1 Introduction

Nature and Nature's laws lay hid in night: God said, "Let Newton be!" and all was light.[1]

Alexander Pope

Optics is one of the oldest fields of human inquiry, the results of which are visible to a sizable fraction of the world's population on a daily basis. Micro-optics is a sub discipline that has been more the domain of scientists and engineers, yet is increasingly, if sometimes almost invisibly, encroaching on the public domain.

The reader may justifiably ask at the outset: How do we distinguish between the two? The physics for optics and micro-optics is identical: image formation is the same for a set of 200 μm diameter microlenses as it is for 20 cm diameter projection lenses, even if secondary effects, such as diffraction, may play more of a role in one than in the other.

Nevertheless, micro-optics has two distinguishing characteristics:

- the feature sizes of micro-optics, and in many cases the sizes of the components themselves, are small, typically in the micrometer to nanometer range; and
- micro-optical components are typically manufactured using highly parallel mass fabrication techniques derived from those used by the semiconductor industry.

It is primarily for the latter reason that the history of micro-optics is a relatively recent one, as it is strongly coupled to developments in semiconductor technology.

Historical outline

Present-day applications of micro-optics range from medicine to entertainment, and it interesting to see how we have arrived at this point. We therefore defer the rigor of the science of optics for one chapter and, in this introductory survey, spend a few moments looking at the origins of optics. The history of physics, of which optics is a part, is well documented in the literature, so we will take only a cursory look at the development of a few key technologies and applications in optics, as well as a glance at how our understanding of light has developed.

Whereas optics stretches into prehistory, micro-optics is at best two centuries old, and most of this field developed significantly only in the latter part of the twentieth century. Having seen how optics evolved through the centuries, we will then focus our

[1] The poet Alexander Pope (1688–1744) intended these lines as an epitaph for Isaac Newton.

attention on the short history of micro-optics, and will look at some of the significant predecessors to the technologies and devices that form the heart of this textbook.

Finally, so as not to leave the reader with the feeling that all we are about to study is abstract or of merely theoretical interest, we will conclude the chapter with a look at a micro-optical component that has undergone an almost unparalleled development, the digital micromirror device or DMD. A commercial product that proudly sits unrecognized in many living rooms, the DMD is hidden in many video beamers but represents micro-optical technology at its finest.

1.1 Optics: history in a nutshell

There is no shortage of texts available to the historically minded optical engineer that provide a detailed look at many aspects of the history of optics: eminently readable, compact histories may be found, for example, in Römer (2006, Chapter 1) or Hecht (2002, Chapter 1), concerning medieval optics in Lindberg (1983), and in the somewhat dated Ronchi (1970). An excellent history of fiber optics is the subject of Hecht (1999). Although history of course unfolds chronologically, we will take a somewhat thematic approach here, considering three fields of inquiry that occupied many of our optical ancestors: What is light? What are its properties? And how can I engineer optics to manipulate it?

1.1.1 The nature of light

Optics is the engineering of light. But what is light, this ethereal luminosity? As obvious as the answer seems to the scientifically trained public today, it took a few thousand years to get here. The Greeks thought a great deal about the subject, and the philosophers well known to us, Plato, Aristotle and Pythagoras, developed various theories of light. In Alexandria, the center of learning for the western world following the fading of Greece's Golden Age, Euclid[2] (about 300 BCE) was one of the first to realize that light travels in straight lines. He was convinced, however, that vision is due to light rays that emanate from our eyes and strike the object seen.

Optically, very little happened in the ensuing millennium, until Ibn-al-Haitham, known in the west as Alhazen (966–1020), who came from Basra in modern-day Iraq but lived in Egypt, wrote numerous books on the study of optics: these, translated into Latin, became the source of virtually all knowledge on the subject for Europeans as they slowly awakened from the Dark Ages. In contrast to Euclid, Alhazen was certain that light is reflected *from* an object, and that the rays enter the eyes, giving rise to vision.

Despite the volume of effort expended in the development of optics in the following centuries, it was well into the Renaissance before the discussion on the nature of light

[2] We will introduce a pantheon of optical individuals in this chapter; in later chapters, we will add a little footnote describing the person for which an equation or a concept is named, thereby adding a face to the effect.

took a new turn, based on efforts to understand the measurements made of light traversing optical components. René Descartes (1596–1650), a Frenchman who lived most of his life in The Netherlands, imagined that light must be due to pressure in an unseen medium. His contemporary Pierre de Fermat (1601–1665), also French, developed the theory of "least time," which states that light will move from source to destination along the path that takes the smallest time: this principle was useful as an aid to understanding refraction.

