of the lenses, and a mounting flange [3].

The first example is a highly integrated plastic optical device. This is a one-piece molded assembly with two integral lenses, interfaces for sensors, and a mounting flange (Figure 2.4).

Figures 2.5 and 2.6 show the viewfinder modules of different types of single-use, entirely plastic cameras. The assembly integrates an imaging path composed of two rectangular meniscus lenses, simple magnifying elements for the exposure counter wheel, and a light-guiding feature to collimate light of the flash control LED. Furthermore it incorporates several mechanical features such as snap hooks, alignment pins, and play-free flexible bearings. Interesting in these modules is the configuration, where the optical and mechanical features are almost all "mounted" on a baseplate. One advantage of this design is the clearly defined gating area and separation line.

A small integrated plastic optical module mounted on a flexible printed circuit is shown in Figure 2.7. Apart from an illumination path, also an imaging path, which runs over several beam-shaping surfaces, is integrated in this example.

Recently, Tan et al. [27] presented a highly integrated miniature plastic optical device to focus and monitor light from a VCSEL for bar-codes reading applications. With integrally-molded pins they realized improved mounting, alignment and fixation functionalities.

An example of a highly integrated plastic optical imaging device is shown in Figure 2.8. This illustrates an integrated waveguide optic structure to detect fingerprint patterns [7] by imaging the evanescent coupled light of an LED. In total the device integrates monolithically seven surface elements between the light source and the two-dimensional CCD imaging device.

The region between the illumination asphere and the output asphere is solid acrylic. Thus, the device can be regarded as a waveguide, where total internal

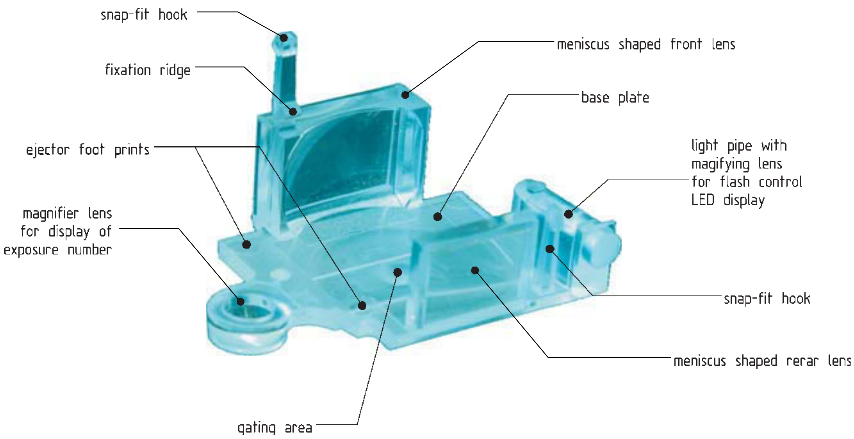

Figure 2.5 Monolithic viewfinder module of a single-use, totally plastic camera. The module integrates three optical features (viewfinder lens pair, exposure number magnified display, and LED flash control display) and several mechanical features, such as a baseplate structure to hold all optical elements and snap-fit hooks and ridges to fix and position the module in a suitable assembly.

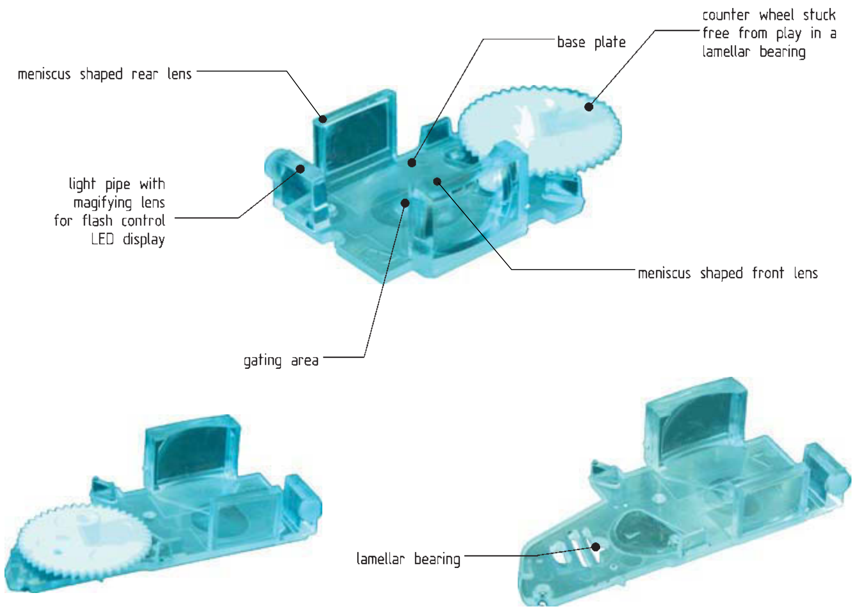

Figure 2.6 Monolithic viewfinder assembly of a similar type of one-use, totally plastic camera to that shown in Figure 2.5. This module additionally integrates a play-free lamellar bearing to hold the cogwheel of the exposure counter. View from left top (top), view from right top (bottom left), and view from top with the lamellar bearing (bottom right).

