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Tutorial

Micro-optics: a micro-tutorial

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Abstract

Micro-optics represents a rich discipline with many features not found in classical optics. Yet micro-optics is not merely 'small optics'. Using the technologies of microfabrication, entirely new fabrication processes, new materials and new types of optical devices have been conceived. Here, we provide a brief introduction to the field, discussing a variety of miniaturized optical components, as well as the materials from which they are made and the novel technologies used to fabricate them. Designed as a tutorial, this brief précis includes adequate literature references to guide the interested reader to more in-depth treatments.

Keywords: micro-optics; tutorial.

1. Introduction

How is 'micro-optics' different from 'macro-optics'? Even though the optical physics does not change as optical structures become smaller, we nevertheless propose three essential qualities which distinguish the two domains:

- micro-optics relies on a wide variety of phenomena, as diverse as optical diffraction, surface tension or micromechanical movement, which can play a much more important role in defining the performance of an optical component than in macroscopic optics;
- micro-optics may realize optical functions employing materials and states of matter, such as liquids, which are not ordinarily used for macroscopic optics; and
- micro-optical components are manufactured using the technologies of microfabrication, which are fundamentally different from those traditionally used for macroscopic optical devices.

Although micro-optical components are generally considerably smaller than classical macro-optical components, we see from the above list that size alone does not matter. Particularly the third point above, fabrication technology, which is based heavily on microfabrication techniques employed for the manufacture of integrated electronics and microsystems, is a fundamental distinguishing feature of micro-optics. Novel materials, advanced fabrication techniques and new physical, optical and chemical effects have been combined to change the nature of what is feasible in optics and provided a primary impetus for the genesis and rapid development of the micro-optics field [1–3].

In the tutorial which follows, we present a brief overview of the most salient aspects of micro-optics. We discuss materials and fabrication processes, focusing on those which are rare or unknown in classical optics. Subsequently, we present a number of important refractive, diffractive and reflective micro-optical components, considering those which either have significant technical or commercial impact or whose nature is unique to micro-optical dimensions. We conclude with a brief glance at what new technologies lie on and over the horizon.

2. Materials

Optical materials are those which allow a controlled interaction with light. For a majority of micro-optical components and their applications, 'light' implies electromagnetic radiation at visible to infrared wavelengths, approximately the range 300 nm$\leq\lambda\leq$2 μm; there are certainly specialized devices and applications at other, particularly longer, wavelengths.

2.1. Relevant properties

For use as the basis for an optical component, macro-optical or micro-optical, an optical material generally needs to refract and/or reflect light, and usually be transparent at the wavelength of interest. Some specialized applications may also require generation, amplification, absorption or polarization rotation of an incident optical field, thus requiring suitably specialized materials.

Even as size scales vary, the same optical material parameters remain relevant: refractive index and dispersion are of primary interest, as are transparency (absorption), birefringence and non-linear effects. For some micro-optical components and assemblies, the mechanical and chemical properties of the material may also be an issue. Sufficient stability is required for devices fabricated on rigid substrates, or for mechanically actuated structures; high flexibility may be an asset for deformable optical devices, particularly those employing liquids or flexible membranes. Chemical interactions between different materials are often an issue for liquid- and polymer-based micro-optics.

2.2. Glass

Glass is historically the classical material for optics yet is also used in a variety of micro-optical components [4, 5]. With high transparency in the visible to mid-IR wavelength ranges, standard SiO_2-based glasses are stable, inert and available with a wide range of refractive indices and dispersion, depending on their composition; refractive index values between 1.4 and 1.6 are typical. Fluoride-based glasses are employed for UV wavelengths ($\lambda \leq 200$ nm) and chalcogenides are useful for mid-IR wavelengths. Glass may be obtained as flat rectangular or circular blanks which may often be processed using the same or similar equipment to that used for semiconductor substrates. In addition, some glasses may be sputtered, allowing deposition on other materials. Such glasses are often useful for realization of glass-based waveguides, or for patterning glasses with customized non-linear or electro-optical properties [6].

2.3. Semiconductors

Micro-optics, to some extent, emanated from semiconductor technology and semiconductor materials play a significant role in many types of micro-optical components and systems. Not only are the optical properties of semiconductors relevant: because many micro-optical devices are either fabricated on or (for the case of micromechanically-based optical systems) positioned or deformed by semiconductor actuators, the mechanical properties are also often important.

Summarized in Table 1 are a few of the semiconductor materials relevant for micro-optics and a selection of their optical and mechanical properties. The energy gap E_g (or the so-called gap wavelength, λ_g) is an important optical parameter, because semiconductor materials are only transparent for photon energies $h\nu<E_g$ (or $\lambda>\lambda_g$); the strong absorption of semiconductors for photon energies above the bandgap energy distinguishes these materials significantly from glasses, polymers or dielectrics.

The refractive indices of semiconductors vary much more strongly than glasses and are subject to high dispersion. As may be seen in Table 1, thermal expansion and thermal conductivity also vary strongly between different semiconductors; these factors must be taken into account if hybrid systems (combinations of different types of materials such as semiconductors, polymers, glasses and others) are designed, as is often the case in complex micro-optical systems.

Table 1 Some material parameters for several semiconductors commonly used in micro-optics.

Symbol	Si	Ge	GaAs	InP	(units)
E_g	1.12	0.66	1.42	1.35	eV
λ_g	1.11	1.88	0.87	0.919	µm
n	3.44	4.00	3.65	3.45	
α_L	2.6	5.8	5.7	4.6	$\times 10^{-6}$ K^{-1}
σ_{th}	1.45	0.6	0.46	0.68	W/cm K

Data is for room temperature and at near infrared wavelengths. E_g is the energy gap, λ_g the bandgap wavelength, n the refractive index, α_L the thermal coefficient of expansion and σ_{th} the thermal conductivity. Table 1 is based on [3] (p. 92); data from [7, 8].