Of what did these light beams consist? The Englishman Robert Hook (1635–1792), who first observed the details of diffraction and investigated the interference that gives rise to colored films, thought that light must have a wave-like nature. His eminent compatriot Isaac Newton (1642–1727) was convinced of the opposite: light must consist of particles. Newton was one of the first thinkers to rely on experiment rather than conjecture, and his extensive optical studies (described in a manner that still manages to captivate the modern reader in his text *Opticks* (Newton, 1740)) led him to assert that only a corpuscular nature of light could explain the rectilinear propagation that was by this time well known. The stage was thus set for an intellectual debate that was to be carried out, often acrimoniously, for several hundred years.

The weight of Newton's considered opinion was such that proponents of a wave theory for light were often ridiculed, or had their qualifications placed into doubt. Prominent corpuscularists, including most of the British scientific community as well as eminent French thinkers such as Jean Baptiste Joseph Fourier (1768–1830) and Pierre-Simon Laplace (1749–1827), stood in opposition to the Dutchman Christiaan Huygens (1629–1695), who developed a wave theory of light involving "wavelets": each point on a propagating light wave emits in turn a secondary wavelet, and the next instant of propagation is defined by the sum of these wavelets, which form a new wave. Alas, he required a medium for this to be explicable, an aether, which posed a problem to which we will return. The wave model was also supported by Francesco Maria Grimaldi (1618–1663), an Italian from Bologna, who used it to explain diffraction phenomena, and, most significantly, by the Englishman Thomas Young (1793–1829) and his French contemporary Augustin Jean Fresnel (1788–1827), who both studied interference and diffraction phenomena (Young, 1804). Young first deduced that light must be wavelike with transverse (as opposed to longitudinal, as in sound pressure waves) undulations; Fresnel extended Huygens' approach to explain rectilinear wave propagation, thereby removing Newton's primary objection to wave propagation.

The nineteenth century witnessed considerable development in the understanding of electric and magnetic phenomena, and these soon became relevant for a further understanding of light. In 1845 Michael Faraday (1791–1869) showed that the polarization of light can be rotated by the application of a magnetic field to a material in which it propagates (Faraday, 1846), hinting for the first time that optics and electromagnetics might be intertwined. The Scotsman James Clerk Maxwell (1831–1879) first unified the known relationships between electric and magnetic fields in his eponymous equations in 1873, from which it appeared that electromagnetic fields could propagate as waves with a velocity suspiciously identical to the known speed of light (Maxwell, 1861). Maxwell's ideas were singularly unpopular, particularly in Britain, and it was a prominent German physicist, Hermann von Helmholtz (1821–1894), who indirectly supported Maxwell's conclusions by offering a prize to anyone who could verify his predictions. The verification did come from another German, the Karlsruher engineering professor Heinrich Hertz (1847–1894), whose experiments showed that electromagnetic fields could be reflected and refracted, and made to form standing waves, just as one had come to expect of light. Hertz's experiments, published in 1888 (Süsskind, 1988), nine years after Maxwell's death, seemed to show unequivocally that light was an electromagnetic wave.

There was one remaining problem. All "waves" known to nineteenth century scientists propagated in a medium: air, water, or the aether. The difficulty with the latter was that it could not be detected, and various experimental (particularly astronomical) observations made sense only if this aether were fixed as objects (such as the earth and the rest of the universe) moved through it. Since the speed of light was known to be constant (in the aether), measurements of its velocity should thus vary if taken parallel or normal to the motion of the earth. The famous experiments of the Americans Albert Michelson (1852–1931) and Edward Morley (1838–1923) showed that there was no detectable motion of the earth with respect to the aether (Michelson and Morley, 1887), shedding serious doubt on its existence (the aether, not the earth). One of the first to interpret the results of Michelson and Morley as implying that there actually was no such thing as the aether was the eminent French scientist Jules Henri Poincaré (1854–1912), and the issue was seemingly put to rest by the special theory of relativity published by Albert Einstein (1879–1955) (Einstein, 1905): light waves always propagate at the same speed in vacuum, regardless of the motion of source or observer. The aether had evaporated.

