Review of Optical Manufacturing 2000 to 2020

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Introduction

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In the history of technology, scientific ideas for systems and components were often conceived in theory well before practical implementation was possible. However, manufacturing capability often sets the practical limit of scientific exploration. Manufacturing technological development has always been the key measure for research and commercial implementation, especially in our field of optics and photonics. Visionary leaders in the field, technical and business, might want to keep up with the advancement of manufacturing capability to effectively invent, develop, and make decisions.

Optics and photonics are often a critical part of the solution to many challenges facing humanity, whether it the constant need for energy sources, medical solutions (as we write this introduction, the world is coping with the Covid-19 crisis), or numerous other industrial, consumer, and defense applications. With this background, it might be a proper time to look back at the industry of optical manufacturing at this critical time in human history, and prepare for the challenges ahead.

During the period of 2000–2020, the industry of optical manufacturing witnessed dramatic changes in key areas for hardware implementation such as optical materials, fabrication methods, and metrology, to name a few. Some of these technologies have incubation periods back to the 1990s or even earlier. This review aims to summarize some of the critical changes that have impacted the way optical systems are manufactured. It evaluates a number of new manufacturing techniques with growing popularity, and points out some trends in optical manufacturing in the future. Several fundamental questions that we try to elucidate in this review book include:

Chapter 2

Optical Materials

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2.1 Introduction

Photonics plays an important role driving innovation and enabling technology for many markets. The application of photonics spreads across very different areas: from optical data communication to imaging, lighting, manufacturing, life sciences, health care, security and safety. Photonics offers new and unique solutions where today's conventional technologies are approaching their limits: speed, capacity and accuracy. The impact of photonics in our daily lives is remarkable. It becomes visible by looking at some current challenges:

- Augmented and virtual reality for consumers and even more relevant for industrial applications.
- Assistance systems in automotive as rear/side-view cameras, LED/laser lighting, lidar, night vision support, head-up displays, etc.
- Industry 4.0 with its connected individual production lines and substitution of humans in mechanical and electric production lines by robots requires exact three-dimensional imaging, object recognition, barcode scanning, quality inspection, distance control, and absolute optical measurements.
- Continuous development of displays with higher resolutions or trends like "internet of things" need lithographic production lines with

2.3.2 Making of fused quartz and fused silica

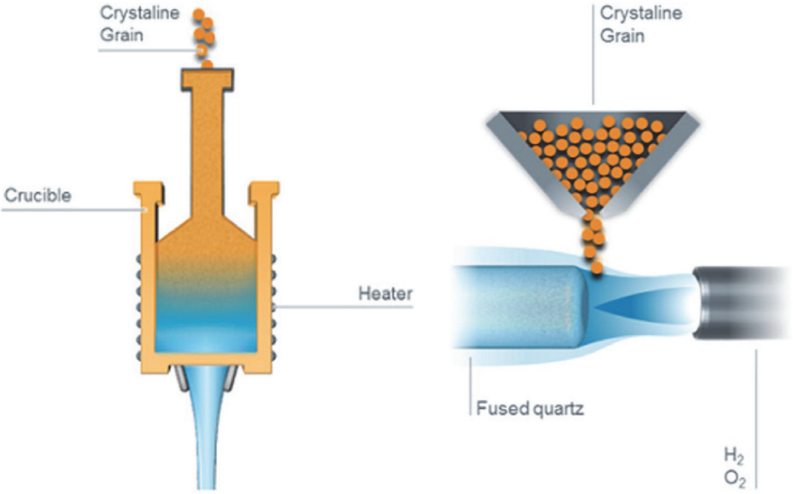
There are two distinctive ways to produce quartz glass. One starts with high purity quartz or other silicon-dioxide-containing minerals that are fused using various heat sources. The other starts with gaseous silicon containing chemicals (e.g., $SiCl_4$) that are burned in the presence of oxygen to form silicon dioxide.