The semiconductors listed in Table 1 are perhaps the most relevant for a wide variety of micro-optical components. Silicon is very popular, due to the advanced fabrication technologies available for it. In addition, silicon makes an excellent, stable substrate for planar micro-optical components and is widely used for the mechanically actuated micro-optics found in micro-opto-electromechanical systems (MOEMS) discussed in Section 7.1.

The III–V compound semiconductors (GaAs and InP in Table 1) are of primary interest for opto-electronics. Unlike silicon, an indirect bandgap semiconductor, GaAs and InP are efficient emitters of light and as such are workhorses (along with their many compound semiconductor cousins) for the realization of light-emitting diodes (LEDs), semiconductor lasers, optical amplifiers, modulators and many other active[1] micro-optical components. Many complex micro-optical systems combine active III–V-based devices with passive optical components made using non-active materials to realize advanced forms of optical functionality.

2.4. Polymers

The field of polymers has undergone very rapid development [9] and a very wide variety of polymer-based materials is now available for realizing a wide spectrum of optical functions, from passive refraction or diffraction to light emission and detection as well as optical modulation and amplification [10]. As polymers are synthesized, their optical, mechanical and electrical properties may often be tuned to some extent; as a result, this very dynamic field is yielding an increasingly attractive catalog of materials for micro-optics. Listed in Table 2 are four well-established polymers used for passive micro-optics fabrication. These materials are of interest in that they may be machined as substrates, but alternatively be deposited using spin or dip coating, and thus configured as thin films, often in combination with other materials. Patterning and structuring is most practically done using molding techniques [14, 15], which allow high-volume fabrication of high-quality optical components; we will look at these techniques in Section 3.3.

2.5. Liquids, dielectrics and other

Glasses, semiconductors and polymers may currently be the most popular basic materials for micro-optics, but as microtechnologies continue to develop and subsume an increasing spectrum of materials and fabrication techniques, the variety of media useful for realizing new types of micro-optical functions will continue to grow.

As we will see in Section 7.3, the small dimensions inherent to micro-optics allow the use of fluids in ways not possible in classical macro-optics [16]. Liquid lenses, waveguides and prisms have been realized using a variety of fluids, manipulated using the technologies of micro-fluidics. The

[1]'Active' implies that energy, typically electrical, is applied to the component to generate light or change its optical properties.

Table 2 Polymer materials frequently used in micro-optics, with refractive index at visible wavelengths and wavelength range for transparency.

Polymer	Acronym	n	λ (nm)
Polycarbonate	PC	1.586	380–1600
Polymethylmethacrylate	PMMA	1.491	400–1100
polystyrene	PS	1.590	350–1600
polyvinyl chloride	PVC	1.54	400–2200

Table 2 is based on [3] (p. 95); data from [11] (Table 4.1), [12] (Table 6.1) and [13].

liquids employed, a variety of water or oil-based fluids, have only begun to be adequately optically characterized and it is expected that increasing numbers of liquids with custom-designed refractive indices, dispersion and fluidic properties (such as viscosity or miscibility with other fluids) will become available in the near future.

Thin films are of great importance for optics at all size scales, and may be used in micro-optics to realize entire refractive or diffractive components but also, for example, classic thin film filters. Dielectrics, such as those listed in Table 3 are of great utility in micro-optics, particularly as many are compatible with standard microfabrication techniques, such that they may be deposited by sputtering and evaporation and patterned using wet or dry etch techniques.

A number of further materials are employed in specialized aspects of micro-optics. Sol-gels, for example, have been used for generating printed arrays of microlenses [17, 18]. Materials such as $LiNbO_3$ are also attractive due to their strong non-linear and electro-optical effects [19], and may be used in substrate or thin film form.

3. Fabrication technologies

As we have stressed repeatedly above, one of the key distinguishing features of micro-optics is how the components are fabricated: rather than classic grinding, polishing and machining techniques, micro-optics tends to use the technologies of microfabrication, as established for microelectronics and microelectromechanical systems (MEMS). Microfabrication not only allows the definition of miniaturized structures but is also based on batch processing, such that fabricating hundreds or thousands of the same structure is no more expensive than fabricating one.

Table 3 Popular dielectrics for micro-optics, with optical data around 589 nm (Na D line); both indices are given (n_o; n_e) for birefringent materials.

Dielectric	Name	n
MgF_2	Magnesium fluoride	(1.38, 1.39)
LiF	Lithium fluoride	1.39
CaF_2	Calcium fluoride	1.43
SiO_2	Silicon dioxide	1.46
Al_2O_3	Sapphire	(1.77, 1.76)
Si_3N_4	Silicon nitride	2.05
SiO_xN_y	Silicon oxynitride	1.5–2.0
Ta_2O_5	Tantalum pentoxide	2.2
Nb_2O_5	Niobium oxide	2.4
TiO_2	Titanium oxide	(2.62, 2.92)

Table 3 is based on [3] (p. 94).

We refer the reader unfamiliar with the basics of microfabrication to the extensive literature [20–23]. Here, we consider three examples of specialized microfabrication technologies developed for or applied to micro-optics.

3.1. Technology example 1: photoresist reflow

Microlenses are generally not fabricated as discrete components (as in a lens one could pick up with a pair of tweezers) but are attached to a transparent substrate, as seen in Figure 1B. One well-established means to fabricate microlenses on a substrate is by means of photoresist reflow [24, 25]: a circular pillar of photoresist is patterned on glass or silicon, as seen in Figure 1A, the temperature of which is then raised above the melting point of the photoresist. Owing to surface tension, the surface of the molten photoresist assumes a spherical shape, which subsequently, upon cooling, becomes the refractive surface of the lens. This technique is an example of self-assembly: we let surface tension do the work of defining the lens surface, which is thus an excellent approximation to a sphere.