Thus light was clearly a wave. Or was it? Seemingly unrelated developments in the earlier nineteenth century were unknowingly providing the seeds for the growth of an entirely new field, atomic physics. William Wollaston (1766–1828) first noted that the solar spectrum showed dark absorption lines (Wollaston, 1802), a fact re-discovered and extensively studied by the Munich glass factory owner and precision optical equipment manufacturer Joseph von Fraunhofer (1787–1826), whose name today graces these optical features. In Heidelberg, Robert Bunsen (1811–1899) and Gustav Kirchhoff (1824–1887) studied the emission spectra of a variety of media, concluding that these spectra are characteristic for any material (Kirchhoff and Bunsen, 1860). The Swiss Johann Balmer (1825–1898) derived a set of empirical expressions for the emission lines of hydrogen in 1885.

Based on these studies, the optical properties of the atom, of hitherto undiscovered structure, came more into focus. Max Planck (1858–1947) proposed that radiation emitted from a body does so in discrete quanta, and Einstein, building on these ideas, suggested that light could consist of particles of distinct, discrete energy (Einstein, 1906). These were among the first building blocks of the field of quantum mechanics, which saw rapid development in the early part of the twentieth century, with contributions by the most illustrious physicists of the age. Niels Bohr (1885–1962) developed the quantum theory of transitions in the atom, which requires discrete optical quanta, and in England in 1927 Paul Dirac (1902–1984) quantized the electromagnetic field (Dirac, 1927). The optical quanta, these "corpuscles of light," were dubbed *photons* by the

Berkeley chemist Gilbert Lewis in 1926 (Lewis, 1926), and it seems subsequently to have become clear that light is both particle and wave, and we now know what light is. Consider, however, that Einstein, toward the end of his life, wrote to his best friend: "All these fifty years of conscious brooding have brought me no nearer to the answer to the question 'What are light quanta?' Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.[3]" Some of us may thus hesitate a bit in affirming that the nature of light is really definitively understood.

1.1.2 The properties of light

While trying to understand its nature, researchers from the time of antiquity have been fascinated by the many aspects of light, many of which were only slowly understood over the centuries. Refraction and reflection were known to exist by the Greeks, even if the effects were not explainable. Euclid and Ptolemy (approximately 130 BCE), both working in Alexandria, wrote about reflection and refraction, respectively, as did Alhazen, almost 1000 years later. Very little happened in between.

The first modern text that addressed these topics was the *Perspectiva* written by Witelo (b. 1230, d. between 1280 and 1314), from Silesia, in modern-day Poland, although some historians argue that the work is merely a translation of Alhazen. The book, which appeared in about 1270, became the standard optics textbook until the seventeenth century. Witelo considered refraction, and was aware that the angle of transmission of light into a medium did not vary in direct proportion to the angle of incidence, but could neither derive the relationship nor explain the phenomenon. Almost 400 years later the German Johannes Kepler (1571–1630) discovered total internal refraction, and noted that the intensity of light decreases with the square of distance from the source, but was also unable to describe refraction adequately. He was also one of the first to consider the speed of light, thinking it infinite.

Willebrord Snell (1591–1626), a Dutchman from Leiden, finally explained the behavior of refracted light, leading to the law of refraction that now bears his name; it was Descartes who first formulated the relationship in terms of sines, the form we are familiar with today. Fermat showed in 1657 that Snell's relationship was consistent with his dictum that light propagates along the path that requires the least time, if the speed of light is slower in the denser medium. The latter point was still a bone of contention at the time.

Shortly thereafter, Robert Hook observed the effects of diffraction, as did Grimaldi for clear apertures and in the shadows of opaque objects. Hook concluded that the colors present in thin films, such as in flakes of mica or in thin soap films, were due to interference phenomena, but could not find a relationship between color and film thickness. The understanding of this effect was aided by Newton, who decomposed white sunlight into its constituent colors using a prism in 1666, causing the poet John Keats (1795–1821) to lament the unweaving of the rainbow, "Philosophy will clip an Angel's wings, Conquer

[3] Albert Einstein to Michele Besso, December 12, 1951 (Klein, 1979)

all mysteries by rule and line, Empty the haunted air, and gnomed mine—, Unweave a rainbow. . ."[4] Those of us who find beauty in science could hardly disagree more.

The Dane Erasmus Bartholinus (1625–1698) first described double refraction (birefringence) in Iceland spar (calcite) in 1669. That this effect is due to polarization of light was known to Newton, and ultimately adequately explained by Christiaan Huygens. It was shown by the Frenchman Etienne Louis Malus (1775–1812) in 1808 that polarization could be induced not only by specific crystal materials, but also through reflection. In his famous (accidental) experiment, Malus looked at the windows of the Palais du Luxembourg in Paris through a crystal of calcite and observed that the reflected light was polarized. The cantankerous Scottish minister David Brewster (1781–1868) experimented extensively on the properties of light, studying reflection, polarization, and absorption; he discovered the polarization angle (now often bearing his name) in 1811, but benefited most (financially and in posterity) from his invention of the kaleidoscope (Brewster, 1831).