2.3.2.1 Fused quartz

Electric fusion

Electric fusion is the most used melting process for manufacturing quartz glass. Two methods of electric fusion can be used:

- Continuous fusion: In the continuous method, quartz sand is poured into the top of a vertical melter that consists of a refractory metal crucible surrounded by electric heating elements; see Figure 2.29(a). The interior is maintained in a neutral or slightly reducing atmosphere that keeps the silica from reacting with the refractory metal. The melted material exits the bottom orifice of the crucible, which is shaped to produce rods, tubes, plates or other products of various dimensions.
- Batch or boule fusion: In the batch fusion method, a large quantity of raw material is placed inside a refractory lined vacuum chamber which also contains heating elements. Although this method has historically been used to produce large single boules of material, it can also be adapted to produce much smaller, near-net shapes.



(a) (b)

Figure 2.29 (a) Continious electric fusion of fused quartz; (b) flame-fused quartz manufacturing.

Flame fusion

Historically, the first method of producing fused quartz was by small-scale fusion of quartz crystals in a flame. Heraeus chemist Richard Küch first began fusing quartz rock crystal in a hydrogen/oxygen (H_2/O_2) flame more than 100 years ago. Heraeus has been producing quartz glass on an industrial scale with this process ever since.

Today, flame-fused quartz is manufactured on a large scale by a continuous process in which highly refined quartz sand is fed through a high-temperature flame and deposited on the surface of a melt contained in a tank lined with refractory material; see Figure 2.29(b). The viscous melt is withdrawn slowly through a die in the bottom of this tank, and it solidifies in a shape determined by the die. In this way, it is possible to produce an ingot of transparent fused quartz of the desired cross-section (round, rectangular or hollow), which is cut off at intervals and removed for further processing.

2.3.2.2 Fused silica

In this process, the silicon containing precursors (e.g., $SiCl_4$) are burned in the presence of oxygen to form nanoparticles of silicon dioxide, also called soot. Because the precursors are specifically produced and refined, they are available in exceptionally high purity and the resulting fused silica has a very low metallic impurity content.

As the production process involves vapors of chemicals (silicon-containing precursors), it is called chemical vapor deposition (CVD). There are two sets of process families, one where the deposited nanoparticles are directly melted to a condensed fused silica layer, and one, where the soot is accumulated and in a secondary process step condensed to transparent fused silica (this process is called vitrification).

One-step fused silica production

> **Direct quartz (DQ)**: This method is widely used to produce fused silica for optical applications. The silicon dioxide nanoparticles generated by the combustion of a silicon containing precursor are directly and transparently fused to a quartz glass ingot which is redrawn in the same speed as the length of the ingot increases due to deposition. OH contents of more than 400 ppm are typical.
>
> **Chemical vapor deposition (CVD)**: To produce optical fiber core rods, deposition of fused silica with a defined refractive index is done inside of fused silica tubes. The chemicals are brought into the tube by a carrier gas. The reaction to form soot is triggered by a heat source. There are different heat sources employed, and they differentiate the flavors of the CVD process. The heat source is either a flame (MCVD), a furnace (FCVD) or a plasma (PCVD). All gases that have not reacted are treated in a scrubber.

Chapter 3
Optical Fabrication

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3.1 Introduction

Optical components, or lenses, have been used for thousands of years. Ancient artifacts that appear to be lens shaped pieces of rock crystal have been dated to approximately 1600 BCE [1]. It was hundreds of years later when we first have documentation about the fabrication processes used to create these optics. Corrective lenses were said to be used by Abbas Ibn Firnas in the 9th century, who had devised a way to produce very clear glass. He shaped and polished his glass into round rocks that he used for magnified viewing. He called these rocks "reading stones" [2]. Circa 1719, Antonie van Leeuwenhoek built a simple microscope with only one lens to examine blood, yeast, insects and many other tiny objects. Leeuwenhoek was the first person to describe bacteria, and he also invented new methods for grinding and polishing microscope lenses that allowed for curvatures providing magnifications of up to 270-mm diameters, the best available lenses at that time [3]. Optical fabrication methods continued to advance over the years, highlighted by Sir Isaac Newton and Frank Twyman. Newton is often cited for his use of optical polishing pitch to polish the optics for his telescope [4]. Twyman also made significant contributions to the field of optical fabrication [1].

