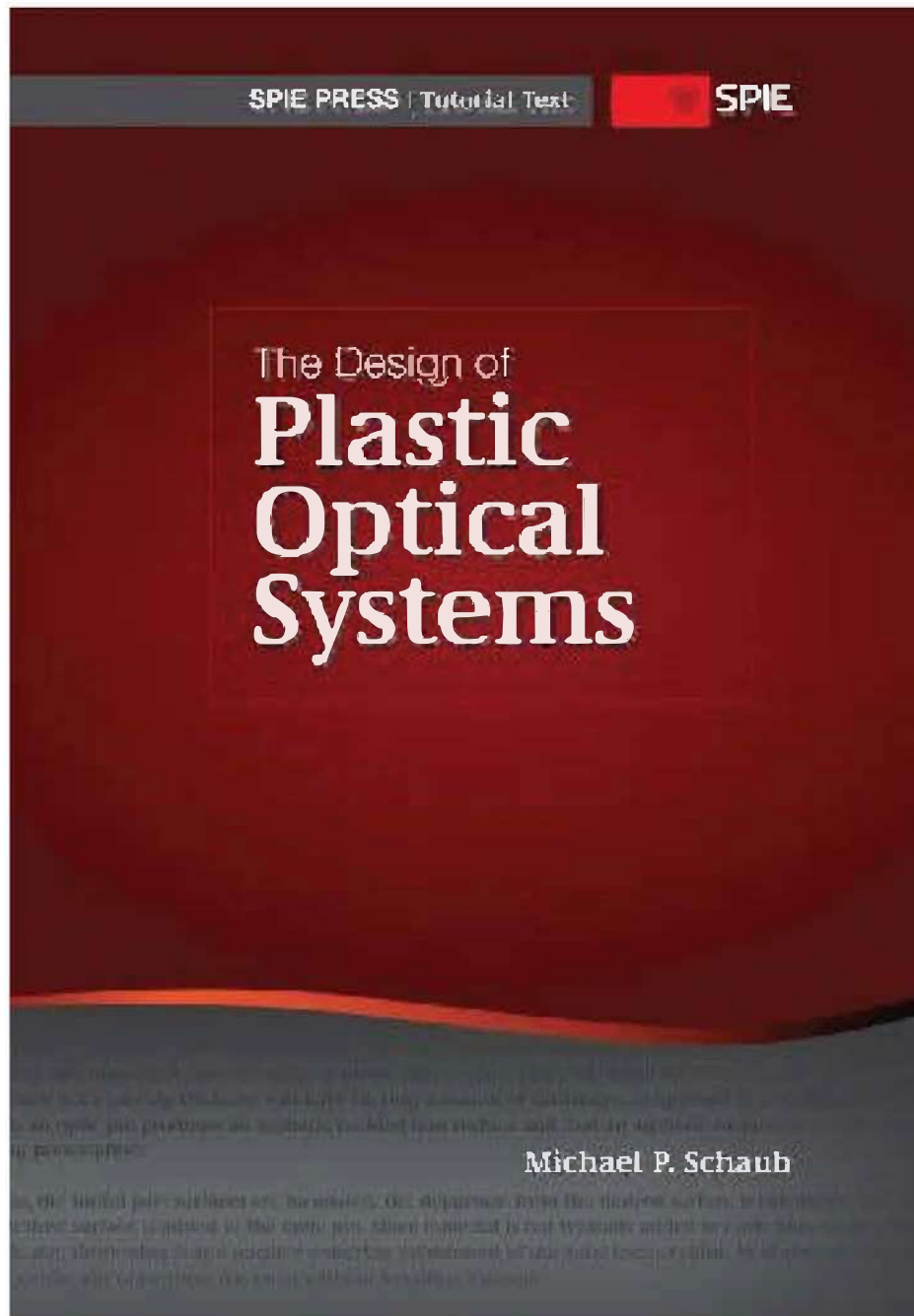




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The Design of
**Plastic
Optical
Systems**

Michael P. Schaub

Tutorial Texts in Optical Engineering
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Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 80 titles covering many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

*James A. Harrington
Rutgers University*

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Preface

We routinely come into contact with and utilize plastic optical systems in our daily lives. As an illustration of this, consider the following events that may occur during a typical weekday. Traveling to work in our car, traffic signals change color to regulate the flow of vehicles. Arriving at work, as we enter the building, motion sensors turn on the hallway lights. At our desk, a fingerprint reader grants us access to our laptop computer. In the lab, we take and send pictures of the latest prototype, using the camera in our cell phone, enabling others to see the hardware. After work, stopping at the store, the bar code reader brings up the prices of our items. Back at home, we enjoy the latest movie released on DVD.

All of these devices—the traffic signals, motion sensors, fingerprint readers, cell phone cameras, bar code scanners, and DVD players—rely upon plastic optical systems to perform their function. As a result, there is a growing need for individuals who are knowledgeable in the design, development, and production of such systems. This tutorial text is written with this need in mind. The book is an elaboration upon the material covered in the SPIE short course “The Design of Plastic Optical Systems.” It is meant to provide an overview of the design of plastic optical systems and is structured along the lines of a typical development project. Following a brief background discussion, the advantages and disadvantages of plastic optics are considered. Next, the available materials and their properties are described, as well as the issues of material selection and specification. Various manufacturing methods are reviewed, followed by a chapter on design guidelines, leading into several design examples. Following the examples, the prototyping and testing of a design is covered. Finally, bringing the design to production is discussed.

There are several groups that should be able to benefit from the material presented. The first group is optical engineers, who often have received training in optical system design, particularly with glass optics, but who are unfamiliar with the special design characteristics of plastic optics. The second group is technical management, who need to understand the advantages and limitations of plastic optical systems. The third, and by far the largest group, is engineers of other disciplines who find they need to design and develop plastic optical systems but lack the knowledge or training to do so.

The text is written at an introductory level. No familiarity with plastic optical parts or their design is assumed. Any background knowledge of optics and optical design will be useful, but not required, to understand most of the subjects covered. Discussions of many of the subjects covered in this text can be found distributed amongst various publicly and/or commercially available sources. There is a wealth of information on plastic optics available in articles, conference proceedings, trade journals, books, the Internet, and various patent databases. We reference many of these throughout the text and encourage the reader to utilize

them as additional sources of information, knowledge, and possibly, creative inspiration.¹⁻⁸

The plastic optics industry tends to be somewhat secretive, with the details of many vendors' processes, techniques, and tooling methods considered proprietary. In spite of this, there are many well-established relationships amongst both individuals and companies in the field. It is a relatively small community, and it is not unusual for individuals to have worked for several plastic optics companies, repeatedly coming into contact with people throughout their career. Referral to and assistance from competing companies is not uncommon. While the proprietary aspects of the field may be frustrating for some readers, not knowing all the intimate details of a particular process will not prevent the successful design of a plastic optical system.

Having completed this book, readers should understand the benefits and limitations of plastic optical systems and be able to determine if this technology is appropriate for their applications. They will have the basic knowledge to undertake the design of these systems, should they choose to do so themselves, or they will be able to have the appropriate conversations with the individuals or companies they ask to perform the work.

Acknowledgments

As with most people in the field of plastic optics, I entered the profession somewhat by chance. During my time in graduate school, a local company (Donnelly Optics, which became Applied Image Group Optics, which later became Aurora Optical) announced a part-time position for an optical engineer. The work involved designing plastic optical systems, with an emphasis on diffractive optics. This was aligned with my dissertation research. After successfully interviewing for the position, I began my career in plastic optics. Part-time work turned to full-time work, to the annoyance of my advisor, Bob Shannon, whose retirement I probably delayed a few years. After graduation, I remained at the company for several more years before moving to my current position at Raytheon Missile Systems (RMS). I continue to be involved with the design of plastic optical systems at work, as a consultant, and through teaching my SPIE short course.

The irony is not lost on me that after an undergraduate optics degree from the University of Rochester, several years of work as a contractor at Kodak, an MSc from Oxford, graduate school at the Optical Sciences Center, resulting, finally, in a PhD with emphasis on optical design, the first design I had go into high volume production was a single-element, lens-in-barrel system that went into a version of the “Barbie Cam,” a silver plastic toy digital camera with a large pink flower surrounding the lens. Maybe not the greatest resume addition or claim to fame, but there must be some positive karma from, to quote my wife, “all those little girls you made happy.” In retrospect, in that simple design were many of the elements of successful plastic optical systems—appropriate material selection, design for molding and assembly, integral mounting features, toleranced performance, and testability. Regardless of the simplicity of the system, there is a certain joy in seeing thousands upon thousands (if not millions) of “my design” being produced.

I have had the opportunity to work with, and learn from, a large group of people throughout my career in plastic optics. I want to acknowledge the influence and work of the following individuals: Chris Bond, Jim Busche, John Daly, Ken Davis, Patricio Durazo, Jeff Fontaine, Rob Gallagher, Dan Joseph, Bill Kuhn, Bob Kuo, Judy Love, Paul McClellan, Paul Merems, Tom Miller, Bill Naylor, Jon Nisper, Rich Pfisterer, Tom Piedmont, Tom Rooney, Dave Strickland, Al Symmons, Jay Tome, Vince Vancho, and Zefy. The list is certainly incomplete. No slight is intended to anyone whose name does not appear.

Additional thanks go to John Schaefer for sharing his expertise in diamond turning, as well as information from some of his presentations on the subject. It is a little known fact that he worked at Donnelly Optics for a short period of time, setting up their entire diamond turning facility.

I thank all those who have taught me about optical design, particularly Bob Shannon, Jose Sasian, and George Lawrence, who are or were at the Optical Sciences Center. I also thank many of my Raytheon colleagues, particularly Dan

Brunton, Pat Coronato, Eric Fest, Greg Hanauska, Jim Hicks, Justin Jenia, Dave Jenkins, Rick Juergens, Dave Markason, Patrick McCarthy, Dan Melonis, Bill Reynolds, Ron Roncone, Wayne Sunne, Byron Taylor, and Dan Tolleson for useful discussions on a variety of optical, optomechanical, and nonoptical topics. Dr. Roncone supplied much of the background information on harmonic diffractive lenses, although any errors in the design example are mine alone.

I especially want to thank Barry Broome, whom I worked with during his time as an optics consultant at Donnelly Optics. He is well known in the plastic optics industry and has extensive experience in the design and production of plastic optical systems. He previously taught the SPIE plastic optics short course, referred me as his replacement in that role, and generously offered much of the material associated with the course.

I thank my parents, Charles and Dona Schaub, for raising me to value education and the possibilities that can come from it. My father never had the educational opportunities that he and my mother worked so hard to provide for their three children, and if he were still alive, I think he would be happy that a tutorial text I authored is being published.

Finally, I thank my wife Elsa, minha querida, for generally putting up with me, and our cat, Shadowzinha, for keeping me company during the writing of this text.

This tutorial text is dedicated in memory of Henry J. Kreis, better known to many of his Tucson friends and colleagues as "Uncle Henry." He was a good friend, a great man, and an extraordinary mold-process engineer. After many years at Polaroid, he moved to Arizona to take on the challenge of leading the mold-processing group at a newly formed plastic optics company. I had the good fortune of having the cubicle next to his, which allowed an easy, on-going discussion regarding manufacturability during the design process, as well as frequent brainstorming sessions. He taught me much of what I know about the design of robust, producible plastic optical systems. On the production floor, as lead process engineer, he taught the art of optical mold processing to the next generation of mold-process engineers and technicians. In addition, he was involved in the design, development, and evaluation of improved tooling methods.

Henry loved, among other things, his family, golf (which I sometimes think is the real reason he came to Tucson), a good meal, and tasty beverages. I am happy to be able to say that many times I had the pleasure of sharing the latter two with him. His passing not too long ago, besides leaving a void in the lives of his friends and family, reduced the already small number of highly skilled and experienced plastic optics mold-process engineers. It is safe to say that there are, and will be, very few people who know as much about processing a plastic optic injection mold as he did. Thankfully, due to his efforts, some of his knowledge lives on in the people he trained, the coworkers with whom he shared his experience, and hopefully, in this tutorial text.

*Michael Schaub
July 2008*

Chapter 1

Introduction

In this chapter, we provide some background information on plastic optics, including a brief history of their development, as well as recent advances in materials, machining, and manufacturing processes. We also discuss issues that may determine if plastic optics should be used for a particular application, as well as their potential advantages and disadvantages.

1.1 Background

Plastic optics have existed for longer than most currently practicing engineers. In 1936, after several years of development, the Rohm and Haas Company announced the commercial availability of polymethylmethacrylate (PMMA), now commonly referred to as acrylic, under the trade name Plexiglas.⁹ In the same year, DuPont began commercial production of its acrylic material, known as Lucite.¹⁰ In Britain, the Imperial Chemical Industries PLC introduced its version, which was called Perspex.¹¹ The following year, Dow Chemical introduced polystyrene in the United States under the name STYRON.¹²

Plastic lenses appeared around the same time, along with colorful marketing campaigns and disagreements over their invention. In London, on March 20, 1934, the KGK Syndicate Ltd. was formed between Peter Maurice Koch de Gooreynd and Arthur Kingston; just under four years later, in February 1938, the partnership was dissolved. The Wellcome Library, also in London, houses copies of documents concerning the partnership, as well as a copy of a letter from Kingston's lawyer regarding a dispute between the partners over who deserved credit for inventing the plastic optical lens.¹³ It seems that a BBC radio broadcast stated that Koch de Gooreynd was the inventor of the plastic lens, a claim that Kingston disagreed with.

In 1937, *TIME* magazine published an article describing competition between U.S., British, and German firms to substitute glass lenses with plastic lenses in cameras, eyeglasses, and binoculars. It is noted that shortly before the article's printing, Gooreynd (of the KGK Syndicate) appears in New York and bounces lenses on the table to show their fracture resistance. A few weeks later, in Los Angeles, a Rohm and Haas customer named E. G. Lloyd goes even further, putting on a dramatic exhibition for the press by taking a hammer to his lenses.¹⁴ Despite the impressive displays, these early lenses suffered from several problems, such as low scratch resistance and discoloration. Nevertheless, the field of plastic optics had begun in earnest.

With materials available, the manufacturers searched for markets to buy them. For instance, Rohm and Haas produced a few acrylic musical instruments, including a flute and a violin. The flute reportedly had good tone, while the violin

did not.⁹ Most early successful uses of optical plastic were either for eyeglasses or window applications. There were various attempts to create the equivalent of modern laminated windows, commonly known as “safety” glass, where a plastic film is sandwiched between glass plates to keep glass shards from flying when the window is broken.

The use of plastic windows in airplanes provided an initial market for the acrylic manufacturers and allowed them to continue development of the material. Acrylic initially was used for small windows, and as the material became more accepted and understood, larger windows; ultimately, even cockpit canopies were produced. With the beginning of World War II, the use of acrylic for military aircraft skyrocketed. Other war-time uses of plastic optics included antitank gun sights and experimental aerial cameras.¹⁵

Demand was high throughout the war period but abruptly declined with the end of the war and cancellation of government contracts. Manufacturers worked to replace the lost sales, putting acrylic into everyday items. Consumers, however, were not particularly interested in plastic products, due to the return of other materials that were not available during the war. In 1947, jukeboxes were the largest market for Plexiglas.⁹ Plastic optical elements began to appear in the auto industry, with acrylic replacing elements previously made of glass, such as tail lights. This association with the auto industry turned into a significant market for plastic optics and remains so today. Another application that developed shortly after the war, which remains with us today, is the illuminated sign.

Polycarbonate was introduced in the 1950s, with GE Plastics developing LEXAN¹⁶ and Bayer developing Makrolon.¹⁷ However, these early versions of polycarbonate were not suitable for most optical uses due to the “golden” tint of the material, as it was described by Bayer’s advertising.¹⁷ Also in the 1950s, Kodak began producing cameras with acrylic viewfinders and objective lenses.¹⁸ Cameras continued to be a large market for plastic lenses in the 1960s, with over 50 million Kodak INSTAMATIC cameras made during the decade.¹⁹ Acrylic and polystyrene lenses were often used together to achieve color correction in these types of systems. Polycarbonate elements were still being used more often in nonimaging applications, such as car tail lights and traffic signals. In 1965, ICI developed polymethylpentene, often known by the trade name TPX. It is used today in some specialty plastic optical applications. In the 1970s, continued development of polycarbonate removed most of its tint, not necessarily enough for imaging applications, but enough to enable it to be used for automotive headlamps.

Significant progress in the use of polycarbonate elements occurred in the early 1980s with the introduction of optical-grade polycarbonate. The optical grade material was used for a variety of applications, such as eyeglass lenses and safety visors, as well as for canopies on fighter jets such as the F-14. Encouraged by the demand for optical data storage discs, optical-grade polycarbonate was used for CDs, first introduced in 1982, as well as for lenses to read them. This provided, in the view of the chemical companies producing the material, an optical application with significant plastic material usage. Having similar optical

properties to polystyrene, optical-grade polycarbonate could be used as an alternative in color-correcting optical systems.

The 1990s saw an increase in available optical plastics. Two newly developed materials to emerge were cyclic olefin copolymers (COCs), commonly known by the trade name Zeonex,ⁱ and cyclic olefin polymers (COPs), known by the names Apelⁱⁱ and Topas.ⁱⁱⁱ These materials are probably the first plastics designed specifically with optical products in mind. They have similar optical properties to acrylic but have higher thermal capability and lower water absorption. We will discuss these materials in more detail in the next chapter.

Besides these new polymers, optical grades of polyetherimide (PEI), best known by the trade name ULTEM,^{iv} and polyethersulfone (PES), known by the trade name RADEL,^v also became available. These materials have excellent temperature capability, beyond the other optical plastics, as well as relatively high refractive indices. Their potential downside is a deep amber color, which limits their use for many visible applications.

Another fairly recently introduced material is optical polyester. One example is OKP4,^{vi} which is produced by the Osaka Gas Chemicals Co., Ltd. This new material has a refractive index over 1.6, birefringence properties similar to acrylic, and a low Abbe number.

In addition to improvements in plastic optical materials, there have also been significant advances in areas that affect the production of plastic optics. In particular, there have been improvements in injection molding machines, as well as in machining technologies, such as single-point diamond turning. Improvements in molding machines have been driven by both product and process innovation.²⁰ Product innovation refers to changes such as reducing the number of components in a system by making the components perform multiple functions. This often results in more complex parts, pushing the capability of the molding machines and spurring their advance. Process innovation refers to optimizing a production process to make it as efficient and capable as possible.

There has been a big push for process control and improvement across many industries, driven by the acceptance of manufacturing philosophies such as statistical process control and “lean” and “just-in-time” manufacturing. These philosophies have created demand for injection molding machines with greater process control and feedback.

Probably the largest change in injection molding equipment, particularly for use in the production of plastic optics, has been the switch from hydraulic-operated machines to hybrid or electric machines. Hybrid machines, as the name suggests, use a combination of hydraulic and electrical drives. Electric machines, sometimes referred to as “all electric” machines, completely eliminate the use of

ⁱ ZEONEX is a registered trademark of ZEON Corporation.

ⁱⁱ Apel is a registered trademark of Mitsui Chemicals.

ⁱⁱⁱ Topas is a registered trademark of Topas Advanced Polymers.

^{iv} Ultem is a registered trademark of SABIC Innovative Plastics.

^v RADEL is a registered trademark of Solvay Advanced Polymers, LLC.