The geometric parameters of a photoresist reflow lens are given by the diameter (D in Figure 1B), the sag height s and the radius of curvature R; these are related as:

$$R=\frac{\left(\frac{D}{2}\right)^2+s^2}{2s} \tag{1}$$

we thus see that the achievable radii of curvature for a given aperture diameter D are limited (because photoresist thicknesses are generally limited to several tens of micrometers). As a result, whereas photoresist reflow is relatively simple and widely used, the achievable lens structures may not be arbitrarily defined.

3.2. Technology example 2: microcontact printing

We may also take advantage of surface tension to define microlenses using the technology of microcontact printing,

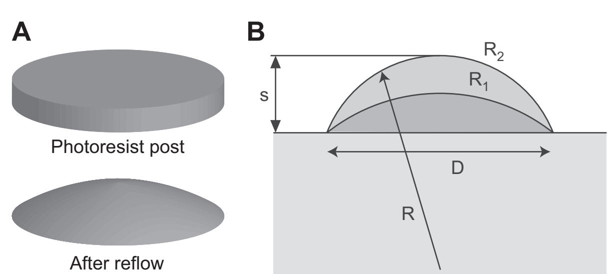

Figure 1 (A, B) The high-temperature reflow of a cylindrical post of photoresist causes the cylinder to assume a hemispherical shape and thus a segment of a spherical lens.

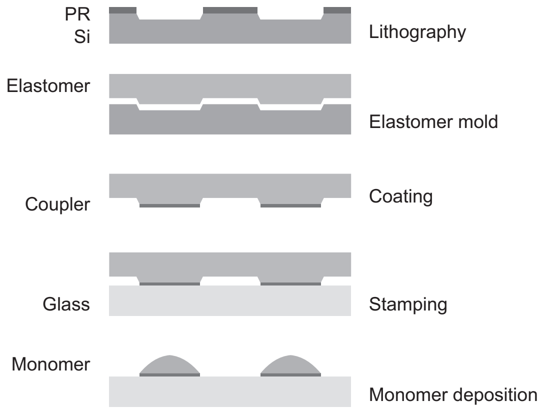

Figure 2 Microcontact printing process for fabrication of self-assembled microlenses: (top to bottom) origination of a master in Si using standard lithography; molding the elastomer stamp; coating the stamp with a hydrophilic coupling agent; stamping on a glass substrate; lenses subsequently formed in a monomer by surface tension. Not to scale.

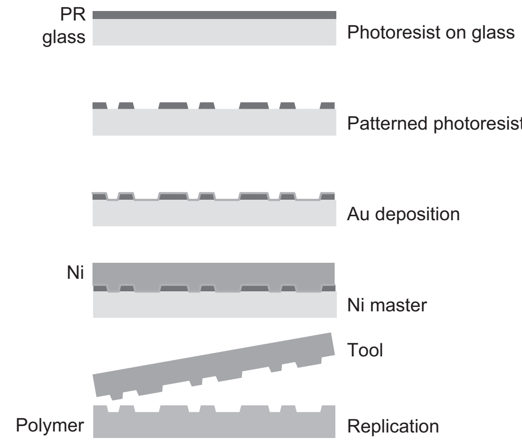

Figure 4 Basics of replication: (top to bottom) photoresist on a substrate, typically glass; exposed pattern, binary or continuous relief; deposition of Au contact layer; electroplating a Ni master; replication in a polymer using the resultant molding tool.

sometimes referred to as soft lithography [26]. This process, schematically illustrated in Figure 2, uses a photolithographically-defined soft elastomeric stamp to define hydrophobic and hydrophilic regions on a substrate; this process can define areas with submicrometer resolution.

This technique has been used to fabricate two-dimensional arrays of microlenses [27, 28], again using principles of fluidic self-assembly. The stamp is coated with a coupling agent and hydrophilic regions are defined on the glass substrate. When dipped into a liquid monomer, spherical caps are formed, again due to surface tension; subsequent polymerization then yields solid lenses, examples of which, using polymethylmethacrylate (PMMA), are shown in Figure 3. We will discuss their optical characteristics in Section 4.1.

3.3. Technology example 3: replication

Replication is mass production technology which allows fabrication of high-precision components, usually in polymers, using variations on molding techniques [14]. As outlined in Figure 4, the molding tool is defined using standard lithography, etching and metallization (particularly electroplating) techniques; the structure is then defined in a polymer using hot embossing [29], injection molding [30] or UV casting processes [31].

Hot embossing of polycarbonate is an established process for manufacture of CDs and DVDs, optical structures with high demands on resolution and precision. These replication processes are also of great utility for fabricating various forms of micro-optical components, such as the Fresnel lens of Figure 5. The most critical (and typically expensive) step is origination of the molding tool; for refractive surfaces, continuous relief lithography is required to define the surfaces. Once the tool is available, however, replication allows subsequent fabrication of high-precision micro-optical components in high volumes.

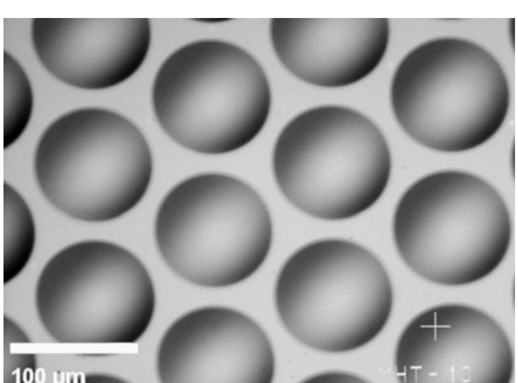

Figure 3 Microcontact printed microlenses, formed in poly-alkylmethacrylate; lens diameter is 90 µm.

Figure 5 Injection-molded discrete Fresnel lens; diameter of the inner lens structure (the Fresnel zones) is 25 mm.