For several centuries, optical fabrication methods stayed fairly consistent. In the 1960s, there were two disruptive technologies that significantly changed how optics were manufactured, the laser and the computer [5,6]. The laser and the computer enabled laser-based interferometry and analysis methods and computer numerically controlled (CNC) deterministic grinding and polishing, all of which are critical in the modern optical fabrication shop.

This chapter will review the fundamentals of traditional optical fabrication methods and mechanisms of material removal, and then focus on advancements in modern optics manufacturing.

Chapter 4

Metrology

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4.1 Introduction

Humanity has been interested in optics for quite some time, the desire to expand our powers of observation being a powerful motivator for discovery and engineering. One example of this is the Nimrud lens, an oval-shaped rock crystal plate discovered by English archaeologist Henry Layard in 1853. The crystal, dated between 900-700 BCE, is bi-convex and has been theorized to have uses ranging from a simple magnifying glass to being a lens in a telescope [1]. Figure 4.1 demonstrates the Nimrud lens as it appears today, along with the surface profile, which is not the perfectly symmetrical shape we are so familiar with today in modern optics.

As civilizations grew and changed, so too did optics. By the fifteenth and sixteenth centuries, the optical sciences had advanced enough that convex and concave lenses for eyeglasses were at least available, if not common place [2]. Of course, these optics were not the precision lenses we are familiar with today. By studying works of art from the same period, it has been observed that some painters used optical elements as an aid in their endeavors. This observation was enabled by the fact that said optical elements had significant aberrations and artifacts that carried over into the final works [3].

In just a few hundred years, a short time span when compared to the scope of humanity, scientists rapidly evolved their capabilities when it came to making optics. While the astral bodies and mysteries of space have been inspiring the search for knowledge since the beginning of humanity, in the sixteenth century, optical devices began to make great strides to expand our ability to peer into this vast frontier of the until then unknown. In 1609,

4.3.2 Non-contact slope sensor scanning

Further methods of measuring mid-to-high spatial frequencies also involve using high resolution optical profilometry using a precision mechanical scanning stage and an optical slope sensing probe. Optical profilometry tools also measure slope but cover the spatial dimension by scanning the device on mechanical stages. The device measures the local slope of the surface, and records over time as it is moved across the entire aperture. Many samples are taken as the device is scanned, leading to very high spatial resolution. To measure the local slope, a light source illuminates a small area on the surface and the reflection is monitored. The change in the reflected angle is used to calculate the local slope value. With these instruments, sub-microradian slope accuracy is achievable, which results in height errors on the order of nanometers RMS [33,34], as shown in Figure 4.12.

4.3.2.1 Practical tips

In order to obtain high-accuracy mid-spatial-frequency data, calibration of the instrument is paramount. Due to the sensitivity of these devices, multiple repeated measurements may be required to average out vibrational or random noise. Finally, it must be noted that while this technique uses non-contact sensors, it nonetheless relies on mechanical stages and motion to capture a full measurement. Thus, the technique is only as accurate as its weakest link, such as systematic bias or errors. Fortunately, high-precision mechanical devices are available. Also, multiple sensors in a specific array can be utilized simultaneously to provide a self-calibration capability during a scanning path.

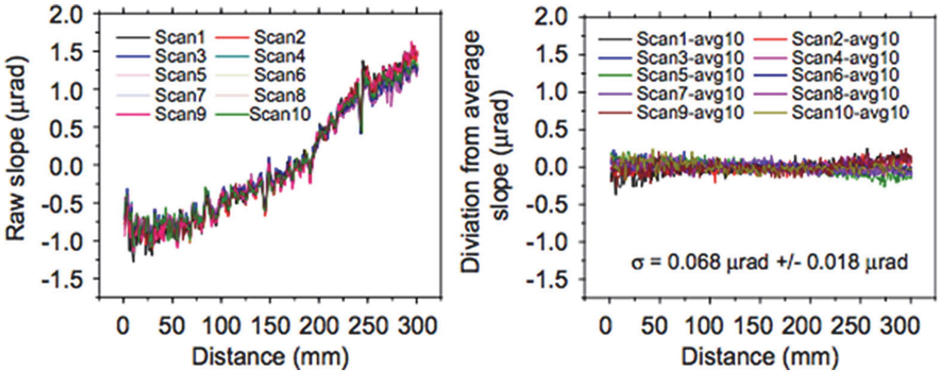

Figure 4.12 Ten measurements of the same surface with the raw slopes on the left, and the deviation from the averaged profile on the right. We see a sub-microradian slope accuracy [33]. Reprinted from *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, J. Qian et al., Performance of the APS optical slope measuring system, Copyright (2013), with permission from Elsevier.