^{vi} OKP4 is a product of Osaka Gas Chemicals.

hydraulics, relying on electrical motors and drives. The transition to electric machines has occurred for several reasons. The primary reason is repeatability. The repeatability of an electric machine (or its potential for repeatability) is inherently higher than for a hydraulic machine.²¹ Given the precision required in optical elements, repeatability of a manufacturing process is a highly desired characteristic. In addition to this, moving from a hydraulic to an electric machine eliminates the use of hydraulic oil in the machine clamp mechanism. Hydraulic oil is associated with several problems. It can cause environmental issues, particularly ground contamination from leaking oil. It creates health and safety concerns such as oil vapors, falls, and fire hazards. There is also a cost associated with its storage and disposal. This argument can only be pressed so far though, for as we shall see, although switching to electric machines eliminates hydraulic oil in the molding machine, oil is still often required for temperature regulation of the mold itself. It can fairly be said that the use of electric machines does not completely remove the use of oil, but it does reduce the total quantity of oil used on the molding floor. In addition, electric machines tend to use less power than hydraulic machines, resulting in energy cost savings.

The general advances in processors and computing, which have also had great influence on the process of optical design, have influenced the development and use of injection molding machines. Most machines are now fully computer controlled, with a flat screen on the side of the machine displaying the current process parameters, as well as time-based graphs of pressure and other parameters for each injection cycle. Multiple sensors provide feedback, for display as well as for closed-loop control. The molding machine can be connected to a personal computer to continuously send process and sensor data for analysis and tracking, and the data can be stored for later download and further evaluation.

Besides the injection molding machines themselves, improvements have also taken place in the ancillary equipment associated with them. This includes improvements in material dryers, thermal conditioning equipment, and automated robotic pickers and degating systems. Improvements in automation have reduced the need for human intervention during steady-state production, which results in reduced cost, as well as less chance of human error or safety incidents. It is no longer necessary to have a person standing by each machine during production.

In addition to the advances in molding machine technology, there have also been significant advances in machining technologies. This affects the precision and complexity of molds that can be built and allows the direct machining of plastic optical parts, either as prototypes or for actual production. Advances in computing and computer control, as well as in other areas, have pushed machining capabilities to previously unthinkable levels. Nowhere is this more evident than in the process of single-point diamond turning, often simply referred to as diamond turning.

Diamond turning is a machining process combining the use of gem-quality diamond tools with precision computer numerically controlled (CNC) equipment. According to Schaefer, advances that have been made over the last 30 years

include going from air bearing to oil hydrostatic slide ways, changing from belt drive to direct brushless DC spindle drives, changing from laser positioning to glass scale positioning systems, using PC DSP instead of tape CNC controllers, using epoxy granite instead of granite machine bases, and switching from ball lead screws to linear motor drive axis drives.²²

The result of these advances has been a factor of eight improvement in surface finish and a factor of four improvement in surface form. In addition, the achievable spindle speeds have increased ten fold and the cost of the diamond-turning machines has dropped by about half. The machines are commercially available with a number of options, including machines with multiple axes.

These machining improvements have enabled the creation of high-precision complex parts. Off axis, nonsymmetric, and microfeatured surfaces can all be produced using modern diamond-turning equipment. For the optical designer, this allows additional freedom in selecting surface forms or in the integration of features such as multizonal surfaces. Proper machine setup, processing, and fixturing can eliminate the need for postpolishing. This means that plastic optical prototypes can be directly machined and that optical mold inserts can be built to high optical surface accuracy and surface roughness requirements. Combining this precision machining with advances in testing, mold compensation is readily performed.

Designers can, and should, take advantage of the improvements that have been made in plastic optical materials, injection molding machines, and machining technologies such as diamond turning. Conversations with vendors and/or suppliers, who need to stay current with these technologies, is usually the best way to be aware of the current state of capability, as well as ongoing development.

1.2 When Are Plastic Optics Appropriate?

As with all optical technologies, plastic optics are not the solution to every problem. When deciding whether to use plastic optics, the first question that needs to be answered is “Are plastic optics appropriate for my application?” There are a number of considerations in determining the answer to this question. Finances, project schedule, and supply chain issues can all play a role. Production volumes, along with cost and weight, are the top reasons that people decide to use plastic optics, while thermal issues such as storage temperature limits or temperature-dependant focus shift are the main reason that they are not chosen. Other considerations, such as the spectral band used, product lifetime, or even biological compatibility, may contribute to the decision whether or not they are appropriate. These issues, along with advantages, disadvantages, and application examples, are briefly discussed in the following paragraphs.

If there is a large anticipated production volume, that is, when many systems are expected to be manufactured, plastic optics may be appropriate. “What’s the volume?” is a question typically heard early in discussions with plastic optics

manufacturers. Certain plastic optics manufacturing methods are suitable for producing large quantities of parts. In certain consumer applications it is not unusual for millions of lenses and lens assemblies to be produced each month by a single manufacturer. As an example, in 2007 worldwide production of cell phone cameras topped one billion units, most of which contained plastic optics. Some manufacturing methods, such as injection molding, allow for the simultaneous production of multiple copies of a part. Molds can also be built with the ability to later increase the number of parts simultaneously produced to allow for additional production. Several plastic optics manufacturing methods will be discussed later in the text.

While large production volumes are often appropriate for plastic optics, low production volumes can also be appropriate, particularly in the case of highly complex parts. It is possible to make a wide variety of complex plastic optical components, some of which may challenge traditional glass fabrication methods, such as the part shown in Fig. 1.1. Multifaceted surfaces, multiple zone lenses, and lens arrays are examples of complex components that are routinely fabricated in plastic. That being said, the advantage of making complex parts from plastic rather than glass is diminishing somewhat. The advances in manufacturing technologies that have improved the quality and performance of plastic optics, particularly computer-controlled machining, can and are being applied to the fabrication of glass optics. Glass elements are regularly molded, although typically at lower rates than comparable plastic elements.^{23–25}

Cost is often a factor in the decision to use plastic optics. In fact, it is typically the primary reason that they are considered. In general, and especially for large production volumes, plastic optics cost less than equivalent glass elements. This is mainly due to the time required to fabricate the element, but also partly due to material costs. The cost of a plastic optical element will be determined by a number of factors, including the fabrication method, the number of parts being made, the complexity of the part, the precision to which it must be made, its size and volume, and the material it is made of.



Figure 1.1 Complex molded plastic optical part. (Photograph courtesy of G-S Plastic Optics.)

Weight is another important reason to consider using plastic optics. For this particular characteristic, plastic optics have a significant advantage over traditional glass elements. Put simply, plastic is much less dense than glass, resulting in less weight for an equivalent volume of material. It can be argued that lenses of a given focal length, one made from glass and one made from plastic, do not necessarily require the same volume. High-index optical glasses allow longer radii of curvature, reducing lens volume, but the reduction does not typically make up the weight differential.

Head-mounted optical systems are an application where the weight advantage of plastic optics is often utilized. Heads-up displays for pilots, night vision goggles for soldiers, and microdisplays of technical manuals for mechanics or technicians are all examples of this. Studies have shown that wearing head-mounted displays can alter neck posture, increasing the stress on the musculoskeletal system of the neck and head.²⁶ Reducing the weight that must be borne will decrease the amount of stress imposed.

Other situations where weight can be a deciding factor for the use of plastic optics are those driven by battery lifetime or fuel limits. For instance, in a camcorder zoom lens, several elements typically move to change the magnification while maintaining focus. The number of times that these elements are capable of being driven before the battery must be recharged or replaced will depend upon the weight of the elements. In this case, replacing a glass element with a plastic element may increase the usage time the consumer experiences with a given battery charge. Another example would be an optical system meant to be carried by an airborne vehicle, such as a micro-UAV (unmanned aerial vehicle). The amount of time that the unit can remain aloft is in part a function of its weight, and plastic optics can be used to reduce overall system weight.

Plastic optics possess superior fracture resistance when compared to glass. Dropping a plastic lens may result in a scratch or dent to the element, but the lens will most likely remain in one piece. As an example of fracture resistance, consider that polycarbonate is often used in the production of "bulletproof glass" for vehicles or buildings. "Safety glasses," which are used for eye protection, are typically made from plastic, not glass. In this case, plastic can provide the fracture resistance necessary to meet the American National Standards Institute (ANSI) requirement that the lenses withstand the impact of a quarter-inch steel ball traveling at 150 feet per second.

Another potential advantage of plastic optics is part-to-part repeatability. Many plastic optics production methods rely upon replication processes. That is, the plastic part is formed by reproducing the shape of a master tool. An optical insert in an injection mold is one example of such a master. As mentioned above, it is possible to simultaneously produce multiple copies of a part. If a set of parts are simultaneously produced, each of the parts within the set may not be completely alike, since they may be formed from individually fabricated masters. However, the subsequent sets of parts will be very similar to the prior set. For a given part parameter, such as surface decentration, this can lead to a set of several narrow distributions. In contrast, traditional glass fabrication methods

typically produce continuous part characteristic distributions. The difference in distributions can play a role in the parameter probabilities used in tolerancing the designs, as well as in the final system performance.

Integration of features is yet another characteristic advantage of plastic optics. In addition to multiple optical surfaces, possibly for transmit and receive functions, or lens arrays for multiple beams, flanges and spacers can also be molded into an optical part. Molded-in flanges can allow multiple lenses to be stacked in a barrel, automatically setting the proper spacing of the elements. This can reduce overall part count and improve assembly, in both case and time. Orientation marks can be added to parts, as can features such as keying or antirotation tabs. Snaps, bosses, through holes, or tapers can also be added for part retention or centration. Figure 1.2 shows a part, an automotive interior light cover, with a snap feature used for retention.

Surface form is an area where plastic optics can offer design advantages, as they are not limited to planar or spherical surfaces. It is quite common for plastic optic components to have highly aspheric, anamorphic, or freeform surface shapes. In addition to these continuous optical surfaces, it is also possible to create discrete or micro-optical features, such as Fresnel lenses, lens arrays, kinoform surfaces, fan-out patterns, diffraction gratings, or microlenses. Nonoptical features, such as channels for microfluidic or “lab-on-chip” applications, have also become common.



Figure 1.2 Plastic optical part using snap feature for retention. Note the complex, multizonal optical surface on the part. (Photograph courtesy of Alan Symmons.)

One particular application that shows the continuing improvements and intriguing possibilities that plastic optics can offer is the intraocular lens. Modern intraocular lenses, or IOLs, as they are commonly called, take advantage of many of the positive characteristics of plastic optics. They are most commonly used to replace the crystalline lens of the human eye when cataracts (clouding of the lens) are impairing a patient's vision. Cataract surgery, with removal of the natural lens and implantation of an intraocular lens, is now the number one surgery performed in the United States of America.

Since they are implanted in the human body, the material the IOL is made from must be biocompatible; that is, it must not be rejected by the body. Sir Harold Ridley, a Royal Air Force (RAF) ophthalmologist, determined during World War II that acrylic was suitable for implantation into the eye. He noticed that airplane pilots who suffered eye injuries due to acrylic shrapnel, which came from their cockpit canopies, did not show rejection of the acrylic pieces. Knowing this, he had an IOL fashioned from acrylic and performed the first intraocular lens implant in 1949.²⁷

These early plastic IOLs were made from rigid material. Given their size, they required a large incision for implantation with a subsequent hospital stay, associated costs, and a significant recovery period. This is no longer the case, as the latest IOLs are implanted through a small, typically 2- to 3-mm incision, on an outpatient basis. This is possible because of available plastic material characteristics, in this case, flexibility. In order to achieve the desired small incision, flexible materials have been developed that allow the IOL to be folded or rolled up, then inserted into the eye through the incision using a syringe-like injector. Once inside the eye, the IOL is unfolded, at which point integrated features come into play. In order to be stably positioned within the eye, the lens must somehow be secured. In some cases an attachment structure, called a haptic, is inserted into the eye separately from the lens. The lens is then attached to the haptic, using integrated features such as loops or snaps. In other cases, the haptic is an integral part of the lens, and the entire lens and support structure is inserted. The haptic is lodged into the physical structure of the eye, securing the lens.

The optical power of standard IOLs are normally selected for far (distant) vision. The final axial position of the lens, along with correct power choice, determines the residual focus error. In some cases, the focus error is too large, and the lens must be replaced or repositioned. This is often done through a second surgical procedure. An alternative solution is to adjust the shape or position of the lens without performing invasive surgery. This can be accomplished by directing a laser onto the haptic to partially melt the structure.²⁸ In this case, we rely on the plastic material's ability to be melted and reshaped. An alternate method of adjusting power that can also be used to correct aberrations has recently been developed. It involves implanting a lens made of a material that is photosensitive, then illuminating it with a low-power light beam to adjust its shape.²⁹

Most patients suffering from cataracts are old enough to have presbyopia, the hardening of the eye lens, resulting in the loss of ability to focus on nearby

objects. Standard IOLs do not provide the focus adjustment of a nonpresbyopic eye. In this situation, reading glasses can be used for near-vision tasks such as reading a computer monitor or book. However, plastic optic characteristics have enabled the recent development of IOLs that provide both distant and near vision. This is typically accomplished in one of three ways. The first method relies upon the ability to create multizone surfaces. In this method, the IOL optical surface has multiple annular zones of different powers, the powers being selected for far, near, and sometimes midvision.³⁰ The second method relies on the ability to form diffractive structures. A diffractive surface is created on the lens that is designed to put light into multiple diffractive orders. The power and diffraction efficiency of the different orders are selected for the desired object distances.³¹ The third method relies on the same flexibility that allows the use of a small insertion incision. In this method, some form of (typically integral) bending structure is created. On insertion, the lens is placed in the correct position for far vision. To focus on nearby objects, the patient uses their eye muscles to bend the structure, moving the lens forward in the eye.³² Multiple element systems, where the lenses move relative to each other to produce a power change, have also been developed.³³

Another advance in IOL technology relies upon the ability to easily create aspheric surfaces on plastic optics. The average eye is not perfectly corrected, but it contains residual spherical aberration. This results from the spherical aberration contributions of the cornea and the natural lens not being perfectly balanced. The amount of spherical aberration in the eye normally changes with age, due to changes in the lens. When the natural lens is replaced with an IOL, it is possible to put in a lens with a desired amount of spherical aberration. The lens could have the correct amount of aberration to cancel that of the cornea, or it could be a lens that is itself corrected for spherical aberration.³⁴ This latter case allows the lens to be decentered upon insertion without introducing coma.

Since it is possible to correct vision when replacing the natural lens, it is a logical step to consider correcting vision not just by replacement, but by addition of an optical element to the eye. This next advance in IOLs, where an inserted lens eliminates or reduces the need for contact lenses or glasses, is underway. It is particularly appropriate for patients suffering from severe myopia. The large power and resulting eyeglass lens weight and thickness can be uncomfortable for patients with this condition. The inserted elements can theoretically be replaced throughout the patient's life to maintain optimum vision, or they can be removed if complications arise.

Intraocular lenses, while a relatively simple optical system, have made significant progress in recent years. It can be seen from this particular application that the judicious use of plastic optics, based on the understanding of their properties and capabilities, can enable advances in performance, reduce cost, and even improve quality of life.

Given all the characteristics discussed so far, plastic optics would appear to be an excellent choice for many applications, which is indeed the case. However, there are also a number of situations where the use of plastic optics may not be

appropriate. One particular area of concern with plastic optics is thermal performance. This generally arises either in regard to storage and/or operating temperature, or focus shift with temperature change.

Optical plastics do not have as high a transition, or melting, temperature as optical glasses. This may rule out plastic optics, or at least certain types of plastic optics, for some thermal environments. In the simplest terms, under certain conditions plastic optics may melt. The various types of plastic optical materials have different service temperatures, so selection of the appropriate material from a thermal standpoint is very important. For instance, in several consumer applications we find that certain plastic optical materials will meet the thermal requirements, while others will not. This has led to specific plastic optical material combinations commonly being used for these applications. While the melting of plastic is often considered a negative characteristic, it is interesting to note that several plastic optics manufacturing methods specifically rely upon the melting, then hardening, of plastic materials.

Athermalization refers to maintaining the performance, most often focus, of an optical system over changes in temperature. Achieving an athermalized design using plastic optics over a large thermal range may be a challenge. This is due to the thermal material properties of optical plastics. Plastic optical materials have a larger coefficient of thermal expansion (CTE) and a much higher thermal change in refractive index (dn/dt) than optical glasses. Since the power of an optical element is determined by its radii of curvature and refractive index (and to a lesser extent its thickness), large changes in these parameters, unless balanced, will result in a large change in optical power. For a typical plastic optical element, the change in refractive index with temperature will dominate its thermal power change. This power change, its performance effect, and its potential compensation must be considered over the operating temperature range of the system. Some systems have either a manual or autofocus mechanism, which may reduce the need for the system to be completely athermalized. In these cases, the total amount of focus adjustment required must be evaluated and enough compensation range provided.

One method of athermalizing systems containing plastic elements is to use a combination of glass and plastic elements. Such designs are often referred to as "hybrid" systems, although this term is also sometimes used for systems that combine refractive and diffractive elements. In this athermalization method, the majority of the optical power is put into the glass elements, while the plastic elements, often aspherical, are used mainly for aberration correction. Since glass has a smaller change in optical power with temperature than plastic, and the majority of the power is in the glass elements, the total change in optical power with temperature is reduced. It is also possible to design systems using several plastic elements, some with positive power and some with negative power, so that their thermal power changes cancel each other.

Application spectral band can be another factor in the decision whether to use plastic optics. In general, plastic optical materials have high transmission between about 450 nm and 900 nm. The actual cutoffs will depend on the

particular material type and grade. Plastics also have absorption bands in the near infrared (NIR), due to their chemical structure, and do not transmit well in the midwave and long-wave infrared bands.³⁵

In general, optical plastics have less resistance to chemicals than do optical glasses. In some (typically nonoptical) cases, solvents are used for “solvent bonding,” the joining of plastic pieces by using a solvent to melt them together. Certain solvents, such as toluene or acetone, as well as other chemicals, can seriously damage or degrade plastic optics. The selection of a specific optical plastic, or the decision not to use plastic optics in a particular application, may depend on the expected chemical environment.

While plastic optical elements are less prone to fracture than optical glass elements, the same cannot be said with regard to scratching. Plastic is softer than glass, and as such, is more susceptible to surface damage, be it due to particulates such as blowing sand or direct contact. Multiple methods are used to prevent scratching plastic optics. One is to coat the surface with an abrasion-resistant coating. A second method is to design housings such that the surface is sufficiently recessed to prevent fingers and other objects from being able to accidentally (or intentionally) touch the lens. This is often seen on camera lenses in the form of a sunshade or stray-light baffle. Another method is to protect the plastic surface with a window, or by having the front or any exposed optical elements made of glass.

Birefringence is another potential issue with plastic optical elements, particularly in applications where the optical system is highly polarization sensitive. Birefringence refers to the separation of an incident light beam into two beams, usually referred to as the ordinary and extraordinary beams, upon entering a material. This separation is due to a difference in refractive index of the material based upon the polarization states of the light. While not a fundamental property of the plastic material itself, the manufacturing method used to produce the plastic optical element may introduce birefringence. For instance, a part that is injection molded may show birefringence, particularly near the gate, (the region of the part where the plastic is injected), if subjected to significant injection or packing pressure.³⁶ In contrast, a part that is produced by diamond turning a cast piece of plastic will typically not show birefringence. Part design, material selection, and processing all play a large role in determining the birefringence of a plastic optic.

The final potential issue we discuss concerning the use of plastic optics is their environmental impact. There is a growing “green” movement that seeks to reduce the consumption of goods and the environmental effects of the goods that are consumed. Plastic items, such as plastic shopping bags, have received considerable attention. Optical plastics, like most plastics, biodegrade slowly (although more rapidly than glass). This can be a positive aspect from a product lifetime standpoint, but can be a negative if the plastic quickly ends up in a landfill, where it can remain intact for a very long time. It is possible to create plastic items that degrade fairly rapidly; for example, garbage bags such as the

BIOBAG,^{vii} use a corn-based polymer. However, currently available optical plastics do not exhibit this property.