Brewster was one of the last undying corpuscularists, but many of his contemporaries were wrestling with the phenomena of polarization, diffraction, and interference, trying to reconcile the effects with the assumed wave nature of light. In France, Jean Augustin Fresnel and Dominique Francois Arago (1786–1853), concomitantly with Thomas Young in England, worked extensively on this problem, coming to the crucial conclusion that light must consist of *transverse* waves. This result paved the way for significant further work on diffraction, notably by Joseph von Fraunhofer, who made the first grating-like structures, using closely spaced arrays of tightly spanned wires, and issued a first comprehensive theory of diffraction in 1823. In England, George Airy (1801–1892) first calculated the form of the diffraction intensity distribution resulting from transmission through a circular aperture (Airy, 1835), a pattern that still bears his name.

Reflection, refraction, and diffraction were effects whose understanding proved to be essential for designing optical components. A further characteristic of light, namely its speed, was also the subject of increasing interest in the seventeenth century. In Denmark, Ole Rømer (1644–1710) used measurements of the time required by Io, one of the moons of Jupiter, to transit behind the planet, taken for two positions of the Earth in its orbit, to estimate the speed of light. Based on imprecise knowledge of the radius of our mother planet's orbit, a value of $c \approx 2 \times 10^8\ \mathrm{m/s}$ was determined.

The first terrestrial measurement of c was performed in 1849 by the Frenchman Armand Hippolyte Louis Fizeau (1819–1896), who used light transmission through a rapidly rotating gear and its reflection from an 8.6 km distant mirror to obtain a more accurate value, $c \approx 3.133 \times 10^8\ \mathrm{m/s}$ (Fizeau, 1850). Also in France, Jean Foucault (1819–1868) demonstrated conclusively that light in a material moves more slowly than in vacuum, and in 1850 employed a rotating mirror arrangement to measure its speed, arriving at $c \approx 2.98 \times 10^8\ \mathrm{m/s}$. Albert Michelson also used rotating mirrors with a 35 km optical path length and determined $c \approx 2.99796 \times 10^8\ \mathrm{m/s}$ in 1926 (Michelson,

[4] John Keats *Lamia*, Part II.

1927). The value for c converged as the century continued; the defined[5] value today is $c = 2.99792458 \times 10^8$ m/s.

1.1.3 The essential optics

The engineering of optical components is likely to be considerably older than structured deliberation about the properties of light. Numerous optical devices are known from the dawn of history: Egyptian mirrors date from 1200 BCE; it is known that the Babylonians had lenses made from quartz or crystal; and similar archeological finds have been made in Assyria, dating from 700 BCE, and in Crete, from about 500 BCE.

It was again Alhazen to whom we are indebted for the first more or less modern description of basic optical components. In his eleventh century work he described spherical and parabolic mirrors, explained the magnifying properties of lenses, and described spherical aberration as well as refraction. One of the first known practical applications for optical components, namely the use of lenses for spectacles, was described in England by Roger Bacon (ca. 1214– ca. 1292), who proposed that these would be useful for correcting vision. Spectacles in general use appeared soon thereafter, notably in Florence, Italy, around 1280: these used solid glass lenses, portions of glass spheres, as opposed to the water-filled spherical containers that had been used as lenses for optical experiments up to that time.

In the sixteenth century Johannes Kepler was one of the first to describe the structure and workings of the eye, realizing correctly that the image is projected onto the retina. He explained how spectacles work, and developed the first-order theory of thin lenses. In 1608 a German-born Dutch spectacle maker named Hans Lippersley (1570–1619) first described in writing the combination of a convex and a concave lens, joined by a tube: the telescope. Hearing of this, Galileo Galilei (1564–1642) built one merely a year later, observed the mountains of the moon and the four moons of Jupiter, and changed for ever the way we look at the universe. Kepler improved on this original design, incorporating a convex rather than a concave eyepiece, and established the basis for the design on which modern refractors are still based.