4. Refractive optics

Using the materials and processes outlined in the previous two sections, a wide spectrum of micro-optical components may be fabricated. We discuss in this and the subsequent sections some of the more popular examples, focusing on refractive, diffractive and reflective components.

Refractive microlenses obey the same physical laws as macrosized refractive lenses. However, as the size of the lens decreases by a scale factor $S<1$, it can be shown that the aperture diameter D, physical feature size (x, y, z) and focal length f scale as ([2], Chapter 2):

$$D'=SD \tag{2}$$

$$(x, y, z)'=S\,(x, y, z) \tag{3}$$

$$f'=Sf \tag{4}$$

for constant numerical aperture. As a result, the optical parameter space for microlenses is often more limited than that of classical macrolenses. In addition, owing to the smaller D, diffraction effects play more of a role in defining the optical performance of microlenses. By contrast, wavefront aberrations are typically less of a problem in microlenses, such that performance limitation is generally due to diffraction rather than aberrations.

4.1. 'Classical' microlenses

As we saw above, one primary difference between macro- and microlenses is that microlenses tend not to be free-standing structures but are usually planar, deposited on a transparent substrate as shown in Figure 6. The lens may be formed using a surface layer, as shown on the right side of the figure and discussed for the case of photoresist reflow in Section 3.1; alternatively, etch processes may be used to transfer the lens profile into the substrate itself (Figure 6, left). The latter structure is typically more robust than the former, because the substrates often used (glass, semiconductors, hard polymers) are more resistant to external influences and more transparent in a wider wavelength range than spin-on surface layers such as photoresist.

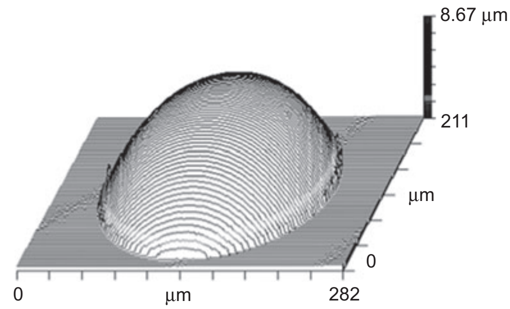

Figure 7 The profile of a polymer microlens fabricated on a silicon substrate, measured using a white light interferometer. The sag height of the lens is approximately 8 µm.

Refractive microlenses tend to be flat, with a sag height (s in Figure 6) limited by available photoresist thicknesses, generally in the range 10–20 µm and rarely >100 µm; we recall from Eq. (1) that sag height, aperture diameter and radius of curvature are geometrically intertwined. This flat profile limits the achievable focal lengths of microlenses, which are generally in the range 100 µm≤f≤10 mm. Values for numerical aperture (NA) vary from approximately 0.15 to 0.45. The profile of a polydimethylsiloxane (PDMS) microlens on silicon is shown in Figure 7; the reflow and liquid self-assembly techniques produce excellent hemispherical surfaces with low roughness, the dominant performance limitation frequently being diffraction or spherical aberration. Numerous approaches for defining aspheric microlenses have been proposed [32, 33].

4.2. Micro-Fresnel lenses

The limitation in sag height, and thus radius of curvature and ultimately focal length, for surface-mounted refractive microlenses may be overcome by using a Fresnel structure as shown in Figure 8. The Fresnel lens 'deconstructs' the curved profile of the curved lens into a series of segments, each with a limited height, but generating the optical function of a lens with a considerably larger sag height. As a result, even though the structure remains thin, the achievable focal length range

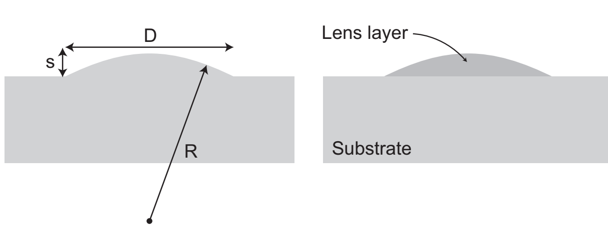

Figure 6 Typical microlens structures, fabricated on a planar substrate; either the substrate material itself is patterned (left) or the lens is fabricated in a surface layer (right). The substrate is typically much thicker then the lens. The sag height is given by s, the aperture diameter by D and the radius of curvature by R.

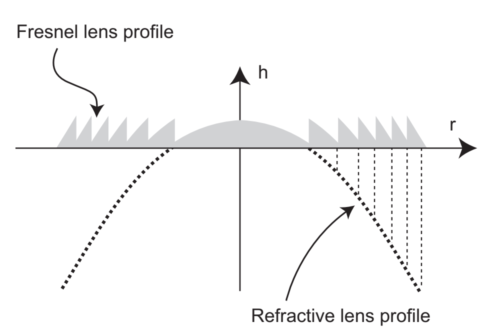

Figure 8 How a Fresnel lens is assembled: the aspheric profile of the lens, shown in exaggerated form by the dotted line of the parabola, is folded upwards in discrete segments. Each segment retains the curvature of that part of the lens from which it was taken.

is considerably extended. In addition, aspherical lens profiles may be approximated using the Fresnel approach, allowing compensation for, for example, spherical aberration.

Fresnel microlenses, whose optical function is purely refractive, are usually fabricated using molding techniques such as those outlined in Section 3.3. The molding tool is originated using continuous relief lithography or classical machining; the lens is then embossed or injection molded in polymer, yielding a structure such as the PMMA lens shown in Figure 9. Many other types of other folded optical structures have been proposed, using the same general technique [34].

5. Diffractive optics

Optical components based on diffraction embody a significant aspect of micro-optics. Because diffraction is an interference phenomenon, many diffractive optical components require coherent, single wavelength illumination, thus occasionally limiting their application. Nevertheless, diffractive effects often allow realization of optical functions not easily achievable using other means.