Optical plastics and elements manufactured from them can and are being recycled and reused. It is a common practice in the (nonoptical) plastic industry to take excess material generated during injection molding of a part, grind it up, and reuse it. In optical molding, the excess material is typically not reused for optical elements, but it is often collected and sold to nonoptical molders or material distributors.

One example of large-scale recycling is seen in the “single-use” camera market. Single-use cameras, frequently referred to as “disposable” cameras, are quite popular at events such as weddings and parties, or on vacation where the traveler does not wish to bring an expensive personal camera. In the single-use model, the entire camera is turned into the processor, allowing the camera body and lens to be collected and reused. KODAK has set up a recycling program for their single-use cameras, claiming that between 77% and 90% (by weight) of the camera may be remanufactured, and that virtually no material ends up directly in a landfill, as the components that are not remanufactured are recycled elsewhere.³⁷

When considering the use of plastic optics, the issues discussed above, as well as any other pertinent application characteristics, need to be considered. In certain situations plastic optics may not be appropriate, but in many cases they are, and their use should at least be considered. Plastic optics are currently used in a broad range of fields, from consumer electronics and medical devices to defense and biosecurity applications. As advances in plastic optical materials, precision machining, manufacturing, and design techniques continue, the number of applications where plastic optical systems are used is expected to increase.

^{vii} BIOBAG is a registered trademark of BioBag International.

Chapter 2

Optical Plastics

In the previous chapter, we discussed some of the issues that determine whether or not plastic optics are appropriate for a particular application. One of the issues was the properties of the plastic optical materials themselves. In this chapter, we discuss in more detail the characteristics of the typically available plastic optical materials, focusing on their optical and mechanical properties. We also discuss the selection and specification of the materials.

2.1 Plastic Versus Glass Maps

When comparing optical plastics and optical glasses, two things are readily apparent. One, there are significantly fewer optical plastics than optical glasses to choose from. Two, compared to optical glasses, there are no optical plastics with relatively high refractive indices. One way of seeing this is to compare the “glass maps” of the two types of materials. Figure 2.1 shows a glass map for optical glasses and plastics, with the glasses shown as triangles and the plastics shown as diamonds. Figure 2.2 shows a similar map for just the optical plastics. For those unfamiliar with these maps, they are a plot of the refractive index of the material (vertical axis) versus the Abbe number or dispersion (horizontal axis) of the materials. Each point displayed on the map represents a specific material. The refractive index of the materials is the ratio of the speed of light in vacuum to the

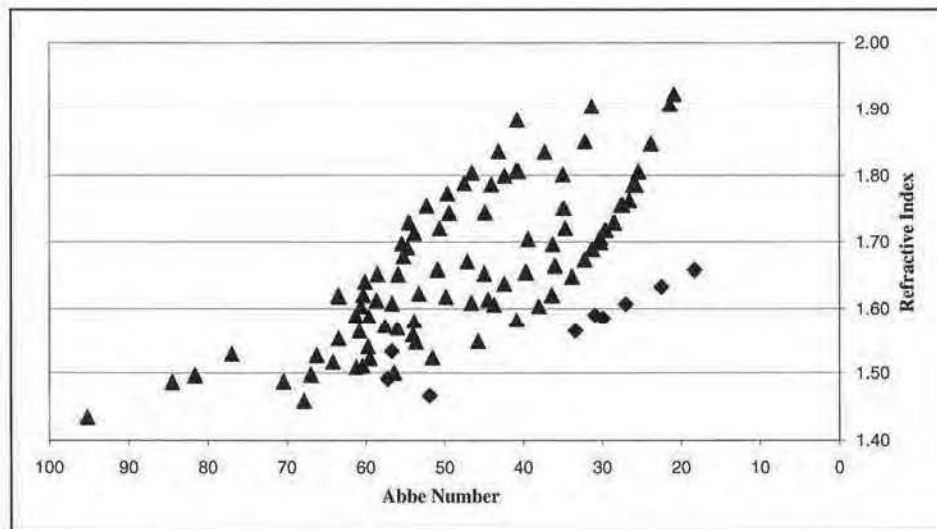


Figure 2.1 Glass map of common optical glasses and plastics.

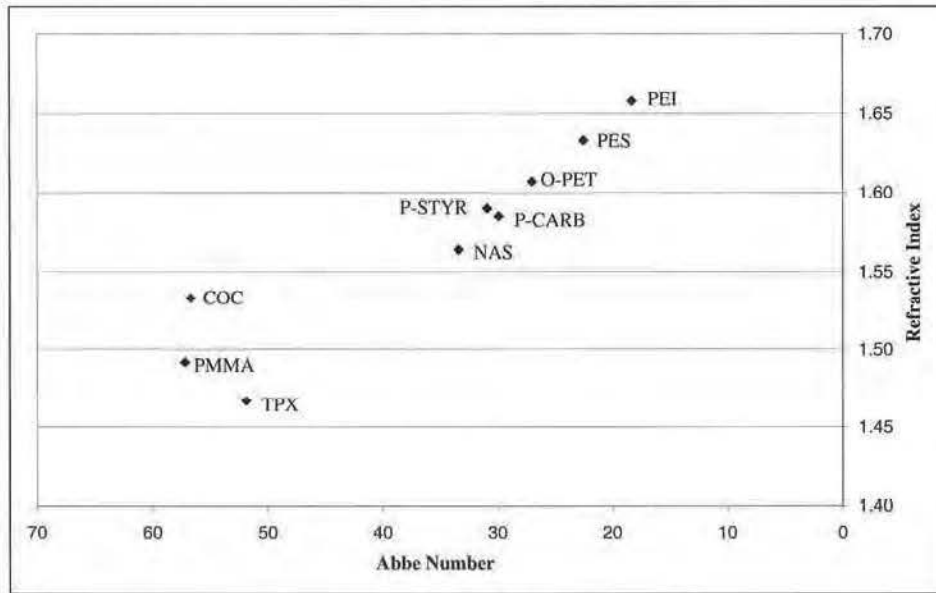


Figure 2.2 Glass map of commonly available optical plastics.

speed of light in the material for a defined wavelength, while the Abbe number is a measure of how much the refractive index varies as a function of wavelength. These maps are typically plotted with the dispersion axis values in reverse.

The refractive index of optical glasses and plastics is not constant with wavelength. Because of this, a given refractive index value must be referenced to a wavelength value. For visible work, the refractive index, usually denoted by n , is most commonly quoted for the helium d line, which has a wavelength of 587.6 nm. We will follow this convention throughout the text. The value of the refractive index of a material determines the amount of refraction, or bending, which will occur when a light ray goes through the boundary of the material. For the remainder of this discussion, we assume the (glass or plastic) material is in air, and that the refractive index of air has a value equal to one. In Fig. 2.3, we see a light ray approaching the air/material boundary from the left. On the right side of the boundary, two rays are shown, corresponding to two possible values of refractive index for the material. For Ray 1, the value of the refractive index of the material is 1.5, while for Ray 2 the index is 1.9. We can see that the ray associated with the higher index (Ray 2) is refracted at a larger angle than the ray associated with the smaller refractive index (Ray 1). When we say that Ray 2 has been refracted at a larger angle, we mean that the change in direction for Ray 2 is larger than the change in direction for Ray 1 when compared to the direction of the input ray. The angle of the ray after refraction can be determined from Snell's law, which relates the sine of the refracted angle of the ray to the sine of the input angle of the ray, through the ratio of the refractive indices of the media on either

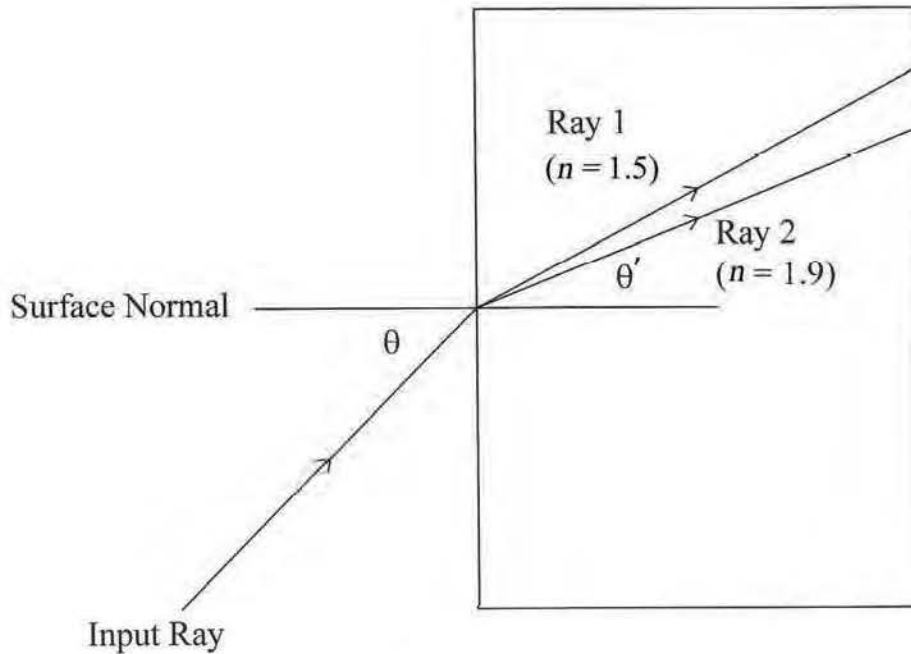


Figure 2.3 Refraction of a light ray at a boundary for different refractive indices.

side of the boundary. Both angles are measured with respect to the surface normal at the point of intersection of the input ray. The equation for Snell's law is shown in Eq. (2.1):

$$n \sin \theta = n' \sin \theta' . \quad (2.1)$$

A second condition of Snell's law, which is often left unstated, is that the refracted ray will lie in the plane formed by the incident ray and the normal to the surface at the point of intersection of the incident ray, which is called the plane of incidence. Because the angles are measured from the normal to the surface, when going from a lower-index material to a higher-index material, a ray that is more highly refracted will actually have an angle θ' that is smaller than a ray that is less highly refracted. Of course, rays can also go from a higher-index material to a lower-index material, as when they are leaving the rear surface of a lens. Again, the angle of refraction will depend upon the angle of incidence and the refractive indices of the materials on either side of the boundary. The larger the ratio of the refractive indices (higher index to lower index), the more the ray will be refracted.

When attempting to go from a higher-index material to a lower-index material, it is possible for the ray not to cross the boundary but to be reflected back into the higher-index material. When this occurs, it is known as total internal reflection. The possibility for this can be seen from Snell's law. For

example, if the material has an index of 1.335 with air on the other side, when the ray is incident on the boundary at an angle of 48.5 deg, the angle of refraction will be 90 deg. That is, the output ray will go in a direction perpendicular to the normal, or for a planar surface, along the surface. The angle of incidence where this occurs, in this case 48.5 deg, is called the critical angle. If the angle of incidence is increased beyond the critical angle, there will be no real solution to Snell's law, and the ray will reflect back into the higher-index material. An example of total internal reflection that the reader may be familiar with is being underwater and seeing a reflection, beyond a certain angle, when looking up at the surface of the water.

We now consider the effect of the value of the Abbe number of the material. The Abbe number, also called the V number, tells us how dispersive the material is. By dispersion we mean how much the index of refraction varies with wavelength, which for the visible waveband means how much it varies with color. The Abbe number is defined as:

$$V_d = \frac{n_d - 1}{n_f - n_c}. \quad (2.2)$$

In Eq. (2.2), n_d , n_f , and n_c are the refractive indices of the material at wavelengths of 587.6 nm, 486.1 nm, and 656.3 nm, respectively. This is the definition for the Abbe number V_d , which is commonly used for visible applications. Alternate V numbers, defined for different wavelengths, are calculated by replacing the n_d , n_f , and n_c values with the index values at other wavelengths. Alternate Abbe numbers can be useful for describing materials in different spectral bands, such as the infrared. A low Abbe number indicates that the material is more dispersive (index changes more with wavelength) than a material with a higher Abbe number.

We saw above that varying the refractive index value resulted in different angles of refraction for a given input ray. Since the Abbe number tells us how the refractive index varies with wavelength (color), it tells us how much variation in refraction angle we will have for different colors. Materials with low Abbe numbers (high dispersion) separate the colors more than materials with high Abbe numbers (low dispersion). The variation in index due to dispersion is much less than the variation shown in Fig. 2.3. For instance, polystyrene has a refractive index of 1.604 for blue light and 1.585 for red light. Thus, the refractive index difference between the two colors is 0.019. While not as large as shown in Fig. 2.3, the separation of colors due to variation in the refractive index with wavelength is the origin of chromatic aberration, which can significantly degrade an image if not corrected.

Returning to the map of optical plastics in Fig. 2.2, we see that plastic optical materials are available with refractive indices from about 1.49 to 1.66, and with Abbe numbers from about 57 to 18. By convention, optical glasses (and plastics) are divided into two groups: crowns and flints. The crowns are materials that

have an Abbe number over about 50, and the flints are materials with Abbe numbers less than about 50. This naming convention allows for easy description of the configuration of a design. For example, a two-element system may be described as having a negative flint lens followed by a positive crown lens.

In addition to being divided into crowns and flints, optical plastics are also divided into two groups based on their ability (or not) to be repeatedly heated and formed. These two groups are known as thermosets and thermoplastics, and there is a fundamental difference between them that affects the manufacturing processes used to create them. Thermoset materials can be formed (hardened) into a desired shape only once. After they have taken a shape, they cannot be reprocessed. Thermoplastic materials, on the other hand, can be initially formed into a shape, then repeatedly heated and reshaped. Thermoset materials tend to be used with casting processes, while thermoplastics are typically used in embossing, machining, and molding processes. In the next section on material properties we focus on the thermoplastic materials.

2.2 Material Properties

The optical and material properties of most optical plastics have typically not been easy to come by. The simple reason for this is demand. The amount of plastic used in the production of plastic optics, even with their increased use, is a tiny fraction of the amount of plastic used in other industries. As a result, plastic material suppliers have had limited incentive to provide the high-quality optical information that the designer desires. Many times, the properties used in the design of plastic optical systems do not come from the material manufacturers, but out of the literature from the fields of optical and material engineering. There are exceptions to this, particularly with some of the newer materials, which were designed specifically with optical applications in mind.

Table 2.1 lists some of the properties of commonly available plastic optical materials. The last column, labeled N-BK7, is not an optical plastic but a frequently used optical glass that is included for comparison purposes. We begin by briefly discussing the materials listed, and then in the remainder of the section we will work our way through each of the lines in the table, comparing the materials and discussing the implications of their properties.

Acrylic (PMMA) is arguably the oldest plastic optical material. For years it was the designer's first choice, and many times still is today. For those familiar with optical design using glass, it is the equivalent of BK7. It has excellent transmission and is lower in cost than most of the other materials. It is a crown material, with an Abbe number of 57.2.

COC and COPs are relatively new optical plastics. They were first developed and became available in the 1990s. Development of these materials is ongoing, with several different grades available. Optically, they have similar properties to acrylic, but physically they have several differences. These materials can be used at higher temperatures than acrylic and have less water absorption. Due to these

Chapter 4

Design Guidelines

In this chapter, we discuss guidelines that apply to the design of plastic optical systems. We begin by reviewing some basics of optical design, consider tolerances and their effects, and cover various element parameters, such as thickness, shape, and different surface types. We also discuss guidelines for optomechanical design, stray light prevention and analysis, issues associated with drawings, and interacting with vendors.

We noted in the last chapter that injection molding is the most popular method of producing plastic optical elements. As such, most of the guidelines discussed are associated with the injection-molding production process. In some cases, the guidelines for injection-molded optics may differ from optics made from other processes, such as diamond turning. In these situations, I will attempt to point out the differences.

It should be kept in mind that what we discuss in this chapter are guidelines, not hard and fast rules. The guidelines presented are based mostly on practical experience (often bad experiences) and an understanding of the manufacturing process. Various designers and vendors may have different opinions regarding any given guideline, and trades can often be made between cost, performance, and producibility.

4.1 Design Basics

Optical design is a skill that previously was learned under the guidance of an experienced designer in somewhat of an apprentice relationship. The optical design community was relatively small; there were few courses of instruction and limited opportunities to enter the field. With the advent of personal computers and a number of commercially available optical design programs, access to tools to easily perform optical design has greatly increased. Currently, almost any company or individual with a computer and enough money to buy or lease an optical design program can get into the field. In this section, we present a brief discussion of the basics of optical design, beginning with a short, general review of geometric optics and aberrations. There are entire books and classes devoted to geometric optics and optical design, and given the length of this text, we will not cover the subject in great depth. We refer the reader to any (or all) of several well-known works for more detailed study.^{56–58}

A basic assumption in our discussion is that light can be represented by rays, and that light rays travel in straight lines (at least in homogeneous media). In Chapter 2, we discussed the refraction of a ray at the boundary between two media of different refractive indices. The rule that governs the refraction of the ray is known as Snell's law. We explained that the refraction of the ray is

determined by the angle of the ray with respect to the normal to the surface and by the ratio of the refractive indices of the two media. We also showed that the higher the ratio of refractive indices between the two materials, the larger the amount of refraction (or bending) of the ray.

In the refraction example discussed above, we considered a single ray at an interface. Although in Fig. 2.3 we drew a planar interface, the boundary between the two media could take any shape. In this general case, Snell's law still applies, with the ray angles taken with respect to the normal to the surface at the point of intersection of the ray. We now consider the situation of a ray crossing an interface that is spherical, such as when a light ray is incident on the surface of a conventional spherical lens. Figure 4.1 illustrates the geometry of this situation, where we have shown the lens as a sphere. We assume the material to the left of the interface to have a refractive index of 1 and the lens material to have a refractive index of 1.5. Similar to our earlier example, we find the angle between the ray and the normal to the surface (at the point of intersection of the ray), and with the values of the refractive indices, we determine the angle between the surface normal and the refracted ray. We can imagine extending the ray further to the right, where it will intersect the second surface of the lens. At this interface, the rear surface of the lens, we can again find the angle of the ray with respect to the surface normal, calculate the angle of refraction, and determine the direction of the ray after it passes through the surface. We have thus computed the path of a ray through a lens.

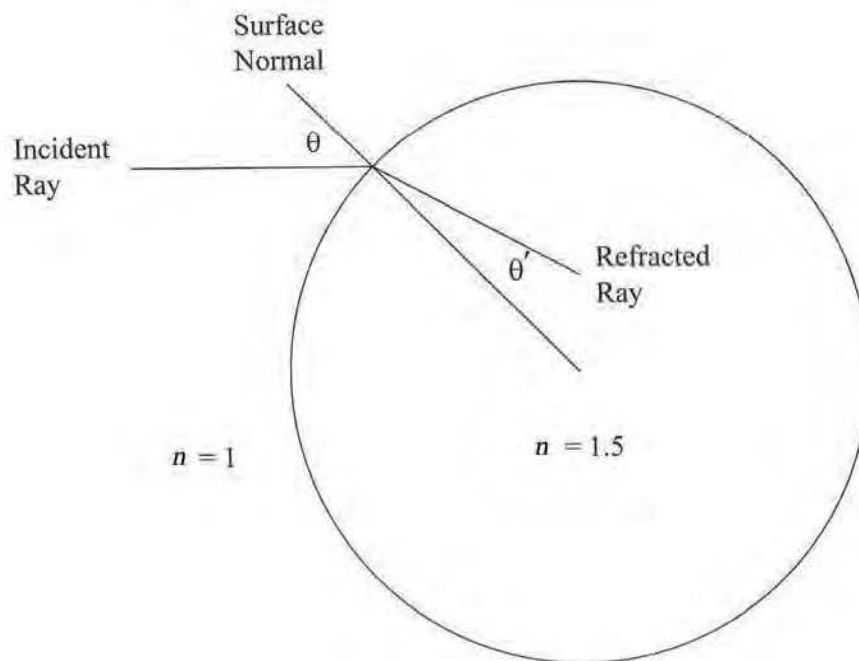


Figure 4.1 Ray refracting at a spherical surface.