In the same era, another Dutch lens maker, Hans Jansen (or, by some accounts, his son Zacharias Jansen), is believed to have proposed the the first practicable compound microscope. Still in Holland, Anton van Leeuwenhoek (1632–1723), a Delft haberdasher who took up microscopy as a hobby, ground his own lenses and made hundreds of observations using a single-lens magnifier: he thereby avoided the strong chromatic aberration that limited the performance of compound lens systems. Robert Hook designed a three-lens microscope, with a converging "telescope" eyepiece, as designed by Christiaan Huygens, which represented a considerable improvement over the original systems.

[5] The speed of light is no longer measured; since 1983 it has been defined based on the definition of the meter, which in turn is the distance light travels in vacuum in $\frac{1}{299792458}$ s.

Chromatic aberration proved to be a serious problem for telescopes as well, and Isaac Newton, believing the problem unsolvable, designed what is known today as the Newtonian reflector in 1668. Despite the quality and future applicability of this telescope design, chromatic aberration was not an unsolvable problem. The English jurist and amateur mathematician Chester Moor Hall (1703–1771) first proposed a combination of crown and flint glass as an achromatic lens; he had it fabricated, and made the first achromatic telescope, but failed to have the lens patented. That latter mistake was not made by the London silk weaver turned lens maker John Dollond (1706–1761), who patented and produced achromatic lenses using this principle starting in 1757, subsequently being appointed as optician to the King.

In the eighteenth and nineteenth centuries, lenses, and the optical equipment made from them, improved rapidly. The American polymath, politician and bon vivant Benjamin Franklin (1706–1790) is credited with having invented bifocals. The astigmatic George Airy used cylindrical lenses to make spectacles that corrected astigmatism, and in 1888 the German Adolf Eugen Fick (1829–1901) first proposed and demonstrated contact lenses (Fick, 1988).

The design and improvement of lenses and lens systems was supported by developments in theoretical understanding of optical systems. Instrumental in these advances was the German Johann Carl Friedrich Gauss, who proposed a comprehensive mathematical description of imaging, forming the basis for what is today known as "Gaussian optics." In England, Joseph Jackson Lister (1786–1869), a wine merchant and amateur microscopist, was the first to propose and fabricate achromatic lens systems for microscopes, and also produced designs that corrected spherical aberration. His son, also Joseph, trained by the father in microscopy, is arguably better known today, for promoting antiseptic procedures in surgery. The German optician Ernst Abbe (1840–1905), professor of physics in Jena and a director of the Carl Zeiss company, finally developed a more detailed theory of image formation, and invented approaches for lens design that corrected many aberrations, including coma; many of these techniques are unparalleled today, and are still in use.

With that we arrive in the twentieth century, the first half of which saw optics established as a considerable industrial enterprise and become the subject of a wide spectrum of research endeavors. Perhaps the two events that did most to irrevocably expand the field were the invention of the light bulb by the American Thomas Edison (1847–1931) in 1879 (Edison, 1881) and the invention of the laser, also by an American, Theodore Maiman (1927–2007) in 1960 (Maiman, 1960). These light sources have become as established in optics technology as much as the lenses first regarded by the Assyrians three millennia ago.

1.2 Micro-optics: a smaller nutshell

The history of micro-optics is considerably younger than that of macroscopic optics. The expression *micro-optics* first appears in the literature only in the 1980s (Iga *et al.*, 1984), but some of the optical components that today constitute our field are considerably older. The diffraction grating is likely the senior member of the micro-optical family, and is probably the first optical device for which micrometer-size features are essential. One of the classic modern texts in diffractive optics is that of Hutley, and his historical introduction (Hutley, 1982, Chapter 1) inspires us here.

The first mention of fabricated periodic structures with an optical effect refers to the studies of the American astronomer and public official David Rittenhouse (1732–1796). Apparently inspired by the transmission of light through a fine silk handkerchief, he fabricated closely spaced arrays of 50 hairs and noted wavelength-dependent diffraction, as well as the separation of an image into its various color components. Rittenhouse, however, made no quantitative analysis of what he saw, so it is Joseph von Fraunhofer, a half century later, who is commonly credited with having invented the diffraction grating. Working with periodic arrays of fine wires and ruled grooves on a mirror in 1821, von Fraunhofer derived the grating equation, quantified the wavelength dependence of diffraction, and for the first time used these advances to measure the wavelength of light.