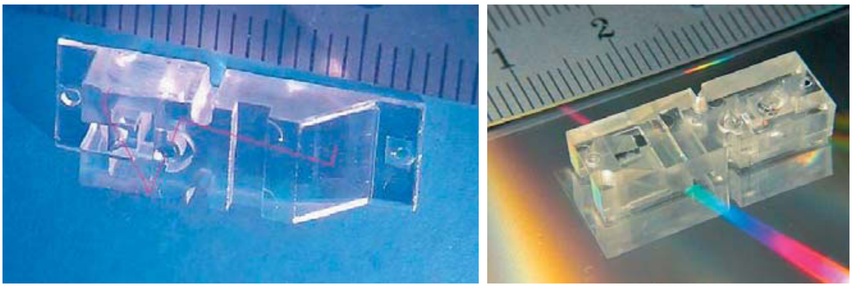

Figure 2.7 Small monolithic plastic optical module (from Ref. [5]). Left: two different configurations of the optical module; right: optical module mounted on a flexible printed circuit.

reflection (TIR) occurs at well-defined surfaces to shape the light bundle: first for illumination purposes (aspheric illuminator surface), and second to relay the image from the sensor area onto the two-dimensional CMOS camera mainly using TIR.

To achieve TIR almost all optical surfaces of the device are strongly off-axis. This, however, results in significant geometric distortions and especially astigmatism, which are accommodated with toroidal elements and differential x–y apertures.

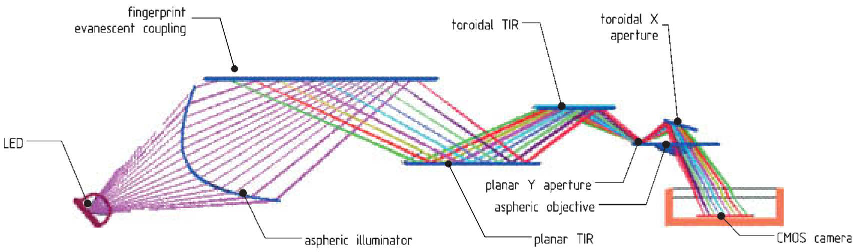

Figure 2.8 Fingerprint waveguide optic structure (from Ref. [7]). Optical layout including LED, aspheric illuminator, and planar, aspheric, and toroidal surfaces or apertures.

According to Hebert [6] this example was a particularly challenging design in that it required image-quality resolution, which only could be achieved in tooling with diamond-turning technology.

Figure 2.9 shows a further example of a highly integrated plastic optical element. This optical module is the functional kernel of a four-channel reflectometer of a single-use device for testing hemoglobin A1c [8]. It monolithically incorporates single and dual off-axis aspheres and toroidal and planar surfaces and apertures.

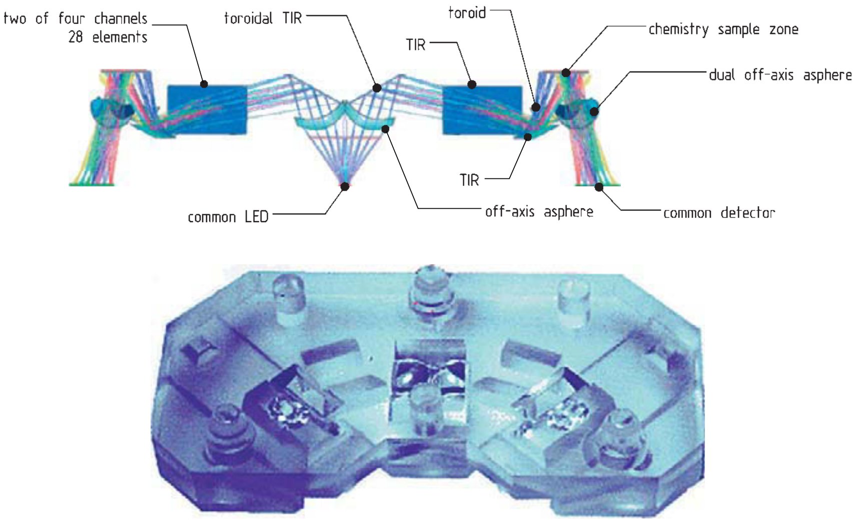

Figure 2.9 Four-channel reflectometer of a single-use device for testing hemoglobin A1c [8]. Top: optical layout including a common LED (for both reference and measurement paths), off-axis aspheres for light collimation, toroidal and dual off-axis aspheres, as well as several planar surfaces or apertures. Bottom: monolithic realization as one highly symmetric plastic optical module.

2.3
Mounting Plastic Optical Elements

As mentioned in Section 2.2, mounting features can easily be incorporated into the optics themselves. Cells and housings can also be configured to minimize the number of parts and assembly labor, and to allow the use of mechanical fasteners, adhesives, or heat sealing.