If we now increase from one ray to several rays, we have the case of a finite-sized beam of light incident on and passing through a lens, as was shown in Fig. 2.4. We can see that the parallel ray bundle incident on the lens is converging after having passed through it. Because of this, the lens is known as a converging (positive) lens. If the ray bundle had been diverging after passing through the lens, it would be known as a diverging (negative) lens.

A lens, to the first order, is described by the location of a set of points known as the cardinal points. The cardinal points consist of the principal points, the nodal points, and the focal points. Each of the cardinal point types come in pairs. There is a front principal point and a rear principal point. The same is true for the nodal and focal points. Figure 4.2 shows a biconvex lens with the cardinal points labeled. The principal points are points of unit magnification. If a plane is drawn perpendicular to the axis, through a principal point, it is known as a principal plane. The principal plane can be considered the representative plane of bending of the rays in the lens. This can be seen by extending the input and output rays and noting that their intersection occurs at the (rear) principal plane. If we were to bring a ray from the rear side of the lens, it will appear to bend at the front principal plane. In a real system, the principal surfaces (which represent the ray-bending surfaces) are not truly planes, but for our discussions it is acceptable to consider them as such.

The nodal points are the points of unit angular magnification. That is, if a ray is aimed at the front nodal point, it will appear to emerge from the rear nodal

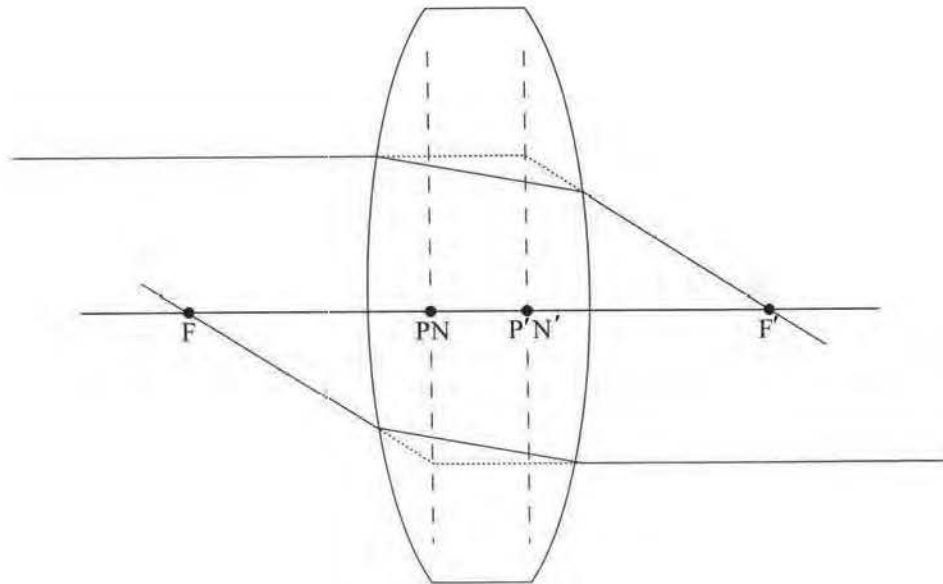


Figure 4.2 Biconvex lens with cardinal points labeled.

point at the same angle. If the lens system is in air, the nodal points will coincide with the principal points.

The focal points are the positions where an input ray that is parallel to the optical axis crosses the axis after passing through the lens. This can be seen for the input ray coming from the left in Fig. 4.2, which crosses the axis at the rear focal point, F' . A ray parallel to the axis coming from the right of the rear surface of the lens would cross the axis at the front focal point, F .

The distance from the principal point to the focal point is known as the effective focal length (EFL) of the lens. Most people have some familiarity with the concept of effective focal length. For a thin lens, the focal length is approximately the distance from the center of the lens to the location along the axis where an input collimated beam comes to focus. For a thick lens, or for a system made of multiple lenses, the focal length is not measured from the center of the lens system. To find the effective focal length, we extend an input ray (parallel and near to the axis of the system) as well as the corresponding output ray and find their intersection. The intersection of the two rays is the principal plane, and as before, the distance from the principal plane to where the output ray crosses the axis is the effective focal length. Depending on the powers and positions of the elements within the system, the principal plane may be in front of, inside of, or behind the physical system.

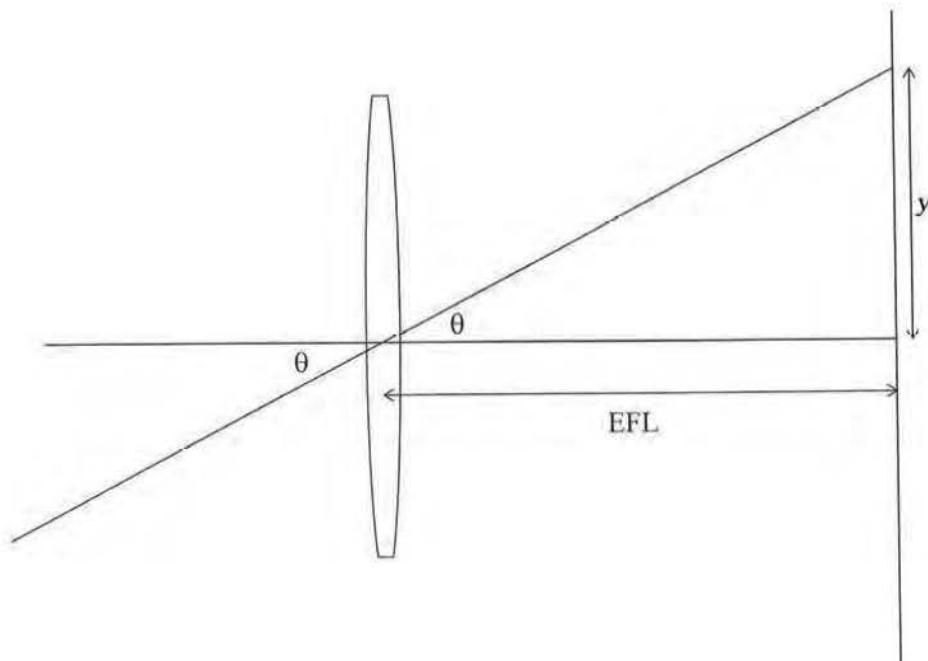


Figure 4.3 Relationship between focal length and image height.

The distance from the last optical surface of the system to the image is known as the back focal length (BFL), while the distance from the last piece of mechanical structure to the image is known as the flange focal length (FFL). In some systems there will be a required length of the BFL and/or FFL in order to provide necessary clearance for other elements, such as a fold mirror.

The focal length of a single lens can be calculated from knowledge of its radii of curvature, its thickness, and its refractive index. The equation for the focal length of a lens in air is shown in Eq. (4.1):

$$\frac{1}{\text{EFL}} = (n-1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n-1)}{nR_1R_2} \right], \quad (4.1)$$

where n is the refractive index of the lens material, R_1 is the radius of the first surface of the lens, R_2 is the radius of the second surface of the lens, and t is the center thickness of the lens. The sign convention for the radii is that the distance is positive if the center of curvature is to the right of the vertex of the surface and negative if the center of curvature is to the left of the vertex. As an example for the biconvex lens shown in Fig. 4.2, the front surface of the lens (left-hand surface) has a positive radius, while the rear surface has a negative radius.

The focal length of a lens or lens system provides the scaling factor between input angles for collimated beams and the height of the image formed by the lens, as is shown in Fig. 4.3. Collimated input beams can be considered to come from object points at an infinite distance (or very far) from the lens. We can see from the figure that the height of the image is related to the focal length and input angle through the equation

$$y' = \text{EFL} \tan \theta. \quad (4.2)$$

Using this equation for any given focal length lens, we can determine the image height as a function of input angle. Alternatively, if we have selected a particular detector and a desired field of view, we can calculate the focal length required to achieve it.

In the case of finite object distances, we can determine the location and size of an image by knowing the focal length of the system and the distance of the object from the front focal point. An example of a finite imaging situation is shown in Fig. 4.4. The relationship between the object and image distances is given by

$$xx' = -ff', \quad (4.3)$$

where x is the distance of the object from the front focal point, x' is the distance of the image from the rear focal point, f is the front focal length, and f' is the rear focal length of the system. For a system in air, f and f' are equal. Setting $f = f'$ and solving for the image distance x' , we obtain

$$x' = -\frac{f^2}{x}. \quad (4.4)$$

The height of the image h' can be determined from

$$h' = \frac{hf}{x} = \frac{-hx'}{f}, \quad (4.5)$$

where h is the height of the object. The ratio of the image height to the object height (h'/h) is known as the magnification and is usually denoted by m . Using Eqs. (4.4) and (4.5), we can determine the image location and size for any object height and position when imaged with a given focal length lens or lens system.

We next consider the concepts of the aperture stop and the pupils. In any optical system, there is some aperture that limits the size of light beam that can pass through the system. In some cases, this aperture may be the diameter of a lens. Alternately, it could be the mounting flange or retaining ring of a lens. In many cases an aperture (such as an iris) is specifically positioned to set the beam size. The limiting aperture is called the aperture stop of the system. In most photographic cameras, there is an adjustable aperture that is the aperture stop. When the aperture is closed down to a smaller opening, it is referred to as “stopping down” the system.

The entrance and exit pupils are nothing more than the images of the aperture stop when viewed through all the elements in front of and behind the aperture stop, respectively. All of the light entering the system appears to go into the

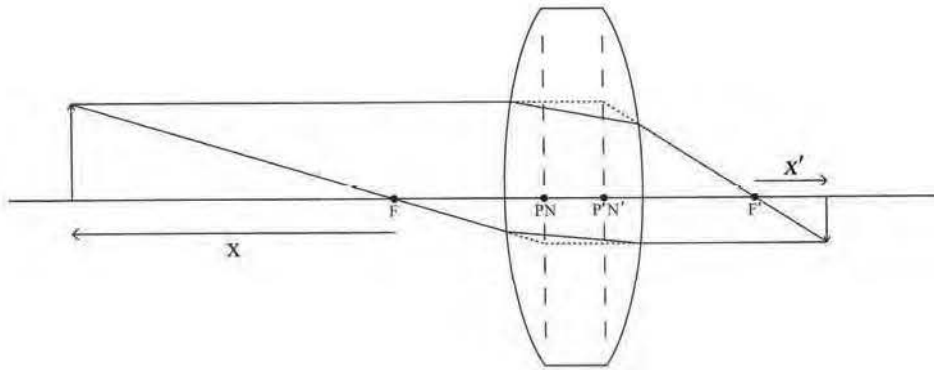


Figure 4.4 Example of imaging at finite conjugates.

entrance pupil, and all of the light exiting the system appears to come out of the exit pupil. When we look into the front of a lens system and see the limiting aperture, we are looking at the entrance pupil. Similarly, when looking into the rear of the lens system, we see the exit pupil.

The ratio of the focal length of the lens system to the entrance pupil diameter is the f number ($f/\#$) of the system. The $f/\#$ describes the system's light capturing ability. Smaller values of $f/\#$ (such as $f/2$ versus $f/4$) are associated with more light capturing ability. Smaller $f/\#$ systems are referred to as "faster" systems; that is, an $f/2$ system is faster than an $f/4$ system. The term comes from early film cameras, where a faster system required the shutter to be open for a shorter period of time than a slower system (i.e., the picture could be taken faster).

Up to this point in our discussion, we have considered only the first-order properties of lenses. We have discussed that we can determine the size and location of an image, but we have not yet concerned ourselves with the quality of that image. By image quality, we refer to how much the image of a point object looks like a point. If we consider a generic object to be made up of a collection of points, the quality of the image will depend on how well the lens system images each point making up the object to a corresponding point in the image.

In general, a point in the object is not imaged to a point in the image but (at best) to a small blur. This is due to diffraction as well as the aberrations of the lens system. Diffraction deals with the wave nature of light and sets a lower limit on how small the image of a point can be in the absence of aberrations. At the moment, we do not concern ourselves with diffraction, only with aberrations. Aberrations are the departure from perfect imaging. When an optical system has aberrations, the image of a point does not look like a point, and/or the image of a point is in the wrong location. We next consider some common aberrations seen in optical systems as well as some general techniques for controlling them. More extensive discussion of aberrations, aberration theory, and techniques for aberration control are found in several works.^{59–61}

We begin our discussion of aberrations by considering chromatic aberrations. Chromatic aberrations can be thought of simply as the variation in first-order characteristics of the lens (or lens system) with the wavelength of light. Consider, for instance, a singlet lens used with the visible spectrum. We know that the different colors in the visible spectrum are associated with light of different wavelengths, with red being longer and blue being shorter wavelengths. Earlier, we discussed the fact that materials have different refractive indices for different wavelengths, which is known as dispersion. We also saw in this section [from Eq. (4.1)] that the focal length of a single lens depends in part on its refractive index. It follows that since the lens has different refractive indices for different wavelengths, it will also have different focal lengths for different wavelengths. This is shown in Fig. 4.5. The rays representing the blue light, for which the lens material has a higher index, focus nearer to the lens than the rays representing the red light, for which the lens has a lower refractive index. The higher blue-light refractive index results in a shorter focal length than the lower red-light refractive

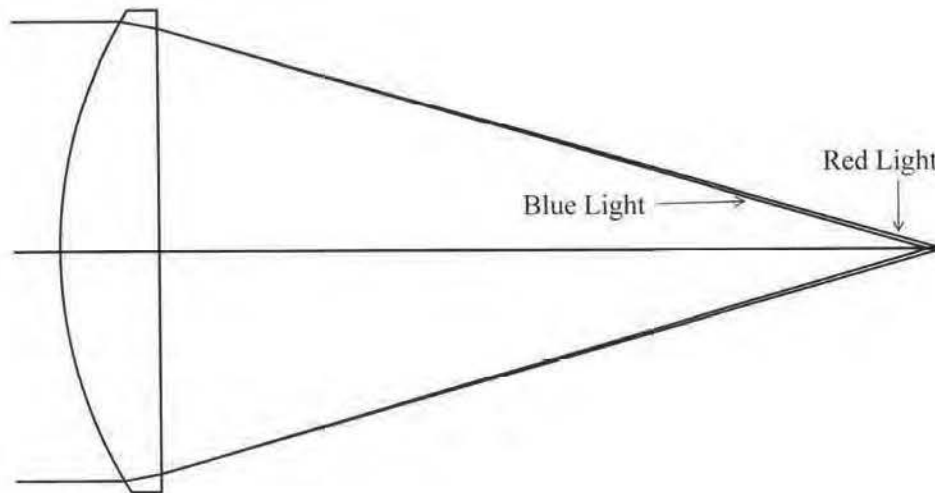


Figure 4.5 Lens exhibiting axial chromatic aberration.

index. This axial separation of the foci of the different wavelengths of light is known as axial chromatic aberration or axial color. The effect of axial color is to create color blurring in the image. If we were to place a screen at the axial position of the focus of the blue light, we would (in geometric terms) see a bright blue spot surrounded by a red blur. The red blur would be due to the fact that the red light had not yet come to focus. In reality, we would not just see a red blur because all the wavelengths between blue and red would be striking the screen, somewhat out of focus.

Now that we understand the potential variation of focal length with wavelength, we can predict what happens due to this variation in the case of an off-axis image point. We stated earlier in Eq. (4.5) that the height of the image depends on the focal length of the lens. If the focal length varies with wavelength, then the image height will also vary with wavelength, and for a given object, different wavelengths (colors) will end up at different image heights. Using the same lens as the previous case, we have a shorter blue focal length and a longer red focal length. This results in the blue light being imaged to a different height than the red light. This separation in height of the different colors is known as lateral chromatic aberration or lateral color.

In addition to chromatic aberrations, there are geometric and nongeometric aberrations. Geometric aberrations result in the rays from a point object not coming together to form a point image, regardless of the image surface location or shape. With nongeometric aberrations, we can adjust the image surface position and shape such that we can obtain a point image for a given point object. We consider the geometric aberrations known as spherical aberration, coma, and astigmatism, and the nongeometric aberrations of Petzval curvature and distortion. Each of these aberrations can vary with color, so we could have spherochromatism, which is the variation of spherical aberration with

wavelength. The variation of these aberrations with wavelength is a higher-order consideration, which we will not discuss in detail here. In our discussion of geometric and nongeometric aberrations, we assume we are using light of only one wavelength.

The first geometric aberration we consider is spherical aberration. Spherical aberration can be thought of (in the case of a simple lens where the pupil and lens are colocated) as a variation in focus with lens aperture radial position. For more complex multielement lenses, it is the variation of focus with respect to the radial position of a ray in the entrance pupil. Figure 4.6 shows a lens with a planar front and a spherical rear surface that is exhibiting spherical aberration. In this case, rays from the outer edge of the lens focus closer to the lens than do rays from the central portion of the lens. The existence of spherical aberration can be fairly simply understood by considering Snell's law. As the rays move farther out from the axis of this lens, the angle of incidence on the rear lens surface increases. Correspondingly, the angle of refraction increases, but not at the rate that would be required for the rays to all pass through the same point on the axis. In the case shown, the rays refract at larger angles than would be desired for perfect imaging. When the rays from the outer portion of the lens (or pupil) focus closer to the lens than the rays near the center, the spherical aberration is said to be "undercorrected." If the reverse were true, and the rays from the outer portion focused further away, the spherical aberration would be "overcorrected." The amount of spherical aberration, that is, how far the rays from the edge of the pupil intersect the image plane compared to the intersection of the ray through the center of the pupil, varies as the third power of the pupil size, but it is constant with field angle.

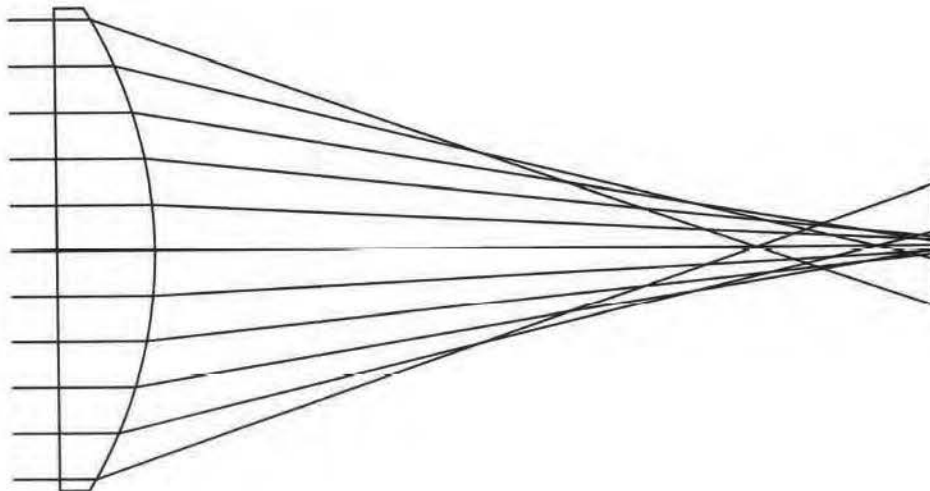


Figure 4.6 Plano-convex lens with spherical rear surface exhibiting a large amount of spherical aberration.

There are several design methods to control spherical aberration. One method is to change the shape of the lens such that the angles of incidence on the surfaces are adjusted (typically reduced). Changing the lens shape while maintaining its focal length is referred to as “bending” the lens. Figure 4.7 shows a lens with a different shape but with the same focal length as the lens shown in Fig. 4.6. We can see that this “bent” lens shape has much less spherical aberration. Another method to reduce spherical aberration is to “split” the lens, dividing the power of the lens amongst multiple elements. This method also reduces the angles of incidence on the surfaces, which reduces the amount of spherical aberration. Yet another method to control the spherical aberration is to use an aspheric surface. By selecting the correct surface shape, we can adjust the angles of incidence such that the rays are all properly refracted to go through the same axial image point. An example of this is shown in Fig. 4.8, where the rear surface of the lens is a conic surface with a conic constant equal to the negative of the square of the refractive index of the lens.