In England, Lord Rayleigh (1842–1919), with the civil name John William Strutt, first used gratings for spectroscopy (Rayleigh, Lord, 1874), showing that the resolution was superior to that achievable using prisms. However, gratings did not replace prisms for this application until the 1950s, primarily because of their high cost, which was based on the way they were manufactured. The American Henry Augustus Rowland (1848–1901), at Johns Hopkins University in Baltimore, invented the grating ruling engine in 1882, and Robert W. Wood (1868–1955), of the same institution, devised the concept of blazing to improve grating efficiency. In 1915 Albert Michelson employed interferometric measurement techniques coupled with servo mechanisms on a ruling engine for precise positioning and spacing of the grating periods. The precision of the manufacturing process made Johns Hopkins the prime source for ruled diffraction gratings world wide in the early twentieth century.

The popularity of diffraction gratings increased markedly with a decrease in their cost brought about by the use of replication techniques for mass-producing the components. Patented by John U. White and Walter A. Fraser of Perkin-Elmer Corporation in 1949 (White and Fraser, 1949), the approach, still the basis for low-cost grating manufacture today, allowed the reproduction of large volumes of high-precision gratings from a single, expensive master. As a result, the spectrum of potential applications expanded rapidly, and replication is still one of the essential techniques employed in the fabrication of modern diffractive optical components.

Working in England in 1948, the Hungarian Dennis Gabor (1900–1979) invented holography (Gabor, 1948). Using a coherent electron beam (the laser was still 12 years away), Gabor showed that an interference pattern generated and written into a film by reflection from an object and a coherent reference beam could be used to store image information about the object, and this image could be reconstructed upon coherent illumination. Although the technique is now done with photons rather than electrons, it forms the basis for the generation of general diffractive structures that, upon illumination with a coherent light source, can yield almost arbitrary intensity patterns.

The invention of the laser in 1960 greatly expanded the capabilities of holography and related techniques. In 1968 it was shown that one-dimensional interference patterns could be used to generate gratings by exposure of photosensitive material (Burch and Tokarski, 1968), thereby obviating the need for mechanical ruling of diffraction gratings: this so-called interference lithography is the method of choice for defining one-, two- and three-dimensional periodic structures today. In the late 1960s the generation of holograms by computer was demonstrated (Lohmann and Paris, 1967), allowing the definition of arbitrary diffraction patterns (no longer necessarily periodic) in a film and their associated intensity patterns generated upon illumination. In the same era, kinoforms, phase-only holograms, were conceived, these reducing the parasitic diffraction orders and improving the efficiency of image generation (Lesem *et al.*, 1969).

The advent of lithography technologies, developed primarily by the burgeoning semiconductor industry, in the early 1970s, provided new opportunities for diffractive optics and ultimately paved the way for micro-optics as we know it today. Newly developed abilities to photolithographically define arbitrary two-dimensional patterns with micrometer accuracy on a semiconductor or glass substrate allowed definition and fabrication of microlenses (Iga *et al.*, 1982), Fresnel zone plates or Fresnel lenses defined by multiple phase levels (d'Auria *et al.*, 1972; Fujita *et al.*, 1981). These were circularly symmetric structures with micrometer-sized features both laterally and in depth, and represent among the earliest microlens structures of the form we often employ now, the wide, relatively flat components fabricated on a transparent substrate. By the mid 1980s these diffractive lenses had advanced in vertical resolution using the concepts of binary optics, in which N masks can be used to fabricate 2^N phase levels (Stern, 1997); for large numbers of phase levels the discrete surface steps in one of these Fresnel-like lenses approach the continuous form of a refractive lens.

The wish to make truly refractive lenses, with a continuous surface profile, became reality in the 1980s through the use of photolithographically patterned circular photoresist posts, which were subject to reflow at high temperatures; surface tension forms a spherical cap of the molten resist and thus, upon hardening, a spherical lens (Popovic *et al.*, 1988; Daly *et al.*, 1990; Daly, 2001). The photoresist itself could be used as the optical element, or the pattern could be transferred into the substrate by etching. The technique allows fabrication of accurately defined single lenses or large arrays, and is still a standard technology.

Micro-optics, however, is more than gratings and microlenses, even if it once might have seemed that way. The field finds itself today at the juncture of numerous technologies, which in combination have considerably broadened the scope of possibilities for miniaturized optics (Sinziger and Jahns, 2003; Borrelli, 2005; Herzig *et al.*, 2005; Kress and Meyrueis, 2009). One of these essential technologies is that of light sources: for micro-optical systems, these are most often laser diodes or LEDs. The history of semiconductor light emitters begins with the invention of the semiconductor laser diode, demonstrated and published by four American groups almost simultaneously in 1962. The rapid development of diode lasers, spurred primarily by the goal of viable optical telecommunications, has resulted in a field that has advanced to the point where