Chapter 5

Optical Coatings

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5.1 Introduction

The primary application of optical coatings on a surface is to control reflection from that surface. It might be to increase the reflection to make a mirror, or it might be to reduce the reflection like an anti-reflection (AR) coating on a camera lens, etc. The coating might also be to control the color or amount of the light reflected or transmitted at that surface like a beamsplitter. This might be a wavelength-selective coating or color-filter. An extreme case of a color-filter coating is one which only passes a narrow band. Such a narrow bandpass (NBP) filter might be produced to pass only a certain laser light while reflecting all the “noise” of other wavelengths as in a fiber-optics communication filter.

The physical principles needed to understand and produce optical thin film coatings were becoming known before the twentieth century and were particularly aided by the work of Huygens, Newton, Fresnel, Maxwell, and others. One generally wants a coating which is solid on the coated surface and which will endure whatever environmental conditions that it is expected to experience in its application. In the early twentieth century, most physical materials for coatings were heated in a vacuum until they evaporated; the atoms or molecules travelled without collisions with other atoms or molecules through a vacuum; and they condensed on a cooler surface to form the coating. This is generally referred to as physical vapor deposition (PVD). A vapor can also be formed by an arc or by sputtering. Sputtering of target materials occur when gaseous ions are formed and accelerated into the target to dislodge atoms or molecules by their momentum transfer. Arcs do similar things by putting a lot of energy like a lightning bolt on a small spot of the target and causing it to boil and throw off particles and vapors. These were already being demonstrated in laboratories in the 19th century.

Chapter 6

Infrared Optical Systems

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6.1 Introduction

From 2000 to 2020, infrared (IR) optical systems have experienced a strong transition from primarily a military technology and application to an increase in commercial and consumer products. This transition has enabled or driven many component advances primarily related to detectors and sources. This chapter discusses two basic aspects of this transition: (1) new applications and (2) component developments. The two categories are, effectively, intertwined; the former often drives the latter or said another way "necessity is the mother of invention." Component developments include advancement in detectors, materials, fabrication techniques, and metrology, to name just a few. A major trend in infrared systems is significant miniaturization of previously bulky systems reducing size, weight, power consumption, and cost (SWaP-C) over the past two decades. It is this factor which paved the way into a large variety of new industrial and commercial applications.

The infrared spectrum division into bands can vary between industries and personal views but tend to be defined from three different perspectives: (1) light propagation through air, i.e., atmospheric transmission; (2) emission source, e.g., lasers, thermal, etc.; and (3) detector materials. In this work, we are taking the latter approach, which is consistent with the approach chosen for ANSI/OEOSC OP1.007 – Spectral bands [1]. Currently, there is interest in an international version of this standard, but it has not been fully resolved.

The IR spectrum ranging from 0.75 μm to 30 μm is divided into near-infrared (NIR), short-wave infrared (SWIR), mid-wave infrared (MWIR), long-wave infrared (LWIR) and very-long-wave infrared (VLWIR). NIR light extends from 0.75 to 1.1 μm and has been widely used for imaging and sensing of digital products and night vision imaging in security cameras. SWIR light, considered to range from 1.1 to 3 μm, is regularly employed in agricultural and industrial inspection and covers the mainstream fiber optical communication wavelength range of about 1.53 to 1.57 μm. Due to transparent windows in the NIR and SWIR in biological tissue, imaging spectroscopy is also used for medical imaging. MWIR light ranges from 3 to 5 μm, lies in the transition zone from reflective radiation to thermal radiation, and is widely used in defense, industrial inspection, and various remote sensing applications. LWIR light is from approximately 5 to 14 μm, measures the thermal radiation of objects, and is commonly utilized for defense, medical imaging, industrial and environmental monitoring. It is important to note that the typical definition of LWIR is around 8 to 14 μm due to the atmosphere having little to no transmission in the 5- to 8-μm region – light absorption of H_2O and CO_2 in the atmosphere. This band is being standardized to cover this atmospheric absorption window for continuity and applications where atmospheric transmission is not a factor or at least has minimal effect on system performance. Additionally, there is a VLWIR region that ranges from 14 to 30 μm with applications in spectroscopy, astronomy and long-range missile detection. All these bands are primarily based on a combination of detector technologies and atmospheric transmission as summarized in Table 6.1 along with typical optical materials.