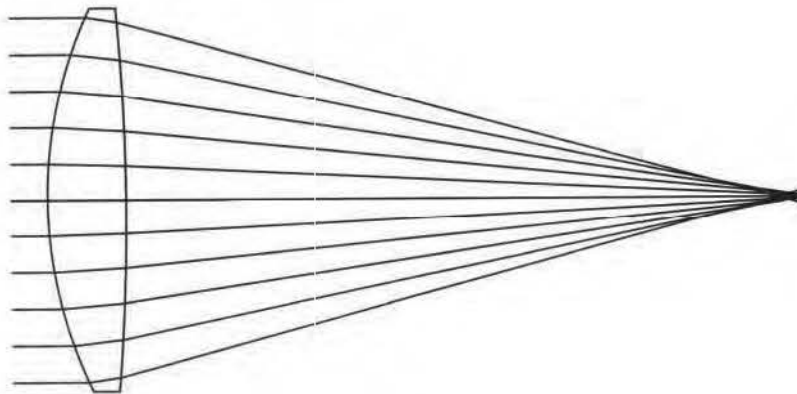


Figure 4.7 “Bent” lens showing reduced spherical aberration.

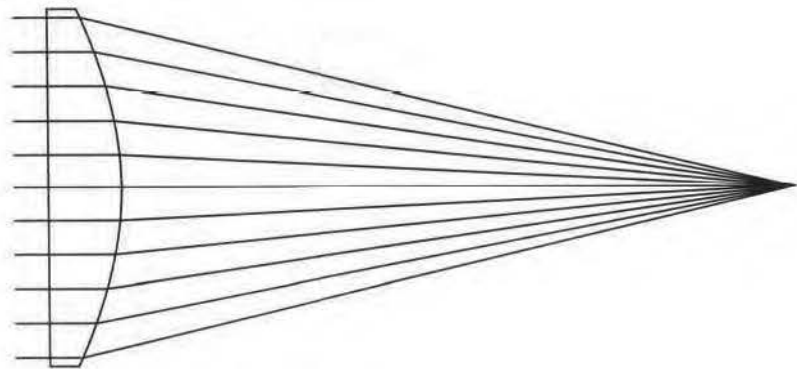


Figure 4.8 Plano-convex lens with rear conic surface, exhibiting no spherical aberration.

The second geometric aberration we discuss is coma. The name for coma comes from the comet-like appearance of a point image when this aberration is present. Coma is a variation in magnification as a function of radial position in the entrance pupil. Rays from different annular zones within the pupil strike the image plane at different heights, as shown in Fig. 4.9. We can see in this figure that the rays from the outer edge of the pupil come together at a different height than the ray from the center of the pupil. The amount of coma varies with the square of the pupil diameter and linearly with the field angle. Coma can be a particularly annoying aberration because it produces an asymmetric image of a point object. There are several methods used to control coma. One method is to move the axial location of the aperture stop, which adjusts where the beam of rays strike the lens. Another way to control coma is through the use of symmetry. If a lens system is symmetric about the aperture stop, the coma introduced by the lenses before the aperture stop will be cancelled by the lenses after the aperture stop. This is technically true only if the object and image distances are the same, which would give a magnification of one. However, even if the system is not used symmetrically, the coma is to a large extent cancelled between the two halves of the lens system.

The third geometric aberration we consider is astigmatism. Some readers may be familiar with astigmatism due to having it in their visual system. When astigmatism is present, rays in two orthogonal planes through the lens system

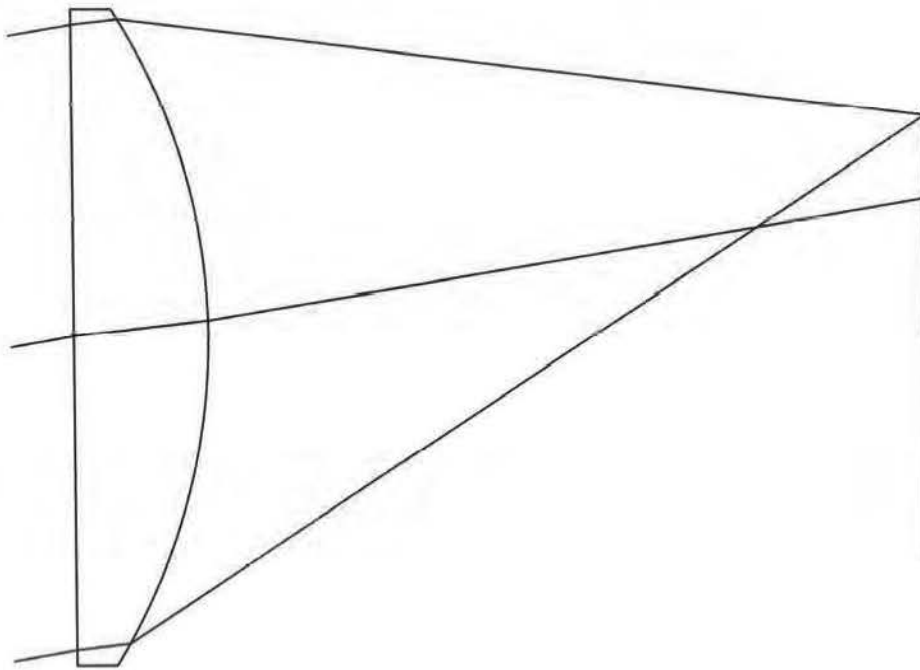


Figure 4.9 Plano-convex lens exhibiting coma.

focus at two different axial locations. At each focus, the image of a point object is a line, due to the rays in one plane being out of focus. In between these two foci, the image of a point object has an elliptical shape. Midway between the foci, the shape is circular. Astigmatism arises from the fact that as the beam strikes the lens at an off-axis position, the height and width of the beam are different. As a result, rays in the two directions have different angles of incidence and are refracted by different amounts. The amount of astigmatism depends upon the shape of the lens, as well as its distance from the aperture stop. For a given lens, astigmatism depends linearly on the pupil size and with the square of the field angle. By adjusting the shape of a lens and its distance from the aperture stop, the astigmatism of an element can be controlled. It can also be controlled through the use of an aspheric surface, which will change the angles of incidence that the beam sees when it strikes the surface.

Having discussed the geometric aberrations, we now consider the nongeometric aberrations. Again, we refer to them as nongeometric because they do not cause the image of a point object to blur; instead, they change where the point-like image of a point object is located. The first nongeometric aberration we discuss is Petzval curvature, which is an inherent curvature of the image surface of a lens. While we often refer to the “image plane” (because our film or detectors are typically planar), the preferred shape for a positive lens, if all other aberrations were corrected, would not be a plane but an inward-curving surface. This curved image plane is known as the Petzval surface and is illustrated in Fig. 4.10. The use of a planar image surface, instead of a curved one, results in the off-axis points being out of focus. The blur depends linearly on the pupil size and quadratically with field height. It should be noted that some optical systems, such as the human eye and the Schmidt camera, use a curved image surface.

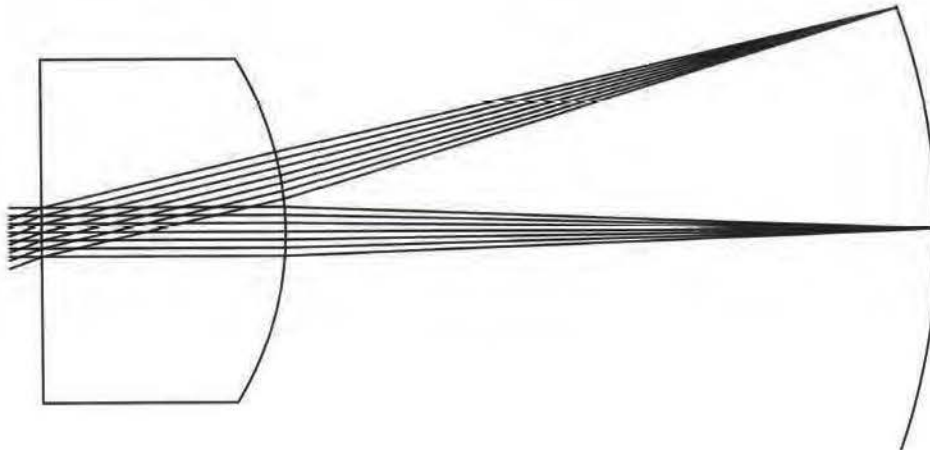


Figure 4.10 Lens showing a curved image surface, known as Petzval curvature.

The amount of Petzval curvature depends directly upon the power of a lens and inversely on its refractive index. Being an inherent property of the lens, the Petzval curvature contribution of a lens does not depend upon its position within a system of lenses. While the Petzval surface of a positive lens is inward curving, the opposite is true for a negative lens; a negative lens has an outward curving Petzval surface. Thus, it would seem logical that one way to reduce the amount of Petzval curvature would be to combine positive and negative lenses. If we were to take a positive and a negative lens with equal and opposite power and combine them in a doublet, we would end up with no Petzval curvature—that is, with a flat image plane. The problem with this arrangement (assuming thin lenses are in direct contact) would be that the powers of the lenses would cancel each other (they are equal and opposite), so we would end up without any optical power. However, while the contribution of any lens element to the Petzval curvature does not depend on its location within the system, the contribution of its power to the total system power does. Therefore, we can separate the two components, which will create optical power, while maintaining the sum of their Petzval contributions, which is zero. Using separated positive and negative elements is a common optical design technique to reduce the Petzval sum. An example of this can be seen in the Cooke triplet, which consists of a positive element, a negative element, and a positive element, all of which are axially separated.

Another method of reducing the Petzval curvature, also known as “flattening the field,” is the use of a negative field lens placed near the image plane. A field lens is a lens that is placed near the image plane or at an intermediate image. We can understand how a negative lens placed near the image plane flattens the field by considering the fact that it provides increasing glass thickness as a function of field height. When a converging beam passes through a block of glass, the focus position of the beam is shifted by an amount related to the thickness and refractive index of the glass. In the case of a negative field lens, the glass thickness increases as a function of the field, so the image is increasingly shifted as a function of the field height. By choosing the correct surfaces on the field lens, that is, by setting the correct thickness variation, the image is shifted by the appropriate amount to make it lie on, or nearly on, a plane. One potential problem with a lens of this type, often referred to as a “field flattener,” is its location near the image plane, where the converging beams have a small cross-sectional area. Any small defect on the lens (such as a dig) or any contamination can block a large portion of the beam heading to a given field point.

The last aberration we discuss is distortion. Most people are familiar with distortion, having seen the distorted image from a wide-angle camera lens. We discussed earlier how to compute the height of an image, given a focal length and field angle. This image height assumes that there is no distortion in the system. If distortion is present, the image of a point object will not be at the expected height, but it will be displaced. The distance that the actual image is displaced from the predicted image is the amount of distortion of the system. The amount of distortion is often quoted as a percentage—the ratio of the displacement of the image to the predicted image height times 100.

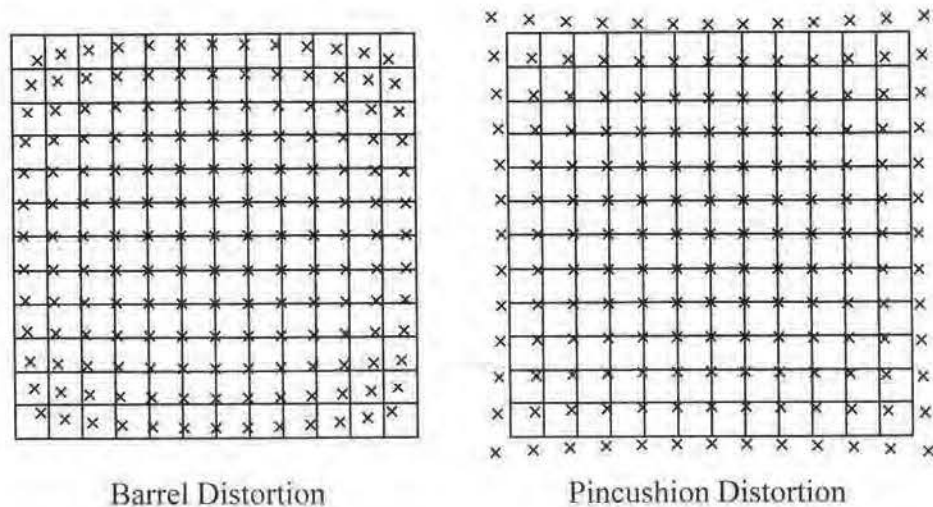


Figure 4.11 Effect of barrel and pincushion distortion on the image of a grid object.

The distortion contribution of an element depends upon the distance of the element from the aperture stop of the system as well as on the element's thickness. The distortion of a system is constant with pupil size and varies with the third power of the field. Because of this cubic dependence, the image of a grid object has the familiar “barrel” or “pincushion” appearance associated with distortion, depending on whether the distortion is positive or negative. Examples of these are shown in Fig. 4.11, where the crosses in the plots show the location in the image of the corners of the squares forming the grid object.

Distortion, like coma, can be eliminated or reduced through the use of symmetric lens element arrangement. The distortion introduced by the front half of the system will be cancelled by the contributions of the rear half of the system. Distortion can also be controlled by the use of aspheric surfaces. In many imaging applications, small amounts of distortion (up to about 2%) can easily be tolerated.

Having briefly reviewed geometric optics, as well as aberrations and some techniques to control them, we now consider the basic process of optical design, the role of the designer, and the role of optical design software. There are several excellent texts that discuss these topics in greater depth than will be covered here.^{62–64} The process of optical design begins with an understanding of the requirements that the completed design must meet. Basic requirements such as focal length, field of view, $f/\#$, and wavelength range are typically imposed. In many cases, specific numbers are not available, but a general desired range is known. Some type of performance requirement, such as encircled energy, modulation transfer function (MTF) value, or resolution is also usually stated. In addition to these basic optical requirements, there are often additional constraints,

such as packaging volume. For plastic optical systems, the factors that drive their selection (such as cost and weight) can be additional constraints. One of the functions of the designer is to understand the effects of the various constraints, as well as their interactions, and to determine if they can all simultaneously be met.

In many cases, the customer requesting the design is not familiar with the specification of optical systems. They know what they want but do not necessarily know how to put their desires in the form of a specification. Here the designer must play the role of interpreter, translating the customer's desires into requirements that the design can be evaluated against. For example, in the design of a web camera, the customer may not know the field of view required, but they know that they want to be able to see a person's head and shoulders when using the camera. Using this information, the optical designer can calculate approximately what field of view is needed, and if a specific detector is to be used and what the focal length of the lens needs to be.

In some instances, the customer cannot even be this specific. They may want to be sure to see the person's head and shoulders but cannot decide how much beyond their shoulders they should see. This may result in the need for a trade study, where, for example, different field-of-view systems are designed, and the performance, cost, and other factors compared. The customer may have multiple, competing, and sometimes unachievable desires. In this case, the designer must communicate closely with the customer, explaining what is and what is not achievable. Additionally, the designer must describe the cost, be it monetary, performance, or something else, that is necessary to meet a certain requirement.

Once the basic requirements, desires, and constraints are understood, a basic lens form, or starting point, can be selected. Often, the design that is required is similar to one that already exists; it is difficult to come up with something completely new. In this case, the existing design may be used as a starting point for the new design. Various parameters (such as focal length) can be adjusted in order to meet the requirements of the new design.

One question that often arises is, "Where do I get such an existing design?" In the design of glass optical systems, there are several sources that can provide a wide range of design forms. Multiple books exist that present the design details of various systems, as well as discussions of how they work, and why they look the way that they do.^{65,66} Patent databases are another excellent source of potential design starting points. Of course, when using a patented design as a starting point, the designer must ensure that the new design does not infringe on the patents. A third source of starting-point designs is the optical design software program used to perform the design work. Most of the optical design programs come with a database of designs.

In the design of plastic optical systems, it can be more difficult to obtain an existing design to use as a starting point. Many plastic optic manufacturers have a database of designs they have developed over the years, but these are typically not shared with the general public. The patent database can be an excellent place to look for a starting point, although at times it can be difficult to find exactly what is desired. Conference or journal articles can also be good places to look for

designs. In many instances, the exact prescription is not available, but the general lens form can be enough to begin with. If comparing glass and plastic solutions, beginning with a glass design and changing the glasses to optical plastics may be one place to begin. If no comparable design can be found to use as a starting point, the designer can always begin by using a single lens and adding lenses as needed.

With a starting point defined, the development of the design can begin. Today, most optical design work is performed on a computer with the assistance of an optical design software program. Readers who are interested in old-school (precomputer) design methods are referred to the book by Conrady.⁶⁷ There are multiple design programs available commercially, the best known of which are CodeV,^x OSLO,^{xi} and ZEMAX.^{xii} These programs are highly sophisticated and enable the designer to perform a wide range of designs and analyses. The choice of which software program to use is often dependent on a number of variables, such as personal preference and cost. For most plastic optical designs, any of the well-known commercial design codes can perform adequately.

There is currently no closed-loop algorithm to design an optical system. While the same result can be arrived at through different paths, wildly divergent designs may also arise from the same starting point. This is partly due to the large number of variables that are available in the design process. Variables are the parameters, such as radius of curvature, that the design program will vary in an attempt to improve the design. Typically, in a plastic optical design, each lens surface (radius and possibly aspheric coefficients), lens material, and to some extent thickness, as well as lens location, are available as variables. It is the job of the designer to determine what parameters are to be assigned as variables as well as their allowed range.

Once the variables are defined, an algorithm for evaluating the lens is developed. This algorithm is commonly known as the “merit function.” The merit function provides a numerical representation of the “goodness” of a design. A small value of the merit function means that a lens is considered better than another lens with a larger value (assuming the same merit function algorithm is used). The optical design codes normally have one or more default merit functions that can be modified by the designer as appropriate. The default merit functions typically use some composite of the performance (such as spot size) at each of the defined field angles to generate the merit function value. In addition to the spot size (or other performance metrics), constraints such as focal length, allowed packaging length, or distortion are also evaluated.

With the variables and constraints defined, the design may now be “optimized.” Optimization is usually performed by slightly changing each of the variables and determining which way they should be adjusted to improve the design—that is, lower the merit function value. At the same time, the adjustment

^x CodeV is a registered trademark of Optical Research Associates.

^{xi} OSLO is a registered trademark of Lambda Research Corporation.

^{xii} ZEMAX is a registered trademark of ZEMAX Development Corporation.

of the variables must be such that the constraints are met. Once the necessary changes are determined, the variables are adjusted (usually by a small amount), the merit function is evaluated, and the cycle is repeated until the improvement in the merit function value is less than some predefined amount. The goal of the optimization is to drive the system to the design form having the lowest value of the merit function. Because the merit function is a function of multiple variables, the solution found may be a local optimum, but not a global one.

Most of the optical design programs feature some type of “global optimization” function. The goal of the global optimization is to find the “best” lens solution given the constraints and variables entered. It must be remembered that “best” is determined solely by the inputs to the computer program. Any constraint that is not included will not necessarily be met. Some constraints (such as cost and manufacturability) are not always easily entered as constraints, although work in this area is ongoing.⁶⁸ The global optimizers can be useful for generating different design forms, which may themselves be used for local optimization. In some cases, the global optimization run will result in the preferred solution; in others, an ideal trade amongst the various constraints will not be achieved, and the designer will have to continue to work on the design.