The design flexibility and the cost-saving potential of polymer optics can only be fully realized when the optical as well as the mechanical design is approached in a fundamentally different manner from that of glass-based optomechanical design. This means that a fully optimized plastic optical system implies not only integrated mechanical features and aspheric and diffractive surfaces, but extends this different design philosophy to mounting and assembly issues. The earlier the housing concept and assembly strategy are considered together, the better is the chance of not hindering parallel innovation concerning other aspects of the development process.

Since the thermal and mechanical properties of most plastic optical materials differ greatly from those of metallic materials typically used in glass-based assemblies, for mounting plastic optical elements one should primarily consider plastic or reinforced plastic materials. There are basically three different types of mounts made of plastic:

- Clamshell mounts. This type of mount consists of two identical half-shells made, for example, by injection molding of plastic material. When assembling, the optical elements are simply inserted in the seats of one half-shell. The second half-shell then serves as a top cover which can be attached by snap-fixations, UV-curing adhesive or ultrasonic bonding, or C-type expansion rings. In particular, the last method mentioned allows expansion of the optical elements, e.g., due to thermal changes. A typical example of this type is shown in Figure 2.10 (left). The internal configuration of the clamshells typically consists of half-ring-shaped local pads which determine the centric position, solid integrally molded tabs defining the axial position of the plastic optical element and serving as aperture stop, and flexible tabs allowing one to clamp the optical element axially (Figure 2.10, right). Benefits of this mounting type are the minimum number of parts and easy assembly. However, according to Ref. [3], control of centering and tilt is considered to be of moderate quality.
- Collet cap-type lens housing. This type of mounting for plastic optical elements is based on a slotted Collet sleeve into which the lens elements are filled and stacked. The orientation tappets of the lens elements are then inserted into the slots of the sleeve. Axially the lenses lean against the shoulders of the seats and are fixed by means of an ultrasonically bonded cap (Figure 2.11).

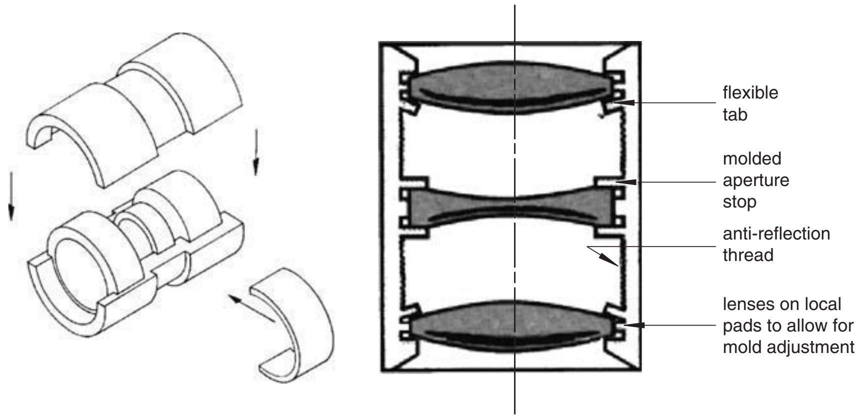

Figure 2.10 Clamshell lens housing. Left: the device consists of two identical housing half-shells, between which the lenses are inserted. The whole assembly is clamped by an expansion C-ring, which is snapped in the slot [2]. Right: internal mounting details [9] such as flexible tabs, integrated aperture stops, antireflection threads, and load pads to allow for mold adjustment [3].

- Barrel-type lens housings. These are similar to glass-based barrel-type lens housings but are made of plastic. Providing better accuracy than clamshell mounts, barrel-type mounts typically require retainers, which can be screwed, adhesively or ultrasonically bonded, or heat-sealed. However, excessively long mounts and wall-thickness variations resulting from draft-angle allowance make it more difficult to mold mounting barrels with high accuracy. An important issue in this context is the definition of the parting line as shown in Figure 2.12, bottom. In the upper section of the figure the parting line is axially set to the aperture stop location, allowing an integral molded aperture stop and few accessory parts. However, accuracy with respect to the concentricity of the elements left and right of the aperture stop may be inferior to the mounting method shown in the lower section of the figure, where the parting line is set to the right.

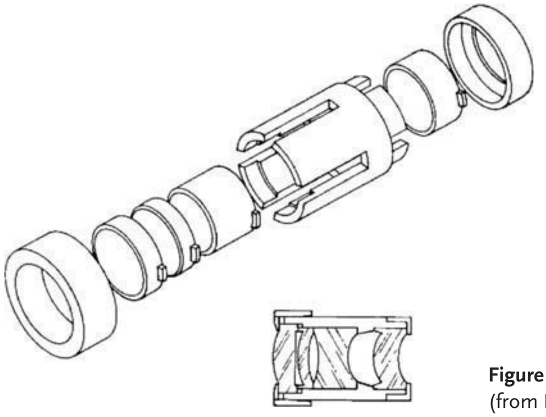

Figure 2.11 Collet-type lens housing (from Ref. [2]).