In the past two decades, NIR optical systems have seen significant development. Common NIR systems include oximeters, heart-rate monitors, proximity sensors, and biometric systems based on fingerprint, face, iris, or vein recognition. These applications have seen explosive growth in consumer

Table 6.1 IR spectral bands, common optical materials, and typical detectors [1].

Spectral Band	Wavelength Range (μm)	Common Optical Materials	Typical Detectors	Prevalent Sources
NIR	0.75–1.1	Visible glasses	Si, InGaAs, HgCdTe	Incandescent lamps, LED, laser diodes, fiber lasers, DPSS
SWIR	1.1–3.0	Visible glasses, Si, ZnSe, ZnS, Chalcogenides, CaF_2, BaF_2	InGaAs, HgCdTe	LED, laser diodes, DPSS, black bodies
MWIR	3.0–5.0	Si, Ge, ZnSe, ZnS, CaF_2, BaF_2, Chalcogenides	InSb, HgCdTe, PbSe	Lasers, QCLs, black bodies
LWIR	5.0–14.0	Ge, ZnSe, ZnS, CaF_2, BaF_2, Chalcogenides	HgCdTe, Bolometer, Pyroelectric, Thermopiles	Lasers (CO_2), QCLs, black bodies
VLWIR	14.0–30.0	NaCl, KCl, Kbr, CdTe, KRS-5, CsBr, CsI, IR Plastics	Doped Si, Bolometer, Pyroelectric, Thermopiles	QCLs, black bodies, monochromator

Chapter 7
Polymer Optics

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7.1 Introduction

The field of polymer optics has expanded at an explosive rate during the period between 2000 and 2020. Reasons for this increased prominence include reduced cost, decreased weight, expanded geometry options, and simplified assembly. Numerous publications focus on the benefits of polymer optics in depth [1,2,3,4,5,6,7,8]. Since such detail is beyond the scope of this work, the summary in Table 7.1 is provided to give the uninitiated reader a sense for the advantages that polymer solutions offer over traditional glass optics.

The use of polymer optical components and systems is now several decades old. Their penetration into commercial and consumer products [9], medical instrumentation for surgical and diagnostic testing [10,11,12,13,14,15,16], and enhanced vision systems and armaments for defense and aerospace platforms [7,17,18,19,20,21] has grown significantly in the preceding two decades. Some recent representative examples are shown in Fig. 7.1. The diversity of applications continues to expand; the final part of this section discusses several of the emerging techniques and applications that form the frontier of polymer optics.

7.2 Polymer Materials

The workhorse materials fabricating polymer optics are polycarbonate (PC), polystyrene (PS), and acrylics such as polymethyl methacrylate (PMMA). In addition to these standard polymers, cyclic olefin polymers and copolymers (COP, COC) and polyethylenimine (PEI) are now in common use. More recent polymers now finding application in optics include high-refractive index options such as the Osaka OKP family (O-PET) and EP5000 (PC), and low-birefringence variants of existing polymers such as ZEONEX F52R (COP)and TOPAS (COC) – the latter also has advantageous transmittance