Up to this point, we have discussed the design process as working towards determining the lens form with the lowest merit-function value. One thing to remember is that the merit function typically only evaluates the nominal lens system. In reality, we do not necessarily want to manufacture a lens with the best nominal performance, but a lens that provides the best “as-built” performance, taking into account the tolerances (and cost) that are associated with building it. The evaluation of the performance (and cost) of the various tolerances on the parts and their assembly is known as “tolerancing” the design and is discussed in the next section. The tolerancing of a design is a critical part of the design process. No design should be considered complete until a tolerance analysis has been performed.

Sometimes, the most difficult decision a designer must make during the design process is the determination that a design is finished. This is particularly true for novice designers. With a deadline approaching, this may not be a problem, as the design is done when time has run out. In other cases, when the design schedule is more open ended, it can be difficult to shake the feeling that “just a little more” performance can be squeezed from the system. Experience (or sheer exhaustion) will often allow the designer to recognize the need to bring the design effort to its conclusion.

4.2 Tolerances

There is potentially nothing more frustrating for an experienced optical designer to hear than the statement that “the design is all done, I just need to tolerance it.” In reality, nothing could be further from the truth. An optical design is not complete until all necessary tolerances have been assigned. The tolerancing of a

design can often take longer than the generation of the nominal optical prescription. Until a design has been toleranced, it is not known if its components can be made accurately enough, or how much it will cost to make the system meet its requirements. In this section, we discuss tolerances that can be achieved on plastic optic elements and consider the basic process of tolerancing a plastic optical design.

While some individuals and vendors in the plastic optics industry do not like to state explicitly what tolerances they can hold (due to part design dependence), we feel that for many typical optical elements there is a fairly standard set of achievable tolerances that a design should initially be evaluated against. Of course, every optical element needs to be individually evaluated, with the assistance of the molder, to assess the chances and/or cost of achieving the desired tolerances. Table 4.1 shows typical tolerances that can be achieved in molded plastic optical elements. The labeling of the columns can be debated as to the accuracy of each term. The terms used are similar to those used in other works discussing tolerances. Coming from a precision plastic optics molding house, the author believes that the tolerances labeled state-of-the-art are actually typical of the tolerances most optics molders hold, and that even slightly tighter tolerances may be able to be achieved. There may, however, be cost savings associated with alternate vendors and looser tolerances, and we suggest that the designer determine what tolerances are actually required to make their system perform adequately, as opposed to what tolerances can be achieved. We now briefly discuss each of the tolerances in the table.

Table 4.1 Typical tolerances for injection-molded optical elements.

	Commercial	Precision	State-of-the-Art
Radius	$\pm 5\%$	$\pm 2\%$	$\pm 0.5\%$
EFL	$\pm 5\%$	$\pm 2\%$	$\pm 1.0\%$
Thickness (mm)	± 0.13	± 0.05	± 0.020
Diameter (mm)	± 0.13	± 0.05	± 0.020
Surface Figure	$< 10f (5\lambda)$	$< 6f (3\lambda)$	$< 2f (1\lambda)$
Surface Irregularity	$< 5f (2.5\lambda)$	$< 3f (1.5\lambda)$	$< 1f (0.5\lambda)$
Surface Roughness (RMS)	$< 100\text{\AA}$	$< 50\text{\AA}$	$< 20\text{\AA}$
Surface S/D Quality	80/50	60/40	40/20
Wedge (TIR) (mm)	< 0.025	< 0.015	< 0.010
Radial Displacement (mm)	< 0.100	< 0.050	< 0.020
Aspect Ratio	$< 8:1$	$< 6:1$	$< 4:1$
Repeatability[†]	$< 2\%$	$< 1\%$	$< 0.5\%$
DOE[§] Depth (μm)	---	± 0.25	± 0.10
DOE Min. Groove (μm)	---	25	10

* diameter/thickness ratio † part to part in one cavity § diffractive optical element

NOTE: Above tolerances are for 10- to 25-mm-diameter elements.

The tolerance on the radius of curvature depends on the precision of the optical insert, the injection molding process, and the shape of the surface. Steeper surfaces can typically be held to a tighter tolerance than weak shallow surfaces. This is due to the increased self support that a steeper surface provides. A tighter tolerance on radius may also be achieved through compensation of the optical insert.

The tolerance on the EFL includes within it the tolerances on both surfaces of the element as well as the refractive index of the material. As such, tighter EFL tolerance may require tighter radii tolerances. In some cases, it is the back focal length (BFL), not the effective focal length (EFL), that is of interest. In this case, the tolerance should be called out on the BFL, perhaps with a loosened requirement on EFL.

The thickness of an element is set by adjusting the positions of the optical inserts within the mold. The inserts typically rest on thick, precision-ground spacers. The spacers are often initially built too thick and then are ground to the correct length after the mold processing has been performed. Any change to the optic insert, such as re-turning the surface to remove a scratch or swapping an insert due to damage, may require adjustment to the spacers. In some cases, the accuracy of the thickness measurement sets a lower bound on the thickness adjustment.

The diameter of the element is typically formed by the feature (hole) that is machined into the mold base. This feature size, along with the material shrinkage, sets the final diameter. Improved machining has resulted in diameter features in the mold that are held extremely tightly. However, in some cases the diameter may increase when the part is removed from the mold. Unless the mold has been machined in a “steel safe” condition (with extra material left on), it may not be easy to correct the diameter size.

Glass optical surfaces are typically specified using the terms “power” and “irregularity.” The terms come from the test process, where a lens surface is compared against a highly accurate spherical test plate. When putting the test plate and lens together, and using a nearly monochromatic light source, a series of rings (fringes) would be observed from the interference of the light reflected from the two surfaces. If the lens surface was perfectly spherical, but of the wrong radius, the fringes would be perfectly circular and the number of fringes seen would relate to the difference in the radii of the lens surface and test plate. Any departure of the lens surface from true spherical shape would result in changes to the circular shape of the fringes, referred to as irregularity. When dealing with plastic optics and aspheric surfaces in particular, the definitions of surface figure and irregularity are not universally agreed upon.

For our discussion, we consider surface form (figure) to be how closely the surface matches the desired surface, in a symmetric way, while irregularity describes how rotationally asymmetric the surface is. This description is most appropriate for surface testing using a contact profilometer. Sometimes the term cylindrical irregularity is used, which allows the radius to be adjusted between measurements instead of using one radius value for all measurements. For

interferometric surface measurement, having only a radius tolerance and a form tolerance is the preferred method. This format can also be used with surface profilers. Whatever specification method is chosen, it is important that the surface description used in the tolerance analysis accurately reflects the specification, and that the designer and vendor agree upon the definitions and test methods.

If we have specified a spherical surface, we would like the surface produced to be spherical as well. However, due to edge break or variation in shrinkage, the surface may end up being slightly aspheric. Provided the asphericity is less than the surface figure tolerance, the surface will conform to its specification. The surface form tolerance is often specified in fringes. Conversion to distance units can be obtained by noting that two fringes correspond to a distance of one wavelength (typically chosen as 632.8 nm).

The surface figure tolerance is typically used in conjunction with the radius tolerance. That is, the radius is first adjusted (up to its allowed tolerance) to minimize the form error, then the form error (surface figure) is evaluated against its tolerance. Surface figure can be adjusted by altering the mold process or by compensating the mold. In some cases, in order to produce a spherical surface, an aspheric optical insert will be used. Surface figure typically gets harder to hold as the size of the part increases. The values in the table are for parts up to about 25 mm in diameter. For symmetric parts up to 75 mm in diameter, Beich⁶⁹ suggests that less than two fringes per 25 mm can be achieved.

While the surface figure tolerance sets how well the surface must match the desired surface, the surface irregularity tolerance sets how symmetric the surface must be. As opposed to the terms surface form and irregularity, other authors use the terms irregularity and astigmatism.²² Plastic optical parts may have some amount of asymmetry in them due to the nonuniform flow of the material during the molding process or due to ejection of the part.

While the surface form and irregularity deal with the surface variation on a larger scale, the surface roughness controls the variation of the surface on a small scale. The main effect of surface roughness is scattering of the light passing through it, which can be particularly troublesome in laser-based systems. In most systems, low enough surface roughness can be achieved to reduce any impact on system performance. In the case of molded plastic optics, the surface roughness largely depends on the surface roughness of the optical insert it is replicated from. Polished stainless steel inserts can achieve excellent surface roughness. The more commonly used nickel-plated inserts, which are diamond turned, also can achieve low-surface roughness values and can be postpolished if necessary.

The surface roughness is called out as a root mean square (rms) value. The actual value of surface roughness reported depends on what spatial frequencies are evaluated in the measurement. There is typically some upper frequency bound set by the wavelengths that the system uses and some lower frequency bound set by the measurement equipment. This is covered in the discussion of testing in a later chapter.

The scratch-dig specification sets how many and how large the scratches and digs (pits or pit-like defects) on the optical surface can be. The nomenclature of the scratch-dig specification is two numbers separated by a slash. The numbers refer to the allowed size of scratch or dig. For instance, a 40/20 callout means that the maximum allowed scratch width is 40 μm , and the maximum pit diameter is 0.2 mm (200 μm). Scratch-dig inspection is usually performed visually using a calibrated set of reference samples. Scratch-dig specifications are typically referenced to some defining document, such as MIL-SPEC-13830, which gives additional guidance on their interpretation. For small elements, scratch-dig issues can be important, as a dig may take up an appreciable amount of the surface area.

The tolerance on wedge in molded plastic optics is controlled in the production of the mold. Because of the way the molds are made, wedge is usually not a large problem. The wedge specification is often called out as a total indicated run-out (TIR) quantity, which should not be confused with total internal reflection. The total indicated run-out is the full range that a dial indicator moves when held against the part during the measurement.

Radial displacement is another tolerance that is largely controlled by the quality of the mold. As we discussed earlier, molds are typically made up of various inserted pieces. Each inserted piece will have some fit tolerance with the piece it goes into as well as centration of its features to its diameter, for example, the centration of the optic surface to the diameter of the optic pin. These tolerances combine to create the final radial displacement tolerance. In actuality, there are two radial displacements that must be considered. These are the displacement of an individual optic surface to the diameter of the lens and the displacement of the two optic surfaces to each other. These values are regularly held to approximately 20 μm , with surface-to-surface values in the 5- μm range held for small elements in cell phone cameras.

Aspect ratio, or the ratio of the diameter of the lens to its thickness, is not really a tolerance but more of a rule of thumb. As this ratio decreases, the parts look less and less like a standard lens and more “cube-like.” If the aspect ratio goes significantly below the values listed, discussion with the molder should take place before proceeding much further with the design.

Repeatability is usually one of the positive characteristics of molded plastic optics. Once the mold has been placed in the injection-molding machine and the process is stable, the parts that are produced from a given cavity will be very much like each other. Part size and shape have some influence on part-to-part repeatability. For instance, a surface with a long radius will tend to vary more than a surface with a short radius, and irregularity on large parts will tend to vary more than irregularity on small ones.

The tolerances on diffractive optical surface features are typically set by the accuracy of the master. With proper mold processing, accurate replication of the master can be achieved. Because of their small feature sizes, shrinkage is usually not a concern. For diamond-turned masters, the depth tolerance is set by the accuracy of the diamond-turning machine, while the minimum groove width is

typically set by the diamond tool size. Smaller feature sizes can be obtained through the use of other mastering techniques. As the features grow smaller, attention must be paid to the ratio of the depth to the width of the feature. As the depth-to-width ratio grows larger, the feature becomes more difficult to replicate.

One tolerance that was not listed in the table was variation in the refractive index. Molders do not typically want to set a refractive index tolerance because it is difficult to measure, and more importantly, because it is largely out of their control. While changes in the mold processing can affect the refractive index, the main contributor to index variation is the plastic optical material itself and how well it is controlled by the manufacturer. As we discussed earlier, several of the plastics were not specifically intended for use in optical devices, and the manufacturers do not necessarily attempt to control the refractive index variation. To be on the safe side, an index variation of ± 0.002 is often assumed. If a design is highly sensitive to refractive index variation, careful consideration of the design is suggested.

Having discussed the achievable tolerances, we now consider the tolerancing of the design. More detailed discussions of tolerancing can be found in Refs. 60 and 63. There are two main types of tolerancing performed: sensitivity analysis and predicted performance analysis. Sensitivity analysis aims to determine the sensitivity of some system characteristic to each of the individual tolerances. The characteristic may be related to image quality, such as MTF, or it may be some other metric, such as system boresight. Predicted performance analysis (as the name implies) aims to predict the performance of the system or the range of its performance, given a set of tolerances and their distributions. As in the sensitivity analysis, various parameters can be used as representations of the system performance. In each of the tolerance analyses, compensating changes, if they exist, must be specified. For instance, in many optical systems, there will be a final focus adjustment. This may occur by moving the lens barrel with respect to the image plane before it is fixed in place. This adjustment, known as a compensator, should be included in the analysis. Without the compensator, the system performance will appear much more sensitive or much worse than it really is.

To conduct the sensitivity analysis, a small change is made to each system parameter (radii, thickness, etc.) associated with a tolerance, one at a time, and the change in the system characteristic is evaluated. After running through each toleranced parameter, a sensitivity table is displayed. This table tells the designer which parameters the characteristic is most sensitive to. If the system performance is extremely sensitive to a particular parameter, the tolerance on that parameter will need to be tightly controlled, or the design needs to be adjusted to decrease its sensitivity.

To perform the performance prediction analysis, the designer must specify ranges for each of the tolerances as well as the distribution of the tolerances. The distribution of tolerances for a plastic optical system may be different from the distribution of tolerances in a glass system. The reason for this is the difference in manufacturing methods. Consider the thickness of a single element. In a

plastic optic, the center thickness will be set by adjusting the optic pin locations, as discussed earlier. The adjustment will be made with the attempt to reach the nominal thickness value, but the final thickness may fall anywhere within the allowed range. For a glass optic, often the center thickness will be on the high side. This is because it is safer for the optician to leave on extra material in case additional polishing is required. Once the surfaces meet their requirements and the center thickness is within the tolerance range, work on the lens will usually stop, leaving the center thickness on the high side of nominal. In this case, the predicted distribution of glass lenses would be skewed toward the high side, while the thickness of the plastic lenses would be more symmetrically distributed.

Because of the repeatability of plastic optics, it is often best to assume that their tolerances will take values near the end of their ranges. This is a more conservative approach than assuming a uniform distribution of values, and it will generally predict reduced performance compared to the uniform distribution. The predicted performance analysis can be run with various tolerance probability distributions to see the effect of distribution choice.

Predicted performance analyses are typically conducted in one of two ways: either through the use of statistical analysis or through the use of Monte Carlo techniques. In the statistical analysis method, the tolerance sensitivities are computed, along with their derivatives, and the performance is predicted by statistically combining the tolerance effects. In the Monte Carlo technique, tolerance values are randomly selected from within their distribution, and the lens is evaluated. This procedure is repeated a large number of times until the performance distribution is obtained. The statistical method is far faster than the Monte Carlo method, but it depends upon the underlying statistical assumptions. The Monte Carlo method, if properly set up, may be more representative of the actual built systems. Often it is useful to use the statistical method throughout much of the design cycle, and then perform a Monte Carlo analysis near the end to verify the performance predictions. We will show an example of Monte Carlo analysis and the effect of tolerance probability distribution in the next chapter.

4.3 Plastic Versus Glass

From a pure design viewpoint, standard techniques used in the design of glass optical systems can be utilized in the design of plastic optical systems. Many techniques, such as the balancing of lower- and higher-order spherical aberration, the use of spherochromatism to balance axial color, astigmatic field flattening, and even the use of chromatic distortion to balance lateral color, can be applied to both glass and plastic optical systems. However, in many cases, factors other than optical design may not allow a standard technique to be used, requiring alternate solutions. A number of classic design techniques are discussed in the lens design book by Smith.⁷⁰ We follow the general order used in that text in our

discussion of the differences in applying these design techniques to plastic and glass.

A common technique used in designing glass optical systems is the “splitting” of an element. Splitting a highly powered element into two (or more) elements, each of approximately equal power, and together having the same total power as the original element, reduces the angles of incidence on each of the surfaces, which results in a reduced amount of aberration. This is true whether the lens is made of glass or plastic. In the design of a plastic lens system, however, there may be a limit on the number of lenses that can be used due, for example, to cost or space constraints. The cost of a plastic optical system increases directly with the number of elements, so a given price point may set the number of elements allowed. An example of a space-constrained system would be a cell phone camera. In this design, a maximum overall length is usually imposed. In theory, increased numbers of elements could be shoved into the available space by decreasing the element thickness and spacing. In reality, there will be a minimum desired thickness such that the lenses can be manufactured. For production using injection molding, the lenses must be thick enough to allow the flow of the injected molten plastic.

A potential alternate solution to splitting the lens would be the use of an aspheric surface. Aspheric surfaces are readily manufactured on plastic optics, and the use of an appropriate aspheric surface may eliminate the need for the extra element created by splitting. Aspheric surfaces are discussed in a later section of this chapter.

A second standard technique in the design of glass systems is the use of an achromatic (or intentionally chromatic) doublet, a technique sometimes referred to as compounding an element. We can think of this technique as creating a new glass type, one that doesn’t exist on its own, by combining two different glasses. In many cases, the compounded element created is a cemented (as opposed to an air-spaced) doublet. The use of achromatic or partially achromatic doublets helps with the correction of chromatic aberrations as well as control of other aberrations (we have introduced at least one additional potentially cemented surface).

We can take the compounding technique further, in the case of a cemented doublet, by separating the cemented elements. By doing so, we introduce additional degrees of freedom. The shape of each element can now be independently changed, without the requirement of a matching cemented interface surface. Separating the elements may require tighter control of the decentration between them. The refraction at the new glass-air interface will typically be larger than at the previous glass-glass interface, with the possibility of total internal reflection without adjustment of the surfaces. This, however, can be dealt with in the design process and should not hinder separating the cemented elements.

As discussed above, cost or space reasons may not allow the use of sets of achromatic doublets. If doublets are used in a plastic optical system, they are usually not of the cemented variety. Some cemented plastic doublets have been

manufactured, but they are not the norm. Instead, air-spaced doublets, or the use of separated elements of varying materials similar to those used in a Cooke triplet, are more likely to be seen. As such, separation of the elements to achieve added performance will already have been used and will not be an additional available technique in the plastic optical system.

Similar to using an aspheric surface instead of splitting a lens, it may be possible in a plastic optical system to use a diffractive surface instead of adding an additional element as required to compound an element. A diffractive surface on a plastic lens, similar to an aspheric surface on a plastic lens, does not increase the cost of producing the element. There is, however, a potential performance cost, in terms of stray light, from using a diffractive surface.

Other standard techniques in the design of glass optical systems, based on material selection, are to raise the index of any positive singlet elements and lower the index of any negative singlet elements, or to raise the refractive indices of all the elements in general. A higher refractive index in a positive element will reduce the amount of Petzval curvature it introduces as well as reduce other aberrations through the use of longer radii surfaces, which typically decreases the angles of incidence on the surfaces. For a negative element, a lower refractive index will increase its (usually correcting) contribution to the Petzval sum. However, it will also result in a reduced radius of curvature, which may have a negative effect on aberrations. The balance of Petzval curvature and aberration correction must be considered when lowering the index of negative singlets. Raising the refractive index of all the elements will again reduce the required curvatures, thus reducing the aberration contribution of the surfaces.

As noted earlier, there are significantly fewer optical plastics to choose from compared to optical glasses. This limits the number of possible material choices available to the designer. In fact, some of the optical plastics, such as polystyrene and polycarbonate, have similar optical properties to each other, effectively reducing the choices even further. Depending on other constraints, such as thermal requirements or spectral band, there may be no higher-index plastic materials that are available. In this case, aspheric surfaces may again be used to provide the aberration reduction that would have been obtained from changing to a higher-index material. In terms of Petzval correction, if alternate materials are not available, it may be that a certain amount of Petzval curvature must be tolerated.