5.1. Gratings

The diffraction grating is a structure well-known to optical engineers and has a long history as a macroscopic element, even if the sizes of the relevant features (the grating period) are typically in the micrometer range; excellent references to its structure and use may be found in the literature [35, 36]. Fabrication of gratings for micro-optics is usually by etching into glass, semiconductor or polymer surfaces, or through replication in polymers; origination is often achieved using interference lithography [37].

The optical function of a diffraction grating is to generate diffraction orders whose angle of propagation relative to the grating surface is strongly wavelength-dependent. Broadband illumination of the grating then results in spatial separation of the wavelength components, such that gratings are essential in many types of spectrometer systems. In micro-optical implementations, gratings are configured for illumination normal to the surface (as in the classic macroscopic case) but also in-plane, for diffraction of light confined to a two-dimensional slab waveguide, for example. In addition, gratings fabricated on channel waveguides serve as efficient wavelength-selective mirrors, as used in distributed feedback (DFB) or distributed Bragg reflector lasers, for example [38].

5.2. Diffractive lenses

Variations on the grating structure may be used for realizing diffractive microlenses [39]. An example is shown in Figure 10: a Fresnel-like structure, reminiscent of that shown in Figure 8, may also be conceived as a diffractive element. Whereas the lens of Section 4.2 was purely refractive (the feature sizes were much larger than the wavelength range employed), the diffractive lens of Figure 10 have individual zones with sizes on the order of the wavelength. As a result, purely diffractive effects result in focusing of an optical field incident from the left at a position f_0 given by:

$$f_0=\frac{n_0 x_m^2}{2m\lambda_0}, \tag{5}$$

where x_m is the position of segment m in the x direction in Figure 10, m is an integer index, λ_0 is the operating wavelength and n_0 is the refractive index of the surrounding medium, typically air.

Because diffraction effects dominate the performance of this lens, two important distinctions can be made between it and the ‘real’ Fresnel lens of Figure 8: (i) the focal length is strongly wavelength dependent, as seen by λ_0 in the denominator of Eq. (5), although material dispersion is irrelevant in this case; and (ii) the exact shape of the segments of the lens is often not terribly important.

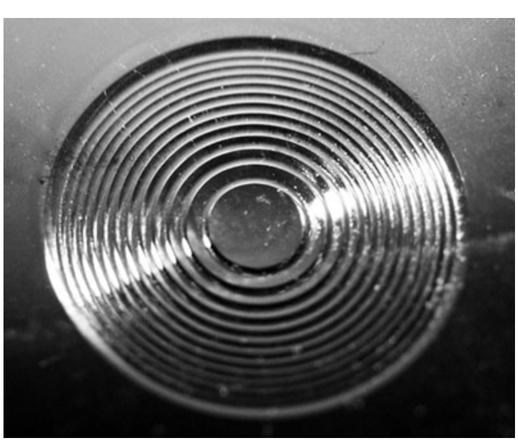

Figure 9 A Fresnel microlens fabricated by embossing into PMMA; the lens has a diameter of 2.7 mm and a maximum sag height of 88 µm.

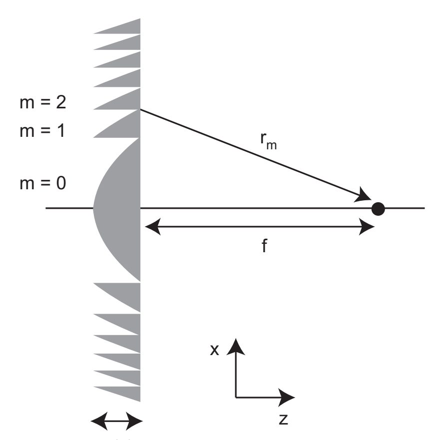

Figure 10 Focusing an optical field using a Fresnel-like diffractive lens. The spacing between zone m and the focus f is an integral number of wavelengths longer than the focus, $r_m=f+m\lambda_0$.

We may expound on this latter point by considering the structures of Figure 11, which show variations of the Fresnel lens structure. Because the generation of continuous profiles (Figure 11, top) is often difficult using the techniques of microfabrication, we can approximate the profile using a binary step-like structure (Figure 11, center) which is more easily generated using standard photolithography. In the limit, the profile may be approximated by a two-level profile (Figure 11, bottom), which is known as a Fresnel zone plate.

All three of the lenses in Figure 11 will focus an incident beam using diffraction, although with varying efficiencies; however, the ease of fabrication increases strongly from top to bottom. The approximation of continuous relief optical structures with step-like profiles is known as binary optics [40], and is a powerful means to realize hybrid diffractive/refractive micro-optical structures. Zone plates are predominantly diffractive, but have the advantage that they may be fabricated using only a single layer of photoresist with or without a subsequent etch into the substrate.

5.3. Diffractive optical elements

Given enough time and computing power, diffractive structures can be designed to perform almost any optical beam-shaping function, far beyond merely focusing a collimated beam. The structures designed for these purposes, known collectively as diffractive optical elements (DOEs), are generally very complex in two dimensions, but consist of only two levels in the third (normal to the substrate) dimension. DOEs are generally custom designed for a desired optical function, remembering that the functionality is highly wavelength-dependent. Typical functions include the generation of arbitrary intensity profiles, beam-shaping or homogenization, or fan-out elements [41].

6. Reflective optics

In comparison to the micro-optical elements we discovered in the previous sections, mirrors might seem boring: after all, they just reflect. Nevertheless, in the menagerie of micro-optical components, micromirrors are by far the commercially most successful. The key to this success is, once again, fabrication technology: at the outset, micromirrors were developed as mechanically scanning structures, fabricated using bulk or surface micromachining in silicon [42]. Relying on the excellent mechanical properties of silicon, the planar mirrors are attached to the substrate using etched springs (all in Si), as shown in Figure 12. Electrostatic or other forms of actuation are used to tilt the mirrors (as shown schematically in Figure 13), such that high-speed scanning in one or two dimensions is possible. As with all batch microfabrication techniques, hundreds or thousands of these mirrors, such as those shown in Figure 14, may be fabricated simultaneously.