Chapter 8

Optical Fibers and Optical Fiber Assemblies

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8.1 Optical Fibers

The guiding of light in various materials (glass and water) using the principle of refraction has been demonstrated throughout history, in fact this phenomenon was known in ancient Egypt and Mesopotamia where colored glass was used for decoration. In the late 19th and 20th century, various pioneers demonstrated the use of bent glass rods to illuminate cavities in the body and for early form of television. The bare glass fibers/rods that were used in these experiments were, however, very lossy which meant that they did not transmit a lot of light. The loss of light in these fibers was due to light escaping when these fibers touched each other or when they had scratches on the surface. These issues were solved during the 1950s when the idea of cladding a fiber was demonstrated by Bram van Heel [1], and in the same year N. S. Kapany and H. Hopkins demonstrated image transmission in a bundle of 10,000 fibers 75 cm long [2]. The theory of light propagation into fibers was described by N.S. Kapany and improved later by E. Snitzer [3]. The theory of the use of optical fiber for communication was developed and promoted by C. K. Kao and G. A. Hockham in 1965 [4,5].

Since 1970, low-loss optical fiber (invented by Corning) has steadily replaced the use of copper wire for long-range telecommunication and data transmission [6]. Although most of the optical fiber produced (in terms of length) is used for telecommunication and data transmission, optical fibers are finding uses in many other applications, such as astronomy, biomedical instrumentation, communication, defense, digital projection, industrial laser, medical, semiconductor manufacturing, spectroscopy, and many others. For these applications, specialty optical fibers are required. A specialty optical

8.2.6 High-power design considerations

When designing a high-power laser delivery cable, there are three main components that must be considered: the fiber material, the input connector, and the mode stripper (if necessary).

The first thing to consider is the fiber and the fiber-to-laser interface. Common to many high-power fibers is a step-index fused silica core and a fluorine-doped fused silica cladding. A high-purity fused silica core is capable of handling huge amounts of laser energy. The challenge to getting the energy into the fiber is the air-silica interface, which occurs at the input connector. The quality of the polish will maximize the amount of power that the interface will handle. Laser polishing of the fiber after the normal polishing step has been shown to increase the power handling by as much as 10–15%. This is done with a CO_2 laser that scans across the face of the fiber and re-melts the top surface, removing any subsurface micro-cracking or scratches left behind from the polishing media.

The failure mode for continuous wave (CW) lasers is thermal, caused by microscopic irregularities in the air-silica interface that absorb energy. For pulsed lasers, the failure mode can either be thermal or a dielectric breakdown at the atomic level, depending on the laser's characteristics. In either case, there is a maximum amount of power per unit of area that can be coupled into the fiber referred to as the laser damage threshold (LDT). For CW lasers, this is expressed in W/cm^2, also known as irradiance. For pulsed lasers it is J/cm^2 and is known as fluence. The reason for the difference is that CW lasers run, as the name suggests, as a continuous stream of unbroken energy, while pulsed lasers operate as a series of pulses, or bursts of repeating energy.

Determining if a laser will damage a fiber involves calculating the irradiance or the fluence for the laser by dividing the CW power or the energy per pulse, by the area of the beam where it makes contact with the fiber. The LDT for a CW laser and at the air-silica interface is 1.5 MW/cm^2 (at 1064 nm) and for a pulsed laser, 16.0 J/cm^2 (at 1064 nm and 1 ns). As a rule, lower wavelengths will require larger fibers or lower powers to couple into the fiber. For a pulsed laser, it may require lower power or a combination of lower power and longer pulses.

There are a few common connectors that are used for high-power assemblies. One is the SMA, another is the D80, but what make them work well are a few common characteristics. The connectors are precision machined and feature an epoxy free termination at the tip. This is done by what is called an air-gap or a cantilevered fiber tip. Epoxies and other organic materials, if left on the fiber face, will cause the fiber to burn when a laser strikes it. So, an air gap removes epoxy from the front where a laser might contact it and cause it to burn or heat up to the point that it fails and causes outgassing on the fiber face. See Fig. 8.26. for a view of an air-gap interface.

Chapter 9

Diffractive- and Micro-structured Optics

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9.1 Introduction

Diffractive- and micro-structured optics technology provide new degrees of freedom for the design and optimization of optical systems. Using this technology one can create: large-aperture, lightweight optical elements; correct optical aberrations and achromatize optical systems; eliminate or reduce the need for exotic materials, such as flint glasses; combine multiple optical functions; and reduce significantly optical system weight, complexity and cost.