Another design technique in glass systems (which we have already proposed as an alternate solution in plastic systems) is the use of aspheric surfaces. In the design of glass optical systems, the use of an aspheric surface should be carefully considered. While improved manufacturing techniques [such as glass molding, computer-controlled grinding and polishing, and magnetorheological finishing (MRF)^{xiii}] have made it possible to produce aspheric glass elements, they still typically cost several times a similar spherical glass element. In some cases, however, the increased cost of a glass asphere is well worth the performance or

^{xiii} MRF is a registered trademark of QED Technologies.

packaging improvements that it brings. In the case of plastic optical elements, an aspheric surface costs no more than a spherical surface and should be used appropriately as needed.

In addition to the classic design techniques discussed above, there are also some “rules of thumb” used in the design of glass optics that do not apply to plastic optics. Probably the best known of these is the conversion (in a glass lens) of a weakly powered long-radius surface to a planar surface. For instance, in the discussion of lens bending, we showed that the optimum form for minimum spherical aberration (for $n = 1.5$), with an infinite object distance, has a weakly powered rear surface. In moving to a production design, the optician making the lens would commonly ask if the surface could be made planar, which would be easier and less costly to manufacture. In the case of molded plastic optics, just the opposite is true. Instead of turning the weak surface into a planar surface, we would want to add more power to it. The reason for this comes from the molding process. A curved surface will have more structural support (or surface tension) than a planar surface. This will help the surface to be stable while the part is cooling, resulting in less variation in radius as well as less surface irregularity. As discussed in the section on molding, when planar surfaces of high quality are required, it is sometimes necessary to move to an injection-compression molding method.

If the lens is not going to be molded but rather diamond turned, it is not necessary to add power to the weak surface. In fact, it may be easier to make the surface flat, which will allow it to be easily fixtured when diamond turning the curved surface.

Another rule in glass lenses that is often not required in plastic optic elements is symmetry. In the case of glass biconvex or biconcave lens elements that are almost symmetric, the rule of thumb is to force them to be symmetric. This serves several purposes, such as reduced tooling and test plates in the optical shop, and it eliminates the possibility of the lens being installed backwards in the assembly. For plastic optics, the optical inserts are usually formed by independently machined optical inserts. The inserts themselves do not necessarily have the same length or diameter on the two halves of the mold, which reduces the possibility of them being inserted into the wrong side. Also, the flanging on many plastic optical elements is not symmetric (often intentionally so), due to mounting or molding design. The use of automated assembly equipment, with indexed features, should reduce the incorrect insertion of elements. In addition, for manual or automated assembly, orientation marks (such as indentations on the flange) may be molded into the part to provide a visual reference.

4.4 Shape and Thickness

In addition to the rule-of-thumb differences between glass and plastic optics mentioned above, there are also often differences in the preferred shape and

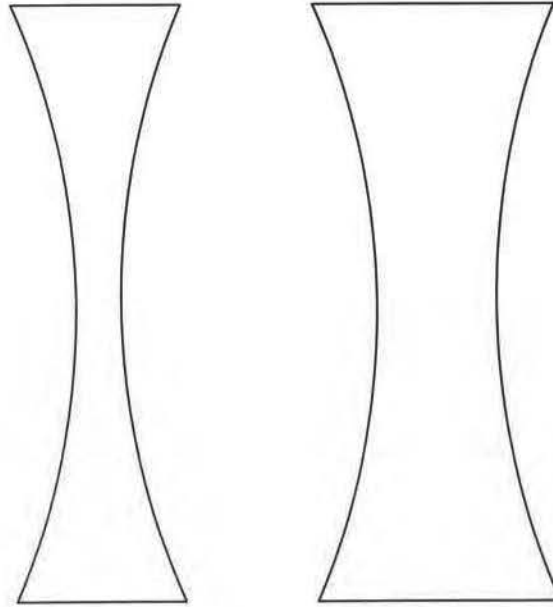


Figure 4.12 Negative lens with thin (left) and with preferred (right) center thickness.

thickness of plastic versus glass optics. These differences are driven by the manufacturing method, in this case injection molding. A fundamental requirement in the molding of plastic optics is sufficient thickness for the molten plastic to flow through. This generally constrains two parameters: the center thickness of the element, particularly for negative lenses, and the edge thickness of the element. Regarding the center thickness, consider the element shown in the left-hand side of Fig. 4.12. This would be a fairly standard glass component, but it is not a preferred plastic element. The reason for this is the flow of plastic during the injection molding process. The gate for injection of the plastic will typically be on the edge of the part. As the plastic enters the mold cavity, it will want to take the path of least resistance, which for this lens will be around the thicker outside portion of the lens. Any flanging added to the part will potentially exacerbate the problem. If the plastic first flows around the periphery of the lens, reaching the center last, the joining of the flow fronts in the central portion of the lens will result in a knit line. In addition to the knit line, the large thickness variation over the part will potentially result in a significant shrinkage variation over the clear aperture, possibly requiring several mold compensation cycles to achieve the desired surfaces.

Increasing the center thickness of the part, as shown in the right-hand side of Fig. 4.12, can eliminate both of these molding problems. With this increased thickness, the mold processor can get the plastic to flow through the center of the part, eliminating the knit line or at least moving it out of the clear aperture. The

reduced thickness variation also helps with the variation in shrinkage over the part. Some plastic optics vendors do not like to specify a standard edge-to-center thickness ratio but prefer to look at each part individually. Others will quote a rule of thumb for the edge-to-center thickness ratio to be less than either three or five, depending on the individual asked.

With regard to edge thickness of the lens, the requirement is to provide enough thickness for a suitable gate. The gate size required will depend on the individual part size and shape, but it is always preferable to have room to enlarge the gate if needed. Small parts may be able to use a smaller gate than large parts, but there will generally be some lower limit on minimum gate size. Gates with a width as small as 0.5 mm have been used on small lenses for cell phone cameras.

Edge thickness can be constrained in the optical design program during the optimization process. It is important that the designer understands how the edge thickness value is calculated in the particular software being used. If it is calculated from the sags of the surfaces at the heights of maximum ray intersection, the value calculated may meet the constraint value entered but not the real manufacturing requirement. This is because the clear aperture of the surface will need to be larger than the height of the ray intersections to allow for edge break in the molding process. Molders typically will ask for at least 0.5 to 1 mm of radial distance between the used portion of the optical surface and the transition into the element flange or diameter. If possible, the designer should attempt to provide greater than this amount, particularly on larger parts or parts with large amounts of thickness variation.

In the case of parts with a relatively large center thickness and a small edge thickness, as is sometimes seen on biconvex parts, adequate edge thickness must be allowed so that the gate can be large enough to prevent “jetting.” Jetting occurs when the plastic entering the cavity sprays across the open cavity space instead of smoothly flowing through the cavity. It can result in numerous knit lines or unusable parts. Limiting the power of the element, or increasing the center thickness, can generally alleviate the thin edge thickness. Jetting is obviously not a concern for parts that are to be diamond turned.

To be clear in regard to our discussion of edge thickness, it is the minimum cross-sectional area that the molten plastic must flow through that is typically the limiting factor. Occasionally, an engineer will attempt to solve the edge-thickness problem by adding a flange to the lens that is wider than the thickness at the edge of the clear aperture. While adding a flange may enable a wider gate, the plastic still must pass through the smaller thickness area. This is not to say that adding a flange will not help. Having the larger gate available may open the process window for the mold engineer; however, in the case of undersized edges it will not completely solve the flow problem.

Due to variations in shrinkage with thickness, from the viewpoint of a molder, the preferred shape of a molded element is one that has a fairly uniform thickness. In practical designs, in order to obtain sufficient optical power, most optical elements will not have this form. The goal of the optical designer should be to create parts that are as moldable as possible while still meeting the system

performance requirements. In some cases, there may need to be a trade between the performance and ease of production of the system. Figure 4.13 shows a series of parts, some of which should mold well, and some of which should, if possible, be avoided. Referring to the figure, Lens A would be a fairly typical glass convex-plano lens. For plastic, however, it is not a preferred shape. The edge thickness is fairly thin, which would limit the gate size. In addition, the rear plano surface would not support itself well during the molding process, potentially leading to sink on the surface. A preferred version of the lens is shown as Lens B. The center thickness of the lens has been increased, which allows a better edge thickness. The plano surface has been changed to a fairly low-powered surface, which will provide better support and less variation in radius and irregularity. Lens C shows a typical meniscus lens. This lens should mold well, due to its relatively uniform thickness. Lens D shows a biconvex lens with mounting flanges added. The flanges have been extended far enough to protect the vertices of the surfaces. The flanges are of reasonable length and should not cause problems when molding the lens. Lens E shows a lens where the flange has been extended in order to act as a lens spacer. This is not a preferred lens shape because the long flange will be difficult to fill while maintaining the optical surfaces. It would be better to use a lens similar to Lens D and add a separate spacer if required.

Because of constraints such as cost or packaging, the number of elements a designer is allowed to use may be limited. In this situation, it may be necessary for each element to “work” as hard as it can. This, in addition to the use of aspheric surfaces, may result in lens shapes that are unfamiliar to those used to working with glass lenses. Figure 4.14 shows two examples of such lenses, which while not typically seen in glass designs, would be considered perfectly normal to those familiar with plastic optical design. The lens on the left comes from a web camera design, and the lens on the right comes from a cell phone

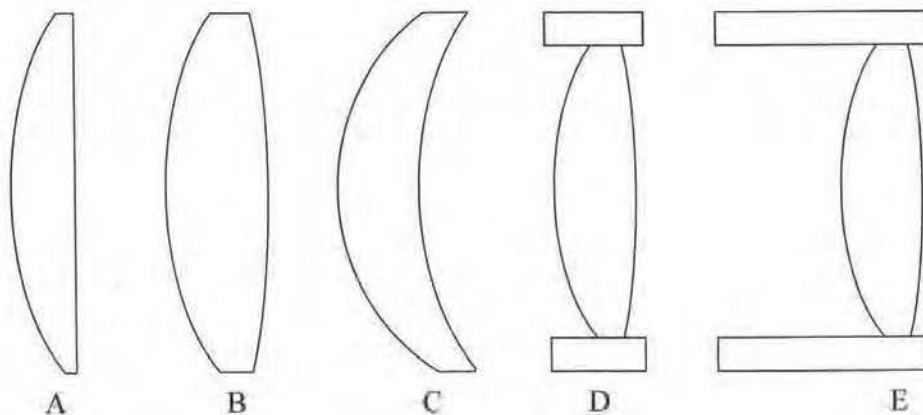


Figure 4.13 Various element shapes, some of which should be avoided (A, E).

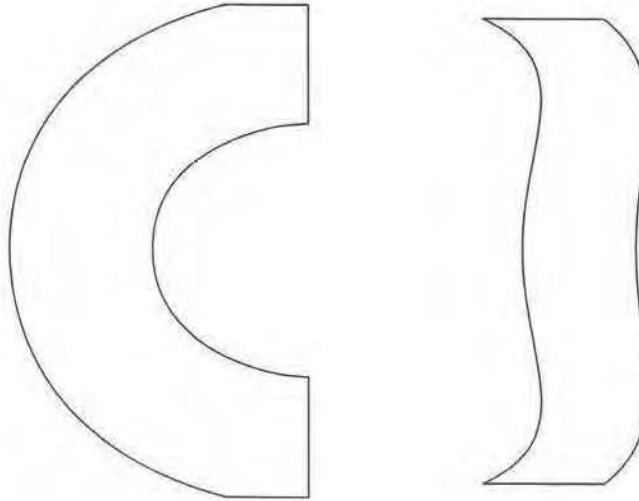


Figure 4.14 Two examples of lens shapes seen in plastic that would be unusual in glass.

camera design. These are not just design study curiosities, as both systems have been put into high-volume production. From a manufacturing standpoint, the lens on the left is considerably easier to produce in plastic than in glass. Manufacturing it in glass requires each lens to be polished individually, as opposed to blocking up a number of lenses on a spindle, which is normally done. In plastic, a multiple-cavity tool produced several copies of the lens with each mold cycle.

Experienced designers of glass optical systems often have familiarity with certain lens shapes as well as an understanding of why systems look the way that they do. They can often get an idea of what the system is doing just by looking at the lenses and comparing it to their knowledge of the “classical” design forms. The same is often true with plastic optical systems. With experience, familiarity with certain plastic lens shapes will develop, and what previously seemed strange will be completely normal.

4.5 Aspheric Surfaces

We have mentioned several times that with plastic optics, unlike glass, creating an aspheric surface costs essentially nothing more than creating a spherical surface. Given this, it makes sense to take advantage of aspheric surfaces in plastic optical designs. An aspheric surface is simply a surface that is not spherical. While a spherical surface can be completely described by defining its radius of curvature, an aspheric surface requires a more complex representation.

We consider two main types of aspheric surfaces, those that are rotationally symmetric and those that are not. Consider first aspheric surfaces with rotational

symmetry, of which there are (at least) two well-known forms. The first form is the family of conics. Those who remember their geometry will already know that conics are plane curves that are created by the intersection of a plane and a right circular cone. If the plane is perpendicular to the axis of the cone, the intersection curve is a circle. As the plane is tilted, the intersection curve becomes an ellipse (of course, a circle can be considered a special case of an ellipse). Continuing to tilt the plane, such that one line in the cone is parallel to the plane, the intersection of the two is an open curve, which is a parabola. Continuing to tilt the plane, now two lines in the cone will be parallel to the plane, and the intersecting curve is a hyperbola. When these intersection curves are rotated about their symmetry axis, they form surfaces that are called conic surfaces. As an example, in the case of rotating the plane curve of a parabola, we would generate a parabolic surface or a paraboloid.

Conic surfaces are easily represented in a closed form, as shown in Eq. (4.6):

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}}, \quad (4.6)$$

where z is the sag of the surface, which is the distance along the axis of the surface from a vertex plane perpendicular to the axis of the surface; c is the base curvature, the inverse of the radius at the vertex of the surface; k is the conic constant; and r is the radial coordinate, which is the perpendicular distance from the axis. An illustration of the sag of an aspheric surface is shown in Fig. 4.15. The conic constant, along with the base radius, completely describe the conic

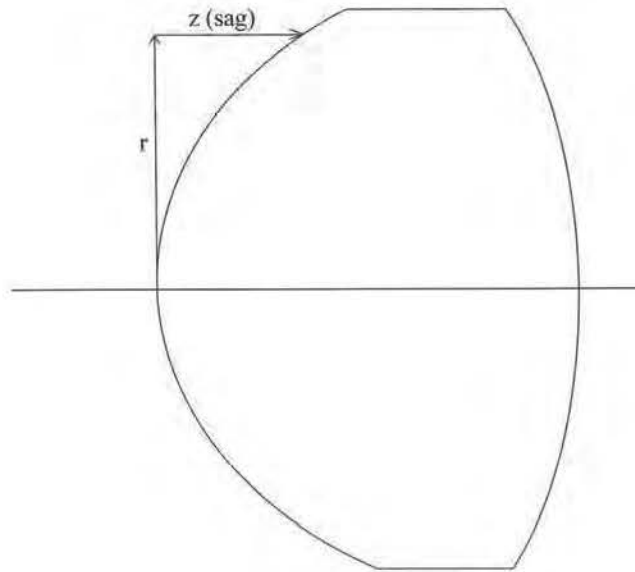


Figure 4.15 Illustration of sag for an aspheric surface.

surface. Using the description in Eq. (4.6), a surface that has a conic constant of 0 is spherical, a surface with a conic constant between 0 and -1 is a (prolate) ellipsoid, a surface with a conic constant equal to -1 is a paraboloid, and a surface with a conic constant less than -1 is a hyperboloid. The conic constant can also be greater than zero, in which case the surface is an oblate ellipsoid.

Conic surfaces have the property of perfect point-to-point reflective imaging for a single pair of points along their axis. For instance, an ellipse provides perfect imaging between its two foci, while a parabola provides perfect imaging of a point at infinity. Thus, a parabolic surface can take a collimated on-axis input beam and focus the beam perfectly at its focal point. As soon as the beam moves off axis, however, there will no longer be perfect imagery.

Conics have long been used in the design of reflecting telescopes. The Ritchey-Chretien telescope form, which consists of hyperbolic primary and secondary mirrors, is an example of this. Conics' property of on-axis point-to-point imaging is useful as a test method in their production. A point source, or input collimated beam in the case of parabolic surfaces, can be used, and the resulting image evaluated. Assuming proper object and focus position, deviation from perfect imagery results from imperfect surface form. Interpretation of the point-source image allows correction of the surface to its proper form.

The second common form of description of aspheric surfaces is a polynomial addition to a sphere or conic, as is shown in Eq. (4.7). This is a fairly standard form used in most optical design software:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + a_2r^4 + a_3r^6 + a_4r^8 + a_5r^{10} + \dots, \quad (4.7)$$

where the a_i terms are the coefficients of the aspheric terms, and the other variables are the same as in Eq. (4.6).

In Eq. (4.7), the asphere is described using even powers. Sometimes, the absolute value of odd power terms is also used (if the absolute value is not taken, the surface will not be rotationally symmetric). The naming convention of this type of aspheric surface is related to the highest power used. For instance, if the highest order coefficient used is that related to the eighth power, we would say that the surface is an eighth-order polynomial asphere. Obviously, there is an assumption that we are using the standard even-ordered form. To be more specific, we may say we have an eighth-order, even-polynomial asphere.

Polynomial aspheric surfaces do not exhibit the point-to-point imagery of conic surfaces. This means they cannot be tested in the same way. In the past, this often led to conics being selected over polynomial aspheres. Developments in machining and testing have made this much less of a concern, and polynomial aspheric surfaces are frequently used in systems where the surfaces will be produced by diamond turning and/or molding, such as in reflective, infrared, and plastic optical systems.

In addition to the conic and polynomial representation of aspheric surfaces, there are several other forms. Most optical design programs provide the choice of multiple aspheric surface representations as well as the option for user-defined surfaces. In some cases, the aspheric surface may not have a closed-form solution but may be represented by an array of points, with a suitable interpolation in between.

When required, nonrotationally symmetric aspheric surfaces are also used. In some cases, the surface is simply an off-axis section of a rotationally symmetric surface. Thus, the parent surface is rotationally symmetric, but the used section is not. In other cases, the surface is an extension of the surfaces already described. Instead of describing the surface by a single radial variable, two variables (often the Cartesian coordinates x and y) are used. For instance, a biconic surface may be utilized, which will be described by (possibly) two radii, and two conic constants, k_x and k_y . Similarly, we can change from the radial variable on the polynomial asphere to two Cartesian variables, resulting in an anamorphic asphere. Nonrotationally symmetric aspheres may be used in applications where some system characteristic is nonrotationally symmetric. For instance, laser diodes often emit a noncircular beam that has inherent astigmatism. Nonrotationally symmetric aspheric surfaces may be used to correct this output beam.