The optical performance of micromirrors is a function of material and process parameters as well as size ([43], Chapter 9). For efficient reflection and beam steering, the mirror surface (often silicon, but with increasing numbers of other materials) must be flat and smooth. Roughness is often as good as that achievable on polished Si wafers, better than $\lambda/10$. Flatness is usually on the same order, but varies strongly with mirror thickness: a thinner mirror, less than approximately 10 µm, tends to show bowing and may be deformed as the mirror is dynamically tilted.

Mirror size affects performance due to incipient diffraction effects as well as the limitations defined by their structuring.

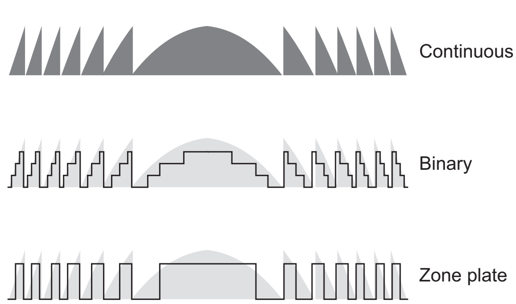

Figure 11 The binary approximation of a continuous Fresnel lens profile (top) using a multilevel (center) or two-level (bottom) structure; the latter corresponds to a Fresnel zone plate.

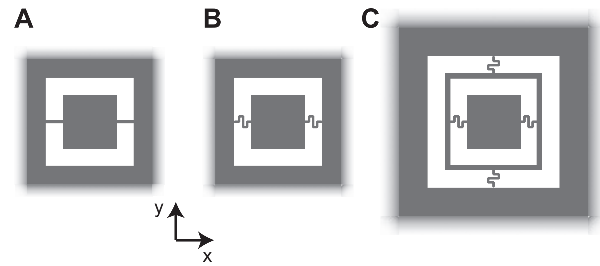

Figure 12 Structural features of scanning micromirrors. A one-dimensional mirror with a torsion bar mount for movement in the *y* direction (A); one-dimensional mirror with a spring mount for movement in the *y* direction (B); and a dual-spring gimbal mount with a moving intermediate frame for two-dimensional movement in both the *x* and *y* directions (C). Not to scale.

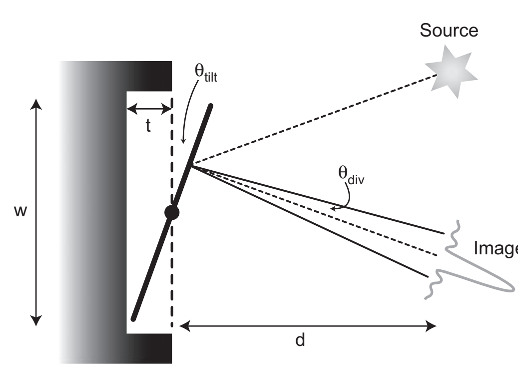

Figure 13 Schematic cross-section of a tilting mirror used to image a point source; the dotted line from source to image denotes the path of the ray, but in reality an optical system would generate a (Gaussian) beam which comes to a focus at the image point. Dimensions and angles are not to scale.

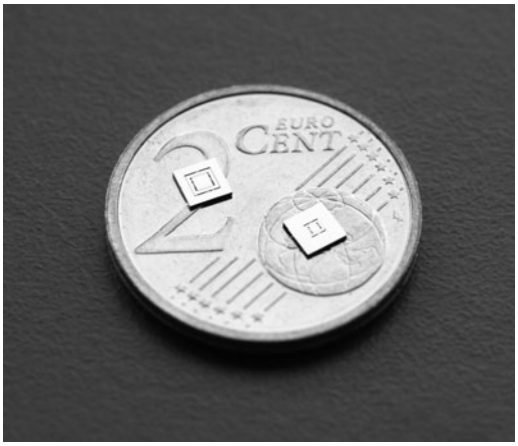

Figure 14 Silicon-based two-dimensional scanning micromirrors on a 2-cent coin, with two differing mirror sizes. The chip sizes for both are 3×3 mm.

Typical micromirror dimensions, which define an effective optical aperture, are several tens to several hundred micrometers. The image generated by the mirror is thus subject to diffraction, as illustrated for the tilting mirror of Figure 13; the diffraction pattern becomes wider as the mirror becomes smaller, so that micromirrors for imaging should be designed to be as large as possible. The structuring, however, limits the size and tilting performance. As also seen in Figure 13, the maximum tilt angle is limited by the depth of the etch below the mirror into the substrate (the actuation electrodes are mounted below the mirror, so we cannot remove the substrate altogether). Because typical values for t are perhaps 10–20 μm and for w are 500 μm, tilt angles are often limited to several degrees and are smaller for larger mirrors.

Scanning micromirrors, which exist in myriad forms, are widely used in many types of optical microsystems. The most popular commercial application is probably the digital micromirror device (DMD) found in digital projectors [44]; DMD chips with up to 1.3 million individually addressable and actuatable micromirrors are standard in these consumer products. It is likely that the DMD is by far the most successfully commercialized micro-optical component.

7. Systems and new directions

We have seen a few examples of micro-optical components and seen how advances in fabrication technology have led to the development of entirely new families of optical devices. The field is continuing to develop rapidly and we look very briefly here at a few promising new technologies.

7.1. MOEMS

The development of much modern micro-optics has been closely related to that of microsystems and MEMS [23]. Because the overlap of micro-optics and micromechanics has become significant, the field of MOEMS has seen rapid growth [45]. In MOEMS, focus is often on mechanical actuation and movement of optical components, using electrostatic, thermal, magnetic or even pneumatic means [46]. The parallel fabrication processes employed again play a major role in defining the relevance of MOEMS: complex optical systems may be realized at lower cost than could be achieved using some sort of manual assembly.