Important applications of diffractive- and micro-structured optics that have been developed, and in many cases have matured, include areas such as visible and infrared imaging systems, laser beam shaping for optical sensors, solid-state (LED) lighting, and display and image projection systems.

A diffractive optical element is an element whose fundamental operating principle is based on the wave nature of light. The basic physics of diffractive optical elements have been studied for hundreds of years and can be found in numerous modern textbooks [1,2,3]. A fundamental principle of wave optics is based on the superposition (or addition) of waves, wherein the notion of constructive and destructive of waves plays a key role, and results in bright and dark regions, bands or spots of light.

One can think of a diffractive optical element as an optical beam (or wavefront) converter, which converts an incident wavefront into the desired output wavefront. Two important attributes of the desired output wavefront are its shape and its diffraction efficiency, i.e., the fraction of the incident wavefront energy that is contained in the desired output wavefront.

Shortly after the invention of the laser and holography in the 1960s, researchers began to develop holographic optical elements. A hologram is a recording of an interference pattern produced by the superposition of spatially coherent light beams, and is one of the fabrication methods that has and can be used to create diffractive optical elements [4,5]. There has been a tremendous amount of work directed toward the development of methods to improve the diffraction efficiency of holograms, which can be divided into three basic approaches – (1) use of volume materials, which relied on the constructive interference from Bragg planes within the material; (2) bleached holograms, which involved the conversion of amplitude (absorptive)-type holograms into phase-type holograms; and (3) blazed surfacerelief- type holograms.

In the late 1960s to the early 1990s, methods of fabrication and applications of computer-generated holograms (CGHs) were developed. Rather than using the superposition of coherent optical beams to record the interference pattern, the interference pattern is calculated mathematically using a computer and then sent to some sort of plotter to create a CGH. Generally, CGHs are binary in nature – either an amplitude- (black and white) or phase- (0 and π) type hologram. One of the major uses of CGHs is for optical testing [6].

In the 1990s a new approach for the fabrication of diffractive optical elements was developed, which was called "Binary Optics" [7]. The binary-optics approach to fabrication is to utilize photolithographic equipment and processes developed for the semiconductor industry to produce surface-relief (or phase-type) optical elements. While multi-level phase elements can be fabricated using these techniques, the nomenclature of "binary optics" has been used to indicate that each step in the fabrication process is binary in nature. The binary-optics fabrication process will be discussed in greater detail in Section 9.2.

While the application of CGHs in optical testing generally does not require high diffraction efficiencies, most applications involving diffractive optical elements do require that the efficiency be as high as possible in the desired wavefront or diffracted order.

It is instructive to consider the maximum diffraction efficiencies that can be produced with various types of planar (thin) holographic gratings as illustrated in Fig 9.1 [8]. An amplitude transmission of "1" represents clear, and "0" represents opaque portions of the grating.

In Table 9.1, the corresponding transmission functions, together with the diffracted amplitude and irradiance in of the first diffracted order, are listed for each of the holographic gratings illustrated in Fig 9.1. In the case of the amplitude (or absorptive) sinusoidal grating, the sinusoidal portion of the transmission function can be written as

Chapter 10

Illumination Optics

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10.1 Introduction

An illumination system consists of the light source(s), some optical components and a target, the latter literally carrying the specs which are defined by the field of application. In our review we will discuss design, technology, and fabrication of light sources and components. As there are considerable differences between the many fields of application, we start with a general view and derive the technical specialties afterwards.

In some cases we will name representative suppliers without the intention to exclude others. With the help of such a reference, the interested reader will be able to gather information, understand the product and find similar suppliers easily.

We restrict the review to visible, incoherent light and related optical elements.

10.2 Fields of Application

We start with an overview on the various fields and markets of lighting and illumination optics:

- General lighting (office lighting, high bay, decorative lighting, hospitality, and much more). *Interestingly, mankind did and does always spend the same share of the gross domestic product for lighting purposes* [1])
- Automotive exterior lighting (low and high beam, daytime running lights)