In classical optical design, designers are often taught to do as much as possible using spherical surfaces, with an asphere grudgingly used as a last resort in order to meet some performance requirement. As such, the general design form may be well established before the addition of an aspheric surface, with the asphere tweaking up the system performance but not necessarily altering the basic form of the system. This design philosophy is changing somewhat as the use of aspheric surfaces becomes less costly. In the design of plastic optical systems, the decision to use aspheric surfaces is often almost a foregone conclusion, changing the point at which they are inserted into the design process as compared to classical glass systems. This can result in design forms that are distinctly different from those created if the asphere were added near the end of the (local) design optimization. In theory, if global optimization is used (and works as desired), similar solutions should be identified regardless of what starting point design the aspheric surface is added to, provided the necessary variables are available. As the use of aspheric surfaces in optical systems has become more common, there have been increased publications on their use⁷¹ as well as courses on the subject.⁷² In addition to these resources, we refer the reader to the chapter by Shannon.⁷³

From a simple viewpoint, the location of an aspheric surface determines the effect it has on aberrations. By location, we are referring to the distance of the aspheric surface from the aperture stop (or pupils) of the system. An aspheric surface that is placed at the aperture stop will only affect the spherical aberration produced by the surface, while an aspheric surface that is placed away from the aperture stop will affect spherical aberration, coma, astigmatism, and distortion. One way to think of this is to consider the beam placements on the surface. At

the aperture stop, all the beams from the different field angles pass together through the stop. Thus, all fields will see essentially the same effect from the surface, affecting aberrations that do not depend on the field angle, such as spherical aberration. When the aspheric surface is away from the aperture stop (or its images, the pupils), the beams associated with different fields are separated on the surface and will each see a somewhat different effect from the aspheric surface. Thus, multiple aberrations can be affected.

There is no definitive rule for selection of which surface or surfaces on which to use aspheres. From the discussion above, it would make sense to place an asphere near the stop if we are attempting to control spherical aberration, and away from the stop if we are trying to control field-dependent aberrations, such as coma and astigmatism. Of course, in a multielement system, it is the combined aberration content that ultimately determines the image quality. If we place an aspheric surface on one element (for instance, near the stop), the ability to control spherical aberration through this asphere means that the other elements do not need to “worry” about spherical aberration as much, and we can change their shape to work on other aberrations. Thus, the addition of an aspheric surface on one element of the system can not only change that element but also potentially change the other elements. In general, placing an asphere on the surface with the largest beam extent will provide the maximum aspheric leverage.

In the design process of plastic optical systems, it may be useful to make one surface on each of the elements aspheric and allow the optimization of the lens design software to use them as appropriate. It is generally not good practice to make all of the surfaces aspheres from the start. In this case, the optimization algorithm may “beat” the aspheres against each other, introducing a large amount of aberration at one surface that is cancelled by a large negative amount of the same aberration at another surface. This is not a preferred design form because it will tend to be more sensitive to assembly tolerances of the system, such as decenter. If one aspheric surface per lens element is not providing adequate performance, additional aspheric surfaces may be added to determine any performance advantage.

When using aspheric surfaces in a design, a few changes in the setup used for spherical lens design are in order. First, the number of field angles defined should generally be increased. In a design using spherical lenses, it is common to have three or four defined field angles. In designs using multiple aspheric surfaces, it is possible for the lens to be well corrected at these three or four field angles and to perform poorly in between them. This can sometimes be seen by looking at the astigmatic field plots, which may curve repeatedly back and forth, crossing zero at each of the defined fields. By adding additional field angles, we can force the optimization algorithm to work on the performance across the entire image plane. We essentially do not provide the algorithm enough room in the field spacing to allow the performance to “wiggle,” as it could with fewer defined fields.

In addition to increasing the number of defined fields, it is also useful to increase the ray density that the optimization algorithm uses. As in the case of too few field angles, if there are too few rays, they may be well corrected, but

other rays that are not evaluated may not be. This can result in a low merit-function value that suddenly increases when a denser ray grid is used. It is a good practice when using a large number of aspheres to increase the ray density and ensure that there is no significant change in performance.

A final adjustment when designing with aspheric surfaces is to either reduce the minimum improvement value that stops the optimization cycle or to repeatedly run the optimization algorithm. Sometimes, systems with multiple aspheric surfaces will stagnate during the optimization process. However, repeatedly running the optimization algorithm often will continue to drive the merit function value down.

Throughout the design process, or at least near its end, all aspheric surfaces should be evaluated against a “best-fit sphere.” A best-fit sphere is a spherical surface with the radius selected such that it has minimal departure from the aspheric surface. In the grinding and polishing of glass aspheres, the use of a best-fit sphere as a starting point minimizes the amount of material that must be removed to create the aspheric surface. In the case of molded parts, if a spherical base surface is used on the optical insert, it may determine how much nickel plating needs to be removed. An important reason to evaluate the asphere against a best-fit sphere is to determine whether the asphere is really necessary. Once aspheric terms are set as variables in the optimization algorithm within the lens design software, they will likely be used, regardless of how small the advantage gained.

If it is determined from comparison to the best-fit sphere that the asphere has a very small departure, then the aspheric surface should be made spherical and the design reoptimized to see if a performance difference results. This may seem at odds with our earlier statements about the cost of aspheres and spheres being the same. In actuality, we are not concerned about cost savings but in creating fewer potential problems by simplifying the system. To put it plainly, there is no need to make the system more complex than it needs to be, just because we can. A sphere, which is defined completely by its radius, is easier to describe than an asphere. This means that fewer terms need to be considered during the manufacture and testing of the surface. This results in less chance for errors due to interchanging digits during any entry of numbers, such as aspheric coefficients. Also, a sphere is easier to test than an asphere, giving more options for the vendor (or customer) to verify the surface.

In addition to comparing the aspheric surfaces to best-fit spheres, the designer should also evaluate the aberration produced by each surface. As mentioned earlier, having too many aspheric surfaces may simply result in them beating against each other. Most optical design codes will provide graphs and/or numerical values of the various aberration contributions of each surface. These can be used to determine if aspheric surfaces are working with or against each other.

While the optical design code can create any shape asphere allowed by the coefficients it can vary, the designer needs to ensure that the aspheric surface can be produced and tested. Most aspheres can be molded, but there are differing

levels of complexity. For instance, if the aspheric surface is so steeply curved that it rolls back past a line drawn perpendicular to its axis (that is, it goes beyond a hemisphere) it may not be able to be manufactured in a straight-draw mold. Also, steeply curved surfaces may be difficult to test, making it hard to verify that they have been correctly manufactured.

For the most part, the ability to use aspheric surfaces provides a positive impact on the design of plastic optical systems. However, there can be one particular drawback to using refractive aspheric surfaces (in plastic or glass), which is the chromatic variation of aberrations. Aspheric surfaces do not change the axial or lateral color introduced by a surface. If the asphere is being used to introduce spherical aberration with the intention of offsetting the contributions from other surfaces, it will also introduce spherochromatism, the variation of spherical aberration with wavelength. The amount of spherochromatism introduced will generally be the amount of spherical aberration created by the surface divided by the Abbe number of the lens material. In some cases, spherochromatism can be used to balance the effect of axial color. Other times, however, it may degrade an otherwise monochromatically well-corrected solution. The designer needs to keep in mind the purpose of each aspheric surface and what benefit it brings to the overall design. Aspheric surfaces that do not provide benefit to the design should be removed.

4.6 Diffractive Surfaces

Diffractive surfaces rely upon the wave nature of light to perform their function. They typically consist of some form of microstructure on the optical surface. As a beam of light passes through the diffractive surface, the various microstructure features impart phase delays (usually 2π) to the different portions of the incident beam. As the beam propagates, these different portions interfere with each other, similar to the way that waves in water can combine to form regions of larger or smaller waves. By correctly designing the diffractive microstructures, we can get a desired beam from the surface in a manner similar to designing an aspheric surface to create or eliminate specific aberrations.

Diffractive optical surfaces are used for a variety of purposes, such as fan-out gratings, athermalization, and beam shaping. In many plastic optics imaging systems employing diffractive optics, they are used for color correction, that is, to control chromatic aberration. In this section, a brief overview of their use for this purpose is given. Readers interested in a more thorough discussion of diffractive optics are referred to Ref. 74.

Probably the best-known diffractive surface is the diffraction grating. A diffraction grating normally consists of a substrate with a pattern of parallel-ruled lines on it. Diffraction gratings are often used to separate wavelengths of light, sending each wavelength away from the surface in a different direction. The diffractive surfaces used for color correction are somewhat similar to a diffraction grating, with the difference that instead of a series of parallel-ruled

5.3 Cell Phone Camera

The next design example we discuss is a cell phone camera. These systems have become quite popular, to the point that it is often more difficult to purchase a cell phone without a camera than a phone with one. Early cell phone cameras used relatively low-resolution sensors and often had single-element lens designs. The original use model was that the camera would be for taking “bar shots,” that is, people would be taking pictures of each other while out socializing. As the cameras became more popular and the convenience of using them was understood, increased image quality was demanded. The detector resolution steadily increased to the point that megapixel sensors are used today. This increase in sensor resolution and size drove complexity into the optical designs. Instead of single-element designs, two, three, and even four elements are used. In fact, the newest generation of cell phone cameras will have autofocus and zoom capability.

Figure 5.27 shows an example of a three-element cell phone camera design. These types of designs are usually heavily constrained, with overall length being a driving factor. This often results in thin, tightly spaced elements. During the design process, the edge and center thickness of the elements must be constrained to manufacturable sizes. Additionally, sensors containing microlens arrays may limit the chief ray angle of incidence on the image plane. This can result in unusual-looking (for glass) rear elements, which bend the ray bundles over to meet the angle of incidence constraint.

In this example, we will not focus on the actual design of such systems but instead concern ourselves with one aspect of their tolerance analysis. In particular, we compare the predicted performance for two different surface decenter probability distributions. Most cell phone camera lens designs tend to be quite sensitive to decenter of the elements, their surfaces, or both. As such, the maximum amount and the distribution of the various decentrations will affect the predicted performance. To show this, a predicted performance analysis was run, conducted through the use of a Monte Carlo simulation. As described before, a Monte Carlo analysis models the production of multiple systems by randomly varying parameters within their tolerance ranges according to a defined set of probability distributions. In this case, the probability distribution used for the surface decenter tolerance was varied.

First, a Monte Carlo simulation was performed for a surface decentration with a uniform distribution. This means that the surface decenter is equally likely to be anywhere within its tolerance range. Next, an endpoint distribution for the surface decenter was used. This means that the surface will always be decentered by the maximum amount allowed, with a rotational orientation of the decentration that is random. For instance, on one system, surface 1 on lens 1 may be decentered upward, while surface 2 on lens 1 is decentered to the left. In another instance, both may be decentered upward, which is similar to the entire lens shifting upward.

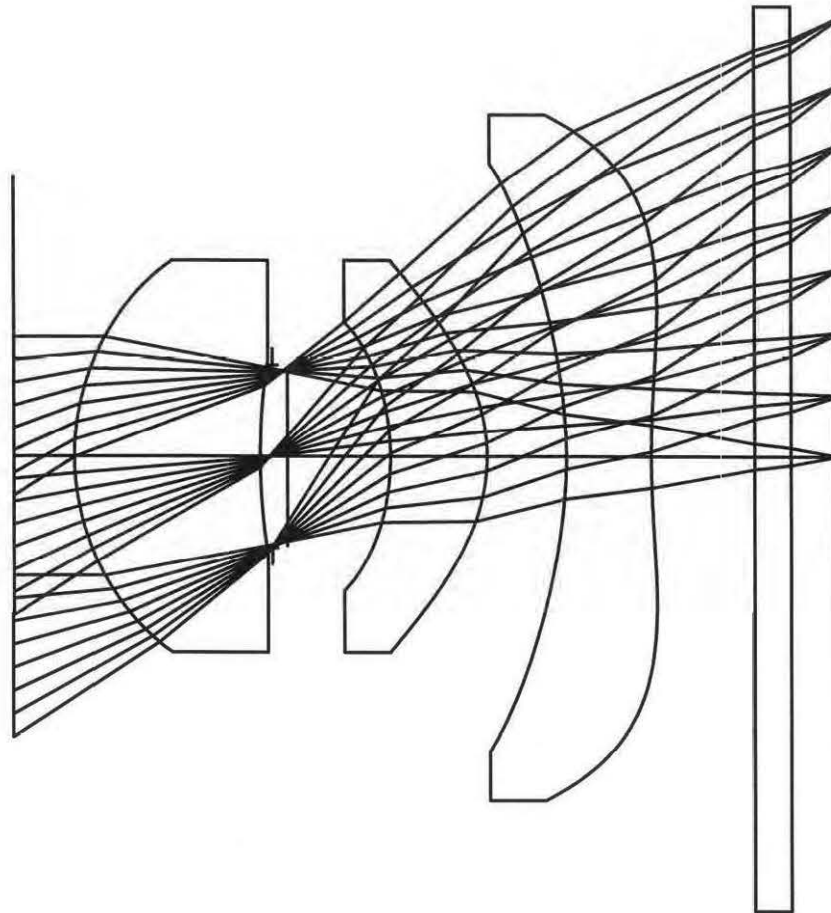


Figure 5.27 Three-element cell phone camera design.

All other tolerances used the same set of probability distributions (uniform) for both Monte Carlo runs. A total of 25,000 lenses were created in each Monte Carlo run, and the MTF data at several field points was collected. The tangential and sagittal MTF values for one off-axis field were averaged, and a histogram was generated from the data, which is shown in Fig. 5.28.

We can see from the histograms that the choice of probability distribution for surface decentration has an effect on the predicted performance distribution of the system. The uniform distribution, shown as the dashed line, has its peak at an MTF value at 50 cycles/mm of 0.465. The endpoint distribution, shown as the solid line, has its peak at an MTF value of 50 cycles/mm of 0.450. The effect of using the endpoint distribution is a general skewing to the left of the predicted performance distribution curve. This can be more clearly seen by plotting the normalized number of systems above a certain MTF value, which is shown in Fig. 5.29.

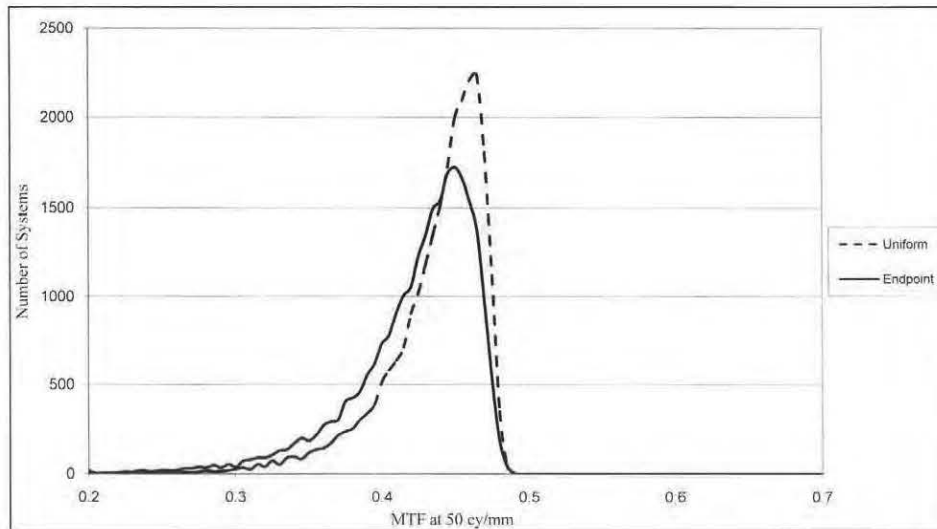


Figure 5.28 Histogram of data collected from Monte Carlo runs.

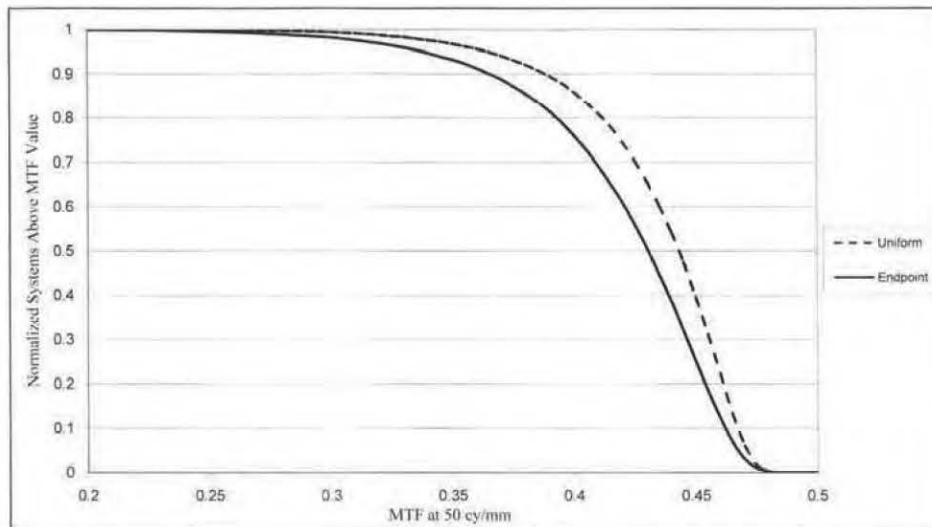


Figure 5.29 Normalized number of systems above a certain MTF value.

If we take the difference between the two curves, as is shown in Fig. 5.30, we can see the percentage difference in systems above a certain MTF value (at 50 cycles/mm) for the two distributions. For instance, consider the number of systems for the uniform distribution that have an MTF value at 50 cycles/mm above 0.35. This value turns out to be just under 97%. So if our system MTF specification were set at 0.35 (and we only considered this field), we would

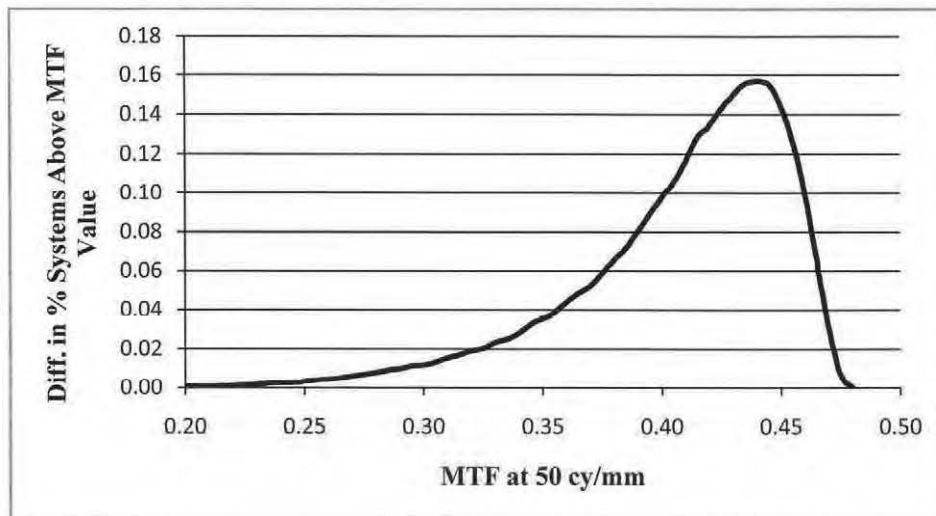


Figure 5.30 Difference in percentage of systems above a certain MTF value (for 50 cycles/mm).

expect a 3% yield loss during production. For the endpoint distribution, the percentage of the system that would meet this criterion is just over 93%. Thus, if the distribution of surface decentration had an endpoint distribution instead of a uniform distribution, we would see an additional 3.5% yield loss or double our uniform distribution prediction.

While 3.5% may not seem like a large value, it can have a significant impact on production, particularly when many thousands or millions of systems are being produced each month. A large amount of wasted material, time, and energy would go into producing and testing these systems. In this analysis, an endpoint distribution was used, which is a conservative selection. A parabolic distribution, which may be considered a compromise between endpoint and uniform distributions, may be more appropriate. Nevertheless, the fact that we saw a potential doubling in yield loss (for only a single field) should serve as a warning to the designer to carefully consider the choice of tolerance probability distributions in their analyses.

5.4 Infrared Multiorder or Harmonic Diffractive Lens

A question that frequently comes up with regard to plastic optics is why they are not seen more often in military or civilian IR systems. These systems, typically operating in the 3- to 5- or 8- to 12- μm region, often use lenses made from germanium, silicon, zinc sulfide, or other expensive materials. Since plastic optics are generally less costly, why not use them for these regions? The answer