7.2. Tunable micro-optics

The small sizes of micro-optical components allow the use of numerous physical effects for tuning the optical characteristics of a device which are not applicable on larger-size scales; in particular, the use of liquids and deformable materials has led to a broad spectrum of inherently tunable micro-optical components ([3], Chapter 12; [47]).

Liquid droplets, as seen in Section 3.1, form excellent hemispherical surfaces, and the shape of these droplets may be tuned using electrowetting on an appropriate substrate [48–50]. This phenomenon has been used to realize tunable liquid lenses, which are en route to being commercialized. Tunable lenses have also been demonstrated using deformable polymers [51], thermopneumatically-actuated membrane based liquid-filled cavities [52] and as liquid compound microlenses [53]. This subdiscipline of micro-optics is under rapid development.

7.3. Optofluidics

Microfluidics is an established part of the microsystems field, and the consolidation of microfluidics with micro-optics has led to optofluidics. Using liquids both as optical media and as actuation means for components has also led to a variety of creative components and systems ([3], Chapter 13; [16, 54]). Among the types of devices demonstrated are fluidic microlenses [53]; fluidic microscopes [55]; fluidic attenuators and irises [56, 57]; fluidic microprisms [58]; and even fluidic lasers [59].

7.4. Nano-optics

Finally, as the abilities for micro- and nanostructuring advance, even smaller structures may be conceived for achieving new forms of optical functionality. Even though the wavelength of (visible) light limits the practical size of ‘classical’ refractive, diffractive or reflective micro-optical components, advances in physics and technology have opened new horizons for nano-optical devices. The concept of photonic crystal is well-established [60], variations of which have been combined with micro-optical and micromechanical structures for fabrication of novel waveguides, filters or optical sensors. Plasmonics, which relies on the use and manipulation of surface plasmon polaritons [61] has allowed the realization of, for example, extremely small waveguides [62] and a plasmon-based laser, or spaser [63]; plasmonic optical sensors are also taking advantage of micro-optics for the development of ultra-miniaturized, high-sensitivity molecular sensors. Finally, metamaterials are artificially structured ‘materials’ with customizable dielectric properties, including exotic effects such as the negative refractive index [64]; metamaterials are excellent examples of nano-optical structures whose applications are only beginning to be realized.

8. Further reading

Introductory overviews of micro-optics may be found in one of several textbooks focusing on the field [1–3]. As micro-optics is a rapidly developing discipline, the interested student or professional is encouraged to survey the literature, particularly journals such as *Optics Express*, *IEEE Photonics Technology Letters*, *IEEE Journal of Microelectromechanical Systems*, *Applied Optics*, *IEEE Journal of Selected Topics in Quantum Electronics* and the *Journal of Micro/Nanolithography, MEMS, and MOEMS*.

Acknowledgments

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References

[1] H. Herzig, Ed., in 'Micro-optics', (Taylor & Francis, London, 1998).
[2] S. Sinziger and J. Jahns, in 'Microoptics', 2nd ed. (Wiley-VCH, Weinheim, 2003).
[3] H. Zappe, in 'Fundamentals of Micro-optics', (Cambridge University Press, Cambridge, 2010).
[4] I. Fanderlik, Optical properties of glass. No. 5 in 'Glass Science and Technology', (Elsevier, Amsterdam, 1983).
[5] H. Bach and N. Neuroth, Eds., in 'The Properties of Optical Glass', (Springer-Verlag, Berlin, 1995).
[6] F. Da More, M. D. Giulio, S. Pietralunga, A. Zappettini, L. Nasi, et al., J. Appl. Phys. 94, 1654–1661 (2003).
[7] H. Zappe, in 'Introduction to Semiconductor Integrated Optics', (Artech House, Boston, MA, 1995).
[8] H. Zappe, in 'Sensors Update', Eds. by H. Baltes, W. Göpel and J. Hesse (Wiley-VCH, Weinheim, 1999) pp. 1–44.
[9] H. Li and W. Huck, Curr. Opin. Solid State Mater. Sci. 6, 3–8 (2002).
[10] L. Eldada and L. Shacklette, IEEE J. Select. Topics Quant. Electron. 6, 54–68 (2000).
[11] J. H. Simmons and K. S. Potter, in 'Optical Materials', (Academic Press, San Diego, CA, 2000).
[12] M. Gale, in 'Micro-optics', Ed. by H. Herzig (Taylor & Francis, London, 1998) pp. 153–177.
[13] S. Yasufuku, IEEE Electr. Insulat. Mag. 8, 7–15 (1992).
[14] M. Heckele and W. Schomburg, J. Micromech. Microeng. 14, R1–R14 (2004).
[15] G. Kopitkovas, L. Urech and T. Lippert, in 'Recent Advances in Laser Processing of Materials', Eds. by J. Perriere, E. Millon and E. Fogarassy (Elsevier, Amsterdam, 2006) pp. 105–136.
[16] C. Monat, P. Domachuk and B. Eggleton, Nat. Photon. 1, 106–114 (2007).
[17] X. Yuan, W. Yu, M. He, J. Bu, W. Cheong, et al., Appl. Phys. Lett. 86, 114102–1–3 (2005).
[18] H. Krause, W. Mönch and H. Zappe, Appl. Optics 45, 4843–4849 (2006).
[19] L. Eldada, Rev. Sci. Instrum. 75, 575–593 (2004).
[20] S. Campbell, in 'The Science and Engineering of Microelectronic Fabrication', 2nd ed. (Oxford University Press, New York, 2001).
[21] Y. Nishi and R. Doering, Eds., in 'Handbook of Semiconductor Manufacturing Technology' (Marcel Dekker, New York, 2000).
[22] M. Madou, in 'Fundamentals of Microfabrication' (CRC Press, Boca Raton, FL, 1997).
[23] Y. Gianchandani, O. Tabata and H. Zappe, Eds., in 'Comprehensive Microsystems', (Elsevier, Amsterdam, 2007).
[24] D. Daly, in 'Microlens Arrays' (Taylor & Francis, London, 2001).
[25] M. Hutley, in 'Micro-optics', Ed. by H. Herzig (Taylor & Francis, London, 1997) pp. 127–152.
[26] Y. Xia and G. Whitesides, Annu. Rev. Mater. Sci. 28, 153–184 (1998).
[27] D. M. Hartmann, O. Kibar and S. C. Esener, Appl. Optics, 40, 2736–2746 (2001).
[28] W. Mönch and H. Zappe, J. Optics A, Pure Appl. Optics, 6, 330–337 (2004).
[29] N. Tsurumi, W. Gao, A. Kimura and S. Kiyono, in 'Optomechatronic Systems Control', Ed. by F. Janabi-Sharifi, vol. 6052 of Proceedings of SPIE (SPIE, Bellingham, WA, USA, 2005) pp. 60520P1–8.
[30] K.-H. Brenner, M. Kufner, S. Kufner, J. Moisel, A. Müller, S. et al., Appl. Optics, 32, 6464–6469 (1993).
[31] J. Pietarinen, V. Kalima, T. T. Pakkanen and M. Kuittinen, Microelectron. Eng. 85, 263–270 (2008).
[32] K. Totsu and M. Esashi, J. Vacuum Sci. Technol. B, 23, 1487–1490 (2005).
[33] L. Shi, C. Du, X. Dong, Q. Deng and X. Luo, Appl. Optics, 46, 8346–8350 (2007).
[34] C. Rooman, M. Kuijk, R. Vounckx and P. Heremans, Optic. Eng. 44, 095005-1–095005-5 (2005).
[35] M. Hutley, in 'Diffraction Gratings' (Academic Press, London, 1982).
[36] E. Loewen and E. Popov, in 'Diffraction Gratings and Applications' (CRC Press, Boca Raton, FL, 1997).
[37] S. Wu and E. Glytsis, J. Optic. Soc. Am. B 20, 1177–1188 (2003).
[38] G. Morthier and P. Vankwikelberge, in 'Handbook of Distributed Feedback Laser Diodes' (Artech House, Norwood, MA, 1997).
[39] H. Herzig, in 'Micro-optics', Ed. by H. Herzig (Taylor & Francis, London, 1998) pp. 1–30.
[40] M. Stern, M. Holz, S. Medeiros and R. Knowlden, J. Vacuum Sci. Technol. B 9, 3117–3121 (1991).
[41] J. Stigwall and J. Bengtsson, Optics Express 12, 5675–5683 (2004).
[42] R. Conant, in 'Micromachined Mirrors' (Kluwer Academic Publishers, Dordrecht, 2003).
[43] O. Solgaard, in 'Photonic Microsystems' (Springer-Verlag, New York, 2009).
[44] P. Van Kessel, L. Hornbeck, R. Meier and M. Douglass, Proc. IEEE 86, 1687–1704 (1998).
[45] M. Motamedi, Ed., in 'MOEMS: Micro-Opto-Electro-Mechanical Systems' (SPIE Optical Engineering Press, Bellingham, WA, 2005).
[46] A. Werber and H. Zappe, IEEE J. Microelectromech. Syst. 17, 1218–1227 (2008).
[47] C. Friese, A. Werber, F. Krogmann, W. Mönch and H. Zappe, IEEJ Trans. Electric. Electron. Eng. 2, 232–248 (2007).

[48] B. Berge and J. Peseux, Eur. Phys. J. E 3, 159–163 (2000).
[49] S. Kuiper and B. Hendriks, Appl. Phys. Lett. 85, 1128–1130 (2004).
[50] F. Krogmann, W. Mönch and H. Zappe, J. Optics A, Pure Appl. Optics 8, S330–S336 (2006).
[51] P. Liebetraut, S. Petsch, W. Monch and H. Zappe, Appl. Optics 50, 3268–3274 (2011).
[52] W. Zhang, K. Aljasem, H. Zappe and A. Seifert, Optics Express 19, 2347–2362 (2011).
[53] P. Fei, Z. He, C. Zheng, T. Chen, Y. Men et al., Lab on a Chip 11, 2835–2841 (2011).
[54] U. Levy and R. Shamai, Microfluid. Nanofluid. 4, 97–105 (2008).
[55] X. Heng, D. Erickson, L. Baugh, Z. Yaqoob, P. Sternberg, et al., Lab on a Chip 6, 1274–1276 (2006).
[56] P. Müller, A. Kloss, P. Liebetraut, W. Mönch and H. Zappe, J. Micromechan. Microeng. 21, 125027 (2011).
[57] C. G. Tsai and J. A. Yeh, Optics Lett. 35, 2484–2486 (2010).
[58] A. Takei, Y. Yoshihata and I. Shimoyama, J. Micromechan. Microeng. 21, 085009 (2011).
[59] W. Song, A. E. Vasdekis, Z. Li and D. Psaltis, Appl. Phys. Lett. 94, 051117 (2009).
[60] K. Inoue and K. Ohtaka, in 'Photonic Crystals: Physics, Fabrication and Applications' (Springer-Verlag, Berlin, 2004).
[61] W. L. Barnes, A. Dereux and T. Ebbesen, Nature 424, 824–830 (2003).
[62] R. Zia, J. Schuller, A. Chandran and M. Brongersma, Mater. Today 9, 20–27 (2006).
[63] M. Noginov, G. Zhu, A. Belgrave and R. Bakker, Nature 460, 1110–1112 (2009).
[64] C. Enkrich, M. Wegener, S. Linden, S. Burger, L. Zschiedrich, et al., Phys. Rev. Lett. 95, 203901 (2005).

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